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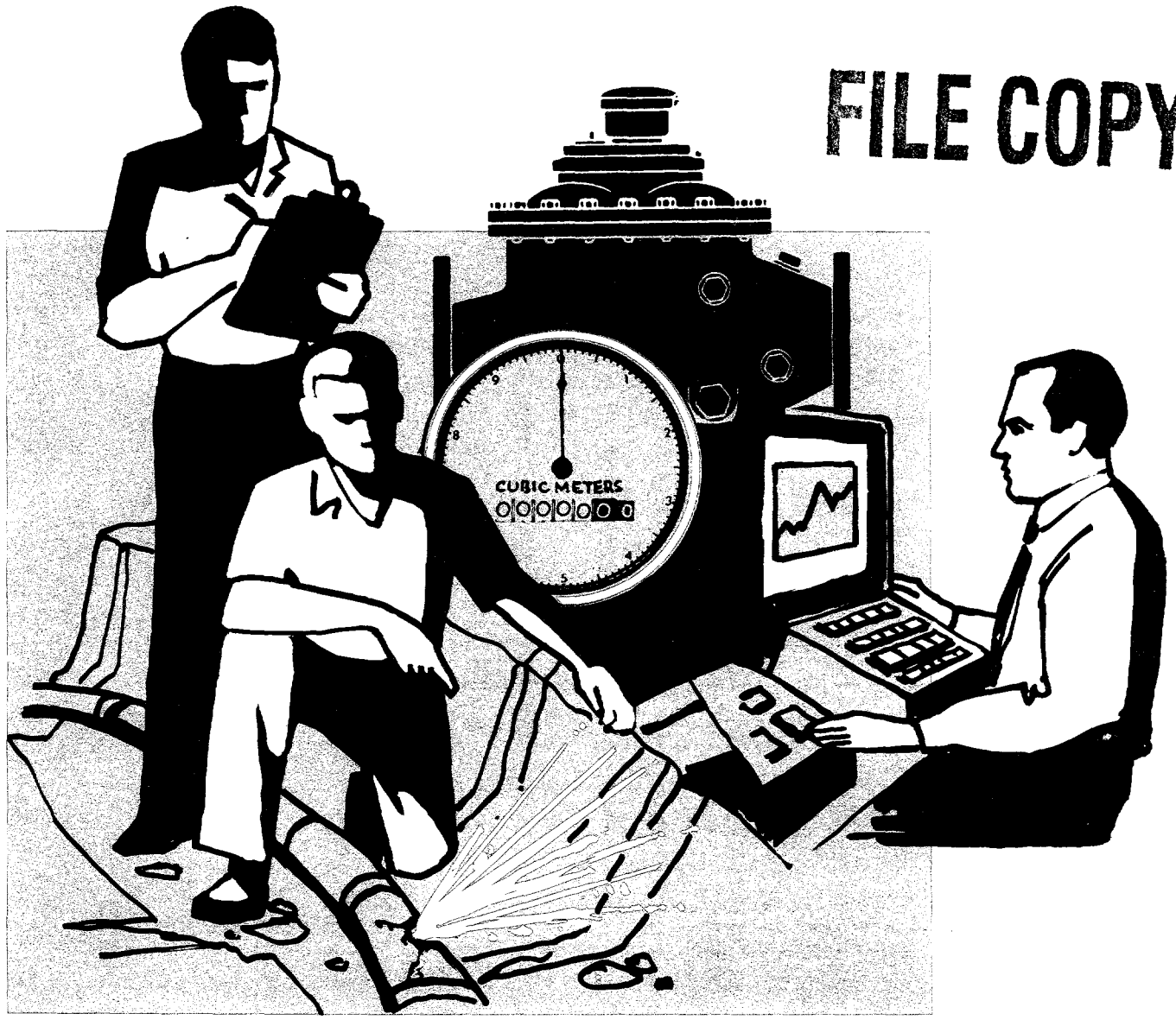# Corrosion Protection of Pipelines Conveying Water and Wastewater

Guidelines

Robert C. Prevost

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Corrosion Protection of Pipelines
Conveying Water and Wastewater

Guidelines

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(Distribution Systems Management)

The management of water supply infrastructure is a complex activity, involving both the operation and maintenance of existing facilities and the construction of new facilities. Water supply managers in developing countries, however, sometimes give a lower priority to operation and maintenance of old facilities than to the construction of new ones. Moreover, the management of water supply distribution systems often has a relatively low status in many water companies compared to the attention given to production facilities. As a consequence, there are large water losses caused by the premature deterioration of water mains, frequent metering failures and decreased revenues. This, in turn, can lead to economic inefficiencies caused by doubtful investment decisions.

This series of technical papers is intended for waterworks managers, distribution system maintenance engineers, and those concerned with making investment decisions for the rehabilitation or replacement of water supply facilities and the construction of new works. A subseries on Distribution Systems Management, of which this is one volume, aims to provide guidance on some of the most pressing institutional, technical and social problems faced by the managers and engineers of water supply distribution system in developing countries. Two other volumes in this subseries will be published shortly:

° The Reduction and Control of Unaccounted-for Water: Working Guidelines

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Proposed future volumes in the Distribution Systems Management subseries will cover topics such as selecting, procuring, and maintaining small domestic water meters; the political, social, institutional, and organizational implications of programs to reduce water losses; detecting and regularizing illegal service connections; and the scope for privatization in operation and maintenance.

Topics likely to be addressed in the main operations management series include reducing losses at source, raw water transmission and water treatment; meter reading, billing, and collection; and the characteristics of users who connect to available supply sources. All of these concerns influence the timing and scale of additional facilities.

Corrosion Protection of Pipelines Conveying Water and Wastewater

Guidelines

Robert C. Prevost

The World Bank
Washington, D.C.

The International Bank for Reconstruction
and Development/THE WORLD BANK
1818 H Street, N.W.
Washington, D.C. 20433, U.S.A.

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Robert C. Prevost is an electrical and mechanical engineer and a consultant to the
Water Supply and Urban Development Department of the World Bank.

ABSTRACT

The social importance and economic cost of water and sewage pipelines make it essential to maintain them in good working order. Corrosion is one of the most common factors in their alteration and possible, untimely destruction, but it can be prevented or controlled, usually at a relatively low cost. Based on an analysis of existing literature and a number of case studies, this document suggests a series of guidelines for effective corrosion control.

Water treatment can play a key role in preventing or controlling internal pipe corrosion; the use of appropriate linings can protect metal components. Coatings or protective outer thin plastic sleeves can effectively guard pipelines against corrosion from external factors (aggressive soils, saline water, stray currents, etc.). Cathodic protection is also effective, but should be used only where required given the high level of technical sophistication needed for successful operation and the problems it can cause for certain pipe types and pipeline systems through improper use.

New techniques are being developed for rehabilitating old pipelines to extend their functional life, thereby avoiding costly replacement. These processes require, however, a high level of expertise as well as specialized equipment; urban areas in developing countries with relatively newer and smaller pipeline networks and lower labor costs may therefore find rehabilitation to be a less cost-effective and attractive option.

ACKNOWLEDGMENTS

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ACRONYMS

ACPA	American Concrete Pipe Association
ASTM	. American Society for Testing Materials
ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
AFEE	Association Française pour l'Etude des Eaux
AGHTM	Association Générale des Hygiénistes et Techniciens Municipaux
BHRA	British Hydromechanics Research Association
BSI	British Standards Institution
Cebelcor	Centre Belge d'Etude de la Corrosion
Cebedeau	Centre Belge d'Etude et de Documentation des Eaux
CEOCOR	Comité pour l'Europe Occidentale Contre la Corrosion des Conduites Souterraines
DIN	German Standardization Institution
DVWK	German Association for Water Resources and Land Improvements
EPA	United States Environmental Protection Agency
IWSA	International Water Supply Association
NACE	National Association of Corrosion Engineers
NBS	National Bureau of Standards
WPCF	Water Pollution Control Federation
WRC	Water Research Council

UNITS AND MEASURES

1 mm = 1/1000 m = millimeter = 1/25.4 inches

1 m = meter = 3.28 feet

1 km = 1000 m = kilometer

1 l = liter = 10^{-3} m^3 = 1/3.785 US gallon = 1/28.32 cubic feet

1 ton (metric) = 1000 kg (kilogram) = 2,205 pounds

1 Pa (Pascal) = N/m^2 (Newton per sq m) = 1/6.895 pounds per square inch

1 MPa = 10^6 Pa

EXECUTIVE SUMMARY

Pipes and pipelines are an essential ingredient of water supply and sewerage systems, the lifelines of human communities. Usually laid underground, these systems carry water to and wastewater from homes, businesses, and industries; they also convey piped irrigation water. All require huge investments: nowadays the cost of constructing water supply and sewerage systems ranges between $20-$50 per capita in rural areas and $300-$700 per capita in cities and towns. A city of one million people may invest up to a total of one billion dollars in water supply and sewerage, the bulk of which is spent on pipelines.

The social importance and high cost of water supply and sewerage systems leave no doubt that the integrity of these systems must be maintained. In particular, these factors imply that corrosion control or prevention is economically justified. They also suggest that among the expenditures of water supply and sewerage utilities, capital investment usually is far more important than operating costs. The latter include only small amounts designated for corrosion control or prevention, which cannot readily be sorted out from other charges, but are needed to safeguard the systems. Further, the direct costs of pipe corrosion that takes place underground—out of reach of common observation—are very difficult to calculate and become evident only late in the process. In addition, there are indirect costs associated with leaks, breakages, service interruptions, sewer collapses, and repairs.

It is therefore not surprising that data outlining the costs of loss and damage from corrosion are quite scarce. One estimate shows that annual losses due to corrosion of water distribution systems in the United States in 1978 totaled $380 million. These losses could have been avoided by stabilizing corrosive waters—one method of corrosion control—using $30 million worth of lime.

The scope of this document is corrosion. It does not include other aspects of pipeline design, construction, or operation except where these aspects have a direct relationship to corrosion. It addresses corrosion in pipelines used for the conveyance of water and wastewater and may extend to piped irrigation water; it includes transmission and distribution mains, but not pipe for in-house plumbing, such as copper pipe, or for industrial uses. Corrosion, however, can take a heavy toll in these installations as well.

By definition, corrosion is the alteration of structures by extraneous agents. Corrosion not only affects pipes, but also, through its by-products, the water conveyed through them. The potential for health hazards cannot, therefore, be overlooked in drinking water supply systems.

Pipe corrosion changes the chemical composition of the water being carried so that it may be loaded with calcium compounds, may be discolored, which is usually a mere inconvenience, or may contain harmful heavy metals such as lead or cadmium compounds. Toxins may be released from bacterial growth

within pipes, but they generally are not present in sufficient quantities to pose a health hazard.

Damage to pipes could result in water seepage--a minor inconvenience compared to large leaks--or to major failures such as structural collapse. Corrosion may proceed slowly, as in encrustation in metal water pipes, or rapidly, as in sulfide corrosion of concrete sewers. Or, in relatively rare cases involving prestressed concrete pipes, corrosion may cause pipes to burst suddenly. Failures attributed to mechanical or soil defects often originate in corrosion. If ignored, corrosion will lead to service interruptions and the eventual ruin of entire systems.

Corrosion has been and remains the subject of countless field and laboratory studies, books, publications of all sorts, and conferences, many of which are excellent and yield the needed answers. Although there is a very wide consensus about many technical matters, uncertainties and debate persist in some areas. Many institutions, committees, and professional associations organize conferences and publish documents on corrosion as part of their statutory activity.

Corrosion is a multidisciplinary problem requiring specialized knowledge in each of its diverse aspects. As a result, literature on corrosion tends to be specific to certain materials, phenomena, or processes and is therefore fragmented. Also, studies on corrosion frequently do not support their conclusions with examples, much less with adequately documented cases providing information such as pipe type, diameter length, design and construction specifications and dates, soil types, climate, operating conditions, maintenance procedures, problems encountered, solutions attempted and results, and other details that the thorough assessment of a case requires. Instead, corrosion studies frequently rely on chemistry, laboratory tests, and simulation (e.g., buried pipes in test sites), rather than actual field experience. This somewhat reduces their usefulness.

Chapter 1 introduces the study and also recommends two general guidelines for "lenders," "borrowers," and "owners" of water distribution and wastewater collection systems. Chapter 2 lists the complete set of 26 guidelines that cover both water and sewer systems. Project officers should find this list useful when they prepare terms of reference for project preparation studies. The remaining chapters discuss inert pipe materials, internal and external corrosion, and rehabilitation technologies, which are the basis for the guidelines. Each chapter describes good and bad experiences in connection with corrosion and concludes with the guidelines relevant to the topic discussed in that chapter; a list of selected references for detailed study completes the chapter. Annex 1 provides a list of institutions that are actively involved in corrosion studies. It is expected that users will find this to be a handy manual in enhancing project design, construction, and maintenance leading to water supply and sewerage systems with long and useful lives.

Chapter 1

INTRODUCTION

1.   Pipe corrosion is not an accidental, isolated phenomenon. It occurs everywhere, as a result of normal chemical, physical, and biological processes. Its effects range from mere inconvenience to total disruption of water and sewer services. Such problems usually take years to develop, but sometimes they evolve very rapidly. If not prevented or treated, corrosion can destroy entire pipe systems in which millions of dollars have been invested.

2.   Corrosion, evidently, has tremendous economic importance. It presents a special problem in developing countries because water and sewerage systems are often deficient, the climate is generally warm, and there is less awareness of corrosion problems.

3.   Pipe corrosion can, however, be effectively controlled--even prevented--in virtually all circumstances through relatively simple design and construction measures and maintenance operations. But prevention and control require an awareness of basic facts that is currently lacking.

4.   Despite the abundance of literature on the subject of pipe corrosion, there are few comprehensive documents on corrosion prevention and equally few supporting case studies based on field experience. This document and the accompanying guidelines represent an attempt to fill this gap.

5.   The core of this study which is based on documented evidence is the series of guidelines that appear at the end of each chapter. They have been drafted in general terms so that they can be applied in most situations and can assist those responsible in preventing major oversights. The guidelines stress the need for technically sound and cost-effective solutions; they apply to both existing systems and new systems planned for construction.

6.   The bibliographic search upon which this paper was prepared was carried out with the assistance of the information center and retrieval service of the Association Française pour l'Etude des Eaux (AFEE), through their Sophia Antipolis branch. Also used were the Aqualine data base of the Water Research Council (U.K.) and the CEOCOR publications. Both of the above-mentioned retrieval systems use internationally accessible data banks as well as their own or those of Pont à Mousson, S.A. Over 700 documents, publications, and books have been reviewed. These were complemented by information provided by individual experts and by additional references found in documents obtained through the computerized retrieval systems. Lists of references for each part of the present paper are appended.

7.   The bibliographic search was primarily intended to find documented cases of pipeline failures due to corrosion. The literature yielded, however, as expected, only a small number of well-documented cases. The major reason for this gap is the reluctance of manufacturers, designers, contractors, and system owners to reveal the problems they are encountering with pipe corrosion. This is unfortunate, since more open discussion among all concerned would help solve some of the current problems and prevent future ones.

8.   This study is based on a worldwide review of available technical literature and documents through 1986. The study does not represent new research nor does it repeat information available in existing literature. Rather, it attempts to present a synthesis of the most important information about pipeline corrosion and provide references to selected documents for those who need more detail. The selection of these materials should not be understood to imply disregard for non-cited works. Some of the processes and field experiences noted in this study are not well known, despite the fact that they have been published in books, international periodicals, or in documents issued by established institutions. Further, in view of the sensitive nature of the recommendations concerning some processes and materials, references are provided to support the statements in the text. All of these statements rest on established facts, and all judgments have been made independently. Some of them may not be in accord with the general consensus; manufacturers and pipe suppliers may disagree with some statements made herein.

9.   The approach taken toward solutions is conservative in that unproven innovations or processes that do not have a well-established record of success are not endorsed. This does not imply that such processes are bad choices in all cases nor that they should not be used when their appraisal indicates a reasonable chance of success and no proven economical alternative is available or when adequate guarantees against failure can be obtained from the supplier.

10.   The types of pipe the document discusses are listed below with the acronyms used in the present document:

Inert material pipes:

    Vitrified clay (VC)
    Plastic (plain or profile wall) (P)
    Glass fiber reinforced plastic or resin (GRP)
    (referred to in the United States as FRP)

Metal pipes:

    Cast-iron (CI)
    Ductile iron (DI)
    Steel (S)

Nonmetal pipes:

    Concrete (C)
    Reinforced concrete (RC)
     (cylinder or non-cylinder types)
    Prestressed concrete (PSC)
     (cylinder or non-cylinder types)
    Asbestos-cement (AC)

11.   Lead pipe, now to be banned, is still mentioned here because of its former widespread use in service lines and the health hazard it causes.

12.   Documents about corrosion usually deal with the subject in terms of the pipe types listed above or by examining specific aspects of corrosion.

This paper departs from these practices. The main sections of this paper are inert materials; internal corrosion, subdivided in terms of water supply and sewerage systems; and external corrosion, followed by a brief discussion of rehabilitation technologies. For the convenience of the reader who is looking for a solution to a specific problem, each section is self-contained, complete with the relevant guidelines and its own references.

13. The guidelines are conclusions drawn from the cases, which are based on short descriptions of the corrosion processes and methodologies for prevention and control. The cases are fully described in the listed reference material. At the end of each chapter are the guidelines relating to the particular corrosion problem discussed in that chapter. For the convenience of the reader and as a handy reference for Bank project officers,[1] all of the guidelines are reproduced verbatim in Chapter 2 of this document.

14. It is important to note that protection against corrosion should be built into the system from the beginning, at the design stage, and pursued at each later stage of construction and operation. Implementation requires competent staff, adequate equipment and materials, and record keeping, which, in turn, necessitate training and appropriate budget allocations. Record keeping is essential since no meaningful decision in connection with corrosion can be made without sufficient understanding of events that occur during pipe system life spans of 50 years and more and cannot reliably be entrusted to operators' recollections. These needs should be included in system planning from the outset and evolve as the project proceeds. There are two very important general guidelines which should be followed during project preparation and implementation. These are the first two guidelines listed in Chapter 2. They are important in projects involving pipeline construction, rehabilitation, and operations and maintenance of distribution and collection systems. They should be incorporated in all terms of reference for the preparation and implementation of such projects.

Selected References

1.01 DeBerry, D. W., J. R. Kidwell, D. A. Malish, and P. Lassovsky. Corrosion in Potable Water Systems. Washington, D.C.: U.S. Environmental Protection Agency, February 1982. (Internal corrosion only.)

1.02 Galka, R., and A. P. J. Yates. Pipe Protection: A Review of Current Practice, second edition. BHRA and Paint Research Association, Cranfield, U.K., 1984. (Discusses primarily metal pipes.)

1.03 Neveux, M. La Corrosion des Conduits d'Eau et de Gaz. Editions Eyrolles, Paris, France, 1968.

1/ The paper deals mostly with design principles, although portions might be included in bidding documents. If that occurs, they should be reviewed on a case by case application by project officers to ensure their technical appropriateness.

1.04 Pourbaix, M. Legons en Corrosion électrochimique. Cébelcor, Brussels,
      Belgium, 1975. English version: Dlenum Press, New York.

1.05 Singley, J. E., B. A. Baudet, P. H. Markey, and P. Lassovsky. Corrosion
      Manual for Internal Corrosion of Water Distribution Systems. Washington,
      D.C.: U.S. Environmental Protection Agency, April 1984.

1.06 Williams, J. "Bibliography of Underground Corrosion." Metal
      Performance, January 1955. (Lists only English documents; covers
      external corrosion; 10 sections in each issue from January to October
      1955.)

Chapter 2

CORROSION PROTECTION GUIDELINES
FOR WATER AND SEWER PIPELINES

General Guidelines

1.   Lenders shall require their borrowers, and owners shall require their designers or consultants, to propose a detailed implementation plan for protecting the system under consideration against corrosion and for addressing design, construction, and operational facets. This plan shall include any needed staff additions, provision for staff training, purchase of equipment or materials, and procedures for routine monitoring and reporting on corrosion problems. Any significant departure from the technical guidelines presented in part B below shall be noted and justified.

2.   Owners shall implement the present guidelines and shall monitor and keep records of corrosion problems. Owners shall employ specialized corrosion consultants as needed, e.g., for cathodic protection or rehabilitation of corrosion-damaged pipes.

Guidelines for Controlling Corrosion in Water Supply Systems with Pipe Made of Inert Materials

3.   Pipe made of inert materials with appropriate joints shall be used where service conditions allow and where such pipe is economical.

4.   Plastic pipe sensitive to permeation by petroleum products or other chemicals shall be protected, where needed, through measures such as installation at a safe distance from possible sources of contamination or the use of protective sheathing.

5.   Glass fiber reinforced plastic or resin pipe and all other plastic pipes may be used provided that for large-size pipe over 200-300 millimeters in diameter the following general conditions are strictly enforced:

(a)   pipe shall have a minimum long-term stiffness meeting the recommendations in References 3.01 and 3.03 (for example, $1500N/m^2$ in "street conditions"; that is, earth cover of one meter plus traffic load) or those of more recent, reliable specifications;

(b)   installation shall proceed along accepted standards such as ASTM, AWWA, or according to manufacturer's instructions (see Reference 3.04) and, in addition, field procedures shall be determined through the installation of test section(s) under actual construction conditions, using the same construction staff and labor, equipment, and backfilling materials that will be employed in the job at hand;

(c)   the above procedures shall secure maximum long-term deflections of 5 percent in any section; pipe that may be expected to exceed 5 percent long-term deflection shall be replaced or reinstalled, depending on the extent of damage; the deformed pipe should remain elliptical in shape;

(d) work shall proceed upon agreement on the above procedures, which shall be reviewed whenever necessary;

(e) close supervision of the work by competent site engineers shall be ongoing, and the pipe supplier shall provide guidance and training assistance;

(f) training of labor and engineers shall be provided as needed; and

(g) pipe characteristics, including stiffness, corrosion tests, and so forth shall be determined according to ASTM or equivalent standards and checked if the engineer so decides by independent laboratories; the pipe supplier shall provide all necessary information about the pipe to be used, including short- and long-term (50 years) stiffnesses, materials used in the manufacture, and barrel composition and shape. There shall be no departure from such specifications unless agreed upon by owner and engineer.

Guidelines for Controlling Internal Corrosion and
 Encrustation in Water Supply Systems

6. Systems shall be designed to minimize corrosion risks, taking into account the quality of the water from present and future sources and its seasonal variations, as well as potential changes in quality within the system, including treatment and disinfection to ensure a safe and potable drinking water.

7. If feasible and economical, water quality in the conveyance system shall be treated to meet the conditions required for forming and maintaining a protective film of complex calcium and iron carbonates and oxides after the methods of References 4.01 and 4.07 or their equivalent. Treatment methods shall be based upon water analyses carried out over a sufficient time period to allow quality variations to occur. Provisions shall be made for the designer, manufacturer, or builder to monitor the treatment for at least one year after start-up. During that year, the process should be adjusted, if needed, staff should be trained, and equipment should be provided to ensure satisfactory operation of the system on ε permanent basis. Treatment shall use locally available chemicals whenever appropriate, even if this means using lower grade materials, as long as this does not compromise the provision of safe and aesthetic water.

8. Where Guideline 7 is not applied, or as an added safety precaution, metallic pipes shall be lined with cement mortar. This lining shall meet CEOCOR recommendations (Reference 4.05), ISO 4179, AWWA C-205, C-206, C-401, or equivalent specifications, with appropriate cement and additives as required. Other lining types such as thick plastic may be used if their success has been proven in at least two systems over a minimum five-year period in circumstances similar to those anticipated.

9. The above guidelines shall be implemented in a manner that permits the use of any type of pipe that satisfies service and standardization requirements, ensuring consideration of different types of pipe and adequate competition among suppliers. However, neither lead pipe nor solder containing more than 0.2 percent lead shall be used.

10.   The systems shall be operated in a manner that prevents pipe corrosion, to which end all equipment shall be maintained in satisfactory operating condition.

Guidelines for Controlling Internal Corrosion in Sewer Systems

11.   Sewer systems shall be designed for a lifetime of fifty years, unless otherwise directed, taking into account prospective sulfide corrosion. Where feasible, designs shall provide for self-oxidizing velocities and slopes of 0.6 percent, good ventilation, low turbulence, flushing facilities, minimal periods of flow in the system, and minimal sewage stagnation. If economical and practical, designs may involve air or oxygen injection or the addition of chemicals.

12.   The least-cost solution shall prevail, taking into consideration construction, maintenance, and operating costs, as well as other constraints such as the availability of trained staff for maintaining the system. Pipes made of inert materials are preferable, if found economical. Alternative pipe materials and linings shall be considered as, for example, in the case of large pipes, reinforced concrete with a sacrificial layer, and PVC-lined reinforced concrete, to ensure competition among suppliers. For metal pipes, the acceptable linings are either a cement mortar lining of appropriate quality and thickness or, possibly, a thick plastic lining. For concrete pipe, mechanically locked PVC sheet lining should be utilized.

13.   In implementing the above guidelines and in evaluating existing systems, designers shall use the most reliable manuals, codes of practice, and standards available (References 5.02, 5.04, 5.05, 5.06, or their equivalent).

Guidelines for Controlling External Corrosion in Pipelines

14.   Soil surveys shall be undertaken at an early stage of design. Surveys shall include a preliminary desk study of topographical and geological maps and a review of other available information in order to assess overall corrosion risks and identify hot spots and areas where detailed surveys and soil analyses will be needed. This desk study shall be checked and completed in the field by all appropriate means, including electric resistance surveys. Office and field surveys shall be used to determine the frequency, location, and depth of soil sampling and analyses and of further electric resistance measurements. When external corrosion problems have been discovered on existing lines, similar procedures shall be used to help determine where remedial action is needed and what the best solutions are.

15.   The procedure for soil surveys shall comply with the recommendations of either Arbeitsblatt GW 9 (Reference 6.08) or other similar documents (References 6.15 or 6.16), depending on circumstances.

16.   Soil surveys shall be carried out even if cathodic protection is anticipated. As accurate an assessment as possible shall be made of the likelihood, nature, and importance of possible corrosion due to changing soil conditions along the pipeline route and of the intensity of anticipated stray currents.

17.   Pipe coatings and other protective measures, possibly even pipe material, shall be selected on the basis of soil survey findings.

18.   High quality concrete of adequate composition shall be required for all types of reinforced concrete pipe. Quality shall be assured through adequate manufacturi ; equipment and procedures and by a systematic or random inspection during th. manufacturing process and a thorough inspection at installation. Permeability of the cement mortar coating protecting the prestressing wires shall not exceed 10^{-9} centimeters per second.

19.   All new reinforced concrete and prestressed concrete pipe shall be fitted with a connector terminal located during manufacture at a specified spot on the pipe and at installation on the crown, allowing for measurement of the electric potential of the steel reinforcement to ground, and for a possible connection to a cathodic protection system, without the risk of damaging mortar or concrete coating. Reinforcing bars, wires, or steel cylinders (if any) shall be electrically bound. The loops of prestressing wires shall be short-circuited by steel strips squeezed between them and the concrete core and shall be thoroughly embedded in a cement paste applied on the concrete core or cylinder just before they are wrapped on it.

20.   Cathodic protection shall be used only in pipe systems that cannot be adequately protected otherwise, such as all welded steel transmission pipelines, electrically continuous lines, and possibly in complex systems where interference may create problems among pipelines of different types and uses, particularly when some of them are cathodically protected. If installed, cathodic protection shall be designed by competent and experienced engineers, in accordance with the CEOCOR guidelines (Reference 6.04), the BSI CP 1020 Code of Practice (Reference 6.02), or other equivalent standards.

21.   Cathodic protection shall not be used with prestressed concrete pipe, unless the pipe is in greater danger of corrosion from factors other than hydrogen embrittlement.

22.   Cathodic protection shall be made operational as system construction progresses.

23.   Provision shall be made at the design or construction stage to provide the system operator with the trained staff, transportation, equipment, and needed supplies in a timely fashion. Operators shall monitor their systems for corrosion problems, make voltage surveys on a regular basis, and keep adequate records and maps of the results. Cathodic protection staff shall be adequately trained.

24.   Close collaboration among underground facilities operators (water, gas, electricity, and transportation) shall be instituted and maintained to secure protection of their systems against corrosion, especially when any one of these facilities is using cathodic protection. Such collaboration shall begin as early as possible, preferably at the design or construction stage.

Guidelines for the Rehabilitation of Pipelines

25.   Proposals for partial or full replacement or rehabilitation of
pipelines shall be based on:

(a)   a thorough evaluation of the system, including, as the situation
      requires, internal/external inspection; soil surveys; flow
      measurements; head loss measurement; examination of plans, records,
      and customer complaints; and other pertinent data;

(b)   cost estimates and work programs for correcting only the deficiencies
      found in damaged sections of the system and including the costs of
      removing and reinstating customer connections, providing temporary
      service to customers during service interruptions, restoring any
      damaged pavement, and disinfecting water systems before resuming
      service; and

(c)   an analysis of the benefits expected to result from the proposed
      improvements.

26.   Contractors employed to carry out rehabilitation work shall be
carefully selected and have the necessary experience, specialized equipment,
personnel, and financial resources to complete the job successfully.

Chapter 3

PIPES MADE OF INERT MATERIALS

1.   As the name implies, pipes made from inert materials--vitrified clay
(VC), to be used only for non-pressure applications, and all plastics (P and
GRP or FRP)--are not adversely affected by a normal soil-water-sewage
environment. They are thus the pipe of preference from the corrosion point of
view, so long as they are economically and structurally acceptable.

2.   Vitrified clay is one of the few pipe types used since antiquity, but
the use of plastic pipe has spread rapidly over the last fifty years. VC and
plastic pipes account nowadays for a large share of the market in sizes up to
about 600 millimeters (24 inches). Structural adequacy is not usually a
problem in pipes up to 100-150 millimeters (4-6 inches) in diameter. These
pipes generally are structurally redundant because of manufacturing
constraints.

3.   As an obvious consequence of this relative immunity and except in the
two cases discussed below, there are no documented cases of corrosion of such
pipes. However, rigid cement mortar joints should no longer be used with bell
and spigot VC pipe, not only because of their lack of tightness but also
because of their possible expansion under sulfide corrosion, which causes
cracking of the bells.

Plastic Pipes

4.   Some organic solvents or chemicals such as trichloroethylene may
permeate certain types of plastic pipe (e.g., PVC) and contaminate the water
being carried, even under pressure. This is most likely to happen when the
surrounding earth is soaked with petroleum products. There are a certain
number of such accidents on record (Reference 3.02) affecting both high- and
low-density polythene service lines in areas where gasoline or other petroleum
products had been spilled, for example in service stations. Some pipes swell
under these circumstances and may burst.

5.   Glass fiber reinforced plastic (GRP or resin) pipes and a few other
types of plastic pipes are susceptible to stress or strain corrosion.
Lamination separation may occur under these circumstances. Alterations of the
glass fiber reinforcement have reportedly resulted from contact with even
plain, chemical-free water because of defects such as cracks in the inner
surface. Excessive deflection, and even pipe collapse or bursts, may occur in
a few years.

6.   Although there are no thoroughly documented cases of these problems,
it is widely known that there have been major difficulties with these very
flexible plastic pipes, which have been available for municipal, irrigation,
and wastewater use for little more than 15 years. In 1983, an estimated $60 to
$80 million was at issue in lawsuits in the United States related to GRP pipe
that had been underground for six to ten years (Reference 3.01). Problems with
GRP pipe have also been reported in Europe and the Middle East. An irrigation
project in an arid country, in which the pipeline was under intermittent

pressure, suffered bursts every week over an extended period of time; the same events took place in another similar project.

7.   Such GRP pipe failures are associated with excessive pipe deflection (deflection should not exceed 5 percent) and are therefore the result of inadequate structural design and/or construction. As the pipe has very little inherent strength with which to withstand external loads after it is buried, the earth around it must provide side support. The backfill must therefore meet certain standards (sand/gravel type; no plasticity) and compaction requirements. Proper installation is thus critical, and, as a consequence, close supervision of construction is essential. However, few contractors or engineers are aware of the stringent requirements that must be observed during the construction process.

8.   The deflection issue is further complicated by several factors. First, as yet there is no universally accepted standard for minimum pipe stiffness, although experience indicates that there are limits (see, for example, References 3.01 and 3.03). Second, the time dependency of stiffness and the creep properties exhibited by all plastics confuse the stiffness issue; this problem is further complicated by the following facts: (a) it is most often not clear whether short- or long-term stiffness is referred to in design standards, guidelines, or experiment reports; (b) the major standardization institutions, ASTM and DIN, specify different test conditions for measuring stiffness, which leads to substantial variations in the quantification of pipe characteristics; and (c) some manufacturers refer to their own definition of this factor. Long-term stiffness may be less than one-half or one-third of short-term stiffness, or even less. Third, damage caused by random deflections, which may be as great as the design deflection, may occur because of the lack of detailed installation procedures taking into account actual soil condition, proper equipment, and the skilled labor needed for each project. Odd shapes occur with very flexible pipes that can result in excessive strain, and hence in cracks or similar defects. Finally, flexible pipe may be made from a large variety of resins or plastics, with as many different barrel compositions in plastic, inert filling like sand, fiber reinforcement, and barrel shapes (profile or plain wall). Each reacts differently. For all these reasons, extreme care in the installation of GRP or other plastic pipe sensitive to stress corrosion is required, which is reflected in Guideline (5). Research and discussions are proceeding on an international basis and it may be expected that, in the not too distant future, the conditions allowing safe use of these flexible, virtually corrosion-free pipes will be well defined (see, for example, manufacturer's instructions Reference 3.04).[2] Because similar structural rules apply to all flexible pipe types (see Reference 3.03), Guideline (5) has been drafted to be universally applicable to all flexible piping.

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[2]   Annex 2, prepared by and introduced into these Guidelines at the request of the Fiberglass Pipe Institute, U.S.A., reports on recent developments in fiberglass pipe technology. The introduction of this Annex should not be interpreted as an endorsement by the author or the Bank.

Guidelines for Controlling Corrosion in Water Supply
Systems with Pipe Made of Inert Materials

(i) **Guideline 3:** Pipe made of inert materials with appropriate joints shall be used where service conditions allow and where such pipe is economical.

(ii) **Guideline 4:** Plastic pipe sensitive to permeation by petroleum products or other chemicals shall be protected, where needed, through measures such as installation at a safe distance from possible sources of contamination or the use of protective sheathing.

(iii) **Guideline 5:** Glass fiber reinforced plastic or resin pipe and all other plastic pipes may be used provided that for large-size pipe over 200-300 millimeters in diameter the following general conditions are strictly enforced:

(a) pipe shall have a minimum long-term stiffness meeting the recommendations in References 3.01 and 3.03 (for example, $1500N/m^2$ in "street conditions," that is, earth cover of one meter plus traffic load) or those of more recent, reliable specifications;

(b) installation shall proceed along accepted standards such as ASTM, AWWA, or according to manufacturer's instructions (see Reference 3.04) and, in addition, field procedures shall be determined through the installation of test section(s) under actual construction conditions, using the same construction staff and labor, equipment, and back-filling materials that will be employed in the job at hand;

(c) the above procedures shall secure maximum long-term deflections of 5 percent in any section; pipe that may be expected to exceed 5 percent long-term deflection shall be replaced or reinstalled, depending on the extent of damage; the deformed pipe should remain elliptical in shape;

(d) work shall proceed upon agreement on the above procedures, which shall be reviewed whenever necessary;

(e) close supervision of the work by competent site engineers shall be ongoing, and the pipe supplier shall provide guidance and training assistance;

(f) training of labor and engineers shall be provided as needed; and

(g) pipe characteristics including stiffness, corrosion tests, and so forth shall be determined according to ASTM or equivalent standards and checked if the engineer so decides by independent laboratories; the pipe supplier shall provide all necessary information about the pipe to be used, including short- and long-term (50 years) stiff-nesses, materials used in the manufacture, barrel composition, and shape. There shall be no departure from such specifications unless agreed upon by owner and engineer.

Selected References

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3.02 Meheus, J., P. Peeters, and J. Celens. Comparison of Different Plastic Water Pipes Concerning Solvent/Carburant Permeation. CEOCOR, Luxembourg Conference, May 1985. CEOCOR, Brussels, Belgium. (Effect on pipeline integrity and water quality.)

3.03 Prevost, R. C., and K. K. Kienow. Design of Non-Pressure Very Flexible Pipe. Advances in Underground Pipeline Engineering, ASCE Conference, Madison, August 1985. Also in Pipes and Pipelines International, November 1985 and January and March 1986. A.S.C.E., New York, U.S.A.

3.04 VEROC. Guideline Specification--Glass Pipe Reinforced Pipe and Flowtite Pipe. Sandefjord, Norway: Veroc Technology A/S, 1986. (Handling and Buried Installation Instructions.)

Chapter 4

INTERNAL CORROSION AND ENCRUSTATION IN WATER SUPPLY SYSTEMS

1.   Most water supply systems are affected to some degree by internal corrosion often associated with encrustation, tuberculation, or the formation of a hard protective scale inside the pipe. The effects range from inconveniences, such as "red" water and minor leaks, to serious operational problems, such as widespread leaks, loss of water pressure, blocked water lines, and contamination of water by heavy metals, such as lead. In one case about 500 tons of pipe materials had dissolved each year in a 250,000 cubic meter per day system comprising asbestos cement, concrete, and cement mortar-lined cast-iron pipes distributing aggressive water (Reference 4.01). Uncontrolled internal corrosion eventually caused such extensive damage that costly rehabilitation or replacement of whole lines became necessary.

2.   This chapter presents case studies of successes and failures with metal and nonmetallic pipes, followed by a description of the internal corrosion processes, a discussion of the general principles of corrosion and methods for controlling internal corrosion, and, finally, the guidelines.

3.   The cases described below illustrate the consequences of internal corrosion of water distribution or conveyance pipeline systems. Some cases are better documented than others. The relative paucity of well-documented cases stems from the reasons noted earlier and from the reliance of most authors on laboratory work or simulation in their tests for corrosion. These technical reports are generally treated as substantive, and, in most cases, they reliably represent field conditions.

        Case Studies:

Metal Pipes

4.   The following cases involve cast- and ductile iron and steel pipe:

    (a) Boston, Massachusetts, United States. The water distributed in this city was low in total hardness (12 milligrams per liter as $CaCO_3$), alkalinity (8 milligrams per liter as $CaCO_3$), and dissolved solids (37 milligrams per liter) and had a pH of 6.7. Although the corrosion indices were positive, pipeline corrosion was not really the problem. Since 1845 the water authority had expressed concern about the dissolution of lead from the pipes used widely in the service lines. Beginning in 1976, corrosion inhibitors were used, but they were soon replaced by pH control. The pH has been increased to 8.5 by the addition of caustic soda at a rate of 14 milligrams per liter. As a result, dissolved lead has dropped from about 0.10 milligrams per liter to the United States mandatory limit of 0.05 milligrams per liter. Copper and iron in the water have decreased as well. The annual treatment cost in 1981 was $0.60 per capita, or $10 per million gallons. Several other cities in the northeastern United States, such as Philadelphia, with similar water quality to that of Boston have had similar experiences with dissolved lead (Reference 4.26).

(b) <u>Columbus, Ohio, United States</u>. The distribution system in this city has a long history of pipe corrosion and tubercle formation. The original pipes were poorly lined, but system extensions since 1963 have used cement mortar-lined pipes, with satisfactory results. Analyses of tubercle content found ferrous and, possibly, manganese compounds, together with concentrations of microorganisms. This type of growth accelerates corrosion, covers pitting, may release into the water pathogens and toxic metal compounds (although probably not in harmful quantities), and increases chlorine demand. Annual corrosion losses in the Columbus system were estimated at $3 million (Reference 4.36).

(c) <u>Brussels, Belgium</u>. Until about 1965 and even later, Brussels was supplied mainly by groundwater from diverse sources, which produced relatively hard water (300 milligrams per liter as $CaCO_3$) with a pH of 7.6. The old, cast-iron pipes were unlined; the newer steel pipes with welded joints were lined with bitumen, which was removed at the joints by the heat applied during welding at installation. Corrosion is virtually nonexistent as a result of the formation of a hard scale that is firmly bonded to the metal of the pipes. This hard scale is composed of calcium carbonate, iron oxides, and more complex iron and calcium oxides and carbonates. It grows to a thickness of about three to five millimeters and remains stable thereafter. The scale layer protects the metal against further corrosion, acting somewhat like a cement mortar lining.

(d) <u>Zagreb, Yugoslavia</u>. The 10-kilometer-long Old City system was composed of 80- to 90-year-old unlined cast-iron pipes, ranging in diameter from 100 to 250 millimeters. In the late 1970s, severe scaling developed, to the point where some pipes were almost completely clogged. Corrosion appeared to be insignificant, and the structural strength of the pipes was unimpaired. Total hardness of the water was reported to be 300-500 milligrams per liter as $CaCO_3$, but no other data are available on water quality. The system was reportedly cleaned and restored in just over one month by crews working between 10:00 p.m. and 6:00 a.m. Interruption of service was thus kept to a minimum. Water pressure in the system increased by about 30 percent as a result of the repairs. Scraping "pigs" were used. The cost of rehabilitation was estimated at 1/30th of the cost of replacing the system. No lining took place nor appeared to be needed (Reference 4.34).

(e) <u>Hong Kong</u>. Part of the water supply to Hong Kong is brought to the main island from a reservoir on Lantau Island by two steel undersea pipelines. The pipes are 750 millimeters in diameter and 10 millimeters thick and have an epoxy (polyurethane lacquer) lining. The epoxy layer is 0.2 millimeters thick and was applied, in Singapore and at site, in five coats over a grit-blasted surface, in accordance with the best methods available at the time. Except for the use of metallic instead of nonmetallic grit, these methods were consistent with the AWWA standard developed later. The system was constructed in 1960-61 and became operational in 1963. Inspection of the short, accessible end sections of these pipelines prior to commissioning

showed extensive blistering of the epoxy lining, which has been attributed to minute particles of grit or metal and moisture trapped under the lining. The possible effect of this on the lifetime of the pipes is unknown. The pipes are protected externally by cathodic protection (Reference 4.24).

(f) Medina, Yanbu, Saudi Arabia. After three months of operation, corrosion and tuberculation began in the epoxy-lined pipes carrying treated, desalinated water to Medina. The lining of the 175-kilometer, 800-millimeter steel main, designed for a maximum pressure of 8 MPa and constructed in 1981, was peeling away in some places close to the pumping station. The water being transported was warm (about 35 degrees centigrade), high in chlorine, and low in alkalinity, and the pH was about neutral. The treatment of the water was changed as indicated by the Legrand-Poirier method (Reference 4.07), and about six months later a calco-ferric protective layer similar to that which formed naturally in the Brussels system discussed above had covered the spots where the lining had peeled away and has held since then (Reference 4.30). A sister feeder line made of asbestos cement, 40 kilometers long and 600 millimeters in diameter, serves Yanbu on the Red Sea coast; it carries the same treated water and is therefore similarly protected.

Case Studies:

Nonmetal pipes

5.   The following cases involve asbestos cement, concrete, and metal pipes with cement mortar lining:

(a) The American Water Works Association study. In response to concerns about asbestos fiber in water, AWWA sponsored research to evaluate the behavior of AC pipe exposed to the waters of ten cities and towns in the United States. All the systems selected had aggressive raw water as defined by the AWWA Standard C-400 corrosivity index, and all experienced a high count of asbestos fibers being released into the water by corrosion of AC pipe. In one case, corrosion was so severe that water meters and coin-operated washing machines clogged and the pH level and calcium content of the water increased after flowing through the system. The AWWA corrosivity index did not, however, prove to be a totally reliable indicator of AC pipe behavior; moreover, aggressive water containing some iron proved to be noncorrosive. Iron, and the less objectionable zinc, in small amounts, seemed to interact with matter drawn from pipe and water to form a complex protective film on the pipe. Research is continuing in this area. The study further indicated that asbestos fibers may appear in the water as a result of boring-tapping pipe under pressure (Reference 4.22).

(b) Oslo, Norway. As part of a seven-year study, water from the Oslo system was run through a 24-meter-long experimental loop of 100-millimeter-diameter AC pipe. The water was soft, low in dissolved solids (3.4 milligrams per liter), and very low in alkalinity (0.8 milligrams

per liter) and had a pH of 6.6. According to the AWWA C-400
corrosiveness index, asbestos cement should not be used to convey such
water. While flowing in the pipes, the pH of the water increased to
over 10, and the calcium concentration went up to 10-14 milligrams per
liter. Both autoclave-cured pipe, which is substantially lower in
free lime and richer in silicium, and water-cured pipe reacted in a
similar manner. Calcium release in the water-cured pipe proceeded to
a depth of 2 millimeters; autoclave pipe lost more calcium, but in
shallower layers, and could release more asbestos fibers than water-
cured pipe. This was not entirely consistent with the expectations
presented in the AWWA Standard (Reference 4.27).

(c) <u>Stavanger, Norway</u>. Water of the same quality as that tested in Oslo
was transmitted through a prestressed concrete pipeline that was 30
kilometers long and 900 millimeters in diameter. Between 1960, the
year the pipeline went into service, and 1967, water samples were
taken four times each year. As occurred in the Oslo case, calcium
leached from the pipes into the water and the pH level increased.
Over time, however, calcium loss from the pipes decreased to a very
low rate, most likely a result of the formation of a protective layer
of magnesium silicate, which has good resistance to erosion (Reference
4.28).

(d) <u>Ghana, The Kpong-Tema-Accra Pipeline</u>. In 1964-65 a transmission
system was installed consisting of 50 kilometers of 0.5-meter- and 1-
meter-diameter steel pipes, respectively 7 and 11 millimeters thick,
with mechanical and welded joints. Another pipeline 0.75 meter in
diameter and 22 kilometers long was already in service, carrying
58,000 cubic meters per day. All of the pipes had been lined on site
with cement mortar, apparently in accordance with AWWA Standard C 602-
1955. In the early 1970s, small-scale peelings from the pipe linings
were observed in the service reservoir at the end of the supply
line. In 1975, complaints about water hardness and chlorides in the
water began to surface. Rumbling noises from the pipes, particularly
when the system was operating at maximum discharge, were heard in
1978. These events were followed in 1979 by a partial blockage of the
smaller pipe. Water flow in the larger pipe stopped altogether,
cutting the supply of water to 750,000 people for a week. The cement
mortar debris blockage at the service reservoir was 10 meters long.

6.   The raw water being carried by the pipes was soft, low in dissolved
solids, and aggressive, with a Langelier index for untreated water of -1.7.
Hardness and pH at the outlet of the pipes were considerably higher than at the
inlet (for example, $CaCO_3$ increased from 11 to 20 milligrams per liter). Water
analyses were not conducted continuously nor simultaneously at the same sites
over a long enough period to allow reliable conclusions to be drawn. Neverthe-
less, based on the analyses that were carried out, it appears that considerable
quantities of calcium compounds had leached into the water over the eight-year
period during which the treatment of the raw water had been suspended,
following the commissioning of the Akosombo Dam on the Volta River. In fact,
the tests tended to show quantities of calcium dissolved into the water that
were greater than the total weight of the pipe lining (over 3,000 tons).
Clearly, the average rate of calcium loss was lower than the analyses indicate,

but the source of the problem is evident. The specific weight of the lining had diminished from a normal 2.2 tons per cubic meter to 1.76; porosity had increased from 10 percent to 25 percent and the lining had lost calcium. While damage to the lining may have been caused during installation, or possibly during a recent earthquake, or by water hammer, this seems to be unlikely.[3] The cement mortar lining was thinner than required at some points, such as the welds, which may have contributed to the failure (Reference 4.31). It is also of interest that the pipeline was severely damaged by external corrosion due to stray currents because the cathodic protection system had been inoperative for years.

Corrosion Processes

7.   There is a general consensus on the causes, theory, and processes of corrosion, with a few exceptions as indicated below.

8.   The fundamental fact is that all waters, ground and surface, contain a few basic elements in solution: oxygen, carbon dioxide, calcium, some magnesium, sodium, chlorine, and other less common substances. These elements occur as chemical combinations or ionized radicals. They are dissolved, absorbed through the air, or leached from the earth and pipes. These elements associate with each other and tend toward stable physical-chemical combinations. This complex chemistry varies with temperature and with exposure to air, pipe material storage, flow conditions, and treatment processes including disinfection. This chemistry is altered and enhanced by biological action.

9.   Pipe corrosion results from the normal interaction between water and pipe materials. Pipe is typically either metal (primarily iron) or nonmetal aggregates (often inert) bound by cement (essentially a calcium complex). The basic physical and chemical water/pipe reactions are, however, fundamentally the same, notwithstanding substantial variations in their processes and effects, depending upon the properties of the pipe materials.

10.   Whatever the pipe material, vulnerability to corrosion can be predicted through water analyses. Water treatment processes can then be determined and lining materials can be selected to control or prevent corrosion. Follow-up, however, is required: corrosion is a complex phenomenon requiring permanent monitoring.

11.   Water with chemical characteristics that suggest it will be corrosive is generally described as "aggressive." This applies basically to the nature of its reaction with calcium carbonate ($CaCO_3$). Because of the natural

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[3]   In San Bernardino, California, shortly after a 7-kilometer-long, 1.9-meter-diameter, cement mortar-lined steel pipeline had been installed, the cement mortar lining began to crack and peel away. This appeared to be the result of faulty operation and very thin lining in some places. About 40 percent of the pipes were relined, which apparently solved the problem.

abundance and chemical properties of calcium (Ca) and carbon dioxide (CO_2), the chemistry between them is indeed a prime factor. Calcium carbonates precipitate or dissolve in water, depending on the relative concentration of Ca and CO_2--or, more specifically, of their ions. This process is affected by the hydrogen ion concentration (pH, or, in lay terms, acidity) of the water, by the presence of oxygen (O_2), and also by other elements such as chlorine (Cl) and sulfates (SO_4).

12.   Several indices are used to assess the degree of corrosivity of water. The most popular is Langelier's Saturation Index (LSI). When the LSI is positive, it indicates that water will tend to precipitate scale; when LSI equals zero, water is at equilibrium; a negative LSI indicates aggressive water. The Langelier Index Study was the subject of a report published in the 1936 AWWA Journal. Ryznar's index (RSI) is also widely used: water is corrosive above 7 and will cause scaling below that level. A modified form of the Langelier index, known as the aggressivity index (AI), is used in AWWA Standards C400 and C402 for asbestos-cement pipes. According to the AI, water is very aggressive with respect to AC pipe below 10 and nonaggressive above 12. All of these indices are based on simplifications of complex processes and may be inaccurate except where water is clearly within or outside the corrosion ranges. None of them can be used to determine corrective treatment.

13.   Two methods have been proposed more recently to accurately assess aggressivity; these methods also provide a means for determining corrective treatment. Both are based on the principles that rule chemical reactions and avoid the simplifications needed in the determination of the above indices. But they were developed based on different methods, and the publications proposing them make no references to one another. Both methods, however, call for water to be treated in a way that causes a hard, protective film composed of calcium and iron carbonates and oxides to form inside the pipe, which occurred naturally in the Brussels's case mentioned above and in a number of other systems. First is the Legrand-Poirier graphic method (Reference 4.07, the first version of which is dated 1972), which is now published with computer programs to facilitate calculations. The second is the Caldwell-Lawrence method (Reference 4.01), which originates from a water-softening process. The application manual, with explanations for this method, was first issued in 1978 (Reference 4.09).

Metallic Pipe Corrosion

14.   The process of metal corrosion is well established. It proceeds, at times rapidly, because of the vulnerability of metal to oxidation and its good electrical conductivity. Metals oxidize, usually reverting to their natural chemical state, either into soluble oxides that may be washed away or otherwise removed, allowing corrosion to proceed, or into insoluble oxides that in a number of cases (zinc, for example) protect the metal against further corrosion. Electrical conductivity allows electric currents to circulate whenever an electromotive force arises as a result of the formation of "galvanic" cells inside or outside pipes or because of external causes, such as

stray currents outside pipes.[4] Electrochemical reactions then occur whereby the metal dissolves--with further chemical reactions--in anodic areas where current flows out from the metal. However, the metal is unharmed in cathodic areas where current flows into the metal.

15.   The formation of galvanic cells between unprotected metal and water loaded with oxygen and other elements starts the corrosion process. An electromotive force develops between different metals; between areas of the same metal in different physical or chemical conditions; because of stresses or strains or due to their differing internal structures; because of differential oxygenation resulting from crevices, joints, or solid matter deposits; or because of surface alteration, or possibly as a result of the corrosion process itself. While corrosion may be accelerated by bacteria, as in the case of tubercles, the determinants are the electromotive forces, which vary with the nature of the galvanic cells and the chemicals (oxygen, carbon dioxide, chlorine) in water, as well as its pH and temperature. Low water velocity also has an adverse impact.

16.   The electrical resistance of water is a good indicator of the amount of material it contains in solution and hence of the risk of corrosion. Water of more than 2,000 ohm cm resistance usually does not cause corrosion problems.

17.   Corrosion rarely spreads evenly. Rather, it usually concentrates in spots or tubercles and causes pitting. Tubercles are the sites of complex biochemical reactions and contain beneath their skins a number of oxidation products and even toxins. The growth of tubercles, combined with encrustation, may clog pipes. Heavy scaling has the same result.

18.   The speed with which corrosion proceeds may decrease over time, possibly because of the creation of protective products. But pits may lead to perforation of pipes within weeks or even days. Long-term corrosion, however, may cause only "red" water, which, while unpleasant, has no real immediate adverse impact, but indicates deterioration in progress. The corrosion rate of the different types of metal pipe in current usage (cast- and ductile iron and steel) varies little. However, these different pipes have substantially different thicknesses, which does affect the time it takes for serious problems to develop.

19.   Lead, which dissolves rather readily in soft waters having low alkalinity and low pH, and other heavy metals, such as cadmium, can create serious health hazards.[5] Recent studies (Reference 4.29) have shown that significant quantities of lead leach out of tin/lead solder often used at pipe joints, primarily those in copper pipes used in residential plumbing. This is

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4/   For details see para. on cathodic protection in Chapter 6.

5/   WHO drinking water standards have a tentative limit of 0.1 milligram
      per liter, above which lead is declared toxic; the United States require-
      ment is half the WHO limit at 0.05 milligram per liter.

probably a galvanic effect enhanced by traces of the flux used in soldering.
This is most likely to occur in new houses or in situations where water has
been standing in the pipes for some time. Flushing the pipes reduces the lead
content. Prudence therefore dictates discontinuing the use not only of lead
pipe but also of solder containing lead. Substitutes for these materials are
available; for example, the alternatives for tin/lead solder are the tin/silver
or tin/antimony solder. Such solders are more expensive, but this is compen-
sated to some extent by their greater degree of workability; solder, in any
event, represents only a minor part of the cost of plumbing (Reference 4.29).

Corrosion of Nonmetallic Pipe

20.   The following applies to all concrete and AC pipe as well as to cement
mortar-lined steel and iron pipe, all of which expose to water a surface of
cement-bonded aggregates or asbestos fibers. Corrosion in these cases is
essentially a chemical reaction between water and cement in pipe or pipe lining
material. If the water is aggressive or contains sulfates, free lime, which is
a component of most cements, dissolves and other reactions proceed. It is
these reactions that may have the most serious consequences (see case
studies). However, if the conditions for scale formation are met and there is
precipitation of calcium carbonate ($CaCO_3$) or of a similar chemical, additional
scale formation may result, but such deposits are usually not thick enough to
cause problems. Even if thick precipitates form, they would not bond with the
pipe surface. In certain circumstances, the corrosion rate may decrease with
time (see Reference 4.28).

21.   There are substantial differences between the European and the
American approaches to corrosion of AC pipe. The CEOCOR documents, which
represent the European view, identify corrosive agents in greater detail than
do the AWWA standards and publications, and they specify acceptable limits for
each agent. CEOCOR documents do not agree with the AWWA that autoclave pipe,
in which curing and composition replace free lime with silicium complexes, is
superior to water-cured pipe. The AWWA publication in Reference 4.22 does,
however, share some of the European views on the question. There are similar
differences between CEOCOR and AWWA standards for cement mortar linings. The
European literature contains references to several types of cement that can
improve resistance to corrosion in specific cases. The debate continues.

Controlling Internal Corrosion

22.   There are two obvious avenues for controlling internal pipe
corrosion: treating the water so that it is not corrosive and using pipes or
pipe linings that are not vulnerable to corrosion. Treating the water can
protect a whole system whatever its nature, including both new and old pipes,
up to the customer's tap and including household plumbing. The chemicals and
manpower needed appear to be affordable in most cases, as will be shown below,
and the target of a near neutral water produced and distributed meets health,
convenience, and other requirements. Water treatment is, therefore, the
preferred solution in most cases, unless proven to be inappropriate, impracti-
cable, or uneconomical. However, it should not preclude the use of an
efficient lining (cement mortar) to provide a safeguard against failure of the
treatment process. The best way to achieve this objective is to create
conditions in the water that cause a hard, protective film to form inside the

system--this sometimes occurs naturally, as in the Brussels's case. Achieving this objective, however, takes time as does the training of staff and close monitoring of the treatment process.

23.   According to the AWWA (Reference 4.01), the optimal water conditions for the formation of a protective scale are:

- small supersaturation in $CaCO_3$ (slightly scaling water) of 4-10 milligrams per liter;

- minimum hardness in $CaCO_3$ (calcium and alkalinity of at least 40 milligrams per liter as $CaCO_3$);

- no excess Cl and SO_4 ions over 1/5th of the above alkalinity;

- pH lower than that which could produce $Mg(OH)_2$ scaling in water heaters, but avoiding pH levels between 8.0 and 8.5;

- adequate water velocity (0.7 m/s); and

- minimum residual chlorine levels in all parts of the system.

The last three recommendations derive from practical considerations and are secondary to the first three listed.

24.   These conditions should be met in all parts of the system, from water treatment plant to the customer's tap, whatever type of pipe is used. Occasional variations are usually not harmful, but the goal should be to maintain these conditions at all times. The result should be a hard, permanent, relatively thin (3-5 millimeters) lining composed primarily of calcium carbonate and several iron oxides and carbonates.

25.   A water treatment scheme to achieve these conditions may best be designed using either the Legrand-Poirier (Reference 4.07) or Caldwell-Lawrence (Reference 4.01) methods. Generally, such water treatment requires no more than the addition of lime or CO_2 (or both) and is, therefore, not an expensive process. Suitable low-grade local chemicals could be used, rather than imported ones, if they meet health or other quality requirements. Changes in the water quality resulting from treatment for other purposes (such as disinfection) or exposure to air, reservoirs, or pipes need to be taken into consideration.

26.   Water can also be treated by the addition of corrosion inhibitors, of which there are many types (see Reference 4.08). Their cost and availability would have to be considered, especially in developing countries. Also, this type of treatment may sometimes have an adverse impact on both water and pipe. Ion exchange water softening processes or polyphosphates may cause serious problems by removing any existing protection caused by scaling all the way up to the consumer's tap and thereby exposing base metal to corrosion (Reference 4.23). If there are lead pipes in the system or in residential plumbing, this process can pose a health hazard. Since hard water is rarely a problem, except in hot water piping, health and economics (reducing the amount of water to be treated) would limit softening to the hot water system. It is

also possible that water softening devices may promote bacterial growth. Therefore, the use of any corrosion inhibitors or processes needs to be carefully considered and would appear to be a second choice in corrosion control.

27.   There are two traditional types of lining that can be used to protect metallic (iron or steel) pipes against internal corrosion: cement mortar lining and enamel-type lining. Cement mortar lining basically converts metallic pipe into nonmetallic pipe for purposes of internal corrosion control. It is widely used and provides good protection, but is not the panacea for internal protection, as evidenced, for example, by the Ghana case mentioned in Reference 4.31. An explanation of its efficacy can be found in Chapter 6 of this study. Cement mortar lining also reduces somewhat the internal diameter of pipe, which causes corresponding increases in head loss that may be important in small-size pipes.[6] It does not support bacterial growth and only protects the part of the system that is lined.

28.   Enamel-type linings include coal tar, bitumen, and epoxy linings. Coal tar, as such, is no longer used because of the terrible taste it gives to water when the phenols it contains react with chlorine, but the name has stuck to more refined products that do not have the same adverse effect and are defined in the standards. All of these enamel linings are widely used, but are not very successful in preventing corrosion over the long term because any minor defect in the enamel, such as pinholes, causes blistering and peeling, leading to extensive corrosion. Also, heat from welding melts bitumen and similar linings and leads them to form a veil within welded steel pipes; the veil breaks up as water flows, and debris may spread throughout the system and into water meters and other appurtenances.

29.   Epoxy resin and polyurethane linings are the most effective of the enamel-type linings, but are difficult to apply and almost impossible to repair in the field. The resin to be used must be carefully selected to minimize bacterial growth. Pinholes are the most common defect in epoxy linings, which are usually 0.2 to 0.3 millimeters thick. Recent research (Reference 4.32) indicates that this problem can be solved by increasing the minimal thickness of the lining to 0.55 millimeters, which requires a nominal thickness of one millimeter, to allow for manufacturing variations. These conditions apply to normal municipal water supply and water conveyance systems. Special linings providing good protection against corrosion and abrasion have been and are being developed for industrial applications, such as slurry pipelines. These are typically thick, often fiber reinforced, epoxy-type or polyurethane linings and could be considered in special circumstances. The actual benefit to be gained from the use of enamel-type linings may therefore be more to keep pipes clean and corrosion-free until installed than to protect them against corrosion in the long term. These types of lining are largely successful as sealing coats for nonmetal pipe, although pressurized water in the porous material under the lining may damage it when the pressure is removed.

6/ In any event, head losses must be determined on the basis of the actual inside diameter which, depending on pipe type (Cl, Dl, S, RC, etc.) and lining thickness, differs from the nominal diameter.

30.   Nonmetallic pipes usually do not require lining. Further, AC and all concrete pipes usually do not require corrosion protection. But when aggressive water is conveyed, the right quality cement must be used; this applies especially to cement mortar lining. Exposed metallic parts, in joint recesses for example, may need protection. Chemical additives to water may improve AC corrosion behavior (Reference 4.01).

31.   The economic importance of internal corrosion cannot be over-emphasized. This fact, along with concerns about health-related consequences of corrosion, led the United States Environmental Protection Agency (EPA) to add requirements for corrosion monitoring to its drinking water regulations in 1981. EPA does not specify which corrosion index should be used (References 4.06 and 4.09). From a health viewpoint, the major concerns regarding corrosion are the possible release into drinking water of toxic substances, such as lead compounds from metal pipe and asbestos fibers from AC pipe. However, while it is true that corrosion of asbestos cement pipe results in asbestos fiber in water, this particular form of exposure to asbestos fiber has not been associated with cancer.

32.   In summary, provided skilled manpower, chemicals, and treatment facilities are available at all times, the best way to prevent or halt internal pipe corrosion appears to be the treatment of water in order to control aggressivity. Cement mortar lining is a useful additional protection for metallic pipe in situations where satisfactory water treatment is not possible. Special linings or corrosion inhibitors may have to be relied upon in difficult cases.

Guidelines for Controlling Internal Corrosion and Encrustation
   in Water Supply Systems

(i) **Guideline 6:** Systems shall be designed to minimize corrosion risks, taking into account the quality of the water from present and future sources and its seasonal variations, as well as potential changes in quality within the system, including treatment and disinfection to ensure a safe and potable drinking water.

(ii) **Guideline 7:** If feasible and economical, water quality in the conveyance system shall be treated to meet the conditions required for forming and maintaining a protective film of complex calcium and iron carbonates and oxides after the methods of References 4.01 and 4.07 or their equivalent. Treatment methods shall be based upon water analyses carried out over a sufficient time period to allow quality variations to occur. Provisions shall be made for the designer, manufacturer, or builder to monitor the treatment for at least one year after start-up. During that year, the process should be adjusted, if needed, staff should be trained, and equipment provided to ensure satisfactory operation of the system on a permanent basis. Treatment shall use locally available chemicals whenever appropriate, even if this means using lower grade materials, as long as this does not compromise the provision of safe and aesthetic water.

(iii) **Guideline 8:** Where Guideline 7 is not applied, or as an added safety precaution, metallic pipes shall be lined with cement mortar. This lining shall meet CEOCOR recommendations (Reference 4.05), ISO 4179, AWWA

C-205, C-206, C-401, or equivalent specifications, with appropriate cement and additives as required. Other lining types such as thick plastic may be used if their success has been proven in at least two systems over a minimum five-year period in circumstances similar to those anticipated.

(iv) **Guideline 9:** The above guidelines shall be implemented in a manner that permits the use of any type of pipe that satisfies service and standardization requirements, ensuring consideration of different types of pipe and adequate competition among suppliers. However, neither lead pipe nor solder containing more than 0.2% lead shall be used.

(v) **Guideline 10:** The systems shall be operated in a manner that prevents pipe corrosion, to which end all equipment shall be maintained in satisfactory operating condition.

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Chapter 5

INTERNAL CORROSION IN SEWER SYSTEMS

1.   Severe damage to sewer pipes from sulfide corrosion has been reported
worldwide since the turn of the century, when many sewer systems were beginning
to age. It is a type of corrosion peculiar to sewer systems. With the
exception of pipes made of inert materials, all sewer pipe is subject to
sulfide corrosion. In a sewer system, the interceptors and rising mains are
those most likely to be affected. Sulfide corrosion, however, does not affect
the secondary and tertiary collection networks, which are usually built of
pipes made out of inert materials. The end result of such corrosion may be
service disruptions, line blockages, and ultimate collapse of the sewer itself.

Case Studies

2.   Of all case studies on pipeline corrosion, those on sulfide corrosion
are among the best documented. They are also the best documented of all types
of pipeline corrosion problems. The following reports illustrate some of the
consequences of sulfide corrosion of sewer pipe.

    (a) Baghdad, Iraq. This is the typical case. The climate is arid with
         ambient temperatures ranging from 45 degrees centigrade to an
         occasional frost. During the period under review, sewage temperatures
         went as high as 35 degrees centigrade. The sewage strength was high
         because of low per capita water consumption. Analysis of the sewage
         showed a pH of about 7, biochemical oxygen demand of 560 milligrams
         per liter, and sulfates of 1,100 milligrams per liter. Sulfides
         ranged from a normal low of 0.8 to a high of 12 milligrams per
         liter. Hydrogen sulfide in the sewer atmosphere varied between 2 and
         85 milligrams per cubic meter, and the relative humidity ranged from
         68 to 96 percent.

         The interceptors were from one to three meters in diameter built in
         situ of reinforced concrete made with sulfate-resistant cement. The
         terrain is flat, and the pipeline gradients were, therefore, low with
         many lift stations and rising mains. The normal minimal design
         velocity of the sewage flow was 0.9 meters per second, and the
         absolute minimal design velocity was 0.76 meters per second. In the
         early years of operation, the flow was quite low.

         The interceptors were put in operation in 1963, and by 1977 the
         maximum depth of corrosion in extended sections of the interceptors
         varied from 75 to 100 millimeters at the crown where reinforcing
         steel, which was designed to be protected by a 50-millimeter concrete
         cover, was exposed and had corroded away in places. The walls were
         also damaged to a depth of 50 millimeters and the access manholes
         showed severe corrosion. Ventilation of some sections had decreased
         corrosion immediately downstream of the air inlets. The rate of
         internal corrosion was estimated at 7.5 millimeters per year, which
         would have led to a critical situation in about 15 years. Repairs,
         including fiberglass patching, proved unsatisfactory because corrosion

proceeded behind the fiberglass patchwork. Rehabilitation had begun in certain sections of the system, and new extensions had been made with PVC or fiberglass-reinforced plastic lining. External sewer surfaces were in good condition despite groundwater with a high sulfate content (Reference 5.01). This experience with sulfide corrosion is similar to that encountered in many other parts of the world, as may be seen in the ensuing case descriptions.

(b) San Diego, California, United States. In 1971, eight years after construction, the reinforcing steel in a 2,500-meter-long, 3-meter-diameter reinforced concrete interceptor--part of a 35-kilometer system that included force mains and tunnels--was found to be exposed over a third of its length, despite a 75-millimeter-thick protective granite aggregate mix concrete cover over the steel at the crown. A 50-millimeter cover was provided at the invert increasing to 63 millimeters at the spring line. PVC lining with integral lugs cast into the concrete showed blisters over a distance of 15 diameters on both sides of junction structures. Attempts at controlling corrosion, such as air injection and addition of chemicals, as well as periodic flushing, proved ineffective and extensive repair was not found to be practical. The design engineers had recognized the potential for a sulfide problem, but could not assess it properly at that time. The corrective methods that are available today were yet to be developed (Reference 5.24).

(c) Cairo, Egypt. As early as 1920, sulfide corrosion of sewer pipe 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, 1.6 meters in diameter and made of local cement concrete, was corroded to a depth of 100 millimeters over a length of 13 kilometers. By 1930, the depth of corrosion had increased to 150 millimeters, nearly half the thickness of the pipe.

(d) Venezuela. Reinforced concrete pipe was corroded to a depth of 70 millimeters within eighteen months of construction in an area downstream from the discharge of a rising main. Vitrified clay pipes used in the same system were not affected.

3. La Baule, France; Sacramento, California, United States; cities in the U.K., India, and Australia; Singapore; and Hamburg, Germany, all have experienced similar problems. In Hamburg, which enjoys a temperate climate, sewage temperature varies from 8 degrees centigrade to 22 degrees centigrade. The corrosion of that city's sewerage system has given rise to a series of German studies of the subject.

The Sulfide Corrosion Process

4. There is general agreement on the complex process that results in sulfide corrosion. Formulas have been developed and tested that are normally capable of predicting the conditions under which it occurs, permitting calculation of the amount of hydrogen sulfide (H_2S) produced, and estimating the life of exposed concrete pipe.

5.   If sewage contains more than 0.1 milligrams per liter (one-tenth parts per million) of oxygen, pollutants are oxidized primarily into water and carbon dioxide by aerobic bacterial action.[7/] There is no odor, little or no hydrogen sulfide is produced, and there is little or no corrosion save that which results from ordinary pipe/water interaction (see Section 4). These conditions usually prevail in the smaller diameter pipes (laterals) of the sewage collection system. However, if dissolved oxygen drops to below 0.1 milligrams per liter, anaerobic bacteria thrive on the nutrients contained in sewage producing hydrogen sulfide and other by-products, such as acetic and carbonic acids or methane and sulfates. This process occurs primarily in the slime layer, which is typically one millimeter thick and covers the sewer wall in the submerged area. This slime layer exchanges nutrients with the sewage stream and releases the hydrogen sulfide and other chemicals into it. The sewage then absorbs oxygen from the air in the sewer and gives off hydrogen sulfide gas.

6.   Hydrogen sulfide is relatively soluble in water, and it dissolves in the condensed water present mainly around the crown of the sewer. At the end of the process, other bacteria (e.g., Thiobacillus Concretivorous) oxidize the hydrogen sulfide, mainly into sulfuric acid (H_2SO_4). The sulfuric acid corrodes the concrete components that are sensitive to it, primarily the free lime in cement, yielding calcium sulfates. Certain calcium sulfates can cause concrete to swell up to five times its normal volume, causing exfoliation. This process causes the pH of concrete to fall from about 12, at which no bacterial action occurs, to less than five. At that point, the concrete begins to spall, become spongy, and develop a whitish layer. This process may take a year to become noticeable. Later, if steel reinforcing bars in the concrete are exposed to the hydrogen sulfide, they will corrode rapidly.

7.   Bacterial activity depends largely on temperature and pH. Such activity is low at about 10 degrees centigrade, fairly high at 38 degrees centigrade, and optimal at pH 7. Hydrogen sulfide in the absence of water has itself little effect on concrete. It has an obnoxious odor at low concentrations (threshold at about 0.001 ppm), but the ability to smell it is quickly lost. It is hazardous at 100 ppm in the air and can be lethal at 300 ppm. Air in sewers may occasionally contain 1 ppm. Hydrogen sulfide is explosive in small concentrations in the air (a few percent by volume).

8.   Sulfide production in domestic sewage increases with biochemical oxygen demand (ranging from 200-300 ppm), sulfates, temperature, and flow time. Other factors affecting the production of sulfides are flow velocity, sediment build-up, pH levels, pipe size, and flow depth. Turbulence in the sewage flow increases the release of H_2S and its reoxygenation, thus increasing corrosion at sewer pipe junctions, sections downstream of manholes, or other similar points. In sewer laterals where there is generally sufficient ventilation to prevent sulfide build-up, a flow velocity of 0.6 meters per second is generally adequate. However, the flow velocity of 0.6 meters per second (2 feet per second), usually recommended for sediment removal, is no

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7/ Saturation of oxygen in plain water is about 10 milligrams per liter under standard conditions.

criterion for corrosion control in the larger diameter sewers. Higher velocities may be needed depending on prevailing conditions.

9.   Conditions in sewerage systems vary widely with the seasons. Large urban systems in developing countries may have greater sulfide corrosion problems as a result of high temperatures and high biological oxygen demand resulting from low sewage flows, low water consumption per person, or, conversely, system overload or poor maintenance.

Controlling Sulfide Corrosion

10.   Manuals issued by the United States Environmental Protection Agency (References 5.05 or 5.06) provide guidance on controlling sulfide corrosion. Formulas incorporating most of the factors discussed above allow reasonably accurate prediction of the probability of sulfates occurring, the quantities that will be produced, and the probable lifetime of reinforced concrete (or asbestos-cement) pipes. These formulas were developed between 1950 and 1976 in the United States and Australia. The Pomeroy-Parkhurst formula for controlling sulfide corrosion is in agreement with comprehensive tests made in Los Angeles and Sacramento and also with other studies. One example of a system utilizing preventative measures is that of Los Angeles County, California, United States. The county sanitation district serves four million people and has over 80 kilometers of interceptors. The system is designed on the basis of Pomeroy's concepts for minimizing sulfide production and uses concrete pipe almost exclusively, with PVC T-lock lining in sections where there is a risk of sulfide corrosion. The Thistlewaythe formula, developed in Australia, yields results that are far greater than those obtained from surveys made in the U.S.A. (Reference 5.21). However, maximal corrosion rates, such as those associated with turbulence, may be as much as 50 percent higher than the formulas indicate. The guidelines at the end of this section are based on the above work and should take into account the following:

- The worst conditions are found in stagnating sewage as occurs in rising mains, pump station sumps, and where turbulence increases the release of hydrogen sulfide gas. Since high turbulence is likely to occur mainly at junctions, outlets of rising mains, and at manholes, all parts of a sewer line do not have to be made equally resistant to corrosion. The life of a sewerage system is therefore inevitably limited in most cases, since corrosion damage will occur and will have to be endured. However, systems as a whole should be designed to last at least fifty years.

- The most expensive solutions for protecting sewerage systems against corrosion, such as PVC linings, are not always necessary. There may be other less expensive, satisfactory solutions. For example, concrete or cement mortar-lined metal pipe may be manufactured with an inner sacrificial layer of concrete, 25-50 millimeters thick. Sulfate-resistant or high alumina cements and, where available, calcareous aggregates may increase the life expectancy of such pipe by three to five times. Therefore, two different methods for increasing the life of concrete pipe are available: either providing material to be consumed by corrosion or using pipe material that is more resistant to corrosion. In any event, the quality of the concrete is of paramount importance. Similar solutions are available for the protection of steel

and iron pipe, but these are not applicable to asbestos-cement pipe. The best way to extend the life of an asbestos-cement sewer pipe is to select a higher "class," i.e., thicker, pipe than needed for structural strength.

- No ordinary bitumen, epoxy-resin, or plastic lining has yet proven effective in construction or repair since even minor defects permit decay to begin behind such linings. The only effective, long-proven lining is plastic sheeting that is mechanically locked to the concrete. This is, however, not compatible with centrifugal casting of concrete pipe. The lining sheets must be carefully welded at the pipe joints during pipe laying. The invert of the pipe, which is permanently wet, needs no protection.

- Good ventilation is important, although it usually removes condensation (which is necessary for the corrosion process to occur) only in the immediate vicinity of the air inlets. Ventilation does not, therefore, solve the corrosion problem in all parts of a long sewer. Chemical additives, such as oxidants and chlorine, are effective but usually are too expensive, except, perhaps, when the injection of oxygen into rising mains is feasible.

- Periodic flushing of sewers is necessary to remove solids.

- Repair of a corroded sewer system is a major undertaking. It is always expensive and causes many inconveniences; therefore, rehabilitation is becoming an increasingly attractive alternative to replacement (see Chapter 7).

Guidelines for Controlling Internal Corrosion in Sewerage Systems

(i) **Guideline 11:** Sewer systems shall be designed for a lifetime of fifty years, unless otherwise directed, taking into account potential sulfide corrosion. Where feasible, designs shall provide for self-oxidizing velocities and slopes of 0.6 percent, good ventilation, low turbulence, flushing facilities, minimal periods of flow in the system, and minimal sewage stagnation. If economical and practical, designs may involve air or oxygen injection or the addition of chemicals.

(ii) **Guideline 12:** The least-cost solution shall prevail, taking into consideration construction, maintenance, and operating costs, as well as other constraints such as the availability of trained staff for maintaining the system. Pipes made of inert materials are preferable, if found economical. Alternative pipe materials and linings shall be considered as, for example, in the case of large pipes, reinforced concrete with a sacrificial layer, and PVC-lined reinforced concrete, to ensure competition among suppliers. For metal pipe, the acceptable linings are either a cement mortar lining of appropriate quality and thickness or, possibly, a thick plastic lining. For concrete pipe, mechanically locked PVC sheet lining should be utilized.

(iii) **Guideline 13:** In implementing the above guidelines and in evaluating existing systems, designers shall use the most reliable manuals, codes of practice, and standards available (References 5.02, 5.04, 5.05, 5.06, or their equivalent).

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Chapter 6

EXTERNAL CORROSION

1.   It is common knowledge that metal structures—made primarily out of steel or iron—whether underground or aboveground, will corrode over time if they are not protected. Concrete structures, normally weatherproof, also decay in certain environments such as saline atmospheres, especially in warm climates. Water and sewer pipes are no exception.

2.   External corrosion damages the pipe wall and eventually causes leaks and bursts. Corrosion-induced bursts mostly affect prestressed concrete pipe, which is often used for major supply lines. Although relatively rare events, such bursts are always disruptive and sometimes catastrophic. Gas distribution and feeder lines, oil pipelines, and even metal-shielded cables are affected by corrosion in a manner similar to water and sewer pipes and provide good examples of failures caused by external corrosion.

3.   After examining the case studies, this chapter discusses the external corrosion process, with a focus on the corrosion of steel within reinforced and prestressed concrete pipe and in reinforcing bars and prestressing wires. Because of the position of the reinforcement, corrosion in reinforced pipe is seldom from internal causes. Coatings, cathodic protection, and soil surveys are discussed.

4.   Very few documented cases of external corrosion of pipes have been published, and much of the available information is incomplete. However, literature on cathodic protection is abundant.

        Case Studies:

Metallic Pipe

    (a) Newcastle, England. Pockets of highly aggressive soil ate through thick iron pipes in less than two years. Since 1966, pipes have been protected by polyethylene sleeves at a cost of 100 pounds sterling per kilometer for 200-millimeter-diameter pipes. This has been successful (Reference 6.23).

    (b) Kuwait. Road work uncovered ductile iron pipe protected by polyethylene sleeves several years after it had been installed in a corrosive, warm, saline soil. Only traces of corrosion were observed.

    (c) Middle East. In several cities, corrosion of ductile iron pipe protected by coal tar-type coating occurred about ten years after installation. Causes were saline groundwater in areas near the sea or a rising water table resulting from wastewater discharges over an otherwise dry soil with high chloride and sulfate content. The soil temperature was 20 degrees centigrade, and the water temperature in the system ranged between 35 and 45 degrees centigrade.

(d) <u>Venice, Italy.</u> In spite of a very corrosive soil and a high water table fluctuating with the tides, thorough graphitization of 15-20-millimeter-thick cast-iron pipe for the conveyance of gas took some eighty years to develop. Recently installed thinner pipes began to leak heavily about fifteen years after installation. In this case it is asserted that the zinc/coal tar coating provided on these thinner pipes would not have been adequate protection even with polyethylene sleeves because the products from zinc alteration would probably have been washed away by the action of the fluctuating water table. The solution in this instance could be the thick polyurethane coating that is now available.

(e) <u>Brussels, Belgium.</u> The original water supply system was constructed of cast-iron pipe with caulked lead joints of relatively low electrical resistance. Some of the pipes were still operational after a century in the soil. Between the two world wars, steel pipe was used, first with rubber gaskets of high electrical resistance, then, after World War II, with welded joints of high electrical conductivity. Several major feeder lines constructed during the interwar period, however, were of reinforced concrete cylinder-type pipes with caulked lead joints. Other pipe materials were used in the system on a limited basis. The gas distribution system was also constructed with iron and steel pipes.

Until the second world war, an old direct current (dc) electricity distribution system was in use in part of the city. The streetcar system also used direct current.

There were few corrosion problems until 1935, when a 600 millimeter, 0.6 Mega Pascal pressure main feeder line burst in a spectacular manner in front of a direct current generating substation of the streetcar system, inside the city. The burst pipe was of the reinforced concrete, cylinder type, and the reinforcing bars showed the typical spindle shape of an electric conductor corroded by electrolysis. The cause of this accident was that the direct current returning to a streetcar substation followed the path of minimal electrical resistance, partly through the water supply feeder line instead of the tram rails, and corroded the pipe reinforcement and the steel cylinder at the current outlet. Following this accident, all of the underground utilities installed cathodic protection in their systems and made periodic surveys of pipe voltage to earth. Close collaboration between the water, gas, transportation, and power utilities was also established. This case provides a good model for urban settings where many different utility lines lie buried in close proximity (Reference 6.24).

(f) <u>Bombay, India.</u> The water distribution system, made of iron and steel pipes, and the streetcar system have had a history similar to that of Brussels. The provision of cathodic protection for a part of the water system is a component of a recently planned extension to the system.

(g) <u>Nairobi-Mombasa, Kenya</u>. The 450-kilometer-long Nairobi-Mombasa oil pipeline, made of 350-millimeter welded steel pipes, had a standard glass fiber reinforced, coal-tar enamel-type coating and was cathodically protected. The cathodic protection system was composed of a large number of magnesium earthing rods, isolating joints, and nine impressed current devices. A nonelectric railway and a high voltage power line ran parallel to the pipeline. Recordings of the electric current circulating in the pipeline showed considerable variations and reversals of polarity. The major cause of these stray currents, of telluric origin, was identified as the daily variations of the geomagnetic field as the earth rotates in the solar wind. The measured current was 0.5 amperes, corresponding to a 10 millivolts predicted electrical potential per meter of pipeline, which increased to 2 amperes during magnetic storms (Reference 6.22). As discussed later in the section on external corrosion processes, telluric currents can cause anodic corrosion at places where the current leaves the pipeline.

(h) <u>The Netherlands</u>. Extensive oil, gas, and chemical product pipelines leading primarily from Rotterdam and connecting major refineries and chemical plants in the Netherlands, Belgium, and Germany led the Dutch government to create "pipeline highways" (Reference 6.08). These areas were 60-100 meters wide where pipelines were concentrated along parallel routes; in them, individual pipelines were laid at least 500 millimeters apart. They all had the same four-millimeters-thick coating of glass fiber reinforced bitumen, were cathodically protected, and monitored together, although each could be controlled individually. Impressed currents were returned to earth through silicon iron sacrificial anodes. Pipelines within the highways were fitted at their boundaries with electrically isolated joints; interference with pipelines outside the highways was found to be negligible (Reference 6.30).

(i) <u>In a major European city</u>, gas leaks due to corrosion resulting from interference between pipe systems, which were not all cathodically protected, caused thirteen deaths in one accident.

(j) <u>In developing countries</u>, poor workmanship in applying external protection has proven quite costly. A two-year delay in completing the cathodic protection system of a 20-kilometer section of an oil pipeline through salty marshland resulted in such extensive corrosion that most of the section had to be replaced. Another pipeline, over 600 kilometers long and 750 millimeters in diameter, installed in particularly aggressive soil, was so poorly coated on the site that the cathodic protection could not be made effective. A few years after its completion, 300 kilometers of the pipeline had to be replaced at the cost of about US$300 million.

Case Studies:

Nonmetallic Pipe

5.   There is virtually nothing in the literature surveyed concerning
corrosion of reinforced concrete pipe. A report is available from Australia
(Reference 6.12) that deals with failures of prestressed concrete pipes and
other prestressed concrete water retaining structures; it analyzes causes and
prescribes remedies. This is probably the most comprehensive extant document
on the matter; it covers such failures worldwide through 1975. Among other
prestressed concrete pipe failures reported in countries including France,
Belgium, Spain, Brazil, Venezuela, the Netherlands, and Japan, the cases from
Australia, Pakistan, Israel, Canada, and Colombia are of special interest and
are discussed below:

    (a) Australia. At the time of the report (1975), 250 kilometers of
        prestressed non-cylinder reinforced concrete pipes had been laid in
        Australia. The Geehi Aqueduct (Snowy Mountains), built in the 1960s,
        included 13.4 kilometers of prestressed non-cylinder concrete pipe,
        0.8 to 2 meters in diameter pressure rated up to 0.9 Mega Pascal.
        Five bursts occurred, each of which was investigated in detail. The
        bursts washed away nine pipes in one instance and thirty in another.
        Wires broke in both ductile (with section reduction) and brittle
        (without section reduction) modes. Several wires were broken where
        the pipes burst; extensive transversal and longitudinal cracks were
        found to be affecting the wires around and outside the area of the
        bursts. The main cause of the accidents was determined to be
        inadequate protective mortar coating of the prestressing wires.
        Coating that was too porous, permeable, and sometimes too thin (less
        than about 19 millimeters) gave water loaded with chlorine and
        sulfates access to the wires. Other defects noted were poor
        workmanship (wires not embedded in cement paste), corrosion of wires
        before pipe manufacture, overloading of pipes during construction, and
        long exposure to weathering (three winters) before they were buried.
        Wire failures and cracks were attributed to stress corrosion and/or
        hydrogen embrittlement.

6.   The other reported failures demonstrate similar features:

    (b) Regina, Canada. Fifty-six kilometers of 36-inch- (900 millimeter)
        diameter pipes manufactured in 1952 appear to have been adversely
        affected by the use of calcium chloride. Instead of the specified 2-3
        percent of cement by weight, the manufacturer had used up to 3.8
        percent of calcium chloride. Further, the pipes, whose cores were
        vertically cast, had been cured under hot water at 60 degrees
        centigrade. This water was recirculated to economize fuel; it had a
        high sulfate content, reaching saturation (1400 ppm) at the end of the
        process. Over 30 percent of the pipes tested did not pass pressure
        tests, and corrosion of the wires was extensive. Litigation led to a
        call for new tenders, and an all-steel line was laid in 1955.

    (c) Karachi, Pakistan. The non-cylinder prestressed concrete pipes, 160
        kilometers in total length and 0.8 to 2.1 meters in diameter, were

locally manufactured about the time of the Australian report in
1975. Thirty-six failures were experienced, which were attributed to
poor protective wire coating and the fact that the pipes had been laid
mostly in aggressive soil. Cracks were caused by overheating of the
wires in the tensioning device (section reducing dies) used when the
wires were wrapped around the concrete core.

(d) Israel. Stray current corrosion appeared to develop in the wires
wrapped around steel cylinders within which a concrete core had been
poured. The wires were not well embedded in their protective
coating. Electrical continuity of the pipelines had been maintained
between steel cylinders by jumpers because rubber gaskets were used.
There was a total of 500 kilometers of this type of pipe, 0.5 to 1.7
meters in diameter. Numerous pipes had to be replaced, largely as a
result of pitting. Some 400 kilometers of the line have been
cathodically protected, with unknown effect.

(e) Bogota, Colombia. About 50 percent of the city's water demand is
supplied through an embedded cylinder prestressed concrete pipeline
that is 50 kilometers long and two meters in diameter. It was
constructed between 1968 and 1972. The pipeline's first 29-kilometer-
long section, laid in the flat floodplain upstream of Bogota outside
the urban area, failed five times between 1972 and 1983. The
failures, which caused great concern in the city, were investigated by
the National University, private consultants, and a panel of
international experts. The detailed study of the case indicates that
the mortar coating protecting the prestressing wires was defective. A
measure of the permeability of the coating was $2.5 \ 10^{-4}$ cm/s, to be
compared with the recommended maximum of $1 \ 10^{-9}$ cm/s. Patches of the
coating (about one foot in diameter) flaked off, uncovering a layer of
sand and gravel with very little cement. There were also indications
of cracks in the coating. The wires showed evidence of brittle
fracture, probably caused by hydrogen embrittlement. The soil around
the pipeline was found to be aggressive in a number of places, but
there seemed to be little correlation between the aggressive areas and
the bursts. The bursts all seemed to be located in the more humid
zones.

(f) In arid countries corrosion has occurred in reinforced and prestressed
concrete pipes when incomplete backfilling left parts of the pipeline
exposed to air for some time and humidity lifted through soil
capillarity conveyed salts from the soil through the pipe material to
the surface of the fills where water evaporated, leaving deposits of
concentrated corrosive salts within the pipes. Corrosion proceeded
even after completion of backfilling. The process was controlled
through the use of polyethylene sleeves and sealing coats and improved
backfilling practices.

External Corrosion Processes

7.   There is a general consensus on the processes of external corrosion,
although uncertainties remain in some areas and debate continues over such
issues as the cathodic protection of prestressed concrete.

8.   The basics of external corrosion are similar to those of internal corrosion, with major circumstantial differences. Groundwater movement around pipe is always slow compared to flow inside pipe, and no pressure builds up under a coating. On the other hand, there is a greater variety of soil conditions and materials present in the soil surrounding pipes and, therefore, more potential for chemical and biochemical interactions than is the case within pipes. Electrical continuity and conductivity of many pipes and pipelines, or of sections thereof, are a further major factor. They allow electrolytic--or galvanic--corrosion to proceed on a greater scale or at a faster pace for the external section of the pipe and also permit the concentration of corrosion in small areas. These factors may have the effect of perforating pipes in a matter of weeks or less. Otherwise, if spread over significant sections of pipelines, galvanic and chemical corrosion of poorly protected metal pipe proceeds at a slower rate, typically 0.01 millimeter per year, but potentially up to 0.24 millimeters per year in an aggressive environment.

9.   Soils are commonly not aggressive: a survey carried out in the United States has shown that only 5 percent of the length of a number of cast-iron systems in the country were in corrosive soils. Nonetheless, this is enough to require attention. Severe adverse conditions usually concentrate in relatively small geographical areas such as present or former riverbeds, marshes rich in humic acids or bacteria, brackish pans, and industrial or city waste dumps. High ground is usually drier and thus less corrosion-prone than low ground. Sand, gravel, and limestone are generally the least corrosive soils; clays are more corrosive. Soils with high levels of natural sodium chlorides (such as coastal soils), sulfates, pyrites, and industrial or other man-made wastes are the most corrosive. Humidity and groundwater are generally adverse major factors. Soils with low resistance, which is usually a result of contamination, are more corrosive than those with high resistance. As a rule, no special precautions are needed if soil resistance is greater than about 3,000 ohm per centimeter. Soil with resistivity lower than about 1,500 ohm per centimeter should be thoroughly investigated so that necessary steps can be taken to provide protection against corrosion.

10.   The above paragraph addresses the problem of local corrosiveness that affects relatively small areas. These spots may be numerous and scattered over several pipes. When metals are involved, such corrosion is referred to as galvanic because the electrical conductivity of the metal allows electric currents within cells where corrosion proceeds and which have their own chemistry. Bacteria accelerate the process, time affects it, as do circumstances such as the level of the water table, and corrosion itself can alter the environment.

11.   Corrosion proceeds also because pipelines cross different soils that may or may not be contaminated by refuse or soils of different humidity and aeration levels; it can also result from the use of different pipe materials or the presence of other pipelines causing differences in electric potential at different points along the pipelines and between pipes and soil. This larger-scale phenomenon is also electrolytic or galvanic in nature, and the electric continuity and resistance of pipelines are major factors in the intensity of its effects on corrosion. Corrosion from such causes does not occur until after a pipeline is constructed, and therefore its extent and effects cannot easily be predicted: the construction of a pipeline changes the environment.

12.   Stray electric currents may be superimposed on the currents of galvanic origin and compound their intensity and worsen corrosion activity, particularly in electrically continuous pipelines. These currents are primarily man-made, typically originating in electric direct current railways or streetcar systems that use the rail as a return conductor of the current or arising from interferences with other power or pipe systems. However, there are many natural (telluric) stray currents, which are the result of galvanic effects or of variations in the earth's magnetic field (Reference 6.22). Electric currents always select the path of least resistance through the earth, its varied soils, and any buried metallic object. In so doing, they may short-circuit isolating joints in pipelines, jump from one pipeline to another or to metallic cable shields. This causes interferences among systems, cathodically protected or not. Electric current, as a rule, causes corrosion at all anodic areas, where it leaves the metal.

13.   Stray currents are direct current (dc), or are considered as such, but alternating currents at industrial frequencies may have similar but lesser effects. In any event, it is the direct current component that causes the electrochemical corrosion, which is measured and needs to be taken into account. In most cases, their intensity is greatly variable as, for example, those caused by dc railway systems. Their effects can be extremely damaging: over a year's time, a direct current of one ampere removes nine kilograms of iron (a volume of about one liter), generally from a small area. This intensity is within the range of telluric currents and may be higher in pipe systems composed of different materials, including poorly isolated cast-iron pipes. Railways that run on direct current can circulate currents of 10 and even 100 times that intensity. Such occurrences are most likely in urban areas.

14.   The resulting electrolytic corrosion may thus proceed very fast, causing holes in 3-to-10-millimeter-thick steel pipe or eating away the steel reinforcement of concrete pipes within a period of weeks or less in cases where a metal pipe coating is defective or the overlap of polyethylene sleeves is insufficient. Longer, electrically continuous sections of pipeline collect higher currents, but proper insulation reduces their intensity. Rubber gaskets and polyethylene sleeves have similar beneficial effects.

15.   Improvements in metallurgical processes and centrifugal casting have, over time, allowed for the use of thinner cast-iron pipe than was once possible, and ductile iron pipe with even thinner wall thicknesses is now being used worldwide. Therefore, in the early days of water system development, cast-iron pipes with heavy, thick walls were laid with no protection against corrosion and lasted for a century or more. As pipe with thinner walls was manufactured, the need for external protection increased--more so when the urban environment worsened with the development of industry and electric transportation systems.

16.   Steel pipe, which is usually even thinner (typically 1/100 of pipe diameter with a minimum of three millimeters), does require adequate protection. In the early days, steel pipe with somewhat thicker walls was used, but it also needed good protection. However, no significant difference is reported in the rate of corrosion of metal pipe, whether of cast- or ductile iron or steel except, perhaps, for a somewhat better performance for iron. The

major factor determining the life of unprotected metal pipe is its thickness, in the absence of the larger-scale activity described in paragraphs 11 and 12.

17.   Concrete and AC pipes corrode externally in much the same way as they do internally, for example, through chemical sulfate decay (Reference 4.04). Protective measures and considerations regarding appropriate cements, aggregates, and curing methods are the same in both cases. This is especially important for all types of reinforced concrete pipe; DIN 4030 (Reference 6.11) sets forth methods for evaluating the aggressivity of waters, soil, and gases to concrete. (See also Reference 6.10.)

18.   Steel reinforcing bars within all reinforced concrete pipe and steel wire in prestressed concrete pipe, including steel cylinder in concrete pipe and metal barrels of cement mortar-lined steel or iron pipe, are naturally protected against corrosion because in the concrete media, which has a pH of 12, steel takes an electropositive voltage of 0.12 volts (measured with a copper sulfate electrode--CSE). This places it in the "passive" corrosion resistant area (Pp) in Pourbaix's diagram, as shown in Annex 3, where protective oxides form with time. However, this could change because of high concrete permeability, cracks, accidental concrete flaking, or the presence of chlorine ions or because, as a result of concrete corrosion, the steel is exposed either to ordinary or to stress corrosion. The steel is then brought into the "corrosion" domain (Pc) with about neutral pH and voltage to concrete in the range of -0.36 volts since wet concrete is an electrolyte (Reference 6.09). A steel potential of this level indicates that corrosion is probably under way, but further investigation would be needed to confirm the position. A more advanced stage of corrosion would be the exfoliation of concrete following steel oxidation. This description points strongly towards the importance of using high quality (low permeability) concrete, effectively embedding steel into concrete or cement mortar and making the steel reinforcing cage and cylinder into an electrically solid body with a well-defined electric potential that can effectively carry electric currents if cathodic protection needs to be provided.

19.   A number of failures of prestressed concrete pipes have been attributed to stress corrosion or to hydrogen embrittlement of steel wires. Neither of these phenomena has yet been thoroughly explained. Australian, French, Belgian, Spanish, CEOCOR, and IWSA documents discuss them, but they are scarcely mentioned in literature from the United States (Reference 6.27).

20.   Stress corrosion and hydrogen embrittlement adversely affect steel reinforcement that is under high stress levels and subject to electrochemical reactions when permeability, cracks, or other defects in the concrete allow water and oxygen and chlorine or other ions access to the steel. Stress corrosion, like ordinary corrosion, may proceed because of differential exposures to oxygen, differently stressed steel areas, or other galvanic action. Hydrogen embrittlement results from the release of hydrogen in cathodic areas where electric current enters a pipe. Hydrogen, in its atomic form at the moment it is released, is very reactive and may penetrate the steel's crystal lattice and distort it, causing high stress concentrations; it may also accumulate in pockets of high pressure gases. In either case, typical fractures show no ductility (no elongation or section reduction). In laboratory tests under conditions that encourage such corrosion, specimens

break after as little as 100 hours (Reference 6.13). Surface conditions such as scratches and cracks are as much a factor as the nature of the steel, the impurities it contains, its actual thermic treatment, and the stress level, which should be moderate. Coating of the wire or the coating process may reduce this fragility. Tensioning devices such as size-reducing dies used when wrapping the wires around the pipe's core may initiate defects, e.g., through overheating.

21.   As hydrogen embrittlement develops in cathodic areas, stray currents worsen the problem and cathodic protection, which does nothing to prevent current leaking into pipes at cathodic areas (on the contrary, it may hasten this process), may enhance the embrittlement process.

22.   Although a relatively small number of pipe bursts have been caused by stress corrosion or hydrogen embrittlement, this problem cannot be ignored, particularly because prestressed concrete pipe is often used for major water supply lines.

Corrosion Prevention and Control

23.   The key subjects to be addressed here are quality (materials and manufacture) of nonmetallic pipe, external coatings, cathodic protection, and soil surveys to design the selection of appropriate prevention and control measures.

Pipe Manufacture

24.   The process by which pipe is manufactured and the selection of appropriate cement are major factors in preventing or reducing corrosion of all concrete pipes and asbestos cement pipe. Good concrete quality is essential: high compacity, absence, or very low quantity, of chloride ions. The quality of the cement mortar coating the wires in prestressed concrete pipe is especially critical. In the latter case, experience indicates that coating permeability should not exceed one 10^{-9} centimeters per second, although 10^{-10} centimeters per second can be achieved (Reference 6.09). In spite of its importance, no such requirement is as yet included in any standard or specification, although means for measuring the permeability of coatings have been devised and can be applied. It is also possible to further seal the cement mortar with a coal tar-type or polyurethane enamel coating, which should perhaps be recommended as an additional general safety measure rather than as a solution for difficult cases. Specifications have recently been developed for prestressing wires that address the problems of stress corrosion and hydrogen embrittlement. They enable the selection of appropriate steels through tests of wires wrapped around a core in environments that favor embrittlement (Reference 6.14). Means are thus available to prevent the accidents discussed in the case studies, which have marred the generally successful applications of prestressed concrete pipe. The guidelines (18) and (19) suggest a series of measures based on the experiences discussed above. Some manufacturers already apply them, at least in part, as indicated in References 6.01, 6.10, and 6.14.

Coatings

25.   External coatings, unlike internal linings, are usually successful on all types of pipes, whether iron, steel, asbestos-cement, or concrete. Bonding of the coating to the pipe is, of course, critical and works particularly well with nonmetallic pipe (Reference 4.21).

26.   A satisfactory bond requires adequate surface preparation (grit-blasting), the use of primers on metal pipe, and the strengthening of the coating with glass fiber, or asbestos felt, or plastic tape. AWWA, DIN, ASTM, and other coating standards specify satisfactory protection for most cases. However, tougher coatings and linings have been or are being developed for the most severe conditions such as offshore pipelines and industrial pipelines subject to abrasion or erosion, which are rare in water conveyance (or sewerage) projects.

27.   The earliest coatings were of coal tar, which is no longer acceptable as an all-purpose protection and has been replaced by more refined products that often use the same name and are sometimes called bitumens. Later, metallic zinc spray coating sealed by coal tar-type varnish was developed for cast/ductile iron pipe. This kind of coating does a good job by self-healing of defects such as scratches that expose the bare metal, but cannot correct severe mechanical damage. It works well, for example, in soils with a pH between 4.5 and 9, and resistivity as low as 500 ohm per centimeter. In 1952, the polyethylene sleeve was developed for iron pipe; it can also be used with reinforced concrete pipe. These sleeves are fitted just before installation and can easily be repaired with tape if damaged. They are satisfactory in most soils for long periods of time even when exposed to anaerobic bacteria or to stray currents, which they virtually prevent unless gaps occur in the sleeves where corrosion can penetrate. In very corrosive soils, although perhaps not in the most severe conditions, sleeves can provide additional protection to iron pipe coated with the above-mentioned zinc/coal tar layer. Further protection may be provided by the tough coatings described in paragraph 26.

28.   Uncoated steel pipe can quite rapidly be damaged because of its thinness. It must be protected by a 3 to 4 millimeter thick well-bonded coal tar, bitumen, or epoxy-type coating, fiber reinforced felt or covered with vinyl tape. (For epoxy protection, see Chapter 4, paragraph 28, Internal Corrosion.) These coatings may be applied either in the field just prior to installation--in which case continuity of the coating is best achieved. (This process implies the use of welded joints.) Or in factory, which provides better conditions for application. In either case, the coating must be checked with a holiday detector (high voltage spark) at the last possible stage during installation, and any defects must be repaired.

29.   There are ASTM and DIN laboratory cathodic disbondment tests (separation of the coating from the specimens as a result of electrolytic reactions). The test conditions are far more severe than those normally encountered in the field.

Cathodic Protection

30.   Cathodic protection can control stray currents (electrolytic) and galvanic corrosion of metal structures such as pipes, steel reinforcement in concrete pipes, steel tanks, and ships by:

(a) bringing them in or very close to the "immunity" domain of Pourbaix's diagram in Annex 2 (Pi) through the application of an electrical potential of -0.85 volts (CSE) or somewhat lower (about -1.0 volts), relative to the surrounding earth (or water, if immersed);

(b) diverting the electric currents from their natural outlets--directly from pipe to ground--and returning them to the earth through special electrodes that corrode in place of the pipes or to the negative pole in dc substations.

31.   The -0.85 volt (CSE) condition must be met in all sections of the protected system; it also works effectively where corrosion is of a chemical or biochemical nature, for example, when it is caused by aggressive soil and in the case of steel reinforcement within concrete.[8] The potential to ground should not be much more negative than the value stated above, particularly in the case of prestressed concrete pipes, which require fine adjustment. One problem that arises is that the laying of a pipeline disturbs the electrical conditions within the soil, making it difficult to predict the ultimate effect.

32.   There are two ways of ensuring the -0.85 volts condition. First, by electrically connecting the structures to sacrificial anodes made of metals, such as magnesium alloys, that are at least 0.85 volts more electro-negative than iron. Second, through impressed currents at the appropriate voltage, drawn from an appropriate direct current source, such as a rectifier unit, connected to the structures to be protected and to either a sacrificial "earth" made of low-cost, massive metallic parts (such as used rails) or to the negative terminal of the direct current substation to which the stray currents have to return, as in a direct current railway system. Impressed current devices can be designed to automatically adjust the voltage of the protected structures to predetermined values somewhat more negative than -0.85 volts.

33.   Joints are a major factor in determining the electrical continuity of pipelines. Caulked lead joints, formerly used with iron, steel, and even reinforced concrete pipes, have relatively low electrical resistance. Rubber gaskets in iron, steel, and reinforced concrete pipes isolate pipes from each other, unless there is direct metal contact. These joints must be electrically bridged to restore electrical continuity where needed. Prestressed concrete pipes need electric wiring for connecting each pipe or group of pipes to the grounding or impressed current devices, which must maintain a very uniform potential to ground all along the protected sections. Welded joints, of course, make steel pipes one solid electrical conductor. Isolating joints, in

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8/   Lesser negative voltage may suffice (-0.5 to -0.7 volts). The degree of protection with a lower voltage is around -0.7 volts.

the form of flanges or Gibbault or Johnson isolating couplings, are designed to break the electrical continuity of pipelines. The ground, however, bridges to some extent any sort of isolation between pipes.

34.   As a rule, pipelines should not be electrically continuous all along their route; instead, they should be divided into sections to better control the intensity and circulation of the electric currents and allow monitoring of the voltage to ground. Major items in the design of a cathodic protection system include the length of these sections, the location of isolating joints, the means to be used for connecting the pipes, and, of course, the location and characteristics of the grounding devices, including the voltage sources. Soil surveys deliver major information in this connection. Isolated sections may be connected as needed after continuity has been monitored.

35.   Cathodic protection is a relatively sophisticated process that operates satisfactorily, provided a few key conditions are met. The pipes must be well isolated from the ground by an appropriate coating, as this reduces the electric currents picked up from the earth and thereby facilitates the operation of the cathodic protection system. The pipe system to be protected must be designed or constructed so that it can be divided into electrically isolated sections through isolating joints or other devices. Sacrificial anodes or impressed current devices must be incorporated in the system at appropriate locations, and the protection must be made operational as soon as pipeline construction has made sufficient progress to avoid early, rapid corrosion damage. Voltage to earth along the system must be monitored during its whole life to ensure that the protection is reacting properly in a changing environment, and immediate action must be taken if a hazardous situation should develop. All industrial and private electrical installations in the area of the protected pipe system must be isolated from it and grounded indepen-dently. Using a pipe system as electric "ground" might disrupt the cathodic protection, pose safety hazards to laborers, or be ineffective if isolating joints or pipes are used.

Because of the inevitable electrical interference among protected and nonprotected buried metal pipe systems, no matter for what usage, a large measure of coordination and collaboration must be established and maintained among all users of buried systems, especially those whose facilities are the sources of stray currents such as electric railway systems. Consequently, cathodic protection also requires a small but well-trained staff with proper tools, measuring instruments, supplies, and vehicles for operation and maintenance or, more precisely, routine monitoring, equipment servicing, and voltage measurements. On the other hand, designing systems, interpreting voltage surveys, and deciding when corrective action is called for require experienced engineers who need not always be on the staff assigned to the system since such tasks are usually not full-time jobs even in well-developed systems. Consultants may be a preferable alternative.

36.   Cathodic protection is a most efficient means of protecting metal and some of the steel-reinforced and nonmetal-reinforced concrete pipes. It is not a passive system like coating, and it requires continuous care and a certain level of expertise on the part of the staff appointed to maintain the pipelines. In developing countries it should therefore be used only where really needed and avoided when the monitoring equipment, spares, and necessary

expertise are not continuously available. But, should there be a need, cathodic protection should be used and all necessary steps must be taken to make it successful. Staff training and retraining is generally the major task involved and should be included in the project together with needed spare parts and equipment.

37.   Cathodic protection is required whenever the electric continuity of a pipe system can cause it to collect significant electric currents, that is, in all welded steel lines and, probably, complex urban networks made of various metals or metal-reinforced pipes for water, gas, and other conveyance. Cathodic protection may be useful or necessary for pipelines with isolating joints where soil is particularly aggressive or interference with other pipe systems is a problem. It should not be systematically applied to reinforced concrete pipe (as sometimes recommended) or to iron pipe. Prestressed pipes should not be cathodically protected except when the pipes (or sections of a pipeline) are under a definite corrosion threat greater than that potentially caused by stress corrosion or hydrogen embrittlement. In such instances, special precautions must be taken.

38.   Whether systems are cathodically protected or not and although voltage surveys cannot yield unquestionable information about corrosion status, particularly in the case of concrete pipes, provision for measuring voltage to ground should always be made. Permanent connections to pipes that are readily accessible on the ground in test stations (a simple meter box-type structure in the ground) a few hundred meters distant from each other (depending on corrosion risk), or in hot spots, are convenient but somewhat expensive. Obtaining access to pipe by excavation is a temporary solution. Voltage surveys of the soil above or close to the pipeline may serve as a crude substitute for direct measurement of pipe/soil potential where absence of significant interference permits and where direct access to metal is not feasible.

39.   Making an electrical connection to metal pipe is not difficult, but gaining access to the steel reinforcement in concrete pipe without damaging the concrete can be difficult if no prior provision was made during manufacture. To prevent such a situation and to allow for future provision of cathodic protection should the need arise, all reinforcement should be made electrically continuous during manufacture and should be connected to a terminal placed flush with the external surface of the pipe barrel in a specified spot (in the bell, for example). This terminal should be located at the crown during installation and protected against corrosion by coal tar. The steel "cages" of reinforced concrete pipe should be welded together and to the cylinder when there is one. The prestressing wires of prestressed concrete pipes should be wound over steel strips laid on the concrete core, when not directly wrapped over the steel cylinder, to short-circuit the wires' loops, and the wires should be well imbedded in cement paste, to secure them against corrosion.

40.   Several very good documents on cathodic protection are available: the CEOCOR general guidelines for developing countries (Reference 6.04) and the detailed BSI Code of Practice for Cathodic Protection (Reference 6.02), as well as those noted in References 6.06, 6.11, and 6.20. They can be relied upon for their information on design, construction, and maintenance. Most of them, however, deal with steel pipe systems and ignore concrete pipes. (See Reference 6.28 for information on these types of pipes.)

41.   In conclusion, there are ways to protect pipelines against external corrosion. Coatings play an essential role. Cathodic protection is a most efficient technique that nonetheless should not be used indiscriminately. It cannot operate properly with metal pipe if the coating is inadequate, and its use requires appropriate and regular maintenance, including trained staff.

Soil Surveys

42.   Soil surveys are an indispensable tool for designing protection for new lines or for controlling or improving the protection of existing systems faced with corrosion problems. Several sets of guidelines for soil surveys are available (see References 6.08, 6.15, and 6.16), the most detailed of which are the German GW 9 (Reference 6.08). They set forth a soil resistivity index which is useful, but, like most indices, does not yield hard and fast rules because of the complexity of the phenomena involved. Expensive, detailed investigation is not always necessary all along the route of a pipeline. The following practical steps are recommended.

- First, a desk study should be made of the pipeline route using topographical, geological, and other local maps; this can yield early indications of where detailed investigation will be required and help to locate hot spots. Maps may indicate topographical features, existing or former farms or industrial areas where contaminated wastes have been dumped, or the location of other pipes and cable systems.

- Next, field surveys should be undertaken to check and complete the data gathered from documentary sources; electrical surveys of the ground's resistivity should be made all along the pipeline route. This is best done using soil resistance meters of the four electrode type which, depending on the distance between the electrodes, permits characterization of the soil at different depths.

- And last, soil analyses should be carried out whenever field or desk studies indicate there is a need and as often as necessary to provide a clear picture of the extent and nature of the potential problems.

43.   If cathodic protection is to be provided, there is less need for detailed soil surveys; the objective in this case would be to locate the source and magnitude of potential problems, to indicate where protection should be strengthened, to help in designing the cathodic protection, and to show where, at a later stage, voltage to ground should be measured.

44.   Pipeline routes may have to be altered as a result of the soil surveys. If intractable problems are encountered in some sections, highly aggressive soil may have to be replaced by appropriate, imported backfills; in such cases, steps should be taken to prevent the new soil from being contaminated by its environment.

Guidelines for Controlling External Corrosion in Pipelines

(i) **Guideline 14:** Soil surveys shall be undertaken at an early stage of design. These shall include a preliminary desk study of topographical and geological maps and a review of other available information in order to assess

overall corrosion risks and identify hot spots and areas where detailed surveys and soil analyses will be needed. This desk study shall be checked and completed in the field by all appropriate means, including electric resistance surveys. Office and field surveys shall be used to determine the frequency, location, and depth of soil sampling and analyses and of further electric resistance measurements. When external corrosion problems have been discovered on existing lines, similar procedures shall be used to help determine where remedial action is needed and what the best solutions are.

(ii) **Guideline 15:** The procedure for soil surveys shall comply with the recommendations of either Arbeitsblatt GW 9 (Reference 6.08) or other similar documents (References 6.15, or 6.16), depending on circumstances.

(iii) **Guideline 16:** Soil surveys shall be carried out even if cathodic protection is anticipated. As accurate an assessment as possible shall be made of the likelihood, nature, and importance of possible corrosion due to changing soil conditions along the pipeline route and of the intensity of anticipated stray currents.

(iv) **Guideline 17:** Pipe coatings and other protective measures, possibly even pipe material, shall be selected on the basis of soil survey findings.

(v) **Guideline 18:** High quality concrete of adequate composition shall be required for all types of reinforced concrete pipe. Quality shall be assured through adequate manufacturing equipment and procedures, systematic or random inspection during the manufacturing process, and by a thorough inspection at installation. Permeability of the cement mortar coating protecting the prestressing wires shall not exceed 10^9 centimeters per second.

(vi) **Guideline 19:** All new reinforced concrete and prestressed concrete pipe shall be fitted with a connector terminal located during manufacture at a specified spot on the pipe and at installation on the crown, allowing for measurement of the electric potential of the steel reinforcement to ground, and for a possible connection to a cathodic protection system, without a risk of damaging mortar or concrete coating. Reinforcing bars, wires, and steel cylinders (if any) shall be electrically bound. The loops of prestressing wires shall be short-circuited by steel strips squeezed between them and the concrete core and shall be thoroughly embedded in a cement paste applied on the concrete core or cylinder just before they are wrapped on it.

(vii) **Guideline 20:** Cathodic protection shall be used only in pipe systems that cannot be adequately protected otherwise, such as all welded steel transmission pipelines, electrically continuous lines, and possibly in complex systems where interference may create problems among pipelines of different types and uses, particularly when some of them are cathodically protected. If installed, cathodic protection shall be designed by competent and experienced engineers, in accordance with the CEOCOR guidelines (Reference 6.04), the BSI CP 1020 Code of Practice (Reference 6.02), or other equivalent documents.

(viii) **Guideline 21:** Cathodic protection shall not be used with prestressed concrete pipe, unless the pipe is in greater danger of corrosion from factors other than hydrogen embrittlement.

(ix) **Guideline 22:** Cathodic protection shall be made operational as system construction progresses.

(x) **Guideline 23:** Provision shall be made at the design or construction stage to supply the system operator with the trained staff, transportation, equipment, and needed supplies in a timely fashion. Operators shall monitor their systems for corrosion problems, make voltage surveys on a regular basis, and keep adequate records and maps of the results. Cathodic protection staff shall be adequately trained.

(xi) **Guideline 24:** Close collaboration among underground facilities operators (water, gas, electricity, and transportation) shall be instituted and maintained to secure protection of their systems against corrosion, especially when any one of these utilities is using cathodic protection. Such collaboration shall begin as early as possible, preferably at the design or construction stage.

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Chapter 7

REHABILITATION TECHNOLOGIES

1.   The very high cost of replacing or repairing water and sewer systems severely impaired by corrosion or other causes has led to a search for less expensive alternatives that do not require opening trenches in congested urban areas.

2.   The success encountered so far in developing new processes has led to an extension of rehabilitation techniques into the area of replacement and enlargement of existing pipelines and even to the potential for installing new pipes by boring under streets.

3.   Most rehabilitation processes have been developed quite recently and either are or were patented devices. They generally require sophisticated equipment, specific materials, extensive know-how, and expert labor; hence, generally, specialized firms are also necessary.

4.   The target of these techniques is generally to enable the main assets of the water and sewerage utilities—the pipelines—to attain the service life that can be expected (100 to 150 years in industrial countries), rather than the conventional 50-year life span usually accorded them. In this regard, the main assets that these utilities possess are the "holes in the ground," in which renovation (rebuilding conduits as they were), renewal, or replacement (rebuilding them as the system requires) takes place.

5.   The cost of such works ranges from 15-40 percent of the cost of laying new pipes, but may sometimes be substantially higher than replacement costs by conventional means. The higher costs connected with rehabilitation may be justified by the fact that it requires shorter periods of service disruption and causes less traffic congestion. The smaller the bore, the greater the justification for using such techniques, because smaller pipe installation costs relatively more.

6.   With the exception of cement mortar lining of water pipes in situ, rehabilitation technologies may have limited applications in developing nations because their water and sewer systems are often relatively new and not usually as extensive as those in industrialized countries and because labor costs are lower in most developing countries.

7.   Before rehabilitation can proceed, a thorough evaluation of the system must be undertaken. General statements about its condition are not sufficient. There should be a detailed inspection, with measurements of appropriate factors, such as loss of head, rate of flow, night flows, and valve positions, as well as investigations of customers' complaints, meters, and soil conditions (Reference 7.01). This inspection should result in a reasonably accurate assessment of the system's status, the extent of damage, and clear indications of the remedial work required, along with a budget and work program. In most systems, problems will not be spread evenly throughout, and some sections or components will need more work than others (such as manholes, junctions in sewers, junctions of pipes of different materials, blockages,

sections conveying waters of different qualities in water systems, and sections located in aggressive soils). Thus local rehabilitation rather than system-wide work may be the answer.

8.   In selecting contractors to carry out the work, care must be taken to choose firms possessing experience, financial capability, qualified personnel, proper equipment, and access to the materials needed.

9.   There will be inevitable service interruptions, and customers must be notified of their nature, duration, timing, and effects. It may be necessary to arrange for temporary service if the interruptions are expected to be lengthy. Once rehabilitation has been completed, it is still a major task to reinstate service connections and restore any damaged pavement.

10.   Reference 7.01 is a detailed manual published by ASCE-WCPF (in 1983) that thoroughly covers the subject of sewer rehabilitation. There is no corresponding document covering the rapidly evolving technology of rehabilitation of water systems. Publications on this subject do not generally enter into details and they tend to be scattered in periodicals such as the AWWA Journal and Pipes and Pipelines International.

11.   Virtually all rehabilitation processes are designed to renovate water pipes from the interior only, even when the problems are a result of external corrosion or structural deficiencies. It may not be possible to rehabilitate a system that demonstrates extensive structural damage.

12.   Relining pipes in the ground is a well-established process; successful on-site cement mortar lining has been achieved for more than 50 years. Bitumen and epoxy resins may also be used for on-site relining, although the long-term effectiveness of these types of linings is doubtful. (See Chapter 3.) Cement mortar and thickly applied selected epoxy resins may provide lasting protection and there are continuing improvements in the field of lining materials, e.g., fiber-reinforced products. Before any type of relining work is carried out, the pipes must be thoroughly scraped and cleaned to remove deposits, tubercles, oxidation by-products, loose bits of old lining, and encrustation. Relining may not improve substantially the structural strength of the pipe. The thickness of the cement mortar lining should be about the same as that of the new pipe (5 to 20 millimeters, depending on size); this applies to all pipe over 75 millimeters in diameter.

13.   Slip lining is being used increasingly. This type of lining involves inserting into the damaged pipe another pipe made of thermoplastic material-- usually high-density polyethylene (HDPE) or glass fiber reinforced resin--or a folded sleeve of thermosetting plastic. In the latter case, known as slip forming or inversion lining, the folded sleeve is expanded under slight pressure against the barrel of the existing duct; hot water or air (up to 80 degrees centigrade) is then circulated to harden the plastic. The process must be completed within a few days after the sleeve has been impregnated at the factory, where it is enclosed in a plastic bag for shipment to the site in a refrigerated van.

14.   High-density polyethylene pipes are transported in sections and must be butt-welded together into one continuous pipe before insertion. Filling the

void between the lining and the existing pipe with grout may be difficult, but it must be done to prevent water from flowing between the lining and the pipe and to strengthen the lining.

15.   The internal surface of the new lining will usually be substantially smoother than that of the existing pipe when it was new. Relining, therefore, may decrease friction; it also decreases the internal diameter. As a result, the hydraulic capacity of large-diameter pipes will usually increase, while the capacity of smaller sizes may decrease.

Guidelines for the Rehabilitation of Pipelines

(i) **Guideline 25:** Proposals for partial or full replacement or rehabilitation of pipelines shall be based on:

   (a) a thorough evaluation of the system, including, as the situation requires, internal/external inspection; soil surveys; flow measurements; head loss measurement; examination of plans, records, and customer complaints; and other pertinent data;

   (b) cost estimates and work programs for correcting only the deficiencies found in damaged sections of the system and including the costs of removing and reinstating customer connections, providing temporary service to customers during service interruptions, restoring any damaged pavement, and disinfecting water systems before resuming service; and

   (c) an analysis of the benefits expected to result from the proposed improvements.

(ii) **Guideline 26:** Contractors employed to carry out rehabilitation work shall be carefully selected and have the necessary experience, specialized equipment, personnel, and financial resources to complete the job successfully.

Selected References

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ANNEX 1

INSTITUTIONS INVOLVED IN PIPELINE CORROSION

Note: Below is a list of institutions involved in pipe corrosion protection and control whose publications have been cited in the present document.

Institution	Activities/Publications
American Concrete Pipe Association (ACPA) 8320 Old Courthouse Road Vienna, VA 22180 U.S.A.	(ACPA) handbooks
American Society for Testing Materials (ASTM) 1916 Race Street Philadelphia, PA 19103 U.S.A.	All materials testing, special studies standards
American Society of Civil Engineers (ASCE) 345 East 47th Street New York, NY 10017 U.S.A.	Conferences, manuals, proceedings
American Water Works Association (AWWA) 6666 West Quincy Avenue Denver, CO 80235 U.S.A.	All aspects of water supply, AWWA Journal, standards, manuals
Association Française pour l'Etude des Eaux (AFEE) Place Sophie Laffitte Sophia Antipolis Branch 06565 Valbonne CEDEX France	Abstracts, books, studies, data retrieval system, Information Eaux, bulletins
Association Générale des Hygiénistes et Techniciens Municipaux (AGHTM) 9 Rue de Phalsbourg 75017 Paris CEDEX 17 France	Corrosion Committee, CEOCOR member, T.S.M., L'Eau

Institution	Activities/Publications
British Hydromechanics Research Association (BHRA) Cranfield, Bedford MK43 OAJ, U.K.	Research, special books, reports, international proceedings, conferences on corrosion
British Standard Institution (BSI) 2 Park Street London W1A 28S U.K.	Standards, Codes of Practice
Centre Belge d'Etude de la Corrosion (Cebelcor) Avenue Paul Heger, Grille 2 B 1050 Brussels, Belgium	Research, consultancy, special reports
Centre Belge d'Etude et de Documentation des Eaux (Cebedeau) Rue A. Stevart 2 B-4000 Liege, Belgium	Conferences, research, Cebedoc Bulletin (La Tribune du (CBEDE) CEBEDEAU)
Comité pour l'Europe Occidentale contre la Corrosion des Conduits Souterrains (CEOCOR) Secretariat Rue aux Laines 70 1000 Brussels, Belgium	Annual meetings, publications, conferences, Cebedoc Bulletin
German Association for Water Resources and Land Improvements (DVWK) Gluckstrasse 2, D-5300 Bonn 1 Federal Republic of Germany	Conferences, reports, bulletins
International Water Supply Association (IWSA--AIDE) 1 Queen Anne's Gate London SW1H9BT U.K.	Congresses, committees
National Association of Corrosion Engineers (NACE) P.O. Box 218340 Houston, Texas 77218 U.S.A.	All corrosion aspects, Metal Protection and Performance

Institution	Activities/Publications
National Bureau of Standards (NBS) Gaithersburg, Maryland 20899 U.S.A.	Corrosion studies

United States Environmental
  Protection Agency (EPA)
401 M Street, S.W.
Washington, D.C. 20460
U.S.A.
	Major corrosion studies, specialized
	  documents, water quality require-
	  ments in the U.S.A.

Water Pollution Control Federation (WPCF) 2626 Pennsylvania Avenue, N.W. Washington, D.C. 20037 U.S.A.	Special reports, manuals, Water and Sewerage Works

Water Research Council (WRC)
P.O. Box 85, Frankland Road
Blagrove, Swindon,
Wilts, SN5 8YR   U.K.
	Studies for its members, special
	  reports, Aqualine Retrieval
	  System

ANNEX 2

FIBERGLASS PIPE

Early in the history of fiberglass pipe it was known to be an expensive product. Indeed, even today some specialty fiberglass pipes are quite expensive owing to sophisticated resin systems required for certain industrial applications. As the process and product technology evolved over the past 40 years, significant performance and cost reduction improvements have been achieved, especially in the last few years.

As a result of these improvements, the relative price differential between fiberglass pipe and other traditional products has narrowed considerably.

Proper specification, purchase, and use of any product are critical to its long-term performance. If a product is abused by not being installed in accordance with the manufacturer's or designer's instructions, problems are likely to occur. Fiberglass pipe is no exception. There have been instances of field problems associated with fiberglass pipe produced in the past. In most of these instances, the products have not been installed within the limits established by the manufacturer. Recognizing these early problems, the industry has made significant strides towards improving the performance reliability of fiberglass pipes by expanding the range of products offered and allowing the user more freedom to adjust the product to the specific end application.

Today, these changes are surfacing in new and revised national and international standards. ASTM has just consolidated six standards on fiberglass pressure, sewer, and industrial pipes into three, while significantly strengthening the performance requirements that must be achieved by the products. For example, a sewer pipe meeting the new ASTM D3262 (the Fiberglass Sewer Pipe standard) must have the ability to withstand for 50 years a strain (deflection) level in 5 percent H_2SO_4 of 50 percent to 75 percent higher than before. Additionally, pipes must achieve short-term deflection levels, without damage, 300 percent higher in the new ASTM standards as compared to the previous standards.

Pressure performance requirements have also been increased. ASTM D3517, the Fiberglass Pressure Pipe standard, now requires a minimum factor of safety of 1.8 on calculated 50-year hydrostatic strength capability. In earlier editions, the factor of safety could have been as low as 1.6 on the 50-year extrapolated strength. A similar requirement has been proposed for the American Water Works Association's standard for Fiberglass Pressure Pipe now currently being reviewed and updated. This standard, AWWA C950, like the ASTM specifications, will have numerous performance changes.

Another important concept that transcends all these standards, as well as two product standards now being developed by the International Organization for Standardization (ISO), is the expansion from one minimum stiffness class (i.e., resistance to deformation from external load) to four standard

classes. Standard fiberglass pipe stiffness classes, as represented by the specific tangential initial stiffness (EI/D^3) are now 1,250, 2,500, 5,000, and 10,000 N/m^2. Some manufacturers produce on a limited basis pipes of higher stiffness ratings, particularly in small diameters, for especially difficult job conditions.

Fiberglass pipe manufacturers have available installation and use instructions that clearly delineate the proper use of their products, including appropriate stiffness classes for a variety of field conditions depending on native soil, trench configuration, pipe zone embedment material, and depth of burial. Interested parties are referred to Reference 3.4 for one such example.

Fiberglass pipes are now one of the fastest growing pipe products to be used worldwide for the conveyance of fluids. Long recognized for their corrosion resistance to many industrial chemical streams where other traditional products fell short of performance needs, fiberglass pipes are now beginning to make significant inroads into water supply and sanitary sewer applications. Acknowledged to be highly resistant to the corrosive environment of a sanitary sewer, as evidenced by their widespread popularity throughout the Middle East (where high temperatures, low flows, and low gradients create some of the most aggressive conditions known to sanitary engineers), fiberglass pipes are now being used in other less demanding parts of the world due to their low life-cycle costs. Nonmetallic fiberglass pipes are also immune to the corrosive effects of stray electrical currents, or galvanic-induced corrosion. As special linings and coatings are not required in fiberglass pipes, the performance of linings and coatings is not an issue.

ANNEX 3

POURBAIX'S DIAGRAM FOR IRON
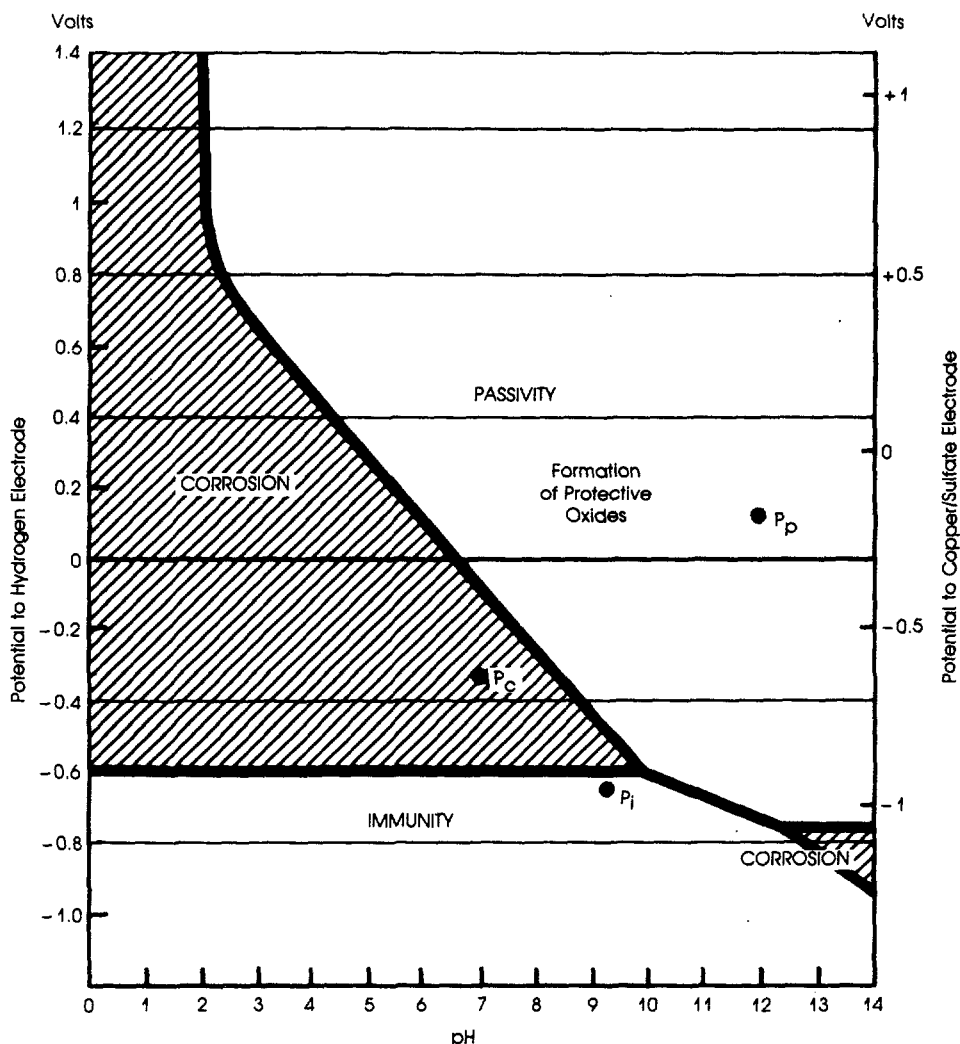
Note

Pourbaix's Diagram represents equilibrium conditions and separates
three different domains: the "corrosion" domain within which
soluble iron oxides and hydroxides and other iron complexes form; at
the boundary with the "passivity" domain, insoluble and sufficiently
impervious films of iron oxides protect the metal; and the
"immunity" domain within which none of the above reactions can
proceed. The boundary lines are equal concentration lines corre-
sponding to a practical absence of iron in solution. These boundary
lines shift somewhat depending on actual iron oxides concentration,
chemical environment, and temperature. (See Reference 1.06.) The
reaction velocity slows down considerably near the boundary lines;
this explains the rule of thumb--0.85 volt cathodic protection limit
which still locates iron in the corrosion domain (Pi) but very near
the "immunity" boundary.

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Cover design by Bill Fraser