PLAINTIFF'S EXHIBIT
CAP-1127

A/C Pipe
Producers Association
Executive Committee
International Affairs Committee

Internal Correspondence

TO J. F. Welch

FROM J. F. Welch, Vice President

DATE: July 15, 1982

SUBJECT U. S. Environmental Protection Agency (EPA) - National Academy of Sciences Report on Drinking Water and Health

ACTION REQUIRED: Review for information

Background

The Safe Drinking Water Act (Public Law 93-523) required the National Academy of Sciences (NAS) to study the adverse effects on health attributable to contaminants in drinking water. Asbestos was one of the contaminants studied. In 1977 the Academy published the first volume of "Drinking Water and Health;" on the matter of asbestos in potable water, the Committee on Safe Drinking Water concluded:

> The results of experiments on the chronic toxicity of asbestos mineral fibers fall very short of vigorously clarifying the risks to health that may be associated with potable water - either qualitatively or quantatively.
>
> * * * *
>
> Research on the unresolved problems of the chronic effects of ingesting asbestos mineral fibers therefore merits strong support.

The Safe Drinking Water Act Amendments of 1977 called for NAS to update these health effects studies every two years and report its findings to EPA. The enclosure is part of that mandate. It identifies chemical and biological contaminants associated with drinking water distribution systems and the health implications of deficiencies in those systems.

Current Status

Enclosed are excerpts from "Drinking Water and Health - Volume IV," recently released. Full copies are available from National Academy Press for $17.95(U.S.).

The report does not draw any definitive conclusion about the health risks of asbestos ingested in drinking water. The statement is made:

> The data do not provide an adequate basis from which to estimate health consequences from ingesting asbestos fibers. Extensive epidemiological studies and laboratory tests now underway at several locations are expected to yield useful information on this subject.

Asbestos cement water pipe receives considerable attention in the section entitled "Chemical Quality of Water in the Distribution System." This is undoubtedly because the asbestos in drinking water controversy prompted more government and academic research on A/C pipe than on other piping materials. Of the members on the Safe Drinking Water Committee, Messrs. Andelman, Characklis, Christman, Englebrecht and Olivieri and Ms. Tate drafted the sections on A/C pipe. Staff believes, based on EPA input, that Carol Tate was largely responsible for the A/C pipe section.

The draft document was subjected to external review by five or six scientists not on the Safe Drinking Water Committee. The NAS project officer would not name these individuals but indicated most were from "consulting engineering firms" also unnamed. It is the Academy's policy not to have the Environmental Protection Agency or affected industries review and comment on NAS drafts prior to publication.

Much is said about the Aggressiveness Index (AI) and its perceived shortcomings in predicting "pipe dissolution." Instead, the Committee seems enamored with the Saturation Index discussed in the research of Shock and Buelow of EPA's Municipal Environmental Research Laboratory (MERL).

NAS currently is reviewing the post-1977 research on the potential health effects of ingested asbestos. Staff will meet with the NAS project officer during the week of June 21, 1982 to determine the publication timetable for that important review.

If you have any questions, please do not hesitate to call.

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Enclosure

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DRINKING WATER AND HEALTH

VOLUME 4

NAS
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Drinking Water and Health

Volume 4

SAFE DRINKING WATER COMMITTEE

Board on Toxicology and
Environmental Health Hazards
Assembly of Life Sciences
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1982

ɛ: The project that is the subject of this report was approved by the Governing Board National Research Council, whose members are drawn from the Councils of the Na- Academy of Sciences, the National Academy of Engineering, and the Institute of ine. The members of the Committee responsible for the report were chosen for their tences and with regard for appropriate balance.
. report has been reviewed by a group other than the authors according to procedures ed by a Report Review Committee consisting of members of the National Academy of es, the National Academy of Engineering, and the Institute of Medicine.

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request of and funded by the U.S. Environmental Protection Agency, Contract No. 0169

of Congress Catalog Card Number 77-089284

ational Standard Book Number 0-309-03198-2

ble from

ONAL ACADEMY PRESS
onstitution Ave., N.W.
ngton, D.C. 20418

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... The man they called Ed said the muddy Mississippi water was wholesomer to drink than the clear water of the Ohio; he said if you let a pint of this yaller Mississippi water settle, you would have about half to three-quarters of an inch of mud in the bottom, according to the stage of the river, and then it warn't no better than Ohio water—what you wanted to do was to keep it stirred up—and when the river was low, keep mud on hand to put in and thicken the water up the way it ought to be.

The Child of Calamity said that was so; he said there was nutritiousness in the mud, and a man that drunk Mississippi water could grow corn in his stomach if he wanted to. He says:

'You look at the graveyards; that tells a tale. Trees won't grow worth shucks in a Cincinnati graveyard, but in a Sent Louis graveyard they grow upwards of eight hundred foot high. It's all on account of the water the people drunk before they laid up. A Cincinnati corpse don't richen a soil any.'

MARK TWAIN
Life on the Mississippi

Preface

The Safe Drinking Water Act of 1974 (PL 93-523) authorized the U.S. Environmental Protection Agency (EPA) to establish federal standards to protect humans from harmful contaminants in drinking water and to establish a joint federal-state system for assuring compliance with the standards and for protecting underground sources of drinking water. One section of the law [1412(e)] and its amendments (42 USC Subpart 300f *et seq.*, 1977) mandated that the National Academy of Sciences conduct studies on the health effects associated with contaminants found in drinking water. It stipulated that these studies evaluate the available data for use in developing primary drinking water regulations, identify areas of insufficient knowledge, and make recommendations for future research. Amendments to the act in 1977 called for revisions of the studies "reflecting new information which has become available since the most recent previous report [and which] shall be reported to the Congress each two years thereafter."

The first study in this series was published in 1977 under the title of *Drinking Water and Health*. That volume examines the health effects associated with microbiological, radioactive, particulate, inorganic, and organic chemical contaminants found in drinking water. Volumes 2 and 3 of *Drinking Water and Health* were published in 1980. Volume 2 compares the efficacy and practicability of chlorination and 11 alternative disinfection methods for inactivating microorganisms, identifies the by-products likely to be formed by the use of each major method, and evaluates the use of granular activated carbon for the reduction or

CAPCO JEN 0032010

moval of organic and other contaminants from drinking water. Volume reviews 12 epidemiological studies concerning health effects associated th drinking water containing trihalomethanes. It also summarizes the rrent state of knowledge on the relationship between cardiovascular sease and water hardness. It adds to the 1977 publication's information estimation of risk to human health by extrapolating data from exrimental animals to humans and also evaluates six models for the timation of carcinogenic risk at low doses. Furthermore, it evaluates the ute and chronic health effects associated with the products of water sinfection and other selected contaminants. One section examines the ntribution of selected inorganic elements in drinking water to the opnal nutrition of humans.

The current study (Volume 4) identifies chemical and biological conminants associated with drinking water distribution systems and the alth implications of deficiencies in those systems. It also contains an aluation of information on the toxicity of selected inorganic and organic ntaminants. Some of them are reviewed for the first time in this report; hers were reviewed in earlier volumes of this series. For the latter, scussions include only information that has become available since the rlier reports.

A reevaluation of the most recent information on the relationship be-'een water hardness and cardiovascular disease was postponed pending tblication of results from several important studies that were presented an EPA-sponsored symposium at the University of Massachusetts at mherst in 1979.

On behalf of the members of the present committee and all of the embers of the previous Safe Drinking Water Committees, I would like to :press our gratitude and appreciation for the special efforts of Dr. Riley ousewright, who has served as the Project Officer for the safe drinking ater studies since their inception in 1975. We wish him the very best in .s new position as Executive Director of the American Society for licrobiology.

We also thank Dr. Robert Golden, who completed this project after Dr. ousewright's departure, and Ms. Frances Peter, who served as Editor of ıe present book. We recognize Ms. Virginia White, Edna Paulson, and arbara Jaffe, who assisted in the search of the scientific literature and ·ference verification.

We also acknowledge the assistance of members of the EPA staff, ;pecially Drs. Krishan Khanna and Joseph Cotruvo.

)HN DOULL, *Chairman*
afe Drinking Water Committee

Contents

I	EXECUTIVE SUMMARY	1
II	ELEMENTS OF PUBLIC WATER SUPPLIES	9
III	CHEMICAL QUALITY OF WATER IN THE DISTRIBUTION SYSTEM	18
IV	BIOLOGICAL QUALITY OF WATER IN THE DISTRIBUTION SYSTEM	108
V	HEALTH IMPLICATIONS OF DISTRIBUTION SYSTEM DEFICIENCIES	137
VI	TOXICITY OF SELECTED INORGANIC CONTAMINANTS IN DRINKING WATER	152
VII	TOXICITY OF SELECTED ORGANIC CONTAMINANTS IN DRINKING WATER	202

CAPCO JEN 0032011

1

Executive Summary

The quality of a public water supply, although quite acceptable when it leaves the treatment plant, may deteriorate before it reaches the user. This may occur as a result of either chemical or biological transformations or by loss of integrity of the system. Serious sources of potential contamination arise when nonpotable water enters the system as a result of cross-connections, backflow, back-siphonage, or during repairs.

Although it is not the purpose of this report to review the optimum engineering design, construction, and operation of distribution systems, it is important to recognize that adverse health effects may result from inadequate attention to any of these areas.

Chapters II, III, IV, and V of this report contain reviews of the factors and conditions associated with retention of water quality in the distribution system and the committee's recommendations for control procedures and future research.

In Volume 1 of *Drinking Water and Health*, the Safe Drinking Water Committee examined the health effects associated with microbiological, radioactive, particulate, inorganic, and organic chemical contaminants found in drinking water. In Volume 3, it considered another selected group of chemical contaminants. Chapters VI and VII of this volume contain evaluations of the health effects of additional organic and inorganic contaminants.

CAPCO JEN 0032012

ISTRIBUTION SYSTEMS

hemical Effects and Water Quality

hanges in the chemical quality of water in the distribution system can ·sult from corrosion, deposition, leaching, and reactions involving water eatment chemicals in the system. The solubility and kinetic factors that :termine whether constituents in water will deposit on pipe walls or hether the materials used in the conveyance system will partially dissolve · corrode into the water are examined in this volume.

orrosion

number of water quality indexes have been used to predict whether ater will produce corrosion of materials used in the distribution system. hese indexes are used not only as criteria for treatment control, but also s a guide to selection of materials. The committee's review and evaluaon of these indexes can be found in Chapter III.

The nature and control of the corrosion process is also described in hapter III. The chemical and electrochemical reactions involved in corsion cause deterioration of water quality, particularly with respect to ich metals as zinc, cadmium, and lead. The economic impacts of corroon in water distribution systems are not a part of this study. Nonetheless, ey are an important consideration since they provide an incentive for educing corrosion, which ultimately affects the water to which the conumer is exposed. The economic incentive for the use of corrosion inibitors may be counterproductive in terms of human health unless the inibitors are selected with a full awareness of their possible toxicity.

A variety of microorganisms are known to be involved in the corrosion rocess. They may be heterotrophic or autotrophic and grow under aeroic or anaerobic conditions. The nature of the biologically mediated corosion process and the organisms involved are described in Chapter IV. Considerable further attention must be directed toward this subject in orler to elucidate the nature and consequences of microbial action on the ipes *in situ*.

.eaching

in contrast to corrosion, which is an electrochemical phenomenon, eaching is a process of dissolution governed by solubility and kinetics. The quality of the water influences the leaching of some materials, such as asbestos/cement (A/C) pipe.

Deposits

Following water treatment, chemicals can deposit in distribution systems and affect the quality of water distributed to the consumer. Among the elements manifesting this behavior, iron and manganese are receiving most attention, primarily because of esthetic and economic considerations. Their effects on human health are not of major importance; however, iron and manganese suspensions are associated with the growth of microorganisms in the distribution system. Furthermore, humans may be exposed to other elements that may be associated with iron and maganese deposits and their resuspension as well as to chemicals added for their control.

The control of manganese and iron in water supply systems has been widespread. Three principal methods have been used: oxidation (followed by precipitation and filtration), ion exchange, and stabilization by dispersing agents. These control measures may alter the concentration of other chemicals that coprecipitate or sorb with them, including organic chemicals; and influence the concentration of bacteria in the system.

Of special interest are the effects of stabilizing agents such as silicates and polyphosphates. Polyphosphates have the potential for adversely affecting human health, especially when complexed with manganese. Just as iron and magnesium can be maintained in solution by the addition of these dispersing agents, so can other heavy metals. The extent to which their use increases human exposure and adverse health effects is not known.

Water Treatment Chemicals

The data suggest that concentrations of trihalomethanes continue to increase in the distribution system when both chlorine and organic precursors are present. It is probable that the nonvolatile reaction products of humic material with chlorine also increases in distribution systems, although no data have been obtained from systems in operation.

Pipes and Linings

A/C pipe was originally believed to be resistant to deterioration. Recent findings, both in the laboratory and in field tests, have shown that A/C pipe, like other pipe materials, can be vulnerable to the corrosive action of water. Under certain circumstances, asbestos fibers can be released from the pipe into water supplies. Control measures for limiting the release of these fibers are discussed in Chapter III. The data do not provide an ade-

CAPCO JEN 0032013

quate basis from which to estimate health consequences from ingesting asbestos fibers. Extensive epidemiological studies and laboratory tests now under way at several locations are expected to yield useful information on this subject.

Plastic pipes used for conveying potable water are made of polyethylene (PE), polyvinyl chloride (PVC), including chlorinated polyvinyl chloride (CPVC), and acrylonitrile-butadiene-styrene (ABS). Although plastic pipe is composed principally of polymerized organic compounds, there can also be residual unpolymerized monomer present in low concentrations. This factor is especially important in PVC pipe, since vinyl chloride monomer is carcinogenic. In general, water quality is not a major factor in plastic pipe leaching, in contrast to the definite effect of water quality on the corrosion of metal or A/C pipe.

Nonmetallic linings are commonly used in potable water distribution systems to prevent corrosion of underlying metal or other components. The most common lining materials are coal tar, petroleum asphalt, vinyl, epoxy, or some combination thereof. Laboratory and field studies have shown that some of these materials, especially coal tar compounds, can be released into the water. Of concern is the content of polynuclear aromatic hydrocarbons (PAH's), several of which are known carcinogens. Some lining materials can reach the drinking water through leaching processes or through physical deterioration, which results in the release of small particles from the linings. Higher concentrations appear to leach from coal tar than from asphalt; however, the tests leading to this conclusion were not definitive.

PAH's have been found in nanogram and microgram per liter concentrations in field studies of water exposed to linings in the distribution system. The compounds most commonly found in these studies have been phenanthrene and/or anthracene. Tetrachloroethylene has recently been found in vinyl-lined A/C pipe. Studies are under way to determine concentrations of this chemical in pipes of different ages receiving varying amounts of usage.

There is a need for more research into the effect of linings on water quality.

Biological Effects and Water Quality

Living organisms may enter the distribution system through raw water receiving insufficient treatment, from in-line reservoirs, or from imperfections or breaks in the pipeline network. The microorganisms found in the distribution system and their effect on water quality are described in Chapter IV.

Microbial processes within the distribution system can significantly increase hydraulic roughness and corrosion of pipes.

Products of microbial activity include undesirable tastes and odors, e.g., "black" water, which contains sulfide, and "red" water, which contains iron. Detachment of biofilms from the pipes provides a continuing inoculum into other locations within the distribution system.

Microorganisms may proliferate in portions of the distribution system if the disinfectant residual is low or absent. A disinfectant residual (usually chlorine) provides a relatively effective barrier to growth of microorganisms in the distribution system.

Distribution networks are dynamic systems. The quality of the water in them can be affected by the quality of the raw water, treatment processes, pipe materials, and the reactions that occur within the pipes.

Implications For Human Health

Outbreaks of acute diseases associated with contaminated drinking water are reported voluntarily to the Centers for Disease Control (CDC) by state health departments or to the Health Effects Research Laboratory of the Environmental Protection Agency (EPA) by state agencies having responsibility over water supply. In the majority of these reports, the etiologic agent is not identified. However, the clinical and epidemiological evidence suggests that most of the outbreaks are caused by infectious agents.

Sources of contamination responsible for outbreaks include untreated surface water or deficient treatment of groundwater, e.g., malfunction of a chlorinator, and deficiencies in the distribution system. Examples include a large outbreak of amebiasis among guests at two Chicago hotels in 1933 and one of infectious hepatitis among members of a football team in 1972. In both outbreaks, potable water was contaminated by wastewater as a result of a defect in the distribution system.

Deficiencies in distribution systems were responsible for 15% of waterborne outbreaks reported in the United States from 1971 through 1978. The most common defects were indirect cross-connections, which permitted wastewater or toxic chemicals to gain access to the potable water system by back-siphonage through hoses or defects in water pipes during periods of low pressure. Less frequent defects include direct cross-connections, contamination of the system during construction, leaching of copper from the pipes, and contamination of open reservoirs. Health effects associated with specific constituents of drinking water and the distribution system are provided in tabular form in Chapter V, with references to discussions in this volume and the first three volumes of *Drinking Water and Health*.

CAPCO JEN 0032014

The committee recommends intensifying surveillance, investigation, id reporting of outbreaks of waterborne diseases at the local, state, and deral levels. An evaluation of the health effects associated with drinking ater depends, both quantitatively and qualitatively, on the completeness id accuracy of the reporting system. The committee also recommends e development of an education program focusing on the preservation of e integrity of the distribution system and emphasizing the necessity of aintaining an adequate chlorine residual throughout the system.

OXICITY OF SELECTED CHEMICAL CONTAMINANTS N DRINKING WATER

he contaminants reviewed in Chapters VI and VII were selected for one r more of the following reasons:

- They are contaminants that have been identified in drinking water ince the first three volumes of *Drinking Water and Health* were published.
- Sufficient new data have become available to justify further examina- ion of contaminants evaluated in the earlier studies.
- Several compounds were judged to be a concern because of potential pill situations.
- They are contaminants that have been associated with drinking water listribution systems.
- They are structurally related to known toxic chemicals.

Thus, the descriptions of some of the contaminants are limited to data generated since the first three volumes of *Drinking Water and Health* were published, whereas other contaminants and their health effects are evaluated in full for the first time. Several metallic ions were selected for evaluation because of their association with drinking water distribution systems, although contaminants such as lead and strontium pose problems only in certain local areas. The chlorine derivatives are evaluated because of their possible use as alternatives to chlorine in the disinfection of drinking water. A review of asbestos was deferred pending the outcome of ongoing feeding studies in animals.

The contaminants reviewed in this volume were selected from a list recommended for evaluation by the U.S. Environmental Protection Agency (EPA). The inclusion of each one was discussed with representatives of the EPA before a final decision was reached. Several were rejected either because the data were insufficient for a new evaluation or because there was not enough new information for a reevaluation.

The committee evaluated the data concerning both acute and chronic exposures to selected chemicals. Information derived from studies of acute exposure provides a basis for judging health effects resulting from accidental spills of chemicals into drinking water supplies. A suggested-no-adverse-response level (SNARL) for acute exposures of 24 hours or 7 days has been calculated for compounds on which sufficient data were available. The acute exposure SNARL's are based on the assumption that 100% of the exposure to the chemical was supplied in drinking water during either the 24-hour or 7-day period. When the chemical was a known or suspected carcinogen, the potential for carcinogenicity after acute exposure was ignored. The calculated acute SNARL's should not be used to estimate hazards from exposures exceeding 7 days. They are not a guarantee of absolute safety. Furthermore, SNARL's are based on exposure to a single agent and do not take into account possible interactions with other contaminants. The safety or uncertainty factors used in the calculations of the SNARL's reflect the degree of confidence in the data as well as the combined judgment of the committee members.

SNARL's for chronic exposure were calculated for chemicals that were not known or suspected carcinogens on the basis of data obtained during a major portion of the lifetime of laboratory animals. An arbitrary assumption was made that 20% of the intake of the chemical of concern was derived from drinking water. Therefore, it would be inappropriate to use these values as though they were maximum contaminant levels.

At the time of the writing of the first and third volumes of *Drinking Water and Health*, the use of statistical methods and model systems to extrapolate data from studies of animals at high doses in order to estimate risk in humans exposed to low doses was a novel and largely untested approach. When considering various approaches to this problem, the committee agreed on four principles to be used as a basis for estimating risk for nonthreshold effects:

- Effects in animals, properly qualified, are applicable to humans.
- Methods do not now exist to establish a threshold for long-term effects of toxic agents.
- The exposure of laboratory animals to high doses of toxic agents is a necessary and valid method of discovering possible carcinogenic hazards in humans.
- Data should be assessed in terms of human risk, rather than as "safe" or "unsafe."

The methodology used by the previous Safe Drinking Water Committees in projecting risk estimates have been described in Volumes 1 and 3.

CAPCO JEN 0032015

That approach stimulated considerable developmental activity in this area that in succeeding years has resulted in the appearance of a variety of statistical models for making such calculations. The regulatory agencies were quick to recognize the utility of the risk estimate approach for dealing with carcinogenisis data, and the concept, if not the specific models, has achieved international recognition.

When preparing the third volume of *Drinking Water and Health*, the Subcommittee on Risk Assessment reevaluated six high-dose to low-dose extrapolation models (i.e., the dichotomous response model, the linear no-threshold model, the tolerance distribution model, the logistic model, the "hitness" model, and the time-to-tumor-occurrence model). Because of uncertainties involved in the true shapes of the dose-response curves that must be used for the extrapolation, the committee judged that a multistage model would be most useful for making the risk estimate extrapolations for the chemicals reviewed in these volumes. It pointed out that more confidence could be placed in mathematical models for extrapolation if they incorporated biological characteristics of the animal studies such as kinetics and time-to-occurrence of tumors. Although these and other concerns have tended to limit somewhat the acceptance of the various extrapolation models by the scientific community, they have led to the development of new and revised protocols for the animal studies that provide the desired information.

The current Safe Drinking Water Committee has again evaluated several of the major extrapolation models in use by the regulatory agencies or by others and has made some effort to anticipate new thrusts in what could be designated as research in applied toxicology. It concluded that since the users of this volume will be likely to favor different varieties of the conventional extrapolation models or will have access to some of the newer developmental methodologies, it is premature at this stage to recommend any single approach by selecting it for calculations in this volume. Since the committee has provided the data from animal toxicity studies for each of the agents discussed in this volume or references to documents containing the data, it should be possible for readers to apply whichever extrapolation model they wish to the data to estimate risk.

CAPCO JEN 0032016

III

Chemical Quality of Water in the Distribution System

Even if one could eliminate the causes of contamination associated with pipe breakages, cross-connections, back-siphonages, and other factors inherent in water distribution systems, there would still be changes in the physical, chemical, and biological properties of the water as the result of either chemical or biological activity.

Chemical activity producing changes in water quality within the distribution system is associated with corrosion, leaching, deposition, and reactions involving water treatment chemicals and their residuals. Each of these topics is discussed separately in this section.

The materials comprising pipes, pumps, storage reservoirs, and other system components can corrode through contact with water or may leach constituents in water over time. Solubility and kinetic factors will determine whether these constituents will deposit (precipitate) onto pipe walls or whether the materials used in the conveyance system will partially dissolve or corrode into the water. Chlorine and other treatment chemicals added at the water treatment plant or in the distribution system itself can continue to react with organic compounds in the water. Thus, the chemical content of water at the consumer's tap may be different from that of water leaving the treatment plant or other source as a result of its contact with materials in the distribution system and the time available for reactions to progress.

CHEMICAL WATER QUALITY INDEXES

A number of water quality indexes have been used to predict whether water will corrode materials used in distribution systems or home plumbing units. In most cases, these indexes are used as a criteria for water treatment control, but they can also be used as guide to the selection of materials. Their principal advantage is simplicity, but they are not always perfect predictors. Long-term tests of materials are more costly to conduct, but provide more direct evidence of water quality and its potential to corrode given materials.

The oldest and most widely used index is the Langelier Index, which is based on the solubility of calcium carbonate and the potential of the water to deposit a scale that would protect the pipe. This index has been applied to both metal and asbestos-cement pipe. A simplified version of the Langelier Index, called the Aggressiveness Index, was developed especially for asbestos-cement pipe to predict whether the water will either deposit a protective scale or seek calcium carbonate saturation by dissolving the pipe's cement. A third index, the Saturation Index, is based on solubility characteristics of a number of compounds, not just calcium carbonate. Its potential application for asbestos-cement pipe is discussed below.

Langelier Index

The Langelier Index was developed in 1936 in order to investigate systematically the chemical relationships involved in the corrosion of iron or galvanized pipe (Langelier, 1936). It is sometimes referred to as the calcium carbonate saturation index or simply as the Saturation Index. (To avoid later confusion with the term Saturation Index, which is used for a number of constituents in addition to calcium carbonate, the term Langelier Index is used herein).

The Langelier Index (LI) can be defined as follows:

$$LI = pH = pH_s, \quad (1)$$

where

pH_s = saturation pH, the pH at which water of the measured calcium and alkalinity concentration is in equilibrium with solid calcium carbonate and

pH = actual or measured pH of the water.

CAPCO JEN 0032017

its simplest form, which is applicable between pH 7.0 and pH 9.5, the uation for calculating pH, is as follows:

$$pH_s = (pK_2' - pK_s') + pCa^{2+} + pAlk, \quad (2)$$

ıere

pK_2' = negative logarithm of second dissociation constant for carbonic acid (H_2CO_3),

$K_2' = \frac{[H^+][CO_3^{2-}]}{[HCO_3^-]}$,

pK_s' = negative logarithm of the solubility product of calcium carbonate ($CaCO_3$),

$K_s' = [Ca^{2+}][CO_3^{2-}]$,

pCa^{2+} = negative logarithm of the molar concentration of calcium, and

pAlk = negative logarithm of the equivalents of alkalinity (titrable base), assuming that $[Alk] = [HCO_3^-]$.

he terms K_2' and K_s' are dependent upon temperature and ionic rength, which is a measure of ionic composition of the water. Correcons for temperature and ionic strength are made for each calculation.

The utility of the Langelier Index is that it predicts whether calcium ırbonate will precipitate, dissolve, or be in equilibrium with solid ılcium carbonate. If it precipitates, calcium carbonate can form a proective scale on pipes including asbestos-cement (A/C) or metal pipe. If alcium carbonate dissolves in water of a given quality, calcium carbonate ale, previously deposited at the water-pipe interface, will be removed, ius exposing the pipe surface to the corrosive effects of the water.

The Langelier Index is interpreted as follows:

When LI > 0, water is supersaturated with respect to solid calcium carbonate and will tend to precipitate and form a scale.

When LI = 0, water is at equilibrium.

When LI < 0, water is undersaturated with respect to solid calcium carbonate and protective calcium carbonate scales on the pipe may dissolve.

Aggressiveness Index

The A/C pipe industry developed the concept of an Aggressiveness Index or use as a guide in determining whether A/C pipe would be appropriate

in a given situation. The original purpose of the index was to ensure the structural integrity of the pipe. More recently, it has been used to predict whether water quality degradation would occur from pipe dissolution. The Aggressiveness Index is a simplified form of the Langelier Index and has some shortcomings, which are noted below.

The Aggressiveness Index (AI) is defined as follows:

$$AI = pH + \log (AH), \quad (3)$$

where

AI = Aggressiveness Index,
A = total alkalinity, mg/liter as calcium carbonate, and
H = calcium hardness, mg/liter as calcium carbonate.

The Aggressiveness Index does not incorporate the corrections for temperature and ionic strength. At a selected temperature (14°C) and ionic strength (0.01) and by converting to alkalinity and calcium concentrations in mg/liter, it can be shown that:

$$AI = LI + 12.0 \text{ (Schock and Buelow, 1980).} \quad (4)$$

Application of the Aggressiveness Index to determine when A/C pi should be used has been incorporated into standards published by the American Society for Testing and Materials (1976) and the American Water Works Association (1975b, 1980). The need for water quality guidelines is also acknowledged by the A/C Pipe Producers Association (1980). The most recent standards apply the Aggressiveness and Langelier Indexes to relate water quality and the use of A/C pipe (Table III-1). These standards recommend that nonaggressive water ($AI \geq 12.0$) be used with Type I (nonautoclaved) or Type II (autoclaved) A/C pipe. Type II pipe is recommended for moderately aggressive water (AI between 10 and 12). For highly aggressive water, "the serviceability of pipe for such applications should be established by the purchaser in conjunction with the manufacturer" (American Water Works Association, 1980). Recognizing the relationship between water quality and the use of A/C pipe, the U.S. Environmental Protection Agency (1979a) recently proposed that the Aggressiveness Index should be ≥ 12 for water transported through A/C pipe in order to prevent adverse effects.

Data published by Millette *et al.* (1979) provide a perspective on the typical quality of water in the United States as it pertains to the use of A/C pipe. Through a sampling of representative utilities throughout the

CAPCO JEN 0032018

TABLE III-1 The Relationship of Water Quality (Expressed as Aggressiveness and Langelier Indexes) to Asbestos-Cement (A/C) Pipe[a]

Aggressiveness to A/C Pipe	Aggressiveness Index	Langelier Index
Highly aggressive water	< 10.0	< −2.0
Moderately aggressive water	10.0 to 11.9	−2.0 to −0.1
Nonaggressive water	≥ 12.0	≥ 0

[a]From American Water Works Association, 1980.

United States, they determined that 52% of the water supplies had water that was at least moderately aggressive (Aggressiveness Index between 10 and 12). Furthermore, 16.5% of the water supplies could be classified as very aggressive. They concluded that these data suggest that as many as 68.5% of the U.S. water systems carry water that is potentially capable of corroding A/C Type I pipe and that water supplies with very aggressive waters (< 10) may be significantly corrosive to any type of pipe, including cast iron, galvanized, and other types of pipes.

When using the Aggressiveness Index, one could assume that the mechanism for A/C pipe deterioration by aggressive waters is related to release of calcium from the cement portion of the pipe. If the water is in fact attacking the pipe, the cement could be dissolving into the water. This would leave the asbestos fibers unprotected or not encapsulated within the cement matrix. This would leave the fibers free to be released into the water. These fibers could be released individually or in bundles. Hallenbeck *et al.* (1978) theorized that once fibers are released into the water, they can be further broken down so that counts of asbestos fiber from the breakdown products are even higher. Thus, if A/C pipe is used, there is a potential for consumers to be exposed to significant concentrations of asbestos in some drinking water supplies.

The use of the Aggressiveness Index represents an advance over the original preconception that A/C pipe is not subject to the effects of water quality. As recently as a decade ago, Bean (1970) stated that A/C pipe does not require lining, even with soft water, which could be classified as aggressive water. Since that time, both manufacturers and pipe producers have acknowledged that it is not judicious to use A/C pipe with aggressive water. Thus, the Aggressiveness Index has been a means for alerting suppliers and users that A/C pipe cannot be used under all situations and

that it is not resistant to corrosion in all cases. It is also simpler to calculate than the Langelier Index.

Since the Aggressiveness Index (as well as the Langelier Index) is based on calcium carbonate saturation, it should yield a fairly accurate prediction of "nonaggressiveness" provided by a protective calcium carbonate coating if water is oversaturated (Schock and Buelow, 1980). However, if the water is undersaturated with calcium carbonate, there is no reason to expect the Aggressiveness Index to predict with accuracy the dissolution of A/C pipe since calcium carbonate is only a minor constituent of the cement and calcium silicate is the predominant pipe component. Furthermore, the Aggressiveness Index does not account for temperature and ionic strength as does the Langelier Index. Finally, the Aggressiveness Index fails to account for protective chemical reactions in drinking water.

The Aggressiveness Index has been used for several years by pipe manufacturers and the water supply industry. Therefore, the majority of the data on water quality and A/C pipe deterioration contains information on the Aggressiveness Index, calcium, and alkalinity of the water.

In the absence of a better predictor of pipe performance, this index has been used extensively and is still a simple first approximation for predicting pipe performance.

Saturation Index

The Saturation Index has been proposed by Schock and Buelow (1980) for use in predicting performance of A/C pipe under given water quality conditions. In this approach, both the solubility of pipe components and the possible protective coating of constituents in the water are considered.

The cement matrix of A/C pipe is a complicated combination of more than 100 compounds and phases. Since electrochemical corrosion is not an issue, the corrosion of A/C pipe is governed by solubility considerations. Possible dissolution reactions in A/C pipe include:

$$Ca(OH)_2\,(s) \rightarrow Ca^{+2} + 2OH^-, \quad (5)$$

$$Ca_3SiO_5(s) + 5H_2O \rightarrow 3Ca^{+2} + H_4SiO_4^0 + 6OH^-, \quad (6)$$

$$Ca_2SiO_4(s) + 4H_2O \rightarrow 2Ca^{+2} + H_4SiO_4^0 + 4OH^-, \quad (7)$$

$$Ca_3Al_2O_6(s) + 6H_2O \rightarrow 3Ca^{+2} + 2Al^{+3} + 12OH^-, \quad (8)$$

where s indicates the solid phase.

The first constituent, $Ca(OH)_2$, is lime, and the others are tricalcium silicate, dicalcium silicate, and tricalcium aluminate. Solubility constants for pure solids in Reactions 5, 6, and 7 are $10^{-5.20}$, $10^{-8.6}$, and 10^{-16}. For

CAPCO JEN 00320 19

Reaction 8, it is not known. The actual solubility constants in pipe are difficult to estimate, since solids in pipe are highly substituted. Schock and Buelow (1980) concluded that these materials are soluble under typical water quality conditions, but that they dissolve slowly. Pipe dissolution by Reactions 5 through 8 would increase pH, calcium, and alkalinity of water in contact with the pipe. The Langelier Index or Aggressiveness Index would also increase. These phenomena have been observed in several studies that are described below.

Schock and Buelow (1980) have also used chemical equilibrium calculations to estimate whether calcium carbonate film would form to protect pipe. Protection by metal precipitation has also been modeled for iron, zinc, manganese, and silica since they could form dense solids.

Models were estimated using the aqueous chemical equilibrium computer program called REDEQL.EPAK (Schock and Buelow, 1980). The thermodynamic state of saturation was quantified by the Saturation Index (SI), defined as the logarithm of the ratio of the ion activity product (IAP) to the solubility product constant (K_{so}). For example, for hydroxyapatite, the equilibrium reaction is:

$$Ca_5(PO_4)_3OH_{(s)} \rightleftharpoons 5Ca^{2+} + 3PO_4^{3-} + OH^-. \quad (9)$$

Assuming activity coefficients equal to unity, the Saturation Index (SI) would be:

$$SI = \log \frac{[Ca^{2+}]^5[PO_4^{3-}]^3[OH^-]}{K_{so}}. \quad (10)$$

If the solid and solution are in equilibrium, IAP = K_{so} and SI = 0. If the solution is supersaturated, the SI is >0, and undersaturation occurs if SI <0.

The results of SI calculations are shown in Figure III-1. Initial water quality is 1.0 mg/liter calcium, 24 mg/liter total carbonate, 0.24 mg/liter magnesium, 0.5 mg/liter zinc, 0 mg/liter iron, 0 mg/liter phosphate, 20 mg/liter sodium, and 11-33 mg/liter chlorine. Based on this model, zinc hydroxycarbonate [$Zn_5(CO_3)_2(OH)_6$] would precipitate if the pH was higher than 8. None of the other species would precipitate. Schock and Buelow (1980) suggested that zinc hydroxycarbonate, once precipitated, could be converted by reactions with silicates in the A/C pipe to a zinc silicate coating, which is hard and should provide good protection.

This approach to predicting pipe performance by modeling equilibrium characteristics of a number of protective solids in addition to calcium carbonate appears to contribute to the understanding of A/C pipe. Schock

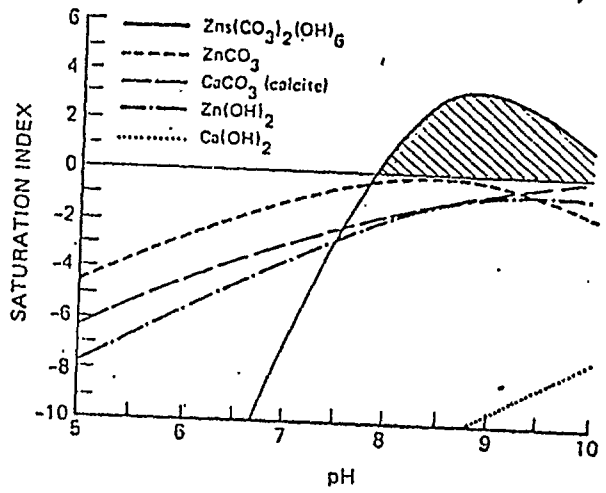

FIGURE III-1 Saturation Index diagram for model system.

and Buelow (1980) have demonstrated the applicability of the Saturation Index to several model systems. Although it is more difficult to use than the Langelier Index, it is expected to produce more accurate predictions.

CORROSION

Uhlig (1971) defined corrosion as "the destructive attack of a metal by chemical or electrochemical reaction with its environment." He also noted that the term "rusting" applies to the corrosion of iron or iron-base alloys to form corrosion products consisting mostly of hydrous ferric oxides. Therefore, other metals can corrode, but not rust.

A principal concern about corrosion in water distribution systems is the possibility that its products will have an adverse impact on the health of consumers exposed to them. Moreover, materials introduced into this system to mitigate corrosion might themselves provide a source of potentially hazardous chemicals. For example, protective coatings on pipes could leach such hazardous constituents into the water, or chemicals added to the water to inhibit corrosion could be toxic. Before discussing all of these concerns, it is necessary to consider some of the mechanisms of corrosion, its inhibition, and measurement.

CAPCO JEN 0032020

Studies of animals showed that manganese and stoichiometric equivalent amounts of sodium hexametaphosphate fed at high concentrations in water interfere with trace metal metabolism, as judged by their effect on growth. They concluded that the biological effects of the entire range of polyphosphate compounds used in water treatment and their various metal complexes should be studied further. Nevertheless, although they did express concern about the use of these polyphosphates, they did indicate that at least for sodium hexametaphosphate it could continue to be used with care at dosage rates in water resulting in concentrations not to exceed that required to complex manganese by more than 10%, i.e., no more than 1 mg/liter.

Pipes and Linings

A variety of materials are available for use in both large and small pipes (Table III-2). Improper selection of piping materials may have an adverse influence on the quality of the distributed water.

Among the metals that can be introduced into the water from the corrosion of these materials are zinc, cadmium, copper, iron, and lead. The latter is probably of the greatest concern because of its known toxicity and the results of numerous studies indicating that it can be corroded readily and accumulate in concentrations higher than generally accepted health-related maximum contaminant levels, e.g., 0.05 mg/liter, which was specified in the Interim Primary Drinking Water Regulations (U.S. Environmental Protection Agency, 1979a, 1980).

Although the use of plastic piping and linings of bituminous coal tar may be effective in reducing or eliminating the adverse impacts of metallic

TABLE III-2 Lined and Unlined Piping Used in Water Distribution Systems[a]

Main System Piping		
Used Without Lining	Used With or Without Lining[b]	Small Piping
Concrete (on steel)	Steel	Plastics (polyvinyl chloride)
Cement-asbestos	Cast iron	Galvanized iron
Plastics (e.g., polyvinyl chloride)	Ductile iron	Lead

[a] From Bean, 1970.

[b] Linings may be cement, factory-applied bituminous seal coat, or coal-tar enamel.

corrosion of pipes, such materials need to be continuously evaluated with regard to the possible leachings of their constituents into the water distribution system. (See section entitled "Leaching" later in this chapter.)

Lane and Neff (1969) have discussed the need to select proper materials to reduce corrosion in hot and cold water distribution systems. Indeed, they regard this step as the first line of defense and believe that chemical treatment should serve only a supplementary role. Although they focused primarily on distribution systems in institutions, their experience is germane to this report because it provides an insight into practical corrosion problems, it is consistent with general principles for reducing corrosion, and it would be applicable to homes as well as to institutions. They noted that compatible materials should be installed in the same system; for example, copper-lined heaters should be used with copper tubing, and the same type of piping used throughout the system. The widespread practice of softening water in homes and institutions to very low hardness values can cause serious corrosion of galvanized steel and other metal piping. Lane and Neff (1969) pointed out that blending to a final hardness of 60 to 90 mg/liter (calcium carbonate hardness) has often reduced corrosion in domestic hot water piping, but at temperatures above 60°C, corrosion is more severe. They suggested that more corrosion-resistant material such as stainless steel should be used when higher temperatures may be required.

The role of water quality and its impact on the corrosion of various materials were also evaluated by Lane and Neff (1969). They categorized midwestern U.S. water supplies into five types, primarily related to their hardness and to their chloride and sulfate content. For example, they suggested that copper piping was preferable to galvanized piping for hard waters with high chloride and sulfate content. In addition, the water should be softened, the pH adjusted to levels between 8.0 and 8.4, and sodium silicate treatment might be required. In contrast, they noted that hard waters that are not aerated and contain low to moderate chloride and sulfate are compatible with galvanized steel piping, although softening may be important in domestic hot water systems. This study by Lane and Neff emphasizes the principles that should be used to reduce corrosion in water systems in homes and institutions, particularly when it they may lead to excessive trace metal concentrations at the tap.

Monitoring and Evaluating Corrosion and Its Control

A variety of methods can and have been used to monitor and evaluate corrosion in water distribution systems. To control such corrosion effectively,

CAPCO JEN 0032021

hese methods must be used to evaluate the success of specific steps that re undertaken.

Wagner (1970) has summarized the methods that have been used. These ıethods can be divided into three groups. In the first, the mass of mate-ial formed is measured visually, by weight determination, or by mea-urement of thickness. In the second, the production of specific corro-ion products, such as the evolution of hydrogen, is measured. The third ıvolves the measurement of electrical and electrochemical parameters, ıcluding electrical resistance, corrosion current, pH, and electrical otential. Many of these tests are standardized by such organizations as ıe American Society for Testing and Materials (ASTM) and the National .ssociation of Corrosion Engineers (NACE).

A recent example in which such tests were used to monitor corrosion-educing measures was reported by Mullen and Ritter (1980). The corro-on problem they encountered arose in a public water supply system in ew Jersey after a hard well-water supply (260 mg/liter calcium carbonate ardness) used for many years was replaced by a much softer surface ater source (68 mg/liter hardness). When the new supply was in use, ıany consumer complaints of discolored water were reported. Various ıemical control measures were then undertaken. Primarily, they exam-ed the rate of corrosion by measuring the weight loss of a mild steel oupon. This was determined both by laboratory tests in which specific ıemical controls and additives in the water were introduced and by the eriodic measurement of coupons placed in the distribution system. They valuated pH adjustment by caustic addition, temperature, and the addi-on of two corrosion inhibitors, sodium zinc-glassy phosphate and zinc thophosphate, each added in amounts to produce zinc concentrations of 5 mg/liter in the water. Initially, the laboratory bench studies showed ıat the sodium zinc phosphate offered little corrosion protection com-ared to that of pH adjustment alone to 7.8 or 8.1, while the zinc hosphate caused an average of 55% reduction. Over a temperature range 4°C to 25°C, adjustment of pH and the use of zinc phosphate were ıore effective than pH adjustment alone. However, below approximately)°C, the inhibitor was more effective without pH adjustment. They then sed the coupon tests over a 5-year period to measure the effectiveness of ıeir corrosion-reduction steps in the actual distribution system, using pH ontrol and the addition of zinc phosphate. In the warm months, their ne dosages were 0.43 to 0.49 mg/liter, and the corrosion rates ranged om 0.8 to 1.4 μm per year.

The example discussed above indicates how steps can be taken sys-matically to mitigate corrosion by the adjustment of water quality ıd the use of corrosion inhibitors and that the effects of such steps can be

CAPCO JEN 0032022

measured. Although the principal interest here is reduction of the possible adverse health effects from the corrosion products, it is highly likely that this will be achieved simultaneously, even though the evaluative process focuses on the integrity of the pipe material, rather than on the potentially harmful corrosion products.

Field Studies of Metallic Corrosion in Distribution Systems

In this discussion of metallic corrosion in distribution systems, the metals of particular interest are cadmium, copper, iron, lead, and zinc. To the extent that they may be present in lower concentrations in pipe or distribution fixtures, other metals such as nickel and chromium might also contribute to corrosion products in water. Corrosion is not the only source of these products in treatment and distribution systems. They could also be introduced as contaminants in chemical additives, such as lime.

In the first volume of *Drinking Water and Health* (National Academy of Sciences, 1977), it was reported that the high concentrations of several heavy metals in household tap water samples from Dallas, Texas, could be attributed to corrosion at various points in the distribution system. Among these metals were iron from the steel water mains, copper and zinc from household plumbing, and lead and nickel due to "local influences." In the Denver, Colorado, municipal system, there were both increases and decreases in heavy metal content between the finished water at the treatment plants and samples taken at the domestic taps, although frequently there were no significant changes (Andelman, 1974). Typically, the maximum decrease at the tap for most metals was approximately 50%, but in some cases they were larger. Iron increased by a factor as large as 25, zinc and copper by approximately 5, and manganese by 4. Corrosion did not necessarily account for all of the increases, but was probably playing a role.

McCabe (1970) reported increases in the trace metal content of the Chicago water treatment system. In this study, 550 samples taken at various points in the distribution system were compared to 2-week composite samples at the treatment plants. McCabe used the criterion that a distributed water sample had "picked up" metal if its concentration was higher than that of any of the composite samples at a treatment plant. On this basis, it can be seen in Table III-3 that a substantial proportion of the distributed samples increased their trace metal content.

Dangel (1975) reported the results of a U.S. Environmental Protection Agency (EPA) study of corrosion products in the Tolt River portion of the public water supply system of Seattle, Washington. That portion was

The chemical quality of the finished water at the treatment plant can affect the rates of corrosion, which can be mitigated by chemical additions, including corrosion inhibitors. Bacteria in the distribution system are also known to affect corrosion.

Although corrosion can be reduced by pipe linings and chemical additives, the latter must be used judiciously to minimize human exposures. Also, there is evidence that potentially hazardous chemicals can leach from some, but not all, materials used to line the pipes. The adverse effects of the chemicals need further evaluations.

LEACHING

In contrast to corrosion, which is an electrochemical phenomenon, leaching is a process of dissolution governed by solubility and kinetic properties of the materials involved. Materials that were initially part of the water distribution system pipes, storage reservoirs, and other components may slowly dissolve into the water. For some of them, such as the components of A/C pipe, leaching is strongly influenced by water quality. For other materials, such as those in linings and plastic pipe, water quality does not appear to govern leaching. In this section, A/C pipe, lining materials, and plastic pipe are discussed.

Asbestos-Cement Pipe

A/C pipe was originally introduced to the water supply industry as a material that was believed to be resistant to deterioration. However, recent findings have shown that A/C pipe is similar to other pipe materials commonly used in water distribution systems in that it can be subject to corrosive action of water in certain situations.

The potential release of asbestos fibers from A/C pipe in the water distribution system is but one potential source of asbestos contamination in potable water supplies. Other sources include natural erosion of asbestos-containing minerals and dumping of asbestos-containing materials from industrial projects, such as those contributing asbestos fibers to the drinking water of Duluth, Minnesota, and other nearby communities using Lake Superior water supplies (Cook *et al.*, 1974). These other sources of asbestos in drinking water are beyond the scope of this study, which emphasizes presence of asbestos fibers in potable water distribution systems resulting from deterioration of the A/C pipe itself.

The concern about asbestos in drinking water from all sources, including pipes, is relatively recent. The first report of asbestos fibers in drinking water was published by Canadian investigators in 1971 (Cunningham and Pontefract, 1971). In the United States, the first major concern arose in 1974 when asbestiform fibers were found in the drinking water of Duluth, Minnesota, as a result of discharges from an iron ore processing plant (Cook *et al.*, 1974). The same year, the American Water Works Association (AWWA) Research Foundation (1974) began its own investigation of the asbestos in drinking water, including a review of the possible effects of A/C pipe. At that time, there was very little information regarding the release of asbestos fibers from A/C pipe. The AWWA concluded:

> At present there are not adequate data for a description of the quantitative or qualitative role of asbestos-cement pipe as a contributor to asbestos fibers found in potable water distribution systems. However, the available data do indicate that additional studies need to be made and also afford a first approximation of the magnitude of the possible health hazard.

The AWWA also concluded that further research was necessary to answer the question, "Does the use of asbestos-cement pipe in potable water systems constitute a health hazard?" Among the recommended research priorities were determinations of the increment of asbestos fibers added to the water as it traverses asbestos-cement, metal, and plastic pipe systems under varying conditions. A more complete understanding of the health effects of ingested asbestos fibers was also suggested as a research need.

Since 1974, a considerable amount of work on health effects of asbestos, water quality impacts of A/C pipe, and control measures has been sponsored by the EPA's Health Effects Research Laboratory and Municipal Environmental Research Laboratory.

At the time of the publication of the first volume of *Drinking Water and Health* (National Academy of Sciences, 1977), the concern about the release of fibers from A/C pipe was noted, and the relationship between soft water and dissolution of the calcium carbonate in the pipe was mentioned. The report noted that EPA studies under way had produced tentative results suggesting that some fibers are emitted from A/C pipe in corrosive waters.

Since that time, there has been a considerable amount of new evidence regarding the release of asbestos fibers from A/C pipe under various conditions. Both laboratory tests and field investigations have shown that, under certain circumstances, asbestos fibers can be released from A/C pipe into water supplies.

The data concerning the health effects of asbestos ingested in drinking water are indecisive, but it is known to be a carcinogen when inhaled (National Academy of Sciences, 1977). Thus, there has been some concern

CAPCO JEN 0032023

ver the use of A/C pipe and possible release of asbestos fibers into drink-
ıg water. The concern over the addition of asbestos fibers and potential
ealth effects in drinking water supplies led to a proposal by the EPA that
ırrosion control be required for systems using A/C pipe. The Ag-
'essiveness Index (discussed above under "Corrosion Indexes") was pro-
›sed as a criterion to determine suitability of water quality for A/C pipe
se (U.S. Environmental Protection Agency, 1979a).

The principal issue regarding the use of A/C pipe and its possible
:terioration within a distribution system is the quality of water
ansported in the pipe. A considerable body of evidence collected to date
ıggests that there is a link between aggressive water and degradation of
ıe pipe. Many investigators have linked a low Aggressiveness Index with
:lease of fibers. However, the Aggressiveness Index does not always
'edict where the fibers will be released.

Current understanding of the factors influencing behavior of A/C pipe
nder various conditions is discussed below. Data from laboratory studies
ıd field investigations regarding the release of fibers from A/C pipe are
!so summarized. Finally, control measures for limiting the exposure of
ıe population to asbestos fibers derived from A/C pipe are presented.

SE OF ASBESTOS-CEMENT PIPE

'riginally introduced in Italy during the early 1900's, A/C pipe is now
idely used in potable water distribution systems throughout the world.
'he formulation of A/C pipe from Portland cement and asbestos fibers
'as originally developed in an effort to provide a corrosion-resistant
ıaterial of sufficient strength to be used for transmission of water. From
906 to 1913, a company (Societa Anonima Eternit Pietra Artificiale) in
ienoa, Italy, combined asbestos fibers with cement to produce a reinforce-
d pipe that would withstand the high pressure necessary to pump salt
'ater up to the City of Genoa for its street-flushing system (Olsen, 1974).
ubsequently, A/C pipe began to be used more widely in Europe and was
ı limited use 20 years later in the United States. Today, A/C pipe is used
hroughout North America and Europe as well as in other parts of the
'orld (Craun and Millette, 1977).

A/C pipe was first introduced in the United States around 1930
American Water Works Association Research Foundation, 1974, 1975b;
lallenbeck *et al.*, 1978). By 1974, there were an estimated 2.4 million km
f A/C pipe in service worldwide and approximately 320,000 km in use in
ıe United States (Olsen, 1974). According to a recent survey by the A/C
ipe industry, approximately 38% of U.S. cities with a population of
,000 or more specify, purchase, or have in service A/C pipe (Craun and

Millette, 1977). Thus, approximately 65 million people in the United States may be receiving water that has passed through an A/C pipe distribution system. As of 1978, approximately one-third of all water distribution pipe currently being sold in the United States was made from an asbestos-cement combination (Hallenbeck *et al.*, 1978). In addition to A/C pipe, gaskets and insulation used in treatment and pumps also contain asbestos (Levine, 1978). Advantages of using A/C pipe have been noted by pipe manufacturers and others. Some of them have been listed by Olsen (1974):

- resistance to corrosion, both internal and external;
- strength sufficient to withstand internal forces imposed by water hammer and shock earthloads from earthquakes;
- benefits to water quality, since A/C pipe does not rust, cause discolored water, or contain jute and other types of joints that serve as focal points for bacterial growth;
- light in weight and easy for contractors to install, resulting in lower installation costs; and
- a permanently smooth interior wall, leading to low pumping costs.

Levine (1978) cites advantages of A/C products over nonasbestos counterparts as follows: better tensile strength, strength to weight ratio, strength under heat stress, resistance to acid, and smoothness of finished surface (critical to ensure laminar flow in pipe used for transport of liquids).

As shown later, the purported advantage of corrosion resistance of A/C pipe has not always been found to be true, especially in aggressive waters.

COMPOSITION OF A/C PIPE

A/C pipe is composed of a mixture of asbestos fibers, Portland cement, and inorganic hydrated silicates. In the manufacture of A/C pipe, asbestos fibers are mixed, either wet or dry, with Portland cement and silica in proportions ranging from 10% to 70% of the total material. Typically, the asbestos fibers comprise less than 20% of the A/C pipe (A-C Pipe Producers Association, 1980; American Water Works Association, 1978a,b).

For dry mixtures, the mixture is generally distributed in a flat layer onto an open surface, where the water is then applied by an overhead spray. The thin layer can then be wound onto mandrels in a spiral mat to produce pipe until the required thickness is built up. For wet mix products, a similar winding process can be used for the slurry or the mixture can be

CAPCO JEN 0032024

(Levine, 1978). After pipes are made, the water content is reduced by ·claving and air drying.

he AWWA specifications for A/C pipe also include physical and nical requirements for the pipe itself. For the pipe composition, it re- es:

stos-cement pipe shall be composed of an intimate mixture of either:

ortland cement or Portland blast furnace slag cement and asbestos fiber with thout silica; (2) or Portland pozzolana cement in asbestos fibers. Both (1) and n be with or without the addition of curing agents. The pipe shall be formed r pressure and cured. The finished pipe shall be free from organic materials ·rican Water Works Association, 1980).·

ıe same specifications limit the amount of uncombined calcium oxide, presumably to curtail pipe dissolution: for Type I, there is no , and for Type II, 1.0% or less uncombined calcium hydroxide is per- ed. Type I, which is not autoclaved, is no longer manufactured in the ed States.

ıe asbestos portion of A/C pipe is composed of naturally occurring ·ated mineral silicates that possess a crystalline structure. There are main types of asbestos, as described by Michaels and Chissick (1979):

chrysotile ($3MgO \cdot 2SiO_2 \cdot 2H_2O$) or white asbestos, which occurs as fine silky ıle white fibers and is mined mainly in Canada, Russia, and Rhodesia;
amosite [$(FeMg)SiO_3$], a straight brittle fiber, light grey to pale brown in col- ınd found in South Africa;
crocidolite [$NaFe(SiO_3)_2 \cdot FeSiO_3 \cdot H_2O$] or blue asbestos, which is found as a ght blue fibre in South Africa, Western Australia, and Bolivia; and
anthophyllite [$(MgFe)_7 \cdot Si_8O_{22} \cdot (OH)_2$], a brittle white fibre mined in ınd and Africa.

ther types of asbestos include tremolite [$Ca_2Mg_5Si_8O_{22} \cdot (OH)_2$] and actinolite $) \cdot 3(MgFe)O \cdot 4SiO_2$].

he principal type of asbestos found in A/C pipe is chrysotile. Accord- to the A-C Pipe Producers Association (1980), the chrysotile is added reinforcement purposes. Another type of asbestos, crocidolite (or blue :stos), is also used for reinforcement of the pipe manufacturing :ess.

ECT OF WATER QUALITY ON PIPE PERFORMANCE

·ontrast to the original expectations that A/C pipe would not be at- ed by corrosive water, it is now recognized that under certain cir- ıstances A/C pipe can be attacked by aggressive water. If the pipe is

exposed to aggressive water, the cement matrix constituents will dissolve, thereby exposing asbestos fibers and releasing some of them into the water. Concepts developed to predict pipe performance are described above under "Chemical Water Quality Indexes."

LABORATORY TESTS

Only a few laboratory studies have been conducted to investigate the influence of water quality on deterioration of A/C pipe. One A/C pipe manufacturer, Johns-Manville, developed a semiclosed recirculating system with 9.1 meters of A/C pipe (Transite) (American Water Works Association Research Foundation, 1974). Water ahead of the pipe was filtered in an attempt to remove all asbestos fibers prior to contact with the pipe. A series of runs at various levels of pH (4.9-7.4) and total hardness (12 to 105 mg/liter) were made from 1969 to 1971. The data do not supply sufficient information to calculate either the Langelier Index or the Aggressiveness Index. Fiber analyses were performed using particle and fiber counts from magnified electron microscope photographs combined with a radioactive tracer technique. They showed that asbestos fibers were present in the water leaving the pipe in average concentrations ranging from 0.37 to 4.44 $\times 10^{-5}$ μm/liter.

In a pilot study conducted in Seattle, Kennedy Engineers (1978) evaluated the aggressiveness of two water supplies, the Tolt River and Cedar River, and the effectiveness of various inhibitors in reducing the aggressiveness of water to A/C pipe. Corrosivity measures were weight loss, electron microscopy spectrum analysis, asbestos fiber pickup, and water quality analysis. The results confirmed the aggressiveness of both water supplies, which were low in pH, alkalinity, calcium, and total dissolved solids (TDS), to A/C pipe. For the Cedar River, a treatment with lime and soda ash appeared to be the inhibitor strategy most likely to provide protection to A/C pipe. For the Tolt River, lime plus zinc orthophosphate gave the best protection.

Since 1973, the EPA has been conducting a series of laboratory tests using A/C coupons in an experimental pipe loop system (Buelow *et al.*, 1980). In one experiment, the EPA noted two important findings: (1) iron dissolved in water precipitates to provide a protective coating to A/C pipe, even under highly aggressive water quality conditions, and (2) waters indexed as moderately aggressive attacked Type II A/C pipe, even though this result was not predicted. Another important finding of this early work was that pipe drilling and tapping operations can greatly influence asbestos fiber counts in water.

Following the pilot-scale A/C pipe loop experiments, the EPA proceeded

CAPCO JEN 0032025

to conduct more rigorous tests with bench scale equipment that could be more carefully controlled. Water was recirculated through 6-in. coupons cut from 4-in. Type II A/C pipe. Findings of these experiments are summarized in Table III-9 (Buelow *et al.*, 1980).

Schock and Buclow (1980) reported that results of several of these EPA experiments and other tests were compared with Saturation Indexes and precipitation diagrams calculated for model systems with equivalent water quality and treatment. A good correlation of experimental and predicted results was found in all cases.

The results of these investigations provided several pieces of information elucidating mechanisms of deterioration of A/C pipe. The principal findings are as follows:

- Zinc can provide a protective coating, which prevents the surface from deteriorating even when Aggressiveness Indexes predict that the water will be moderately aggressive to A/C pipe. This protective action of zinc appears to be dependent on pH, higher pH's providing more effective protection.
- Zinc orthophosphate and zinc chloride appear to provide equivalent protection. This suggests that the protective mechanism is related to zinc rather than to the anion or to the compound as a whole.
- The Aggressiveness Index alone cannot be used as a single means of predicting performance of pipe under a given water quality condition. This observation is based on the fact that water with a high Aggressiveness Index, but not saturated with calcium carbonate, has attacked A/C pipe.
- Control of calcium carbonate saturation may, under certain situations, prevent deterioration of A/C pipe.

Some of the more promising findings are being tested by the EPA in field applications for controlling pipe deterioration.

FIELD TESTS

In recent years, concern that A/C pipe can deteriorate under certain water quality conditions has led to numerous studies, including field observation of water quality, pipe conditions, and/or other factors. These studies are summarized below chronologically.

Effects of A/C pipe on water quality were first observed in 1945 in Vermont. Tracy (1950) reported increases in pH, hardness, and alkalinity in water after exposure to A/C pipe. The tendency for water quality changes diminished after several years of exposure to the pipe. Another problem with A/C pipe was reported in 1971 (American Water Works Association,

TABLE III-9 Summary of Individual EPA Bench Scale Tests of A/C Pipe[a]

pH	Calcium as Calcium Carbonate, mg/liter	Total Alkalinity as Calcium Carbonate, mg/liter	Aggressiveness Index	Corrosion Control Method	Findings
8.2	6	20	10.28	None	Inner pipe surface softened.
8.2	6	20	10.28	Zinc orthophosphate	Gray coating on pipe surface; pipe remained hard and smooth.
7.0	10	10	9.3	None	Pipe softened.
7.0	10	20	9.3	Zinc orthophosphate	Pipe somewhat softened: increase in alkalinity and calcium.
8.2	6	20	10.28	Zinc chloride	Protective film formed; clean and hard surface on A/C coupon.
7.5	145	125	11.76	None	Pipe softened; light coating present; pipe attacked despite high Aggressiveness Index.
7.9	145	125	12.16	Slightly positive Langelier Index	Pipe hard and clean.
9.0	25	40	12.00	Calcium carbonate saturation	Pipe very slightly softened.

[a]From Buelow, 1980.

CAPCO JEN 0032026

1971). The investigators reported that the pH of water exposed to new A/C pipe would rise as high as 11.5, if the pipe was not used continuously.

Kay (1974) published a summary of asbestos concentrations found in distribution system samples from 22 cities in Ontario, Canada. Fiber counts by electron microscopy ranged from 136,000 to 3.87 million fibers per liter. The calculated mass concentrations ranged from a low of 0.93 to a high of 35.4×10^{-4} μg/liter. Although there was evidence that the distribution samples contained asbestos, it was not clear whether the fibers originated in the raw water supply or whether they were contributed by action of the water on A/C pipe.

Johns-Manville researchers studied the waters from nine cities using A/C pipe from 8 to 17 years (Olsen, 1974). The asbestos content of the water at the source and at a point in the distribution system following exposure to A/C pipe was tested with an electron microscope technique. Source concentrations varied between 0.26 and 1.32 μg/liter. Fiber content after exposure to A/C pipe ranged from 0.26 to 1.58 μg/liter. The differences do not appear to be significant.

Two municipalities using A/C pipe in their distribution systems were sampled from 1969 through 1970 (American Water Works Association Research Foundation, 1974). In Malvern, Pennsylvania, the content of fibers in well water prior to exposure to A/C pipe was 0.04 μg/liter. After exposure to water having an Aggressiveness Index of 11.3, the water in the distribution system had an average fiber level of 0.12 μg/liter. The water in Glendale, Arizona, had an Aggressiveness Index of 11.8 and an average initial fiber level of 0.006 μg/liter. After exposure to A/C pipe, the average fiber level was 0.01 μg/liter. Thus, both of these early field studies of water in the distribution system indicated an increase in asbestos fiber content.

In 1975, the EPA conducted a study in the Seattle area to determine if water quality changes were occurring as a result of exposure of aggressive water to A/C pipe (Dangel, 1975). Prior to entrance into the distribution system, the pH of the raw water was low (5.4), as was its alkalinity (approximately 4 mg of calcium carbonate per liter) and calcium content (2 mg/liter), and its Aggressiveness Index was 6.7. After exposure to approximately 3.2 km of A/C pipe mains, the water exhibited changes in pH, alkalinity, calcium content, and conductivity, all of which increased with longer exposure to the pipe. Dangel concluded that as the cement binders dissolved, asbestos fibers may have been leaching from the pipe walls. This study was conducted by the EPA to determine if asbestos pipe was degrading. Later studies found that the concentration of asbestos in the raw water was approximately the same as in some parts of the distribution system that were not exposed to A/C pipe. Therefore, subsequent studies

were conducted on removal of asbestos from the raw water itself (Kirmeyer *et al.*, 1979).

Another aspect of the A/C pipe deterioration—potential economic losses—was addressed by Hudson and Gilcreas (1976). In a water utility described by the authors, alkalinity of water leaving the treatment works increased by 6 mg of calcium carbonate per liter by the end of the distribution system, which consisted of reinforced concrete, asbestos-cement, and cement-lined cast-iron pipe. The plant was not able to provide sufficient lime-feeding capacity to produce an effluent stable in calcium carbonate content. Based on alkalinity increases in the distribution system, the authors concluded that the water system was losing approximately 455 metric tons of transmission and distribution piping annually as calcium carbonate. No comment was made about the potential introduction of asbestos fibers from the A/C pipe.

McFarren *et al.* (1977) reported an EPA survey of six public water supply systems that used A/C pipe for distribution. These systems had various combinations of pH, alkalinity, and calcium hardness with Aggressiveness Indexes ranging from 5.34 to 12.85. The results of this year-long survey are summarized in Table III-10. Asbestos fiber counts, measured by transmission electron microscope, were consistently quantified only in the two systems with very aggressive waters. The authors stated that the pH, alkalinity, and calcium hardness increased as the water passed through the pipe, presumably as a result of the water's reaction with the cement in the pipe, which caused the water to become less aggressive to pipe downstream. In a sample of pipe taken from the King County water district system in Seattle, pipe exposed to the water was shown by scanning electron micrographs to have been changed substantially as compared to new pipe.

Craun and Millette (1977) studied the use of A/C pipe in Connecticut public water supplies and the incidence of gastrointestinal cancer. A total of 149 public water supplies in 82 towns were evaluated. Preliminary electron microscopy measurements indicated that 19 water samples exposed to A/C pipe contained chrysotile fiber ranging from below detectable limits (10,000 fibers/liter) to 700,000 fibers/liter. Some amphibole fibers were detected, but concentrations were less than 50,000 fibers/liter. The majority of towns had an Aggressiveness Index under 9.8. The observation of relatively low fiber counts leads to the conclusion that the Aggressiveness Index alone is not a sufficient predictor of the release of fibers from A/C pipe.

Information on exposure of A/C pipe to other types of water quality has been presented by Webster (1974). Photographs of A/C pipe that had

CAPCO JEN 00032027

TABLE III-10 EPA Survey of Systems Using A/C Pipe[a]

Location	pH	Alkalinity as Calcium Carbonate, mg/liter	Calcium Hardness, mg/liter	Aggressiveness Index	Average Chrysotile Fiber Count, fibers/liter
Pensacola, Fla.	5.2	1.0	1.4	5.34	5.52×10^6
King County Water District #58, Seattle, Wash.	7.2	14	14.5	9.51	0.66×10^6
Grant Hill Association, Bloomfield, Conn.	7.5	88	82	11.56	NSS[b]
Clark Counties Utilities, Northridge, Ohio	7.8	220	250	11.54	BDL[c]
Lockhart, Tex.	9.4	50	44	12.74	BDL
Cleburne, Tex.	9.7	36	39	12.85	BDL

[a]From McFarren *et al.*, 1977.
[b]NSS = Not Statistically Significant.
[c]BDL = Below Detection Limit.

been carrying brine (water with a high Saturation Index) for several years showed a well-marked deposition of calcium salts in the interior of the pipe, which should protect the pipe from corrosion. A/C pipe subject to acid conditions while carrying sewage developed rough interior surfaces, which presumably could release fibers through erosion. The sewage probably contained hydrogen sulfide, which can attack A/C pipe (McCabe and Millette, 1979). High levels of hydrogen sulfide in a Florida well water source were apparently responsible for attacking A/C pipe. The Aggressiveness Index calculated for this water would not lead to such a conclusion, but it does not take into account the corrosive effects of water quality characteristics other than pH, calcium, and alkalinity. Removal of hydrogen sulfide from the Florida well water supply is being studied.

Hallenbeck *et al.* (1978) reported the results of a study of water samples from 15 public water supply systems in Illinois before and after exposure to A/C pipe of various ages, length, and diameter. Five were groundwater systems, and 10 were surface water systems from Lake Michigan. Aggressiveness Indexes ranged from 11.2 to 12.8; Langelier Saturation Indexes were calculated at −0.8 to 0.5. Pipe ages ranged from 0.5 to 50 years. Measurements by transmission electron microscope indicated that there was no statistically significant difference in the fiber content of water samples collected before and after exposure to the A/C pipe. Thus, there was no statistically significant release of chrysotile fibers from the A/C pipe into these moderately aggressive to nonaggressive water supplies.

In an investigation of domestic water supplies in the San Francisco Bay Area, Cooper *et al.* (1978) reported on asbestos concentrations within distribution systems that contained an A/C pipe. The authors concluded that there was no substantial increase in fiber counts, measured by transmission electron microscopy, after the water passed through A/C pipe. Some increases were observed, but they were not significant compared to the error of measurement.

Millette *et al.* (1979) compiled a summary of more than 1,500 analyses of asbestos in the water supplies of 43 states, Puerto Rico, and the District of Columbia to assess the overall exposure of the U.S. population to asbestos in drinking water. Some of the highest concentrations of asbestos fibers were attributed to A/C pipe (Table III-11). This report also contains tabulations of the miles of A/C pipe, concentrations of fibers, and other information for the 1,500 water samples, which had been collected by the EPA.

Millette *et al.* concluded as follows:

> The majority of persons receiving water from asbestos cement pipe distribution systems are not exposed to significant numbers of fibers from the pipe. Many

CAPCO JEN 0032028

CAPCO JEN 0032029

TABLE III-11 Selected Locations in Which Asbestos Concentrations Have Been Attributed to A/C Pipe[a]

City	Reported Concentration, million fibers/liter	Probable Source	Remarks
Bishopville, S.C.	Up to 547	A/C pipe	Aggressive water
Kentucky Dam Village, Ky.	Up to 45	A/C pipe	Aggressive water
Pensacola, Fla.	Up to 32	A/C pipe	Current levels below 2 million fibers/liter
Lakeland, Fla.	Up to 16	A/C pipe	Hydrogen sulfide attack on pipe; corrective studies under way
Paint, Pa.	Up to 19	A/C pipe	Aggressive water
Amherst, Mass.	Up to 190	A/C pipe tapping	Low concentrations in the system, but high in hydrant
Farmington, Conn.	Up to 10.2	A/C pipe tapping	Resampling showed much lower concentration
Greenwood, S.C.	Up to 3.1	A/C pipe	Aggressive water
San Francisco, Calif., and cities within the Bay Area	Up to 9	Erosion of natural serpentine and some A/C pipe	

[a]Adapted from Millette *et al.* 1979.

residents using asbestos cement pipe may be exposed to intermittent amounts of asbestos fibers in their water if pipe tapping work is done improperly. In areas of very aggressive water (estimated to be 16 percent of the U.S. water utilities) consumers using asbestos cement mains may be exposed to high concentrations of fibers, over 10 million fibers/liter.

Tarter (1979) has conducted a statistical study of the size of asbestos fibers in the San Francisco Bay Area water systems. A slight but not necessarily statistically significant shift to longer fibers was observed in water after it flowed through A/C pipe in the East Bay Municipal Utility District distribution system. Examination of samples obtained before and after passing through A/C pipe in the East Bay system and in the San Francisco Water Department Hetch-Hetchy system led to the conclusion that water exposed to A/C pipe contained a significantly larger portion of long fibers than did raw water. Craun and Millette (1977) also reported that samples obtained after passing through A/C pipe in a Connecticut system had a higher percentage of fibers exceeding 1 μm in length than a sample with a natural source of fibers obtained from the San Francisco raw water reservoir. The respective median values for the asbestos fiber length were 2.0 μm from the A/C pipe distribution system and 0.7 μm from the natural fiber source.

McCabe and Millette (1979) have summarized a number of EPA-sponsored studies pertaining to deterioration of A/C pipe under varying water quality conditions. In an update on the Connecticut study, they indicated that source waters in 45 Connecticut A/C pipe systems were thought to be very aggressive because the Aggressiveness Indexes were less than 10. However, an epidemiological evaluation of the exposures revealed that there were no high concentrations of asbestos in the distributed water sampled after passing through A/C pipe in any of the systems. Furthermore, none of the pipe that had been dug up over the years had been reported to be significantly deteriorated. With one exception, all samples collected from the Connecticut A/C pipe system contained asbestos concentrations below 1 million fibers per liter, measured by electron microscopy. Distribution system maintenance work and tapping were believed to be the sources of asbestos in one Connecticut sample, which contained 10 million fibers per liter on one occasion and less than 1 million fibers per liter on another. The higher concentration was believed to be the result of pipe tapping. If devices are not used to flush the cutting debris from the pipe or if samples are collected from dead-end areas or from fire hydrants that have not been completely flushed, samples may contain high concentrations of asbestos fiber that are not an accurate representation of the system as a whole. Thus, what may be attributed to pipe deterioration

TABLE III-12 Summary of EPA Field Studies[a]

Initial Aggressiveness Index	pH	Alkalinity as Calcium Carbonate, mg/liter	Calcium Hardness as Calcium Carbonate, mg/liter	Consistently Quantifiable Fibers	Pipe Wall Deteriorated, as Determined by Inspection
5.34	5.2	1.0	1.4	Yes	Yes
5.67	4.8	3.0	2.5	Yes	Yes
7.46	6.0	4.0	7.5	No	No
8.74	7.1	89	0.5	Yes	Yes
9.51	7.2	14	14.5	Yes	Yes
10.48	8.3	20	7.5	Yes	[b]
11.56	7.5	88	82	No	[b]
12.54	7.8	220	250	No	[b]
12.74	9.4	50	44	No	[b]

[a] Adapted from Bucłow *et al.*, 1980.
[b] Not inspected.

in some cases may actually be a result of accumulation of sediments from previous pipe tapping.

In a summary of EPA field work, Bucłow *et al.* (1980) discussed evaluation studies at nine water utilities using A/C pipe with various water qualities (Table III-12). Asbestos fiber counts, made by transmission electron microscopy, were consistent in four of the five systems where the Aggressiveness Index was less than 10.0. Inspection of one system with an Aggressiveness Index below 10 (third line in the table) revealed that the pipe had a protective coating resembling iron rust. Fibers were also found in one system with an Aggressive Index greater than 10.0. In the systems with an Aggressiveness Index exceeding 11.56, there were either no asbestos fibers or their occurrence was very inconsistent, regardless of the combinations of pH, alkalinity, and calcium hardness. Unfortunately, water quality data from field studies were insufficient to calculate Saturation Indexes.

Results from this field study also indicated that the longer the water was exposed to the A/C pipe, the greater were the increases in pH and calcium. This should cause the water to become less aggressive. Therefore, the investigators concluded that major pipe deterioration will usually occur in the sections of the pipe located just after the water enters the A/C pipe distribution system. However, a section of pipe farther from the source will not always be attacked less than the pipe closer to the source due to different flow patterns through different distribution lines.

Bucłow *et al.* (1980) reported the major conclusions from this study as follows:

1. Calculation of the Aggressiveness Index alone is not always sufficient to predict actual behavior of A/C pipe.
2. Collecting a single sample for an asbestos fiber count is often insufficient to judge the actual behavior of A/C pipe in a given situation.
3. Wet drilling and tapping of A/C pipe, if not performed with a flushing device on a tapping machine, can cause a major release of fibers.
4. Metals such as zinc, iron, or manganese in the water can change A/C pipe behavior.
5. Water is not expected to be attacking A/C pipe when the initial Aggressiveness Index is above about 11, the pH or the concentration of calcium do not change significantly as the water flows through the pipe, and no asbestos fibers are found consistently in representative water samples....
6. Water is likely to be attacking A/C pipe when the initial Aggressiveness Index is below 11, and the pH and the concentration of calcium as the water flows through the pipe increase significantly, and the water does not contain iron, manganese, or similar metals....

CAPCO JEN 0032030

In summary, this study has demonstrated that asbestos cement pipe behaves much like other piping materials, except PVC, that are commonly used for distribution of drinking water. If aggressive water conditions exist, the pipe will corrode and deteriorate; if aggressive water conditions do not exist, the pipe will not corrode and deteriorate.

CONTROL OF A/C PIPE DETERIORATION

Various methods have been suggested for curtailing or preventing the corrosion of A/C pipe within water distribution systems. These methods fall into the following basic categories:

- adjustment of water quality to control Langelier Index;
- adjustment of water quality to control Aggressiveness Index;
- addition of materials expected to form protective films or coatings such as zinc, iron, and manganese;
- elimination of hydrogen sulfide;
- rehabilitation of distribution system;
- institution of proper maintenance procedures;
- limitation of the use of A/C pipe; and
- judicious selection of new locations for A/C pipe use.

Adjustment of water quality by controlling Langelier Index is also used to prevent corrosion of metal pipe. Therefore, it is a method with which many utilities are already familiar. The EPA listed adjustment of water quality to a positive Langelier Index as a method for corrosion control and mentioned it specifically for A/C pipe (U.S. Environmental Protection Agency, 1979b). McFarren *et al.* (1977) suggested that A/C pipe corrosion might be controlled by adjusting the pH upward and adding calcium (in effect adjusting either the Langelier Index or the Aggressiveness Index upward). He added, however, that some people might object to an increase in hardness of their water. Buelow *et al.* (1980) agreed that calcium carbonate saturation can be used to prevent attack on A/C pipe. However, it is acknowledged that the greatest weakness in the use of the Saturation Index occurs with water of relatively low alkalinity and calcium. Nevertheless, corrective lime treatment is an option.

Adjusting the Aggressiveness Index is another alternative for controlling the corrosion of A/C pipe. Methods for accomplishing this would include adjustment of pH upward or the addition of calcium or alkalinity to the water. Adding lime, caustic, or soda ash might be considered, but pilot tests should be conducted for an exact selection of chemicals.

In certain cases, the addition of small amounts of metal salts such as

those of iron, zinc, and manganese may contribute to the formation of a protective film. The EPA is in the process of evaluating natural inhibitory factors in a Massachusetts drinking water supply to determine why water that would otherwise be classified as very aggressive is not extremely corrosive to A/C pipe and other materials (U.S. Environmental Protection Agency, 1979c). The potential protective effect of these metal compounds is being investigated. Since coatings resembling iron rust have been observed in laboratory experiments on existing systems, the addition of iron may be able to protect A/C pipe. Zinc and manganese have also been shown to have protective effects. However, applicable drinking water standards and potential effects on industrial users would have to be considered before control measures using either compound could be implemented. In addition, the anion of choice needs to be carefully considered. For example, a study in Seattle showed that although zinc phosphate was effective in reducing corrosion, the phosphate demonstrated a potential to stimulate algal growth in open distribution reservoirs (Courchene and Kirmeyer, 1978). This finding suggests the need for study of other forms of zinc, such as zinc chloride. The costs for adding zinc orthophosphate and zinc chloride have been estimated by the EPA (1979b). Coating of pipe with zinc orthophosphate and pH adjustment are being evaluated as control measures to prevent deterioration of A/C pipe in Greenwood, South Carolina (McFarren *et al.*, 1977).

In a few cases, deterioration of A/C pipe may be curtailed by removing hydrogen sulfide, which may attack the pipe under low pH conditions. A Florida town is currently studying the hydrogen sulfide problem and is planning to implement treatment to eliminate it from water prior to exposure to A/C pipe (McCabe and Millette, 1979). In an EPA-sponsored research project, a utility is adding zinc to the water to determine if it can reduce the amount of asbestos fibers released from A/C pipe that is slightly attacked.

The institution of proper maintenance practices is another approach to controlling occasional additions of asbestos from the distribution system itself. This may be applicable in situations where the water itself is not attacking the pipe, but where occasional high asbestos fiber concentrations have been attributed to residues remaining from improper maintenance procedures. Some tapping devices on the market today force debris from cutting operations to be flushed from the pipe, preventing contamination of drinking water with those fibers. The A-C Pipe Producers Association (1980) recommends that equipment with a positive purge should be used to tap A/C pipe under pressure. This equipment is reported to eject 99% of the asbestos cement chips. Another alternative is the use of heavy walled tapped couplings supplied directly from the factory. According to Buelow

CAPCO JEN 0032031

et al. (1980) many regular pressure tapping machines can be modified by adding a flushing valve from a commercially available kit. New tapping machines can be purchased with a flushing valve.

The American Water Works Association (1978a,b) has published detailed procedures for the use of A/C pipe in water utilities. For "dry" tapping of pipe not under pressure, it recommends that dust and cuttings should be removed from the pipe's interior by flushing with water, wet mopping, or vacuuming prior to placing the pipe in service. This should minimize the fouling of valves, regulators, meters, and other equipment with chips and minimize the unnecessary addition of asbestos to drinking water. For "wet" tapping of pipe in service, it recommends that provision should be made for downstream flushing or use of tapping equipment with positive purge or "blow-off" features.

Another approach to preventing the occurrence of asbestos fibers in drinking water supplies has been to restrict the use of A/C pipe by legal means. Some cities have either banned the future use of A/C pipe or are in the process of considering such bans.

The more careful selection of locations where A/C pipe should be used is a preventive measure with merit. During the past 10 years, pipe manufacturers and trade organizations have recommended caution in the use of A/C pipe with aggressive waters, but this advice has not always been heeded. By using predictors such as the Saturation Index and the laboratory coupon tests developed by the EPA, a utility should be able to determine judiciously if A/C pipe is an appropriate material for a given water quality.

Summary and Conclusions

Under certain water quality conditions, A/C pipe can deteriorate. Evidence from laboratory and field tests has shown that asbestos fibers can be released from deteriorated pipe. Other water quality changes observed after exposure to A/C pipe include increased pH, calcium, and alkalinity. Consistent with these observations, the cement portion of the pipe, consisting principally of calcium silicates plus a small amount of free lime, can dissolve if water is not saturated with a number of calcium compounds. Release of cement constituents would be followed by increased pH, calcium, and alkalinity. After cement is dissolved or otherwise weakened, asbestos fibers in the matrix are released. Since asbestos in A/C pipe is principally the chrysotile form, the majority of fibers released to the pipe are chrysotile.

A number of indexes have been developed to predict pipe performance under given water quality. The Langelier Index estimates whether water will be oversaturated, undersaturated, or at equilibrium with respect to

calcium carbonate. If water is oversaturated, this index is positive and a protective calcium carbonate film can deposit on A/C or other types of pipe. The Aggressiveness Index, a simplified version of the Langelier Index, has been used extensively in the water supply field.

Since both the Langelier Index and the Aggressiveness Index are based on calcium carbonate solubility, there are shortcomings in their ability to predict the performance of A/C pipe. When the indexes indicate oversaturation, experimental and field observations have frequently (but not always) shown that pipe is not deteriorated. When exposed to water predicted to be aggressive by the Aggressiveness Index, some pipes deteriorate and others do not. In the latter instance, protective films of zinc, iron, or other material compounds have been found. Thus, it is clear that water quality factors other than pH, calcium, and alkalinity should be considered before water's aggressiveness to A/C pipe can be determined.

Schock and Buelow (1980) have proposed a chemical equilibrium model that accounts for the potential protective action of silica, iron, manganese, and zinc as well as that of pH, carbonate, calcium, temperature, and disinfectant residual in determining a Saturation Index for several compounds. This appears to be a promising method for predicting performance of A/C pipe, but it will require field tests for confirmation.

Plastic Pipe

In recent years, plastic pipe materials of various compositions have been used in transmission mains of water distribution systems and in individual home services. Plastics were brought into use to provide low-cost pipe materials that were not subject to the action of aggressive waters. Within the past few years, however, there has been some concern over possible leaching of organic compounds and other constituents of plastic pipe into the water. The limited number of tests that have been conducted on this subject have dealt primarily with polyvinyl chloride (PVC) pipe. This section contains discussions of the types of plastic pipe commonly used in the United States, their composition, their use in water distribution systems and home plumbing, the effects of water quality as measured by laboratory and field studies, control measures, and conclusions.

Use of Plastic Pipe

Thermoplastic pipe was first introduced as a commercial product in the United States about 1941, but initially its use in potable water supplies was limited. By 1968, Parish (1969) reported that approximately 234

CAPCO JEN 00032032

CONCLUSIONS AND RECOMMENDATIONS

Suggested No-Adverse-Response Level (SNARL)

The acute toxicity of 2,4,6-trichlorophenol is relatively low, but there is only very limited information on its subchronic or chronic toxicity. Technical 2,4,6-trichlorophenol has been shown to be carcinogenic to rats and mice; however, it is not clear whether this activity is derived from dioxins or other impurities present in the commercial preparation.

24-Hour Exposure The minimum toxic dose for 2,4,6-trichlorophenol in the rat is 500 mg/kg (National Cancer Institute, 1979). Using this value, an uncertainty factor of 1,000, assuming that 2 liters of drinking water daily provides the only source during this period for a 70-kg human, one may calculate the 24-hour SNARL as:

$$\frac{500 \text{ mg/kg} \times 70 \text{ kg}}{1{,}000 \times 2 \text{ liter}} = 17.5 \text{ mg/liter.}$$

7-Day Exposure No data are available for calculation. Using the acute 24-hour SNARL of 17.5 mg/liter for 2,4,6-trichlorophenol and dividing by 7 days:

$$\frac{17.5 \text{ mg/liter}}{7} = 2.5 \text{ mg/liter.}$$

Chronic Exposure No chronic SNARL can be calculated because tests with technical 2,4,6-trichlorophenol have yielded positive results in animal carcinogenicity bioassays.

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CAPCO JEN 0032043

Index

ABS (*see* acrylonitrile-butadiene-styrene)
absorption (*see* metabolism)
acetonitrile, 202-206
  health effects, 204-205
  metabolism, 203-204
  SNARL, 205-206
  TWA standard, 203
  see also nitriles
A/C pipe (*see* asbestos-cement pipe)
acrylonitrile-butadiene-styrene pipe, 4, 13
acute diseases, waterborne, 5
  bacteria, protozoa, and viruses implicated in, 137
  defined, 138
  outbreaks of, 140-149
Aerobacter, 29
Aggressiveness Index, 19
  A/C pipe and, 20-21, 49-57, 61
  A/C pipe degradation and, 44-45, 58
  adjustment, 58
  applications of, 20-23
algae
  growth in reservoirs, 98-99, 124, 141
  polysaccharides produced by, 113
alicyclics, 247, 251
alkanes, 247, 251
alkalinity, A/C pipe effect on, 51
aluminum, 95, 155-167
  conclusions and recommendations pertaining to, 166-167
  daily intake, 156
  health effects, 158-166
  metabolism, 157-158
  SNARL, 166
  sources in human diet, 156
  uses, 156, 158
aluminum chloride, 164
aluminum nitrate, 164
aluminum salts, 156, 163
aluminum sulfate, 156, 164
Alzheimer's disease, 160, 167
amebiasis, 5, 138
American Water Works Association
  on chlorination, 130
  specifications for A/C pipe, 46
  study of asbestos in drinking water, 43
ammonia, chlorine interaction with, 96-97
anthracene, 4, 99
aromatic hydrocarbons in petroleum, 247, 248, 249, 252
arsenic, 95, 167
asbestos, 6
  health effects, 3-4, 43, 150
asbestos-cement pipe, 2, 42-61
  advantages of, 45
  city water supplies with asbestos concentration from, 54
  composition, 45-46
  corrosion, 3, 22-23
  deterioration control, 58-60