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QUALITY ASPECTS OF WATER DISTRIBUTION SYSTEMS

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and the
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University of Illinois
Department of Civil Engineering

IN COOPERATION WITH THE
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CONTENTS

Introduction .................................................. 5
What Is Quality Water? ........................................ Raymond J. Faust 6
Corrosion Phenomena, Causes and Cures .................... T. E. Larson 9
Some Experiences in Scale and Corrosion Control .......... A. H. Ullrich 15
Manganese, Iron, and Copper Problems ..................... John C. Kearns 20
Manganese in Water Distribution Systems ..................... A. E. Griffin 28
Copper Corrosion ............................................... George B. Hatch 32
Residual Chlorine in Distribution Systems .................. James V. Feuss 41
Adverse Effects of Poor Circulation
  in Small Water Distribution Systems ..................... John G. Guillou 52
Effects of Poor Circulation
  in Large Water Distribution Systems ..................... J. J. Rossbach, Jr. 58
Actinomycetes in Water Distribution Systems ............... J. K. G. Silvey 62
Pathogenic Bacteria and Viruses in Water Supplies ........... P. W. Kabler,
  S. L. Chang, N. A. Clarke, and H. F. Clark 72
Animal Infestations in Distribution Systems ............... W. M. Ingram and
  K. M. MacKenthum ........................................ 79
Iron Bacteria .................................................. F. M. Clark 85
Biologic Infestations in Water Distribution Systems ...... M. P. Crabill 90
Program .......................................................... 94
INTRODUCTION

Is control over the quality of water lost once it leaves the treatment plant? Must the deterioration of water quality between the time it is treated until it arrives at the tap continue to frustrate the efforts of waterworks men to deliver a high-quality product? How can infestations of clams be combated? Is it possible to prevent gross accumulations of slime-forming bacteria in water mains? What means are available for protecting the distribution system of a community (frequently, its most valuable piece of property) from the aggressive attack of corrosion and, at the same time, avoid the "hardening of the arteries" caused by scale deposition? If the water being forced into the mains is iron-free, why does iron appear in the product delivered? On the other hand, why does the residual chlorine, with its oxidizing energies, disappear, thereby creating doubts as to the bacteriological safety of the water? What benefits in water quality are obtained by improved circulation in, or flushing of, the distribution system? How can we avoid stains, either red, black, or blue, in our consumer's wash basins and sinks?

These and many other very real problems were considered at the Fifth Annual Sanitary Engineering Conference at Urbana, Illinois. The conference, sponsored jointly by the Illinois Department of Public Health, Sanitary Engineering Division, and the University of Illinois, Department of Civil Engineering, had as its theme, Water Quality in Distribution Systems.

To the uninitiated, this general topic might seem rather trivial. After all, at least in terms of quantity (and neglecting leaks), what goes in a pipe must come out. And, of course, quality is controlled at the treatment works. However, from the observations and personal experiences of the conference speakers, it became painfully clear that in many cases water quality problems begin with the distribution systems. The conference committee would like to take this opportunity to again thank the speakers for their participation and excellent presentations.

Conference Committee

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WHAT IS QUALITY WATER?

RAYMOND J. FAUST

The word "quality" in this title means very little until we define the use to which the water is to be put. Only then can we become specific. Since our interest is public water supply, the term "quality water" relates primarily to domestic water and will be so treated in this discussion.

The quality of water from public systems has changed as local needs have changed. In the early nineteenth century, the beginning of our earliest public water supplies, the primary need for water from the public system (one may use New York City as an example) was for fire protection and sanitation. The sanitation needs then were not the same as they are today. At that time water was needed to flush the streets of animal manure and other wastes to control odor and fly problems. Bacteriological safety was not recognized as a problem at that time because contaminated water was not yet suspect as a vehicle of disease. It must be remembered that the germ theory of disease was still not known; nor was clarity a problem because turbid water was just as efficient in street flushing and in fighting fires as was clean water.

As our villages and cities grew, increasingly more dependence was placed on the public supplies for water for additional purposes, chief of which were for drinking and other domestic uses. These new uses placed additional burdens on the quality of the water delivered. Dirty or turbid water was not suitable for drinking, cooking, bathing, or washing clothes and fecally contaminated water was a serious deterrent to health and happiness. So the country, particularly the water supply industry, faced the serious problem of how to treat raw surface water to make it safe for people to drink and to make it reasonably clean for other domestic uses. It was then that the term "quality water" or "water quality" took on a new meaning. It had to, because safe water was necessary to protect lives and to help make city life practical.

Water quality was being changed to meet new problems and new conditions.

Providing safe and clean water was not an easy task. In our country it took the sacrifice of thousands of lives, much money, and about fifty years to accomplish. It was ultimately accomplished by scientists, engineers, public health people, and the will of the public. It was a national struggle in every sense, fought largely at the local level.

Some of the fringe benefits of that struggle were: (1) the development and adoption of drinking water standards whose primary objective was safe water; (2) a solid corps of qualified sanitary engineers, water bacteriologists, and water biologists in both private and public practice; (3) qualified water treatment plant operations at the local level; (4) public health department personnel strongly qualified in environmental engineering problems; (5) a strong water works association which provided a forum for the public discussion of all related problems. This association also publishes and thereby records and communicates important industry information, and develops and provides material standards used in the industry.

The evolution in the water industry during the last half century has produced astonishing results in the health, comfort, and welfare of our people, and has also opened up many new frontiers that have provided jobs for thousands of our people. Today the water industry again stands at the crossroads. It must decide whether to go forward or to stand still. Safe and relatively clean water is not enough. The people want something more. They want water that meets the needs of the home much more closely than do present supplies. They want the consumer characteristics of water improved.

What are the consumer aspects or characteristics of water? They are those features that the consumer can recognize. If they are not satisfactory they cause irritation and ill will. For example, one consumer aspect of water supply is hardness. The consumer is readily aware of this quality by the amount of lather obtained with soap. People do not like hard water for domestic use. Its pres-
ence will always be a source of irritation and finan­
cial waste.

Taste and odor are two aspects of water that are readily detected and often cause consumer diffi­
culty. The solution of taste and odor problems can be vexing and expensive. However, the industry has made great strides in solving or minimizing such problems and I expect this progress to con­
tinue. Needless to say, neither an acute taste or odor problem nor a chronic one will win friends for
the water utility.

The remaining consumer aspects of water that need attention are staining, color, corrosion, tur­
ridity, and temperature.

Staining of sanitary fixtures and laundry pro­
duces unsightliness in the home that is particularly vexing to the housewife. Brown stains in the bat­
tub, wash basin, and toilet bowl produced by iron­
and manganese-bearing water are not a recom­
manded way to promote friendship for the water utility. Nevertheless, hundreds of water suppliers in this country continue to deliver iron and man­
ganese rich waters.

Another type of staining is produced when copper piping in the home is delivering a low pH water. The copper carbonate stain which results is blue-green in color and rather difficult to remove. It is also a constant cause of irritation for the cus­
tomer. Corrective treatment is relatively simple and inexpensive.

Color is a problem, but perhaps not quite as widespread as some of the others. However, in those supplies where color is high, it presents a serious problem for the fastidious housewife. It is disconcerting to wonder when you look at a tub of off-colored water if you are going to take a bath or have already taken it.

A corrosive water is also readily recognisable to the consumer in high plumbing bills and in turbid and colored water. It should be avoided. Scale formation in the household water system could also be a problem for the consumer but the chances of his being aware of it are somewhat min­
imized. This condition is practically the opposite of corrosiveness, chemically speaking.

Turbidity in water is another feature often rec­
ognized but not appreciated by the consumer. The 1962 U.S. Drinking Water Standard permits five units of turbidity in a supply. This standard repre­
sents a 50 per cent reduction from the previous standard. But even so, it is unrealistic. It could be much lower and still be within practical reach.

The final characteristic of water that the con­
sumer is sharply aware of is temperature. Practi­
cally every home provides hot water, but very few homes have cold water; nor is a cold (refrigerated) water faucet desirable or needed in most homes. The ice cube tray and the refrigerator water pitcher are providing our cold water needs. Even so, I believe that there is a need, although not a vital one, for a cold water tap at the kitchen sink in homes located in warm areas and served by a pub­
lic supply derived from a shallow surface supply or impoundment. This is not a serious consumer problem nor is it a problem that the water utility must resolve. Nonetheless, it is a consumer prob­
lem in certain areas which might need a more sophisticated solution than the refrigerator now provides. If so, the answer lies in the home by pro­
viding refrigerated water on tap at the kitchen sink.

To achieve the goal of quality water for the consumer will, in my judgment, require a new wa­
ter standard promulgated by the industry through the American Water Works Association. I take this position because the U.S. Drinking Water Standards developed and applied in the interest of public health were never intended to be a standard for non-health objectives. Because the authority back of this standard is public health law, it is of necessity limited in scope. The consumer aspects of water have few if any public health connota­
tions. Thus, if the water industry is to do the job expected of it, new goals or targets must be estab­
lished.

With that thought in mind, the AWWA in 1959, at its San Francisco Conference, established a task group to study the matter of water quality criteria. The task group is composed of Elwood L. Bean, chairman; Herbert O. Hartung; Herbert E. Hud­
son, and Richard L. Woodward. Its report was presented at the Philadelphia AWWA Conference in June, 1962, and was printed in the November, 1962 Journal of the American Water Works As­
sociation. I commend it to you for study. It is thought-provoking. It also charts the next step forward in water quality. Its application will aid materially in attaining a higher standard of living for our country.

One of the most interesting statements in the report is: “Water delivered to the consumer should be clear, colorless, tasteless, and odorless.” This, of course, is ideal. Nonetheless, there is a lot of prac­
tical sense to the statement. For example, the
phrase “water delivered to the consumer should be” poses a problem of superior distribution system house cleaning to which the water industry has not faced up. The industry has accomplished much in water treatment and control, pumping and delivery, but in my judgment is lax in maintaining distribution system cleanliness which would permit the continuous delivery of quality water to the consumer. The reasons for this are many. Cost, no doubt, is the chief deterrent.

The limits for the consumer characteristics of water as set forth by the task group are not “blue sky” objectives. They are obtainable within the current knowledge and skills of our profession. Like everyone else, the water industry must set its goals or targets and then sell them to the people. This can be accomplished and at not too great a cost. To do less is unthinkable. Water utilities provide a service, and their only objective for the future must be “better service.”

The water industry must keep up with an advancing civilization. It can do its share by improving its service to the people by supplying quality water.
CORROSION PHENOMENA, CAUSES AND CURES

T. E. Larson

Corrosion is a phenomenon associated with a metal and its environment. For the purpose of this discussion, the environment will be water, generally of domestic quality. Corrosion takes place when a metal dissolves in water. In fact, water must be present in almost all instances for metals to corrode, even if the chief environment is other than water. A second step in the process may be the deposition of the oxide of the metal at the corrosion site. Other metallic compounds such as carbonates or hydrated oxides may also deposit. These second-step products develop particularly when the water contains dissolved oxygen.

It is nature’s tendency for a metal to corrode and thus to revert to its native stable state as an oxide. However, due to differences in the mineral and gas contents of water supplies, some waters promote the solution of metal more rapidly than others. Others may help to develop a protective mineral or an oxide layer against continued corrosion.

Waters which generally permit corrosion are called corrosive, and waters in which the metal does not corrode are called noncorrosive or protective.

To add a degree of clarification (and perhaps, confusion) different metals have different tendencies to corrode or not to corrode with the same water. One type of water may be corrosive to one metal, but for a water of another quality, the reverse might be true. It is therefore difficult to make generalizations which are always true.

Physical factors which affect corrosion and corrosion control are temperature, velocity of water movement over the metal, changes in direction and velocity of flow, and contact with a second metal or nonmetal.

At the risk of over-generalization, several conditions usually hold true: Higher temperatures cause higher corrosion rates. Higher velocities generally increase corrosion rates. Wet contact with a second metal causes corrosion of one or the other. Notable exceptions and reversals of these will be pointed out later in this discussion. All are intimately associated with the mineral and gas composition of the water.

It is generally accepted that corrosion results from the flow of electric current between electrodes or anodic and cathodic areas on the metal surface. These areas may be microscopic and in very close proximity, thereby causing generally uniform corrosion and often “red” water; or they may be large and somewhat remote from one another and cause pitting, with or without tuberculation. Electrode areas may be induced by various conditions; some by the characteristics of the metal and some by the character of the water at the boundary surface. Especially significant are variations in the composition of the metal or the water from point to point on the contact surface. Impurities in the metal, sediment accumulations, adherent bacterial slime, accumulations of the products of corrosion all are related either directly or indirectly to the development of electrode areas for corrosion circuits.

In almost all forms of pipe corrosion, the metal goes into solution at the anode areas. Because a movement of electrons occurs when the metal dissolves, the metal develops an electric potential. Electrons liberated at these areas flow through the metal to the cathode areas where they become involved in another chemical reaction and the metal develops another electric potential. Control of corrosion by water treatment methods aims at retarding either or both of the primary electrode reactions.

Because electric currents are carried by ions as conductors in water, and because these ions affect the potentials at both the anode and cathode, some discussion of the soluble components in water is warranted.

To some extent, almost all mineral salts dissolve in water; from insignificant traces to gross concentrations exceeding that of salt in sea water. On solution, these salts separate into two types of ions, anions and cations. These ions have opposite electric charges and are kept apart by the water itself.
These ions are responsible for the ability of “water” to conduct an electric current. Pure water has relatively few ions. Only one one-hundred thousandth of one percent of water separates into hydrogen cations and hydroxyl anions. Therefore, pure water, free from mineral salts, has very little capacity for carrying electric current. Its electric conductivity therefore, is extremely low.

However, when minerals are dissolved in water, the resultant ions provide the necessary conductivity to permit the corrosion current to flow, with negatively charged anions moving to the anode and positively charged cations moving to the cathode. Their accumulation at the respective electrodes is limited by other reactions which take place at these points.

The basic electrode reactions involving the transfer of electrons may be represented as follows:

Anode: \[ \text{Fe} - 2e \rightarrow \text{Fe}^{2+} \]

Cathode: \[ 2e + 2\text{H}_2\text{O} \rightarrow \text{H}_2 + 2\text{OH}^- \]

When dissolved oxygen is present, the cathode reaction may be represented as cathode: \[ 2e + \text{H}_2\text{O} + \frac{1}{2} \text{O}_2 \rightarrow 2\text{OH}^- \]. Therefore, with or without dissolved oxygen the same amount of hydroxyl ion is formed at the cathode and an alkaline condition prevails.

The effect of dissolved oxygen is felt in a critical way at the anode where the following side reactions can take place.

\[ 2\text{Fe}^{2+} + \text{H}_2\text{O} + \frac{1}{2} \text{O}_2 \rightarrow 2\text{Fe}^{3+} + 2\text{OH}^- \]

The ferrous \((\text{Fe}^{2+})\) iron is oxidized to the ferric \((\text{Fe}^{3+})\) state and reacts with water (hydrolyses) to precipitate the insoluble ferric hydroxide.

\[ \text{Fe}^{3+} + 3\text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3 + 3\text{H}^+ \]

The over-all result is the formation of hydrogen ions which maintain a condition of acidity at this point.

\[ 2\text{Fe}^{3+} + 5\text{H}_2\text{O} + \frac{1}{2} \text{O}_2 \rightarrow 2\text{Fe(OH)}_3 + 4\text{H}^+ \]

The acidity at this point increases the solution rate of iron and maintains a high potential difference between the anode and cathode areas.

The corrosion rate is limited somewhat by the barrier of porous ferric hydroxide at the anode and the accumulation of hydroxide ions at the cathode. It may be further limited by deposition of a dense calcium carbonate deposit at the cathode area. This occurs with waters containing significant concentrations of carbonate hardness.

The corrosion rate is also limited by the diffusion rate of dissolved oxygen to the anode corrosion product. The greater the dissolved oxygen concentrations, the greater will be its rate of diffusion. In a like manner, the greater the velocity of water past the anode, the greater will be the rate at which dissolved oxygen is brought to the anode corrosion products. The net result of oxygen delivered to the anodic area is to increase corrosion rates.

On the other hand, dissolved oxygen does not affect the alkaline condition at the cathode, but greater velocity of water flow and greater concentrations of calcium and bicarbonate as well as carbonate ions increase the rate at which these are brought to the hydroxyl ion concentration developed at the cathode. The net reaction with hydroxyl ions is as follows: \[ \text{Ca}^{2+} + \text{HCO}_3^- + \text{OH}^- \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \] and the net result is to provide a cement-like barrier that reduces the corrosion rate.

This brief summary does not include discussion of many other factors, such as relative conductivity of ions, relative potential of different metals, the effect of hydrogen or hydroxyl ions on these potentials, polarization, and the diffusion of anions and cations. It is evident, however, that the primary and secondary reactions offer a highly complex set of mechanisms which are interrelated and dependent to a great extent on the mineral and gas content of the water.

Iron has been used as the example metal. With notable variations, similar mechanisms and reactions are involved with other metals. Because of these variations, all metals do not corrode equally with each water.

Steel has excellent structural properties and, where possible, is used extensively in the water industry. However, experience has usually dictated that protective measures be used when steel is exposed in a water environment. In some instances, severe chemical treatment is constituted for coatings when the water is not used for domestic purposes. Steel pipe and other steel containers are seldom used for water distribution systems or household or industrial water uses without protective coatings of zinc (galvanized iron), cement, enamel, paint, or heavy bituminous or coal tar. Such coatings are necessary not only to reduce corrosion and the loss of structural strength but also to avoid rust and “red water” problems. Coatings, however, must be complete and continuous to be entirely effective.

Hazardous corrosion conditions can develop at holidays in the coatings, at joints, or other expo-
sures of bare metal. The effect of water quality is noted at these points, and the results are of great concern. The degree of corrosion hazard is, to a considerable extent, dependent on the water quality.

**GENERAL CLASSIFICATION BY WATER QUALITY**

The following classification of waters considers the mineral content, dissolved oxygen, and pH (acidity) relative to the effect on the corrosion of mild steel.*


**No Minerals — Dissolved Oxygen Present.** In the absence of minerals, increasing pH decreases corrosion rates by water containing dissolved oxygen. However, if the pH is near, but not above, that required for complete protection, pitting occurs, which rapidly decreases the useful life of mild steel. Crevices at joints and welds which do not permit oxygen to be maintained at the surface are subject to localized corrosive attack.

Pitting takes place at local unprotected points of corrosion where the corrosion products prevent the diffusion of oxygen to the metal surface, thereby permitting differences in oxygen concentration at the metal surface. Similar pitting can occur under deposits of debris. Also, differences in oxygen concentration, as at the water line of surfaces exposed partly to air and partly to water, will cause pitting. The rate of corrosion increases at higher temperatures.

**No Minerals — Dissolved Oxygen Absent.** In the absence of dissolved oxygen, the pH of “high-purity” water in mild steel containers adjusts itself to about 8.4 and corrosion becomes negligible. However, all natural waters are mineralized to some degree.

**Noncarbonate Minerals — Dissolved Oxygen Present.** In the absence of carbonate minerals, increasing concentrations of other common minerals, such as chloride and sulfate salts, increase the corrosion rate at all pH values below the pitting range of pH, and increase pitting when the pH is just below that required for protection in the presence of dissolved oxygen. Increasing temperature accelerates both general corrosion and pitting.

**Carbonate Minerals (no calcium) — Dissolved Oxygen Present.** Carbonate minerals, indicated by the alkalinity determination for bicarbonates, inhibit corrosion. They act contrary to the accelerating salts of chloride and sulfate in waters containing dissolved oxygen. In the absence of calcium, this inhibition is maximum at pH 6.5 to 7.0 in concentrations above five to ten times the chloride and sulfate salt concentration. It is minimum at pH 8 to 9. At concentrations decreasing below five or ten times the chloride and sulfate salts, corrosion rates increase. Since nearly all natural domestic waters or carbonate minerals contain alkalinity, and in addition usually contain chloride and sulfate salts, this too is a criterion in classification.

**Calcium Salts — Dissolved Oxygen Absent.** From the standpoint of corrosivity, stability as indicated by saturation with calcium carbonate is the most widely accepted criterion in classification. However, for uncoated mild steel, a very significant supersaturation must exist to form a visible deposit. However, even this criterion is not infallible. It has specific limitations:

1. A minimum alkalinity of 50 to 100 mg/l (calculated as CaCO₃) and a minimum of about 50 mg/l (as CaCO₃) calcium must be present at normal temperatures (32° to 160°F) for even a small degree of extended life.

2. The greater the concentrations of calcium and alkalinity, the greater the protective action of the water. However, such increasingly high concentrations are responsible for an additional tendency to deposit objectionable quantities of scale at temperatures above that at which saturation stability is established.

3. The protective action is enhanced by movement of the water and decreases at near-stagnant conditions.

4. The protective action may be nullified at higher temperatures when the pH is high enough to deposit nonprotective magnesium hydroxide.

5. Pitting and tuberculation will occur in the
presence of dissolved oxygen if the stability and velocity are near, but still below that required for complete protection.

(6) The protective action is decreased by increasing proportions of chloride and sulfate salts above a ratio of about 0.1 or 0.2 to 1 with respect to alkalinity. This limitation becomes less significant in the absence of dissolved oxygen.

TYPES OF CORROSION

There are many types of corrosion. Each has its own characteristics and offers clues to the causes and sometimes to the characteristics of the environment. The possible types of control may also be deduced.

Uniform Corrosion is recognized as taking place at a generally equal rate over the surface. The loss in weight is directly proportional to the time of exposure; the rate of corrosion is constant. It is usually associated with acids, or water with a very low pH and very little protective properties. Mild steel corrodes in neutral, low calcium, and low alkalinity salt water at a rather uniform rate.

Pitting Corrosion is nonuniform and more generally observed than uniform corrosion. It occurs in an environment which offers some but not complete protection. The pit develops at a localized anodic point on the surface and continues by virtue of a large cathodic area surrounding the anode. Chloride ions are particularly notorious for their association with this type of corrosion of steel. Even stainless steel is subject to pitting corrosion with relatively high chloride solutions. Pits may be sharp and deep or shallow and broad, and can occur without chlorides. In water containing dissolved oxygen, the oxide corrosion products deposit over the site of the pitting action and form tubercles.

Pitting-type corrosion may also be associated with galvanic corrosion, concentration corrosion, and crevice corrosion.

Galvanic Corrosion is associated with the contact of two different metals or alloys in the same environment. Almost all metals and substances have different solution potentials whether in the same or in different environments. When two metals come together, the difference in potential results in current flow, and one of the metals becomes anodic to the other, which serves as the cathode. The anodic metal corrodes and the cathodic metal does not (or if so, at a relatively low rate). The cathodic metal is said to be protected at the expense of the anodic metal. To be exact, all corrosion is galvanic in the sense that an electrochemical cell is the source of the corrosion current.

The rate of galvanic corrosion is increased by greater differences in potential between the two metals. It is increased by large areas of cathode relative to the area of the anode. It is generally increased by closeness of the two metals, and also by increased mineralization or conductivity of the water.

Galvanic corrosion is often a great source of difficulty when brass, bronze, or copper is in direct contact with aluminum or galvanize, or iron. Copper-bearing metals are cathodic to aluminum, zinc, and iron, and their underwater contact very often results in corrosion of the latter metals. Similarly, mill scale on steel is cathodic to the steel; iron oxide is cathodic to iron; cement is cathodic to copper; carbon is cathodic to iron; iron is cathodic to aluminum; and iron is cathodic to zinc. These are generalizations.

Galvanized (zinc coated) steel is usually more serviceable than steel alone, because the iron exposed at joints and holidays is protected at the expense of the zinc. In general, longer life may be expected with greater thickness of the zinc coating. Zinc in many natural waters containing alkalinity of 50–100 mg/l or more will form an insoluble protective coating of zinc carbonate or zinc hydroxyl carbonate in the pH range of 7.5 to 8.5 at room temperature or lower. In hot water tanks, there is some evidence that zinc becomes cathodic to iron at temperatures above 140° to 160°F with certain types of waters. Traces of copper (0.1 mg/l) in the water can “plate out” on zinc and result in local pitting. Copper-containing waters have a similar, if not more serious, effect on aluminum.

Concentration Cell Corrosion is perhaps the most prevalent type of corrosion. Because it is difficult to ascertain by field measurement, it is usually deduced by inference. It occurs when there are differences in the total or the type of mineralization of the environment. Differences in acidity (pH), metal ion concentration, anion concentration, or dissolved oxygen cause differences in the solution potential of the same metal. Differences in temperatures can also induce differences in the solution potential of the same metal.

It has been previously noted that in water containing dissolved oxygen, the corrosion products
deposit at the anode, and in the secondary reaction of oxidation of ferrous iron to ferric iron and subsequent hydrolysis, hydrogen ions are formed. This greater acidity at the anode results in a hydrogen ion concentration cell at this point and increases the rate of corrosion. In the same instance, dissolved oxygen cannot diffuse or penetrate to the anode surface because it first reacts with the ferrous iron; thus, there is an absence of oxygen at the anode. But oxygen can diffuse to the cathode area and result in an oxygen concentration cell which also increases the rate of corrosion at the point of absence of oxygen. In a like manner, it has been previously noted that hydroxyl ions accumulate at the cathode area. This results in a drastic reduction in hydrogen ion concentration which, therefore, enhances the concentration cell related to the development of hydrogen ions at the anode.

It should be noted that although the dissolved oxygen usually stimulates corrosion, the loss in metal takes place at the anode — "where the dissolved oxygen ain't."

Oxygen concentration cells develop at a water surface exposed to air, and corrosion is accelerated at a level which is a discreet distance below the surface. The dissolved oxygen concentration is replaced by diffusion from air and remains high at and near the surface, but does not replenish as rapidly at lower depths because of the distance. Therefore, the corrosion takes place at a level slightly below the surface rather than at the surface.

Dirt and debris on a metal surface hinder oxygen diffusion by covering the metal at local areas. Thus, corrosion takes place under the deposit.

So, it is evident that any nonadherent deposition on metal can start a chain of circumstances which will result in an oxygen concentration cell.

Corrosion Cure might be classed as a form of concentration corrosion, because, when oxygen is spent on corrosion in a crevice, it is difficult for more oxygen to reach the metal by diffusion into the depths of the crevice. The crack or crevice, or the uneven joint between two surfaces of the same metal bound together face to face, behaves as a pit where oxygen can reach the exposed surface but becomes deficient in the crevice; thus, an oxygen concentration cell is formed and corrosion takes place in the crevice.

There are other types of corrosion, such as desincification of brass, graphitization of cast iron, stress corrosion, corrosion fatigue, erosion corrosion, cavitation, and corrosion caused by stray currents. Their relevance to this discussion is minor.

One other possible factor in corrosion is worthy of mention. This concerns the effect of sulfate reducing bacteria. Corrosion induced by such bacteria is not uncommon on the soil side of pipe but is seldom discussed in connection with internal pipe corrosion. This has been due to the absence of a good test for the organisms and the assumption that the organism would not live in the presence of air or chlorine. This may well be true, but there is mounting data to show the presence of such bacteria in distribution systems. This results from new procedures for their cultivation in water samples.

Their presence may be explained by the fact that the underside of tubercles provides an anaerobic environment with an oxidation-reduction potential (ORP) probably less than —100 m.v., and neither chlorine nor dissolved oxygen can get to them. Their mode of growth is usually ascribed to a reaction of sulfate with organic matter or hydrogen as reducing agents to form H₂S. Recent information suggests that they do not thrive on hydrogen without organic matter. However, hydrogen accelerates growth. Possibly, there should be further exploration to determine if the ferrous ion as a reducing agent accelerates growth. Oxidation and precipitation as magnetite (Fe₃O₄) as well as ferrous sulfide would result in an excess of hydrogen ions to enhance the corrosion rate of iron.

Corrosion Cures

Most of the usual procedures are impractical as cures for internal corrosion of distribution piping. Cathodic protection and metallic coatings are frequently applied procedures. The extent to which alloying can be made effective, as well as commercially competitive, has not yet been proven in the published literature. These methods are rarely, if ever, used for internal protection of pipe.

Cast iron pipe is used extensively in present distribution systems. The following remarks are therefore directed primarily to the use of this material. These remarks must not be quoted out of context and should only be classed as generalizations. Organic coatings such as enamels or tar and bituminous coatings are effective only to the extent of their coverage and durability. The same can be said for the newer organics such as epoxy coatings.
The tar and bitumastic coatings have in many installations, particularly for un-aerated ground water, performed yeoman service but have on occasion failed when used for unstabilized soft surface waters and for some aerated ground waters. Many of these failures could have been prevented by adequate water treatment.

The best general records of success with coatings appear to center around cement linings. Usually these records are dependent on the quality of the water. With hard waters the record is very good, but with very soft waters the record is less enviable. However, for many years bituminous seal coatings have been applied to the cement linings and have met with good to excellent results, again depending upon the coverage and durability.

What is said about cement linings is generally equally true of cement-lined steel and of nonmetallic pipe such as transite. Other nonmetallic pipe, such as plastic, have yet to be made competitive.

The remaining methods for prevention and cure lie in alteration of the environment and in hydraulic design. These two are associated because the design, as related to the velocity of flow, can be a strong factor in the successful application of environmental inhibitors.

By far the most applicable and successful condition for preventing red water and tuberculation is the natural occurrence, or controlled production, of a stable or a supersaturated water with respect to calcium carbonate. This is not always a cure-all. There are limitations. Some of the limiting factors have been mentioned, such as velocity of flow and minimum concentrations of calcium and alkalinity. Protection by a calcium carbonate film or coating must be complete, or tuberculation will occur. Partial protection can be worse than no protection, from the standpoint of carrying capacity, although partial protection may reduce red water to a considerable extent.

A few practical passing comments can be made. For lime-softened waters of low alkalinity and calcium concentrations approaching 50 mg/l, the saturation index may have to be as great as 1.0 to 1.3. At summer temperatures the rate of deposition is greater and may be excessive in the areas close to the treatment plant. The use of a trace (0.25 to 0.5 mg/l) of polyphosphate should be of help under such conditions and should also serve to prevent lime build-up and growth on the sand grains in the filters. Polyphosphate has no effect on the tendency for deposition of magnesium hydroxide.

Open-air reservoirs tend to add CO₂ to the water at the high pH levels (increasingly at pH levels above 8) and to reduce the saturation index. Heavy chlorination for algae control at these reservoirs also tends to reduce the pH and the saturation index. Dead-end difficulties may be overcome by application of caustic or soda ash to the discharge from these reservoirs.

Sulfate-reducing bacteria are of no help. However, too little is known about their manner of growth and their effect in aqueous conditions to know what to do about them. Certainly, organic matter should be absent, if this is their only source of carbon for growth.

Ammonium-oxidizing bacteria convert ammonia in the presence of oxygen to nitrate, thus converting a cation to an anion which results in an increase of hydrogen ions. Again, too little is known about the magnitude of this effect, and proof is absent on the association of these bacteria with corrosion.

Some comment must also be made on the McCaulley procedure for coating metal with calcium carbonate within a few hours after a section of water main has been cleaned. The procedure is sound but delicate and difficult to perform in the field. One factor in Dr. McCaulley’s success is different from field conditions. This concerns the reported application to a clean, sand blasted pipe. Whether this is essential or not has yet to be demonstrated, but it is certain that coating a clean pipe should be easier than coating a tuberculated or partially clean pipe. Also, from the available data, few if any of the McCaulley tests were made at pH less than 8. For such conditions, an effective supersaturation would require several times the amount of alkalinity used to provide the high degree of supersaturation. This of necessity would require that only sodium bicarbonate rather than soda ash be added to obtain the necessary excess. This then requires more chemicals. However, chemical costs are negligible. The solubility of sodium bicarbonate is lower than that of soda ash, and a larger stock solution container (possibly 500 gallons) may be required. Again, however, this should not be an insurmountable objection. This writer believes that further field work with the McCaulley technique is worth while. Aside from cement lining, no other satisfactory in-place protection has been suggested for the many miles of low-capacity pipe now in use, although the need is great. Of course, it is essential that a properly balanced water be used after this type of deposition has been applied.
SOME EXPERIENCES IN SCALE AND CORROSION CONTROL

A. H. ULLRICH 1

IMPORTANCE OF SCALE AND CORROSION CONTROL

In the author’s opinion the four most troublesome and costly results of excessive and uncontrolled corrosion are:

1. Unsightly water, such as red water.
2. A water which stains plumbing fixtures.
3. Failure of mains and consumers’ services, piping, and fixtures.
4. Excessive loss in carrying capacity of mains and consumers’ services and piping.

The most troublesome and costly result of excessive scale formation is, of course, loss in carrying capacity of mains and consumers’ services and piping.

There have been many discussions on the seriousness of these problems, and progress in solving them has been and is being made. However, in order that we may not become too smug with respect to our progress, it is well to remind ourselves that as late as 1955 T. E. Larson1* reported that in many systems the carrying capacity has been reduced by more than 50 per cent through corrosion and precipitation.

Excluding such obvious factors as partially closed valves and other obstructions, the carrying capacity of a given water main is dependent on the smoothness (or roughness) of the inside surface and on the pipe diameter. Both the smoothness of the inside surface and the pipe diameter can be adversely affected by corrosion and by the deposition of material from the water.

Corrosion seldom proceeds at a uniform rate over the entire inside surface of pipe. Uneven or nonuniform corrosion increases the roughness factor and results in reduction of carrying capacity. If the products of corrosion adhere to the interior surfaces of the pipe, as in tuberculation, then the carrying capacity is reduced both because of the resulting roughness and because of a reduction in effective pipe diameter.

Scale formation or the deposition of material on the interior surfaces of pipe will also reduce the effective pipe diameter. If the rate and uniformity of deposition can be controlled so as to result in the formation of a smooth, thin protective coating which materially reduces corrosion, then the benefits far outweigh the probable negligible reduction in pipe diameter. If, however, the uniformity of deposition of incrusting material is not, or cannot, be controlled and the resulting deposit or scale is irregular and rough, then the carrying capacity of the pipe may be seriously impaired even though the deposit is relatively thin.

EXPERIENCES IN CORROSION CONTROL

The author’s earliest responsible experience in water treatment dates back to the late nineteen-twenties when he assumed the position of chemical engineer with the Fort Smith, Arkansas Water Department. At that time, Fort Smith used the Poteau River for its source of supply. This water had an average bicarbonate hardness of about 75 parts per million, a reasonably low sulfate hardness, and a total dissolved solids content of less than 150 parts per million. While turbidities were sometimes quite high, the raw water was generally of good quality and not too difficult to treat. Treatment consisted of coagulation with alum and lime, sedimentation, filtration, and chlorination. No particular difficulties were experienced except from occasional saline and very turbid backwaters from the Arkansas River and from infrequent discharges of acid mine water from coal mines in the drainage area. There were few complaints from red water or from corrosion of consumer piping. There was, of course, some tuberculation in cast iron mains, but this was accepted as something you had to live with. It was also believed, perhaps with some justification,2* that chemically treated water (other than lime-softened water) is, by nature, more corrosive than the same water in its natural, untreated state.

While the normal Poteau River water was of good quality, acid mine water discharges in the
The empounded Clear Creek water is a very soft water. It has a total bicarbonate hardness of the order of 15 mg/l and a total dissolved solids content of only about 50 mg/l. The pH range of the raw water varies from about 6.8 to about 7.1. The dissolved oxygen at or near the surface of the lake is near the saturation point. At depths greater than 37 feet the dissolved oxygen may be as much as 50 to 75 per cent of saturation. The raw water contains traces of manganese, more being present near the bottom of the lake than at the surface. The greater part of the drainage area is wooded so there are infrequent periods of high turbidity.

The original Clear Creek project included an empounding reservoir, a modern treatment plant, and a gravity pipe line into town. Treatment facilities were provided for coagulation with alum and lime, flocculation, sedimentation, filtration, and chlorination and ammoniation. Facilities were also provided for use of activated carbon, if needed, for seasonal taste and odor control.

No particular problem in the treatment of the Clear Creek water was anticipated. It was thought that the water would respond well to coagulation with alum and that any possible corrosion problem could be solved by a slight adjustment of the pH at the time of coagulation. However, it was soon found that the optimum pH for coagulating with alum was somewhat below pH 7.0 and that the range of satisfactory coagulation was exceedingly narrow. Due to the almost complete absence of buffering action, a slight change in either the alum or lime feed would result in the loss of floe or in the formation of pin point floe. Since no good means had been provided for adjusting the pH of the filtered water, we started treatment by coagulating with alum at a pH of 7.0 to 7.2.

As might be guessed, we started receiving red water complaints soon after the soft, high dissolved oxygen content water reached our distribution system. We knew that part of the trouble was caused by the disintegration of old rust deposits in the mains and that part of it was due to a reversal of flow in the mains, but we also soon recognized the fact that we were faced with a rather severe corrosion problem. Red water from galvanized tank hot water heaters became especially troublesome, and failure of new galvanized tank hot water heaters began to be reported within eighteen months after the change to the new supply.

Our first attempt at corrosion control was a reduction in the chlorine dosage. We had been treating to a chloramine residual of about 0.6 mg/l in the filtered water. Since we practiced prechlorination and preammoniation, we found that a safe water could be produced by maintaining a chloramine residual of only 0.35 mg/l in the filtered water and only about 0.1 mg/l in the distribution system. While this did not solve the corrosion problem, we did notice a definite reduction in red water complaints.

Our second attempt at corrosion control involved pH adjustment. We started experimenting with chlorinated copperas for coagulation but, fortunately, Monsanto Chemical Company’s ferric sulfate, Ferrisol, was placed on the market about this time and we immediately began converting to its use. We found that the optimum coagulation pH for it was about 6.7 and that it had a much wider satisfactory coagulation pH range than did alum. We also found that we could coagulate at pH 6.7 and then add a second dose of lime at the end of flocculation, but prior to settling, without damaging the floe. Finding this simple method of adjusting the pH led us to adjust to the then much publicized calcium carbonate stability point which, for the Clear Creek water, was about pH 9.2. The adjustment to this higher pH resulted in a new wave of red water complaints, but these subsided after the distribution system became stabilized to the new treatment.

We continued the higher pH adjustment until the author noticed that small, whitish “blisters” were forming on the exterior of the galvanized piping of the Bayliss type surface filter washing system which we had installed. On examination of the material in the blisters we found it to be zinc oxide or zinc hydroxide and we came to the sudden, unpleasant realization that the high pH water, instead of leaching down a deposit of calcium carbonate, was actually removing the zinc from galvanized surfaces. The reason was simple. In order to deposit a protective film of calcium carbonate by pH adjustment, the water must contain sufficient calcium and carbonate or bicarbonate. The Clear Creek water did not contain enough of either calcium or carbonate ions.

It was, of course, realized that removal of zinc
EXPERIENCES IN SCALE CONTROL

The author returned to Austin, Texas, late in 1947 to assume charge of the water and sewage treatment plants. Austin had been lime softening Colorado River water since 1925. The practice had been to soften to such a degree that twice the phenolphthalein alkalinity of the filtered water would be a little less than, or equal to, its methyl orange alkalinity. The filters were used for partial stabilization but a slight supersaturation of calcium carbonate remained in the filtered water. Although there had been talk from time to time that perhaps recarbonation should be started, conditions did not seem to warrant the added trouble and expense. Corrosion was definitely not a problem and, while some loss in the carrying capacity of the mains was recognized, this also did not appear to be a serious problem. Because of this excellent history of the system it was the author’s decision to continue the same general method of treatment.

The author’s belief that, for Austin’s water supply the partial stabilization achieved by passage of the softened water through the filters was adequate, was further strengthened in 1950 when some experiences in scale and corrosion control

planned changes in the plant necessitated removal of a section of 24-inch cast iron wash water line which had been in service since 1925 and a section of a 20-inch cast iron high service pump discharge line which had been in service since 1936. Inspection of these lines showed each to have a very thin, dense and smooth calcium carbonate coating—approximately the thickness and smoothness of an egg shell. There was no evidence of corrosion and the film of calcium carbonate appeared to be as near perfect as one could wish. For this reason and perhaps because everyone was too busy with the post World War II expansion program, it was not until 1953 when flow measurements were made on a three-year-old 30-inch steel cylinder concrete trunk main that serious trouble came to our attention. These measurements showed a pronounced loss in carrying capacity. On opening the main for inspection it was found that the calcium carbonate film was thicker than desired and very rough. One of our men described it as being “saw toothed” and I could think of no better way to describe it. An interesting but disturbing observation was that the “teeth” all pointed into the direction of the flow of water. Another observation was that the deposit was roughest in the upper half of the main.

After inspection of the almost new 30-inch trunk main, consideration was immediately given to recarbonation ahead of filtration or to further stabilize the already partially stabilized filtered water with sodium hexametaphosphate. Stabilization with sodium hexametaphosphate was finally chosen because of the ease with which dosages could be controlled and because of the possibility that this treatment would slowly remove the sharp “teeth” from the existing rough films, prevent the formation of additional rough deposits, and give more uniform protection to the entire distribution system.

The use of sodium hexametaphosphate was started in 1954. A dosage of 2.0 mg/l was used for about three months. After this period the dosage was reduced to 1.0 mg/l. Subsequent inspections of the 30-inch trunk main have shown a continuing removal of the calcium carbonate deposit. Inspections of a 42-inch trunk main which was installed in 1954, shortly before the sodium hexametaphosphate treatment was started, has shown no appreciable film formation. Flow measurements on both the 30-inch steel cylinder concrete trunk main and from galvanized surfaces would increase rather than decrease the corrosiveness of the water to customers’ galvanized piping and hot water heaters, so we reduced the pH without delay. Subsequent laboratory tests and field experience indicated that adjustment to pH 8.8 would be safe and thereafter we maintained the finished water pH between the limits of pH 8.5 and pH 8.8.

Treatment to low chloramine residuals and secondary lime treatment to pH 8.5 to 8.8 solved the red water problems but did not solve excessive galvanized tank hot water heater failures. Examination of a number of galvanized tank heaters showed that they contained uninsulated tin cold water down pipes and some of them contained uninsulated brass fitted thermostats. It was quickly proven that the excessive corrosion was caused by galvanic action and that the “good mountain water” just did not contain sufficient calcium carbonate (hardness) to deposit a protective scale as had been the case with the former Poteau River water. Since “glass” lined heaters were still very new, customers were advised to install monel metal or copper lined heaters or protect their galvanized tank heaters with the slowly soluble sodium hexametaphosphate, Micromet.
on older cast iron mains have shown a continuing improvement in the carrying capacity of the mains under observation. Since the use of sodium hexametaphosphate there has also been a pronounced improvement in meter maintenance. Prior to the use of this treatment we had frequent meter stoppages due to calcium carbonate deposition. Now stoppages from this cause are unknown and considerably less time is required for meter cleaning and repair.

When we started the use of sodium hexametaphosphate we anticipated that the treatment would first blunt the sharp “teeth” of the calcium carbonate films. This has been the case in some mains while in other mains removal of the film seems to be at a greater rate in the areas between the “teeth” than from the “teeth.” When the latter occurs some of the “teeth” eventually break off during peak flows and appear in consumers’ fixtures as “sand.” Complaints about this so-called “sand” have not been a problem, but we believe that a much faster rate of removal of the incrustation could pose a problem.

From the above discussion it might appear that all of our older mains have or have had an excessively rough incrustation. Contrary to this, in perhaps the greater percentage of our mains, the deposit has been quite smooth. We do not know why there should be a difference in this roughness factor in different mains. However, we have observed that usually the deposit is rough and irregular only in those mains which carry water at high velocities.

While the sodium hexametaphosphate treatment has definitely given us relief we are still not entirely satisfied with it. For example, we believe that if we could remove more of the supersaturation, either during coagulation and settling or in the filters, the sodium hexametaphosphate would be more effective. This could result in a lower sodium hexametaphosphate dosage requirement. As yet, we are not even certain that our dosage of 1.0 mg/l is the best dosage to use with our particular water. Unfortunately, as is true with many water utilities, we are long on ideas but short on time and personnel and we find it impossible to engage in extensive experimental and research work.

CONCLUSIONS

From his experiences in treating various types of water and from a study of the literature, the author has reached the following general conclusions:

1. Cast iron, steel (except stainless steel), and wrought iron all have a pronounced tendency to corrode in water.

2. All waters have a tendency to corrode iron. This tendency is greatest in acid or low pH waters and lowest in alkaline or high pH waters. In the treatment of very soft waters the pH cannot ordinarily be increased sufficiently to give good protection by pH adjustment alone.

3. Free carbon dioxide and other acids increase corrosion both by increasing the corroding tendency of iron and, in some instances, by destroying protective coatings.

4. High pH waters reduce the corroding tendency, but if the pH is excessively high, it may be destructive to protective coatings such as galvanizing and thereby actually increase corrosion in systems utilizing galvanized pipe, hot water heaters, etc.

5. Dissolved oxygen or other oxidizing agents must be present in any except acid waters to support continuing corrosion. Also, the rate of corrosion is dependent on the oxygen concentration and on the rate at which it is replenished. Very acid waters may support continuing corrosion in the absence of dissolved oxygen.

6. Excessive chlorine residuals may increase the corrosiveness of already corrosive water.

7. High temperatures, other conditions remaining the same, will increase the rate of corrosion.

8. High water velocities increase the rate of oxygen replenishment and therefore tend to increase the rate of corrosion.

9. In concentrations as found in potable waters, corrosion usually increases with increases in concentrations of chlorides and sulfates.

10. The composition and physical nature of iron rust may be influenced by the mineral content of the water, particularly the calcium and magnesium bicarbonates and silica. If present in sufficient concentrations, these substances may combine with the oxidized iron to form dense, adhering and fairly impervious coatings. A loose coating favors a high corrosion rate while a dense coating favors a lower corrosion rate. It is probably for this reason that soft waters are generally more corrosive than hard waters.

11. Dissimilar metals in contact with each
other and with water will cause corrosion by galvanic action.

(12) At atmospheric temperatures, iron will not corrode in the absence of water or moisture, nor in the absence of oxygen. Therefore, if we can provide a coating which will prevent water and oxygen from reaching the iron surface we can protect iron.

(13) Waters which contain sufficient calcium bicarbonate may be treated with lime so as to deposit a protective film of calcium carbonate.

(14) Lime softening of waters high in calcium bicarbonate can be employed, not only for softening the water but also to deposit a protective film of calcium carbonate on the inside surfaces of water systems. Deposition of the film must, however, be controlled to assure that it is smooth, thin, and dense. Irregular or rough deposits will seriously lower the carrying capacity of mains and piping.

(15) Judicious treatment with sodium hexametaphosphate may be useful in reducing the corrosiveness of certain waters. Sodium hexametaphosphate may also be useful in the prevention of irregular and rough calcium carbonate deposits from unstabilized lime softened water.

REFERENCES


MANGANESE, IRON, AND COPPER PROBLEMS IN WATER SUPPLIES

JOHN C. KEARNS

With the possible exception of tastes and odors, the three elements which compose the title of this paper are responsible for more quality complaints from water consumers than are any other substances. Red and black water problems associated with iron and manganese are the source of numerous complaints, and the blue-greenish stains resulting from copper corrosion are far too common today to be passed over lightly.

In reviewing the records of over 95 water systems which make up the operating subsidiaries of the American Water Works Company, it is revealing to note that all three of these elements have been a factor of concern at one time or another in over 90 per cent of these facilities. It is also interesting to note that, from a problem standpoint, manganese ranks as the most troublesome, iron as the most frequent in occurrence, and copper as the most difficult to classify. All three are a distinct hazard to good public relations. The remarks which follow will attempt to point out a few of the experiences that we have encountered in recent years which have been directly related to the presence of these undesirable substances in a public water supply.

MANGANESE

In chemical behavior, and in its occurrence in natural waters, manganese resembles iron. Manganese is, however, much less abundant. As a result, the concentration of manganese in water generally is much less than that of iron, and manganese determinations are often omitted from water analysis. While the necessity for determining manganese is slowly being recognized, the main deficiency in published records remains, as always, insufficient analysis for manganese in the various raw waters used for public water supplies. An important reason for this oversight is the fact that people have too often taken it for granted that iron and manganese are very similar. Had the two substances been initially regarded as dissimilar, and, had it been recognized that manganese, even when present in minute quantities, is a much more troublesome substance than iron, the problems attendant to manganese removal might have been solved long ago. The reason why manganese is often overlooked is because of its reluctance to precipitate from solution and its consequent delayed appearance in the water distribution system. In contrast to iron, manganese rarely makes its presence immediately known in the system. Its deposition depends upon the formation of manganese dioxide. Once a coating of this oxide is formed, further deposition of additional manganese proceeds at a rapid rate and often causes serious problems in the water system.

The presence of manganese is objectionable in water because it gives rise to complaints of discoloration, turbidity, deposits, and taste. Ordinarily, manganese is seldom present in natural waters in concentrations above 1 mg/l inasmuch as the carbonate and hydroxide forms are only sparingly soluble and it is more common in ground water than in surface water. For domestic water supplies, a maximum concentration of manganese as low as 0.017 mg/l has been recommended. Concentrations as low as 0.1 mg/l are reported to cause laundry trouble. Values in excess of this amount will usually give rise to consumer complaints. The latest U.S.P.H.S. Drinking Water Standards recommend a limiting concentration of 0.05 mg/l manganese. Our experience points very strongly to the conclusion that, to avoid complaints entirely, the manganese content of the finished water should be reduced to 0.05 mg/l or less.

The manganese found in water is probably most often the result of the solution of the element from soils and sediment aided by bacteria or complexing with organic materials. In some areas, manganese occurs in sediment carried by streams; when such sediment eventually deposits in a reservoir, it may yield manganese to the water in storage. This process is doubtlessly aided by the organic matter
present in the sediment and by bacterial action. Because of this effect, water supplies obtained from impounding reservoirs are likely to experience difficulty from manganese at certain seasons of the year. Manganese concentrations above 1 mg/l are usually associated with streams receiving substantial amounts of acid mine wastes. Occasionally, industrial waste disposal may add manganese to water.

The influence of microorganisms on problems involving manganese, as well as iron, can be illustrated by a condition which existed for many years in the major water supply of Richmond, Indiana. There, over the past fifty years or more, the water supply was derived entirely from underground sources through the development of wells, springs, and a series of infiltration galleries. The water was characteristic of the region, being rather highly mineralized but showing no discernible amounts of either manganese or iron. Chemical treatment consisted solely of chlorination, applied in low dosages to the combined sources as they entered a collecting basin prior to being pumped to the distribution system. Periodically, an outbreak of consumer complaints would arise and as quickly subside. The blame for these disturbances was always placed upon an abnormal usage of water in the affected area created by a fire, the use of hydrants for street flushing, or to the flushing of mains at an improper hour of the day. An open storage reservoir on the system would occasionally become suspect when a particularly irate consumer produced a bottle of the fouled water containing debris assumed to have originated in the reservoir. Around 1955, problems of dirty water seemed to center on a dairy processing plant which began producing cottage cheese. After suffering the loss of his product a few times, the plant manager delivered evidence of his problem to the water company. This evidence, when placed under analysis, revealed a high percentage of manganese as well as some iron. Up to this time, manganese had never been mentioned as a contributor to the problem. The exasperating experience of this plant in producing a marketable quality of cottage cheese provided an interesting clue. Subsequently, a drought period, coinciding with a high summer water demand, brought on more frequent complaints of black water that became more widespread. An investigation to locate the source of the problem was intensified by the water company. The suggestion by the writer that bacterial action might be the cause and that relief could be secured by installing filters to strain the suspended material from the water received no favorable response. Finally, during the course of draining the collecting well at the pumping station, slime growths were observed on the walls. It was also noted that patches of fibrous material had entered the well through cracks in the wall. The plant was surrounded by a large number of trees of various kinds which gave the area the pleasing appearance of a park. Having assured themselves that the fibrous material was actually tree roots and ignoring the evidence of the slime growth, the water company cut down the trees. Fortunately, before the property was entirely cleared of trees, the writer again had an opportunity to look at the problem and this time was successful in obtaining a slime sample from one of the galleries. A microscopic examination confirmed a long held suspicion that the culprit was a form of bacteria known to feed on manganese and iron. It was tentatively identified as Clonothrix polyspora. Further investigation indicated that only the infiltration galleries were affected and attempts were made to treat them by the use of heavy dosages of both copper sulfate and chlorine. The treatment proved to be only partially effective due to the inability to locate the uppermost ends of the system for the application of chemical treatment. However, the finding of a more plausible cause for the problem, plus the remorse felt over the loss of the trees, resulted in the installation of a gravity filtering system. Complaints ceased almost immediately following the installation of filters. Chlorine remains the only chemical additive and is now applied immediately ahead of the filters. In 1960 a study of the offending organism by Professor Wolfe of the University of Illinois resulted in its further identification as Clonothrix putalis. *

An example of the failure to fully evaluate the treatment requirements, particularly insofar as they apply to manganese in the development of a new source of water supply, is afforded by the experience of a plant in Virginia. In 1950 this company abandoned its previous source and moved to another watershed about twenty miles away. Operations began in the fall of 1950 without difficulty, but by late December it was quite evident

that the new source of supply contained manganese. The first indication was the appearance of black specks in the water trays of the chlorinators followed quickly by a noticeable staining of the walls and floor of the clear well. The plant had not been designed for the removal of manganese. Equipment for break-point chlorination was lacking and pH adjustment could be applied only to the raw water and to the treated water following filtration. Since color removal was also a problem, coagulation had to be carried out at a pH value below about 6.3 with both lime and chlorine being applied following filtration. This treatment permitted the oxidation of manganese to take place entirely after processing. Like so many surface supplies containing manganese, the problem was seasonal and was more or less indirectly related to the stream flow with concentrations ranging from 0.01 to 0.3 mg/l. Despite the most careful control of the available chemical facilities, the manganese problem, as gaged by consumer complaints, showed a continual increase in magnitude. Considerable effort was spent in seeking a solution to the problem. This finally led in 1957 to the adoption of superchlorination of the raw water to maintain a chlorine residual in excess of 1 mg/l through the filtration stage, followed after filtration by dechlorination. This treatment has proved to be quite effective despite the fact that, after its introduction, a high dam was constructed across the stream which created a large impounding reservoir which modified the former seasonal pattern of manganese concentrations and increased the range to over 2 mg/l. Despite this change, as well as occasional periods of color values up to 150 mg/l, the finished water delivered from this plant today rarely contains color above 2 mg/l and the manganese content is always below 0.01 mg/l.

The removal of manganese in the water purification process presents a more difficult problem than does iron because the oxidation proceeds much slower. This almost always results in the removal taking place entirely within the filters and leads to eventual fouling of the filter media. Deposition becomes even more serious where manganese removal must be effected at high pH because of the additional build-up of carbonates which in time cause the media to become coated until it is no longer effective for the removal of fine precipitates. For many years, the treatment of Ohio River water at Huntington, West Virginia, did not concern itself with manganese. In time, the frequency of black water complaints increased to the level where they could no longer be ignored. The dosage of lime for pH adjustment was then changed from the clear well to application immediately ahead of the filters. This change made a noticeable improvement in the complaint situation. However, it did not entirely eliminate manganese from the finished water because dosage control of lime is difficult and operations were unable to maintain the required pH level. The change in lime application did result in the filter media becoming so heavily incrusted with deposits of manganese and carbonates that all of the sand had to be replaced after a service period of about eight years. A study of the problem was undertaken in 1957 in which consideration was first given to break-point chlorination. This proved to be impractical from an operating standpoint because of the widely varying chlorine demand of the raw water. It was reasoned that, if coagulation and settling could take place at a high pH level of 9.2 to 9.4 rather than the then in use pH value of 6.8, all chemicals could be applied to the raw water as it entered the plant. This would afford a longer reaction time at the optimum pH and would greatly lessen the load on the filters. In 1959 this change was made by substituting ferric sulfate for alum and moving the lime application to the raw water. Almost at once improved clarification was noted, with lengthened filter runs and the absence of any trace of either manganese or iron in the finished water. Since this change was made, there have been no further outbreaks of black water, nor further consumer complaints of stained laundry or discolored sanitary fixtures. In 1962 a further change in treatment was made by the discontinuance of activated carbon in favor of potassium permanganate. This change was dictated by the need to further improve upon a taste and odor problem of long standing. Despite the progress made in a most active clean-up program of Ohio River pollution during the past five or more years, Huntington has found it necessary to continually increase its dosage of carbon to the point where this chemical amounted to over 70 per cent of the total chemical cost of treatment. At the same time consumer agitation mounted to the point where public relations were far worse than they had previously been in the black water days. Since the change to potassium permanga-
The presence of iron in water supplies is a more common problem than is manganese. Iron is not only one of the most abundant constituents of rocks and soils but it has also been the favored metal for water piping. In evaluating the desirability of a particular water supply for domestic and industrial use, it is very important to know not only the amount of iron that is present in the water but also the form in which it is present. Many times in the past, one or both of these determinations was overlooked when a new supply source was being developed. Later, and at considerably more expense, the water purveyor was compelled to correct for his initial oversight. Today, largely as a result of improvements in water-using household appliances, the water industry is facing up to increasing public demand for a higher quality product. This demand has been strengthened by the latest revision of the U.S.P.H.S. Drinking Water Standards which no longer combine iron and manganese together, and thus properly assign limiting concentrations to each substance. Our experience with iron problems indicates that a further reduction in the suggested limit of this element may be advisable in the future to a value perhaps as low as 0.1 mg/l.

Iron occurs in water at two levels of oxidation, either as bivalent ferrous iron or as trivalent ferric iron. The chemical behavior of the two forms is somewhat different, although both may be present in the same water under certain circumstances. Under reducing conditions, iron in water will tend to be in the ferrous state. However, the ferrous salts are unstable in the presence of oxygen or air. These salts are changed to the ferric state through oxidation when natural water is exposed to the atmosphere. The chemistry of iron is further complicated by a tendency for the formation of complex ions and is influenced by certain kinds of microorganisms.

Complaints generally result when the water reaching the consumer contains iron in excess of 0.5 mg/l. At this concentration, the water will leave an unsightly ring on the bath tub, stains on porcelain or enameled fixtures, and will make laundering extremely difficult due to the discoloration imparted to clothing. Commonly termed “red water,” the problem may be caused by allowing an iron-bearing water to enter the distribution system untreated or with insufficient or incorrect treatment. On the other hand, the cause is not infrequently created by an originally iron-free water entering a system where, because of its aggressive character, it attacks unlined cast iron and
steel pipe lines taking up iron which eventually arrives at the consumer's tap.

Red water troubles due to corrosion can normally be controlled effectively by raising the pH of the water with alkali treatment at the source point to a value equal to or slightly in excess of its calcium carbonate equilibrium point. The use of a polyphosphate compound may also be employed quite successfully. Because of the ease and control of their application, many corrosive water supplies are treated with such compounds. Our experiences with polyphosphates have indicated no hard and fast rule of application that will assure success in every case, except that the treatment should not be attempted on water which contains oxidized or partially oxidized iron. However, we have installations in operation today where the former aggressive nature of the water supply is effectively suppressed, both with and without pH correction, down to a pH value of about 6.0. From an economic standpoint, lime is the chemical for pH correction. Lime is also the most effective alkali in most instances. However it does have drawbacks, that is, its application will increase the hardness of the water so treated and because of its limited solubility, it is more difficult to accurately control its dosages and to maintain the feeding facilities. Soda ash, as well as caustic soda, finds extensive usage in the treatment for pH correction. Caustic soda in liquid form is now generally available in both drums and tank truck lots. In this form it deserves more consideration because of its adaptability to automatic metered control.

Over the years, we have encountered several cases where red water conditions arose following the installation of an iron-removal plant. In one such instance, a treatment plant was placed in service following a long period of distributing an iron-bearing well water. Consumer complaints of red water persisted for well over a year in this system after iron-removal treatment was started. In a more recent case, complaints due to iron actually increased for a time following the introduction of iron-removal treatment. In this case, the urgent need for additional water caused the new well supply to be placed in service a few months in advance of the iron removal facilities. Table 1 illustrates the conditions encountered in this particular system. The pH values for these samples are higher than those usually reported in the literature as causing staining; yet this water was the cause of considerable trouble. It was attributed mainly to the water being in contact with old iron rust deposits in the water mains. However, as the problem unfolded during the course of the investigation, it became apparent that a portion of the difficulty resulted from a lack of uniform chemical treatment with the equipment originally provided. Dry feed of hydrated lime was first employed for pH adjustment. This was followed later by a change to soda ash. The problem was finally corrected by resorting to an application of liquid caustic soda and a temporary use of a polyphosphate compound for a period of six months.

The influence of iron pick-up in a distribution system is further illustrated by the results shown in Table 2 of sampling from a portion of the Alexandria, Virginia, water distribution system. This particular area comprises the oldest portion of the distribution system, with piping entirely of cast iron, largely unlined, and with some having more than a century of continuous service. The pH of the water delivered to the entire system from a single point of production has, over the past ten or more years, been maintained at a value of about 7.0. This has been the case not because it is proper but rather because of the inability of treatment to raise the pH higher with lime without creating a subsequent turbidity problem. Every attempt to add sufficient lime in the past to elevate the pH to a more desirable level of 7.8 to 8.0 has caused the water to take on a distinct and quite noticeable cloudy appearance identified by complainants as "white water." During 1957 an opportunity was afforded to determine the effect of pH on iron pick-up in this particular section of the system while investigations were being carried out on the economic feasibility of using either soda ash or

### Table 1

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Station</th>
<th>1/2 Mile from Station</th>
<th>1/2 Mile from Station</th>
<th>3/4 Mile from Station</th>
<th>1/2 Mile from Station</th>
<th>3/4 Mile from Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>Average</td>
<td>8.1</td>
<td>7.4</td>
<td>7.3</td>
<td>7.7</td>
<td>7.5</td>
</tr>
<tr>
<td>Total Alk.</td>
<td></td>
<td>150</td>
<td>140</td>
<td>146</td>
<td>144</td>
<td>140</td>
</tr>
<tr>
<td>Iron as Fe</td>
<td></td>
<td>0.05</td>
<td>0.8</td>
<td>0.5</td>
<td>0.4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Plant</th>
<th>Tap A</th>
<th>Tap B</th>
<th>Tap C</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/30</td>
<td></td>
<td>7/30</td>
<td>7/26</td>
<td>7/30</td>
<td>7/26</td>
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<tr>
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<td></td>
<td>7/30</td>
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<td>7/30</td>
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<tr>
<td>8/5</td>
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<td>8/5</td>
</tr>
<tr>
<td>pH</td>
<td>7.1</td>
<td>7.9</td>
<td>6.7</td>
<td>7.9</td>
<td>6.8</td>
</tr>
<tr>
<td>Iron as Fe</td>
<td>0.0</td>
<td>0.0</td>
<td>0.7</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>
The influence of pH is rather clearly demonstrated by the reduction in iron content at the three sampling points obtained over an interval of only one week. Since 1957 iron corrosion in this particular section of the system has been reasonably well controlled by the addition of a 1 mg/l dosage of sodium hexametaphosphate. In contrast with this older part of the system, the other service areas have never been bothered with complaints due to iron corrosion. This is because they are served with mains laid since 1950 and no unlined cast iron or steel mains are in use.

Two situations involving a change in the iron content of a well supply are worthy of mention. The first concerned an iron-removal plant at Barrington, Rhode Island, consisting of coke-tray aeration, pressure filtration, and post-chlorination. The supply was obtained from a group of three wells having a reasonably stable iron content of 1 mg/l. After eight years of successful operation, well production capacity showed a decrease and the plant decided upon an acidizing program to restore the wells to their previous capacity. The first well was treated in mid-1962. Capacity tests indicated a satisfactory recovery but redevelopment failed to return the iron content of this well back to its original level. Furthermore, after a period of several weeks, the iron content of the remaining wells began to increase and by the end of the year they were averaging 2.6 mg/l. The increase in the iron content of this supply has now overloaded the treatment equipment and there is every indication that, before the problem is entirely corrected, a substantial change in facilities will be required. The second case involved the major supply source of St. Marys, Pennsylvania, where an impounded surface supply was augmented during the annual dry season by ground water obtained from two drilled wells located along the shore line of the reservoir. These wells contained less than 0.5 mg/l of iron and also a trace of hydrogen sulfide. However, with the dilution afforded by the reservoir, they were used seasonally without complaints. Increased consumer demand eventually led to the drilling of a third well in 1960 which had a higher specific capacity and also a much higher concentration of iron. This latter feature caused red water trouble in the distribution system whenever it was operated, despite the fact that it also discharged into the reservoir before delivery. Nevertheless, the decision was made to deepen the original two wells to further increase production capacity. This was carried out in 1961. The result was three unsatisfactory wells. Finally, the company is today engaged in a crash program to provide iron-removal equipment for all three wells.

Before leaving the subject of iron, one should mention the effect that excessive hydrant flushing can have on red water troubles. The usual procedure, when a complaint of red water is received from a consumer, is to send a serviceman into the affected area to flush out the offending water. This pacifies the complainant and, temporarily, the procedure clears the supply in that immediate area. However, flushing hydrants at a high flow rate creates abnormal velocities in the adjoining mains which tear loose corrosion deposits from the metal surface of the piping. These deposits are soft and loosely adherent, but their presence on the pipe wall retards the rate of further corrosion. Once they are removed, bare metal is again exposed to the dissolving action of the water and a new cycle of corrosion begins. The effect of excessive flushing can, therefore, defeat rather than cure its own purpose. The story of one of our associated companies in western Pennsylvania will serve to illustrate this point. An unlined cast iron main 800 feet long was cleaned with a mechanical scraper to improve pressure and fire flows. The water supply carried by this pipeline originated from an impounded source having a pH of 6.7, alkalinity of 15 mg/l, hardness of 26 mg/l and total solids of 85 mg/l. Soft water such as this would be expected to be quite corrosive. Immediately following the cleaning operation, a number of irate consumers complained of rusty water. In attempting to clear up the condition, the pipeline was repeatedly subjected to heavy flushing. However, this did not help the condition. The situation became so bad that the water company, in desperation, was prepared to replace the entire line with one of cement-asbestos pipe. Fortunately, before the replacement work could be started, a suggestion was made that the method of flushing be changed to a procedure whereby a terminal hydrant would be opened only enough and for only sufficient time to gently change the water in the entire line. This was done each morning over a period of about ten days. Then the complaints ceased. The gentle flushing and
displacement of the pipe's contents allowed the main to heal and become coated.

COPPER

Turning next to copper as a source of concern in waterworks operation, we find that problems arising from this element occur with much less frequency than do those involving iron or manganese. Our experience indicates that the likelihood of copper presenting a problem is limited to those waters which are delivered at a pH value below about 7.0. Copper occurs in natural water only in trace amounts and its presence generally results from pollution attributable to the corrosive action of the water on copper and brass tubing, to industrial effluents, or perhaps as frequently, to the use of copper compounds in the control of plankton organisms. The latest revision of the U.S.P.H.S. Drinking Water Standards has reduced the suggested limit of copper from 3.0 to 1.0 mg/l as the copper ion.

Nearly all of the surface supplies in the water companies under our operation employ copper sulfate as an algicide. Several companies occasionally find it necessary to apply this chemical to control aquatic growths in their open distribution reservoirs. Our practice has been to restrict both the frequency and dosage of copper sulfate to the minimum. We have never experienced any significant increase in the copper content of waters so treated. In only rare instances have we found it necessary to employ copper sulfate on a continuous feed basis. In those cases we have always restricted the application to the raw water ahead of all other chemical additives and have maintained a pH value well above 7.0 in the water reaching the filters. Copper sulfate becomes increasingly more soluble below a pH of 7.0 and we believe it is not good practice to continuously feed this chemical where filtration is not provided.

The problems we have encountered from copper have always originated in the distribution system and they are usually characterized by complaints from consumers of troublesome staining of porcelain fixtures. The majority of such complaints have been confined to systems located in states lying along the Atlantic seaboard. In these states both surface and ground waters are low in mineral content and pH, but high in carbon dioxide. Since many of these supplies are obtained from wells and are objectionable only because of their low pH and aggressive action on metallic piping, they require no elaborate treatment other than pH correction and simple chlorination. With the trend today toward unattended, automatically controlled stations, our efforts have been directed toward the use of the most simple and effective methods of treatment that will prevent corrosion of the piping systems. In the course of our investigation we have been somewhat surprised to find the content of copper that may be present at times in household piping and apparently causes no harm other than the problem of staining. Complaints most frequently arise from homes where a leaky faucet allows a constant drip of water to fall on the porcelain surface of the fixture. By trial and error adjustment of the pH of the water at the source points, we have concluded that correcting the pH value to 7.0 or over will eliminate further staining problems. We have also studied the use of polyphosphates on such waters and find, contrary to our previous understanding, that such compounds do provide a measurable amount of stabilization, provided the pH value of the water is not less than 6.0. More recently we have resorted to the use of caustic soda, both with and without polyphosphates, in new supply developments.

Occasionally in connection with a copper staining problem, we have suspected the influence of electrolytic action created by the common practice of grounding electric fixtures to the plumbing system. Our studies, however, do not indicate that this practice is a significant factor in this problem. Perhaps we have been unduly influenced by an aggravating situation that occurred a few years ago in a water system in New Jersey. There a serious copper corrosion problem was reported in the home of a consumer occupying one side of a double house. The occupant claimed it was necessary to obtain water from his adjoining neighbor to prepare his meals because of the unsavory quality of food cooked with water from his service. Investigations indicated that the trouble began when all the household piping in his home was renewed with copper tubing; the other side of the house still retained its galvanized iron piping. After months of investigation which included the removal of all grounding connections from both the electric and telephone services, the installation of an insulating coupling in the water service, and finally the replacement of the outside service connection, the trouble remained unsolved. Unfor-
 Fortunately, the story of this case ends at this point because the complainant refused to cooperate any further and we were forced to abandon our study. I am advised, however, that he still remains a consumer of this water supply but his complaint, if still present, is no longer being shared with the water company.

Another instance of copper corrosion involved a consumer in another New Jersey community who complained repeatedly of blue stains on diapers washed in an automatic washer. While the water system serving this consumer had relatively few complaints over the years that were traceable to corrosion, it was evident that the recent completion of a new well in her immediate area was a potential source of trouble. The new well supply had a pH of 5.0, total alkalinity of only 7 mg/l and a hardness of 26 mg/l. Prior to delivery into the system, the supply was chlorinated and received a 1 mg/l dosage of a polyphosphate compound. Samples collected from the kitchen tap of this home showed up to 4 mg/l of copper upon withdrawal in the morning following no night-time usage. Other samples collected during the day, after thoroughly flushing the tap, showed concentrations up to 1 mg/l of copper. Water at the well station had a copper content of 0.12 mg/l but such samples passed through 50 feet of copper tubing before reaching the point of collection. A test was made on the water at a normal pH of 5.0, the copper content increased from 0.12 to 3.2 mg/l. However, when the pH was adjusted from 5.0 to 6.5, the copper content increased to only 0.6 mg/l. When adjusted to a pH of 7.0, the copper increase was negligible. Shortly thereafter, caustic soda treatment was introduced at this well station to raise the pH to 7.0. Since that time no further complaints have been received.

In relatively few instances have we been confronted with the problem of actual structural failure of an underground service of copper tubing. However, quite recently our attention was called to such a failure in a copper service line on a system in Indiana. The full story of this episode is yet to be determined but the facts brought to light thus far indicate that the cause was due to imperfections arising out of the manufacture of the tubing. Nevertheless, the case called attention to the fact that quality control of the finished water was not being maintained at all times. This particular supply is obtained from a river source and it requires widely varying coagulant dosages to affect proper clarification. Following filtration, the water is treated with lime for pH correction. In recent years, there has been a noticeable increase in the coagulant usage brought on by the further pollution of river water. The plant, however, has shown a reluctance to vary the lime dosage consistent with the dosage of alum being used with the result that periods of a week or more occur when the pH of the finished water is permitted to drop below a value of 7.0. While no reported evidence of pipeline corrosion has resulted from this practice, experience at other locations where water of high mineral content is processed prompted our recommendation that the pH of the finished water be maintained at a value of 7.6 to 7.8 in the future.

CONCLUSIONS

Progress in the art of water treatment is proceeding today at a greatly accelerated rate. The increasing demand of the public for water of higher quality, coupled with the current population explosion and the trend toward urbanization in our society, requires that this progress be continued and its rate be further intensified. Technically, it is possible to treat any water to give it a composition that will be satisfactory for any special use. But, if the water requires extensive treatment, it may not be economically feasible to utilize the supply. It is of utmost importance that water quality be fully considered in any water treatment plant design. Treatment methods which are successful in removing manganese are also successful in the removal of iron, but the reverse of this statement is not true. Supplies containing manganese should be treated to reduce the concentration to less than 0.05 mg/l. Iron removal treatment should be considered for any supply containing more than 0.3 mg/l, regardless of the form in which it may exist. Pipeline corrosion investigations should be a continuous program in any water supply system.
MANGANESE IN WATER DISTRIBUTION SYSTEMS

Attmore E. Griffin

Manganese deposits in water distribution systems occur throughout the world. This does not mean that every distribution system, or all water supplies, contain manganese; it does mean manganese difficulties are not confined to any one country or hemisphere. Its presence is probably best documented in the United States. This may make it appear that this country has more manganese than is found elsewhere; however, a study of the subject shows that practically all countries where records are kept have had their share of trouble.

Although manganese difficulties have been reported throughout the world, there are few precise data in the literature describing how much manganese may collect on the interior of a given length of pipe over a given period of time. Nor is there much information concerning whether or not it sloughs off from time to time, what depth of deposit may be optimum for sloughing, what may induce sloughing, the state of oxidation of the deposits, what organisms are most frequently responsible for manganese build-up, or whether or not manganese deposits in pipelines without the aid of organic growths. There are a few papers describing how very minute amounts (less than 0.01 mg/l) can cause a great deal of difficulty. However, precise scientific data relating to its early detection or rate of build-up are generally lacking. There are, however, many generalized statements referring to laundry troubles, black water, or reduced pipe capacities. These statements are for the most part presented in loose generalized terms.

Manganese occurs in both ground and surface waters, especially in those areas where the rock or soil contains significant amounts of manganese. In the United States it is present almost everywhere except in the extreme northeastern and northwestern sections. For example: it has caused considerable trouble in northern New Jersey water supplies; has been found in several aqueducts of the New York City water supply; requires constant vigilance in the Carolinas and Georgia to keep it out of distribution systems; has been deposited in considerable amounts in the distribution systems of several cities in the Dakotas; has had to be removed from many Wisconsin water supplies to forestall difficulties and reduce consumer complaints; has required the construction of a manganese removal plant at Lincoln, Nebraska; has required special treatment at Lake Charles, Louisiana; and has been a continuing problem in San Diego County, California. Canada as a whole has reported little or no trouble with this bothersome element.

Manganese is an insidious element. It resists removal to a remarkable degree but will drop out of solution in the most inaccessible places and at the most inopportune times. It defies detection to a considerable extent and perplexes researchers as to how it originally enters solution.

Manganese usually is detected quite readily in a treatment plant. But where the water goes directly from the source to the transmission main and thence to the distribution system it may defy detection for a surprisingly long time. This is partly because more routine tests are made at a full treatment plant than where only chlorination is required. Also the quality of water used where chlorination alone is required is generally better than where full treatment, including filtration, is used.

Psychology may have something to do with its detection in the distribution system because even though the presence of manganese may be suspected there could be a reluctance to take action because of the cost or complexity of removal.

Today's demand for a high purity water, especially in the industrial field, make it quite imperative that management of water supplies exercise extreme vigilance regarding the quality of the delivered product. The private consumer does not appreciate water that regularly or periodically stains the family wash. Unless the situation is very bad he will complain only mildly. Industry, on the other hand, may even move elsewhere if it becomes
necessary to re-treat the water to make it usable in the manufacture of some specialized product. TV tube makers, for instance, must have clear water essentially devoid of substances such as manganese, especially if the manganese is combined with organic matter. Commercial laundries are using increasingly more automatic equipment and depend more and more on a continuous supply of high-quality water devoid of anything that will stain textiles.

Manufacturers of textiles, especially those who use dyeing operations, must have a high-quality water as free as possible from manganese. No longer can industry afford to close up shop for several days while wauganue deposits, including slimes, are removed from the mill distribution system as happened at Enka, N.C., some twenty years ago. Today it is up to the water superintendent to prevent such occurrences.

Even though routine manganese tests are faithfully made, manganese has been known to pass into the distribution system and thence into an industrial plant in spite of the fact that tests indicated its absence. As a last resort, a water chemist passed many gallons (50-100) of the water arriving at the plant through membrane filters. Enough manganese was caught on the filters for accurate analysis. This testing showed that manganese was passing into the manufacturing plant and was the culprit. This type of chemical sleuthing is becoming increasingly common throughout the country and demonstrates the insidiousness of manganese in water supplies. It also serves to show the necessity of setting the tolerable limit of manganese at its present low figure, even though it is considered by some to be lower than the ability of present routine methods to detect.

Manganese usually reveals its presence at the treatment plant either by false orthotolidine chlorine readings, by accumulation of dark deposits on the plant structure, or on glass or hard rubber components of the chlorinator. These symptoms may occur even though routine testing indicates that manganese is zero. Sometimes it reveals itself by dark rings where leaky faucets drip on white enamel.

In the case of direct flow from a reservoir or direct pumping from ground sources there are few places where visual symptoms may be observed (unless in the chlorinator) until consumer complaints begin to come in or dark stains appear on porcelain.

Little reliance can be placed in the orthotolidine test when used on untreated water. This is because the test does not react to manganous manganese, the usual form in which it arrives at the plant. This was clearly demonstrated about 1931 at the Wanaque, N.J., laboratory of the North Jersey District Water Supply Commission. This reservoir, about 30 billion gallons capacity, was first filled early in 1930. Within months of filling it was put into limited use. The only treatment was chlorination. Early in the fall of 1931 the chlorine residuals suddenly started to rise without any increase in chlorine application. At first it was thought this was caused by a decrease in chlorine demand. The presence of manganese was suspected but not considered serious because no false color to orthotolidine showed in raw water samples. Things became serious when coliforms appeared in the treated water. As the chlorine dosage was increased, so did the orthotolidine yellow color. After much frenzied experimentation it was demonstrated that more and more manganese was oxidized as the chlorine dosage was increased. This continued until enough chlorine was added to oxidize all of the manganese and to produce enough excess chlorine to kill the coliforms. When this point was reached all coliforms disappeared.

Within the next few years the pipelines (72 inches in diameter) were inspected and revealed a thin, sloppy film of manganese that was apparently held in place by biological growths. Fortunately, other than periodic complaints of dark colored water following excessive flows in the pipelines, such as during fires or during the filling of swimming pools, this manganese has caused only minimum difficulty.

Sioux Falls, South Dakota, prior to construction of a water softening plant in the late 1940s or early '50s, presented an excellent example of how manganese may infiltrate a distribution system. The source of supply consisted of several wells. The water, as taken from the wells, contained considerable iron and manganese in true solution, several ppm iron and up to 2.0 mg/l manganese. When the supply was first developed, red water conditions were so serious that an iron removal plant was constructed. It consisted of aeration, filtration, and post-chlorination. This treatment reduced the iron content to about 0.3 mg/l, an acceptable figure. Although it was known that manganese was present it seemed to present little if any difficulty until it was noticed that the chlorinators were gradually
losing capacity. Investigation as to the cause showed that the injector parts were clogged with a black deposit of manganese. After the injectors were cleaned the chlorinators again delivered the designed amount of chlorine. Periodic cleaning and replacement of injector throats then became standard practice.

The next indication of trouble was an apparent loss in water delivery capacity. Investigation showed a considerable deposit of manganese in the main feeder line near its point of delivery to the distribution system. Periodic inspection did not indicate any appreciable increase in build-up at this point but it did show that the manganese film was gradually pushing further and further into the system.

This situation became a constant source of worry and eventually led to the construction of a water softening plant. This automatically removed the manganese within the plant and stopped all further build-up in the distribution system.

Southern California has at various times been subject to epidemics of turbid water accompanied by stained plumbing, ruined laundry, and low meter readings.[1] Water in many of the wells in the area contains as much as 17 mg/l manganese. When water from the various sources and reservoirs is rerouted (as it must be from time to time) strange things have happened. Manganese films on pipeline interiors have suddenly let go, causing havoc in the distribution systems, and turbidity has increased in water that was practically devoid of turbidity at the source. Even pipeline flows have been reduced.

One supply in the area obtains water entirely from wells with no treatment other than light chlorination which is insufficient to carry a residual into the distribution system. Eventually, as in the large supply in New Jersey, coliforms made their appearance. The chlorine dosage was increased, the coliforms disappeared, but the manganese-organic film sloughed off the pipe interior, turning the water as black as ink. The chlorine dosage was increased again, vigorous flushing was undertaken, and the situation cleared up.

Manganese films on the interior of distribution lines appear to remain soft practically forever. This means that the slightest increase in velocity or reversal of flow may loosen considerable amounts. Black water, with its attendant ills, almost invariably follows. There is a city in Wisconsin where this has happened periodically for the past 70 years. The consumers "stood it" until, just a few years ago, a softening plant was authorized and built.

Water for this city is obtained from twelve wells, some of which contain from 0.0 to 2.40 mg/l iron and 0.0 to 5.66 mg/l manganese. The plant effectively removes iron and manganese but during the shake-down period it was again demonstrated how cantankerous manganese can be.

The iron came out very nicely at a pH of 8.4, but to remove the manganese it was necessary to raise the pH to about 9.5. At other places it sometimes can be removed at very much lower pH values.

No report has yet been received as to the behavior of manganese in the water mains since the start of softening and manganese removal.

Lake Charles is another example where manganese removal has long been a necessity. Like so many other histories of manganese a minimum of data is available as to the facts that led to removal, but there are plenty of data as to how it is being removed. The method here is somewhat unique, in that small quantities of copper sulfate are applied along with the coagulant. It is theorized that the copper acts as a catalytic agent to assist oxidation in the presence of a chlorine residual. There is considerable supporting evidence for this theory. There are several plants in the Georgia[2] area very effectively using the same technique.

In addition to the examples previously cited there are many others that could be given but they would serve no particular purpose.

Detection of manganese in a distribution system sometimes becomes a rather long drawn-out procedure. Unless the system is large enough to support a full time chemist, estimation of the significance of the traces of manganese known to be present in the water can lead one on a long and baffling chase. For instance, it is generally known that manganese deposits in pipelines are black. If a tubercle is pried away from a pipe interior and cut open it will usually reveal a series of alternate layers of reddish and black material. Some layers may be somewhat whitish in appearance. The first reaction usually is to assume that the black layers are made up of manganese. This can be a false assumption because most of these black layers are composed of black ferrous sulfide. Manganese deposits are seldom as firm as the black deposits in
tubercles. Manganese deposits are almost invariably held to the pipe interior by organic growths. When this organic material is destroyed it loses its adhesive power which allows organic matter and manganese to be spilled into the water.

The real problem in detection is when the water shows no manganese when using ordinary test methods. The increasing demands of modern industry for superfine water make it almost mandatory that when there is even a suspicion of manganese in the raw water, the operator use every trick he knows to make sure that none is being passed on to his demanding customers. Black arcs on white porcelain should be checked and analyses of pipe debris and meter sludge should be analyzed. Sometimes it may be necessary to place very fine filters, such as membrane filters, at several points in the system. The rates through these filters should be controlled so that some idea will be obtained as to the amount of water passing through. It is not unreasonable to assume that it may be necessary to pass several hundred gallons through such filters to arrive at a significant conclusion.

Indications are that manganese drops out of the water quite rapidly in the distribution system. It does this under the continuing oxidizing influence of the chlorine introduced for sterilization and the dissolved oxygen content which usually is greater in finished water than in raw water. If lime is added to increase the pH the oxidation of the manganese will be considerably more rapid.

It might be theorized that manganese would accumulate at a given distance from the plant where it would interfere with the water flow. This may happen to a limited degree, but practice seems to indicate that the initial build-up becomes relatively static after the first brisk period of deposition. After this period the manganese film progresses slowly into the system. This theory could stand substantiation by a careful study of conditions in a new system where manganese is known to be present. Collection of such data would be a slow process, perhaps requiring five to fifteen years to obtain conclusive results.

It is well known that manganese accumulates, along with other debris, in low spots in the system and in water meters. Here again, however, one should not jump to conclusions just because the "mud" is black. It may be ferrous sulfide, which is just as black as manganese manganese.

Considerable stress has been placed on chemical oxidation of manganese to an insoluble form. This is not the only factor in the process because there are some organisms in water that have the ability to draw energy from manganese in water and deposit it in an insoluble form in their sheath. This is done in much the same way that iron is extracted by the iron bacteria. Some authorities seem to feel that the same organism may remove both iron and manganese. Whichever it may be, the net result is usually a black slimy deposit.

That the organisms do play a very prominent part is evidenced by the fact that when enough chlorine residual is maintained in a manganese-slime pipe area the organic bonding material will be damaged to the extent that whole slabs of material will slough off and be carried away by the moving water.

In cases where manganese is deposited as black manganese dioxide on surfaces, such as filter sand, the presence of chlorine will not remove it. Instead, chlorine seems to cause it to cling very much tighter if the pH is maintained above 7.0.

It is somewhat difficult to draw conclusions, based on precise knowledge, regarding the habits of manganese in distribution systems. It is equally difficult to measure its economic significance in distribution systems. Apparently it depends a great deal upon where one sits and how much of a gambler one is.

There are many supplies in the country where the amount of manganese in the distribution system verges on the colossal and where, according to all theory, complaints should be constant and serious, yet nothing happens. Other supplies, where manganese is not suspected or not even detected by routine testing, have manganese problems that have been close to catastrophic.

About the only conclusions that can be drawn is that eternal care and watchfulness must be practiced. If too many chances are taken the consequences can be very serious. It is also quite evident that manganese detection methods should be carefully studied for sensitivity and for differentiation between suspended and soluble manganese.

REFERENCES


COPPER CORROSION

G. B. Hatch

Corrosion of copper is not a serious problem in most potable water systems. Although copper is quite susceptible to attack under certain conditions, fortunately these are not widely encountered in such service. As a result, substitution of copper for steel or galvanized lines is perhaps the most common means employed to avoid real or anticipated corrosion problems in consumer water systems. However, as with most generalities, there are exceptions; the trouble-free operation of copper lines is such an exception. It is this exception which is of primary interest in the present discussion.

Copper owes much of its resistance to corrosion to the thin film of cuprous oxide which normally forms on its surface when it is exposed to potable waters. Generally, this oxide film is very fine grained, tightly adherent, and quite highly protective. Frequently it is overlaid with thin deposits of basic cupric salts which often help to augment protection. Occasionally, this oxide film may break down or fail to provide adequate protection. It is on such occasions that corrosion problems develop.

Excessive leakage through or solubility of the film as a whole will result in general corrosion. Attack of this type seldom proceeds at a rate sufficient to decrease the life of the tubing appreciably, although it can produce undesirable side effects. Generally corrosion of copper usually is readily alleviated by water treatment.

Local breakdown of the protective oxide film and interference with its subsequent repair can lead to localized attack. Corrosion of this type often markedly decreases the life of the tubing. Excessive flow velocity (i.e., impingement) is the most common cause for localized attack on copper. The remedy for such attack is self-evident (i.e., reduction of the flow velocity). Occasionally localized attack may occur in the absence of excessive flow velocity. Such pitting is quite rare. This is perhaps fortunate, since generally neither the exact causes nor the appropriate remedial measures are known.

GENERAL ATTACK

The chief difficulties arising from general corrosion of copper result from copper pickup by the water. The most obvious problem raised by this pickup is the green or blue staining of washbowls, bathtubs, etc. However, a more serious consequence results from the accelerative action of the dissolved copper on the corrosion of more anodic metals.

Zinc (for example, galvanized steel) and aluminum are particularly sensitive to traces of dissolved copper. This has often been mentioned in the literature. Unfortunately, this is too frequently ignored in practice. Concentrations of the order of hundredths of a part per million of copper suffice to increase significantly the attack on zinc or aluminum. Most of this acceleration is in the form of pitting which makes the problem particularly serious. The attack of iron and steel also is subject to acceleration by copper in the water, but not to as pronounced an extent as that of zinc and aluminum. In addition, corrosion of steel in an untreated system often dislodges the previously deposited copper from the surface of iron and steel. In contrast, the copper generally remains on the surface of aluminum and zinc and continues to exert an accelerative action on their attack.

Elevation of the pH to 6.8 to 7 usually suffices to reduce the general attack and the resultant copper pickup to very low levels. Occasionally, somewhat higher pH values are required, particularly when high chloride concentrations are involved.

IMPINGEMENT ATTACK

Impingement is one form of corrosion to which copper is quite susceptible. In this respect, it is perhaps the least resistant of the metals commonly employed for water service.

Impingement results from excessive flow velocities. It generally is of a localized character. The resultant pits usually are undercut on the downstream ends. Often they are of a horseshoe shape. Occasionally, impingement will produce a rippled surface without definite undercutting on the down-
stream ends. The affected areas remain essentially free from deposits when impingement is active. Although most of these features are suggestive of purely mechanical action, the attack actually is of an electrochemical nature. The high flow velocities interfere with normal formation of protective films; as a result, the attack proceeds at an abnormal rate.

The flow velocity, which can be tolerated by copper tubing without danger of impingement, is dependent on the character of the water handled. It is influenced by the speed with which the protective film can be formed and repaired. The presence of a second phase (for example, entrained solids or air bubbles) also is an important factor; it markedly reduces the velocity which can be tolerated. From a practical standpoint we do not favor velocities in excess of 5 feet per second for most municipal waters and considerably lower if entrained solids or air bubbles are present. (This value applies specifically to copper. Many of its alloys show markedly superior resistance to impingement.)

**LEAD-IN**

An example of severe and widespread impingement attack of copper is afforded by the lead-in of a motel shown in Figure 1. The water involved was a hard bicarbonate well supply with a pH of 7.3. The undercutting on the downstream side (i.e., the upper side of Figure 1) was so extensive that the tube surface had the feel of a rasp. The downstream ends of the pits where the attack was most active were essentially clean. Light deposits were present between the pits and on the upstream ends thereof. Such widespread impingement is rather unusual. It indicates that the lead-in was markedly undersized (i.e., the flow velocity was much too high).

**REJCIRCULATING HOT WATER SYSTEM**

Recirculating hot water systems appear quite susceptible to impingement attack. The return lines near the suction side of the circulating pump are particularly vulnerable to such attack. Air which separates from the water as a result of the pressure reduction together with that pulled into the line from leaky faucets appears responsible for the particular vulnerability of these portions of the system to such attack.

Severe impingement attack of copper was experienced throughout the recirculating hot water system of a hospital. The municipal supply used for their system showed the following typical analysis:

<p>| | |</p>
<table>
<thead>
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<tbody>
<tr>
<td>pH</td>
<td>7.5</td>
</tr>
<tr>
<td>Chloride</td>
<td>5 mg/l</td>
</tr>
<tr>
<td>Sulfate</td>
<td>12 mg/l</td>
</tr>
<tr>
<td>Total Alkalinity</td>
<td>66 mg/l (as CaCO₃)</td>
</tr>
<tr>
<td>Total Hardness</td>
<td>80 mg/l (as CaCO₃)</td>
</tr>
</tbody>
</table>

Temperatures in the system were maintained in the range of 140° to 160° F.

The appearance of a pickled section of copper tubing from this system is shown in Figure 2a. The pits show a rather unusual elongation at right angles to the tube axis. They are markedly undercut on the downstream end (i.e., the right side of Figure 2a).

Numerous replacements have been required in this system. From the condition of the sections examined, it would appear only a matter of time before all of the lines will require replacement. Even the bronze tube fittings show signs of impingement in this system. (This alloy is much more resistant to attack of this nature than is copper.)

Steel also was present in this recirculating hot water system. Its corrosion caused "red water" problems. A sodium zinc phosphate glass was applied to the system at a rate of 5 mg/l to protect the steel. Although the pH was sufficiently high (7.5) so that some calcium phosphate deposition
could be expected at this feed rate, the primary aim was to eliminate the "red water" as soon as possible. A section of copper tubing removed from the system several months after treatment was started is shown in Figure 2b. The pits contain light deposits and show no bright bare copper areas. Impingement no longer appears active.

Normally the glassy phosphates form very light films on copper (unless it is the cathode in a galvanic cell) and are not particularly effective copper inhibitors. Hence, it appears that the mechanical shielding of the copper surface by the light deposit was the factor primarily responsible for inactivation of the impingement attack.

The deposits, primarily calcium phosphate containing small amounts of zinc, are rather loosely adherent. Their physical characteristics are certainly not such as would be expected to offer much resistance to mechanical removal. Their inhibitive action on the impingement attack suggests that mechanical disruption of the normally protective oxide film is not a major factor in this type of corrosion. It also suggests the action of the higher velocities to be the removal of the copper ions before oxide film formation or repair can occur. On this basis the loose deposit would tend to retard the removal of copper ions from the metal surface and thereby allow more time for the oxide film to form. Added effective life of the rather unstable cuprous ion would be afforded by reduction of cupric ions by the copper surface:

\[ \text{Cu}^{2+} + \text{Cu} = 2\text{Cu}^{+} \]

The chief reason for including the above example is the insight which it provides with respect to the impingement mechanisms. Deposits are not suggested as an ideal means to alleviate impingement. The best cure for impingement is to avoid excessive flow velocities and entrained gases or solids. Metals more resistant to impingement than copper (for example, certain of the copper alloys used for industrial condenser tubes) should be employed if higher flow velocities are essential. In fact, such alloys might well bear consideration for use in recirculating hot water systems.

The above discussion concerns only the type of impingement normally encountered in water systems. Impingement by high velocity steam, particularly wet steam, can cause mechanical damage. Such attack is more analogous to corrosion-erosion than to the impingement encountered in domestic lines or cooling water systems.

**PITTING ATTACK**

Localized attack of copper can occur in the absence of excessive flow velocities. The resultant pitting does not show the undercut orientation characteristic of impingement pits. The following
discussion will be concerned only with straight pitting—that which does not involve impingement.

Pitting of copper in potable waters is quite rare and equally unpredictable. Isolated cases can suddenly turn up in a water system where innumerable other copper installations have given and continue to give excellent service. The attack is so unexpected that pertinent detailed information in regard to the tubing and its exposure conditions generally are scarce. Laboratory investigation is impeded by the difficulty of initiating pitting by any treatment which conceivably might be encountered in service.

**INDUSTRIAL LINES**

Serious pitting of copper tubing was encountered in portions of an industrial system after two years of essentially cold water (45° to 75° F) service. The well water was quite hard, but otherwise of good quality. A typical analysis showed:

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.8</td>
</tr>
<tr>
<td>Chloride</td>
<td>6 mg/l</td>
</tr>
<tr>
<td>Sulfate</td>
<td>3 mg/l</td>
</tr>
<tr>
<td>Ammonia</td>
<td>0.05 mg/l</td>
</tr>
<tr>
<td>Total Alkalinity</td>
<td>192 mg/l (as CaCO₃)</td>
</tr>
<tr>
<td>Total Hardness</td>
<td>196 mg/l (as CaCO₃)</td>
</tr>
</tbody>
</table>

One of the more striking features of the attack was its abrupt change at the joints between adjacent sections. A section which showed only light general attack might be followed by a severely pitted section and vice versa. Where pitting occurred it was concentrated on half of the tube circumference. However, there was no specific orientation of the portions thus affected with respect to their positions in service. Thus, a section with pits on the top half could be followed by one with pits on the side, by one pitted on the bottom, or by one entirely free from pits. One of the few consistent features of the attack was the maintenance of an essentially uniform pattern throughout the length of an individual section.

Light malachite (basic cupric carbonate) deposits together with minor amounts of silica were present on both the pitted and unpitted sections.

The marked differences in behavior of the different sections of tubing in this system appear to defy explanation on the basis of water characteristics alone. It suggests a difference in susceptibility of the individual sections to pitting attack. In fact, this susceptibility to pitting appears to be further localized on only one half of the tube circumference.

No differences of either composition or structure could be detected between the pitted and unpitted portions of the tubing. Differences in surface conditions are suspected to have been the cause for the differences in susceptibility to pitting. No peculiar surface conditions could be detected around the pitted areas at the time the tubes were examined. This does not preclude the possibility that such conditions disappeared or became obscure during service. Hence, it neither supports nor disproves this hypotheses.

It is perhaps of interest that no further failures in this system have been reported since replacement of the seriously pitted sections five years ago.

**SPRINKLER SYSTEM**

Copper pitting was encountered in a sprinkler system served by a well water of the following typical composition:

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.3</td>
</tr>
<tr>
<td>Chloride</td>
<td>35 mg/l</td>
</tr>
<tr>
<td>Sulfate</td>
<td>9 mg/l</td>
</tr>
<tr>
<td>Total Alkalinity</td>
<td>184 mg/l (as CaCO₃)</td>
</tr>
<tr>
<td>Total Hardness</td>
<td>112 mg/l (as CaCO₃)</td>
</tr>
</tbody>
</table>

A peculiar feature of the attack was the localization of pitting in one size of tubing. The 1½-inch main lines in this system pitted whereas the 1-inch laterals did not. The pits in the larger tubes were deeper on the bottom of the tubing than elsewhere; those in other portions of the tubing appeared to be in the early stages of development.

The surface of the tubes were covered by a thin light green deposit. This consisted essentially of malachite (basic cupric carbonate) with a light covering of calcite and siliceous material. Beneath the deposit was a thin film of fine grained cuprous oxide. Occasionally the thin deposit on the bottom of the larger tubing was broken by green nodular malachite tubercles. Removal of the tubercles revealed pits partially filled with relatively large, well-formed crystals of cuprous oxide.

The relatively thin deposit on the unpitted areas of the larger tubing could be readily flaked off. The underlying fine grained cuprous oxide was broken in spots by small bright areas which appeared to be essentially bare copper. These bright spots appear indicative of localized breakdown of the oxide film and active attack of local areas of
the metal surfaces; they are suggestive of early stages of pit development.

The differences in behavior of the two sizes of tubing again indicate that differences in the tubing were the determinant factor in regard to pitting susceptibility. Water composition may have been a contributive factor, but certainly not the determinant one. Here again, differences in surface conditions were suspected. It was suspected that the surface conditions of the larger tubing rendered it particularly susceptible to pitting attack, but again no evidence as to the particular surface condition involved was obtained.

**DOMESTIC LEAD-INS**

Failures of numerous copper lead-ins as the result of pitting attack were experienced in a small Canadian village. The failures were restricted to the soft Type K lead-ins; no trouble was encountered with the hard Type L copper tubing used for interior domestic lines.

The well supply of this village was a hard bicarbonate water of rather high sulfate content. A typical analysis showed:

- **pH**: 7.0
- **Chloride**: 1 mg/l
- **Sulfate**: 160 mg/l
- **Total Alkalinity**: 168 mg/l (as CaCO₃)
- **Total Hardness**: 306 mg/l (as CaCO₃)

Examination of a section of one of these lead-ins showed pits in all stages of development—from mere bright spots to complete penetration of the tube wall. The major portion of the tube surface was covered with a thin, rather loosely adherent nodular green deposit of malachite (i.e., basic cupric carbonate). Beneath this was a very smooth dark film. *In situ* examination of this dark film revealed only cuprous oxide. There were numerous small breaks in the dark film where pitting appeared active. The film also was disrupted in a band roughly 3/8 inch wide which extended lengthwise along the tube. The dark oxide film was tightly adherent except in areas adjacent to the pits where it could be chipped off quite readily. The underside of the film in the latter cases showed relatively large cuprous oxide crystals. These relatively large, well-formed oxide crystals also were quite prevalent in the pits. They were present in the lengthwise band of disrupted film mentioned above.

![Figure 3. Pits in a domestic copper lead-in](image)

The general appearance of the pitted tubing is shown in Figure 3. The white spots in the pit in the center were caused by light reflections from properly oriented faces of relatively large cuprous oxide crystals. The dark area immediately above the pit also consists of the coarse oxide crystals. The area around the pits and extending towards the lower right corner is essentially bare copper; the light spots in this area are due to light reflections from the roughened metal surfaces. The light spot in the lower portion of the pit at the right is due to light reflected from the bare metal. The rather smooth dark oxide film is shown in the upper portion of the photograph as well as the lower left portion. At the left and extreme right of the pits are portions of the overlying malachite film.

The smoothness of the dark oxide film on the unattacked portions of the tube surface is suggestive of the contour of the original drawn metal surface. (In fact, the appearance is such as would result from a thin coating of dark lacquer on the interior of a new tube.) It suggests that either the oxide film was initially present or formed sufficiently rapidly in service to preserve the initial smoothness of the tube interior. Evidently, this oxide film was insufficiently impervious and protective to prevent the slow growth of relatively coarse oxide crystals beneath the initial fine-grained film. Apparently these large crystals eventually disrupted the fine grained film in numerous areas and exposed
the underlying bare metal to attack. When the fine grained cuprous oxide film was disrupted over a rather wide area (e.g., the band which extended along the tube), the attack on the metal was essentially uniform. When local disruption of the film occurred, the resultant attack was of a pitting type. The latter suggests that the oxide-film-covered areas were markedly cathodic to the bare metal.

Growth of the coarse oxide beneath an initial fine-grained film suggests a somewhat porous character of the latter. A continuous cuprous oxide film normally would be expected to thicken by outward diffusion of cuprous ions through the film and subsequent formation of additional oxide.

The smooth, fine-grained oxide film on these lead-ins appears analogous to the “glassy” cuprous oxide film of Campbell (1) (i.e., his use of the term “glassy” refers to the superficial resemblance rather than to a true super-cooled liquid state). He found these smooth, shiny cuprous oxide films to promote pitting attack; apparently films of this type were quite cathodic to the bare metal. He also noted (3) that oxide films of this type often were formed during British bright annealing practices prior to 1960; subsequently, precautions were taken to remove such films. The formation of such films during the bright anneal generally restricted their presence to the soft tubing. This perhaps accounts for the freedom of pitting in the hard Type L tubing used for the interior plumbing in this village.

ENGLISH WATER LINE

It perhaps is of interest to note that a smooth dark cuprous oxide film, very similar in appearance to that encountered on the pitted lead-ins considered above, also was observed on a section of pitted copper tubing from an English cold water line which had failed after two years of service. We are indebted to Mr. C. W. Drane of Albright and Wilson, Ltd., for this specimen of pitting copper tubing.

The tube surface Figure 4a was covered with a thin grain deposit of malachite (basic cupric carbonate). Scattered along this surface were green tubercles of nodular malachite. Ferric oxide deposits were present on the surface of some of these tubercles. Beneath the tubercles were deep pits Figure 4b. Within the latter were scattered relatively large, well-formed crystals of cuprous oxide. Portions of the underlying dark oxide film were visible around the pits where the overlying malachite deposit had cracked off. The identity of this dark cuprous oxide film was confirmed by in situ X-ray examination. Again, this smooth oxide film appears analogous to the “glassy” cuprous oxide which Campbell (1) has found to promote pitting.
Failure of copper pipe (as distinct from tubing) occurred as the result of pitting after approximately 32 years' service in a Pittsburgh building. The pipe handled cold Pittsburgh tap water, a low bicarbonate, high sulfate surface supply with moderate average hardness; the pH during this period generally was in the range of 5 to 7.

The pipe surface was covered by a thin, rather loosely adherent brown deposit of high iron content. This was broken in spots by protruding bluish-green tubercles which consisted chiefly of basic cupric sulfate. Figure 5a shows a portion of the deposit-covered surface together with several tubercles. There were deep pits beneath these tubercles; in fact, elsewhere in the section they had perforated the tube wall. Within the pits were scattered relatively large crystals of cuprous oxide. Removal of the loosely adherent brown deposit revealed an underlying shiny black deposit. In spots where this deposit could be chipped loose there were relatively coarse cuprous oxide crystals adjacent to the metal surface. In situ X-ray examination of the black surface (after mechanical removal of the loose brown coating and bluish-green corrosion products) showed graphite and cuprous oxide.

The exact source of the graphite is uncertain. However, it seems probable that it is a residue of the pipe drawing lubricant and was present when the pipe was installed. Judged by the life of the pipe it seems to have provided a rather effective barrier to attack for a considerable period. However, corrosion apparently proceeded at a slow rate beneath the graphite film with the gradual formation of relatively large cuprous oxide crystals. The latter probably eventually disrupted the graphite film in spots and exposed essentially bare metal (as the oxide crystals were too coarse to form an effective barrier). The graphite would be expected to be cathodic to the copper. Hence conditions at breaks in the film (i.e., a high cathodic to anodic area ratio) would be such as to favor accelerated attack on the metal.

Campbell[10] has found carbonized residues to cause pitting of copper in hard waters (i.e., 100 ppm as CaCO₃). These residues can form by thermal decomposition of tube drawing lubricants. They are reputedly quite rare with tubes drawn in this country. The carbonized residues apparently are quite cathodic to copper, hence promote pitting wherever breaks in the film expose the underlying metal. Amorphous carbon would be expected to be the major cathodic ingredient of such residues, hence to be chiefly responsible for the pitting. The graphite film found on the copper pipe discussed...

Figure 5. Tuberculation and pitting in a copper cold service line
(The dark film after cleaning is a graphite layer.)
above is perhaps the closest to such carbonized residues from an electrochemical view which we have encountered. It would be expected to give a film of lower electrical resistance, hence to provide an even more effective cathode than the amorphous carbon.

Campbell(1) also has found manganese deposits to cause pitting of copper tubing. This is of particular interest since quite a few manganese bearing waters are encountered in this country. While we have encountered manganese deposits on several pitted copper tubes, other copper in the systems showed similar deposits but no pitting. Hence, it appeared difficult to attribute the observed pitting to manganese deposits, or at least solely to such deposits.

All of the pitted tubes which have been discussed were checked specifically for manganese and carbon deposits. With the exception of the graphite film discussed earlier, neither was found.

It might be noted in conjunction with manganese deposits that their removal by acid can cause trouble. Such deposits provide a powerfully oxidizing environment in strongly acid media, and copper is quite rapidly attacked under such conditions. For example, covering a copper panel with a thin manganese dioxide layer increased the loss on pickling in 10 per cent sulfuric acid roughly 50-fold. Many copper alloys are similarly affected.

For example, an admiralty tubed industrial condenser was severely attacked in an attempt to remove a manganese deposit by acid cleaning.

**DISCUSSION**

Most of the cases which have been considered point to the condition of the cuprous oxide film as the determinant factor as to whether or not appreciable attack on copper will occur. Apparently, when a continuous, impervious, fine-grained cuprous oxide film can be formed and maintained, attack on the underlying metal is quite slow. When formation of such a film is prevented, attack is quite rapid.

The normal slow general attack on copper in potable water appears to reflect leakage through the cuprous oxide film. Conditions which affect the solubility of this oxide (e.g., pH) will affect the extent of such leakage, but marked acceleration of attack will not be encountered as long as the fine-grained film remains intact.

Impingement attack apparently results when the flow is sufficiently rapid to remove the copper ions before formation of the protective cuprous oxide film can take place. Shielding of the surface with a loose deposit (e.g., the calcium phosphate considered in one of the preceding examples) prevents this rapid removal and inactivates the impingement attack.

Relatively large crystals of cuprous oxide do not form an effective barrier on the metal surface. Relatively unimpeded attack can proceed through voids between such crystals. Rather large well-formed crystals generally imply relatively slow formation. Hence, it would appear that rapid attack can occur—in the absence of excessive flow velocities—if the cuprous oxide forms at an abnormally slow rate. When such retardation of cuprous oxide formation occurs over rather large areas, essentially general attack proceeds at an abnormal rate; when it is restricted to small local areas, pitting results.

The factors responsible for the slow growth of cuprous oxide crystals apparently involve the condition of the metal surface. If they were solely characteristic of the water composition, pitting attack, if encountered, would be expected throughout the system; this is rarely the case. The manner in which the metal surface influences the rate of oxide formation is not clear. Possibly certain films on the metal surface interfere with reduction of cupric to cuprous ions by the metal and thus restrict the effective life of the rather unstable cuprous ion to a degree such as to prevent the formation of a protective cuprous oxide film. While this is strictly hypothetical, some degree of plausibility is afforded by impingement results. For example, the inhibition of impingement attack by loose deposits implies that their function is to keep the copper ions adjacent to the metal surface for an appreciable period to permit formation of a protective cuprous oxide film. This in turn suggests an added effective life of the rather unstable cuprous ion—as the result of reduction of cupric ions by the metal surface—to be involved.

In several of the cases considered above, the nature and origin of the surface conditions which rendered the metal particularly susceptible to pitting have been identified. The graphite film on the copper pipe appears to have been a residue of a tube drawing lubricant, as have been the carbo-naceous films which have given the British trouble from pitting. The smooth, shiny oxide films dis-
cussed in conjunction with the cases of the Canadian and English water lines also appear to have originated during manufacture (i.e., during the tube annealing process). In the remainder of the cases other surface conditions appeared to be involved, although their exact nature was not identified.

In quite a few instances we have suspected improper storage or fabrication subsequent to manufacture to be involved in the susceptibility to pitting attack. In one case pits were detected in an unused heat exchanger where soldering flux had run down the interior of the tubes. In another, basic cupric chloride deposits with underlying small pits were detected inside tubing which had been stored in an unwrapped coil.

Avoidance of the use of pitting-susceptible tubing would appear to be the most practical means to avoid copper pitting. Careful inspection of the tubing prior to use would appear an advisable precautionary measure. Admittedly, the exact surface conditions to be avoided are somewhat obscure. However, it would seem advisable to consider any unusual surface films or evidence of corrosion with suspicion. If used, such tubes should be cleaned thoroughly to remove such material prior to installation. Such cleaning probably would require acid pickling. This in itself requires precautions—thorough rinsing including a neutralizing rinse—to avoid leaving an acid residue in the tubes.

Water composition perhaps is a contributory factor to the pitting. However, it appears doubtful that the extremely few cases of copper pitting which might be anticipated in a given distribution system would justify corrective water treatment, even if it were available.

REFERENCES

RESIDUAL CHLORINE IN DISTRIBUTION SYSTEMS

J. V. Feuss

Treated water entering a distribution system may be disinfected, but it is seldom completely sterilized. While the organisms remaining in the water may have no public health significance, their growth in the system and the subsequent build-up of organic and inorganic materials can create serious problems. The primary reason for maintaining residual chlorine in distribution systems is often to control those non-pathogenic slime-forming organisms. Maintaining residual chlorine in the distribution system does more than just this. It provides added protection against water-borne pathogens, in the event that the water entering the distribution system is not completely disinfected, and it is often instrumental in increasing the palatability of the water. In addition, it provides at least partial consumer protection in the event of system pollution through cross connections, infiltration, and even sabotage. It is simply good quality control of a finished product—potable water.

Practical experience provides sufficient proof that chlorine is a powerful tool. Analytical chemical and bacteriological studies have also provided information which serves as a guide to the proper use of this tool. The purpose of this paper is to summarize some of the available technical and practical information on chlorination in the hope that it may be of assistance to those engineers evaluating the merits of maintaining residual chlorine in the distribution system.

CHEMICAL REACTIONS OF CHLORINE

Any detailed discussion of chlorine inevitably involves some chemistry. The reactions of chlorine with water and with the many substances that may be in the water and the effect temperature and pH have on these reactions are all related to the performance of the chlorine added.

There are a tremendous number of reactions that can be initiated when chlorine is added to natural waters. It would take considerably more data than we now have on the kinetics of these many reactions, a very detailed analysis of the water prior to chlorination, and a computer to predict exactly what will take place when chlorine is added to the water.

To simplify the ensuing discussion, the majority of materials with which chlorine will react in dilute solutions will be roughly categorized into five groups: inorganic substances, ammonia, amino acids, proteins, and carbonaceous matter.

Of course, the first reactions that should be considered are those between chlorine and water (Reactions 1 and 2). In chemically pure water, chlorine reacts with the water and hydrolyzes to hypochlorous acid (HOCl) and hydrochloric acid (HCl).

\[
\text{Reaction 1: } \text{Cl}_2 + \text{H}_2\text{O} \rightarrow \text{HOCl} + \text{H}^+ + \text{Cl}^- \\
\text{Reaction 2: } \text{HOCl} \leftrightharpoons \text{H}^+ + \text{OCl}^-
\]

When the pH is above three and the concentration of chlorine is less than 1000 mg/l, the reaction is, for all practical purposes, irreversible and instantaneous. The hypochlorous acid dissociates to hypochlorite ions (OCl⁻) and hydrogen ions (H⁺). The equilibrium condition for this reaction is a function of the pH and temperature as shown graphically in Figure 1. Because the dissociation is so rapid, the equilibrium ratio at any given pH remains constant even though the hypochlorous acid concentration may be decreasing.

Since the oxidizing agents in water are the hypochlorous acid and the hypochlorite ion rather than molecules of elemental chlorine, the unreacted excess has been classified as free available residual chlorine. As the pH of a solution containing 1.0 mg/l of free available residual chlorine is elevated, the oxidation potential decreases as shown in Figure 2. The curve plotted by Chang for 8.7 mg/l of free available residual chlorine is almost identical. The oxidation-reduction potential is a measure of the tendency chlorine has to react with other materials. Unfortunately, it is not a measure
of the speed with which these reactions will take place. In essence, as the pH increases, chlorine tends to react with fewer substances, and it is generally accepted that, as the temperature increases, the reactions that do take place will be faster.

The oxidation reactions of chlorine with inorganic reducing agents are generally very rapid. Sulfides, sulfites, ferrous iron, and nitrates are examples of such agents. Some dissolved organic materials also react with chlorine rapidly, but the time required for completion of most organic chlorine reactions is a matter of hours.

The kinetics of the reactions of chlorine with ammonia, amino acids, and proteins, and the products produced by these reactions have been extensively studied at Harvard by Fair, Morris, Chang, Weil, Burdon, and Culver, and, in England, by Palin. The common goal of their work was to theoretically explain the findings of Griffin and other investigators of the breakpoint process. Griffin has shown that when chlorine is added to water containing ammonia or ammonia ions, a residual oxidant is obtained. However, when the initial molar ratio of chlorine to ammonia is greater than 1, oxidation of ammonia and reduction of the chlorine starts to take place. When the initial molar ratio of chlorine to ammonia is around 2, all of the free ammonia is oxidized and chlorine reduced if sufficient time is allotted for the reaction. The reactions of chlorine with albuminoid nitrogen were found to produce a form of the breakpoint curve. But, the hump and the breakpoint in the curves were usually less discernible than those obtained with free ammonia.
The conclusions made from the research conducted at Harvard and that by Palin differed with respect to certain points. Essentially, however, they established that the reactions of chlorine with ammonia can be represented by Equations 3, 4, and 5.

Equation 3: \( \text{HOCl} + \text{NH}_3 \rightarrow \text{NH}_2\text{Cl} + \text{H}_2\text{O} \)
Equation 4: \( \text{HOCl} + \text{NH}_2\text{Cl} \rightarrow \text{NHCl}_2 + \text{H}_2\text{O} \)
Equation 5: \( \text{HOCl} + \text{NHCl}_2 \rightarrow \text{NCl}_3 + \text{H}_2\text{O} \)

The authors also agreed that the rate of chlorine substitution and the reaction products are a function of the pH, temperature, time, and initial chlorine to ammonia ratio. For pH values less than 5, the reactions between ammonia and chlorine may require several minutes. The actual products of the breakpoint reactions and the mechanisms of the reactions are yet to be clearly defined. The amount of dichloramine (NHCl₂) formed during the reaction is also questionable. It is agreed that the amount of dichloramine formed is also a function of the temperature, pH, time, and initial ratio of chlorine to ammonia. The amount formed, as found by Palin, is much lower than that found at Harvard under the same conditions. Fair et al.\(^{189}\) report that the equilibrium condition between monochloramine and dichloramine can be expressed as follows:

\[
\frac{[\text{NH}_3^+ \cdot \text{NHCl}_2]}{[\text{H}^+ \cdot \text{NH}_2\text{Cl}]} = 6.7 \times 10^3
\]

This relationship for a chlorine to nitrogen molar ratio of 1 is plotted in Figure 3 (Curve A). Curves B and C in Figure 3 are the relationships obtained by Palin. Baker\(^{191}\) adds support to Palin's findings. In any event, at pH values below 6, some dichloramine formation is to be expected. Palin's research also indicates that at pH values below 7.5 some nitrogen trichloride formation is to be expected as well.

Morris and co-workers,\(^{126}\) as well as Palin\(^{189}\) found the reactions between chlorine and glycine, the simplest of the amino acids, followed a form of the breakpoint pattern. Palin also investigated the reactions of chlorine with valine, alanine, leucine,
tyrosine, and cystine. Figure 4 is from Palin's work and shows the resemblance of the reactions to those of ammonia. Morris noted that there is also some oxidation of carbon occurring which tends to offset the stoichiometric relationships between the available ammonia and chlorine in these reactions.

The oxidation-reduction potential of the chloramines is much lower than that of free available chlorine and is also affected by pH. For pH values between 6 and 8, the chloramine oxidation potential is shown in Figure 2 with a similar curve for a 1.0 ppm combined residual formed with glycine. The influence of the ammonia-chlorine ratio upon the oxidation potential is shown graphically in Figure 5.

The lower oxidation potential of the ammonia chloramines indicate that they are less reactive than free available chlorine. The research conducted by Ingols et al. on the reactions of free and combined available chlorine with various amino acids also indicates that the chloramines react slower and to a lesser degree.

**DISINFECTION WITH CHLORINE**

The mechanics of disinfection with chlorine are still an academic puzzle. If the present accepted theories were thrown together in a general fashion, disinfection with chlorine could be explained as a result of oxidation of a key enzyme or enzymes. The difference between the potency of free and combined available chlorine could thus be explained by the difference between their oxidation potentials, reaction rates, and extent to which they react. Moreover, it is possible that some of the reactions of the chloramines with a key enzyme may be reversible. The varying resistance of organisms to chlorine may be a result of variations in physical resistance to chlorine diffusion offered by the cell wall.

Thus, in practice, the rate of disinfection with chlorine is a function of many variables. It is dependent upon the concentration of chlorine (C), ammonia-nitrogen (N), and other organic and inorganic materials with which chlorine will react (O). In addition, temperature (T), pH, the natural resistivity of the strain of the organism to chlorine (NR), and the imposed resistivity (IR) of the organism as a result of the protection provided by suspended materials in the water all affect the degree of disinfection. For those interested in mathematical expressions, I offer:
\[ \frac{dD}{dt} = f(C) \times f(N) \times f(O) \times f(XR) \times f(IR) \times f(T) \times f(pH) \times f(etc.) \]

This equation has absolutely no practical use in its present form and it will take considerably more coordinated research before anyone will be in a position to integrate it. However, substantial contributions to our knowledge of the relationships between disinfection and some of these variables have been made.

The principal known water-borne enteric bacterial diseases in this country are: typhoid, paratyphoid, bacillary dysentery, and gastroenteritis which are caused by salmonella and shigella organisms. The most significant protozoan disease is amoebic dysentery, the causative organism being the cyst of Endamoeba histolytica. The only virus organism proven to be capable of using water as a mode of transmission is the infectious hepatitis virus.

Butterfield et al.\(^{40}, 41, 49\) have done the most extensive work on the relative resistance of vegetive organisms and E. coli to residual chlorine at various pH values and temperature. Chang\(^{42}\) has studied the chlorine requirements to inactivate amoebic cysts and Snow\(^{43}\) has evaluated this work. Neele\(^{44}, 45\) with the aid of human volunteers, examined the treatment required to inactivate the infectious hepatitis virus.

The following is a summary of the general conclusions made by Butterfield and his co-workers. While many factors were considered during the performance of this research, the effect which imposed resistivity and organic matter may have on the disinfection criteria was necessarily ruled out by using chlorine-demand-free distilled water. All references to combined available residual chlorine are solely ammonia-chloramines.

1) The hydrogen ion concentration has a marked effect on the bactericidal efficiency of both free and combined available residual chlorine. Their killing power is diminished as the pH is increased.
(2) An elevation in water temperature tends to increase the rate of disinfection.

(3) At pH values between 7.0 and 8.5, there is an apparent reversal in the relative resistivity of *E. typhosa* and *E. coli* to free available residual chlorine. At the lower pH values, *E. typhosa* was more resistant.

(4) *S. sonnei*, the most resistant of the six shigella species tested, and some strains of *E. typhosa* appeared to be slightly more resistant to combined available residual chlorine than *E. coli*. None were found to be more resistant than *A. aerogenes*.

(5) The presence of excessive amounts of ammonia did not markedly affect the bactericidal efficiency of the resultant combined available residual chlorine.

(6) Under the most favorable conditions, pH 7.0 and water temperatures between 20°C and 25°C, 100 per cent kills cannot be obtained with 1.2 mg/l combined available residual in ten minutes but they may be obtained with twenty minutes contact time.

(7) At pH 7.0 and water temperatures between 20°C and 25°C, 100 per cent kills are obtained with 0.04 mg/l free available residual chlorine in one minute.

(8) *The longer the contact time with either free or combined available residual chlorine, the more effective the disinfection.*

Chang's investigation of the cysticidal efficiency of chlorine shows it to be dependent upon temperature, contact time, cyst density, and pH. Tests were performed to determine the residual required to inactivate the cysts in water containing about 0.097 mg/l organic nitrogen and between 60 and 80 cysts per ml. For pH values of 7.0 to 8.2, approximately 3.2 mg/l residual chlorine and thirty minutes contact time were required to destroy the cysts. Additional studies led to the general conclusions that the chlorine requirements for cyst inactivation are halved for every 20°F temperature elevation, quartered when the contact time is doubled, increased by 25 per cent when the cyst density is doubled or the pH is raised to 9.0, and halved when the pH is lowered from 7.0 to 6.0. The death of colon bacilli was found to precede that of the cysts.

Becker et al. also examined the effects of chlorine on the life span of *Endamoeba histolytica*. They were concerned primarily with the fact that the cysts used for Chang's work had been carried in the laboratory on artificial media for a considerable length of time and thus may be less resistant to chlorine than cysts derived from man. Many tests were run, the exact number not specified, using various doses of chlorine and contact times. Twenty-two times during the conditions examined (2.0 mg/l residual after twenty minutes to 10 mg/l residual chlorine after sixty minutes) a complete kill was not realized. The major portion of the residuals was probably free available since the initial molar chlorine to ammonia ratios were all above 2 at pH 7.0 and 18°C. The conclusion from this work, as of that from the investigations conducted by Brady and others, showed that the maintenance of a free available residual of 2.0 mg/l and contact periods of thirty minutes or even an hour do not guarantee complete destruction of the cysts.

The apparent disagreement may be due to the different methods used while conducting the laboratory investigations. However, variations in natural and/or imposed resistivity could well have been a significant cause.

As an Army captain, Neefe proved to the misfortune of two volunteers that 1.08 mg/l total residual chlorine (dose = 2.5 mg/l) in raw water for thirty minutes was not capable of inactivating the infectious hepatitis virus. Supercolorination to a 15 mg/l residual after thirty minutes apparently was capable of inactivation.

As a major, Neefe determined that the application of sufficient chlorine to provide a free available and total residual of 0.4 and 1.1 mg/l after thirty minutes contact time was adequate to disinfect previously coagulated, settled, and filtered water containing the virus. The pH values during the tests were slightly below 7.0.

**SLIME GROWTHS**

Growths in the distribution system can considerably reduce the carrying capacity of the conduits, cause objectionable taste and odors, discolor the water, and cause corrosion. During the past twenty years, our research laboratories have examined slime samples from all over the United States. Algae samples from open equalizing reservoirs to felt-like interwoven growths of Gallionella, Leptothrix, and Crenothrix were received for identification.

The ability to form slime on capsular materials
is a characteristic of many fungi. Almost all bacteria, the smallest and most common fungi organisms associated with pipeline growths, have the ability to surround themselves with a gelatinous sheath or capsule during their smooth growth phase. Because of the adhesive properties of slime, it tends to accumulate on the interior surfaces of the pipe. Any insoluble matter in the water tends to adhere to it. Some of the spore-forming bacilli have also been found in many of the samples tested. Some organisms that may adhere to the slime are not actively producing the material. As a result, attempts to correlate the laboratory data on chlorine requirements for destruction of the slime with actual requirements in the field are frustrating.

The concentration of organic matter, the types and concentration of inorganic compounds, pH, temperature, dissolved oxygen, and electrolyte concentration are the predominant factors that decide what, if any, growths will flourish.

With oxygen depletion, many of the lower bacteria are capable of reducing organic sulfur to the odorless hydrogen sulfide. Inorganic sulfur compounds are also readily reduced by at least one species, the anaerobic Sporovibrio desulfuricans. The latter species grow best in warm, sulfate-bearing waters that are low in organic matter. Under aerobic conditions, the Thiobacilli can reverse the procedure and oxidize inorganic sulfur to corrosive sulfates.

The most troublesome growths are usually caused by the higher branching and specialized forms of bacteria. The higher bacteria are usually considered to be autotrophic, but some have been found to be slightly heterotrophic. The common iron bacteria, Gallionella, Leptothrix, and Crenothrix (Figure 6) are capable of deriving their energy from the oxidation of ferrous carbonates. The latter two organisms may use manganous salts as well. The resulting growth is a mesh of threads which encase insoluble oxidized iron or managnese. In time, these growths tend to die, decay, and release the insoluble metallic salts. In cold waters, the growth of Gallionella is favored. When summer comes along, the problem created by Gallionella is alleviated but Leptothrix and Crenothrix can then take over the invasion task.

Beggioata, one of the so-called "specialized" forms of bacteria, oxidizes hydrogen sulfide to free sulfur. These organisms also grow in long filaments and encase granules of free sulfur (Figure 7).

**PERSISTENCE OF RESIDUAL CHLORINE**

In the preceding sections of this paper, the object was to condense some of the technical information concerning chlorination in general. However, this material is as pertinent to the distribution system as it is to chlorination at any other point in the water works. There are other parameters that are specified for each system which govern the desirable type and amount of residual chlorine to be carried. These include the extent of raw water treatment, the amount of bacterial activity and sedimentation in the system, the temperature and pH of the treated water, the materials in the treated water, and the layout and the amount of circulation in the distribution system.

The common statement that combined available
residuals are more persistent than free available residuals is seldom qualified; that is, they are more persistent when the chlorine requirement of the materials in the treated water has not been completely satisfied and/or when the system has been fouled with slime growths or readily oxidizable deposits.

Where raw water is coagulated, settled, and filtered, keeping a free available residual in the water until it reaches the consumer’s tap is usually easier and results in fewer complaints. The major portion of suspended materials is removed and thus, troublesome accumulations of precipitated matter in the system are minimized. The opportunity for oxidation of phenol and related derivatives, ammonia, and albuminoid nitrogen, is usually there.

As the quality of the raw water and/or the degree of treatment decreases, the problems encountered when attempting to keep a free residual throughout the system usually increase. Continued reaction of chlorine with substances in the water while it is in the distribution stage has been known to cause odors not apparent at the treatment plant. Where complete oxidation or saturation of the possible chloro-organics is not practical within the confines of the treatment plant, distribution of the less reactive combined available residuals may solve the aesthetic problems. The need for breakpoint or superchlorination prior to distribution is in no way diminished by maintaining a residual in the transmission lines. Conversion of the free residual to a combined residual with ammonia is common practice in many areas. Williams, at Brantford, Ontario, is now evaluating the use of ammonia for both partial dechlorination and the conversion step. He reports that the process is working well and the complaints of nitrogen trichloride odors in the delivered water have all but ceased.\(^{(123)}\)

If the distribution system is badly infested with slime growths, attempting to maintain a free residual in the system will clean it up several times faster than a combined residual would. But, during that period of time, several consumers would probably complain about the “chlorox cocktail” they were getting. That slime growths can be brought under control with combined residuals was shown by Amsbary\(^{(11)}\) in Champaign-Urbana, Illinois, about 30 years ago. Initially, he added 1.2 mg/l of ammonia and about a year later he was able to maintain a residual throughout the system with a dose of only 0.67 mg/l. On the other hand, Brown\(^{(114)}\) was able to clear up the slime problem in the Santa Rosa, California, system in a few weeks by employing a dose of 3.0 mg/l of chlorine (without ammonia). The newspaper editorials did not praise him for solving the growth problem so rapidly.

The effect water temperature variations have on the persistence of a combined residual were noted in the answers to the questionnaires sent out by Griffin\(^{(104)}\) and the investigations of Plowman and Rademaker.\(^{(117)}\) In general, as the temperature increases, the residuals become more reactive. The critical water temperature appears to be between 60 to 65°F, for at temperatures above these, the rate of residual depletion increases much more rapidly than a corresponding temperature change below 60 to 65°F.

Plowman and Rademaker, with the aid of residual recorders, also found short circuiting through storage reservoirs to be one of the major causes of residual chlorine fluctuations in the system. However, poor circulation in any part of the system will make it difficult to maintain a residual. Where it is impossible or impractical to maintain residuals throughout the system by chlorinating the filter effluent, chlorination controlled by residual recorders at main points in the system may make it feasible. Suggested points of application are in the transmission line just ahead of the grid system, at pump stations, or at storage reservoirs.\(^{(24)}\)

The actual residual level that should be maintained in the distribution system can only be determined by the engineer in charge of that particular system. In Illinois, Klassen has recommended that not less than 0.10 to 0.15 mg/l of free available residual chlorine or 0.4 to 0.5 mg/l combined available residual chlorine be maintained in all active parts of the distribution system.\(^{(24)}\) Griffin’s\(^{(20)}\) survey of 92 water treatment plants showed that thirty of them maintained an average free available residual of 0.18 mg/l and fifty-one maintained an average combined available residual of 0.51 mg/l at the ends of the distribution system.

**PUBLIC HEALTH ASPECTS**

There are points upon which disinfection authorities will disagree. But the fact that the bactericidal efficiency of chlorine increases with time of contact is concurred with by all. If there were no minor leaks in the system, no slime growths, or no possibility of decaying organic matter accumu-
lating in the distribution system, maintenance of residual chlorine is still added consumer protection.

It is difficult, if not impossible, to design a system that can be guaranteed not to leak. It is also difficult, if not impossible, to avoid some crossover of water and sewage lines. The chance of creating a negative head in a distribution line is possible. The chance that more people are getting water infection than we know of is also very possible. It is true that chlorine can only be effective if the pollution of the system is very gradual. How many systems are subject to such gradual infiltration? In the case of mass contamination of the system, the residual chlorine would probably be reduced quite rapidly. But the disappearance of residual chlorine can be monitored. With the help of residual recorders in the distribution system and/or by tap testing for residual chlorine, the possibility of system pollution is brought to the attention of the authorities and the points of pollution are more discernible.

Elissen's analysis of the water-borne disease outbreaks among consumers of public water between 1938 and 1945 reveals that contamination of the distribution system caused the greatest number of cases. One of the largest outbreaks occurred at Newton, Kansas. An epidemic of 3000 cases of bacillary dysentery was reported in 1942. In 1952 the Kansas State Board of Health requested the cities using surface supplies to maintain a minimum of 0.4 mg/l of free available residual chlorine at all consumer taps. Toward the end of 1952, 30 cases of amoebic dysentery broke out among factory workers in South Bend, Indiana. The reason was, again, contamination of the distribution system. In 1956 Kansas reviewed the water quality improvements as a result of their four-year-old request. The request was made into an order.

In some parts of the United States, intentional pollution of the distribution system is once again a real threat. To most communities, sabotage seems very remote. Anyone planning to pump infectious organisms or toxins into the water would probably add a dechlorinating agent if a residual is carried in the system. Twenty years ago, this argument was raised when the federal government requested all municipal water works to maintain residual chlorine in their distribution systems. With the advent of reliable residual recording equipment, this becomes an argument in favor of maintaining residuals. While the field of biological warfare has probably made tremendous "gains" in the last few years, and the original estimation that 1 gram of the toxin of Clostridium botulinum will kill 7 million people has been somewhat diminished, the possibility of intentional contamination due to either nationalism or insanity is real.

CONCLUSIONS

This paper is in essence the conclusions of many papers on the subject of chlorination arranged in such an order so as to aid these engineers considering the merits of maintaining residual chlorine in the distribution system. Proper chlorination can control growths in the system, increase the palatability of the water, give added consumer protection against water-borne diseases, and at least partial protection against accidental or intentional contamination of the system. It is quality control and, in accordance with the motto of the American Society of Sanitary Engineering, "Prevention Rather Than Cure."

REFERENCES

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ADVERSE EFFECTS OF POOR CIRCULATION IN SMALL WATER DISTRIBUTION SYSTEMS

JOHN C. GUILLOU

INTRODUCTION

The purpose of this discussion is to call attention to the fact that large size pipes in small town distribution systems may lead to serious problems with water quality. It is generally recognized that large size mains are desirable for fire protection purposes. Designers frequently fail to recognize that satisfaction of design criteria for fire protection is accompanied by inadequate satisfaction of water quality criteria.

John R. Freeman, who was one of the earliest and most effective of the champions for adequate mains size, is reported to have stated in 1889 that any man who laid a 4-inch main near a factory ought to be hanged. This discussion is not at odds with this early, and probably very true, pronouncement, but it is intended to demonstrate that satisfaction of fire criteria is only one part of the effective design of small town water distribution systems. In addition to the need for an adequate rate of water flow is the need for an adequate quality of water supply. It is in meeting the quality criteria that the designer is forced to consider the problem of circulation in the proposed system. The water leaving the treatment plant may be of very high quality, but upon reaching the customer, the same water may be of very poor and unacceptable quality.

SYMPTOMS OF POOR QUALITY

Two examples of poor water quality which result from excess travel time, or from inadequate circulation, are "red" and "black" water. These two problems are responsible for a large percentage of complaints from distribution system customers. "Red" and "black" water chiefly occur in systems which receive their supply from aquifers containing raw water with dissolved iron or manganese. When these soluble metals are oxidized they change to the insoluble state. In the case of dissolved iron, in the ferrous state, oxidation causes the formation of ferric hydroxide and a distinctive red-rust color precipitate is formed. When the raw water contains manganese, oxidation forms a black precipitate which is equally objectionable. Development of the precipitates is occasionally accompanied by objectionable odors.

Unfortunately, the occurrence of red water is not limited to systems which draw their basic supply from beneath the ground. Many systems which have surface sources also experience red water problems even though there is no appreciable dissolved iron in the raw water supply. In this case, red water is caused by the corrosion of metal surfaces within the distribution system. Iron is dissolved from the pipe and tank surfaces and oxidized to insoluble rust. It is then carried through the system to accumulate in those pipes where there is a low velocity of flow.

It is interesting to consider the actual surface area of pipes in small distribution systems. Table 1, based on evaluation of 1955 operating data, has been prepared to illustrate that very appreciable contact area is available even in small systems. The calculations are based upon an assumed pipe diameter of 6 inches which is possibly excessive for small towns, but is conservative for larger towns.

The table indicates that for a town with population of 10,000 persons the contact area, only within the pipe, is 384,000 square feet, or 24 square feet per person.

<table>
<thead>
<tr>
<th>Population Group</th>
<th>Population</th>
<th>Miles of Main</th>
<th>Pipe Area Square Feet</th>
<th>Acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16,000</td>
<td>2.9/1,000</td>
<td>384,000</td>
<td>8.8</td>
</tr>
<tr>
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<td>2.0/1,000</td>
<td>339,000</td>
<td>12.4</td>
</tr>
<tr>
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<td>37,000</td>
<td>2.4/1,000</td>
<td>538,000</td>
<td>16.9</td>
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<tr>
<td>4</td>
<td>60,000</td>
<td>2.4/1,000</td>
<td>1,190,000</td>
<td>27.3</td>
</tr>
</tbody>
</table>

* Based on 8,280 square feet per mile.
CONTROL OF OXIDATION

One method of chemical control of red water is the addition of polyphosphates to the water as an initial step in treatment. The usual rates of application are between two and four parts per million of polyphosphates per part of iron up to a limit of about two to four parts per million of iron. The mechanism whereby polyphosphate inhibits the formation of the red water is known as sequestration. Examination of available literature indicates that the addition of polyphosphates is by no means a cure-all to the situation. It is apparent that in time the effectiveness of polyphosphate decreases and that if too much iron is in the water supply polyphosphate is sometimes ineffective. Furthermore, the development of a phosphate environment may stimulate the growth of certain bacteria within the distribution system.

It is also common practice to add polyphosphate to active, but iron-free, waters which would attack exposed iron surfaces. In this case, the sequestration process is supposed to occur at or near the wall of the tank or pipe. Continuous treatment is required because the process is a consumptive one. Unless a continuing supply of polyphosphate is available at the point of attack, sequestration will exhaust the available supply, and red water will result.

A method of eliminating the pickup of iron from exposed surfaces, as opposed to controlling the change of state, is to coat the inside surface of the pipe and tanks with water-borne additives. Several investigators have reported remarkable success with this procedure.

IMPORTANCE OF CIRCULATION

The importance of flow velocity within the main cannot be overemphasized. If the raw water contains iron and is treated by the addition of polyphosphates, the finished water should be relatively stable. Obviously, the shorter the delivery time of the treated water the closer the delivered water will approximate the quality of water leaving the treatment plant.

Velocity of flow is even more important when iron pickup from the distribution system is considered. If it is accepted that the iron pickup for a given volume of flow is a function of contact time then it follows that as the contact time is decreased the water quality must increase. Thus, high velocities will be associated with high quality and low velocities will be accompanied by poorer quality.

The mechanics of iron pickup, and the consequent occurrence of red water, relative to flow velocity, may be visualized by reference to the velocity curves of Figure 1.

Considering the velocity diagram for laminar flow, it is noted that the rate of movement is zero at pipe wall and that it increases gradually to a maximum at the pipe centerline. Thus, for the case of the laminar flow, there will always be a substantial thickness of slow-moving water in close proximity to the pipe wall, and as a consequence substantial iron pickup should be anticipated. Under full laminar flow rates the development of substantial iron concentrations within the thick laminar flow layer adjacent to the wall produces excessive red water complaints when surges of flow to higher velocities destroy the flow structure and introduce the iron into the main body of the flowing water in the system.

From the viewpoint of chemical treatment for sequestration, or for coating the pipe wall, it is apparent that the slowly moving water will be deficient in polyphosphate as well as in the coating agent.

Considering the turbulent flow profile the figure indicates that the major volume of flow is insulated from the boundary of the pipe by a relatively thin laminar film. In this case, the iron pickup is re-
Figure 2. Water distribution system analysis; Hammond, Illinois: Existing flow conditions

Notes:
1. Concentrated take offs are in gal per day.
2. Travel times in hours shown thusly.
3. Darcy equation used.
4. Areas of red water indicated thusly. 
ADVERSE EFFECTS OF POOR CIRCULATION IN SMALL WATER DISTRIBUTION SYSTEMS

55

The Hammond Situation

A study has recently been completed regarding the occurrence of red water in the water distribution system of a small town in central Illinois. The town of Hammond, with a population of about 400 persons, is a farming community without industry but with some residential area devoted to homes for individuals working in nearby, but not local, industrial developments.

Raw water is obtained from wells founded in a fairly shallow glacial drift. In 1957 the demand for water was at the rate of about 11,220 gallons per day, or less than 30 gallons per capita. The well pumps were capable of delivering the required volume in about 30 minutes. After treatment, flow was delivered to a 50,000-gallon capacity elevated steel tank.

Treatment included aeration for removal of hydrogen sulfide and methane, oxidation of iron, prechlorination, filtration, and softening to reduce the hardness from 375 to 95 mg/l. The system was installed in 1935 and consistently produced a finished water low in hardness; without taste, odor, or color; and of excellent sanitary quality.

Despite the treatment process, and the flushing of mains within the capability of the 50,000-gallon elevated tank, red water plagued the system from the outset. During 1955 and 1956, water samples from the distribution system showed iron concentrations as large as 4.6 and 7.5 mg/l.

As shown in Figure 2, the Hammond system consists of a 6-inch diameter peripheral loop with internal distributors 4 inches in diameter. All of the pipe is cast iron. The topography is flat and all mains are virtually level. Analysis of flow distribution in the system, using the Darcy equation and Moody diagram because of the low velocities, developed that the mean flow time to the most remote point of the main system was 163 hours or 7 days. The maximum average velocity was 0.045 foot per second and the pressure drop was less than 0.005 foot. Take-off flows and travel times to various points in the system are indicated in Figure 2.

Comparison of calculated flow times with the record of red water complaints showed that if the computed travel time was in excess of 40 hours an objectionable deterioration of water quality should be anticipated.

In an effort to increase water quality by recirculation, or by increasing the velocity of flow, several flow distribution analyses were completed.

As indicated in Figure 3, a return line to the treatment plant was assumed to exist at the north end of the system and a valve was closed to cause clockwise circulation in the system.

When the recirculation rate was assumed to be 50 gpm the travel time to the southwest corner of the system was reduced from 65.1 to 8.2 hours. Similar reductions in travel time for other points in the system may be noted by comparing Figures 2 and 3.

Similar calculations were performed for recirculation rates of 25 and 150 gpm. The results of these calculations are summarized in Table 2.

A plot of the travel time and recirculation rate data is presented as Figure 4. From this curve it is noted that the travel time to the southwest corner of the system may be reduced to less than 40 hours if the recirculation rate is only about 5 gpm.

Based on the preceding calculations it appears that minimal rates of recirculation would result in eliminating the deterioration of water quality which was experienced by the utility.

Substantial experimental work was undertaken in the field to correlate the reduction of iron in the system with different rates of recirculation, valving of the system, and chemical treatment. The final schedule of operation included 6 hours of recirculation per day at the rate of 31 gpm, the addition of 20 mg/l of sodium hydroxide to the finished water at the plant and 8 mg/l to the recirculated

<table>
<thead>
<tr>
<th>Recirculation Rate (gpm)</th>
<th>System Velocity (Ft. per sec.)</th>
<th>Travel Time (hr.)</th>
<th>Reduction in Travel Time (hr.)</th>
<th>Volume Recirculated (Gal.)</th>
</tr>
</thead>
<tbody>
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<td>0.045</td>
<td>65.1</td>
<td>0</td>
<td>20,100</td>
</tr>
<tr>
<td>25</td>
<td>0.216</td>
<td>13.6</td>
<td>0</td>
<td>20,100</td>
</tr>
<tr>
<td>50</td>
<td>1.31</td>
<td>8.2</td>
<td>0</td>
<td>24,400</td>
</tr>
<tr>
<td>150</td>
<td>8.82</td>
<td>3.5</td>
<td>0</td>
<td>31,700</td>
</tr>
</tbody>
</table>

* To southwest corner of system

---

Table 2

Recirculation Data
Notes:
1. Concentrated take-offs are in gal per day.
2. Travel times in hours shown thusly.
3. Darcy equation used.

Figure 3. Water distribution system analysis; Hammond, Illinois: 50 gpm take-off flow condition
flow, and the addition of 2.7 mg/l of chlorine to the finished water and 2.0 mg/l to the recirculated water. The cost of scheduled operation was $12 per month for chemicals and less than $1 per month for recirculation costs. It is interesting to note that the demand increased from 11,220 gpd when the study began to about 18,000 gpd when the final schedule of operation was developed.

**CONCLUSIONS**

Two major factors appear to be important in determining the quality of water in a small town distribution system for any given quality water leaving the treatment plant.

The first and most important of these items is the relation between pipe size and the demand for water. It is apparent that a 6-inch diameter pipe with a low demand will cause red-water trouble through iron pickup and quality deterioration while at a high demand rate the same pipe with the same water would not cause trouble. The reason is that during the low demand period, low flow velocities exist in the pipe and sufficient contact time is provided for substantial iron pickup. When turbulent flow exists in the distribution system, or when the flow rate is high, most of the water moving through the system is not in contact with the pipe wall, because of the insulating effect of the laminar boundary layer. Also, with turbulent flows, the effectiveness of chemical treatment is greatly enhanced to prevent any iron pickup.

A second factor which contributes to the development of the red water problem is the elevated tank. For optimum conditions of water quality the tank should be situated away from the treatment plant, preferably with the load center located between the plant and the elevated tank. It appears that the elevated tank should be of relatively small capacity with ground or distribution storage being provided to satisfy the storage requirements of fire flows. The increasing availability of excellent mechanical equipment in the form of booster pumps, sensing equipment, and flow controllers indicates that it may no longer be necessary or desirable to maintain the bulk of the fire storage in the elevated tank. It should be recognized that regardless of the location of the tank, unless the treatment plant discharges directly into the tank and not into the system, most of the water in the tank is riding on the line and does not change from day to day or possibly from week to week.

Two considerations are probably responsible for the development of an overdesigned system. First, major reliance is placed upon fire flow criteria for the determination of pipe and elevated tank sizes. Fire demand is extremely large when compared with normal demands, even during periods of peak flow, in small town distribution systems. Consequently, if the designer provides a main size which is capable of delivering the fire flow he is courting problems of quality deterioration. Secondly, current practice often anticipates a considerable growth of population which never materializes. Again, the result is oversized mains and possible problems of quality deterioration.

It is suggested that, in the case of small towns in particular, the designer must accord equal attention to fire flows and water quality.

**REFERENCES**

EFFECTS OF POOR CIRCULATION IN LARGE WATER DISTRIBUTION SYSTEMS

Joseph J. Rossbach, Jr.1

It is reasonable to presume that the effects of poor circulation in a large system are somewhat the same as those in any system, with the difference only in proportion. If poor circulation is not corrected, the ultimate result is a degrading of the water quality in the system. This, in my opinion, is inevitable.

One can not talk about the effects of poor circulation without discussing, or at least mentioning, the water plant product or, in some systems, water plant products of the past. The quality of water of the past is generally hard to establish. Even if past records are available, it is impossible to run laboratory tests of water that has already been consumed by the customers. Therefore, it is assumed that in discussing effects of poor circulation in any system it must be presupposed that all efforts have been made to supply to a system an excellent quality of water that is stable and has the characteristics that do not aggravate the system through which it is to flow. This is a basic premise. The environment through which this water flows then becomes the subject of our discussion.

If all systems had piping which had been extremely well designed, with no dead ends or dead loops, or had piping that was adequately lined with a noncorrosive, nonleaching material, and had piping on which a constant load was always imposed and had always contained the highest quality water, there would be no subject for discussion. However, the brutal fact remains that no such system exists today and every detail of variance from the ideal makes the problems of water quality in the system more perplexing.

These variations from the ideal are what I would like to discuss. Since my job with the Metropolitan Utilities District basically is an operating job, I would like to point out how these variations from the ideal affect the man operating a water distribution system. He is generally faced with a system that inherently is not conducive to good water quality. There are several reasons for this:

1. A water system of the past and of today is basically designed for fire flow.

2. Dead ends are sometimes permitted or even fostered by some main extension policy.

3. Gridded systems become dead loops.

4. Some lines in the water system are designed for reverse flow for continuity of service.

Let us now discuss these points and examine briefly how these common design elements contribute to poor circulation in a water system.

Because of the role placed on the water system of a modern city for fire protection, the system is primarily designed for fire flows, instead of for domestic or commercial flows. A large percentage of points out of a total for the complete NFBU rating of a city are assigned the city's water supply. Cities that rate poorly in this matter contribute greatly to increased fire insurance rates. Consequently, most designers are conscious of this fact in their design.

Modern fire pumper units are capable of pumping 850 to 1,000 gallons a minute from a fire hydrant. Most fire departments are beginning to want the amount they are capable of pumping. In modern design of water distribution systems, six-inch minimum-size mains are being replaced by eight-inch and twelve-inch minimums to provide heavy grids to support the desired fire flows. The developers of new subdivisions are changing from the old square block of a tenth- to a twelfth-mile square to long sweeping streets without cross streets, leading to semithoroughfares which reduce traffic in these suburban wonderlands. The designer still must provide adequate fire protection in these, as in a well-gridded area, and must compensate with larger mains to feed the thirsty fire hydrants.

The domestic flows required to supply water to the customers in residential and suburban areas fall far below the fire requirements. In a simple study made in 1960 in our system, consumption was recorded from IBM meter reading in a purely resi-
dential area. Along with this, accurate customer counts were made. From these data and other data from our pumping stations for peak demand hours, we found that the average peak hour consumption was as low as one-third to one-half gallon per minute per household. This is low compared to the old rule of thumb of one to one and one-half gallons per minute peak hour consumption. These peak demand flows fall far below the fire demands for the same areas of the system. When the fire flows are compared to non-peak hour consumption, which are a large number of small intermittent demands required by each household, or when compared to the eight- or nine-hour period between 10:00 p.m. and 7:00 a.m. of virtually no flow, the ratio of flows becomes even greater. These small domestic flows in pipes designed for fire flows then result in a condition of poor circulation throughout the system. These are what I would like to refer to as dead loops. Experience has shown us that there are areas in our system where adequately gridded systems exist between adequate feeder mains in which there is very little flow under ordinary circumstances. How often do we realize when looking over a system that there are no flow conditions in areas where there is no demand? We more often think of a system as constantly flowing.

Take, for instance, a six-inch main, thirteen hundred feet long between two eight-inch feeder mains. If sixty-foot lots are assumed, there would be approximately forty customers along this line in a residential area. If our one-half gallon per minute per customer is assumed, there would be a demand of twenty gallons per minute for the whole main or ten gallons per minute from each end under peak conditions. Even if we were to use the old rule of thumb of one and one-half gallons per minute per customer we would have a demand of only sixty gallons per minute, or thirty gallons from each end. This means that under peak demand conditions the velocity in the six-inch pipe at the point of take-off from the feeder main is only .34 feet per second. As the water moves along the main the demand decreases as each customer is served, so that near the center of the main is virtually a dead end and practically no velocity. The retention time of water in the main based on average velocity becomes seventy-two minutes under peak flow conditions. This problem is magnified in the long reaches of the newer subdivision developments.

The most habitual offender for poor circulation is the dead end. The dead end is readily recognized and in most cities is dealt with properly. The same situation exists in a dead end that exists in one half of a dead loop, except that there is no chance for circulation. This can only be dealt with by flushing in one way or another. Consequently, the operator is again faced with long retention times.

These retention times in a system are increased by the nightly periods of nonuse, as pointed out before, and are naturally extended by the size of the system and the distances from the plant. Because of less demand, many points close to the plant may be further away in time-distance than more remote points in the system.

To cope fully with such a problem the operator should be able to determine these time-distances. The present methods of computing these, even with an electronic computer, become overwhelming in a large system. It is the author’s belief that some way of determining these time-distances in a large system on a practical basis would be very worthwhile to the operator. Some rough estimates of these times for water to reach remote parts of our system were accidentally discovered by performing polyphosphate determinations of distribution samples. However, a better method is needed. Perhaps a nontoxic tracer could be used. It is hoped that eventually someone will arrive at a fairly reliable and practical method of determining retention time in various parts of a system so that in the future an operator can base his operations on such results.

Even the best of water can be bottled up only so long; then it begins to lose its fine quality. The environment in which its exists is an important factor in its enduring quality. As the water flows from the plant to the remote ends of the system under normal demand conditions, it hurries along the large trunk mains, then flows to the smaller feed mains, and there moves into the vast network of distribution mains as water in a main stem river moves into the quiescent pond of the backwater of a dam. All along its way it travels through a varying environment. It may be introduced to products of corrosion or soil bacteria; to deposits of precipitated chemicals, such as alum, magnesium, carbonates, or to just plain dirt. When this water is sent from the pumps at the plant, all of its characteristics are carefully in balance. In its fury to reach a customer demanding an abnormal amount somewhere in the system, it may pick up some of
these foreign materials and carry them along until the demand is satisfied, at which time the water quickly loses its velocity, and deposits this material at another corner of the system. This material provides a new atmosphere in this part of the system. During the quiet times the water reacts with its new environment and loses its original well-established, well-guarded qualities.

Trouble may start with an insignificant change in pH when the water absorbs the products of corrosion. Or it may cool down a little in the summer, affecting its stability. Thus, the never-ending chain starts in the deterioration of water quality. These changes, if based on chemical action, generally take place faster in summer. The summer also is the time of peak demands and thus there is more opportunity to stir up the system.

Perhaps the greatest offender in most systems is iron oxide. Our system is an excellent example. There is no iron in the source, yet in a few of the more poorly circulated points, tests have shown as much as 10 to 15 mg/l of iron. This was flocculent iron resulting from the corrosion of cast iron. Although they do not admit it, many cities have red water problems. However, in their own back yard they are faced with these problems and try to do what they can about them.

There are additional color symbols that manifest water-quality change. Some may have white, green, blue, or even black water, but whatever the color symbol, these changes probably result from too long an exposure of perhaps originally good quality water, in a system environment that is far from ideal. It happens in the best of systems.

Granted that unsatisfactory conditions exist—namely, poor circulation, water quality degradation by system environment, or conditions existing from the past—what steps can an operator take to alleviate these problems that generally manifest themselves in the classic series of events of loss in water quality, corrosion, tuberculation, loss of capacity, and customer complaints, along with the cringing knowledge within the soul of the operator that these conditions exist? In some cases they are put aside with the thought that maybe they will go away. However, when the operator faces reality, he realizes the problem is his and that something must be done.

The remedies can be divided into two categories: permanent solutions and temporary stopgaps. But before cures can be offered, the disease must be diagnosed. This alone can take many months of concentrated work. During this period, the utility operator begins to know his system. He must ask himself many questions, such as: Where do the conditions exist? Why do they exist, how frequently, and on what occasions? Only when these questions are answered can a cure be prescribed.

An investigation may take many forms, for example: exhaustive chemical determinations and chemical analysis of water from the system, examination of scales from tapping coupons, colored photographs at cut-in locations, or test pipe throughout the system. Often an educational program to make construction crews semitrained observers of existing conditions in the system piping helps gather information. Of course, careful scrutiny of the water flowing from the plant is always necessary. Very often, outside aids can help focus attention on the forest and still leave the trees standing. These outside aids also provide fresh ideas about the problem.

In our system we are in a period of investigation. By these investigative efforts we hope to improve water quality in our system. Many things have been done and many remain to be done. The one thing that has been done, that can be considered a temporary stopgap, is an extensive flushing program. The many dead ends are thoroughly flushed about every twenty-five to thirty-five days from April to October. Our water temperature varies from thirty-three degrees to eighty-eight degrees. Thus, when anticipated chemical action is greatest because of warm water temperature, the flushing program is most active. In addition to these operations, periodic flushing programs in low-flow areas are accomplished in an attempt to continue the flow of good quality water into these areas. Crews doing the flushing record the water used in flushing and also determine iron contents. This is done with packaged pillows of chemicals to fix the effectiveness of flushing operations. The criteria used for flushing durations are low iron contents. These planned flushing operations take into account terrain, hydrant sequence, and total volume of the lines flushed, all of which are considered important in our program. Last year we performed 2,800 flushing operations and used over 24 million gallons of water for these operations. In some areas where conditions are particularly bad, we have found that continuous flushing is the only solution to the problem. This still does not
entirely remove the cause of the trouble. Another operation that we feel is important in our attack is the handling of customer complaints. We feel that these complaints should generally be settled within an hour from the time the customer calls. The reason for this is that, with this kind of service, we feel that we rebuild public relations that have been somewhat reduced by the complaint and we also get at the cause for the complaint before it becomes untraceable.

Other phases of our present program are many chemical determinations and tests of the water in the system, such as, determinations for alkalinity, saturation index, iron, dissolved oxygen, and tests for sulfate-reducing bacteria, as well as statistical studies for other bacteria in the system.

Scattered throughout the system, mostly in the areas of poor circulation, are test-pipe sections that are periodically observed and photographed. In addition to this, coupons are saved and studied and a short-card form describing the internal condition of the mains is filled out by construction and repair crews. This program has shown us that the mains laid in the 1920's and early 1930's are the greatest offenders, as far as tuberculation is concerned. According to our records, we have about sixty miles of main in our system which fall in this category.

Attempts have been made at specific chemical treatment for given sections of the system in order to provide a more durable remedy than flushing. In October of 1961, an experimental process, fairly successful to date, was begun in the system to clean the small mains and chemically coat the lines with a thin calcite lining by the McCauley process. Again this summer more lines were cleaned and calcite lined with some success. Although there were disappointments in this field research, we hope that this process can be used to line successfully the mains in a system, thus providing an economical and yet permanent solution to some of the problems of poor circulation in a large system.

Of course, some things have been done that will permanently improve the water quality in our system. Over the past fifteen years, every major unlined pipe from 54 inches down to 20 inches has been lined in place with cement mortar. All pipe that has gone into the system in the last twenty years is also lined pipe. It is not economical to line all the old pipe in the system, but progress is being made. And, of course, considerable progress has been made in the past few years in the quality of water going into our system. Many safeguards have been established and better facilities have been built to meet the rapidly changing conditions of the raw water from the Missouri River.

In the meantime, work will continue and improvements will be made until it can be assured that the water reaching all customer taps is as high in quality as that leaving the plant. This must be accomplished in spite of the inherent poor circulation in the system.

Though many of my examples refer to our system, there are many others that grimly remind others of their systems. If this paper does nothing other than arouse an interest in what can be done about these matters it has accomplished its purpose.
ACTINOMYCETES IN WATER DISTRIBUTION SYSTEMS

J. K. G. Silvey

In recent years, considerable interest has been expressed in the tastes and odors in potable waters that have a musty, earthy, or woody taint, and which reduce water quality. Attention has been focused on the actinomycetes as the causative organisms in the production of these types of odor compounds. It is noteworthy that Rullman(1) over half a century ago, along with Beijerinck(2) concluded that many of the pungent odors described as earthy and which were detected in newly tilled soil arose from the actinomycetes growing in the fertile topsoil. Berthelot and Andre(3) concluded that the odors occurring in fresh water were very similar to those encountered in freshly plowed soil and probably were of actinomycetic origin. Adams(4) cited the earthly tastes in potable waters that had been filtered from the Nile River, and suggested that they were due to the by-products of the actinomycetes growing adjacent to the shoreline. Thaysen(5) noted the same intense earthy and woody odors in salmon removed from certain streams in England, and in his investigations found that actinomycete odors or muddy taints were one and the same in origin; thus he concluded by experimentation that the organic compounds produced by these organisms had been absorbed by the gill membranes of the salmon, had penetrated the flesh, and had conveyed the same tastes and odors to the meat that occurred in water supplies. Issatchenko and Egorova(6) observed odors in the Moscow River and concluded that these odoriferous compounds were produced by actinomycetes, probably of soil origin, and had dissolved in the waters of the river, imparting earthy and woody taints that rendered the water unpalatable. Umbrecht and McCoy(7) did detailed studies on the occurrence of actinomycete spores in the bottom mud deposits of certain northern lakes. However, no mention in particular was made concerning the role of these organisms in the economy of the lake.

In 1950 Silvey et al. (8) summarized a five-year investigation of reservoirs in Texas and concluded that the major tastes and odors previously attributed to algae were apparently due to actinomycetes growing in the water, in mud, and on the aquatic vegetation and organic residues in or around reservoirs. Since that date, considerable field and laboratory work has been completed which indicates that the actinomycetes are of prime importance in producing the musty, woody, and earthy odors found in raw water as well as in potable water in areas where proper thermal conditions and nutrients were available to support the growth of these organisms. In England, MacKenzie(9) and Taylor(10) have shown that actinomycetes do create a problem under certain conditions in Great Britain in water supply distribution systems. Complaints of earthy, moldy, and musty tastes and odors arose from the growth of actinomycetes or of microfungi in the pipes inside buildings, particularly under conditions where cold pipes ran alongside hot water or steam pipes, or through basement boiler houses, or bake houses, especially where there was little use of water at night or weekends and where the temperature rose above the critical point of 18°C to 19°C for long periods. In all such cases, the taste problem arose only in the building. Samples taken from hydrants in the street were satisfactory. Furthermore, it occurred only in river-derived water, and not from deep chalk well water, indicating that some dissolved organic matter is necessary for growth of the organism. From time to time, papers concerned with tastes and odors in potable water have made reference to the fact that the filtered water in the clear well was free of tastes or odor, but that samples collected from parts of the distribution system had either a musty, woody, or earthy taint. Also, a few observations have made reference to the fact that as the distribution system extends further from the water plant, intensities of the odors may increase. It should be pointed out that all such citations have occurred during times when the temperature was 20°C or above, and most often when the water in the distribution system exceeded 25°C. In areas
where the temperatures remained cold, there are few notations indicating the same difficulty in underground distribution system samples.

The bacteriological examination of water supplies has generally been directed largely toward the assessment of the probability of pollution with materials that carry disease organisms, and, in special cases, toward the detection of causative organisms of waterborne diseases. Its usefulness in these respects continues to increase the introduction of new methods, and it has now reached a stage where it is possible, not only to form an accurate opinion regarding the presence or absence of dangerous pollution, but also to estimate with some degree of accuracy the probable future condition of a particular supply. Increasing attention, which has been given in recent years to the biology of water supplies, was pointed generally to the desirability of investigating not only the bacteria and viruses of dangerous pollution, but also the great variety of organisms which may be either washed into the reservoirs, rivers, or lakes from the surrounding terrain, which may grow along the border of the reservoir, which may reproduce in the mud, or which may, in addition, flourish in the waters of the lake or reservoir itself. As these studies have progressed, continuous emphasis has been placed on the organisms that contribute tastes and odors to water supply. It has not been difficult to explain that certain types of algae or microfauna may be responsible for fishy, putrescent, pigpen, cucumber, or other types of tastes and odors, particularly if the tastes and odors arose at the same time there was a bloom of one of the organisms in question. In many instances these types of flora and fauna have been reared under laboratory conditions and continued to produce the taste and odor with which they were originally associated. This is particularly true where unspecific cultures have been studied in great detail, as shown by Palmer and by Provasoli. It would be anticipated that almost any type of organism growing in water would produce metabolites which would, in turn, give rise to organic compounds that might elicit an odor or a taste when consumed by man. There has, however, been some question concerning the origin of the musty, woody, and earthy taints that occur in water supplies. It is generally agreed that these organic compounds are the product of the metabolism of the actinomycetes. There is some question by different investigators concerning the origin and identity of the type of actinomycete responsible for the tastes and odors. Certain investigators feel that the terrestrial forms contribute the odor components, while other investigators feel that the major contributors are actinomycetes that are natural to an aquatic environment. As the field and laboratory investigations continue, these questions will be ultimately solved. In the meantime, the potability of water becomes a more important issue, since the quality is unquestionable. The unfortunate superintendent of water works is certain to have a very distinct and unpleasant problem on his hands.

It is perhaps desirable to give the reader some idea of the general conditions under which the actinomycetes may grow, an introduction into their generalized structure, and a brief description of their isolation and general growth characteristics. The actinomycetes are considered to represent an intermediate stage between the bacteria and the filamentous fungi, and, therefore, may be confused with one or the other types of organisms. They were obscure forms until they became highly important in the production of certain antibiotics and were, therefore, largely of academic interest only. Today they have assumed an important place in medical science, and considerable research has been directed toward understanding the mechanisms of their metabolic activity. In general, the actinomycetes are saprophytic forms that flourish under many variable conditions found in soil, fresh water, and salt water. The soil-inhabiting species have been studied in great detail. This investigation has been stimulated, to a certain extent, by the fact that they have considerable economic importance. In these forms, one may observe that the morphological characteristics employed to designate genera have been based almost entirely on the formation of spores in a mature mycelium. Thus, the members of the genus Streptomycetes produce chain spores, while those belonging to the genus Micromonospora produce terminal spores occurring either singly, or, at time, in clusters. The third group of saprophytic actinomycetes belong to the genus Nocardia which do not produce conidia and seldom are found with any of the small filaments extending above the surface of a growth medium (Figure 1). The sources of nutrition for these saprophytic forms may be a large assemblage of organic materials containing
Carbon, nitrogen, and small quantities of phosphates of various varieties, either organic or inorganic in nature. The rate of growth of the actinomycetes is in part dependent on the temperature or thermal conditions. Growth normally begins at around 7° to 8°C, but makes very little progress until after a temperature of 20° is obtained. From here the growth rate is very rapid up through 33° or 34°C at which point it begins to diminish slightly, and when 41°C is reached, growth diminishes abruptly (Figure 2). Thus we can see by the thermal relationships that these organisms are more important in regions of high temperature than in zones that are continuously cold. The aquatic forms of the actinomycetes apparently are mutants from the soil forms, since they possess characteristics of both the Streptomyces and Micromonospora, depending upon the type of nutrition and the organic matter available for growth. It is interesting to note that the adaptations which the aquatic forms have made permit them to grow in multitudes of environments. Since spores are necessarily the intermediate stage in the production of the aquatic actinomycetes, we note that on germination very small filaments are formed, which are referred to as hyphae, and under normal conditions of growth the hyphae will unite or fuse, so as to give rise to a very finely spread mat, referred to as the primary mycelium. At each point of union or fusion, there is normally a small projection produced that may, under optimum conditions, give rise to additional growth. The additional growth produced at each point of fusion results in the production of larger filaments or hyphae, so that the development from the primary stage results in larger groups of branching hyphae, known as the secondary mycelium (Figure 3). In reality, the secondary mycelium may grow and completely enshroud the primary, increasing in size in submerged cultures to five or six millimeter spherical colonies resembling small fluffy balls. Color may begin to be imparted from the growth of the actinomycete to the medium in which it is developing. If the medium is clear, generally a light yellow color is elaborated by the secondary mycelium, indicating it is in the process of forming spores. As long as it is submerged, the spore formation is usually lateral. If and when the mycelium reaches the surface, it will produce aerial hyphae that grow above the medium and which will produce chain spores under normal conditions. There are two situations in which the odor components may be formed. While the secondary mycelium is in the process of developing and as pigmentation is elaborated into the medium, odor components appear in the fluid medium. The solubility of these compounds in water is relatively low—something on the basis of 1 per cent. Thus
are subject to cyclizing, which changes their molecular figuration so that chemical analyses by common methods such as distillation and derivative formation are not successful procedures. If and when the mycelium ultimately develops into a state of chain sporation, it may frequently give rise to earthy odors in addition to woody odors. We must admit that this situation exists more commonly when the hyphae or the mycelium becomes aerial. For example, we would naturally suppose that in rivers and reservoirs, earthy odors would develop more frequently than they would develop in distribution systems, due to the fact that it would be difficult to obtain an aerial position inside a distribution system. We should point out, however, that odors that are earthy in nature when they enter a distribution system may chemically alter due to storage, exposure, or to additional organic compounds. If a water with earthy odors goes into a dead end in a distribution system and is stored for a period of a week or two without use, it is likely that the odors will return to a woody condition. This is a molecular change in the configuration of the aromatic amines that are decyclizing in the distribution system, probably due to the bacterial degradation. If the water is permitted to stand long enough in the distribution system, and few actinomyces are growing, it is likely that bacterial degradation will go to completion so that no tastes and odors are available (Table 1). The time involved in this instance may be relatively short, depending upon temperature.
If temperatures are as high as 25°C in the distribution system, it is likely that the gram-positive, spore-forming bacilli will degrade the odor compounds in a period of five days (Table 1). If temperatures are lower, this period is extendable and will be dependent upon temperature. If the temperature is as low as 16°C, there would probably be very little if any degradation of the compounds.

During the past ten years, rather detailed studies have been made on distribution systems during times when taste and odor compounds were available in the tap water. These investigations have involved geographical areas in which the temperature of the tap water was from 23° to 27°C, especially during the months of July, August, and September. There are numerous methods by which studies may be accomplished on distribution systems, but undoubtedly the easiest and best system is to employ routine bacteriological techniques that are involved in the collection of samples. The size of the sample usually collected is 300 milliliters placed in sterile bottles and returned to the laboratory for general plating techniques. Numerous types of isolation media may be involved in studies or investigations on distribution samples. Recently Safferman and Morris have contributed a technical report entitled "A Method for the Isolation and Enumeration of Actinomycetes Related to Water Supplies." The method described in this report is precise and may be followed by any technician in a water plant. They have suggested two types of media that may be used in the isolation of the actinomycetes from water supplies. In our own instance, we are interested in obtaining a maximum number of bacteria with a maximum number of actinomycetes. Generally, our medium contains 10 gms. glucose, 10 gms. sodium citrate, 4 gms. ammonium nitrate, 2 gms. dipotassium phosphate, 2 gms. disodium phosphate, 2 gms. calcium chloride, 0.1 gm. magnesium sulfate, .01 gm. ferrous sulfate, .1 gm. asparagine, and 15 to 20 gms. agar per 1000 ml. of medium. We suggest this isolation medium because it does not tend to grow many bacteria. The amount of inoculum added to each plate from the water sample is 1½ ml., usually added while the agar is still warm, and normally mixed well with the warm agar so as to obtain rather rapid growth. If the technician so desires, he may add actidione in order to suppress the growth of fungi. We have found that it suppresses the growth of actinomycetes to the extent that counts may be erratic. In addition, we are interested also in the microfungi, since they have been shown by Taylor to contribute musty odors, although the odors do not definitely increase upon chlorination. Since the actinomycetes, whether they are soil or aquatic in origin, have a very slow rate of growth, it is generally necessary to leave the plates for a period of five to seven days before attempting to make a count. It is desirable to always maintain plates for a minimum of 14 days before final counts are made. It is interesting to note that in enumeration of actinomycetes, we are not necessarily depending upon spores for growth. Any part of a hyphal element, either primary or secondary, may result in the growth of a complete actinomycete colony. Therefore, when colony counts are quoted they may represent any stage or structure of an actinomycete that is capable of producing hyphae. The question generally arises in the mind of the investigator, "If I find one actinomycete on a culture plate, does it indicate that the distribution system is actually supporting a growth of these organisms?" In our opinion, the number is too small to be of any particular importance. We generally assume that the count should consistently obtain at least 20 per ml. before there is evidence of actual actinomycetica activity present in the distribution system. In order to be accurate the samples should be run in triplicate on a daily basis, and an average value established. The count is multiplied by two, since only 1½ ml. of inoculum was originally employed. To be accurate, it is desirable that dilutions be made at the same time, so as to obtain as much information as possible. If the laboratory of a water plant is properly equipped, and if technicians have adequate experience, it is far better to prepare the liquid part of the medium, mix it completely, and run it through a Sefitz or membrane filter, adding it to warm, sterilized agar. This produces much more rapid growth than mixing all the ingredients and then autoclaving them, since this practice reduces slightly the quantity of glucose. Also, the practice of cold sterilization minimizes the quantities of calcium phosphate that precipitates in the solid medium. Both calcium and phosphorus are required for complete development of all of the aquatic actinomycetes in an artificial medium.

It is probably desirable to consider the inci-
dence of distribution system contamination as it occurs in various parts of the country along with counts and attending threshold odors. As a typical example, the data in Table 2 shows that a purification plant was producing a finished water with a threshold odor of 2 and that the actinomycete count in the raw water was 700 per ml. The distribution system two miles from the plant had an actinomycete count of 44 and a threshold odor of 10. At four miles from the plant, the actinomycete count was 106 and the threshold odor number was 16.

It should be observed that the spores of the actinomycetes and the hyphal fragments are exceedingly small and therefore capable of passing through most water plant filters. Spores and mycelia produced by the aquatic forms grow in an aqueous medium and therefore submerge readily while those produced by the terrestrial forms apparently have a hydrofuge surface and are generally prone to float through a distribution system. Thus, it is apparent that the latter type rarely produce growth in pipes. Table 1 summarizes varying situations in distribution system contaminations showing the thermal data, the chemical analysis of the water, and the conditions that contributed to actinomycete growth. We would suspect in most situations that the raw water would contain apparent threshold odors prior to the time that the potable water became contaminated with spores. This is not always the circumstance, but generally it occurs after the water plant has solved most of its problems and the odors have diminished in raw water so that they may be properly handled. Thus, after contamination, the distribution system may continue to carry tastes and odors for a period of three weeks to three months depending upon the temperature and the bacterial population of the system.

Distribution system contamination is not restricted to the South or the Southwest. It is rather common in the Middle West, particularly during periods when the water level in the lakes or rivers is low and when higher temperatures prevail for a period of six to eight weeks so that the temperature of the tap water is 26°C or above. The greatest numbers of distribution system contaminations were found in the summers of 1952, 1953, 1954, and 1955, when the rainfall, and therefore, the river flows, were low in the West and Southwest. In 1956 and 1957 a similar situation of distribution system contaminations was found in the Middle West and in eastern areas, particularly from Chesapeake Bay south. In 1958 it was relatively wet in that area and as a consequence the flows in the rivers were high and the quantity of actinomycete growth was reduced as were the tastes and odors from distribution systems. Again in 1960 flows in that area were relatively low and threshold odors were noticeable from distribution systems as well as from raw water. The same occurred in 1961. During the past summer, the odors were less intense. Thus, such contaminations become somewhat predictable when related to water flows, quantity of pollution, characteristics of the water, thermal conditions, and other situations over which man apparently has very little control.

It has been observed that well water pumped through a distribution system under normal conditions does not have adequate quantities of organic matter to furnish proper nutrition for the growth of actinomycetes. Rivers and reservoirs in particular normally have adequate quantities of organic matter, and in instances where softening plants are available, scales formed on the interior of the pipes during times of summer flows form encrustations which have considerable quantities of organic matter. Analytical procedures in our laboratory demonstrate that approximately 50 per cent of the scale may be organic in nature. Since the scale normally has adequate quantities of phosphate, we find the actinomycetes usually associated with other fungi, which are particularly common in water as well as the small growths of blue-green algae. The growths may occur on tuberculations, or they may be found in depressions between tuberculations. Growths also occur very commonly in dead ends and at unions between mains where there is an irregularity in the elevation, due either to a slight seepage or a loss in the sand bed beneath the pipe end. It is understandable that the quantity of actinomycetes growing in a distribution system may be dependent somewhat on the amount and rate of water flow through the pipe. For example, in fast flows there will not be much growth, but wherever the water flow slows

<table>
<thead>
<tr>
<th>Threshold odor</th>
<th>Actino count</th>
<th>Temp H2O°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Water</td>
<td>Finished Water</td>
<td>Clear Well</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>22</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 2

ACTINOMYCETES IN WATER DISTRIBUTION SYSTEMS
down in areas the growth becomes more dense; consequently, in small pipes radiating from the distribution system and having low water usage, the quantity of actinomycetes frequently increases, sometimes obtaining counts in excess of 100,000 per ml, and threshold odors as great as 70. In cities that experience difficulty with red water, particularly at dead ends, and which infrequently flush their fire hydrants, we have found a biological paradise as regards microorganisms on the interior of these mains. This applies especially to the actinomycetes which may grow in those areas in accompaniment with various types of bacteria, with a special reference to the gram-positive, spore-forming group.

METHODS OF CONTROL OF DISTRIBUTION SYSTEM CONTAMINATION

Once finished water gains access to a distribution system, additional treatment is generally minimized. We assume that the addition of specific quantities of chlorine should take care of most emergencies. As a matter of fact, the minimum total available chlorine residual suggested by the Public Health Service assumes that larger quantities were originally present in the water prior to the time it flowed into the distribution system. In most instances, however, organic matter dissolved or suspended in the water may bring about a reduction in chlorine residual at a more rapid rate than normal resulting in very low concentrations. This is especially true when fragments or spores of the actinomycetes pass through the filters and start growing in the clear well and distribution system. Studies on the effects of chlorine on spores and hyphal elements of the actinomycetes in the laboratory are not as conclusive as field experience in determining chlorine residuals necessary for complete eradication. For example, in certain distribution systems in the Middle West, the total available chlorine one mile from the plant was .86 mg/l. When the water left the clear well, it contained 1.4 mg/l total available chlorine, of which 1 ppm was combined and .4 mg/l was free available. One may speculate concerning the reason for the loss of chlorine in such a short distance, but in examining the distribution system, it was found that not only were actinomycetes available, but also gram-negative heterotrophic bacteria embedded in the slimes produced by the growth of \textit{Phormidium}. In a sample collected from a tap, the water required a considerable period of rapid flow before contaminants could be obtained, indicating that the microorganisms were not free in the distribution system, but were rather well secured on the interior of the pipe. Since numerous varieties of true fungi were also isolated, it was assumed that they may be important in forming a dense mat that would aid other organisms in remaining affixed to the pipe lining. For example, we frequently found an association of \textit{Fusarium} with actinomycetes, as well as with \textit{Tubercularis}, actinomycetes, bacteria, and fragments of blue-green algae. (Table 1.) On other occasions we have found a fungus belonging to the genus \textit{Cephalodochium} in samples of tap water indicating that these organisms were relatively common. In addition, we should not overlook the fact that fungi such as \textit{Tubercularis} and \textit{Botryosporium} are also associated with deposits in a number of the distribution systems. Apparently these fungi are more resistant to chlorine than the actinomycetes, and in the association, as they existed in the pipe, they seemed to have a greater affinity for picking up the chlorine without damage so that the actinomycetes continued their growth.

It is possible to control the actinomycetes in a distribution system with high chlorine residual provided the populace consuming the water will tolerate the high quantities of chlorine. It has been our experience that the quantity of free available chlorine essential for bringing about destruction of the spores or the primary and secondary mycelia of the actinomycetes is 1.2 mg/l. If all of the total available chlorine exists as combined available, very high concentrations are required depending upon the pH and temperature of the water. It should be observed that different strains of actinomycetes have varying resistance to the types and quantities of available residual chlorine. In laboratory experiments, we have studied forms isolated from distribution systems and have shown that they could live in concentrations as high as 6 mg/l. We are not certain whether continuous exposure to chlorine induced resistance or if certain spores were more resistant than others and thus propagated the naturally resistant strains. It would seem, therefore, that the application of chlorine for the control of actinomycete contaminations in distribution systems is not always successful. On a few occasions when only chlorine was available for control, we
ACTINOMYCETES IN WATER DISTRIBUTION SYSTEMS

have advised the public by means of the press that high quantities of chlorine were essential for control of tastes and odors for a short period of time: usually 24 hours. In such instances, 6 or 7 mg/l were added to the finished water for approximately one day. Usually such episodes have passed with very few complications. In other instances where high quantities of chlorine have been applied without any former advisement, the situation, as you are well aware, has not been a particularly pleasant one. It is desirable to be certain that a distribution system is contaminated before resorting to practices that might prove unsuccessful. This is accomplished by doing plate counts from the clear well and different parts of the distribution system and noting the quantity of actinomyces that develop. In addition, threshold odors should be run on each set of samples. If the counts and the threshold odors increase in samples as one collects progressively from the water plant to the distribution system, it is likely that contamination does exist. If only counts or odors alone increase, it should be concluded that a batch of water got through the plant with improper treatment.

Chlorine dioxide may also be employed for the eradication of these organisms from distribution systems. In practice, it is best to add the gas for a period of five to six hours, preferably from 9:00 p.m. to 3:00 a.m. so that the early morning flows will rapidly distribute the ClO₂ throughout the system. The concentration desirable for eradication of fungi and actinomyces, as well as blue-green algae, is roughly 2.5 mg/l. There are exceptions to the required dosage however, which are dependent on demand. In one water system, chlorine dioxide was added for two days before any residual could be obtained at the taps near the ends of water lines. This was due to the fact that there were organic deposits clinging to the interior of the pipes, and it was necessary to satisfy the chlorine dioxide demand before we could obtain a concentration of 2.5 mg/l. We should add that the addition of this gas did not increase the threshold odors as much as chlorine, and that the detectability from the standpoint of taste was much less. If the equipment is available to a water plant, it is frequently an excellent idea to begin adding chlorine dioxide to the distribution system prior to the time a contamination occurs on the lining of the pipes. Thus, when tastes and odors of actinomyctic origin appear in the raw water, it is advisable to add chlorine dioxide to the finished water rather than chlorine so as not to aggravate the taste and odor components. At the same time, the ClO₂ should provide an unfavorable environment for growth of microorganisms in the distribution system.

It was noted earlier that the major odor-contributing compounds appear to be aromatic amines with low solubility in water, particularly if the pH was distinctly basic. The higher the pH, the less the solubility; therefore, the greater the liberation of the odor compounds, resulting in higher intensities of taste and odor from a water. It is a well-known fact that finished waters produced by softening plants with a pH from 10.5 to 11.4 exhibit far more intense tastes and odors than water with a pH of 7.4 to 7.8. If water could be produced for the consumer with a pH of 5, the quantities of tastes and odors detected in the finished water would be low. This particular phenomenon was observed in jar-testing investigations several years ago, but was not at first put to any practical use. After laboratory investigations showed that a finished water with a pH of 10.5 would have a threshold odor twice as great as the same water at a pH of 7.6, it was decided that some practical application should be made of this characteristic. The cities where tastes and odors were a problem and where softening was necessary were suitable sites for testing the usefulness of this method for reduction of taste and odor components. Thus, as soon as tastes and odors became detectable, the pH of the finished water was lowered as much as possible. Care was taken to insure adequate alkalinity so as to minimize the chances of producing red water. At the same time the change was not rapid enough to distress laundries and similar organizations with exceptionally hard water. In one southwestern city, we attempted this for a period of three years and found that there was no leftover taste and odor in the tap water after the raw water had lost its threshold value. In prior years in that city residual tastes and odors remained in the distribution system for several weeks after they had disappeared from the raw water. We discovered quite by accident that it was not the compounds remaining in the distribution system, but rather the growing organisms, especially the actinomyces, that produced the tastes and odors.

Laboratory and field studies on several distri-
bution systems have shown the usefulness of control of pipe deposit as a method of minimizing growth in the distribution system. In softening it appears desirable to add the scale in the winter and spring and to remove it slowly as the warm weather appears. During the taste and odor period of August and September, if the plant practices recarbonation, the pipe deposits may be reduced to a minimum. If the plate counts continue to show positive proof of contamination, recarbonation should be stopped and a thin deposit added over the microorganisms. This will result in loss of activity on the part of the taste- and odor-producing forms. In any softening plant, the control of scale formation may determine whether a contamination can persist or not. Actually, a small quantity of red water is not generally as important to the consumer as repulsive tastes and odors.

In water plants that do not employ softening, it is desirable, when tastes and odors appear in the raw water, to run the pH as low as possible or just above corrosion level. The pipes are kept clean by that technique and sites of contamination are minimized. As soon as the odors disappear from the raw water, lime should be added over and above the common complement so as to form a very thin layer on the lining of the pipe. If some contamination is present, it will be killed; if none is present, the plant can resort to normal lime feed within a few days. We have had no experience with concrete pipe lining. This type of construction might be more suited to these procedures than other varieties, since the pH of the water could certainly be lowered considerably without danger of corrosion, and the contamination might be eradicated even more rapidly. Since we lack experience in that field, it is not desirable to make any specific comments.

So far as the writer is aware, there are no other simple methods that may be employed for control of distribution system contamination. We do believe that more attention should be given to the microbiological study of the pipes that carry water to the consumer. Such studies should involve large samples collected in duplicate from various parts of the distribution system. One set should be run through membrane filters and used for direct microscopic examination. This technique shows the presence of algae, fungi, protozoa, and associated organisms. The second set of samples should be concentrated and placed on different media designed to rear actinomycetes, fungi, or bacteria. It is desirable to keep records on an annual basis, with greater frequency of sampling in the summer and early fall. When the results from the distribution system investigations are compared with analyses from the raw water and water plant, the total story of the microbiology of water will be known.

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PATHOGENIC BACTERIA AND VIRUSES IN WATER SUPPLIES

P. W. Kabler, S. L. Chang, N. A. Clarke, and H. F. Clark

Outbreaks of water-borne disease occur infrequently in the United States, although laboratory evidence indicates that most of the streams are contaminated with human and animal excreta. Pathogenic microorganisms probably do not multiply in natural waters, and disappear rapidly because of predators, lack of food, and other unfavorable environmental factors. Treated water supplies are increasingly infrequent sources of enteric disease because of improvements in water treatment processes, in sanitary control of water systems, and in procedures for the detection and enumeration of pollution indicators.

OCCURRENCE AND SURVIVAL OF PATHOGENS

Salmonella

The London Metropolitan Water Board Laboratories have examined raw river waters since 1927, during which time *Salmonella typhosa* has been isolated frequently. Stewart and Ghosal isolated *S. typhosa* from the River Hugli in India, and Mom and Schaeffer reported a large series of isolations from sewage and river water at Bandoeng, Dutch East Indies, London and Mackenzie recovered *S. typhosa* from water of the Wallington River, Hants, England. Collet et al. identified *S. typhosa* from the water of a dug well near Pataskala, Ohio. They were not able to isolate the organism from the same sample after four hours storage at 5°C. Numerous other isolations of *S. typhosa* from waters have been accomplished at other times and places.

In their review of the literature on the occurrence and survival of enteric pathogens, Rubbols, Falk, and Ragotzkie found that *S. typhosa* survived in distilled or sterilized water a few weeks to a few months and in polluted waters and sewage only a few days, usually a week or less. This indicated that the survival time of the organism was in inverse relation to the degree of contamination; that the survival time varied inversely with the temperature; and that the pH range of greatest tolerance was 5 to 6.4 and increases of acidity resulted in rapid mortality. Kranz and Weber showed that *S. typhosa* survived in impounded surface water up to 26 days and *S. schottmuelleri* was still present after 70 days.

*Salmonellae* was demonstrated in 19 of 53 river samples by the London Water Board and were identified as *S. schottmuelleri, S. typhimurium, S. enteritidis var. jena, S. anatina, S. braenderup*, and *S. thompson*. Of 25 samples taken from the Leine River, up to three miles below the sewage outfall near Hanover, Germany, five contained *Salmonella*. Ferranola et al. identified 15 species of *Salmonella* from the Mendoza River in Argentina. Of 481 water samples examined, *Salmonellae* were found in 31.3 per cent. The predominant species were *S. newport, S. melagravidis, S. oranienburg* and *S. typhimurium*. Brock and Mom repeatedly demonstrated *S. schottmuelleri* and *S. paratyphi* in polluted ditch waters near Waalwijk, Netherlands. Norman and Kabler recovered *Salmonella* from each of four South Platte River water samples and from eleven of sixteen irrigation waters, one of which contained eight types. Darrasse, LeMinor, and Leonmote isolated five serotypes (*S. jay, S. owkam, S. rubislaw, S. nebana* and *S. salford*) from tap water in Dakar. A cistern reservoir in the distribution system was contaminated by lizard droppings.

Kranz and Weber found that the mortality of *Salmonella* was irregular and was affected by water composition, temperature, and other factors. Papp showed that *Salmonella* persisted in the River Ober, Germany, for fifteen to twenty-one miles below the point of sewage discharge.

In summation, the several members of the genus *Salmonella* survive varying times, depending on environmental conditions.
**Shigella**

Because of the frequent occurrence of diarrheal disease and the prevalence of enteric carriers, *Shigellae* might be expected to be common constituents of sewage; however, they have been demonstrated infrequently in polluted water. Ross and Gillespie\(^\text{(15)}\) isolated *Sh. sonnei* from river water to which an outbreak of gastro-enteritis was attributed. Kratochvil and Tarabek\(^\text{(16)}\) recovered *Sh. flexneri* from well water. *Shigellae* were not found in river water in Argentina by Leiguarda, Peso, and Kempany\(^\text{(17)}\) although 67 per cent of the samples examined showed the presence of *Salmonellae*. Gispen and Gan\(^\text{(18)}\) also failed to isolate *Shigellae* from river water in Indonesia although *Salmonellae* were frequently present.

Shrewsbury and Barson\(^\text{(19)}\) compared the survival of National Collection of Type Cultures *Sh. sonnei*, *Sh. flexneri*, and *Sh. dysenteriae* in tap water, distilled water, and normal saline, with initial populations of one billion cells per milliliter. *Sh. sonnei* survived 68 hours in tap water, 211 hours in distilled water, and 153 hours in saline; *Sh. flexneri* was alive after 86 hours in tap water and after 118 hours in distilled water and saline; *Sh. dysenteriae* was viable after only two hours in tap and distilled water, and 68 hours in saline.

Outside the human body *Shigella* organisms are extremely sensitive to environmental conditions and tend to die off rapidly, as shown by the studies of Wang et al.\(^\text{(20)}\)

**Pasteurella Tularensis**

From 1937 to 1943, epidemics of tularemia\(^\text{(21)}\) occurred in the basins of the Volga, the Don, and the Dnieper Rivers in Russia; the disease was said to be spread by water on some occasions. Wells in the Moscow Oblast\(^\text{(22)}\) became contaminated when rodents gained entrance. *P. tularensis* was isolated from natural waters in Montana by Parker et al.\(^\text{(23, 24)}\) and by Jellison et al.\(^\text{(25)}\). In 1950, Jellison et al.\(^\text{(26)}\) also isolated the organism from a spring that served as a domestic water supply. *P. tularensis* was recovered from water of shallow wells, irrigation ditches, and streams during an epizootic of tularemia\(^\text{(27)}\) in meadow voles in central and eastern Oregon and northeast California.

The organisms persist in bog muds and in streams for several weeks.

**Table 1**

<insert table data here>

**Enteric Viruses**

The “enteric viruses” as used here include infectious hepatitis (I.H.), poliovirus, Coxsackie A and B, ECHO and adenovirus subgroups. Since all these viruses (except I.H.) are readily demonstrated in sewage, they can presumably find their way into surface waters.

Toomey, Takas, and Weaver\(^\text{(28)}\) isolated a polio-like virus from creek water in Ohio by direct inoculation of a cotton rat, and Kling\(^\text{(29)}\) found poliovirus in well water in Sweden. An unclassified adenovirus was recovered from the water from an ejector-type drinking fountain at a boys’ camp,\(^\text{(30)}\) and enteroviruses were isolated from Hudson River water 400 feet from the Albany sewage outfall.\(^\text{(31)}\) Clarke\(^\text{(32)}\) has recovered poliovirus from the Ohio River 1,000 feet below the sewage outfall. Neefe and Stokes\(^\text{(33)}\) demonstrated the infectious hepatitis virus in well water in an experiment with human volunteers.

Coxsackie A2 virus survived more than 72 days in distilled water at 8°C, and 41 days at 20°C;\(^\text{(34)}\) in raw Ohio River water, at 8°C it survived 16 days, and at 20°C only 6 days. Poliovirus was demonstrated in experimentally contaminated river water after 188 days of storage.\(^\text{(35)}\) Contaminated well water after 10 weeks of storage infected human volunteers with infectious hepatitis.\(^\text{(36)}\)

Table 1 shows the relative survival times of some viruses and bacteria in river waters.\(^\text{(37)}\) In these studies, the bacteria or viruses were added directly to relatively clean Little Miami River water (natural coliforms 54/ml.) and Ohio River water (natural coliforms 197/ml.). The survival times of bacteria and viruses lengthened with lowered temperature. In Little Miami water the viruses, except Coxsackie A9, survived approximately twice as long as any of the bacteria; in Ohio River water the bacteria, with the exception of *E. coli*, survived longer than the viruses. These variations in results illustrate the effects of the specific characteristics.
of waters on survival times, and the difficulties involved in formulating generalizations.

**EFFICACY OF TREATMENT PROCESSES**

**Floculation and Sedimentation**

Chemical floculation when carefully applied removes much of the turbidity and also effectively reduces the bacteria and larger microorganisms as well as viruses in the water.

Early studies by Carlson et al.\(^{29}\) and Kempf et al.\(^{29}\) yielded inconclusive results showing negligible to significant removal of poliovirus by floculation. In these studies the floc volumes were minimal and the methods of virus measurement inexact. Later studies on the removal of viruses and bacteria by Chang et al.\(^{49, 41}\) showed that the removal of viruses from water by aluminum sulfate and ferric chloride floculation was the result of formation of a metal-virus complex by a metal cation-protein reaction; that although the floculant dosage-virus removal relationship followed the Freundlich adsorption isotherm, dosage alone was not necessarily a measure of the efficiency of the process unless it was satisfactorily carried out; and that the amount of floc was a reliable indication of the removal performance of the process.

The results of Chang’s work are summarized in Table 2 and show that chemical floculation removes viruses and bacteria in amounts parallel to the removal of turbidity from waters with turbidities up to 240 mg/l. From 93.8 to 99.8 per cent of Coxsackie A2 virus and coliform bacteria were removed by floculation at 25°C with alum or ferric chloride at a dosage of 25 mg/l. Two-stage floculation achieved removals of 99.9 per cent or more.

At lower temperatures (5°C) the virus and bacterial removals were not significantly reduced, although the time required for floculation might be lengthened.

**Filtration**

There has been considerable speculation recently as to the possible movement of enteric viruses through the ground with subsequent contamination of subsurface aquifers. Outbreaks of viral disease have been attributed to polluted well waters; however, these pollutions have usually occurred because of fissured rocks, gravelly soil, or improper well construction.

Using an attenuated poliovirus Type I (Mahoney strain), Robec, Clarke, and Dostal\(^{42}\) studied the movement of the virus through porous media. Although there was some lack of reproducibility in the observations, the results indicated that viruses were retained on the surface of particles. The results are presented in Table 3.

The poliovirus did not pass in any appreciable numbers through two feet of a clean sand bed, although the pores were 100 to 1,000 times larger than the virus. It thus appears that well-packed sandy soil is a good protector of ground water, provided one uses proper design criteria and dosing rates in disposal systems. When filtration rates were increased the per cent of virus removal by clean sand beds gradually decreased until most of the organisms passed through at rapid filtration rates.

When a low but well-mixed dose of alum was fed just ahead of filters operated at 2 or 6 gpm per square foot more than 98 per cent of the virus was removed by sixteen inches of coarse coal on top of eight inches of sand. When the alum dose was increased and conventional flocculators and settling were used, the removal was increased to more than 99 per cent. When a turbid water was treated, a floe breakthrough was usually accompanied by increase in virus penetration even though the fin-
E. coli and S. typhosa. At normal pH values, approximately forty times more chloramine than free chlorine was required to produce a near 100 per cent kill of E. coli in the same time period. For S. typhosa this ratio was about 25 to 1. To obtain a near 100 per cent kill with the same amounts of residual chloramine and free chlorine required approximately 100 times the contact period for chloramine.

Poliovirus (Type I, MF 500, and Mahoney strains) and Coxsackie virus (Group B, Type 5, EA 800) in water were inactivated by combined residual chlorine, the effective concentration depending on pH, contact time, and strain of virus. Longer contact times were required to destroy Type I polioviruses than Coxsackie B virus in this study, and increasing the pH decreased the rate of inactivation. At a pH of 7 and 25°C, a combined chlorine concentration of at least 9 mg/l was necessary for inactivation of poliovirus with a contact period of thirty minutes, and 6 mg/l with a one-hour contact period. A concentration of 0.5 mg/l required a contact period of more than seven hours.

Chambers, at the 1961 conference, discussed the germicidal efficiencies of several disinfectants, including considerable detail relative to silver, iodine, and quaternary ammonium compounds. Chlorine dioxide, bromine, ozone, and ultraviolet light may also be useful disinfectants; however, their efficiencies in comparison with that of free chlorine and as governed by pH, temperature, dosage, and contact time have not been established.

Sanitary Significance of Coliform Organisms

Insofar as bacterial pathogens are concerned, the coliform group is considered a reliable indicator of adequate treatment. As an indicator of pollution in drinking water supply systems, and indirectly as an indication of protection provided, the coliform group is preferred to the fecal coliform organisms. The ratio of enteric virus density to coliform density in human feces is about fifteen virus units per every million coliforms. It has also been shown that sewage and water treatment processes exhibit comparable efficiencies for removal of enteric bacteria and viruses except for disinfection procedures to which viruses are more resistant. A negative coliform test, therefore, does not necessarily exclude the presence of viruses.

Under unusual conditions, where the raw water supply contains large amounts of sewage (New Delhi) or where there have been mechanical or human failures in the water treatment plant operation, water-borne disease may result. However, under normal conditions of raw water supply and treatment plant operations in the United States, the virus content in drinking water is below the infectious level when the Standard Methods coliform test shows no gas in any tube. The purity of water-borne disease outbreaks supports this view.

SUMMARY

1. Pathogenic bacteria of the Salmonella genus can be readily isolated from polluted surface waters.
2. Raw water sources may be contaminated with P. tularensis by infected animals.
3. Enteric viruses have been demonstrated in surface waters.
4. Pathogenic bacteria and viruses survive in water for a few days to several weeks, depending on the kind of microorganism, characteristics of the water, predators, competitors, ambient temperature, etc.
5. Chemical flocculation, sedimentation, and filtration when properly applied remove 95 to 99.99 per cent or more of the bacterial and viral contents of water.
6. Different types of enteric viruses vary widely in their resistance to free chlorine; poliovirus, Coxsackie, and some ECHO viruses seem to be more resistant than coliform or enteric pathogenic bacteria. The free chlorine residuals required for inactivation depend on pH, temperature, and contact time.
7. Combined chlorine is considerably less germicidal than free chlorine, and requires higher concentrations or longer contact periods to achieve comparable inactivation.

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ANIMAL INFESTATIONS IN DISTRIBUTION SYSTEMS

W. M. Ingram and K. M. MacKenthum

INTRODUCTION

Published records describing animal infestations in distribution systems in the United States are meager. The modern water treatment plant with coagulation, sedimentation, rapid sand filtration, disinfection and subsequent storage in covered clear wells and distribution reservoirs has done much to minimize household infestations. Finished water stored in uncovered distribution reservoirs, however, may mitigate the elaborate steps in purification at the water treatment plant. Treated water can be degraded by dirt, lawn fertilizers, leaves, or other organic contaminants entering the open reservoir. Such materials increase fertility and initiate organism food chains similar to ones that may develop in raw water (Figure 1). Thus, immature and adult animals, as well as algal cells, pose potential, if not always actual, infestation dangers to the consumer. Water supply systems lacking filtration prior to storage in open water reservoirs foster maximal nuisances to plague the householder (Figure 2).

Animals that have been reported in distribution systems and that are of special interest to the water works operator, and in certain instances to the consumer are: nematodes (roundworms), mollusks (snails and clams) (Figure 3, a-c), midge larvae (bloodworms), and crustacea (copepods and water fleas) (Figure 4, a-c). Other animals causing occasional nuisances in distribution systems are: protozoa, sponges, rotifers, bryozoans, segmented worms, and aquatic sow bugs (water lice). A manual discussing these and other animals, written solely for water works operators, has recently been issued by the American Water Works Association. This manual has stimulated many to examine microscopically water from various basins in the water treatment plant as well as finished water in the distribution system.

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**NEMATODE WORMS**

Among animals that have been reported in distribution systems, nematode worms (Figure 3-a) are currently of great interest. A series of papers on roundworms in potable supplies has stimulated water works personnel to obtain precise information on occurrence of nematodes in finished water. Chang et al.\(^9\) first reported a single species of nematode, *Diplogaster nudicapitatus*, taken from the distribution system of a city water supply which used the Ohio River as the raw water source. Examination of tap water revealed worms at densities ranging from 1 to 20 per gallon; on one occasion as many as 100 worms were found in a gallon of water. Chang et al.,\(^10\) in a survey of twenty-two water supplies, reported that sixteen contained live, free-living nematodes; he recorded these additional genera: *Rhabditis, Cheilobus, Monhystera, Aphelenchus, Cephalobus, Dorylaimus,* and *Turbinaria*. He stated:

While these nematodes are harmless *per se* when ingested, those of the Rhabditidae family may possibly serve as carriers of human enteric pathogens. This is based on the facts that members of this family are frequently present in large numbers in trickling filters of municipal sewage treatment plants (unpublished observations of S.L.C.)\(^{(9)}\) and that they feed readily on *Proteus mirabilis, Aerobacter aerogenes, Ae. cloacae* and *Pseudomonas sp.* in laboratory cultures.

Chang et al.\(^{10}\) reports on the experimental laboratory control of two worms, *Cheilobus quadrilabiat us* and *D. nudicapitatus*, by chlorine application. He states:

These nematodes are so highly resistant to the destructive action of free chlorine in water that they were not affected by 2.5-3.0 ppm of chlorine in a 120-minute exposure or by 15 to 45 ppm of chlorine in a 1-minute exposure when the water temperature was 25°C, pH 6.6-7.2, and the chlorine residuals were only slightly lower than initials. Even with an initial chlorine as high as 95-100 ppm, 50-60% of these nematodes survived a 5-minute contact and 10-20% survived a 15-minute contact. The *C. quadrilabiat us* appeared to be somewhat more resistant than the *D. nudicapitatus*, but the difference was reduced as the chlorine dosage was increased from 15 to 95-100 ppm.

Chang\(^{13}\) discusses possible control measures on a plant scale basis, stating:

At present it appears that the most practical method for preventing nematode infestation is to

\(^*\)The name of the city was withheld by request (Chang et al., 1959).
prechlorinate the raw water for 6 hr; a free residual of 0.4-0.5 ppm chlorine should result at the end of this period. Although many of the nematodes are not killed, they are sufficiently affected so that they can no longer swim; therefore, they will be settled out in the flocculation process. The pH, in the range of 6.0-8.2, appears to have no detectable influence on the vermicidal activity of the free chlorine.

McCall’s studies suggest that nematode worms, although not numerous, did occur in the Merrimack River, a raw water source of the Lawrence, Massachusetts, water treatment plant. Examination of finished water did not reveal worms to be present. The finished water had had the following treatment: rough and fine screening, prechlorination, coagulation with alum, mixing, settling, rapid sand filtration, pH control with lime, aeration, and postchlorination.

Fortunately, from an aesthetic point of view, the roundworms discussed above are microscopic (100 to 500 microns in length and 10 to 40 microns in width). Thus, even though they may occur in finished tap water they are unnoticed by the consumer because of their minute size. Occurrence in finished water does, however, indicate that modern water treatment methods are not always fully successful as barriers to invasion by microorganisms. The public health significance of microorganisms in drinking water has been pointed out by Chang and coworkers. Supplies that reveal worms on microscopic examination should be scrutinized by the operator or others in authority to make certain that a public health hazard does not exist and that measures of disinfection are put into practice that will effectively destroy roundworms.

MOLLUSKS

To date, published literature on mollusk nuisances in distribution systems in the United States...
refers to only one snail, *Bythinia tentaculata* (Figure 3-b) originally introduced from Europe. Other snail genera have been found as occasional residents of finished water in clear wells but have not caused difficulty in distribution systems. Clam nuisances have not yet been reported in distribution systems in the United States; however, one species, *Corbicula fluminea* (Figure 3-c) introduced from Asia and bordering Pacific Islands, has been recorded as causing trouble in raw drinking water supplies and in the canal transportation system of the LaVerne water softening plant of the Metropolitan Water District of Southern California. This clam has a life cycle that, in prognostication, should eventually cause it to be listed as a nuisance in treated supplies. It is established as a pest in pipes of irrigation systems in California. Since the time of the first published record of its distribution in the United States as an inhabitant of certain streams in California and Washington, it has spread to waterways in Arizona, Oregon, Idaho, Tennessee, and Ohio.

The snail, *Bythinia tentaculata*, as the mollusk invader of bathtubs and kitchen sinks, has been named the faucet snail. Baker, while studying drinking water from Lake Michigan, first collected this snail in the United States in 1898 as an intermittent household guest. The snails were pumped into the distribution system of the Chicago area, which was supplied by the Lake View crib intake. During this infestation they were found ocluding small water pipes in residences; in a number of instances tumblerfuls of snails issued from faucets. Two other snails associated with this snail in the crib structure were not reported from faucets (*Pleuroccra elevatum* and *Goniobasis live-scens*). Remedial measures are not described.

Sterki records an infestation of the Erie, Pennsylvania, water system when the raw source was Lake Erie. The intake at the time was four to five miles out in the lake. He noted that "wagon-loads" of snails were taken from the crib structure when it was cleaned and that snails often plugged faucets. Two genera of snails that were collected with *Bythinia* but not reported to cause nuisances were *Physa* and *Helisoma* (= *Planorbis*). Bahlman found empty shells of *Planorbis* (= *Helisoma*) in the clear well of the Cincinnati, Ohio, filtration plant but did not report snail nuisances in the distribution system drawing from the clear well.

**MIDGEFLY LARVAE**

In the water treatment profession the well-known "bloodworm" is the immature, larval stage of a midgefly (Figure 4-a). Taxonomically it is placed in the genus *Tendipes* (= *Chironomus* is the common generic term used by professional water supply journals). In most instances, the worm-like larvae that have been reported in distribution systems have been ones with blood-red coloring, although the larvae of various species may range from red, through yellow, brown, or green. Invariably, bloodworms enter distribution systems from uncovered, finished-water reservoirs or from covered reservoirs with broken screens over side vents.

Adult midges lay their eggs in jelly-like strings, enveloped by a gelatinous covering. The eggs are free floating on the water surface or attached to aquatic plants, twigs, or stones. One species, *Tendipes* (= *Chironomus* plunmosus), has been associated with finished-water supplies, as well as with streams polluted by domestic sewage. Populations of 250 larvae per square foot have been recorded in eutrophic lakes.

Bahlman's papers are among the early ones that report bloodworms from finished water that had been thoroughly treated in a filtration plant. He first discovered these organisms in the uncovered clear well on the grounds of the Cincinnati plant and concluded that they multiplied by feeding on algal growths and decaying leaves that had accumulated, forming a bottom sludge. He noted that "... a complete covering of the clear well reservoir is the only means of maintaining an aesthetic supply." Bloodworms were eventually reported emerging from bathtub faucets and in toilet bowls in a suburban family hotel.

Hechmer reported that *Chironomus plumosus* was found in finished-water tanks in the filtration plant of the Washington, D.C.-Maryland Suburban Sanitary District. He states that they did not pass through the sand filters, but developed in the finished water from eggs that were deposited directly on the finished-water tanks. Larvae discharged from faucets caused consumer complaints. The bloodworm problem was eliminated for the household by covering the filtered finished-water tanks.

Fentje reported on the elimination of colorless, pale-green bloodworms, four to five millimeters long, from the distribution system at Alexandria, Virginia. The foci of the infestation were
two finished-water reservoirs. Flentje recorded his overall experiences with bloodworms from many years in the water works field, and summed the literature.

Brown discussed a bloodworm infestation of a distribution system and found the point of development to be a reservoir of the Stockton, California, potable supply. The reservoir had a collapsed roof.

CRUSTACEA

Crustacea represented by water fleas (Daphnia and Bosmina) and cyclops (Cyclops) have long been of interest to water treatment plant operators since they have been reported from various basins in the filtration plant. They are frequently observed in unfiltered supplies.

Water fleas in finished water in distribution systems have been reported by Hart. Kelly reported Daphnia in finished water in the effluents of slow sand filters. Hobbs states that slight difficulty has been encountered from penetration of filters by Daphnia. Cox indicates that they are removed from potable supplies by filtration.

Adult cyclops were prevented from entering finished water by sand filters at Indianapolis, Indiana, however, the eggs did go through filters and hatched in the finished water, which resulted in adults being carried to the consumers. As many as twenty eggs per litter were counted from finished water by sand filters at Indianapolis, Indiana. In potable supplies. Baylis reported that cyclops eggs, rather than the adults, pass through filters, thus accounting for the appearance of mature forms in potable supplies. Baylis reported that cyclops were taken from filter surfaces of Chicago's South District Filtration Plant. No mention was made of their occurrence in finished water.

The authors wish to thank Dr. Shih Lu Chang, in charge of Water Treatment Evaluation Studies, Basic and Applied Sciences Research, Division of Water Supply and Pollution Control, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio, for furnishing the diagrams of roundworms included as (a) on Figure 3. Acknowledgment is due the American Water Works Association for permission to use Figures 3 (a) and (b), and (a), (b), and (c) of Figure 4; these appeared originally in "Animals Associated With Potable Water Supplies: Operators Identification Guide," AWWA-M7. Credit is given Mary Juanita Churchill who was the delineator of Figures 1 and 2 that were based on prototype sketches of the senior author.

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IRON BACTERIA

F. M. CLARK

Iron bacteria are an important type of nuisance organism found in water. Their importance results from their ability to transform soluble iron into insoluble iron compounds that may be precipitated in water or in water distribution systems. They may produce deposits that tend to reduce the water-carrying capacity in pipes. They also may form slime in water holders and produce a scum on water surfaces. They may also produce turbidity and discoloration of water.

The iron bacteria are typical water organisms. In the manual, “Standard Methods for the Examination of Water and Waste Waters,” this characterization is given: “Iron bacteria are considered to be capable of withdrawing iron present in their aqueous habitat, and of depositing it in the form of hydrated ferric hydroxide or in the mucilaginous secretions.” The manual further states, “... bacteria of this type, to obtain energy, oxidize ferrous to ferric iron which is precipitated as ferric hydrate.” This statement has not been proven conclusively for some of the organisms that are included in a discussion of iron bacteria.

Even though the presence of these bacteria in water has been observed for many years, confusion appears in the literature concerning the name of the organism described. This, undoubtedly, is a result of the fact that the organisms have not been studied in pure culture and their variability determined. Thus, certain morphological variations resulting solely from environmental conditions have been described as different organisms by various workers. To eliminate this confusion of names we will follow in our discussion the classification of this group as outlined in Bergey’s manual:

Chlamydbacteriales (sheath-forming bacteria)
Sphaerotilus
Leptothrix
Crenothrix

Pseudomonadales
Caulobacteriaceae (stalk-forming bacteria)
Gallionella
Siderocapsaceae
Siderocapsa
Ferribacterium
Ferribacillus

No attempt will be made to discuss all the genera of organisms reported under the Siderocapsaceae. Siderocapsa, Ferribacterium, and Ferribacillus have been selected as being characteristic of this group.

In addition to these organisms, considered as iron bacteria, certain common organisms found in soil and sewage may cause a precipitation of iron under special conditions. They will be discussed briefly in a later part of this paper.

Sphaerotilus. The organisms belonging to this genus are usually associated with sewage or sewage-polluted streams. They produce colorless filaments which may be attached or free floating. The filaments contain rod-shaped or oval cells surrounded by a firm sheath that is soft and slimy. The sheath may be several millimeters long and several sheaths may be held together by adhering slime. Ordinarily, bacteria in this group are not considered as iron bacteria, but under certain conditions iron can be demonstrated in the sheath by treating it with ferriyanide and HCl. If iron is present they exhibit the Prussian blue reaction. Sphaerotilus has been cultivated in organic medium and its ability to live solely on iron compounds is questioned.

Leptothrix. The members of this group consist of rod-shaped cells in chains surrounded by a sheath. In young cells there is little evidence of a sheath but as the cells become older the sheath thickens from the deposition of iron or manganese and becomes yellow-brown in color. As this sheath becomes heavily encrusted, cells may escape leaving an empty tube of ferric hydroxide. The cells then form a new sheath that often tapers toward the end.

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False branching may occur. Some species are free floating while others are attached. These organisms are common inhabitants of fresh and stagnant iron-bearing waters containing small amounts of organic material. Pringsheim\(^3\) reports evidence that Leptothrix is a form of Sphaerotilus. Employing pure cultures of *Sphaerotilus natans* he had isolated from different sources, he was able to produce in his laboratory, by modifying the cultural conditions, forms of this organism that would be identified as Leptothrix.

**Crenothrix.** These organisms represent chains of cells in a sheath that is attached to a firm substance. The sheath is thin and colorless at the tip and encrusted with iron or manganese at the base. The free end is swollen or enlarged and both large and small conidia escape from this enlarged tip. These conidia may form new chains or develop into a zoogloial mass on the old sheath. It is found commonly in wells and water pipes, but will also grow in running water containing organic matter and iron salts.

**Gallionella.** The organisms in this group belong to the Caulobacteriaceae or stalk-forming bacteria. Stalks secreted by the cells are slender and twisted and are attached to solid surfaces. The cells are rounded or kidney-shaped and are located at the top of the stalk. The twisted stalk, characteristic of this organism, makes its identification relatively simple. Electron microscope pictures of these stalks taken by Vatter and Wolfe\(^4\) have indicated that the stalks are made of a series of strands rather than one solid band. Gallionella occurs in iron-bearing waters where organic material is absent. It appears to be an autotrophic organism.

**Siderocapsa.** These organisms are without a sheath but frequently are embedded in a thick, mucilaginous capsule in which iron or manganese may be deposited. These organisms are cocccoid or short rods that occur in small colonies of one to one hundred cells. The colonies may form surface films or may cover the surface of submerged objects. Most results seem to indicate that they utilize organic materials and are not autotrophic.

**Ferribacterium.** These are rods usually occurring in pairs. In most cultures the cells are enclosed in a gelatinous capsule which is surrounded by deposits of iron compounds. The organisms produce a surface film on liquid medium and water. They have been isolated from iron- or manganese-containing waters.

*Ferribacillus.* These rod-shaped bacteria oxidize ferrous iron to the ferric state in acid environments. They appear to be strictly autotrophic, deriving their energy for growth by oxidizing ferrous iron. Silverman and Lundgren\(^5\) have found that when the ferrous iron had been completely oxidized to the ferric state, growth ceased in their cultures. The organisms have been isolated from bituminous coal, mine drainage, and waters receiving such discharges. Ferribacilli frequently form relatively hard granules of ferric iron in which the bacteria are entrapped.

Like all organisms, the growth of iron bacteria is affected by many factors. Our knowledge of these factors is often incomplete because it is difficult to cultivate these organisms in laboratory media. A brief consideration of some of these factors may aid in suggesting conditions under which they are likely to be found.

The iron bacteria are essentially all aerobic, depending on the presence of free oxygen. Under conditions where large amounts of organic matter is decomposing and removing the dissolved oxygen, they are found only at the surface. In water where algae are developing they may be found associated with these plants. The organisms that depend on the oxidation of ferrous iron for their energy will develop only where there is an adequate supply of both ferrous iron and oxygen.

There is much conflicting evidence regarding the influence of organic matter on the growth of iron bacteria. *Sphaerotilus* develops luxuriously in waters containing a large amount of organic matter. Lackey and Wattie\(^6\) found this organism in large numbers in their study of bulking in an activated sludge plant. It has been reported by Schuring\(^7\) in streams polluted with sulfite liquor from pulp and paper mills. In dirty running water it thrives in great tassles held together by slimy tubular sheaths. Molish\(^8\) cultivated *Sphaerotilus* on a 1 to 2 per cent peptone solution in which no iron was added. Under these conditions the cells were colorless and the sheath contained no iron. Leptothrix grows much like *Sphaerotilus* but will develop in lower concentrations of organic material. Various investigators have grown these organisms in the laboratory on organic media in the absence of iron. *Crenothrix* grows in the presence of organic matter and there is evidence of its ability to grow at the expense of ferrous iron. Thus, this group of organisms appears to have the ability to grow hetero-
trophically in the presence of organic matter or autotrophically in inorganic media when ferrous iron is present. When grown autotrophically, large amounts of ferric hydroxide are produced. When they grow on organic material large amounts of filamentous fouling matter is produced.

Gallionella, according to Saroty and Meyer, are strictly autotrophic organisms that depend on the oxidation of ferrous iron for their energy. Several investigators have reported the presence of small amounts of organic matter as toxic to these organisms when grown in pure culture. Nevertheless, Gallionella have been encountered in water under natural conditions where organic matter was present. Ferribacillus has also been reported as being an autotrophic organism by Silverman and Lundgren.

Siderocapsa and Ferribacterium appear to be heterotrophic organisms utilizing organic iron compounds and depositing iron in their capsule.

The iron bacteria, therefore, may be grouped as follows: Sphaerotilus, Leptothrix, Siderocapsa and Ferribacterium appear to require organic matter and are heterotrophic bacteria. Crenothrix may develop with or without organic material and can be classed as a facultative autotroph; Gallionella and Ferribacillus as autotrophic bacteria. Starkey indicates that in waters containing relatively large amounts of organic matter Crenothrix and Leptothrix are commonly found, whereas Gallionella usually predominates in water low in organic matter.

The nitrogen requirements for the growth of iron bacteria have not been studied in many cases. For the autotrophic member of this group ammonium salts probably serve this requirement. Others that have been cultivated in the laboratory are often grown on organic nitrogen sources such as peptone and beef extract. It is probably true that most waters contain sufficient nitrogen to support the growth of these organisms.

Most of the iron bacteria show a preference for relatively low temperatures. It has been reported that 15°C can be taken as an optimum temperature for growth. In the laboratory Gallionella grew in culture medium from 0° to 27°C with an optimum from 6° to 10°C. This organism has been found in mineral springs with water temperatures of 27° to 32°. Leptothrix have been isolated from water at 1° to 2°C, but their optimum is considered to be higher. Molish obtained good growth of this organism at 25°C.

Natural waters vary greatly in their reaction. Iron bacteria as a group seem to develop best where there is a slight acidity. This is especially true when the acidity is produced by carbon dioxide, a condition which increases the iron-carrying capacity of the water. However, Gallionella has been found in mineral springs with a water pH of 7.0 to 7.6. Crenothrix has developed in water nearly free of iron at pH 7.3 to 8.0. Under these conditions it is presumed the iron came from pipes and sufficient organic matter was present to permit growth of the Crenothrix. Hardman and Henrici were able to isolate Siderocapsa regularly from alkaline hard-water lakes in Minnesota. They were not isolated from neutral or acid soft-water lakes. Silverman and Lundgren, in studies on the iron bacterium Ferrobacillus ferroxidans, report development of this organism at pH 2.0 to 4.5, with an optimum of pH 3.0 to 3.5.

The concentration of iron required for the development of iron bacteria appears to vary greatly. They have been found usually in water containing 10 to 30 ppm of iron, however they also occur where the iron content is as low as 0.1 to 0.3 mg/l. Harder found active development of iron bacteria in water pipes carrying water with 1.3 mg/l iron. Halvorson found these bacteria in spring water carrying 1 to 10 mg/l iron. Other reports indicate iron deposits in pipes where the iron content of the water was 0.2 to 0.3 mg/l. Usually we think of these bacteria as being associated with water containing a high content of iron. However, they may develop in water with a relatively low iron content if the supply of iron is continuous as would be obtained in flowing water.

Chlorination of water appears to be the most satisfactory method of controlling the development of iron bacteria. Duchon and Miller found that chlorine and hypochlorite were the most effective chemical agents for controlling growth of Crenothrix. In a symposium on control of growth in water distribution systems chlorine was reported to have been used successfully. Blair indicated that maintaining free residual chlorine throughout the distribution system was an effective means of combating infestation. He warned, however, that even though the kill was effective, taste and odor were still possible. In dealing with heavily polluted water Scheuring found that growth of
Sphaerotilus could be inhibited if the water had a pH below 6.0.

Many different organic compounds of iron occur in natural waters. Organisms that have the ability to decompose or utilize the organic radical may cause a precipitation of iron. In the decomposition of organic matter carbon dioxide is often formed. Under proper conditions this may lead to the formation of ferrous carbonate. When this is exposed to the air carbon dioxide may be liberated with the formation of ferric hydroxide. This later change often is chemical and takes place some distance from the place of its formation. Thus, no organisms would be observed in this type of precipitate even though its original formation was biological. Halvorson and Starkey[177] made a study of this type of reaction.

In addition to the iron bacteria which may cause iron precipitation, various other bacteria found in soil- or sewage-polluted streams may be the cause of this precipitation. With these organisms iron is only incidental to their development. Much of the laboratory work reported on this group of non-specific bacteria has involved the use of ferric ammonium citrate as an organic iron complex. Lewis[178] using a synthetic medium containing 1 per cent ferric ammonium citrate reported iron precipitation by Acrobacter aerogenes and related organisms, certain strains of Pseudomonas, Bacillus subtilis, Bacillus cereus, spore formers isolated from soil, Serratia marcescens and some strains of Salmonella. Starkey[179] refers to the precipitation of iron from this compound by Acrobacter aerogenes.

In our laboratory, plates made from streams in this area using a synthetic medium containing ferric ammonium citrate seldom fail to yield colonies showing typical iron precipitation. In the majority of cases, cultures produced by picking these colonies proved to be Acrobacter aerogenes.

Three cultures that gave indication of iron precipitation in surface water were sent to our laboratory by Mr. Robert Scott of the State Department of Public Health. One culture was identified as Serratia indica, the other two were spore-forming rods and have not been completely characterized. These three cultures along with known cultures of Acrobacter aerogenes and isolates from plates made from water samples have been tested for their ability to precipitate iron from a synthetic medium containing ferric ammonium citrate as the only source of iron and carbon. When streaked on an agar medium, iron was precipitated around the colonies giving them a reddish-brown color.

In liquid medium, Acrobacter and Serratia rapidly formed a scum on the surface, with indications of iron precipitation in three to five days. One culture of Bacillus produced similar results, but a week to ten days was required. The second culture of Bacillus produced very little surface film and precipitation only on prolonged incubation. Attempts to grow these organisms in the synthetic medium under anaerobic conditions resulted in their failure to precipitate iron during a two-month incubation period.

To test the extent of iron precipitation, much of the heavy surface film which had developed in the flasks of liquid medium was removed. The remaining solution was filtered to remove the precipitate. Tests for total iron on the filtrate were run colorimetrically using hydroxylamine-phenanthroline solutions. An aliquot from the unincubated flask of the original medium was run as a control. No more color developed in the filtrate than in the blank run with reagents and distilled water, indicating complete removal of iron. The surface film containing precipitated iron and organisms was suspended in water, was washed by centrifugation, cells were resuspended in water, and the test for iron was run. The color that developed was almost as intense as that from the medium in the control flask that had not been inoculated. The organisms used in these tests tended to produce some slime or capsular material which surrounded the cell. It appears possible that much of the precipitated iron was imbedded in this slime layer. No attempt has been made to quantitatively determine the amount of iron in the cell mass, or the amount of iron needed to produce evidence of precipitation in our culture medium.

In conclusion, there is no question but that the precipitation of iron from water results from several causes, both biological and chemical. Iron bacteria have an important role, but under certain conditions other bacteria may also play an important part.

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BIOLOGIC INFESTATIONS IN WATER DISTRIBUTION SYSTEMS

M. P. Crabill

What is a biologic infestation? For the purpose of this discussion, we can define it as a population of plant or animal organisms growing or reproducing in the distribution system. However, in a broader definition, organisms growing in any part of the treatment plant, pumping station, or in raw water should be included. For the most part, an infestation probably has more impact upon public relations than it has on the sanitary quality of water; although, admittedly, it can have sanitary significance.

I presume that almost all water works operators using a surface supply, mixing and sedimentation basins, and filters have at one time or another observed the two-winged midge fly about the plant. This is commonly classified as the adult chironomid. It lays eggs in a gelatinous mass sometimes extending to a length of several feet. The egg mass may be deposited on the water surface in a settling basin, on a filter, or in the clear well, if the midge fly has access to finished water. This may seem to be an unlikely possibility, but some years ago, during a routine examination for structural maintenance, we discovered a multitude of egg masses in the chlorination basin at our plant. We estimated that the volume of the mass which was located in a dead area of the basin would have more than filled a bushel basket while the eggs and the gelatinous or jelly-like strings were wet. This discovery came as a real shocker to us.

In this situation, it is obvious that the first task is to remove the egg masses from the basin. This was accomplished in a short time by closing off the chlorination basin in favor of a bypass conduit and then by making a 30-inch square sieve of gauze, framed on the end of a rake handle. All of the egg masses were then dipped out of the basin while they were still buoyant and floating. Having accomplished this, the basin was drained, was given a heavy brushing on the sidewalls through the distance where normal water levels vary, and then refilled with a water having approximately 150 mg/l chlorine residual. It was then left standing for two days before draining to waste and then returned to service after a normal refill. Needless to say, the alarm of this experience raised a great deal of concern as to what might be expected in the distribution system in the way of larvae. We immediately initiated a schedule for flushing all dead ends in the system. Upon completion of the entire system we flushed about 15 per cent of them and collected samples for microscopic observation. The 15 per cent spotted were selected to give a wide coverage of the system. Those selected were also spotted for being some of the longest runs of stagnated water. The chironomous larvae were discovered in only two of the samples in spite of the 15 per cent flushing schedule which was repeated four times. No customer complaints were received following the removal of the egg masses from the basin. On this occasion, it appears that we were most fortunate in the timing of the discovery of the eggs and that the cycle for their reproduction in the system was arrested by their removal and the subsequent flushings.

A careful observation of the plant to discover the method of entrance for the flies to the basin was being carried on at the same time other work was in progress. We finally concluded that the flies made their entrance to the basin through the screen of one or more of the three ventilators on the basin. The screens originally installed on the vents were wire mesh and had in some cases rusted out. As a temporary measure, the screens were covered with gauze until wintertime when new and smaller mesh screen could be installed.

The whole episode established several practices which are precautionary measures to reduce the possibility of a recurrence. First, in the early warm weather of spring, while the nights are yet cool, the midge flies can be identified as they swarm...
about the doors of a heated building. The identification is easily made and is a fair warning of trouble if access points are not sealed. There is no practical method for eliminating the fly. However, shortly after observing the fly, you will likely discover larvae on the surface of the sand filter; and, if so, you are certain to find that some of them have burrowed to some depth in the filter sand. At this stage, the problem has advanced to a point where something must be done. Upon observing this condition we have done three things:

1. We backwash the filter on a short-time schedule so that as many of the larvae as possible will be washed out of the sand.

2. If the larvae are numerous, we frequently take one filter at a time out of service and chlorinate it to approximately 100 mg/l residual and permit it to stand overnight before backwashing.

3. We set up a sampling device on the filter effluent so that we will observe either larvae or eggs should they pass the filter. If this situation should be observed, it would then call for initiating the flushing schedule to clear the distribution system of any eggs, or larvae.

It is difficult to be certain that all access points to the midge are closed. As mentioned, a vent screen with openings of sufficient size to permit access is an open invitation. The older type loss-of-head meters which took water off the top of the filters and also off the filter levee below the underdrains often had a vent pipe extending vertically to bleed off air traps. These pipes were open to atmosphere and were not screened. In spite of the mercury well separation in the meters, it is an ideal condition for the midge fly to gain access to the finished water by entering the vent pipe and laying eggs which upon hatching permit access directly to the finished water and on into the system. Any kind of structural fault or separation of joints permits direct entrance to the stored water.

Laboratory studies relating to bloodworms and chironomous larvae, under the heading of chemical treatment, mention extremely high concentrations of copper sulfate (such as 10 mg/l with twenty-four hours contact, chlorine dioxide 7 mg/l with twenty-four hours contact) as being effective killing concentrations. Some insecticides such as DDT report a lethal dosage of .94 mg/l with eight hours contact, .007 for dieldrin and .012 for Aldrin. These were reported in 1956 in an article by J. K. G. Silvey.\(^{(1)}\)

M. E. Flentje\(^{(2)}\) reported using .01 mg/l DDT to destroy chironomous larvae in two reservoirs successfully.

Although the author has had no experience with the use of the insecticides in a public water supply, it is obvious that their use would of necessity require the approval of the state and federal health authorities. Even then, by preference, I would use it in parts of the plant or the system that could be isolated from the public supply during the treatment and holding period.

To sum up the case against chironomous, we can conclude that all avenues of entrance to the finished water should be closely checked and closed; that certain backwashing procedures and sampling should arrest and check the advance of the larvae through the plant, and that flushing and/or chemical treatments are available as a corrective measure if the problem is located in the distribution system.

Another not uncommon infestation is cyclops. An adult cyclops can sometimes exceed 2.0 mm in length and if present in a drinking water glass can be seen by the naked eye. They will attract attention when light is reflected off the body. They are quite common in surface waters and are carried into the plant and onto the filters. However, the adult cyclops is very easily killed.

We were alerted to an infestation of cyclops in our distribution system in 1953 when we received calls from five or six customers located in a very small area of the extreme east end of the city. This area is served from our Fall Creek treatment plant and each of the calls came from the extreme end of mains, which were dead ended as they met a railroad. Collection of samples from the residences and the hydrants at the end of mains confirmed the presence of cyclops and canthacamptur. Collection of samples from dead ends in that part of the system served by the White River plant did not show any evidence of an infestation.

The Fall Creek stream has a six million gallon impounding reservoir in the main channel about twelve miles upstream from the plant intake. We immediately began collecting samples from the reservoir bayous, from the outflow, along the stream, at the plant intake, from the settled water, and on filter effluents, as well as from other loca-
tions in the distribution plant. The evidence collected by samplers showed that the cyclops were present in larger numbers than usual at the reservoir. In particular, they were blooming in the bayous and being carried in the water that flowed out of the reservoir, which at that time was below the spillway. They were in evidence through the entire stream flow and, of course, at the plant intake.

Sampling of settled water at the plant, however, indicated that all of the adult cyclops were being killed by the normal chlorine application to the raw water. This application was 4 to 5 mg/l which produced a free available chlorine residual of approximately 1.2 mg/l at the end of the mixing portion of the basin or after 45 minutes contact. At the end of the settling basin, or approximately four hours after the initial chlorine application, the residual is normally .8 mg/l. This is normal treatment in our plant and is 100 per cent effective in killing off the adult cyclops. However, in observing those adults carried onto the top of the filter, we discovered that many of the females were carrying egg sacs. Even though the adult was dead, the egg sacs had not been penetrated. The eggs could be hatched in a relatively short time in the 20°C incubator and a normal active adult cyclops developed after going through the growth cycle. Each female carried two egg sacs and the number of eggs in each sac varied between seven and twenty. An individual egg measured 3 to 4 microns in diameter. At one time, twenty-two egg sacs were counted per square inch of filter surface. The egg sacs ruptured on the filter surface and sampling of the filter effluents showed that as many as three to five individual eggs per liter of water were present. These individual eggs were hatched out in the incubator. We concluded that the cyclops infestation was due entirely to the eggs being released from the sacs, passing the filter, being carried through the system until the velocity was insufficient to move them, and finally coming to rest and hatching.

On the basis of laboratory work, we found that an application of copper, chlorine, and ammonia was applied to produce a copper residual of 3 mg/l as Cu SO₄·5H₂O. A combined chlorine residual of no less than .5 mg/l was effective in less than five hours in killing the species as it emerges from the egg.

A 2 mg/l copper residual with the same residual chlorine killed the emerging cyclops in about 12 hours and a 1 mg/l copper residual killed them in about 24 hours. Our corrective treatment at the plant, then, was the application of copper, chlorine, and ammonia on settled water to provide between 2 and 3 mg/l residual copper in the distribution system. This application continued until settled water samples showed that the bloom of cyclops had ended and the adults were no longer carrying egg sacs onto the filter.

Along with the chemical treatment, the dead ends were flushed, both to rid the system of those organisms already there and to move the copper residual into the dead ends as quickly as possible. This provided an effective instrument of control and, although the bloom of cyclops continued over a long time—in fact, until the rainfall was sufficient to restore the reservoir to full elevation—no further complaints were recorded from the customers once the copper-chlorine-ammonia treatment reached the dead ends.

The laboratory work indicated that some worms, water fleas, and rotifers were also effectively killed by the copper-chlorine-ammonia treatment. The most immediate lesson seems to be that the effectiveness of any kind of treatment depends in a large measure on the cleanliness of the distribution system. No treatment can be effective if the dead ends of the system remain stagnant, hold chlorine-demanding material, or contain a water which is favorable for an infestation to develop.

This kind of experience demands that the water works operator set up a routine schedule for the flushing of all of the dead ends in a distribution system periodically and that regular sampling of filter effluents be established so that the operator will be aware of any possible causes of an infestation at the time it is going through the plant. This requires more than a catch sample.

Many other animal organisms or species have been recorded as predominant in infestations. We do not have the time to discuss each one individually. A listing of those most commonly recognized includes—Nematoda, nais worm, Daphnia, and Bosmina and some of the algae. I urge all of you to obtain a copy of the American Water Works Association M7 manual entitled Animals


Associated With Potable Water Supplies. It is an identification guide which illustrates many of the common offenders in infestations, giving general descriptions and ecology. The manual was composed by Dr. William M. Ingram and Dr. Alfred F. Bartsch, of the Robert A. Taft Sanitary Engineering Center at Cincinnati.

REFERENCES


PROGRAM

Tuesday, January 29, 1963
8:30 a.m. Registration: R. K. Newton, Corridor, Third Floor, Illini Union
MORNING SESSION: G. E. Margrave, Presiding; Room 314, Illini Union
10:30 a.m. Welcome and Introductory Remarks: C. W. Klassen and N. M. Newmark
11:00 a.m. "What Is Quality Water?": Raymond J. Faust
12:00 noon Luncheon: Ballroom, Illini Union
AFTERNOON SESSION: R. E. Speece, Presiding; Room 314, Illini Union
1:00 p.m. "Corrosion Phenomena, Causes and Cures": T. E. Larson
1:30 p.m. "Some Experiences in Scale and Corrosion Control": A. H. Ullrich
2:00 p.m. "Manganese, Iron and Copper Problems": John C. Kearns
3:00 p.m. "Manganese in Water Distribution System": A. E. Griffin
3:30 p.m. "Copper Corrosion": George B. Hatch
4:00 p.m. "Residual Chlorine in Distribution Systems": James V. Feuss
4:30 p.m. Adjourn
EVENING SESSION: W. J. Downer, Presiding; Garden Room, Urbana-Lincoln Motor Inn
7:00 p.m. Dinner
8:00 p.m. Address: W. J. Roberts

Wednesday, January 30, 1963
MORNING SESSION: O. S. Hallden, Presiding; Room 314, Illini Union
9:00 a.m. "Adverse Effects of Poor Circulation in Small Water Distribution Systems": John C. Guillou
9:30 a.m. "Adverse Effects of Poor Circulation in Large Water Distribution Systems": J. J. Rossbach, Jr.
10:30 a.m. "Actinomycetes in Water Distribution Systems": J. K. G. Silvey
11:00 a.m. "Pathogenic Bacteria and Viruses in Water Supplies": P. W. Kabler
11:30 a.m. "Animals Infestations in Distribution Systems": W. M. Ingram
12:00 noon Luncheon: Ballroom, Illini Union
AFTERNOON SESSION: J. T. O'Connor, Presiding; Room 314, Illini Union
1:00 p.m. "Iron Bacteria": F. M. Clark
1:30 p.m. "Biological Infestations in Water Distribution Systems": M. P. Crabbill
2:00 p.m. Adjourn

Speakers
Dr. Francis M. Clark, Professor of Microbiology, University of Illinois, Urbana, Illinois
Mr. Marshall P. Crabbill, Vice-President of Operations, Indianapolis Water Company, Indianapolis, Indiana
Mr. William J. Downer, Chief, Bureau of Public Water Supplies, Division of Sanitary Engineering, Illinois Department of Public Health, Springfield, Illinois
Dr. Richard S. Engelbrecht, Professor of Sanitary Engineering, University of Illinois, Urbana, Illinois
Dr. Ben B. Ewing, Professor of Sanitary Engineering, University of Illinois, Urbana, Illinois
Mr. Raymond J. Faust, Executive Secretary, American Water Works Association, Inc., New York, New York
Mr. James V. Feuss, Technical Consultant, Water and Waste Treatment, Wallace and Tiernan Inc., Belleville, New Jersey
Mr. Attmore E. Griffin, Water Treatment Consultant, Pompton Plains, New Jersey
Mr. John C. Guillou, Associate Professor of Hydraulic Engineering, University of Illinois, Urbana, Illinois
Dr. George B. Hatch, Chemical Research and Development, Hagan Chemicals and Controls, Inc., Pittsburgh, Pennsylvania

Dr. William M. Ingram, In Charge, Biological, Chemical, and Oceanographic Activities, Field Operations Section, Technical Services Branch, Division of Water Supply and Pollution Control, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio

Dr. Paul W. Kabler, Chief of Microbiology, Division of Water Supply and Pollution Control, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio

Mr. John T. Kearns, Chief Sanitary Engineer, American Water Works Service Company, Inc., Philadelphia, Pennsylvania

Mr. Clarence W. Klassen, Chief Sanitary Engineer, Division of Sanitary Engineering, Illinois Department of Public Health, Springfield, Illinois

Dr. T. E. Larson, Head, Chemistry Section, Illinois State Water Survey, Urbana, Illinois

Mr. Gerald E. Margrave, Sanitary Engineer, Bureau of Public Water Supplies, Division of Sanitary Engineering, Illinois Department of Public Health, Springfield, Illinois

Dr. N. M. Newmark, Professor of Civil Engineering and Head, Department of Civil Engineering, University of Illinois, Urbana, Illinois

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Dr. John T. O'Connor, Assistant Professor of Sanitary Engineering, University of Illinois, Urbana, Illinois

Mr. W. J. Roberts, Engineer, State Water Survey, Champaign, Illinois

Mr. Joseph J. Rossbach, Jr., Metropolitan Utilities District, Omaha, Nebraska

Dr. J. K. G. Silvey, Professor of Biology and Chairman, Division of Science, North Texas State University, Denton, Texas

Dr. Richard E. Speece, Assistant Professor of Sanitary Engineering, University of Illinois, Urbana, Illinois

Mr. Albert H. Ulrich, Superintendent, Department of Water and Sewage Treatment, City of Austin, Austin, Texas
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