PHOSPHATE BASED CORROSION INHIBITORS: EFFECTS ON DISTRIBUTION SYSTEM REGROWTH

By
Stephen C. Olson, P.E.*
(Presented May 20, 1996)**

ABSTRACT

As part of the recently finalized Lead and Copper Rule, USEPA has specified compliance based treatment techniques for the control of lead and copper in public water supplies. One treatment technique recommended by USEPA for the control of lead and copper is the use of phosphate based corrosion inhibitors. However, many water suppliers have expressed concern that the addition of phosphorus into their distribution system could increase the potential for biological regrowth, resulting in non-compliance with the Total Coliform Rule. There have been several studies conducted recently that address this concern. One investigation found that phosphate based corrosion inhibitors did not significantly influence the growth of several strains of coliform bacteria. Other studies have demonstrated that the use of phosphate inhibitors actually reduces the presence of biofilms. Numerous successful full scale applications of phosphate based corrosion inhibitors for lead and copper control support these results. It has been suggested that system wide reductions in corrosion due to the addition of an inhibitor reduce the area of habitat (i.e., tubercles in the pipeline) of biofilm microorganisms, thereby reducing regrowth potential. In light of recent work, corrosion control (including the addition of a phosphate inhibitor) is part of USEPA's recommended Biofilm Control Plan. This paper discusses the results of recent studies and full scale applications of phosphate based corrosion inhibitors on biological regrowth within distribution systems.

INTRODUCTION

One of the most comprehensive and controversial drinking water regulations promulgated by the United States Environmental Protection Agency (USEPA) is the Lead and Copper Rule (LCR). The provisions of the LCR include various treatment techniques (optimal corrosion control treatment, source water treatment, public education for lead, and lead service line replacement), monitoring requirements, analytical methods, public notification requirements, record keeping and reporting requirements, and a compliance schedule based on system size. One treatment technique recommended for the potential control of tap water lead levels is the application of phosphate based corrosion inhibitors. The use of phosphate based corrosion inhibitors to prevent corrosion in water distribution systems is well documented (AWWARF, 1990a; USEPA, 1992a; USEPA, 1993; Schock, 1989). They are applied to create a passivating film of insoluble phosphate products on the interior surface of pipe materials. However, many water utilities have expressed concern that the use of phosphate based corrosion inhibitors could stimulate biological growth in drinking water treatment systems, resulting in regulatory non-compliance and/or a potential risk to public health.

*Senior Project Engineer, S E A Consultants, Inc., Cambridge, MA
**At NEWWA's National Conference on Integrating Corrosion Control

Biological regrowth, or the formation of a distribution system biofilm is undesirable in water systems. Potential negative impacts of distribution system regrowth are summarized below:

Public Health Risk - formation of a distribution biofilm may lead to the proliferation of opportunistic pathogens. Also, increased bacteria levels in the bulk water may interfere with coliform test results, thus potentially hiding external contamination.

Customer Dissatisfaction - biofilms can result in the formation of objectionable tastes, odors, and color in distribution water. Explaining these problems due to the presence of a distribution system biofilm may diminish consumer confidence in the quality of their water.

Regulatory Non-Compliance - biological regrowth may result in a failure to meet the requirements of the Total Coliform Rule. Depletion of the disinfection residual may cause a failure to meet the minimum disinfection requirements of the Surface Water Treatment Rule. Increased disinfection residuals required to combat the biofilm may lead to unacceptable disinfection by product (DBP) levels.

Increased Costs - the formation of distribution biofilms can accelerate corrosion leading to higher maintenance costs. Higher disinfectant demands, resulting in increased chemical doses can increase chemical costs. The formation of a distribution system biofilm can also decrease the hydraulic capacity of water mains, leading to higher energy costs for pumping.

Therefore, water utilities should make every effort to actively avoid the occurrence of distribution system regrowth.

The specific role of phosphate based corrosion inhibitors on biological regrowth in oligotrophic aquatic environments such as drinking water distribution systems, is poorly understood. Phosphorus is commonly associated with the application in agricultural fertilizers to bolster plant growth and its contribution to the occurrence of algal blooms in surface water bodies. Phosphorus is a necessary nutrient for all forms of life. In the natural environment, phosphorus is almost exclusively found in the form of orthophosphate (PO_4^{-3}).

Microorganisms play a significant role in the cycle and bioavailability of phosphorus in aquatic environments (Mhamdi et al., 1994; Cerco and Cole, 1993). This paper will review and discuss research related work, field studies, and recent full scale applications on the affects of phosphate based corrosion inhibitors on distribution system regrowth.

OVERVIEW OF BIOLOGICAL REGROWTH / BIOFILMS

A comprehensive review of distribution system regrowth and the formation of biofilms can be found elsewhere (LeChevallier, 1990; AWWARF, 1990b; USEPA, 1992b; Safe Drinking Water Committee, 1982). A summary of the causes, influences, and characteristics of distribution system regrowth is provided below.

Biological regrowth has been defined as the multiplication of microorganisms either in the bulk water or attached to surfaces as biofilms. A biofilm refers to an organic or inorganic surface deposit consisting of microorganisms, microbial by-products, and detritus (Safe Drinking Water Committee, 1982; USEPA, 1992b). In most drinking water distribution systems, the conditions for suspended biological regrowth are unfavorable (relatively short detention times, low nutrient concentrations, and typically the presence of a residual disinfectant). In contrast, conditions within water distribution systems can be favorable for attached biological regrowth (higher nutrient concentrations, protection from residual disinfectants, and protection against washout).

Microorganisms that have been detected in distribution system biofilms include heterotrophic plate count (HPC) bacteria (Tuovinen et al., 1980; LeChevallier et al., 1987), coliform bacteria (Victoreen, 1984), fungi and yeasts (Nagy and Olson, 1985). The predominant genera of HPC and coliform bacteria detected in water distribution systems are presented in Table 1. The major constituent of biofilms is water, between 79% and 95% on a wet basis (Flemming, 1993). In addition, both organic and inorganic materials have been identified in biofilms. Extracellular polysaccharides (EPS) account for over 70% of the organic matter measured in biofilms (Flemming, 1993). Inorganic chemicals identified in biofilms include iron, calcium, magnesium, aluminum, silicon, phosphorus, sulfur, and zinc (Safe Drinking Water Commit-

TABLE 1
Common Bacteria Identified in
Water Distribution Systems

Common HPC Bacteria	Common Coliform Bacteria
Achromobacter	*Citrobacter freundii*
Acinetobacter	*Enterobacter agglomerans*
Aeromonas	*Enterobacter amniggenus*
Alcaligenes	*Enterobacter cloacae*
Arthrobacter	*Erwinia herbicola*
Bacillus	*Klebsiella oxytoca*
Flavobacterium	*Klebsiella pneumoniae*
Gallionella	*Serratia marcesens*
Moraxella	
Pseudomonas	

tee, 1982; Ridgway and Olson, 1981; Ridgway et al., 1981; Tuovinen et al., 1980). The exact relative proportions will vary depending on the pipe material and the quality of the water.

Factors that Affect Regrowth

Regrowth involves the introduction of bacteria into the water distribution system, followed by subsequent growth. Bacteria can enter a distribution system either due to a breakdown in the treatment processes or by external contamination (cross connections, back siphonage, line breaks). Although biofilms themselves may not directly contribute to coliform regrowth occurrences, they may indirectly contribute by consuming residual disinfectant, thus providing a more favorable environment for coliform survival in the bulk water. Factors that affect distribution system regrowth are summarized below:

Environmental Factors

Temperature - temperature is perhaps the most important factor affecting microbial growth because it influences treatment plant efficiency, microbial growth rate, disinfection efficiency, dissipation of disinfectant residual, corrosion rates, and distribution system hydraulics (seasonal water demands) (LeChevallier, 1990; USEPA, 1992b). The seasonal affects of temperature on the occur-

rence of bacteria have been reported for many water distribution systems (Hudson et al., 1983; Wierenga, 1985; LeChevallier et al., 1991; Smith et al., 1989; Lowther and Moser, 1985; Rizet et al., 1982; Neden et al., 1992; Donlan et al., 1994). Typically, coliform and HPC bacteria levels increase during the warm weather months. LeChevallier and Co-workers found a clear relationship between coliforms and temperature above 15°C (AWWARF, 1990b).

Rainfall - episodes of rainfall have frequently been associated with distribution system coliform occurrences (Lowther and Moser, 1985; AWWARF, 1990b; LeChevallier et al., 1993). Work by LeChevallier and Coworkers found a significant relationship between coliform occurrences and a seven day lag period after rainfalls (AWWARF, 1990b). It is speculated that rainfall events may wash excessive nutrients into the watershed, stimulating bacterial growth and/or increasing the number of particles (turbidity) that can provide protection against disinfection.

pH - pH has a significant affect on both water chemistry and microbiological activity. In the use of chlorine for disinfection, pH will effect the distribution of hypochlorous acid (HOCl) and hypochlorite ion (OCl⁻). Since HOCl is a stronger disinfectant than OCl⁻ bacterial inactivation by

chlorine would be favored at lower pHs. In the absence of chlorine, elevated pHs >9 using lime for adjustment, have been shown to inactivate Klebsiella pneumoniae (Martin et al., 1982). pH also has an affect on the corrosion rates of metals.

Bicarbonate - the growth rate constant of six strains of bacteria was found to be highly dependent on bicarbonate in oligotrophic waters (Fransolet et al., 1988). It was assumed that bacteria assimilated bicarbonate, or carbon dioxide in equilibrium with bicarbonate, for growth and energy. However, nitrogen as nitrate was not controlled in the study.

Nutrients

The principal nutrients required for bacterial growth and energy are carbon, nitrogen, and phosphorus. HPC bacteria require an approximate C:N:P ratio of 100:10:1 (USEPA, 1992b). Typically only a fraction of the total organic carbon (TOC) present in drinking waters is readily assimilable for bacterial growth. Therefore carbon is often a limiting nutrient for regrowth. Ratios of assimilable organic carbon (AOC) to dissolved organic carbon (DOC) in surface and ground waters in southern California were reported between 0.5% and 31% (Bradford et al., 1993). AOC levels have been shown to be an indication of the biological stability of drinking water (Van der Kooij, 1992; LeChevallier, 1990; AWWARF, 1990b; LeChevallier et al., 1991). It has been proposed that AOC levels less than 50 μg/L acetate carbon equivalents are required to limit the growth of coliforms in drinking water (LeChevallier et al., 1991). A survey of 79 water utilities in the United States indicated that 95% of the surface water supplies and 50% of the groundwater supplies participating in the study would violate the 50 μg/L AOC criteria (Kaplan et al., 1994).

Nitrogen is often present in raw water supplies due to vegetative decay, runoff containing agricultural fertilizers, leachate form landfills, or wastewater discharges (USEPA, 1992b). The forms of nitrogen found in drinking water include organic nitrogen, ammonia, nitrite, and nitrate. Microorganisms classified as nitrate reducers, nitrite oxidizers, and ammonia oxidizers have been detected in water distribution main tubercles (Tuovinen et al., 1980; Tuovinen and Hsu, 1982; Nagy and Olson, 1985)

Disinfection

The relationship between disinfection and regrowth is affected by the type of disinfectant, pipe materials, water chemistry, and the microbial population. It has been demonstrated that the use of ozone for primary disinfection can increase the availability of readily biodegradable organics, thus increasing the potential for regrowth (Lund and Ormerod, 1995). Both chlorine and chlorine dioxide are more effective than monochloramine for the inactivation of suspended bacteria, however monochloramine has been shown to be more effective than chlorine and chlorine dioxide for the inactivation of bacteria on attached surfaces (Wolfe et al., 1985; LeChevallier et al., 1988a, 1988b).

The results of several studies have demonstrated that free chlorine can be used to control biofilm bacteria in copper, galvanized, PVC, and HPDE pipe systems (Lund and Ormerod, 1995; LeChevallier et al., 1990). However, several public water supply systems have reported biological regrowth problems, despite the maintenance of free chlorine residuals (Wierenga, 1985; Martin et al., 1982; Hudson et al., 1983; Goshko et al., 1983). The results of a mathematical model that accounts for the simultaneous transport of substrata, disinfectants, and microorganisms demonstrates the limited role of chlorine for controlling the accumulation of biomass on iron pipe surfaces (Lu et al., 1995). In iron pipe systems, monochloramine has been shown to be more effective than free chlorine for the inactivation of biofilm bacteria, especially at increased corrosion levels (LeChevallier et al., 1993; Neden et al., 1992).

Research on the disinfection of biofilm bacteria has indicated that distribution system corrosion decreases the disinfection efficiency of free chlorine. It has been suggested that because monochloramine is significantly less reactive with other compounds, when compared to free chlorine, it is better able to penetrate the biofilm layer and inactivate bacteria without being consumed by surface reactions. However, the use of monochloramine as a secondary disinfectant should be carefully controlled and monitored. Increased ammonia levels, associated with the formation of chloramines, have been reported to have caused increased HPC bacteria levels in public water distribution systems (Skadsen, 1993).

Area of Habitat

Bacteria have been detected in distribution main sediments, water main tubercles, and suspended inorganic and organic matter in public water distribution systems (Allen and Geldreich, 1977; Victoreen, 1984; Tuovinen et al., 1980; Tuovinen and Hsu, 1982; Ridgway and Olson, 1981; Donlan et al., 1994). Surfaces provide an area for nutrient accumulation and protection against disinfectant residuals, which are supportive of bacterial growth. The removal of potential habitats for bacterial growth is an integral part of a successful biofilm control plan. (LeChevallier et al., 1993; USEPA, 1992b; Hess, 1996).

Hydraulic Effects

Water system flow dynamics have been shown to influence the number of bacteria detected in the bulk water and the thickness of a biofilm layer in a public water distribution in Philadelphia, Pennsylvania (Donlan et al., 1994). Increased velocities can result in a greater flux of nutrients, greater transport of disinfectants, and a greater shearing force on biofilms (Safe Drinking Water Committee, 1980). Stagnated water in dead end mains are susceptible to increased corrosion, the loss of a residual disinfectant, and the accumulation of sediments, all of which are favorable for microbial growth. Increased customer tap water bacterial levels have been associated with water from dead end water mains (LeChevallier, et al., 1987).

PHOSPHATE INHIBITORS AND REGROWTH

Research on the specific role of phosphate based corrosion inhibitors on distribution system regrowth has been limited. However, the results of several laboratory investigations, model distribution system studies, and full scale study applications on the affects of phosphate based corrosion inhibitors on biological regrowth has been reported in the literature. This section will review the results of several studies on the affects of phosphate based corrosion inhibitors on biological regrowth. In addition, water quality information from three full scale water distribution systems in Connecticut that recently began the use of phosphate based inhibitors for corrosion control will be presented.

[1] Virchem 932, Technical Products Corporation
[2] Shan-No-Corr, Shannon Chemical Company
[3] SK-7542, Stiles-Kem Division of Met-Pro Corporation

Laboratory Research

A comprehensive study on the influence of phosphate based corrosion compounds on bacterial growth was conducted in the mid 1980s at Drexel University (Rosenzweig, 1987). The laboratory investigation consisted of adding various amounts of phosphate based corrosion inhibitors to suspended coliform cultures, and examining the effects on growth. Two separate phosphate based corrosion inhibitors (zinc orthophosphate[1] and sodium-zinc metaphosphate[2]) and three strains of coliforms (*C. freundii, E. cloacae, and K. pneumoniae*) were examined. The experiments were conducted in 250 mL flasks, using dechlorinated, filter sterilized water, incubated at 25°C. Coliform counts were recorded in triplicate after 24 hours, 48 hours, and 168 hours. Several water quality characteristics of the tap water used in the study are presented in Table 2.

Based on a statistical analysis of the results, it was reported that the sodium-zinc metaphosphate had no significant affect on coliform growth in the range of 0.07 mg/L as PO_4 to 1.34 mg/L as PO_4. These concentrations correspond with an applied zinc dose between 0.007 mg/L and 0.134 mg/L. The results also indicated that the zinc orthophosphate compound inhibited the growth of coliforms at a product dosage above 0.3 mg/L as PO_4. This corresponds with a zinc concentration of 0.3 mg/L. The addition of 0.1 mg/L of iron to the tap water showed an increase in the inhibitory effect of zinc orthophosphate on coliform growth.

A similar laboratory investigation to the one completed at Drexel University was completed at Eastern Illinois University in 1990 (Weiler et al., 1990). This study examined the affects of adding a blended phosphate corrosion control compound[3] on the growth of two coliform strains, *E. coli and P. aeruginosa*. The water used for the experiments was collected from three separate sources; a groundwater supply system in Joliet Illinois; a surface water supply system from the Marin Municipal Water District in Corte Madra, California; and Lake Michigan treated water from the City of Chicago. Water samples were dechlorinated and filter sterilized using membrane filters. The experiments were conducted in 100 mL glass bottles and incubated at 25°C. Coliform plate counts were recorded in quadruplicate at 24 hour intervals, over a period of one week.

TABLE 2
Water Quality Characteristics
for Laboratory Experiments

Parameter	Mean
pH (standard units)	6.1
Alkalinity (mg/L as $CaCO_3$)	45.2
Turbidity (N.T.U.)	0.18
Total organic carbon (mg/L)	2.6
Nitrogen (mg/L as NO_2-NO_3)	1.67
Orthophosphate (mg/L)	0.04

No significant difference in the growth of coliforms was reported for the surface water samples after the addition of the blended phosphate inhibitor up to a dosage of 0.9 mg/L as PO_4. However, at concentrations above 0.225 mg/L as PO_4, the results suggested that the growth of *E. coli* was inhibited in the groundwater supply sample. The inhibition of *E. coli* was apparent after the fourth day at a dose of 0.9 mg/L as PO_4, and on the fifth day at an applied inhibitor dose of 0.225 mg/ L as PO_4. There was no significant affect on the growth of *P. aeruginosa* observed for the groundwater supply sample.

Another laboratory study, conducted at the Illinois Institute of Technology in 1983, examined the effects of adding increased levels of phosphorus, iron, carbon, ammonia-nitrogen (NH_3 - N) and nitrate nitrogen (NO_3 - N) on the growth of HPC bacteria in Lake Michigan raw water (Haas et al., 1988). The source of phosphate used in the study was dipotassium hydrogen phosphate. Untreated surface water was used in the study, which was collected from the City of Chicago Central Water Filtration Plant intake. All of the nutrients listed above were increased 100 percent over background levels. The resulting phosphate concentration used in the experiments was 0.02 mg/L. The samples were prepared in 100 mL bottles and incubated at 5°C. HPC levels were measured at 3, 6, 8, 10, 13, 16, 25, and 26 days.

On the basis of statistical analyses, it was reported that phosphorus was the primary limiting nutrient for the microbial consortium present in the raw water. The statistical results indicated that the affect of a phosphate concentration 2 times greater than background

levels was significant and positive after 6 days of incubation. HPC levels in the phosphate sample were reported between 2.1 and 4.3 times greater than the control for the period between 6 days and 21 days. However, there were fewer HPC bacteria in the phosphate sample on day 3 compared with the control. This may have been indicative of a lag growth phase. There was no significant variation in HPC levels between the control and the phosphate sample at the start of the experiment.

Model Distribution Systems

Work completed by Rosenzweig also included an examination of the affects of phosphate corrosion compounds on bacterial growth in a model distribution system (Rosenzweig, 1987). The system was constructed of several sections of ductile iron and asbestos cement pipe, polyvinyl chloride (PVC) tubing, and a 10 gallon reservoir. The model was originally designed as a flow through system, and then later converted to a recirculating system. The system was operated at a temperature of 25°C and a flow rate that achieved a velocity of 0.3 ft/s within the pipes. Experiments were run using manufacturer recommended maintenance dosages of a sodium-zinc metaphosphate[2] and a zinc orthophosphate[1] corrosion inhibitor.

Water from the City of Philadelphia distribution system was used in the flow through study. HPC populations between 10^2 and 10^3 per mL were established prior to the addition of any phosphate inhibitor. Daily sampling results indicated that the implementation of the recommended maintenance doses of sodium-zinc metaphosphate (0.2 to 1 mg/L as PO_4) and

zinc orthophosphate (0.3 mg/L as PO_4) had no affect on HPC levels measured in the model system effluent. In addition, coliform bacteria were not isolated in any model system effluent samples.

When the model distribution system was converted to a recirculating system, each experiment was inoculated with a non-coliform heterotrophic bacterial population of approximately 10^4 to 10^5 cells per mL, and a *C. freundii* population of approximately 10^1 to 10^2 per 100 mL. Daily sampling results indicated that the addition of sodium-zinc metaphosphate and zinc orthophosphate at recommended maintenance dosages had no significant influence on the survival and growth of the established heterotrophic bacterial population, over the 5 week study period. In addition, the experiments were unable to establish a coliform population that was detectable by the standard membrane filtration procedure (Standard Methods, 1985).

LeChevallier and Co-workers studied the affects of corrosion control on the disinfection efficiency of biofilms in a model distribution system (LeChevallier et al., 1990; AWWARF, 1990b). The disinfection efficiency of chlorine and monochloramine was measured before and after implementing corrosion control. A polyphosphate corrosion inhibitor[4] applied at a dose of 10 mg/L as PO_4 and a zinc orthophosphate corrosion inhibitor[5] applied at a dose of 10.8 mg/L as PO_4 were used to reduce corrosion rates in the model distribution system to less than 1 mil per year (mpy). The model distribution system was constructed of iron, galvanized, copper, and PVC pipe, joined with PVC couplings. The temperature and pH were maintained during the experiments at 25°C and pH 7, respectively. The water in the experiments consisted of deionized water into which a low-nutrient growth medium was added. At the beginning of each experiment, the system was inoculated with HPC bacteria and *K. pneumonia*. Microbial populations were allowed to grow for two weeks prior to the addition of disinfectants. However, the corrosion inhibitors were added at the onset of the experiment.

In the absence of the phosphate inhibitors, an applied free chlorine residual of 4 mg/L was found to be ineffective at reducing viable biofilm counts. In the presence of a 10 mg/L polyphosphate dose as PO_4,

viable biofilm counts were reduced a hundred fold (2 log_{10}) after the addition of a 4 mg/L chlorine residual. Similarly, the addition of 10.8 mg/L as PO_4 of zinc orthophosphate reduced viable biofilm counts by as much as one thousand fold (3 log_{10}), in the presence of a 3.4 mg/L chlorine residual. However, in the zinc orthophosphate system, viable biofilm counts increased after 10 days. The study reported that the formation of a zinc hydroxide floc may have exerted a significant chlorine demand, thus reducing the free chlorine concentration available for disinfection. Based on the results of the study it was concluded that minimizing the corrosion of iron pipes increased the effectiveness of chlorine disinfection thus contributing to better control of distribution system biofilms. Another experiment that used pH/alkalinity adjustment to limit corrosion in the model distribution system supported the general conclusions of the study.

Another model distribution study completed by LeChevallier and Co-workers examined the impact of iron corrosion on the disinfection of biofilm bacteria (LeChevallier et al., 1993). In this study, a model distribution system was constructed of black iron pipe connected with plastic couplings. The source water was prepared by treatment through a reverse osmosis system, followed by the addition of various chemicals (calcium, magnesium, chloride, sulfate, and bicarbonate) to control water chemistry. The pH in the system was maintained at pH 7.3. Several phosphate based corrosion inhibitors (zinc orthophosphate[5], zinc polyphosphate[6], and polyphosphate[4]) were used to vary the corrosion rates in the model distribution system.

The results of the study indicated that the reduction in corrosion rates increased the disinfection efficiency of free chlorine on biofilm bacteria attached to black iron pipe. Regardless of the phosphate based inhibitor used, disinfection of biofilm bacteria using free chlorine was effective as long as low corrosion rates (<1 mpy) could be achieved. The use of monochloramine was generally more effective than free chlorine at reducing biofilm bacteria, especially at increased corrosion rates. Increased phosphate levels resulted in decreased corrosion rates and increased disinfection efficiency. The results of a multiple linear regression analysis indicated that 75% of the variation in biofilm inactivation could be explained by variations in corrosion rates, phosphate levels, disinfectant residuals, and Larson Index.

[4] AquaMag, Kjell Corporation
[5] C9, Calgon Corporation
[6] C39, Calgon Corporation

Herson and Co-workers conducted a model distribution study using a section of water main removed from the Wilmington Delaware distribution system (Herson, et al., 1984). Water from the Wilmington distribution system was recirculated through the model system. Temperature and pH were not controlled during the study. In one experiment the system was inoculated with a coliform concentration (*E. Cloacae*) of 1.4×10^3 organisms per 100 mL. After 5 days the coliform concentration was reported to be 3.7×10^1 organisms per 100 mL and the phosphate level was 0.03 mg/L. At this point a pH 7.2 phosphate buffer was added to the system to achieve a phosphate concentration of 0.41 mg/L. After 24 hours coliform levels increase approximately 10 fold ($1 \log_{10}$). HPC levels were also reported to have increased. Another cycle of phosphate loading to an approximate concentration of 0.45 mg/L resulted in an increase of coliform levels from 1×10^1 per 100 mL to 5×10^1 per 100 mL, after 24 hours. The coliform levels were measured from the bulk water and no chlorine was added to the system. The authors concluded that the growth of coliform organisms was influenced by the level of phosphate in the recirculating water. However, the independent affects of phosphate on coliforms may not be conclusive, since temperature, pH, and background nutrient levels were not controlled in the experiments.

Full Scale Studies and Applications

Documented Case Studies

A comprehensive field study was completed by Rosenzweig on three small public groundwater supply systems located in Chester County, Pennsylvania (Rosenzweig, 1987). Background water quality levels were established for approximately two to three months prior to the addition of either sodium-zinc metaphosphate[2] or zinc orthophosphate[1]. Sodium-zinc metaphosphate was added to two systems at a passivation dose of 2 mg/L as PO_4 for four months, and then reduced to a maintenance dose of 1 mg/L as PO_4. Zinc orthophosphate was added to the other water system at a passivation dose of 1 mg/L as PO_4 for one month, and then reduced to a maintenance dose of 0.3 mg/L as PO_4. Distribution system sampling was conducted for two periods after the addition of phosphate. The first period was conducted for approximately three months directly following the implementation of the inhibitors. The second sampling period was conducted for approximately five months following a four month postponement in sampling during the winter. Phosphate addition was continued during the winter months.

Chlorine residuals and pH levels remained the same throughout the pre-additive and post-additive phases. Chlorine residuals were typically reported between 0.3 and 0.4 mg/L and pH levels were reported between pH 6.4 and pH 6.5. Mean coliform counts reported before and after the addition of phosphate were similar for the first post-additive sampling period while mean coliform counts were significantly lower for the second post-additive sampling period for all three systems. The predominant coliform specie detected in the water samples was *E. cloacae*. HPC levels were reported to be significantly greater for both post additive sampling periods, except the first sampling period for the water system using zinc orthophosphate. Although increased levels of HPC bacteria were reported in the post-additive phases, it was reported that these increases could not be conclusively explained by increased phosphate levels due to strong correlations that were found between uncontrolled parameters such as TOC, nitrogen, calcium and temperature.

HPC and coliform levels were lower in all sampling periods for the system that used zinc orthophosphate. It is interesting to note that the mean free chlorine residuals were the same in all three sampling periods for the zinc orthophosphate system, however the maximum free chlorine residual reported for this system was significantly less in the second post-additive period. This may have been due to the formation of a zinc hydroxide layer on the pipe surfaces in this system.

Weiler and Co-Workers collected bacteriological data from three public water supply systems for representative periods before and after the addition of a blended phosphate corrosion inhibitor[3] (Weiler et al., 1990). The number of positive coliform samples prior to the addition of the blended phosphate product were compared with the number of positive coliform samples after the addition of the inhibitor for equal time periods. Phosphate dosages and chlorine residuals were not reported in the study. The total number of samples collected for both sampling periods was similar. For all three systems, a reduction in the number of positive total coliform samples was reported after the addition of the blended phosphate inhibitor.

The American Water Works Service Company documented a coliform outbreak episode in one of their public water supply systems located in Seymour, Indiana (Lowther and Moser, 1985). The Seymour Water Treatment Plant (WTP) is a conventional filtration facility that treats river water which is subject to turbidity spikes. Episodes of positive coliform samples were reported in the distribution system in 1982 and 1983 when raw water temperatures were above 55°F, which only occur in the spring and summer. An increased free chlorine residual of 6 mg/L was the only means of controlling coliform levels in the distribution system during the warm weather months of 1982 and 1983. However, maintenance of a 6 mg/L free chlorine residual was not considered to be an acceptable long term solution to the problem.

The results of extensive investigations indicated that the coliform episodes were not the result of treatment breakthrough or external contamination. It was therefore concluded that the coliform episodes were due to the presence of a distribution system biofilm resulting from distribution system corrosion. In the spring of 1984, at the onset of warm water temperatures, coliforms were again detected, and the application of a zinc orthophosphate corrosion inhibitor[1] was implemented. The inhibitor was applied at a passivating dose of 3 mg/L as PO_4 for three days, then reduced to a maintenance dose of 0.5 mg/L as PO_4. During this time a chlorine residual of 2 mg/L was maintained in the distribution system. A reduction in the number of positive coliform samples was reported after the addition of the zinc orthophosphate corrosion inhibitor. Only one positive coliform sample was reported in the summer of 1984.

The South Central Connecticut Regional Water Authority (RWA) provided a detailed description of their experiences with biological regrowth in their water distribution system (Smith et al., 1989). After several years of excessive positive coliform samples detected in the distribution system, the RWA modified its corrosion control program in September 1988. The application of a sodium-zinc metaphosphate inhibitor[2] was increased from a dose of approximately 0.7 mg/L as PO_4 to a dose of approximately 1.4 mg/L as PO_4. This resulted in average total phosphorus concentrations, measured in the distribution system, to increase

from 0.31 mg P/L to 0.43 mg P/L. A reduction in weekly positive coliform samples was reported after the corrosion control modification. Weekly average positive coliform distribution samples over a 30 week period (March through September) were reported to be 12.89 percent before the modification and 5.12 percent after the modification.

Additional Information

The Connecticut Water Company (CWC) is a private water company that manages and operates numerous drinking water supply systems in the State of Connecticut. One system maintained by CWC in the Town of Plymouth, Connecticut is the Terryville System. The Terryville system is a groundwater supply system with an approximate service population of 6,600, and an annual average daily demand of approximately 450,000 MGD. The Terryville System uses sodium hypochlorite for disinfection and potassium hydroxide for pH adjustment. The system recently implemented the use of a polyphosphate corrosion inhibitor[7] in May 1994, at an applied dose of 1.5 mg/L as PO_4, for the control of lead and copper corrosion.

Six months of water quality information both before and after the addition of the phosphate inhibitor was provided by the CWC. The water quality information includes the results of monthly distribution system sampling from four individual sites. Approximately 11 samples are collected per month. The average water quality within the distribution system before the addition of phosphate was a pH of 7.0, a chlorine residual of 0.2 mg/L, and a turbidity of 0.03 NTU. After the addition of phosphate, the average pH was 7.2, the average chlorine residual was 0.2 mg/L, and the average turbidity was 0.04 NTU. Out of 62 coliform samples prior to the addition of phosphate, and 63 samples after the addition of phosphate, there were no coliforms detected. An analysis of the water quality information indicates that there was no significant change in the biological quality of the water after the addition of a phosphate inhibitor at a dose of 1.5 mg/L as PO_4.

Additional water quality information was collected from two water systems owned and operated by the Bridgeport Hydraulic Company (BHC). BHC is a private water company located in Bridgeport, Connecticut, that provides drinking water to approximately

[7] Sodium Hexametaphosphate, Rhone-Poulenc, Inc.

500,000 people in 24 municipalities in southern Connecticut. BHC recently implemented the addition of phosphate based corrosion inhibitors at two of its water systems in the early 1990s. Historic distribution system sampling results from a surface water supply system and a groundwater supply system were obtained from BHC's water quality database.

The surface water supply system began the application of a zinc orthophosphate corrosion inhibitor[8] in mid December 1991. Distribution system water quality information from the period May 1991 through December 1991 (before the addition of phosphate), and December 1991 through July 1992 (after the addition of phosphate), from nine sampling sites is summarized in Table 3. A review of the information provided in Table 3 indicates that the bacteriological quality of the water in the distribution system improved after the addition of the zinc orthophosphate inhibitor. As measured by the membrane filter technique (MF), the average coliform concentration, including 637 total samples, was zero for both sampling periods. The average non-coliform bacteria colony concentration, reported as part of the membrane filter technique, was 31.95 per 100 mL for the seven month period prior to the addition of phosphate and 1.89 per 100 mL after the addition of phosphate. In addition, average HPC levels measured before and after the addition of phosphate were 52.86 per mL and 8.5 per mL, respectively. pH levels and chlorine residuals were similar for both study periods. However, average phosphate levels detected in the distribution system increased from 0.02 mg/L prior to the addition of phosphate to 0.97 mg/L after the addition of phosphate.

Average MF-bacteria concentrations for eight of the nine distribution sampling sites are shown graphically in Figure 1, and average HPC concentrations for each distribution sampling site are presented in Figure 2. A review of the information provided in Figure 1 indicates that all of the individual sampling sites experienced lower MF-bacteria levels after the addition of phosphate. In addition, the information shown in Figure 2 indicates that average HPC levels declined in six of the nine sampling sites after the addition of phosphate. At one sampling site, not shown on Figure 1, MF-bacteria levels were zero for both study periods. These data illustrate that the overall bacteriological

quality of the water improved throughout the distribution system.

The groundwater supply system began the application of a sodium-zinc metaphosphate[2] corrosion inhibitor[2] in mid July 1992. Distribution system water quality information was obtained for the period January 1992 through December 1992. Phosphate levels detected in the distribution system before July 1992 were 0.01 mg/L. After the addition of the inhibitor, the average orthophosphate concentration detected in the distribution system was 0.17 mg/L, while the average total phosphate concentration was 0.76 mg/L.

A summary of the water quality information reported for two distribution system sampling sites is presented in Table 4. Based on a comparison of water quality conditions provided in Table 4, average HPC levels were lower after the addition of the phosphate based inhibitor while total coliforms and non-coliform bacteria were not detected in either sampling period, using the membrane filter technique. Average HPC levels for the two groundwater system distribution sampling sites are presented in Figure 3. A review of the information provided in Figure 3, reveals that average HPC levels declined at both sites after the addition of phosphate. During the study period pH and chlorine residuals were similar.

Based on an analysis of the information obtained from CWC and BHC, it appears that the application of phosphate based corrosion inhibitors had no deleterious effect on coliform levels measured in three public water supply distribution systems. In fact, the information suggests that phosphate residuals of around 1 mg/L may contribute to improved bacteriological quality of the water in the distribution system, provided a residual disinfectant is maintained. The results of various research efforts and full scale demonstration studies indicate that the application of phosphate based inhibitors, to reduce corrosion in drinking water distribution systems, can improve the bacteriological quality of the water by reducing corrosion. In various studies, the control of corrosion products, especially in iron pipes, has been shown to increase the disinfection efficiency of free chlorine on attached growth bacteria. A recent survey of 31 public water systems in North America found that the use of phosphate based corrosion inhibitors were associated with lower distribution system coliform levels (LeChevallier et al., 1996). On

---

[8] Virchem 939, Technical Products Corporation

TABLE 3
Water Quality Characteristics
Surface Water Supply: BHC

Parameter	Number of Samples	Mean	Maximum	Minimum
Pre-Phosphate				
pH (S.U.)	325	7.43	8.7	6.7
Chlorine (mg/L)	325	0.64	2.4	0
Ortho-PO_4 (mg/L)	10	0.02	0.03	0
T. Coliform (#/100 mL)	322	0	0	0
MF-bacteria (#/100 mL)[1]	322	31.95	6,200	0
HPC bacteria (#/mL)	310	52.86	4,104	0
Post-phosphate				
pH (S.U.)	294	7.59	8.7	6.3
Chlorine (mg/L)	294	0.76	2.1	0
Ortho-PO_4 (mg/L)	41	0.97	1.17	0
T. Coliform (#/100 mL)	315	0	0	0
MF-bacteria (#/100 mL)[1]	313	1.89	113	0
HPC bacteria (#/mL)	307	8.5	1,026	0

TABLE 4
Water Quality Characteristics
Groundwater Supply: BHC

Parameter	Number of Samples	Mean	Maximum	Minimum
Pre-phosphate				
pH (S.U.)	33	7.44	7.8	6.9
Chlorine (mg/L)	33	0.42	0.55	0.3
Ortho-PO_4 (mg/L)	1	0.01	0.01	0.01
T. Coliform (#/100 mL)	32	0	0	0
MG-bacteria (#/100 mL)[1]	32	0	0	0
HPC bacteria (#/mL)	32	1.41	24	0
Post-phosphate				
pH (S.U.)	28	7.51	7.7	7.2
Chlorine (mg/L)	28	0.45	0.75	0.3
Ortho-PO_4 (mg/L)	28	0.17	0.3	0.09
T. Coliform (#/100 mL)	28	0	0	0
MF-bacteria (#/100 mL)[1]	28	0	0	0
HPC bacteria (#/mL)	28	0.65	5	0

[1] MF-bacteria: non-coliform bacteria colonies reported for the membrane filtration total coliform test method.

Figure 1

BHC Surface Water Supply

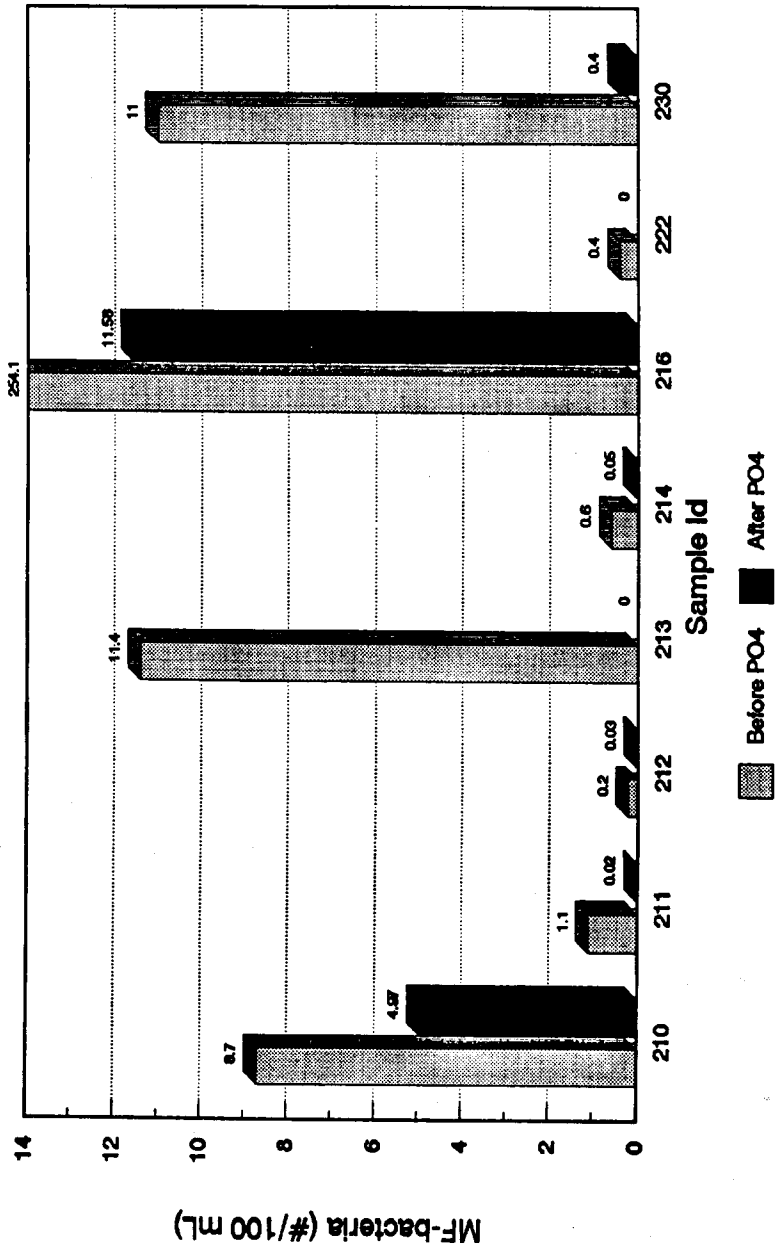**Average Non-Coliform Bacteria: Membrane Filter Method**

Figure 2
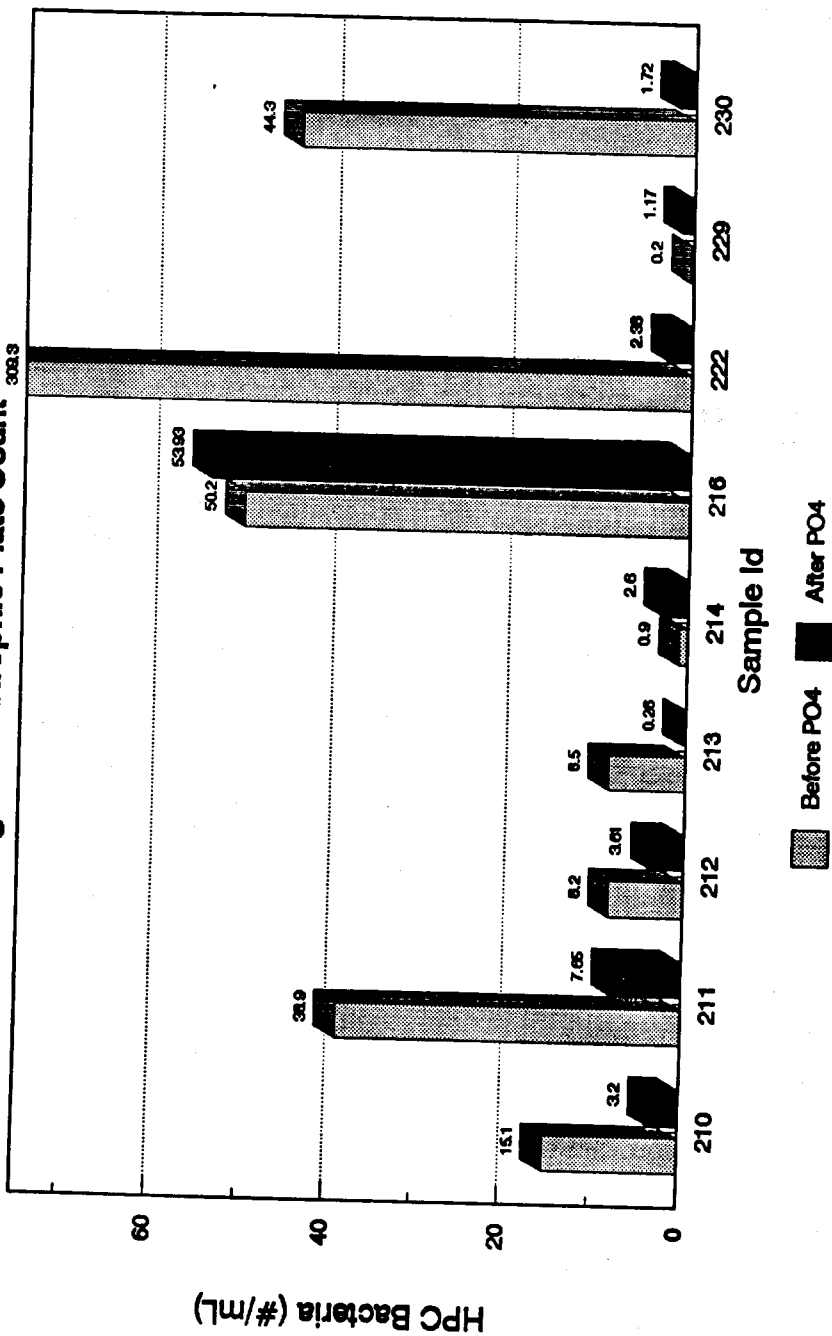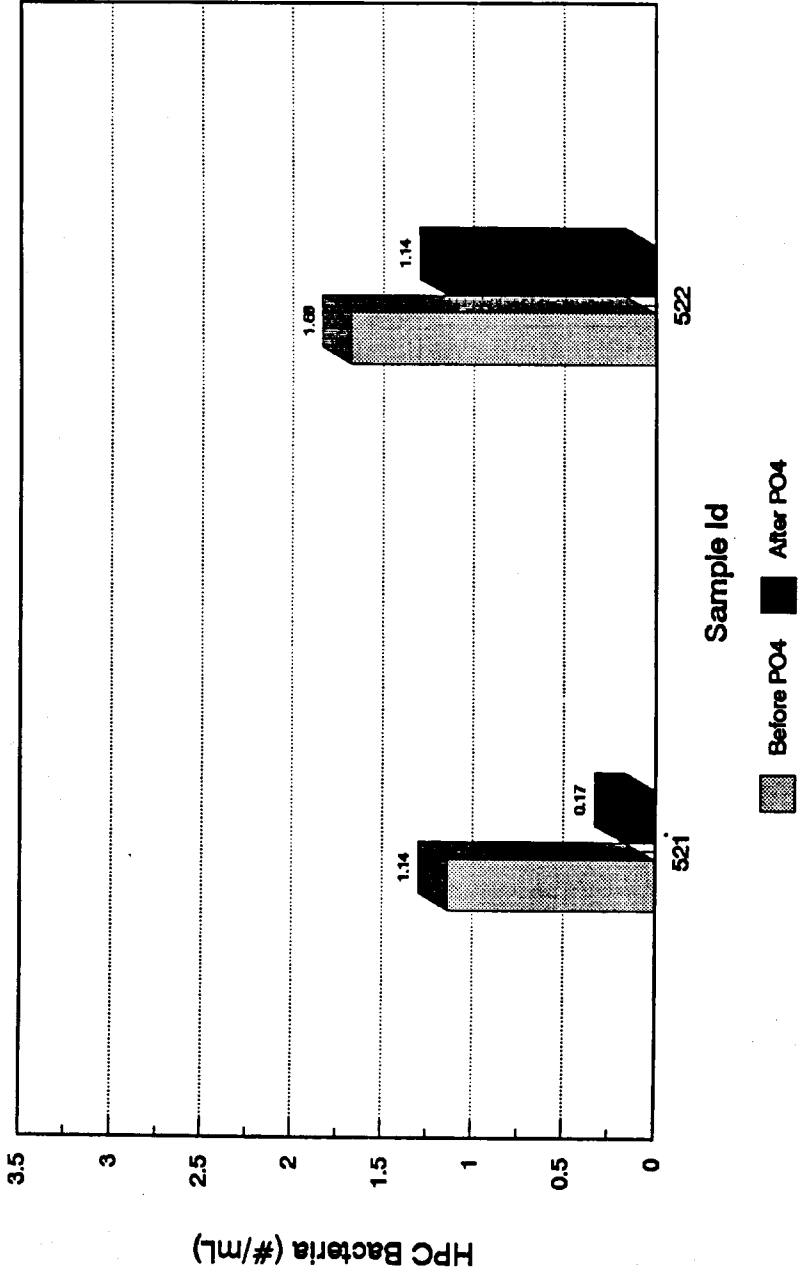BHC Surface Water Supply
Average Heterotrophic Plate Count

Figure 3
Ground Water Supply
Average Heterotrophic Plate Count

average, coliform levels were reported to be 36% lower in free chlorinated systems having phosphate levels greater than 0.1 mg/L, than for systems with lower phosphate levels.

SUMMARY AND CONCLUSIONS

Although the role of phosphorus has a clear history of stimulating biological growth in open surface water bodies, such as algae blooms, there is little evidence to suggest that the use of phosphate based corrosion inhibitors in public water distribution systems stimulates biological regrowth. Documented case studies have demonstrated the effectiveness of phosphate based corrosion inhibitors to control episodes of increased distribution system coliform levels. New information presented as part of this study suggests that the application of phosphate based corrosion inhibitors has no significant negative impact on coliform levels in distribution systems, and may actually improve the overall bacteriological quality of the water. It has been suggested that system wide reductions in corrosion reduce the area of habitat (i.e., tubercles in the pipeline) of biofilm microorganisms, thereby reducing regrowth potential. There is no evidence to suggest that one corrosion product would be preferred over the other, provided that reduced corrosion is achieved. In addition, the practice of secondary disinfection, or the maintenance of a residual disinfectant, plays a significant role in the control of biological regrowth.

ACKNOWLEDGEMENTS

REFERENCES

1. Allen, M.J. and Geldreich, E.E. (1977). "Distribution Line Sediments and Bacterial Regrowth", AWWA WQTC.

2. AWWARF. (1990a). *Lead Control Strategies*, Denver, CO.

3. AWWARF. (1990b). *Assessing and Controlling Bacterial Regrowth in Distribution Systems*, Denver, CO.

4. Bradford, S.M., Palmer, C.J., Olson, B.H. (1993). "Assimilable Organic Carbon Concentrations in Southern California Surface and Groundwater", Water Research, 28:2:427.

5. Cerco, C.F. and Cole, T. (1993). "Three-Dimensional Eutrophication Model of Chesapeake Bay", J.Env.Eng. ASCE, 119:6:1006.

6. Donlan, R.M., Pipes, W.O., Yohe, T.L. (1994). "Biofilm Formation on Cast Iron Substrata in Water Distribution Systems" Water Research, 28:6:1497.

7. Flemming, H.C. (1993). "Biofilms and Environmental Protection", Wat. Sci. Tech., 27:7:1.

8. Fransolet, G., Depelchin, A., Villers, G., Goossens, R., Masschelein, W.J. (1988). "The Role of Bicarbonate in Bacterial Growth in Oligotrophic Waters", J.AWWA, 80:11:57.

9. Goshko, M.A., Minnigh, H.A., Pipes, W.O., Christian, R.R. (1983). "Relationships between Standard Plate Counts and other Parameters in Water Distribution Systems", J.AWWA, 75:11:568.

10. Haas, C.N., Bitter, P., Scheff, P.A. (1988). "Preliminary Determination of Limiting Nutrients for Standard Plate Count Organisms in Chicago Intake Water", Water, Air, and Soil Pollution, 37:65.

11. Herson, D.S., Marshall, D.R., Victoreen, H.T. (1984). "Bacterial Persistence in the Distribution System", AWWA WQTC.

12. Hess, A.F. (1996). Personal Communication.

13. Hudson, L.D., Hankins, J.W., Battaglia, M. (1983). "Coliforms in a Water Distribution System: a Remedial Approach", J.AWWA, 75:11:564

14. Kaplan, L., Reasoner, D.J., Rice, E. (1994). "A Survey of BOM in U.S. Drinking Waters", J.AWWA, 86:2:121.

15. LeChevallier, M.W., Welch, N.J., Smith, D.B. (1996 in press). "Factors Related to Coliform Regrowth in Drinking Water: Full Scale Studies", Appl. & Env. Micro.

16. LeChevallier, M.W., Lowry, C.D., Lee, R.G. (1990). "Disinfecting Biofilms in a Model Distribution System", J.AWWA, 82:7:87.

17. LeChevallier, M.W. (1990). "Coliform Regrowth in Drinking Water: A Review", J.AWWA, 82:11:74.

18. LeChevallier, M.W., Cawthon, C.D., Lee, R. (1988b). "Inactivation of Biofilm Bacteria", Appl. & Env. Micro., 54:10:2492.

19. LeChevallier, M.W., Cawthon, C.D., Lee, R. (1988a). "Factors Promoting Survival of Bacteria in Chlorinated Water Supplies", Appl. & Env. Micro., 54:3:649.

20. LeChevallier, M.W., Schulz, W., Lee, R.G. (1991). "Bacterial Nutrients in Drinking Water", Appl. & Env. Micro., 57:3:857.

21. LeChevallier, M.W., Lowry, C.D., Lee, R.G., Gibbon, D.L. (1993). "Examining the Relationship between Iron Corrosion and the Disinfection of Biofilm Bacteria", J.AWWA, 85:7:111.

22. LeChevallier, M.W., Babcock, T.M., Lee, R. (1987). "Examination and Characterization of Distribution System Biofilms", Appl. & Env. Micro., 53:12:2714.

23. Lowther, E.D. and Moser, R.H. (1985). "Detecting and Eliminating Coliform Regrowth", AWWA WQTC.

24. Lu, C., Biswas, P., Clark, R.M. (1995). "Simultaneous Transport of Substrates, Disinfectants and Microorganisms in Water Pipes", Water Research, 29:3:881.

25. Lund, V. and Ormerod, K. (1995). "the Influence of Disinfection Processes on Biofilm Formation in Water Distribution Systems", Water Research, 29:4:1013.

26. Martin, R.S., Gates, W.H., Grantham, D., Sumarah, R., Wolfe, P., Forestall, P., (1982). "Factors Affecting Coliform Bacteria Growth in Distribution Systems", J.AWWA, 74:1:34.

27. Mhamdi, M.A., Aleya, L., Devaux, J. (1994). "Phosphorus Exchanges Between Sediment and Water in Trophically Different Reservoirs", Water Research, 28:9:1971.

28. Neden, D.G., Jones, R.J., Smith, J.R., Kirmeyer, G.J., Foust, G.W. (1992). "Comparing Chlorination and Chloramination for Controlling Bacterial Regrowth", J.AWWA, 84:7:80.

29. Rizet, M., Fiessinger, F., Houel, N. (1982). "Bacterial Regrowth in a Distribution System and its Relationship with the Quality of the Feed Water: Case Studies", AWWA Annual Conference.

30. Rosenzweig, W.D. (1987). "Influence of Phosphate Corrosion Control Compounds on Bacterial Growth", Drexel University, Philadelphia, PA., prepared for USEPA.

31. Safe Drinking Water Committee. (1982). *Drinking Water and Health*, Volume 4, National Academy Press, Washington D.C.

32. Shock, M.R. (1989). "Understanding Corrosion Control Strategies for Lead", J.AWWA, 81:7:88.

33. Skadsen, J. (1993). "Nitrification in a Distribution System", J.AWWA, 85:7:95.

34. Smith, D.B., Hess, A.F., Ophaim, D. (1989). "Control of Distribution System Coliform Regrowth", AWWA WQTC.

35. Tuovinen, O.H. and HSU, J. (1982). "Aerobic and Anaerobic Microorganisms in Tubercles of the Columbus, Ohio, Water Distribution System", Appl. & Env. Micro., 44:3:761.

36. Tuovinen, O.H., Button, K.S., Vuorinen, A., Carlson, L., Mair, M., Yut, L.A. (1980). "Bacterial, Chemical, and Mineralogical Characteristics of Tubercles in Distribution Pipelines", J.AWWA, 72:11:626.

37. USEPA. (1992b). *Control of Biofilm Growth in Drinking Water Distribution Systems*, EPA/625/R-92/001, ORD.

38. USEPA. (1993). *Control of Lead and Copper in Drinking Water*, EPA/625/R-93/001, ORD.

39. USEPA. (1992a). Lead and Copper Rule Guidance Manual Volume II - Corrosion Control Treatment, USEPA, Washington D.C.

40. van der Kooij, D. (1992). "Assimilable Organic Carbon as an Indication of Bacterial Regrowth", J.AWWA, 84:2:57.

41. Victoreen, H.T. (1984). "The Role of Rust in Coliform Regrowth", AWWA WQTC.

42. Weiler, W.A., Pederson, C.L., Lookis, K.G., Malehorn, S.H. (1990). "Phosphate Corrosion Control Compounds: Their Effects on the Growth and/or Survival of Selected Bacteria", Env. Biol. and Bot. Prog., Eastern Illinois University, Charleston, Illinois.

43. Wierenga, J.T. (1985). "Recovery of Coliforms in the Presence of a Free Chlorine Residual", J.AWWA, 77:11:83.

44. Wolfe, R.L., Ward, N.R., Olson, B.H. (Inactivation of Heterotrophic Bacterial Populations in Finished Drinking Water by Chorine and Chloramines", Water Research, 19:11:1393.