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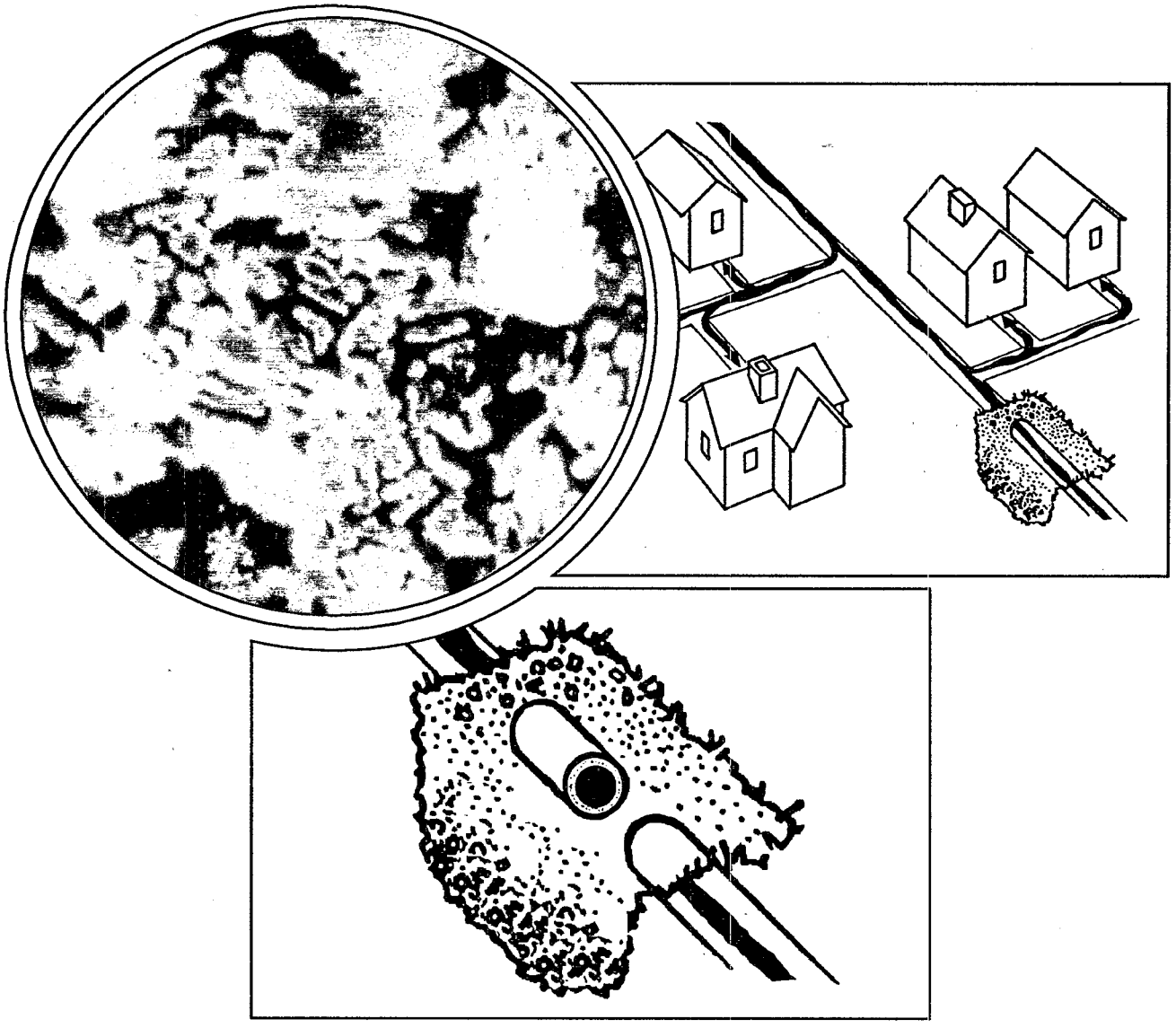
Seminar Publication:

Control of Biofilm Growth in Drinking Water Distribution Systems



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SEMINAR PUBLICATION: CONTROL OF BIOFILM GROWTH IN DRINKING WATER DISTRIBUTION SYSTEMS

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Notice

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Acknowledgments

In November 1990, the U.S. Environmental Protection Agency (EPA) called together a wide range of experts to discuss the issue of biofilms in drinking water distribution systems. Workshop participants represented EPA, states, public water systems, academia, trade organizations, and a public interest group. They assisted EPA in defining nationally applicable criteria for the issuance of variances to the maximum contaminant level for total coliforms when distribution system biofilms are present. This seminar publication is based on their discussion of the issues central to biofilm occurrence and control.

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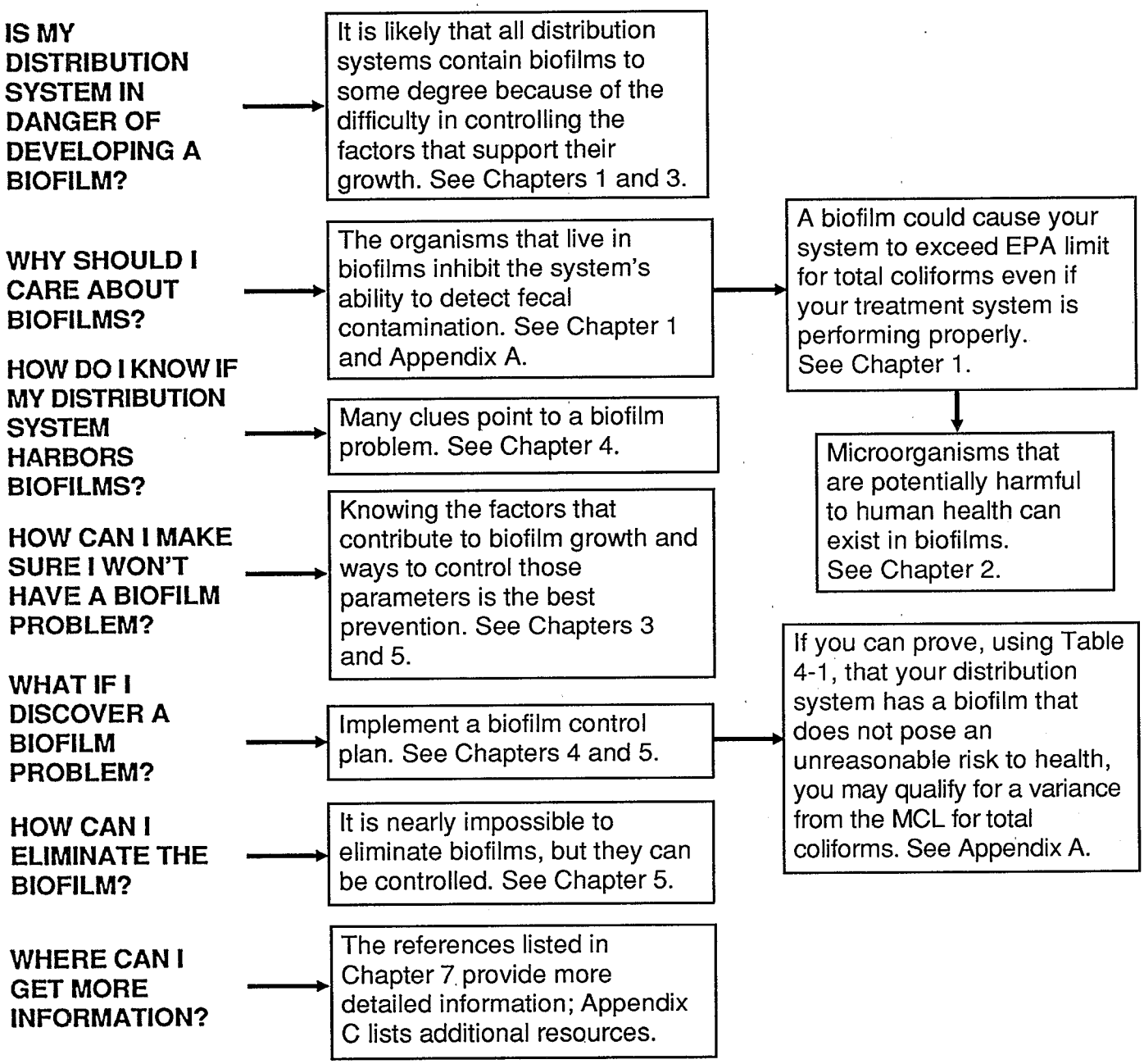
This document was reviewed and approved as an EPA publication. Mention of trade names, products, or services does not convey, and should not be interpreted as conveying, official EPA approval, endorsement, or recommendation.

Finding Answers in the Guidance Manual



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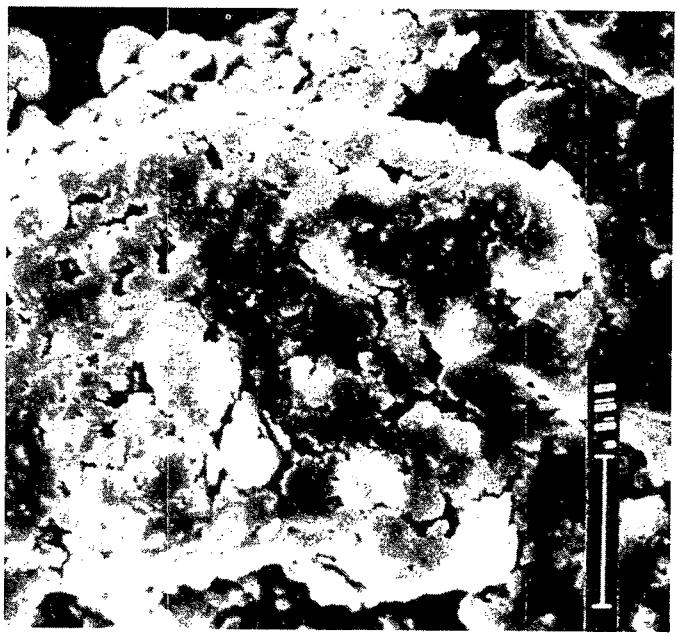
CHAPTER 1
Introduction

The occurrence of bacterial growths in finished drinking water is not new. In 1930, the American Water Works Association (AWWA) Committee on Water Supply reported on the problem of regrowth of "*B. coli*" (Committee on Water Supply, 1930). Adams and Kingsbury (1937) described "bacterial growths" in distribution water that seemed to come from nowhere: bacteria could not be detected in the finished water at the point of entry; however, microorganisms were apparently multiplying in the distribution pipelines (Schoenen and Scholer, 1985).

Later, scanning electron microscope (SEM) photographs of water distribution pipes showed complex communities of microorganisms on pipe surfaces and in pipeline tubercles (knob-like mounds of corrosion on pipe surfaces) (Allen et al., 1979; Tuovinen et al., 1980; Ridgway and Olson, 1981; Ridgway et al., 1981). Researchers realized that water treatment and disinfection systems were merely inactivating bacteria in the raw water; the microorganisms were surviving the treatment process. Once sent into the distribution system, the microorganisms could adapt to the distribution system environment.



Scanning electron micrograph of a distribution pipe surface

This problem persists today. While water treatment and disinfection systems can remove most of the bacteria found in raw water, the water produced is not sterile, and low levels of bacteria do persist even in properly treated supplies. Bacterial growth in the drinking water distribution system makes monitoring for bacterial quality in the distribution system difficult, hiding significant bacterial contamination introduced after treatment via cross connections, pipe breaks, or backsiphonage. Growths of bacteria on pipe walls, called *biofilms*, also can provide a haven for potentially pathogenic (disease-causing) bacteria (van der Kooij, 1992).

The current definition of a biofilm is an organic or inorganic surface deposit consisting of microorganisms, microbial products, and detritus (Marshall, 1976; Characklis, 1981; Characklis and Marshall, 1990). It is likely that biofilms exist in all distribution system pipelines, and they are now recognized as part of the normal aquatic system. Factors that influence the types and numbers of microorganisms found in finished drinking water are poorly understood, but probably include the type and quality of source water; the effectiveness of treatment and disinfection; physicochemical parameters (i.e., temperature, degree of corrosion); and the engineered system (Geldreich, 1988; LeChevallier et al., 1991a).

Biofilms and the Total Coliform Rule

The U.S. Environmental Protection Agency's (EPA's) goal in developing regulations regarding microbial water quality is to reduce the threat to public health from microorganisms found in source waters through adequate treatment and disinfection (U.S. EPA, 1989a, 1989b, 1991). The Total Coliform Rule states that coliform bacteria (a class of microorganisms used as indicators of the presence of disease-causing microorganisms) should not be detected in more than a certain percentage of samples taken from finished drinking water. The presence of coliforms in drinking water represents a potential threat to public health because it may indicate that disinfection has been inadequate to kill all pathogenic organisms associated with human and animal waste. It is recognized, however, that biofilms can harbor coliform organisms. Although these coliforms usually are not of fecal origin, they can cause violations of the Total Coliform Rule when

released into the distribution system. For this reason, the Total Coliform Rule allows states to grant a variance if the system can prove that biofilms are the sole cause of positive coliform results and the contamination does not pose an unreasonable risk to health.

How This Document Is Organized

This document describes the types of organisms often present in drinking water distribution system biofilms, how biofilms are established and grow, the public health problems associated with having biofilms in the distribution system, and tools that water treatment personnel can use to help control biofilm growth. Chapter 2 describes the formation and composition of biofilms in drinking water systems. Knowledge of the types of organisms usually present in biofilms and their requirements for survival will aid the water treatment facility in anticipating biofilm problems and preventing their occurrence. Chapter 3 provides information on the factors that influence biofilm growth. It is these factors that water utilities need to know to control biofilm problems. Chapter 4 explains how to recognize a biofilm occurrence and describes how various utilities have worked to pinpoint and solve biofilm problems. Chapter 5 provides guidance for controlling biofilm growth, using EPA's outline for an acceptable biofilm control plan.

Finally, Appendix A outlines the federal regulations pertaining to microorganisms in drinking water and their implications for systems with biofilm problems. Appendix A also includes a reprint of the January 1991 *Federal Register*. Appendix B is a glossary containing often-used terms, and Appendix C lists resources for additional information on the topics covered here.

CHAPTER 2
Biofilms

Knowing the types of organisms that can grow in a distribution system biofilm and their requirements for survival can help facility operators provide safe drinking water by anticipating biofilms and taking precautions to prevent their occurrence. Once you have read this chapter, you will have a general overview of the organisms present in drinking water, how they can survive treatment to colonize the distribution system, and how they can pose a public health threat.

What Is a Biofilm?

Biofilms are formed in distribution system pipelines when microbial cells attach to pipe surfaces and multiply to form a film or slime layer on the pipe (Figure 2-1). Probably within seconds of entering the piping system, large particles, including microorganisms, adsorb to the clean pipe surface. Some microorganisms can adhere directly to the pipe surface via appendages that extend from the cell membrane; other bacteria form a capsular material of extracellular polysaccharides (EPS), sometimes called a glycocalyx, that anchors the bacteria to the pipe surface (Geldreich, 1988; Costeron et al., 1978; Bitton and Marshall, 1980, 1990a). The organisms take advantage of the macromolecules attached to the pipe surface for protection and nourishment. The water flowing past carries nutrients (carbon-containing molecules, as well as other elements) that are essential for the organisms' survival and growth.

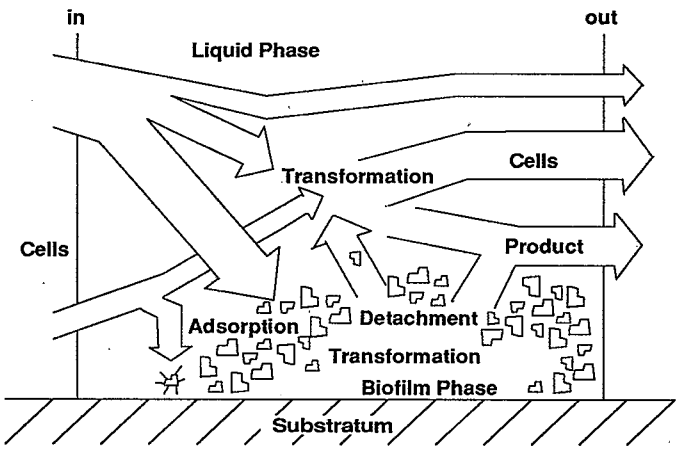
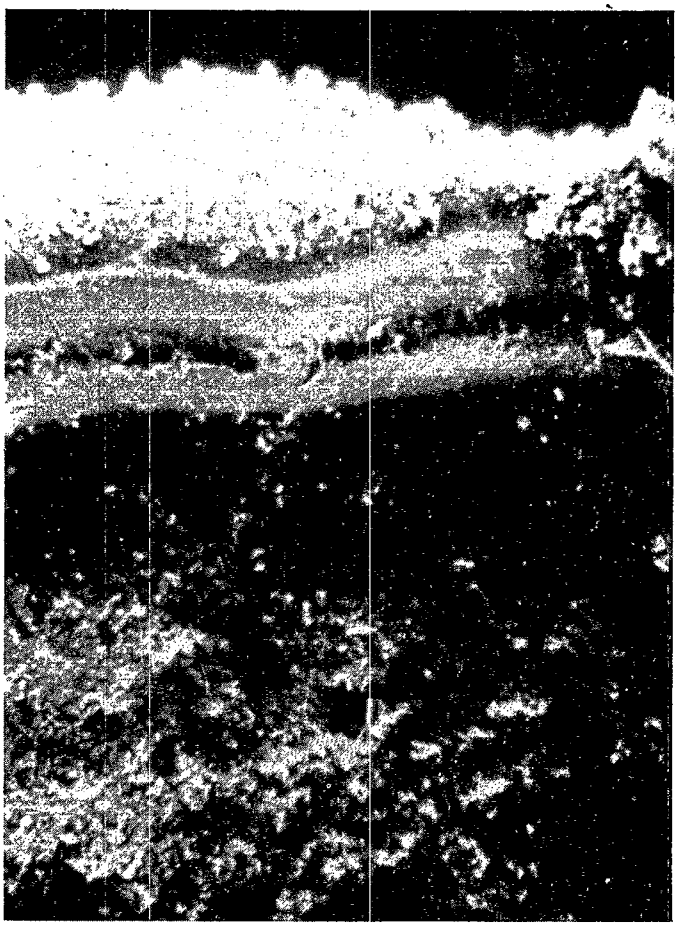


Figure 2-1. A composite of all processes contributing to biofilm accumulation: (1) transport and adsorption of macromolecules to form a film, called a substratum; (2) transport of cells to the substratum; (3) adsorption/desorption of cells at the substratum; (4) growth, product and spore formation, and death within the biofilm; and (5) attachment/detachment at the biofilm-water interface (Characklis and Marshall, 1990).

Biofilms are dynamic microenvironments, encompassing processes such as metabolism, growth, and product formation, and finally detachment, erosion, or "sloughing" of the biofilm from the surface (Characklis, 1981; Safe Drinking Water Committee, 1982; Characklis and Marshall, 1990). The rate of biofilm formation depends on the physicochemical (chemical, thermodynamic) properties



Cut-away of biofilm on a pipe surface

of the interface, the physical roughness of the surface, and physiological factors of the attached microorganisms (Fletcher and Marshall, 1982). Sheer forces generated by fluid velocity and possible effects of disinfectants on EPS may be important in the release of biofilms from surfaces (Characklis, 1981; Safe Drinking Water Committee, 1982). The biofilm may grow until the surface layers begin to slough off into the water (Geldreich and Rice, 1987). The pieces of biofilm released into the water may continue to provide protection for the organisms until they can colonize a new section of the distribution system.

The ability of bacteria to attach to surfaces in flowing, generally nutrient-deficient environments (such as drinking water) demonstrates several important ecological observations (Fletcher and Marshall, 1982):

- Macromolecules tend to accumulate at solid-liquid interfaces, creating a favorable environment in an otherwise nutrient-deficient situation.
- A high flow rate in the system can transport tremendous quantities of nutrients to fixed microorganisms, even when the nutrient concentration in the water is low.
- Production of EPS helps to anchor attached bacteria; EPS also may be a factor in nutrient capture.
- Bacteria embedded in EPS matrices are protected from disinfectants by a combination of physical and transport phenomena.

These factors and others have led microbiologists to conclude that most bacteria in aquatic environments can exist at solid-liquid interfaces, as long as sufficient nutrients are available.

Scanning electron photomicrographs of pipe "coupons" (small pieces of pipe material) that have been submerged in distribution water flow provide a picture of the biofilm microenvironment. The photomicrographs reveal a hard but porous surface, a complex of crystals beneath the surface, and microcolonies of similarly shaped organisms, suggesting growth, at the biofilm surface (Allen et al., 1979). They also show that microcolonies of cells tend to form at rough surfaces, such as cracks, crevices, and pits in old and corroding pipes. Such corrosion provides an increased surface area and greater protection from the shear force of the flowing water.

What Kinds of Microorganisms Make Up the Biofilm?

Knowing the types of organisms likely to survive in the distribution system and their requirements for growth will aid in controlling biofilm organisms or preventing them from becoming established. In situ studies of biofilm communities in the pipe are difficult to perform, but analyses of samples scraped from the pipe walls and growth on pipe coupons have revealed large variations in the number and types of microorganisms.

Few organisms living in distribution system biofilms pose a threat to the average consumer. The following survey of the organisms found in biofilms shows that, although water treatment is intended to remove all pathogenic (disease-causing) bacteria, systems should be aware that treatment does not produce water free of all microorganisms (that is, it is not sterile). In fact, some otherwise harmless organisms may survive the treatment process and cause disease in children, the elderly, or others with weakened resistance to infection. (These types of organisms are called *opportunistic pathogens.*)

Bacteria

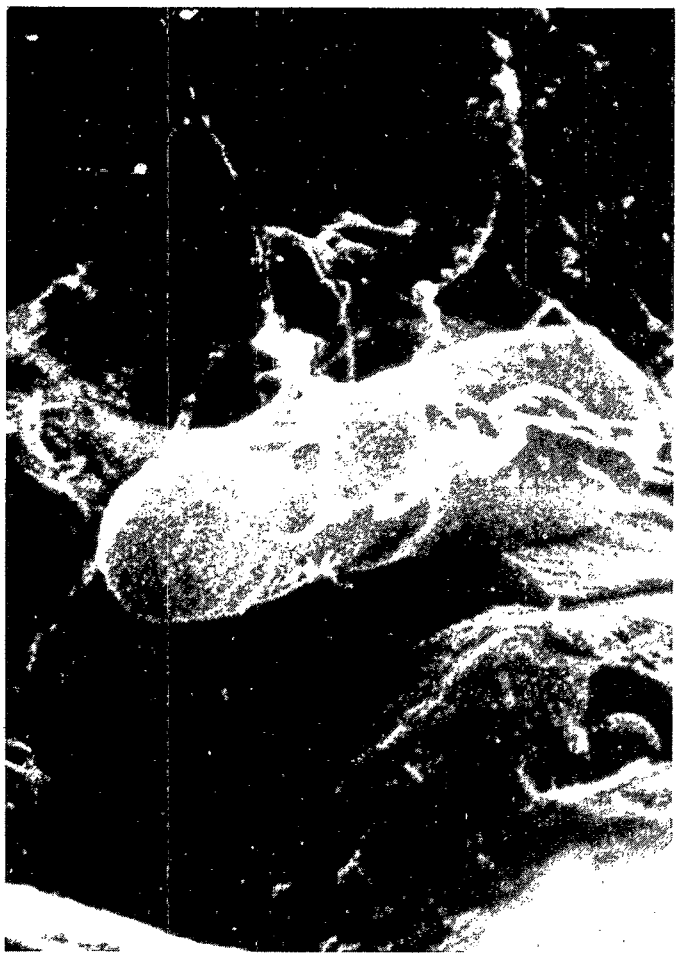
Bacteria comprise the largest portion of the biofilm population. Heterotrophic bacteria (those requiring organic compounds as sources of carbon and energy) are often measured by the Heterotrophic Plate Count (HPC) method. These bacteria are the most common, and their source normally is not known. These organisms may survive the disinfection process to colonize the distribution system at the time of installation, or they may be introduced through cross connections, backflow events, line breaks, or repair operations. The public health risk from these organisms is not known (Geldreich, 1990a), although a study by Payment et al. (1991) describes a correlation between heterotrophic bacteria growing in home water filtration devices and gastrointestinal illness.

Among the heterotrophic bacteria are a group of closely related microorganisms, the total coliforms. Coliforms are usually present at high densities in water contaminated with human and/or animal feces, but may also grow in nonfecal environments such as water, soil, and vegetation. Although they do not cause disease as a group (Geldreich 1986, 1988), they are usually present when enteric pathogens are present. This is one reason coliforms are used as the primary microbial indicator of drinking water quality.

> Coliforms are used to determine the efficiency of treatment, integrity of the water distribution system, and as a screen for fecal contamination, even in the absence of fecally contaminated samples at the times and locations of sample collection.

Fecal coliforms are a subgroup of the total coliform group. The predominant fecal coliform is *Escherichia coli*, a bacterium closely associated with the gut of warm-blooded animals. Because *E. coli* usually do not survive long in the aquatic environment, their presence in drinking water indicates that fresh fecal contamination is present and, consequently, that an urgent public health problem probably exists, since human pathogens usually coexist with fecal coliforms.

The types of coliform bacteria found in distribution system biofilms may vary according to location and the pro-



Scanning electron micrograph of the bacteria *E. coli*

cedures used to analyze samples, but the predominant coliform species (spp.) generally include *Enterobacter cloacae*, *Klebsiella* spp., *Citrobacter freundii*, and *Enterobacter agglomerans* (Geldreich, 1986). *E. coli*, most often used as an indicator of fecal contamination, has been found in distribution system biofilms, but only rarely (Olson, 1982; LeChevallier et al., 1990a). More often, when *E. coli* is found it is evidence of recent fecal contamination (Geldreich, 1986).

There are many problems associated with trying to detect specific enteric pathogens. Because of these problems, bacteria that are not themselves pathogenic are measured as surrogates for the more harmful bacteria. The ideal indicator for drinking water contamination is:

- Suitable for all types of drinking water.
- Present in polluted water at higher concentrations than harmful bacteria.
- Able to survive in water at least as long as pathogens and is at least as resistant to disinfection.
- Easy and inexpensive to measure in drinking water samples.
- Generally not present unless harmful contamination is also present.

Coliforms of both fecal and nonfecal origin may enter the drinking water distribution systems and grow in biofilms even in the presence of excess chlorine remaining after treatment (called the chlorine residual) (LeChevallier et al., 1987; Earnhardt, 1980; Lowther and Moser, 1984; Olivieri et al., 1985; Smith et al., 1989; Wierenga, 1985; Hudson et al., 1983; LeChevallier et al., 1990b). Although biofilms may represent the greatest concentration of biological material (biomass) in the distribution system, health surveys conducted in systems experiencing biofilm growth problems (New Haven, Connecticut; Springfield, Illinois; and Muncie, Indiana) have revealed no increase in illnesses due to contaminated drinking water (Geldreich, 1988). However, coliform bacteria that do not themselves necessarily pose a health threat can interfere with the system's ability to detect the presence of bacteria that do cause diseases (those that enter the water system because of loss of integrity of the treatment or distribution systems).

Opportunistic Pathogens

An opportunistic pathogen is an organism that can cause disease in individuals with compromised immune systems, but that a healthy person's immune system can resist. Elderly people, infants, cancer patients receiving chemotherapy or radiation, people with AIDS, and burn or transplant patients in hospitals are especially susceptible to infection by opportunistic pathogens (Jarvis, 1990). Opportunistic bacteria include some species of mycobacteria, *Pseudomonas aeruginosa*, *Legionella* spp., *Aeromonas* spp., *Flavobacterium* spp., and some species of *Klebsiella* and *Serratia* (Geldreich, 1988; Jarvis, 1990).

Klebsiella spp. have been widely studied as opportunistic pathogens. Different strains of *Klebsiella* may originate from environmental sources such as fruits and vegetables, wood and bark, other plants (Geldreich and Rice, 1987), and soil. They also inhabit the intestinal tracts of 30 to 40 percent of all warm-blooded animals. Some *Klebsiella* spp. can produce capsular material that surrounds the cell and helps protect the organism from disinfection (LeChevallier et al., 1988a). When grown in a biofilm, these capsule-producing organisms may form a slime layer that provides protection against disinfection for many bacteria (Geldreich, 1988; LeChevallier et al., 1988a,b, 1990b).

Nosocomial (hospital) infections have been attributed to several strains of *Klebsiella* (Jarvis et al., 1985; Jarvis, 1990; Highsmith and Jarvis, 1985); however, these cases have not been attributed to drinking water. In fact, *Klebsiella* have been isolated from many sources in hospitals, including carpeting, sinks, flowers, and other sur-

faces. Hospital workers' hands are often contaminated with *Klebsiella* (Bagley, 1985). The bacteria isolated from these types of environments are probably less able to cause disease and therefore not considered a public health threat (Duncan, 1988; Bagley, 1985).

Antibiotic-Resistant Bacteria

Some bacteria have developed or acquired resistance to antibiotics as a result of previous exposure to the antibiotics (for example, in farm animals treated with drugs), heavy metals, or genetic transfer. This may create a public health problem if the resistant bacteria are also pathogens (Armstrong et al., 1981). Armstrong et al. (1981) showed that water treatment actually may increase the percentage of bacteria present in treated water that are resistant to multiple antibiotics. As a result, a large percentage of the heterotrophic bacteria in distribution system biofilms, and therefore in the water throughout the distribution system, may be resistant to antibiotics (Armstrong et al., 1981).

Disinfectant-Resistant Bacteria

Most bacteria survive in disinfected drinking water by finding or creating environments where they are protected from the disinfectant residual. Factors related to increased survival of bacteria in chlorinated water include attachment to surfaces, encapsulation, aggregation, low-nutrient growth conditions, and strain variation.

Surfaces. Extensive research has shown that bacteria are more resistant to disinfection when they are attached to or associated with various surfaces, such as turbidity particles, macroinvertebrates, algae, pieces of carbon from treatment filters, and pipe surfaces (Tracy et al., 1966; Levy et al., 1984; Hoff, 1978; Hejkal et al., 1979; Silverman et al., 1983; Ridgway and Olson, 1982; Herson et al., 1987; LeChevallier et al., 1980, 1988a,b). Ridgway and Olson (1982) showed that the majority of viable bacteria recovered from chlorinated drinking water were attached to particles. Presumably, microbes entrapped in particles or adsorbed to surfaces are shielded from disinfection and are not inactivated. LeChevallier et al. (1988a,b) showed that bacterial resistance to disinfection increased more than 600 fold when the organisms were grown on pipe surfaces.

Biofilms may not only protect bacteria from disinfection, but also provide an environment where disinfectant-injured cells can repair cellular damage and grow. Watters and McFeters (1990) examined the ability of *Enterobacter cloacae* and *Klebsiella pneumoniae* to recover after being injured by exposure to monochloramine. Chloramine is a combination of chlorine and ammonia. They found that reducing agents, such as sodium sulfite, can reverse the chemical oxidation caused by monochloramine. They also found that biofilms can provide that same reducing environment, aiding in repair-injured cells.

Encapsulation. Production of an extracellular capsule provides protection from disinfection when the cells are grown under low-nutrient conditions (as in drinking water). In fact, several investigators have reported isolating encapsulated bacteria from chlorinated drinking water (Reilly and Kippen, 1983; Clark, 1984). LeChevallier et al. (1988b) showed that encapsulated *Klebsiella pneumoniae* were three times as resistant to inactivation as unencapsulated cells when each was exposed to the free chlorine remaining in the treated water after disinfection.

Aggregation. Sloughing of clumps of cells from treatment filters or pipe walls has been suggested as a possible mechanism by which coliform bacteria enter drinking water supplies. This clumping, or aggregation, may afford bacteria defense against disinfectants. For example, Stewart and Olson (1986) reported that aggregation of *Acinetobacter* strain EB22 increased resistance to free hypochlorous acid (a form of chlorine) over 100 fold, while aggregation increased resistance to monochloramine only 2.3 fold. The researchers found that treatment of the strain with Tween® 80 (a surfactant) prevented aggregation and eliminated the increased disinfection resistance.

Scanning electron micrograph of aggregated cells

Growth Conditions. The environment that microorganisms grow in and become accustomed to plays a large role in determining their sensitivity to disinfection. Carson et al. (1972) reported that *Pseudomonas aeruginosa* growing in distilled water were markedly more resistant to acetic acid, glutaraldehyde, chlorine dioxide, and a quaternary ammonium compound than cells cultured on Tryptic Soy Agar, a growth medium with a high concentration of nutrients. Similar work by Berg et al. (1983) and Harakeh et al. (1985) has shown that bacteria grown in low-nutrient and low-temperature conditions, conditions similar to the natural aquatic environment, were resistant to several disinfectants. *Legionella pneumoniae* grown in a low-nutrient "natural" environment have been reported to be six to nine times more resistant than agar-grown cells (Kuchta et al., 1985).

Strain Variation. Wolfe et al. (1985) found that a number of types of bacteria recovered from chlorinated water demonstrated a variety of disinfection resistance patterns to free chlorine and monochloramine. Ward et al. (1985) reported a strain of *Flavobacterium* that was more sensitive to monochloramine than to free chlorine, unlike other species of *Flavobacterium.* Conversely, Olson and Milner (1990) indicated that certain strains may develop resistance to monochloramine with repeated exposure. The fact that disinfection itself can select for a variety of bacteria is demonstrated by the work of several researchers (LeClerc and Mizon, 1978; Armstrong et al., 1982; Murray et al., 1984) who presented evidence that chlorination selects for survivors that are resistant to multiple antibiotics. The results of these studies indicated that the selective pressures of different aspects of water treatment can produce microorganisms with resistance mechanisms that favor survival in an otherwise restrictive environment.

Interaction of Resistance Mechanisms. When LeChevallier et al. (1988a) examined the interaction of disinfection resistance mechanisms, they found that resistance mechanisms were multiplicative (that is, the resistance conferred by one mechanism was multiplied by the resistance factor of a second). For example, the resistance conferred by attachment of bacteria to a glass surface (a 150-fold increase) and the resistance gained by production of extracellular polysaccharides (a 3-fold increase) made attached encapsulated bacteria 450 times (3 x 150) more resistant to free chlorine than were unattached, unencapsulated bacteria. The researchers concluded that, given the scenario of encapsulated bacteria growing under low-nutrient conditions attached to pipe surfaces for long periods of time, it is easy to understand how bacteria can survive in biofilms within chlorinated distribution systems.

Pigmented Bacteria and Actinomycetes

Some heterotrophic bacteria that live in biofilms may cause esthetic problems with water quality, including off-tastes, odors, and colored water problems. Biofilm organisms that fall into this nuisance category include *Actinomyces, Streptomyces, Nocardia,* and *Arthrobacter* (Geldreich, 1990a; LeChevallier et al., 1987). Complaints about taste and odor have resulted from *Streptomyces* and *Nocardia* spp. at concentrations greater than 10 organisms per 100 mL of water. For pigmented bacteria, the degree of pigment formation observed in cultured cells will depend on the media used for isolating the bacteria in the water sample. Many HPC bacteria isolated from distribution system biofilms will produce yellow, orange, or pink colonies when grown on R_2A agar (Herman, 1978; Geldreich, 1990a). These organisms may occur at high levels, coloring the treated water.

Fungi

Fungi, which include yeasts (single-celled spherical fungi) and molds (multibranched, filamentous fungi) (Boyd, 1984), can be found in finished water and can colonize and multiply in the pipe system (Jarvis, 1990; Geldreich, 1990a; Hinzelin and Block, 1985). Fungi have been found on pipe surfaces in densities ranging from 0.0 to 5.6 x 10^4 cells/100 cm^2 for yeast and 0.0 to 2.0 x 10^3 colony-forming units (cfu)/100 cm^2 for filamentous fungi (Nagy and Olson, 1985). Yeast are more resistant to disinfection than bacteria, probably due to their thick cell walls (Geldreich, 1990a).

The primary concerns for fungi in drinking water are taste and odor complaints, although some strains may cause allergies and toxic reactions when inhaled in vapors or through contact while bathing (Geldreich, 1990a). Drinking water, however, is not a major source of fungal infection. Food, soil, and even air contain far more fungi and are probably more important factors in human infection (Jarvis, 1990).

Protozoa and Other Invertebrates

Biofilms in potable water systems may contain a variety of nonpathogenic protozoa and other invertebrates including amoebae, nematodes, amphipods, copepods, and fly larvae (Levy, 1985). There is no evidence that these organisms present any health risk themselves, al-

Photo of copepods, magnified

though recent research has shown that *Legionella* may grow and survive inside certain amoebae (Smith-Somerville et al., 1991).

Potable Does Not Mean Sterile

Biofilms provide protection for microorganisms, including disinfectant-resistant microorganisms and opportunistic pathogens. These microorganisms may be present in water obtained at the tap. Therefore, it is possible to drink disinfected water and still become ill.

Problems arise when health care facilities view disinfected water as sterile (U.S. EPA, 1990e). Hospitals and other clinical facilities (including home health care agencies) need to be aware of the presence of microorganisms in finished water. EPA's pamphlet, *Protecting Our Drinking Water from Microbes* (U.S. EPA, 1989c), describes drinking water treatment and related federal regulations in simple language. The pamphlet is useful for educating facility managers about this issue. Moreover, health care facilities should be aware of guidelines for operation and maintenance of clinical water systems (hot water heaters, plumbing systems, faucets, showers, and condenser systems).

CHAPTER 3
Factors That Favor Biofilm Growth

For years researchers have investigated the factors that lead to biofilm growth. Geldreich et al. (1972, 1977) and Hutchinson and Ridgway (1977) concluded that in general, growth occurs when organic materials and sediment accumulate in distribution pipes, disinfectant residuals dissipate, and water temperatures increase. Environmental factors (e.g., pH, temperature, and rainfall); nutrient availability; the presence and effectiveness of disinfectant residuals; internal corrosion and sediment accumulation; and hydraulic effects have been related to growth of coliform bacteria in drinking water (LeChevallier et al., 1990a; Smith et al., 1990). The results of these studies are summarized below. These results can help you develop an investigative protocol to determine whether and when your system is susceptible to biofilm growth. They also can suggest ways to manipulate the environmental variables to control bacterial growth in the system.

Environmental Factors

Water temperature is perhaps the most important rate-controlling factor regulating microbial growth (LeChevallier, 1989). Directly or indirectly, temperature affects all of the factors that govern microbial growth. Temperature influences treatment plant efficiency, microbial growth rate, disinfection efficiency, dissipation of disinfectant residuals, corrosion rates, and distribution system hydraulics and water velocity through customer demand (i.e., watering lawns, filling swimming pools, washing cars). Unfortunately, most water utilities can do little to change water temperature. Therefore, efforts should focus on controlling the parameters that contribute to temperature's influence. For example, if changes in temperature affect the effectiveness of disinfection residuals, the system should monitor the temperature and adjust the residual concentration accordingly.

Most investigators have observed significant microbial activity in water at temperatures of 15°C or higher (Howard, 1940; Rizet et al., 1982; Fransolet et al., 1985; Donlan and Pipes, 1988; LeChevallier et al., 1990a). *E. coli* and other enteric bacteria (bacteria that normally live in animals' intestines) are known as mesophiles, growing in temperatures ranging from 5° to 45°C. Fransolet et al. (1985) found that growth of *E. coli* and *Enterobacter aerogenes* was very slow (growth rates divisions per hour) at temperatures lower than 20°C.

In temperate climates, seasonal phases of coliform growth often are observed in distribution systems (Geldreich, 1986; Smith et al., 1989). Smith et al. (1990) observed seasonal coliform occurrence trends in 81 water distribution systems, with highest coliform levels occurring during summer months (Figure 3-1). The researchers also found that the species of coliform bacteria present varied with water temperature (Figure 3-2). However, in warm climates, or in large buildings where the plumbing is kept at room temperature, seasonal variations in temperature are less pronounced, and therefore seasonal variations in coliform presence will be less dramatic as well.

In a careful study by Fransolet et al. (1985), the investigators found that water temperature influenced not only the growth rate, but the lag time (the length of time after entering the system before cell division starts) and cell yield as well. The length of the lag time was found to be quite important to the organisms' survival in the distribu-

Season	Mean Temperature (°C)	Mean percent of samples containing coliforms	Mean cell count (cells/100 mL)
Spring (Mar, Apr, May)	10.2 +/- 2.9	5.2 +/- 4.9	0.57 +/- 1.07
Summer (Jun, Jul, Aug)	19.2 +/- 3.1	12.3 +/- 8.3	1.98 +/- 1.89
Fall (Sep, Oct, Nov)	16.0 +/- 3.2	9.4 +/- 6.0	1.15 +/- 1.41
Winter (Dec, Jan, Feb)	7.1 +/- 1.8	2.0 +/- 2.1	0.14 +/- 0.28

Figure 3-1. Seasonal distribution system temperature (°C), mean percent of samples containing coliforms, and mean coliform count in the New Haven, Connecticut, water system from 1986 to 1988 (Smith et al., 1989).

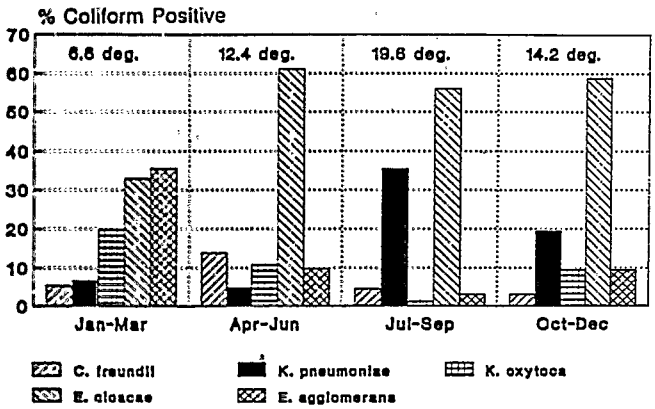


Figure 3-2. Distribution system coliform species occurence by season in the New Haven, Connecticut, water system, 1986 to 1988 (Smith et al., 1989).

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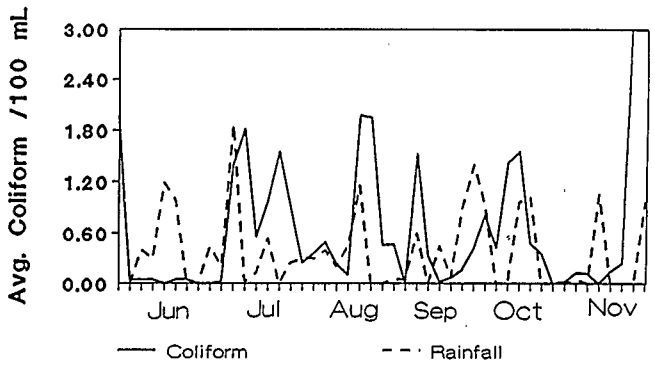

Figure 3-3. Relationship between rainfall and daily coliform levels in the New Jersey American distribution system. Coliform data have been offset by 7 days (LeChevallier et al., 1991a).

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tion system. For *Pseudomonas putida* the lag in the growth phase was about 3 days at 7.5°C, but only 10 hours at 17.5°C. These results show that at low temperatures, cells are washed out of the distribution system before significant growth is achieved.

Rainfall is another environmental factor that influences the bacterial quality of drinking water. Some investigators have suggested that rainfall is a catalyst for coliform growth (Lowther and Moser, 1984; LeChevallier et al., 1990a). Lowther and Moser (1984) found that raw water organic nutrient levels were highest when turbidity increased after rainfall events. LeChevallier et al. (1990a) observed that coliform bacteria routinely appeared in distribution system waters 7 days after rainfall events (Figure 3-3). The authors speculated that rainfall washed nutrients into the watershed resulting in increased bacterial densities after a transit period and growth lag. For some systems, however, rainfall events can lead to breakthrough of bacteria from the treatment system directly into the distribution system. The increased turbidity caused by runoff may provide bacteria with particles for attachment and protect the organisms from disinfection (LeChevallier et al., 1980; Baker, 1984), and the high load of bacteria and particles can overwhelm the treatment system capacity. For example, in Rochester, New York, coliform occurrences were preceded by heavy rainfalls that increased turbidity in the system's open surface water reservoirs. Several New England water systems have experienced increased coliform densities after heavy rainfall as well (Geldreich, 1986).

Hydraulic Effects

Flow velocity may regulate microbial growth on pipe surfaces in several ways (Safe Drinking Water Committee, 1980). Increased velocities cause greater flux of nutrients to the pipe surface, greater transport of disinfectants, and greater shearing of biofilms from the pipe surface. Changes in water velocity can be due to seasonal conditions. As seasonal consumer demand changes, corresponding changes occur in the hydraulics and water pressure throughout the distribution system. Changes in water velocity also can be changed by flow to fire hydrants, pipe network design and pipe size, water main breaks, or distribution maintenance practices such as flushing (Smith et al., 1989; Geldreich, 1988).

Reversal of water flows can shear biofilms, and the "hammer" effect that occurs upon sudden opening or closing of the lines (e.g., when firefighters open and close hydrants) can dislodge tubercles from pipe surfaces. Opheim et al. (1988) found that bacterial levels in an experimental pipe system increased 10 fold when flows were started and stopped. Larger releases of bacteria were noted when the system was exposed to physical and vibrational forces.

Distribution system hydraulics also can affect corrosion and sediment accumulation. Stagnation of water in the distribution system can result in loss of disinfectant residual and accumulation of sediment and debris, leading to microbial growth. Donlan and Pipes (1988) showed that water velocity had an inverse relationship with biofilm counts. Dead-end lines often show significant deterioration in microbial water quality (Smith et al., 1989; Geldreich, 1986; Hanson et al., 1987; Opheim et al., 1988; LeChevallier et al., 1987; Geldreich, 1980; Rae, 1981). Stagnation of water in service lines also can result in high bacterial counts at the customer's tap (Brazos et al., 1985; LeChevallier et al., 1987).

Researchers have developed hydraulic models to monitor the fate of chlorine residuals and their reaction products in distribution systems (Characklis et al., 1988; Clark

et al., 1988). Applying these hydraulic models to better understand microbial growth in distribution systems could be useful.

Nutrient Availability

To grow, organisms must derive from the environment all the substances that they require to synthesize cell material and generate energy. For coliform and heterotrophic bacteria, the principal nutrient sources are phosphorus, nitrogen, and organic carbon. Trace nutrients also are required, but these compounds have not been investigated in drinking water.

Carbon

Organic carbon is utilized by heterotrophic bacteria for production of new cellular material (assimilation) and as an energy source (dissimilation). Because heterotrophic bacteria require carbon, nitrogen, and phosphorus in a ratio of approximately 100:10:1 (C:N:P), organic carbon is often a growth-limiting nutrient. Most organic carbon compounds in water supplies are natural in origin, derived from living and decaying vegetation. These compounds may include humic and fulvic acids, polymeric carbohydrates, proteins, and carboxylic acids.

Carbon in drinking water is measured in three ways, as total organic carbon (TOC), which is the total amount of soluble and insoluble organic carbon compounds present in the water; dissolved organic carbon (DOC), which is the soluble fraction of TOC; and assimilable organic carbon (AOC), which is the fraction of DOC that can be readily digested and used for growth by aquatic organisms. The U.S. EPA National Organic Reconnaissance Survey found that the nonpurgeable total organic carbon (NPTOC, see *Standard Methods*, section 5310 [AWWA, 1989]) concentration of finished drinking water in 80 locations ranged from 0.05 mg/L to 12.2 mg/L, with a median concentration of 1.5 mg/L (Symons et al., 1975). Often, AOC comprises just a fraction (0.1 to 9.0 percent) of the total (van der Kooij et al., 1982b).

AOC is measured using a bioassay first proposed by van der Kooij in 1978. The method employs inoculation of a water sample with a variety of microorganisms (*Pseudomonas fluorescence* strain P17, *Spirillum* sp. strain NOX, *Flavobacterium* sp. strain S12 or *Klebsiella pneumonia* strain CF17) (van der Kooij et al., 1982a,b; van der Kooij and Hijnen, 1985, 1988). The organisms' growth is monitored and the maximum growth yield is determined. Based on known yield coefficients, the equivalent amount of carbon (usually expressed in µg of acetate-carbon/L) is calculated (van der Kooij et al., 1982b). The method is labor- and materials-intensive, and care is needed to properly handle water samples to avoid contamination with extraneous organic material. Using this method, drinking water supplies in North America have been found to contain between 1 and 2,000 µg acetate carbon equivalents/L (Characklis et al., 1988; Gaidish et al., 1987; LeChevallier et al., 1987, 1988a, 1990a, 1992).

Application of the AOC Test

HPC Bacteria. The AOC test has been used in the Netherlands for the past 10 years to help determine treatment strategies to limit bacterial growth in water (van der Kooij, 1987, 1990; van der Kooij et al., 1989). The European guideline for safe water limits heterotrophic plate count (HPC) bacteria in water to less than 100 bacteria/mL. In their work to help water suppliers achieve the guideline, researchers in the Netherlands have found that growth of HPC bacteria is limited at AOC levels of less than 10 µg/L. In ranges of 20 to 50 µg/L, problems with excessive plate counts occasionally occur. At AOC levels greater than 50 µg/L, bacterial growth always occurs. Control of AOC levels has so effectively limited bacterial survival and growth that secondary disinfection has been discontinued in some systems (Schellart, 1986; van der Kooij, 1987).

Coliform Bacteria. Most of the information related to the growth of coliform bacteria in drinking water has been obtained from the Swimming River Treatment Plant of the New Jersey American Water Company. It is uncertain, however, how the results from that plant will apply to other distribution systems; research is currently under way to examine other systems across North America.

Based on other research at the New Jersey American Water Company, however (see pp 14 to 15), LeChevallier et al. (1992) recommended that systems trying to reduce coliform levels in drinking water supplies limit total AOC levels to less than 100 µg/L (median AOC concentrations can range from 1.5 to 135 µg/L). The level of secondary disinfection (e.g., the residual concentrations maintained in the distribution system) could be lowered if AOC levels were reduced to very low levels (van der Kooij, 1987; Schellart, 1986). This approach will be valuable to the water industry as it tries to limit bacterial levels while simultaneously reducing disinfection by-products (the potentially harmful compounds formed when free chlorine reacts with organic compounds in the water).

BDOC Analyses. Researchers at the Compagnie Generale des Eaux in France developed a method to measure biodegradable dissolved organic carbon (BDOC) (Pascal et al., 1986; Hascoet et al., 1986; Servais et al., 1987), which is essentially the same portion of dissolved carbon measured by the AOC procedure. In the BDOC test, indigenous bacteria are allowed to grow for a specified time in a water sample, and then are removed by filtration through prewashed 0.22 µm membrane filters. Finally, the DOC remaining in the filtered water is measured. If the bacteria are incubated in the water samples for 10 to 30 days, the test allows measurement of slowly degradable organic materials (Pascal et al., 1986). This procedure has some disadvantages, including insensitivity at low DOC levels and the relatively high cost of a TOC

analyzer. Recently, a rapid (3- to 5-day) procedure has been developed to measure biodegradable organic carbon using aerated biofilms on sand particles (Joret et al., 1988). There are no operational data to relate specific BDOC levels to HPC or coliform problems; however, a level of less than 0.1 BDOC mg/L is thought to produce biologically stable water (i.e., water that is unable to support bacterial growth).

Nitrogen and Phosphorus

Nitrogen is used by microorganisms to build amino acids and genetic material. The exact role of nitrogen in growth of coliform bacteria is unclear, especially because some strains of *Klebsiella* can fix molecular nitrogen (Orskov, 1984). Nitrogen is often present in raw water supplies due to vegetation decay, runoff containing agricultural fertilizers, leachate from landfills, or wastewater discharges. An Indiana University study examining biofilm problems in the Eastern and Midwestern United States found that many bacterial occurrences corresponded with applied agricultural fertilizer that entered source water in stormwater runoff (Geldreich, 1986).

Ammonia, a reduced form of nitrogen, can promote bacterial growth in distribution systems. Rittmann and Snoeyink (1984) found that ammonia concentrations in ground-water supplies were frequently high enough to allow bacterial survival and growth. Bacteria that can use ammonia for growth and need only carbon dioxide as a carbon source (autotrophic nitrifiers) sometime prove to be a problem when water utilities use chloramines (chlorine plus ammonia) as a disinfectant in the distribution system. Because autotrophic bacteria grow slowly, long retention times and warm water temperatures also contribute to their growth, which leads to more problems. For example, the proliferation of ammonia-oxidizing bacteria in large, covered finished-water reservoirs in Southern California was found to eliminate total chlorine residuals, increase nitrite levels, and stimulate the growth of HPC bacteria (Wolfe et al., 1988). To a lesser extent, heterotrophic nitrifiers are known to contribute to nitrite and nitrate levels in ambient waters (Verstraete and Alexander, 1973), and also may increase levels in drinking water.

Phosphorus in the environment occurs almost exclusively as orthophosphate (PO_4^{3-}). Phosphates are sometimes added to the water supply to control corrosion. Rosenzweig (1987) found that phosphate-based corrosion inhibitors did not significantly influence the growth of several strains of coliform bacteria. High levels of Virchem 932, a zinc orthophosphate, showed inhibitory effects for certain coliform species.

Other Sources of Nutrients

Certain construction materials, including rubber, silicon, polyvinyl chloride (PVC), polyethylene, and bituminous coatings, have been reported to stimulate bacterial growth (Schoenen and Scholer, 1985; Frensch et al., 1987; Schoenen and Wehse, 1988). Ashworth and Colbourne (1986) reported that a substantial proportion of customer water quality complaints was due to microbial growths on polymeric materials used in the construction of storage tanks, fittings, and pipework for buildings. After exposure of a bituminous coating to water, 48 organic compounds could be detected in the water by gas chromatography/mass spectrometry (GC/MS) analysis (Frensch et al., 1987). A dose of 30 mg/L chlorine was necessary to reduce bacterial counts on the coatings.

Disinfection Residual Concentrations

An inability to maintain a disinfectant residual may allow bacterial growth in drinking water supplies. If disinfectant levels are too low (e.g., if more than 5 percent of monitoring samples do not contain a detectable disinfectant residual), then the utility should increase disinfectant doses, install "booster" stations that add disinfectant at various points in the distribution system, or use a more stable disinfectant (e.g., chloramines).

Experience has shown that maintenance of a chlorine residual alone cannot be relied on to prevent bacterial occurrences, however. Several researchers (Reilly and Kippen, 1983; Goshko et al., 1983; Olivieri et al., 1985, Ludwig, 1985; LeChevallier et al., 1987) have indicated that maintenance of a free chlorine residual did not correlate with reduced bacterial counts in the water. Reilly and Kippen (1983) found that 63 percent of the coliform bacteria in two water systems in Massachusetts were isolated from drinking water that contained greater than 0.2 mg/L chlorine. Nagy et al. (1982) reported that a 1- to 2-mg/L chlorine residual reduced bacterial levels in the Los Angeles aqueduct biofilms by 2 logs, but the bacteria were still present at 10^4 cfu/cm^2. Maintenance of a 3- to 5-mg/L chlorine residual was necessary to reduce bacterial biofilms by 3 logs, to 10^3 cfu/cm^2. These investigators, however, found no correlation between free chlorine residuals (0.15 to 0.94 mg/L chlorine) and the densities of HPC bacteria in the distribution system biofilms (Nagy and Olson, 1985). Even direct contact with chlorine does not stop biofilm growth for long: Seidler et al. (1977) recovered coliforms in a potable water supply 1 week after scrubbing redwood tank biofilms with a 200-ppm chlorine solution.

Ridgway et al. (1984) found that a 15- to 20-mg/L chlorine residual was necessary to control biofilm growth on reverse osmosis membranes. Characklis et al. (1979) reported that application of 12.5 mg/L free chlorine for 60 minutes contact time was required to reduce the thickness of experimental biofilms 29 percent in an annular fouling reactor (Rototorque system). The authors predicted that disinfection using 5 mg/L chlorine would result in continued biofilm development. None of the experiments, however, resulted in complete biofilm removal.

During coliform episodes at Muncie and Seymour, Indiana, disinfectant residuals were boosted as high as 15 mg/L, because coliform occurrences could not be reliably controlled with free chlorine residuals less than 6 mg/L (Lowther and Moser, 1984; Olivieri et al., 1985). In most cases, this course of action is not acceptable to water utility operators since the use of high chlorine levels to control biofilms causes other problems, including excessive trihalomethane (THM, a disinfection by-product) formation; customer complaints about chlorinous tastes and odors, and increased corrosion rates.

LeChevallier et al. (1988a,b) indicated that various disinfectants may interact differently at biofilm interfaces. In a companion study, LeChevallier et al. (1990b) found that low levels (1 mg/L) of either free chlorine or monochloramine could reduce viable counts by greater than 100 fold (2 logs) for biofilms grown on galvanized, copper, or PVC (plastic) pipe surfaces. However, free chlorine residuals ranging from 3 to 4 mg/L were ineffective for biofilm control when the microorganisms were grown on iron pipes. In this situation, only monochloramine residuals greater than 2.0 mg/L were successful for reducing biofilm viable counts. Haas et al. (1991) have modeled the interaction of free chlorine and monochloramine with biofilm surfaces and suggested that free chlorine, because of its high reaction rate, was largely consumed before it penetrated the biofilm. Because monochloramine is more limited in the types of compounds with which it will react (Jacangelo et al., 1987), it is better able to penetrate the biofilm layer and inactivate attached organisms.

The inability of the disinfectant to penetrate distribution system biofilms can account for the occurrence of coliform bacteria in highly chlorinated waters. A better understanding of the interaction of disinfectants with distribution system interfaces is necessary to formulate appropriate strategies for biofilm control. The remaining sections consider these interfaces, including the pipe surface and the particles adsorbed to it.

Corrosion

Corrosion provides a protective surface for microorganisms, slows water flow, and contributes to backflow occurrences where iron pipe walls corrode. Corrosion of distribution system pipes can be due to chemical, physical, or biological action (O'Connor and Banerji, 1984). In iron pipes, electrochemical reactions at the pipe surface dissolve the metal to form pits (releasing free ferrous ions) at one point while building a tubercle or nodule (composed of ferric hydroxide) at a remote spot. The pits and nodules formed may catch and concentrate nutrients and provide the organisms with protection from water shear (Allen and Geldreich, 1977; Victoreen, 1977, 1980, 1984). In scrapings from inside several distribution systems, high levels of coliforms were found to be associated with iron tubercles (LeChevallier et al., 1987; Opheim et al., 1988). LeChevallier et al. (1987) found that corrosion of the iron pipe surface could protect HPC and coliform bacteria from disinfection by free chlorine. Free chlorine itself promotes the pitting type of corrosion by reacting with the ferrous ions and precipitating ferric hydroxide. This not only accelerates corrosion but also represents another demand on the free chlorine residual (U.S. EPA, 1984). Some corrosion also may be caused by iron or sulfur bacteria (Jarvis, 1990).

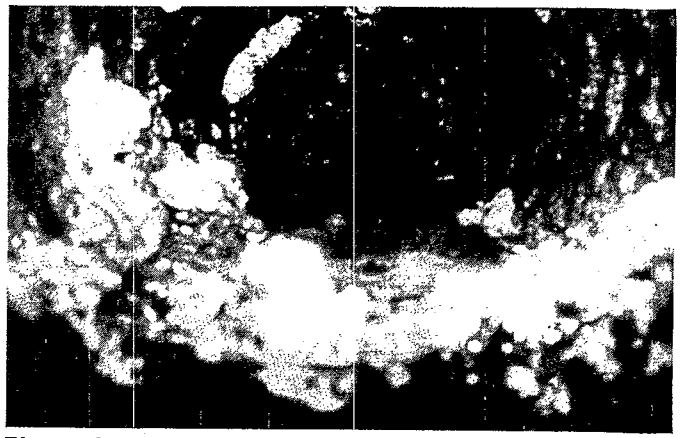

Photo of corroded pipe

Victoreen (1977, 1980, 1984) indicated that iron may be an important nutrient for microbial growth. He found that substantial coliform growth was stimulated by iron oxides found in distribution system tubercles. Under these conditions, coliforms could increase to 2×10^8 bacteria/100 mL within 90 hours at 20°C. Armstrong et al. (1981) found that increases in copper levels due to corrosion of household plumbing can increase the proportion of multiply antibiotic-resistant bacteria. At the same time, copper ions also can cause injury to coliform bacteria, making detection of these organisms difficult by conventional media (Domek et al., 1985).

Sediment Accumulation

Sediments and debris in pipe systems can provide habitats for microbial growth and protection from disinfection. Carryover of aluminum floc from primary treatment or improper formation of calcium carbonate scale (used in the distribution system to protect pipes against corrosion) may form uneven deposits on pipe walls, increasing the concentration of organic compounds available for assimilation and protecting bacteria from disinfection (Dixon et al., 1988).

Organic and inorganic sediments can transport microorganisms into the distribution system and provide protection from disinfection. Carbon fines from application of powdered activated carbon and granular activated carbon filters in the treatment system can break through the treatment process and enter the distribution system (Camper et al., 1986; Stewart et al., 1990). Because carbon particles are black, they may not be detected by

AOC Levels and Coliform Growth: Experience at the New Jersey American Water Company

The first indication of the relationship between growth of coliform bacteria and AOC levels was observed in 1986 (LeChevallier et al., 1987). The New Jersey American Water Company (then named Monmouth Consolidated) had been experiencing episodes of elevated coliform levels since 1984. AOC determinations at various sites in the distribution system showed high levels in the plant effluent and lower levels as the water flowed through the pipe network (Figure 3-4). AOC levels declined rapidly over distance and time: At Site 1 (0.7 miles [1.13 km] from the treatment plant, about 1 hour flow time) the AOC level had declined 37 percent, while at the dead-end site a short 2,000 ft beyond, AOC had declined to 40 percent of the original starting level. When an *E. coli* isolate from another portion of the distribution system was inoculated into dechlorinated water samples, cells grew in the plant effluent and Site 1 water, but not in water from the dead-end site (Figure 3-5). The amount of growth in each sample was proportional to the amount of AOC and suggested that growth of coliform bacteria could be limited at AOC levels less than 50 µg/L.

These studies were followed by a survey of factors that could contribute to growth of coliform bacteria in water (LeChevallier et al., 1991a). The research found that growth of coliform bacteria was related to a complex set of nutritional and physicochemical parameters. Of the nutritional parameters examined, only AOC levels declined as the water moved through the distribution system (Table 3-1). Overall, AOC levels in the dead-end site were 73 µg/L lower than levels in the plant effluent. It was calculated that this amount of carbon could provide sufficient nutrients to support the growth of 7×10^4 bacteria/mL. The decrease in AOC levels as the water flowed through the distribution system was greatest during the summer months when microbial activity was the highest. During August 1987, when coliform levels were the highest (averaging up to 5 coliforms/100 mL), the concentration in the dead-end site, the test site furthest from the entry point, averaged almost 300 µg/L lower than that in the plant effluent.

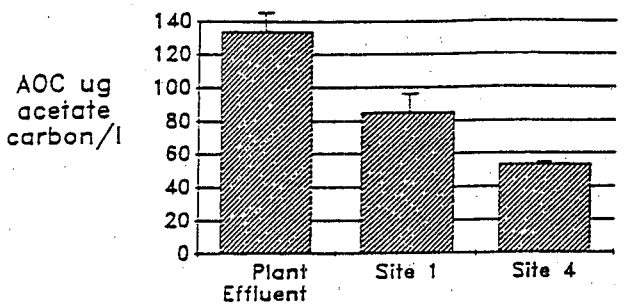

Figure 3-4. Changes in AOC in a New Jersey distribution system, August 23, 1986. T-Bars represent standard deviations; AOC values at each site were significantly ($p < 0.05$) different (LeChevallier et al., 1987)

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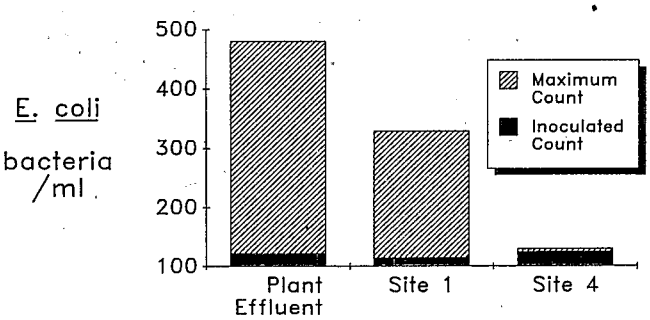

Figure 3-5. Growth of *Escherichia coli* in the New Jersey distribution system samples, August 23, 1987 (LeChevallier et al., 1987).

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Table 3-1. Changes in bacterial nutrients at various points in the New Jersey American Distribution System

Site	Nitrate-N (mg/L)	Nitrite-N (mg/L)	Ammonia-N (mg/L)	Ortho-P (mg/L)	Total-P (mg/L)	TOC (mg/L)	AOC (mg/L)
1	0.64	0.05	0.01	0.13	0.15	2.31	214
2	0.64	0.05	0.01	0.12	0.15	2.31	145
3	0.64	0.04	0.02	0.14	0.18	2.32	134
4	0.66	0.04	0.03	0.14	0.14	2.31	141

Abbreviations: Ortho-P, ortho-phosphate; Total-P, total phosphates; TOC, total organic carbon; AOC, assimilable organic carbon (LeChevallier et al., 1991a)

Most of the coliform occurrences in the New Jersey American system could be related to AOC levels between 100 and 2,000 µg/L. An experiment conducted during the first 12 days of August 1988 showed fluctuations in AOC levels (ranging as high as 170 to 900 µg/L) in treated drinking water. When these data were compared to coliform densities in the drinking water 7 days later, the peaks in AOC concentration corresponded to peaks in coliform density (Figure 3-6). The time delay between AOC and coliform peaks was thought to be due to transport of the water through the distribution system and growth of the coliform bacteria.

Monitoring of the New Jersey American system through August 1990 showed a continued relationship between AOC levels and occurrences of coliform bacteria (LeChevallier et al., 1992). Peak coliform levels were related to total AOC levels averaging 180 to 260 µg/L. At AOC levels less than 100 µg/L, coliform densities were generally 0.1 bacteria/100 mL or less.

Under the new Total Coliform Rule (U.S. EPA, 1989b), which took effect in 1991, coliform occurrences greater than 5.0 percent per month trigger a violation of the MCL. The results shown in Figure 3-7 indicate that the New Jersey American Water Company exceeded this MCL in June 1989, when AOC levels averaged 260 µg/L. Generally, when total AOC levels were below 100 µg/L, coliform occurrences were less than 1 percent per month.

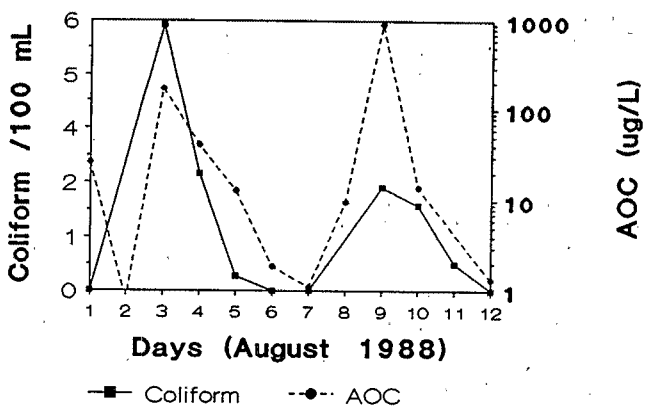

Figure 3-6. Relationship between daily fluctuations in AOC levels and distribution system coliform levels, August 1 to 12, 1988. Coliform data have been offset by 7 days (August 8 to 19) (LeChevallier et al., 1991a).

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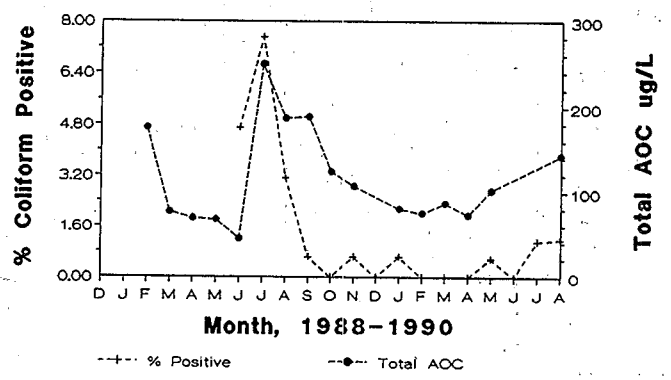
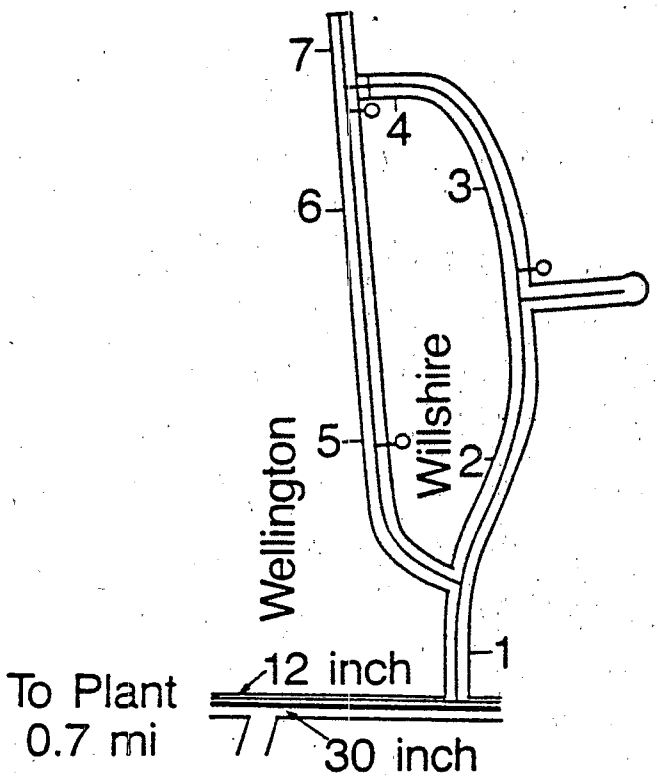


Figure 3-7. Relationship between percent coliform-positive samples and total AOC levels, New Jersey American Water Company, 1988 to 1990 (LeChevallier et al., 1992).



New Jersey American distribution system study area

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turbidimeters, which would otherwise alert the system operator to a breakthrough. As a result, bacteria on the surfaces of these particles are carried into the distribution system protected from disinfection by their attachment (LeChevallier et al., 1984). If these organic and inorganic sediments accumulate in dead-end and low-flow areas of the distribution system, they can provide protection and nutrients for significant microbial activity.

CHAPTER 4
How to Recognize a Biofilm Occurrence

Pathogens may occur in drinking water supplies due to breakthrough of contamination into the distribution system from the treatment facility; disruption of the integrity of the distribution system (e.g., cross connections or pipe breaks); or growth of bacteria in distribution system biofilms. It is usually difficult to distinguish with reasonable certainty between coliforms associated with biofilms and those from other sources. For example, low-level breakthrough contamination may subsequently result in growth in the distribution system. It is important, therefore, to thoroughly examine treatment practices and distribution system maintenance procedures (which can detect and control contamination events) before deciding that growth of biofilm bacteria is the cause of excess total bacteria and/or coliform levels. This decision is no trivial matter because contamination may be intermittent or not detectable by traditional monitoring methods.

The conclusion that bacteria are growing in the distribution system often is based on negative findings, i.e, an inability to find an alternative cause, such as a problem in the treatment system. However, once the available information supports the consistent reliability of the treatment procedures and integrity of the distribution system, the water system should turn its attention to locating and controlling the growth of biofilm bacteria, particularly fecal coliform bacteria.

Detection of Breakthrough Contamination

Characteristic of breakthrough and regrowth events is a large initial episode of coliform organism occurrence followed by a gradual decline in bacterial levels over time, possibly as long as several months. If a system experiences occurrences of coliform bacteria, the first priority is to determine whether fecal contamination has occurred. The criteria listed in Table 4-1 are intended to help rule out a treatment failure or cross connection. Criteria #1a and #4 address the detection of *E. coli* in treated effluents and distribution system samples. Although *E. coli* is generally harmless and may be found in distribution system biofilms not associated with pathogens, its presence may be an indication of recent fecal contamination, and immediate steps should be taken to protect public health.

Criteria #1 and #5 in Table 4-1 demonstrate adequate treatment plant performance. If coliform bacteria, spikes of turbidity, or periods of low chlorine residual are detected, then treatment efficiency is suspect. Other indicators of treatment deficiency may include increases in particle counts, heterotrophic bacteria, or changes in the number of non-coliform background bacteria in the membrane filter (MF) total coliform test. Treatment plant monitoring should include not only the treatment plant effluent but also individual filter effluents. It is possible for the faulty performance of one filter in a series (or in parallel) to be masked, or averaged, by the good performance of the other filters. Particulates and microorganisms from the faulty filter can enter the distribution system and be responsible for bacterial problems. Wierenga (1985) identified several sources of contamination in the Grand Rapids system including turbid discharge from a treatment filter, seepage of rainwater into the filter beds, cross connections, and leaks in the clearwell, where the treated water is held after disinfection. Only by intensive examination were operators at Grand Rapids able to locate and correct these problems. Each contamination event, however, resulted in a prolonged occurrence of coliform organisms in the distribution system.

Breakthrough of coliform organisms in treatment plants may occur even when effluents are apparently of good microbiological quality. Incomplete disinfection may only injure bacteria, which may not be detected using standard coliform media (LeChevallier and McFeters, 1985; McFeters et al., 1986). Observations made by McFeters et al. (1986), McFeters (1989), and Kippen (1986) indicate that injured coliform bacteria in treatment plant effluents may be recoverable on conventional media after spending some time in the distribution system. Watters and McFeters (1990) showed that injured bacteria can repair cellular lesion and resuscitate in biofilms. A medium to recover injured coliform bacteria (m-T7 agar) is commercially available. For chloraminated systems, m-T7 agar should be supplemented with 0.1 percent sodium sulfite (Watters et al., 1989). Several reports describe situations in which the detection of injured coliforms in treatment plant effluents has helped plant operators detect and correct microbiological problems (McFeters et al., 1986; Clark, 1988; Bucklin et al., 1991).

Bacteria also may break through treatment barriers by attachment to organic or inorganic particles. Because tur-

Table 4-1. Criteria for Obtaining a Variance to the Total Coliform Rule

The following criteria serve as a guidance for states in identifying systems that could operate under a variance without posing an unreasonable risk to health:

1) Over the past 30 days, water entering the distribution is shown to:
   a) be free from fecal coliform or *E. coli* based on at least daily sampling
   b) contain less than 1 total coliform/100 mL of influent water in at least 95 percent of all samples based on at least daily sampling.
   c) comply with the total turbidity requirements under the Surface Water Treatment Rule.
   d) contain a continuous disinfection residual of at least 0.2 mg/L.
2) The system has had no waterborne disease outbreak while operating in its present configuration.
3) The system maintains biweekly contact with the state and local health departments to assess illness possibly attributable to microbial occurrence in the public drinking water system.
4) The system has evaluated, on a monthly basis, at least the number of samples specified in the Total Coliform Rule and has not had an *E. coli*-positive compliance sample within the last 6 months, unless the system demonstrates to the state that the occurrence is not due to contamination entering the distribution system.
5) The system has undergone a sanitary survey conducted by a party approved by the state within the past 12 months.
6) The system has a cross connection control program acceptable to the state and performs an audit of the effectiveness program.
7) The system agrees to submit a biofilm control plan to the state within 12 months of the granting of the first request for a variance.
8) The system monitors general distribution system bacterial quality by conducting heterotrophic bacteria plate counts on at least a weekly basis at a minimum of 10 percent of the number of total coliform sites specified for that system size in the Total Coliform Rule (preferably using R_2A medium and the procedure outlined in *Standard Methods* [AWWA, 1989]).
9) The system conducts daily monitoring at distribution system sites approved by the state and maintains a detectable disinfectant residual at a minimum of 95 percent of those points and a heterotrophic plate count of less than 500 colonies/mL at sites measured without a disinfectant residual.

Source: U.S. EPA, 1991.

bidity interferes with detection of coliform bacteria by the membrane filter method (LeChevallier et al., 1981), particle-associated bacteria may not be detected in plant effluent samples.

The solution to solving breakthrough and subsequent growth problems is to eliminate the source of contamination (Geldreich et al., 1972). A thorough sanitary survey can help detect treatment deficiencies and distribution system problems (e.g., cross connections, breaks in pipes, backsiphonage). Application of microbiological media that will support and allow identification of injured coliforms (e.g., m-T7 agar), an intensive sampling regime, large volume analysis, or desorption of particle-associated bacteria, however, may be necessary to identify sources of contamination.

Some utilities have used an automatic sampler to aid in the investigation of microbiological episodes. Some samplers can be programmed to collect 250 mL into an individual bottle every hour. The sample line is flushed first, then thiosulfate is automatically added as the sample is collected. The 24 bottles are stored in a refrigerated compartment until analysis. In several investigations, using an automatic sampler has provided the necessary information to adequately address the contamination problem. Pipes and Minnigh (1990) evaluated the use of a composite sampler to improve coliform detection in finished drinking water. The researchers found that the probability of detecting contamination events increased through the use of an automatic sampler.

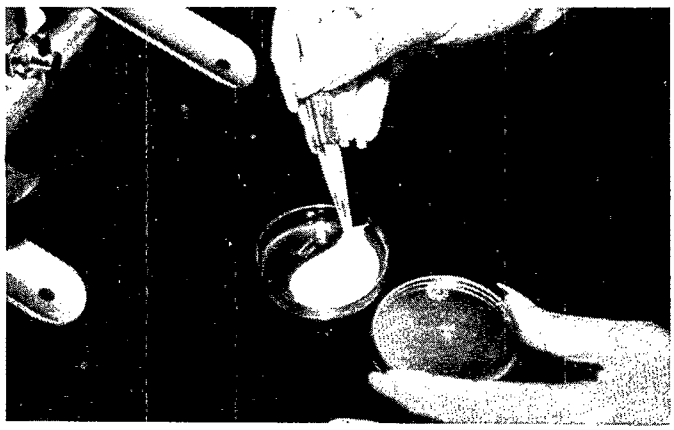
Another important criterion listed in Table 4-1 is maintenance of an effective disinfectant residual throughout the distribution system (Criterion #9). Coliform and HPC bacteria may grow in distribution system sections that are unable to maintain an effective disinfectant residual (McCabe et al., 1970; Geldreich et al., 1972). McCabe et al. (1970) showed that free chlorine levels of 0.2 mg/L or more were associated with HPC levels (standard pour plate technique) of less than 500 cfu/mL in 98 percent of the water samples.

Detection of Biofilms

In systems with biofilm problems, the phenomenon of bacterial growth is best characterized by the persistent occurrence of coliforms in the treated drinking water.

Several factors distinguish chronic coliform growth in distribution systems (LeChevallier et al., 1987, 1990b, Geldreich, 1990b):

- No coliform organisms (or extremely low counts) are detected in treatment plant effluents even when sensitive methodologies (m-T7 agar, high-volume sample analysis) are employed.
- High densities of coliform bacteria are routinely detected in distribution system samples.
- Coliform bacteria persist in distribution system samples despite the maintenance of a disinfectant residual.
- The duration of the coliform episode is prolonged (several years).
- Proper operations and maintenance practices have been carried out, including:
  - Consistently maintaining positive pressure in the distribution system.
  - Implementing an aggressive cross connection control program.
  - Thoroughly flushing pipes after repairs and new construction.



Lab technician performing a test to detect *E. coli* in a drinking water sample

When coliform growth occurs, the increased bacterial levels typically occur as randomized patterns in different types of pipes, valves, and fittings throughout the distribution system. In severe cases, the occurrence can be nearly continuous, even though coliform counts for water entering the distribution system are below 1 per 100 mL. In less severe cases, coliform occurrence may be sporadic, random throughout the system, and last for short periods of time (although these short episodes may occur repeatedly over several years). Such occurrences often are not associated with treatment disturbances. Often, no other water quality parameters (e.g., HPC and chlorine levels, water temperature) indicate any deterioration in water quality; the only deviation from normal water quality is the coliform level in the sample (Hubbs, 1991).

Coliform occurrence due to the presence of a biofilm first may appear to be the result of laboratory contamination, especially if identification of the coliform isolates is not performed. Any utility experiencing possible biofilm problems must take extra measures to establish quality control in the bacteriological laboratory. The laboratory must record the order of analysis of the samples and the equipment used (e.g., numbering the funnels) to verify that randomness of the coliform occurrence is not due to contamination of laboratory equipment (Hubbs, 1991).

Characteristics of Biofilm Problems

Several characteristics of the bacterial population in the distribution system may point to the development of a biofilm: seasonality, density, types and diversity of bacteria, and the persistence of coliforms in spite of a disinfectant residual.

Seasonality

Smith et al. (1989) reported that coliform occurrences frequently show a seasonal distribution that may be characteristic of biofilm problems for systems in temperate climates. The typical pattern was:

- Increased recovery of distribution system coliforms usually began in March or April.
- The greatest percentage of coliform-positive samples usually occurred in July or August.
- More than 50 percent of the samples were coliform-positive for several sampling periods.
- Coliform occurrences usually began to subside by mid-October.

An investigation of biofilm problems at the South Central Connecticut Regional Water Authority in New Haven revealed that coliform occurrences began in the spring and peaked in August. (Figure 3-1 shows the mean coliform densities during each season.) A statistical analysis of variance (ANOVA) showed that coliform P/A was significantly different between the seasons. Coliforms were found throughout the system, where water from two different sources mixed, and in two hydraulically isolated systems (Smith et al., 1989).

A seasonal pattern to coliform occurrence does not necessarily point to a biofilm problem, however, because at warm temperatures the concentration of organisms in the source water will increase as well.

Density Pattern

During warm weather, or when there is a release of some biofilm material, it is not unusual to detect coliform densities ranging from 1 to 125 organisms per 100 mL (Geldreich, 1988).

In a study of a New Jersey distribution system, LeChevallier et al. (1987) noted that a 20-fold increase in coliform densities occurred in a 0.7 mi-long (1.13 km-long) segment of transmission line near the treatment plant. This

increase could not be explained by bacterial growth in the water. Computer modeling of the distribution system showed that the flow time between the plant effluent and the sampling point was between 97 and 102 minutes. The researchers calculated that the bacterial growth rate in the water would have had to exceed one division every 0.5 hr, a rate not possible given the low nutrient levels, low temperature, and high chlorine residuals in the trunk lines. There was only a low level of injured coliforms relative to the total number recovered, suggesting that the bacteria had not passed through the treatment system. Finally, because cross connection and back siphonage had been ruled out as causes of coliform occurrence, biofilms were considered the most likely explanation.

The finding of bacterial growth close to the plant, despite the high disinfectant residuals, is not unexpected. This is the point where nutrients enter the distribution system and provide the first opportunity for growth. Characklis et al. (1988) described growth of biofilms in a series of reactors following treatment. The greatest growth occurred in the first reactor where nutrients were first available. As chlorine residuals were increased, biofilm growth was "pushed" farther back into the system.

Coliform Species Diversity

Geldreich (1988) noted that *Klebsiella* or *Enterobacter* coliform species usually predominate in systems experiencing biofilm problems. Camper et al. (1991) examined the growth rates of clinical and environmental coliform isolates, on the theory that the higher growth rate of a certain strain can help it become established in the biofilm. However, higher diversity of coliform species in the distribution system also may indicate that a biofilm is providing a favorable environment for bacterial growth. In the New Jersey distribution system studied by LeChevallier et al. (1987), only 3 species were identified in the first part of the distribution system, while 6 to 10 were isolated from the ends of the study area (Figure 4-1).

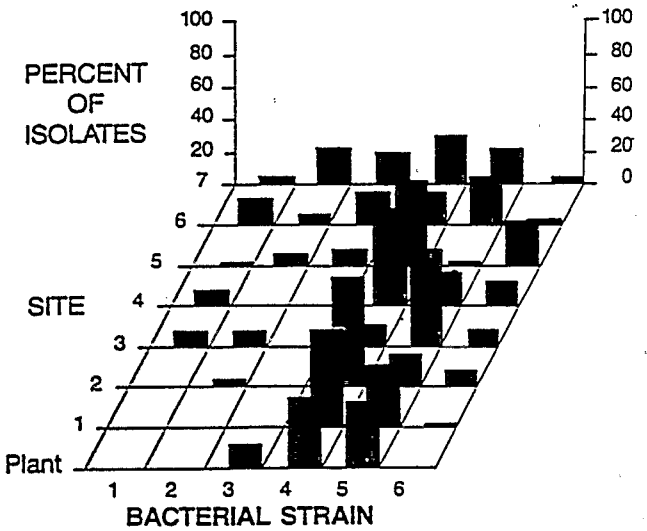


Figure 4-1. Coliform diversity at various sites in a New Jersey distribution area. Bacterial strains: 1, *E. Coli*; 2, *Klebsiella pneumoniae*; 3, *K. oxytoca*; 4, *E. agglomerans*; 5, *E. cloacae*; 6, others (LeChevallier et al., 1987).

Coliform Persistence in the Presence of a Disinfectant Residual

If a biofilm is present, coliforms may be recovered in distribution system samples even in the presence of a free chlorine residual. In 1984, *Klebsiella pneumonia* isolates were recovered from the distribution system of the South Central Connecticut Regional Water Authority, frequently when free chlorine residuals exceeded 5 mg/L (Ludwig, 1985). Similarly, coliform levels averaging 19 cfu/100 mL were recovered from the New Jersey American Water Company during the month it averaged free chlorine residuals of 4.2 mg/L (LeChevallier et al., 1987). Earnhardt (1980) reported recovering 51 coliform bacteria/100 mL in samples containing between 10 and 12 mg free chlorine/L.

> The following protocol can help determine if coliform bacteria in the water may have come from a biofilm (Geldreich, 1986; LeChevallier et al., 1987):
>
> Select one of the distribution locations where there are coliforms as well as adequate disinfection, and collect two samples: one in a sterile sample bottle containing *no* sodium thiosulfate, the other in a bottle with sodium thiosulfate. Hold the sample without sodium thiosulfate for 10 min (out of the light) and then add 0.01 percent sodium thiosulfate. Repeat this experiment a number of times. If, upon examination, the two samples contain an equivalent number of coliforms, the implication is that the bacteria are aggregated or on particles and may have come from biofilms near the point of sampling.

Increases in the Concentration of HPC Bacteria

Graphing trends in HPC levels may help determine the presence of a biofilm. Growth of heterotrophic bacteria frequently occurs before coliforms are detected in tap samples (Geldreich, 1986). Although background levels of HPC bacteria will vary among systems, levels of more than 1,000 cfu/mL may indicate a growth problem (Geldreich, 1990a). Table 4-2 summarizes the distribution and species of HPC bacteria found in the New Jersey American distribution system (LeChevallier et al., 1987).

The method used to monitor the level of heterotrophic bacteria can have a significant effect on the number of bacteria recovered. LeChevallier et al. (1987) reported that the standard pour plate method produced counts as much as 2.5 x 10^5-fold less than spread plate counts incubated on R_2A agar at 20°C for 7 days. Determinations

Table 4-2. Occurrence of HPC Bacteria In Distribution System Biofilms

Bacteria	Location*				
	Water	Zinc Floc	Flushed Sediment	Iron Tubercle	Pipe Surface
Pseudomonas vesicularis	++	++	+		++
Flavobacterium spp.	++	++	+		++
Pseudomonas diminuta	+			+	
Pseudomonas cepacia					+
Pseudomonas picketti					+
Pseudomonas stutzeri			+		+
Pseudomonas fluorescens			+	+	
Pseudomonas putida				+	
Pseudomonas paucimobilis	+			+	
Pseudomonas maltophilia	+				
Alcaligenes spp.					+
Acinetobacter spp.	+				+
Moraxella spp.	+		+		+
Agrobacterium radiobacter					+
Arthrobacter spp.	+		++	++	+
Corynebacterium spp.				+	+
Bacillus spp.					+
Yeasts					+
CDC group II J	+				
Enterobacter agglomerans					+
Micrococcus spp.	+				

* ++ indicates predominant organisms in that location.
Source: LeChevallier et al., 1987.

of HPC levels using R_2A agar may indicate fluctuations in bacterial populations that are undetected by less sensitive methods. It is recommended that HPC monitoring suggested in Criterion #8 (Table 4-1) be performed using R_2A agar.

Examination of Pipe Surfaces

A direct method of biofilm analysis is examination of the pipe surface itself. This approach is complex and should be considered a long-term research approach. Because coliform bacteria occur at specific, discrete locations within the distribution system (LeChevallier et al., 1987), a random sampling of pipe surfaces may not detect these organisms; coliform bacteria have not been isolated by all researchers examining distribution pipe surfaces. Tuovinen and Hsu (1982) failed to recover coliform organisms in 24 tubercle samples they examined. Coliform bacteria initially were not detected in 15 tubercle samples collected from the New Haven distribution system (Characklis et al., 1988); however, followup experiments (Opheim et al., 1988) detected coliform bacteria in tubercles flushed from the distribution system. Coliform isolates including *Enterobacter cloacae, E. agglomerans, E. alvei, E. sakazakii, Citrobacter freundii, Klebsiella pneumonia,* and *K. oxytocia* were similar to isolates recovered from the water with respect to biochemical tests, antibiotic resistance, and plasmid composition.

LeChevallier et al. (1987) isolated only one coliform organism from 20 pipe coupon samples collected from six distribution systems. This inability to detect coliform bacteria may be more related to the sampling methodology than to the lack of biofilm organisms, since the same researchers detected coliform bacteria in pipeline tubercles by scraping, or pigging, a 2,000-ft (610-m) section of distribution main. Nylon netting over the end of the pipe collected all the debris scraped from the pipe surface by the polypropylene pig.

Donlan and Pipes (1988) developed a corporation sampling device that could be used to insert pipe coupons into pressurized water mains (Figure 4-2). Using this method, various pipe materials could be inserted into different sections of the distribution system to examine the effects of flow velocity, water temperature, and chlorine residuals on biofilm development relative to the type of pipe material. In Vancouver, British Columbia, this method detected the growth of biofilm bacteria in the presence of water with a chlorine residual of 3 to 4 mg/L (Geldreich, 1986).

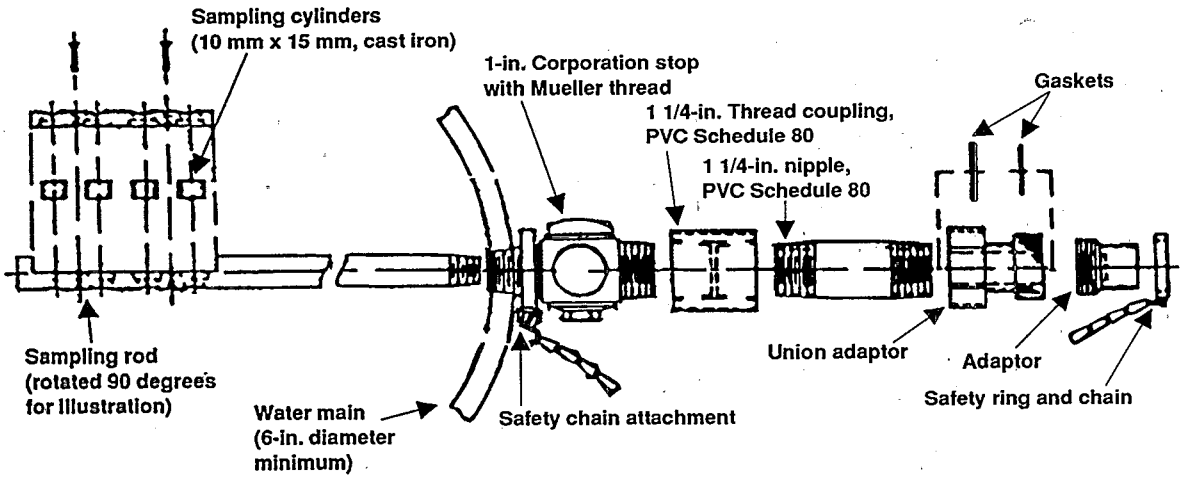


Figure 4-2. Exploded view of a corporation sampling device (Donlan and Pipes, 1988).

Some utilities have installed vaults at various points in the distribution system where sections of the active pipe network can be removed for analysis. During analysis, water can be diverted to a bypass line.

Measurement of Nutrient Levels

Nutrient levels play an important role in the growth of biofilm organisms. LeChevallier et al. (1987, 1990a, 1992) showed that AOC declined as the water flowed through the distribution system (see Chapter 3). The decline in AOC levels is consistent with bacterial growth in the distribution system. Measurement of AOC or BDOC levels at different points in the distribution system may help to determine the activity of pipeline biofilms. The supplement to the 17th edition of *Standard Methods* (AWWA, 1989) contains the methodology for the AOC procedure.

Corrosion

As described in Chapter 3, accumulation of corrosion products may provide a protective habitat for growth of heterotrophic and coliform bacteria. Therefore, if coliform occurrence decreases in response to enhanced corrosion control, biofilms may be the source of the bacterial contamination.

In New Haven, Connecticut, the South Central Regional Water Authority modified its corrosion control program in September 1988 by increasing the concentration of corrosion inhibitor (SHAN-NO-CORR®, a zinc metaphosphate mixture) from 1 mg/L to 2 mg/L (Smith et al., 1989). Total phosphorus (P) concentrations in the distribution system increased from an average of 0.31 mg P/L to an average of 0.43 mg P/L. While no immediate effect was observed, long-term occurrence of coliform bacteria decreased. Comparison of weekly distribution system coliform occurrences and turbidity averages for comparable 30-week periods before and after undertaking increased corrosion treatment showed a statistically significant decrease for both variables (Figure 4-3). Mean coliform occurrence was 12.9 percent before the increase and 5.1 percent after ($t = 3.88$, $p = 0.001$). Mean turbidity in distribution system samples was 0.19 NTU before the increase and 0.14 NTU after ($t = 5.92$, $p = 0.000$). For 1990 and 1991, coliform bacteria have been virtually eliminated from the New Haven system.

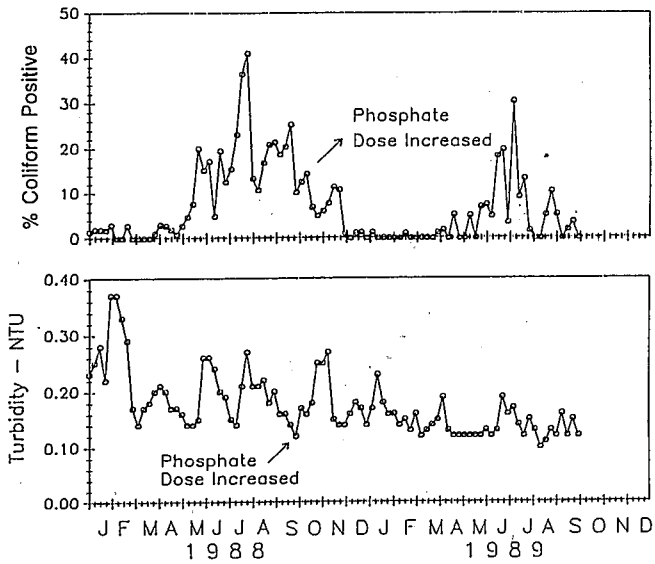


Figure 4-3. Effect of corrosion inhibitor concentration on (A) percent coliform positive and (B) distribution system turbidity (Smith et al., 1989).

Examination of Hydrodynamics

Hydrodynamic changes in the distribution system can influence the transport and detachment of materials at the pipe-water interface. Decreased flow can lead to stagnation and loss of disinfectant residuals, while sudden increases in flow can result in increased biofilm detachment. Increased coliform levels in the water may occur after changes in distribution system hydrodynamics due to increased flow resulting from fire-fighting, flow reversals, or distribution system flushing. Costello (1984) emphasizes periodic sampling of the distribution system to assess problems caused by rainfall as well.

Dead-end locations may show increased coliform levels due to loss of disinfectant residual and accumulation of bacteria dislodged from upstream biofilms. LeChevallier et al. (1987) found that the farther the sample site was from the plant, the lower the free and total chlorine residuals and the higher the pH and heterotrophic bacteria levels. Statistical modeling showed that a 1.2-mg/L residual chlorine level would be required to maintain HPC levels below 100 cfu/mL (LeChevallier et al., 1990b). Smith et al. (1989) found the highest coliform levels in sections of the distribution system with low flow (Figure 4-4). Sampling sites with long service lines or long flushing times, while below the average percentage of total coliform-positive samples for all sites, had nearly twice the average of sites located in high-flow areas.

Sites	Average percent of samples containing coliforms
Low-flow/dead-end areas	9.91
Areas with low internal flow rates	9.37
Areas with extended flush times	6.27
High-flow areas	3.20
Average for all sampling sites	7.42

Figure 4-4. Average percent of samples containing coliforms in the New Haven, Connecticut, water system (Smith et al., 1989).

CHAPTER 5
Biofilm Control Strategies

After determining that a biofilm problem exists, the system manager should not assume that all coliforms are due to the biofilm. Coliforms in the water could indicate an important treatment or distribution system deficiency, and therefore a potential public health threat. If potable water samples are positive for total coliforms, particularly if the system has had no problems in the past, the possibility of a treatment breakthrough or cross connection should be investigated. The system should take precautions to ensure that public health is protected at all times through careful monitoring and followup testing. Figure 5-1 describes steps that can be taken to control biofilms.

When a biofilm problem occurs, drinking water systems should take immediate steps to limit the factors that favor bacterial growth. Sometimes a task force can be formed to deal with coliform occurrences. For example, Massachusetts established a group of EPA, state health department, and local water treatment officials to address water quality problems. Water systems have found this approach helpful because the problems of different treatment systems are not always alike, and group members' pooled knowledge can yield a solution more quickly (Geldreich, 1986).

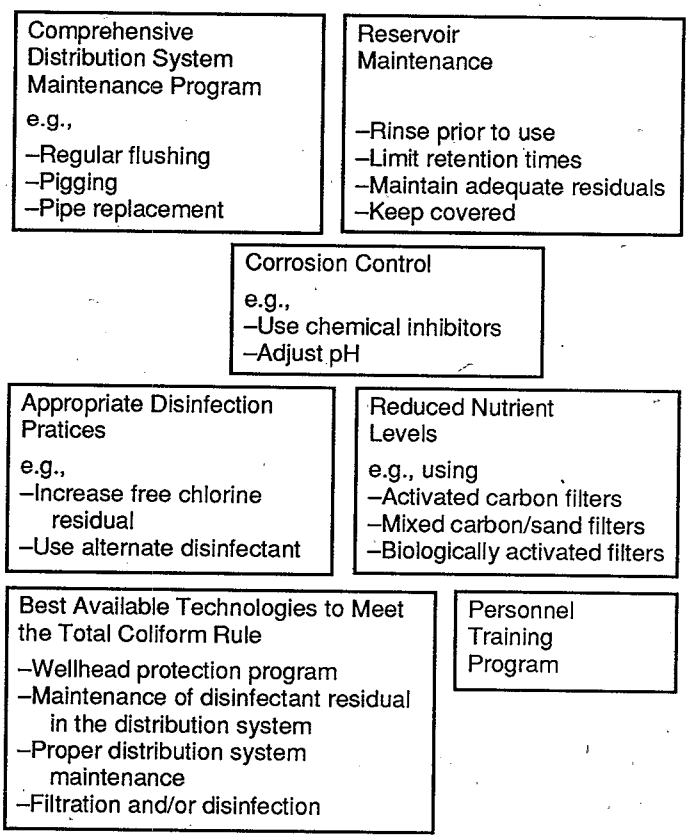


Figure 5-1. Biofilm control measures.

The best way to avoid coliform biofilm problems is to anticipate their occurrence. Knowing the factors that contribute to biofilm growth gives the system a head start in ensuring that biofilm growth is limited in the distribution system. The system may consider instituting a coliform biofilm control plan *before* positive tests for coliforms appear.

The Biofilm Control Plan

EPA has developed national criteria for granting variances to the Total Coliform Rule when coliforms are present in distribution system biofilms (U.S. EPA, 1991). One criterion for obtaining a variance to the rule is to develop and implement a biofilm control plan (Criterion #7, Table 4-1). The following section describes the strategies that should be included in a plan to prevent and control biofilms (U.S. EPA, 1990d). Biofilm control measures are described in the order of ease of implementation.

Comprehensive Maintenance Program

A maintenance program for the distribution system is central to controlling and preventing biofilm growth. However, routine systematic flushing, a primary component of distribution system maintenance, is frequently neglected due to a need to cut costs or lack of personnel. *Regular flushing helps to distribute the disinfectant residual to all portions of the system and scour existing biofilms.* Procedures for designing and conducting a flushing program have been outlined by the American Water Works Association (1986). More aggressive cleaning, using cable-drawn or water-propelled devices (pigging), may be necessary when corrosion tuberculation is severe (AWWA, 1987).

Rae (1981) described a survey of the Colorado Springs water treatment system to assess biofilm growth in 17 dead ends, each equipped with a hydrant. Researchers

took samples at each dead end, two from the hydrant placed at the dead end of the pipe, and one from the household tap nearest the dead end. The sample from the house represented the water that the household near the dead end routinely received. The first hydrant sample, taken after 1 min of flow, provided an overview of the types of organisms present in the stagnant mains. The last sample, taken from the hydrant after the water had cleared, revealed the quality of water supplied in active portions of the distribution system. Bacteria, fungi, and algae were cultured and identified in each sample. The researchers also recorded the type of pipe, type of water treatment, amount of chlorine residual, pH, temperature, and turbidity at each sampling location.

They found that distance from the treatment plant was the most important determinant of microorganism density. Dead-end sites sampled 5 mi from the point of treatment showed bacterial densities more than two times greater than those in dead ends within 1 mi of treatment. The amount of free chlorine in the treatment effluent did not seem to affect bacterial densities in the dead ends, nor did the type of pipe seem to determine the bacterial densities. PVC (plastic) and cast iron dead-end pipes showed little difference in bacterial densities. Flushing the dead ends via the hydrants was sufficient for restoring water quality in this case (Rae, 1981).

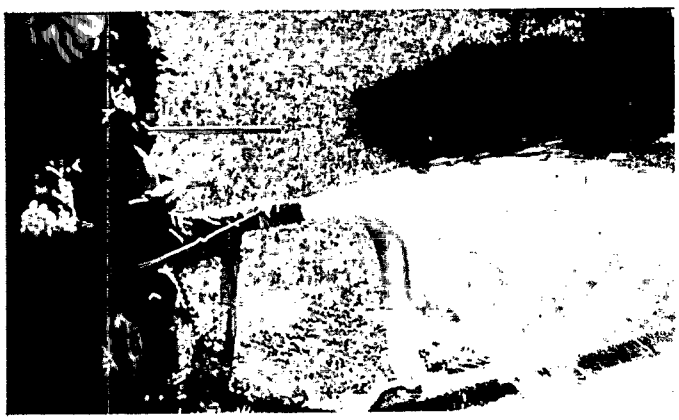
Flushing and mechanically cleaning distribution system lines can be effective preventive procedures, but may not be sufficient to resolve biological growth once the problem has become severe. Increased chlorination and flushing of the New Haven distribution system actually increased coliform levels in drinking water, presumably by releasing biofilms from the pipe surface through changes in shear forces or oxidative processes (Centers for Disease Control, 1985). Three days after systematic flushing of the distribution system in Muncie, Indiana, 126 coliforms/100 mL were recovered just a few blocks away from the treatment plant (Earnhardt, 1980).

In practice, it is difficult to apply flushing and pigging procedures effectively to transmission mains and trunk lines without extreme effort, high costs, and, usually, disruption of service to customers. Flushing only sections of the distribution system, however, has not proven effective. In Seymour, Indiana, flushing sections of the system did not eliminate coliform occurrences (Lowther and Moser, 1984). Flushing and mechanically cleaning a section of the New Jersey American system did not eliminate coliform bacteria because the organisms were later found to originate in other parts of the system.

In some cases, these procedures can rupture older water pipes. *It may be more economical to replace or rehabilitate pipe sections than to continue to apply more temporary solutions such as flushing and pigging.* The AWWA Research Foundation (1990) has assessed various traditional and innovative water main rehabilitation practices.

When new portions are added or used to replace old sections of the distribution system, the following AWWA standard procedures should be used (AWWA, 1986):

- Choose pipe-joining materials that are nonporous (e.g., plastic, rubber, or treated paper) and use nonnutritive lubricants such as food-grade oils (White and LeChevallier, 1991). Microorganisms can colonize joint-packing materials, drawing nutrients from lubricants used in seals. Biofilms also can derive nutrients from surfaces of nonporous materials that release solvents (Schoenen and Scholer, 1985).
- Keep new pipe sections, fittings, and valves covered while in storage, and guard against habitation by animals. Protect the materials from contamination by soil, runoff, and water or sewer line leaks.
- Before using new materials:
  - Flush all pipes with clean water to remove visible debris and soil. A water system in Halifax, Nova Scotia, experienced coliform problems when a piece of wood left in a new pipe section provided nutrients for bacteria (Geldreich, 1986).
  - Fill pipes with water containing 50 mg/L free chlorine and hold for 24 to 48 hr. Chlorine levels should not fall below 25 mg/L during the holding period.



Flushing the distribution line

Demonstration of pigging

- Test for total coliforms and heterotrophic bacteria. Repeat the disinfection step until no coliforms are detected and HPC bacteria are below 500/mL.

Maintenance of Reservoirs

Reservoirs used to store finished water are constructed below ground, above ground, or at ground level. All are subject to bacterial growth from a variety of factors. Above-ground tanks, usually constructed of steel with a corrosion-resistant liner, can suffer from bacterial growth on the liners. These problems may be severe within the first several months of service as organic compounds leach from the liner surface (Frensch et al., 1987; Alben, 1989). *These reservoirs should be rinsed prior to use, retention times should be limited, and adequate disinfection residuals should be maintained.* Frequent monitoring of the reservoirs, especially immediately after placement into service, can help detect problems before they become severe.

Below-ground basins and ground-level tanks are prone to bird, animal, and human contamination. *Reservoirs of treated water always should be covered to guard against contamination by animals, birds, insects, air pollution, accidental spills, and surface water runoff.* Several water systems have found coliform contamination resulting from contamination of uncovered reservoirs (Wierenga, 1985; Geldreich, 1988). Even covered reservoirs, however, can become contaminated when air is drawn through air vents to replace exiting water; installing air filters can help guard against pollution entering the system.

Many smaller storage tanks in the western United States are constructed of redwood, which, especially when unlined, supports microbial growth (Seidler et al., 1977). The tanks should be lined, and a free chlorine residual of at least 0.2 to 0.4 mg/L should be maintained (Geldreich, 1990a; Talbot et al., 1979).

Hospitals and health care facilities have complex plumbing systems and may store water in tanks that are prone to biofilm growth. These facilities should be aware of the problems that can occur in these systems and apply appropriate control measures (Highsmith, 1988).

Corrosion Control

Limiting corrosion in distribution system pipes inherently limits biofilm growth by reducing the numbers of places available for attachment by microorganisms (AWWA, 1990). Corrosion can be monitored by direct or indirect methods. Direct methods involve sampling scale from the inside of the pipes or immersing coupons in the distribution water for a period of time and determining the amount of weight loss. Electropotential devices (e.g., the Corrater by Rohrback Cosasco Systems in Santa Fe Springs, California) can provide immediate readouts of water corrosivity. These instruments are useful because they can provide immediate information on changes in treatment practices. In this way, utilities can operate at a target corrosion level. If resources and equipment are available, x-ray diffraction and Raman (infrared) spectroscopy may be used to examine the pipes.

Indirect monitoring may draw information from customer complaint logs; calculated corrosion indices that predict problems for the treated water, such as the Langelier Saturation or Aggressive Indices; or analysis of water samples from various points in the distribution system (U.S. EPA, 1984; AWWA, 1990). Customer complaints, when plotted on a map of the distribution system, can help correlate frequent complaints in a distribution area with the type of pipe materials used in that area (U.S. EPA, 1984). The presence of iron and sulfur bacteria in the water samples also may provide an indication that corrosion is taking place. Because corrosion can be very slow, indirect monitoring methods require a data base gathered over a long time period.

Since corrosion occurs at the pipe surface and involves chemical reactions between the pipe material and the water, *the primary methods for controlling corrosion serve to separate the water and pipe, or change the corrosive characteristics of either one.* These methods include:

- Modifying the water quality (e.g., changing the pH and/or reducing oxygen content) to make it less corrosive.
- Providing a protective barrier between the water and pipe, such as corrosion-resistant linings, coatings, or paints.
- Using corrosion inhibitors (e.g., sodium silicate or phosphate-based inhibitors) that form a molecular layer on the pipe surface, protecting it from the water.

Corrosion control measures such as chemical inhibitors and pH adjustments have been shown to increase the effectiveness of free chlorine for disinfection of biofilms on iron pipes (LeChevallier et al., 1990b; Lowther and Moser, 1984; Martin et al., 1982). LeChevallier et al. (1990b) showed that application of polyphosphate, zinc orthophosphate, and pH and alkalinity adjustment resulted in improved (10 to 100 fold) biofilm disinfection by free chlorine. There is some danger, however, that the biofilm could simply slough off and cause a coliform occurrence if corrosion control chemicals are improperly applied.

Lowther and Moser (1984) suggested that corrosion may have contributed to the occurrence of coliform bacteria in the Seymour, Indiana, distribution system. They reported that levels of coliform bacteria decreased within a few weeks following the application of zinc orthophosphate. Zinc orthophosphate also has been used successfully at other Indiana operations to control coliform occurrences (unpublished data). Martin et al. (1982) reported that addition of lime to treated water supplies was an effective method of pH and bacterial control. The authors pre-

sented data suggesting that the high pH levels killed the bacteria. Hudson et al. (1983) increased distribution system pH to 10.2 and free chlorine residuals to 3 to 5 mg/L to control coliform occurrences successfully in the Springfield, Illinois, network. In both of these situations, reduced corrosivity of the water could have resulted in improved free chlorine disinfection of biofilm organisms.

As illustrated by the experience of the South Central Connecticut Regional Water Authority (Figure 3-5), application of corrosion control will not have immediate effects. LeChevallier et al. (1987) also applied zinc orthophosphate and elevated pH levels at the New Jersey American Water Company. Corrosion chemicals were applied for short periods of time, and no immediate effects were observed. If applied over time, microbial habitats are eliminated and the system is able to maintain disinfectant residuals more easily.

Appropriate Disinfection Practices

One of the first steps that utilities usually take to control bacterial problems is to increase disinfectant residuals. The disinfectant chosen to control bacteria originating from distribution system pipe surfaces must be evaluated carefully, however. The problem requires a disinfectant capable of penetrating the biofilm and inactivating attached microorganisms. The disinfectant also must be relatively stable to be able to persist in the distribution system. In addition, it must be potable and not produce hazardous by-products. Removal of compounds that use up the disinfectant through selection of appropriate treatment practices, pipe relining, or main replacement—or all three—can help maintain a disinfectant residual. In the end, a more stable alternative to free chlorine residual (e.g., chloramines) may be needed to help control bacterial growths. Note, however, that for first-stage disinfection of pathogenic organisms in the treatment system, chloramines are not recommended unless the utility can demonstrate adequate inactivation of *Giardia* and viruses (U.S. EPA, 1989a).

Resolving bacterial problems in situations where disinfection residuals are low is straightforward: The system is flushed and disinfectant applied so that a residual is maintained in all parts of the distribution system. In some cases, rechlorination facilities may help boost disinfectant residuals. In many cases, this can resolve the problem. It has been the practice of utilities experiencing coliform regrowth problems to maintain high free chlorine residuals in the distribution system in an effort to control bacterial occurrence (Earnhardt, 1980; Martin et al., 1982; Reilly and Kippen, 1983; Hudson et al., 1983; Centers for Disease Control, 1985; Ludwig, 1985; Olivieri et al., 1985; LeChevallier et al., 1987). *In general, free chlorine residuals of 3 to 6 mg/L have been necessary to control coliform regrowth events.* However, Earnhardt (1980) reported recovering 51 coliform bacteria/100 mL in samples containing between 10 and 12 mg/L free chlorine. *If higher residuals are not effective, or if effective residuals cannot be maintained throughout the distribution system, the utility should consider using an alternative disinfectant.*

Many in the water industry have found that applying a second disinfectant such as a combined chlorine residual just before the water enters the distribution system can effectively control bacterial levels in the distribution system (Brodtmann and Russo, 1979; Norman et al., 1980; Shull, 1981; Mitcham et al., 1983; Kreft et al., 1985; Dice, 1985; Means et al., 1986; MacLeod and Zimmerman, 1986). Although there is no perfect disinfectant, recent research has suggested that monochloramine may be more effective for biofilm control than free chlorine (LeChevallier et al., 1988b, 1990b). As reviewed by Kreft et al. (1985), *more than 70 utilities in the United States effectively use chloramines for disinfection of distribution water supplies.* MacLeod and Zimmerman (1986) reported that before conversion to chloramines, 56.1 percent of the distribution system water samples were positive for coliform bacteria and that, after conversion, only 18.2 percent of the samples contained coliform organisms. Although there may be many reasons for the reduced coliform counts, the system has remained coliform-free since February 1984 (MacLeod, 1989).

Hackensack Water Company converted to chloramine in their distribution system in 1982 (Fung, 1989). Initially the system was dosed with a 2 mg/L chloramine residual, but because of sporadic occurrences of what were thought to be coliforms and evidence of nitrification in the distribution system, the company increased the chloramine dose to 3 mg/L in 1986. In that year, only a few coliform bacteria were recovered during the summer months. In August 1986, chloramine doses were increased to 4 mg/L (average distribution system residuals ranged from 2 to 3 mg/L) for the remainder of the summer. Since November 1986, no coliform bacteria or nitrification problems have been found in the distribution system. *The results of more recent studies (LeChevallier et al., 1990b) suggest that biofilm control can be achieved using chloramine levels ranging from 2 to 4 mg/L.*

LeChevallier et al. (1990b) showed that there was a "threshold" concentration at which monochloramine was effective for biofilms on iron pipes. The authors indicated that a 2 mg/L monochloramine residual was necessary to inactivate attached bacteria. In actual practice, the threshold level will likely vary depending on water quality and pipe characteristics.

Controlling Nutrient Levels

Controlling the levels of nutrients available for bacterial growth is the most direct means of resolving biofilm problems. Unfortunately, it is also the most difficult. *To control bacterial nutrients, utilities must adopt new monitoring and treatment techniques.*

Data presented in Figures 3-4 through 3-7 show the relationship between AOC and growth of coliform bacteria in the New Jersey American distribution system. *Based on these data, LeChevallier et al. (1987, 1990a,b) recommended total AOC levels (measured using both P17 and NOX strains of bacteria) of less than 100 µg/L for utilities trying to control growth of coliform bacteria in distribution system biofilms.* The advantage of reducing AOC in the finished water is two fold: Not only is bacterial growth limited, but less residual chlorine is consumed in side reactions with organic compounds.

One way to reduce AOC levels in water is through the use of activated carbon filters. Granulated activated carbon (GAC) and powdered activated carbon (PAC) are porous particles that adsorb and hold organic contaminants. They are commonly used to remove contaminants that cause taste and odor problems in drinking water. In the context of biofilm control, they are agents for removing dissolved organics from the source water, discouraging bacterial growth. In fact, LeChevallier et al. (1991b) noted that many of the published descriptions of biofilm problems involve systems that did not practice GAC filtration.

Mixed filters of GAC and sand can be more effective for reducing AOC levels than are filters made of sand alone (monomedia filters). This is probably because GAC has a greater surface area to support biological growth and adsorb organic substrates. Bablon et al. (1988) found that biologically active GAC/sand filters (16 in. [41 cm] of GAC over 24 in. [61 cm] of sand) performed better than monomedia sand filters. The GAC/sand filters had better turbidity removal, lasted longer, used less energy, showed greater biological activity, and were less affected by changes in water temperature. Although the dual media filter was not as effective for AOC removal as systems using sand filters followed by a GAC filter, the authors concluded that mixed GAC/sand filters are an economical and practical alternative to two filters in series.

LeChevallier et al. (1991b) observed that addition of PAC as a sludge blanket reactor (a reactor in which coagulation, flocculation, and sedimentation are combined) correlated to reduced AOC levels. These results support Hamann et al.'s (1986) findings that addition of PAC in a sludge blanket reactor (Superpulsator) reduced instantaneous concentrations of disinfection by-products by 50 to 75 percent.

LeChevallier et al. (1991b) suggested that allowing microorganisms to attach to the PAC, producing a "biologically activated" sludge blanket, could further reduce AOC levels. This type of biological treatment is a widely used method of reducing the concentration of organic compounds in source water. This treatment process encourages microbial activity within the treatment system, removing nutrients before the water passes to the distribution system, and therefore limiting bacterial growth in the distribution system. When microbial activity is sufficient, biologically stable water results, because all nutrients that might support significant bacterial growth in treated effluents already have been removed. In addition, Bablon et al. (1987) reported that rechlorination stations in the distribution network were not needed due to improved chlorine stability of biologically treated waters.

Application of biological processes may take many forms. Biological removal of organic material has been reported for aerated submerged media reactors (Sibony, 1982); fluidized-bed filters (Foster, 1972; Short, 1975; Jeris et al., 1977); slow sand filters (Eberhardt et al., 1977; Schmidt, 1979); rapid sand filters (Eberhardt et al., 1977; Sontheimer et al., 1978; Bourbigot et al., 1982; van der Kooij and Hijnen, 1985); and GAC filters (Miller and Rice, 1978; Committee Report AWWA, 1981; Bablon et al., 1986; van der Kooij, 1987). A number of recent reviews of biological treatment are available (Sontheimer and Hubele, 1988; Crowe and Bouwer, 1987; Faust and Aly, 1987; Rittmann and Huck, 1989).

The choice of disinfectant for primary treatment will influence biological activity in the treatment system. For example, ozonation converts complex, long-chain, non-easily degradable compounds in the raw water to more readily biodegradable substances that can be adsorbed to GAC or consumed by microbes (Janssens et al., 1984; Baozhen et al., 1985; Maloney et al., 1985; Bablon et al., 1986). The increased oxygen content of water by ozonation also stimulates microbial activity.

The increased biodegradability of ozonated compounds may overwhelm treatment capabilities, however. Janssens et al. (1984) reported that ozonation increased biodegradable organic carbon levels to the extent that an early breakthrough of organics was observed in treatment plant effluents. Van der Kooij (1987) has indicated that in certain instances ozonation actually increased AOC levels in treated effluents. In addition, high ozone doses may also produce low molecular weight and polar oxidation products that are adsorbed less readily onto activated carbon (Janssens et al., 1984).

LeChevallier et al. (1991b) compared the effects of using ozone, free chlorine, chlorine residual neutralized using sodium thiosulfate, monochloramine, and no predisinfectant on a mixed GAC/sand filter's effectiveness for AOC removal. The results suggest that many conventionally operated GAC filters already may be achieving good AOC removals. Preozonation increased AOC levels in the water an average of 2.3 fold, and filter effluent AOC levels were always increased relative to nonozonated water. Because GAC can rapidly neutralize free chlorine, application of free chlorine to GAC filters did not inhibit biological activity. Application of chloramines to GAC filters showed an inhibitory effect relative to free chlorine, and the stability of the chloramine residuals allowed residual disinfectant to appear in the filter effluent. HPC bacteria levels in the prechloraminated filters were 10

times lower than in the prechlorinated or preozonated filters.

Empty bed contact time, or the length of time each volume of water remains in contact with the adsorbent, is another variable to consider when using biologically activated carbon. Prevost et al. (1990) reported that 62 to 90 percent of the AOC was removed within 2 min of contact time in biologically active filters. LeChevallier et al. (1991) showed that 5 to 10 min of contact time was sufficient to reduce the AOC concentration in preozonated raw water from over 450 µg/L to below 100 µg/L.

Other Issues Related to Biofilm Control

Training/Upgrading Personnel

The technical ability and level of understanding of the water treatment plant operator is crucial to the success of the treatment and monitoring required under the Safe Drinking Water Act (SDWA). The Surface Water Treatment Rule, for example, states that the operator must meet qualifications set by the primacy state. Most states have operator license certification programs. Not only do system operators need to have an understanding of the regulations and requirements under SDWA, but they must be familiar with the day-to-day operations of the plant. System operators must be responsible for:

- Protecting public health.
- Maintaining the distribution system and source water pump.
- Maintaining water quality according to federal- and state-required monitoring and testing.
- Determining sources of contamination and developing methods for managing those sources.
- Obtaining and understanding power sources used in the treatment plant.
- Carrying out emergency procedures.
- Performing detailed recordkeeping and reporting according to federal and state regulations.

Operators also should participate in continuing education programs to learn new treatment and distribution system maintenance techniques (U.S. EPA, 1990a). Various programs are available through state trade associations, national meetings sponsored by EPA or AWWA, and AWWA Research Foundation technology transfer conferences. With experienced and knowledgeable operations staff, utilities have greater latitude in choosing treatment options, maintenance and analytical procedures, and equipment.

Applying Best Available Technology

Best available technologies (BATs) are determined by EPA based on effectiveness for removing or treating contaminants and availability to the regulated community. BATs are proposed with the Maximum Contaminant Level (MCL) for any contaminant or pollutant. Under the Total Coliform Rule (U.S. EPA, 1989b), the BATs for controlling coliforms in drinking water include:

- Protection of wells from contamination by coliforms through proper well placement and construction. This comes under the State Wellhead Protection Programs described in the SDWA (Section 1428) and administered by state governments.
- Maintenance of a disinfection residual of at least 0.2 mg/L throughout the distribution system.
- Proper maintenance of the distribution system including pipe replacement and repair, operation of water main flushing programs, proper operation and maintenance of storage tanks and reservoirs, and maintenance of continual positive water pressure in all parts of the system.
- Filtration and/or disinfection of surface water according to the SWTR, or disinfection of ground water.

These techniques were chosen by EPA as feasible for meeting the MCL for total coliforms, but water systems are not required to use these particular methods. Other state-approved methods that maintain the water quality may be used as well (U.S. EPA, 1989b).

The BATs listed above may not be adequate for resolving coliform occurrences in systems with biofilm problems. Once all BATs are in place and the criteria in Table 3-1 are met, the utility may apply for a variance to the MCL for total coliforms. The biofilm control plan, in effect, becomes the BAT for that system.

Consideration of Financial Burden

Both the SWTR and the Total Coliform Rule provide estimates of the costs and benefits of implementing the regulations (see Appendix A). As with most regulations, small systems will pay the highest incremental cost of implementing the SWTR and Total Coliform Rule. It may be possible, however, to obtain federal or state grants or loans for improvements. Appendix C lists several information resources for small systems, including information about loans and financial management assistance.

In some cases a small community can share resources with other small communities or a larger community through a cooperative or regional water supply authority. Multi-community cooperative arrangements can improve cost effectiveness, upgrade water quality, and result in more efficient operation and management. Cooperative approaches include:

- Centralizing functions such as purchasing, maintenance, laboratory services, engineering services, and billing.
- Pooling resources to hire highly skilled personnel who travel within a region.

- Physically connecting existing systems to achieve economy of scale.
- Creating a satellite utility that taps into the resources of an existing larger facility without being physically connected to, or owned by, the larger facility.
- Creating water districts that combine resources and/or physically connect systems and provide for public ownership of the utilities, making the facility eligible for public grants and loans.
- Creating county or state utilities under jurisdiction of the county or state government.

Establishing Timetables for Carrying Out a Biofilm Control Plan

If a variance is granted, the state will prescribe a timetable for carrying out the components of the biofilm control plan. The schedule may include progress reports that show the state that the system is on its way to meeting the MCL (U.S. EPA, 1990c).

Public Notification

In October 1987, EPA set forth new regulations (U.S. EPA, 1987) for notifying the public when a water system is found in violation of EPA regulations regarding drinking water treatment and monitoring (53 FR 41534; 40 *Code of Federal Regulations* [CFR] 141.32). These requirements remain in place even if a variance is granted by the state or EPA, although notification is not necessarily required as often.

System representatives should use the following guidelines regarding public notification when the water system exceeds the limit for total coliforms (Geldreich, 1986; U.S. EPA, 1987):

- Use the language spelled out in the Total Coliform Rule to notify customers of the exceedance.
- Place one person in charge of answering questions and providing information to the public and the press. That person should be both technically knowledgeable and able to communicate effectively with the public.
- Indicate to the public the steps under way to find and eliminate the cause of the contamination.
- Ask state and federal regulators to assure the public that there is no immediate health problem posed by the exceedance, if indeed this is true.
- Inform local health directors and hospital officials of the MCL exceedance and describe the actions being taken.
- Hold frequent press conferences and public meetings to field questions. (The New Haven, Connecticut, water supply, when faced with a chronic biofilm problem, sent a public affairs representative to a local radio talk show to provide information and answer questions.)
- Work *with* reporters; reporters want to provide accurate information to the public, and the system has that information.

In addition, larger water supply systems that provide water to smaller distribution-only systems should help the smaller system communicate with the public and pinpoint and remediate problems.

CHAPTER 6
Summary

Distribution system monitoring and biofilm control strategies require a thorough understanding of many aspects of water supply and distribution, as well as information about water chemistry and microbiology. Bacterial growth has been found in many water systems, but the conditions favoring biofilm growth have not been completely characterized. Armed with the knowledge of the conditions that allow microbes to pass into the distribution system and the factors that favor microbial growth, the water system can develop a comprehensive monitoring strategy to identify trouble spots before they cause full-blown problems. This strategy includes monitoring of not only easy-to-reach outlets but also peripheral portions of the distribution system. Consistent, thorough monitoring provides a historical data base from which to detect changes in bacterial quality problems and determine the sources of the contamination, whether biofilms, cross connections, or treatment breakthrough.

The biofilm control plan is not only a remediation plan but a prevention program as well. Systems that maintain an adequate treatment residual, flush the distribution lines regularly, and practice good pipe maintenance will have a lower risk of developing a biofilm problem. Figure 6-1 summarizes the steps to be taken when increased coliform levels are detected.

Finally, if a potential public health problem is identified, the system should take quick action to resolve the issue and protect the health of consumers. Providing the public with accurate information on the problem and its status will ensure that consumers understand the problem and its implications without undue alarm.

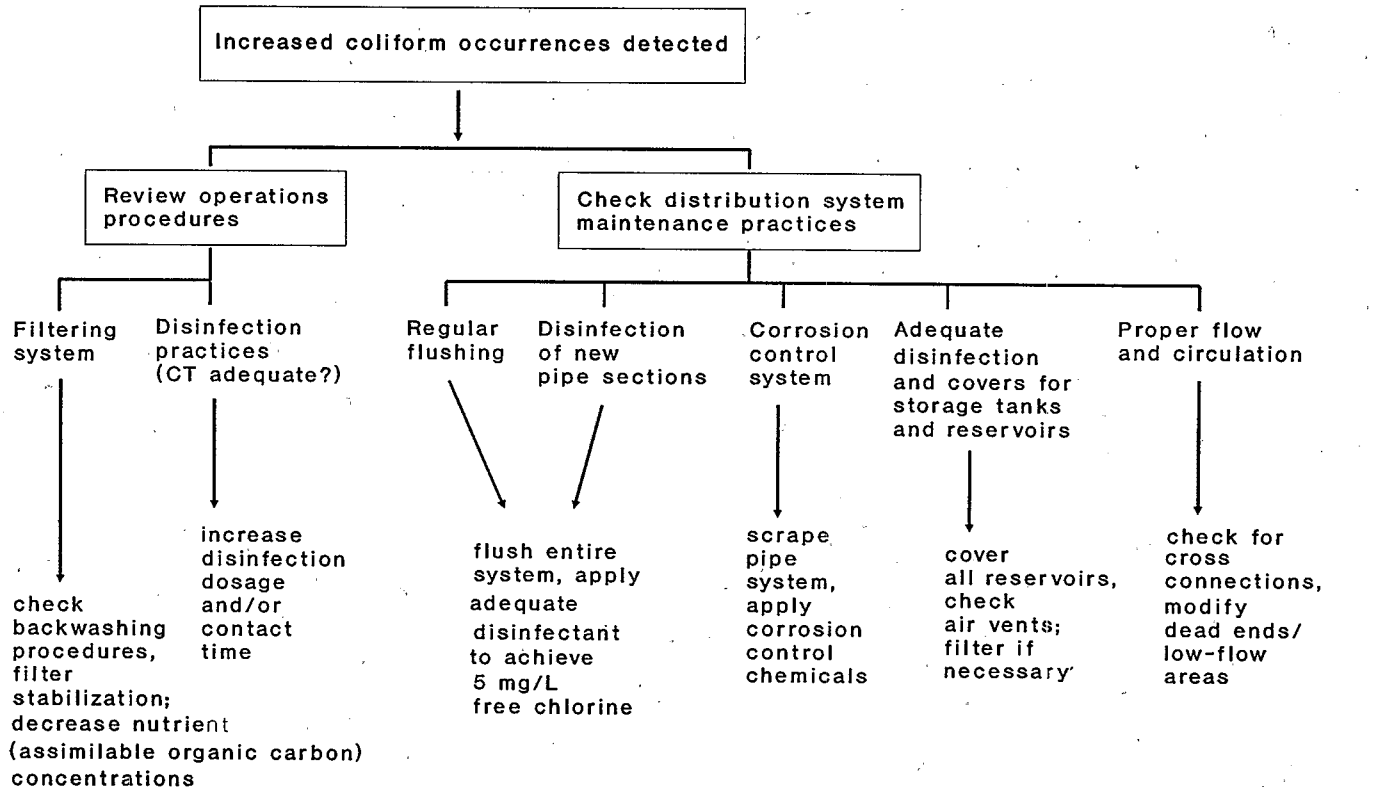


Figure 6-1. Steps for controlling biofilm growth.

CHAPTER 7
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APPENDIX A
Drinking Water Regulations for Microorganisms

Under the 1986 Amendments to the Safe Drinking Water Act, EPA must set Maximum Contaminant Level Goals (MCLGs) for any drinking water contaminant that is known to, or may, occur in public water systems and that may have an adverse effect on human health. An MCLG is a nonenforceable health goal that is set at a level (with an adequate margin of safety) at which no known or anticipated adverse health effects occur. A second regulatory level, the Maximum Contaminant Level (MCL), is set as close to the MCLG as possible, but takes economic and technical feasibility into account as well as public health considerations (represented by the MCLG). MCLs are usually specific drinking water levels, but in some cases required treatment technologies are set forth instead. MCLs are enforceable levels, enforced either by the state or EPA. States are allowed to enforce MCLs if they have primary enforcement responsibility (i.e., the state enforcement program is approved by EPA).

In June 1989, EPA promulgated final MCLs and MCLGs for surface water treatment under the Surface Water Treatment Rule (SWTR) (54 *Federal Register* [FR] 27486). EPA also set an MCL for total coliforms as part of the Total Coliform Rule (54 FR 27544). The Total Coliform Rule applies to all drinking water treatment systems. These rules specify treatment and monitoring requirements that must be met by all public water suppliers, whether community or noncommunity systems. Noncommunity systems include those serving nonresidential populations, such as restaurants, schools, office buildings, and campgrounds. Public water systems (either community or noncommunity) have at least 15 service connections to year-round residences or serve 25 or more persons for at least 60 days per year. The SWTR applies to facilities that use surface water (or ground water that is directly influenced by surface water) as raw water, while the Total Coliform Rule applies to all ground and surface water.

Surface Water Treatment Rule

The MCLGs set under the SWTR are zero (0) for *Giardia lamblia*, viruses, and *Legionella*. These organisms are regulated via treatment requirements rather than specific concentration levels (i.e., MCLs), because EPA believes that monitoring for these organisms is not technically or economically feasible, especially for small systems (U.S. EPA, 1989a). The treatment is based on the removal or inactivation of 99.9 percent of *Giardia*, and inactivation of 99.99 percent of any enteric (human intestinal) viruses as determined by CT values. The state (or EPA) must be sure that the system meets this requirement by enforcing Best Available Technology (BAT) treatment options based on certain site-specific and surface water quality criteria.

Although EPA has not published MCLGs for turbidity or heterotrophic bacteria, low turbidity and heterotrophic bacteria counts suggest that adequate treatment is in place. Therefore these measures are used under the SWTR as indicators of treatment effectiveness. One of the recommended variance criteria for systems using surface water (see Table 4-1) is that they comply with the SWTR, including those requirements for turbidity and heterotrophic bacteria.

Total Coliform Rule

The presence of coliforms in drinking water above the MCL is cause for concern, because it may indicate that disinfection has been inadequate to kill all organisms associated with human and animal wastes. Therefore, the MCLG for total coliforms is zero, and the MCL limits the percentage of samples per month that may have any total coliforms present. Total coliform measurements include *E. coli*, which come from the human intestinal tract, as well as other coliform bacteria that are not normally associated with human disease. Therefore, each sample that is positive for total coliform (total coliform-positive) is tested for fecal coliforms or *E. coli*.

The regulations specify that for systems collecting 40 or more samples per month, the MCL permits no more than 5.0 percent total coliform-positive samples per month. For systems that collect fewer than 40 samples per month, no more than one sample may be total coliform-positive in each month. The number of monthly samples ranges from less than 1 to 480 samples, depending on the population size served (U.S. EPA, 1989b). In addition, the system must develop a sample siting plan indicating where the samples will be taken; this plan will be reviewed and approved by the state. Other monitoring requirements state that:

- If total coliforms are detected in any sample, the system must collect repeat samples within 24 hours and have them analyzed for total coliforms (the 24-hour limit may be waived by the state in extenuating circumstances).
- If total coliforms are detected in any repeat sample, then more repeat samples must be taken, unless the MCL has already been exceeded and the system reports this to the state.
- If a system collecting fewer than 5 samples per month detects total coliforms in any sample, that system must collect at least 5 routine samples the next month.
- Systems that use unfiltered surface water, or ground water under the influence of surface water, must analyze one sample for total coliforms every day that the turbidity of the raw water exceeds 1 NTU (nephelometric turbidity unit).

Some public water systems have persistent coliform biofilm problems that may not pose risks to human health but may cause the system to violate the MCL for total coliforms. Therefore, the Total Coliform Rule allows primacy states to grant a variance (an exception to the MCL) if the system can prove that distribution system biofilms are the sole cause of the positive coliform results, and the contamination does not pose an unreasonable risk to health (U.S. EPA, 1990c).

The variance summary in the *Federal Register* (U.S. EPA, 1991; Table 4-1; also included in full as an Attachment to this Appendix) summarizes the steps that states may require when a system applies for a variance to the rule because of coliform biofilms. The criteria are an attempt to ensure that biofilms are the sole cause of the occurrence and that human health will not be compromised by the granting of a variance. The system must prove that there have been no treatment lapses or deficiencies, there is no measurable fecal or pathogenic contamination present, and proper operation and maintenance procedures have been carried out (U.S. EPA, 1991). The state will examine the evidence carefully, possibly taking into account the criteria listed in the variance notice. If the system is able to meet all the requirements listed under Criteria #1 and #2, then the primary treatment is assumed adequate to protect human health.

Criterion #3 directs the system to maintain biweekly contact with state and local health departments so that health officials can assess any illnesses that may be attributable to microbial contamination in the finished water. It is important that any disease associated with drinking water contamination be recognized immediately so that immediate action can be taken to prevent further infection.

If Criteria #4 through #6 are met, then a cross-connection problem can probably be ruled out as the source of contamination. The remaining criteria prove that the system is carrying out maintenance and monitoring actions. To resolve distribution system growth problems, Criterion #7 indicates that the system should put in place a biofilm control plan.

When a variance is granted, the state must set up a compliance schedule for the system. Biofilm control measures should be undertaken immediately when a variance is granted, if not before. The best way to ensure that a variance will not be needed at all is to establish a biofilm control plan now.

federal register

Tuesday
January 15, 1991

Part II

Environmental Protection Agency

40 CFR Parts 141 and 142

Drinking Water; National Primary Drinking Water Regulations; Total Coliforms; Partial Stay of Certain Provisions of Final Rule

ENVIRONMENTAL PROTECTION AGENCY

40 CFR Parts 141 and 142

[WH-FRL-3858-8]

Drinking Water; National Primary Drinking Water Regulations; Total Coliforms

AGENCY: Environmental Protection Agency (EPA).

ACTION: Partial stay of certain provisions of final rule.

SUMMARY: On June 19, 1989, EPA promulgated revised National Primary Drinking Water Regulations (NPDWRs) for total coliforms (54 FR 27544, June 29, 1989) pursuant to section 1412 of the Safe Drinking Water Act (SDWA). Sections 141.4 and 142.63 of the rule prohibit States from granting variances and exemptions to violators of the total coliform maximum contaminant level (MCL) of § 141.63(a). Today's action stays the no variance provisions of §§ 141.4 and 142.63, thus allowing States to issue variances to the requirements of § 141.63(a) under limited conditions.

EFFECTIVE DATE: January 15, 1991.

FOR FURTHER INFORMATION CONTACT: Paul S. Berger, Ph.D., Office of Drinking Water (WH-550D), Environmental Protection Agency, 401 M Street, SW., Washington, DC 20460, telephone (202) 382-3039; or the Safe Drinking Water Hotline, telephone (800) 426-4791; callers in the Washington, DC area and Alaska may reach the Hotline at (202) 382-5533. The Safe Drinking Water Hotline is open Monday through Friday, excluding Federal holidays, from 8:30 a.m. to 4 p.m. Eastern Time.

SUPPLEMENTARY INFORMATION: On June 19, 1989, EPA promulgated revised regulations for total coliforms (54 FR 27544, June 29, 1989), with an effective date of December 31, 1990. Sections 141.4 and 142.63 of the rule prohibit States from granting variances and exemptions to the total coliform rule. Pursuant to section 1412 of the Safe Drinking Water Act and section 705 of the Administrative Procedures Act, 5 U.S.C. 705, as required by justice, today's action stays parts of §§ 141.4 and 142.63 and allows States to grant variances to the total coliform MCL of § 141.63(a) of the rule under certain conditions.

Section 142.63 of the revised total coliform rule does not permit variances to the rule. In the preamble to the final rule, the Agency explained that total coliforms are the primary indicator of the microbiological quality of water. To the extent a variance would permit the continued presence of coliforms, the potential for pathogens to be present also would remain. As stated in the preamble, EPA believed that States would be unable to make the statutorily required determination that no unreasonable risk to health would result from a variance or exemption, since a variance or exemption would permit the continued presence of total coliforms in drinking water above the MCL (see 54 FR 27557, June 29, 1989).

The Agency also stated that we were aware of systems with persistent coliform problems in distribution systems not associated with fecal or pathogenic contamination or with waterborne disease (54 FR 27557-8). The source of these coliforms are often biofilms, which are accumulations of bacteria which line the walls of some water distribution pipes. Coliform bacteria which are released from biofilms can indicate a violation of the total coliform MCL when an unreasonable risk to health does not exist. The Agency did not allow variances to the total coliform MCL in the rule promulgated on June 29, 1989 because of difficulty in distinguishing these types of total coliform exceedances from those resulting from sources of contamination which are an actual threat to health.

The American Water Works Association (AWWA) has petitioned the U.S. Court of Appeals for the District of Columbia to review EPA's decision to prohibit variances and exemptions under the total coliform rule. AWWA believes that a number of systems have a persistent biofilm problem that does not pose a risk to public health but will nonetheless cause the system to violate the rule. They request that States be permitted to review the particular circumstances of each such system's violation and therefore request that EPA suspend the prohibition against variances for these systems.

More specific data are now in the docket that were made available to the Agency by AWWA and as the result of a recently held workshop. These data indicate that some water systems will experience repeated total coliform violations due to biofilms that do not appear to be associated with fecal or pathogenic contamination or with waterborne disease.

The Agency does not believe it is in the public interest to have continuous monthly public notification where the exceedance of the total coliform MCL is not associated with fecal or pathogenic contamination of the drinking water. Besides the adverse impact on the public confidence in the quality of water being delivered, repeated public notification would diminish the efficacy of the public notice where there in fact is a threat to public health.

The Agency has stated that variances to the total coliform presence/absence MCL of § 141.63(a) might be appropriate if a finding of no unreasonable risk to health could be established (see 54 FR 27557). The difficulty has been in developing nationally applicable criteria for variances which would assure continued protection of public health while there is positive coliform occurrence and violation of the MCL. Until the Agency finalizes criteria for distinguishing whether a system categorized as above is not at risk, today's action will provide assurance of no unreasonable risk. This will be done by limiting variances to a small number of systems that can demonstrate to the State protection of public health is at least equivalent to that provided by the total coliform MCL.

Specifically, variances shall apply only to systems not at risk of fecal or pathogenic contamination because there is no evidence of treatment lapses or deficiencies, measured fecal or pathogenic contamination, or improper operation or maintenance of the distribution system. Such systems can demonstrate compliance with section 1415 requirements by operating in conformance with the BAT requirements identified under 141.63(d).

The following criteria are guidance to States seeking to identify systems that could operate under a variance without posing an unreasonable risk to health:

(1) Over the past thirty days, water entering the distribution system is shown to:

(a) Be free from fecal coliform or *E. Coli* occurrence based on at least daily sampling,

(b) Contain less than one total coliform per hundred milliliters of influent water in at least ninety-five per cent of all samples based on at least daily sampling,

(c) Comply with the total turbidity requirements of § 141.13, except that surface water sources presently filtering should comply with § 141.73, and

(d) Contain a continuous disinfection residual of at least 0.2 mg/l;

(2) The system has had no waterborne disease outbreak while operated in its present configuration;

(3) The system maintains biweekly contact with the State and local health departments to assess illness possibly attributable to microbial occurrence in the public drinking water system;

(4) The system has evaluated, on a monthly basis, at least the number of samples specified in § 141.21(a)(2) and

has not had an *E. coli*-positive compliance sample within the last six months, unless the system demonstrates to the State that the occurrence is not due to contamination entering the distribution system;

(5) The system has undergone a sanitary survey conducted by a party approved by the State within the past twelve months;

(6) The system has a cross connection control program acceptable to the State and performs an audit of the effectiveness program:

(7) The system agrees to submit a biofilm control plan to the State within twelve months of the granting of the first request for a variance:

(8) The system monitors general distribution system bacterial quality by conducting heterotrophic bacteria plate counts on at least a weekly basis at a minimum of ten percent of the number of total coliform sites specified for that system size in § 141.21(a)(2) [preferably using the R2A medium in method 907A, 907B, or 907C, as set forth in the 16th edition of *Standard Methods for the Examination of Water and Wastewater*, 1985, American Public Health Association, et. al.]; and

(9) The system conducts daily monitoring at distribution system sites approved by the State and maintains a detectable disinfectant residual (measured as specified in § 141.74(a)(5)) at a minimum of ninety-five percent of those points and a heterotrophic plate count of less than 500 colonies per ml (measured as specified in § 141.74(a)(3)) at sites without a disinfectant residual.

The Agency believes the above criteria identify a set of conditions that insure equivalent protection to the current total coliform MCL. When the Agency ultimately proposes nationally applicable variance criteria, it is likely that these requirements or a subset thereof will be included.

A workshop was held in November 1990 to assist the Agency in refining nationally applicable criteria for issuance of variances to the total coliform MCL. The workshop was attended by a wide range of experts familiar with biofilm problems. A copy of the workshop proceedings is included in the docket for the total coliform rule.

This stay is issued in order to allow the Agency time to consider the recommendations of the workshop and determine what additional factors may need to be considered in order to issue nationally applicable variance criteria.

Pursuant to section 705 of the Administrative Procedures Act (APA), 5 U.S.C. 705, "when an Agency finds that justice so requires, it may postpone the effective date of action taken by it, pending judicial review." In addition pursuant to section 553 of the APA, 5 U.S.C. 553, "when the Agency finds good cause exists, it may issue a rule without first providing notice and comment and make the rule immediately effective."

This Notice defers a pending legal challenge to the total coliform rule while the Agency reviews the issue of variance criteria. Since it is in the public interest to avoid unnecessary litigation and since this action provides relief for certain systems, the Agency finds there is good cause not to solicit comment and to have the stay immediately effective.

List of Subjects

40 CFR Part 141

Chemicals, Microorganisms, Indians—land, Intergovernmental relations, Radiation protection, Reporting and recordkeeping requirements, Water supply.

40 CFR Part 142

Chemicals, Microorganisms, Indians—land, Intergovernmental relations, Radiation protection, Reporting and recordkeeping requirements, Water supply, Administrative practice and procedure.

Dated: December 31, 1990.

F. Henry Habicht,

Administrator.

Parts 141 and 142 of title 40 of the Code of Federal Regulations are amended as follows.

1. The authority citation for part 141 continues to read as follows:

Authority: 42 U.S.C. 300f, 300g–1, 300g–2, 300g–3, 300g–4, 300g–5, 300g–6, 300j–4 and 300j–9.

2. Section 141.4 is amended by designating the existing text as paragraph (a) and by adding paragraph (b) to read as follows:

§ 141.4 Variances and exemptions.

* * * * *

(b) EPA has stayed the effective date of this section relating to the total coliform MCL of § 141.63(a) for systems that demonstrate to the State that the violation of the total coliform MCL is due to a persistent growth of total coliforms in the distribution system rather than fecal or pathogenic contamination, a treatment lapse or deficiency, or a problem in the operation or maintenance of the distribution system.

3. The authority citation for part 142 continues to read as follows:

Authority: 42 U.S.C. 300f, 300g–1, 300g–2, 300g–3, 300g–4, 300g–5, 300g–6, 300j–4 and 300j–9.

4. Section 142.63 is amended by designating the existing text as paragraph (a) and by adding paragraph (b) to read as follows:

§ 142.63 Variances and exemptions from the maximum contaminant level for total coliforms.

* * * * *

(b) EPA has stayed the effective date of this section relating to the total coliform MCL of § 141.63(a) of this chapter for systems that demonstrate to the State that the violation of the total coliform MCL is due to a persistent growth of total coliforms in the distribution system rather than fecal or pathogenic contamination, a treatment lapse or deficiency, or a problem in the operation or maintenance of the distribution system.

[FR Doc. 91–925 Filed 1–14–91; 8:45 am]

BILLING CODE 6560–50–M

APPENDIX B
Glossary

activated carbon. Carbon that has been exposed to very high temperatures and steam to form pores that will adsorb and hold organic substances.

Aggressive Index. A criterion for establishing the corrosive tendency of the water relative to asbestos-cement pipe.

ANOVA (analysis of variance). A statistical method for determining the precision of numerous individual measurements.

AOC (assimilable organic carbon). The portion of DOC that is easily used by microorganisms as a carbon source.

autotrophic bacteria. Bacteria that can use carbon dioxide as their sole source of carbon.

backflow. Reversal of flow in the water distribution system resulting in contamination due to a cross connection.

backpressure. Increased pressure, for example, due to a pump or elevated tank, that causes backflow in the distribution system.

backsiphonage. Backflow caused by reduced pressure in the water distribution system.

BDOC (biodegradable dissolved organic carbon). The portion of dissolved TOC that is easily degraded by microorganisms. (See AOC; BDOC is the same dissolved carbon, measured with a different method.)

biofilm. Organic or inorganic surface deposit consisting of microorganisms, microbial products, and detritus.

biologically stable. Water from which almost all nutrients have been removed and that therefore will not support bacterial (or other) growth.

breakthrough. An increase in the numbers of bacteria in the distribution system that passed through or avoided disinfection.

cfu (colony-forming units). When spread on a plate of medium, each bacterium will divide to form a visible colony. These colonies are counted and the count used to determine the number of bacteria originally present in the original water sample.

chlorine demand. The amount of chlorine that will combine with impurities and therefore not be available to act as a disinfectant.

coliform bacteria. A group of microorganisms, characterized by their rod-like shape and fermentation of lactose. These bacteria are usually found in the intestinal tract of mammals.

community water system. A PWS serving at least 25 people or at least 15 service connections year round.

coupon test. A method for determining the rate of corrosion. It involves inserting sample strips (coupons) of the pipe material into the distribution system.

cross connection. A junction between a potable water system and contaminated air, water, or solids.

CT value. The disinfection effectiveness, as determined by multiplying the concentration of residual disinfectant (C, mg/L) by the disinfectant contact time (T, in minutes).

disinfection. A process that inactivates or kills pathogens using chemicals or ultraviolet light.

DOC (dissolved organic carbon). The fraction of TOC that is dissolved in the water sample.

empty bed contact time (EBCT). The volume of the tank holding a bed of activated carbon divided by the flow rate of the water. The result, in minutes, represents the length of time each volume of water spends in contact with the bed.

enteric bacteria. Bacteria that normally reside in the intestines of animals.

heterotrophic bacteria. Bacteria that require preformed organic compounds as carbon and energy sources. Almost all pathogenic bacteria are heterotrophic bacteria.

HPC (heterotrophic plate count). A method for enumerating heterotrophic bacteria.

lag phase. The length of time from a microorganism's entry into the system until cell division begins.

Langelier Index. A calculated saturation index for calcium carbonate, useful in predicting the scaling behavior of water.

MCL (Maximum Contaminant Level). The highest concentration of a contaminant permitted in drinking water under the Safe Drinking Water Act. The MCL takes into account public health and economic and technical feasibility.

nitrification. Oxidation of reduced nitrogen (e.g., ammonia) by microorganisms to form nitrite and nitrate.

noncommunity water system. A PWS that is not a community water system. These systems serve transient or nonresident populations, such as a campground, school, factory, or restaurant.

opportunistic pathogen. A microbe that can cause disease in immunocompromised individuals (e.g., the elderly, the very young, or ill persons), but usually not in healthy individuals.

pathogen. A microbe that causes disease.

public water system (PWS). A system that distributes potable water to at least 25 people or has at least 15 service connections.

regrowth. Growth of microorganisms in the distribution system.

residual. Disinfectant remaining in the finished water after primary treatment has been carried out.

surface water. According to the Surface Water Treatment Rule, water that is 1) open to the atmosphere and subject to surface runoff; or 2) directly influenced by surface water, such as springs or wells.

Surface Water Treatment Rule (SWTR). Regulations published by EPA in 1989 requiring disinfection for all surface waters, and filtration if necessary (54 FR 27486, June 29, 1989).

TOC (total organic carbon). The total amount of organic compounds, both soluble and insoluble, present in the water.

Total Coliform Rule. Regulations published by EPA in 1989 specifying limits on coliforms in drinking water (54 FR 27544 June 29, 1989).

trihalomethanes (THMs). A type of disinfectant by-product (e.g., chloroform) formed when chlorine reacts with organic compounds in water.

tubercles. Knob-like mounds of corrosion on pipe surfaces.

waterborne disease outbreak. When two or more people become ill within a short time due to contaminated drinking water.

APPENDIX C
Resources

Safe Drinking Water Hotline

1-800-426-4791

This hotline, directed by the U.S. Environmental Protection Agency, provides information on drinking water regulations, policies, and documents to the public, state and local government, public water systems, and consultants. Up-to-date EPA publication lists are also available. The Safe Drinking Water Hotline's hours are 8:30 a.m. to 4:30 p.m. Eastern Standard Time, Monday through Friday, excluding holidays.

U.S. Environmental Protection Agency Regional Offices

Regional offices of the U.S. Environmental Protection Agency are listed in Table C-1.

State Drinking Water Agencies

State agencies responsible for public water supervision are listed in Table C-2.

Organizations Assisting Small Systems

American Water Works Association (AWWA) Small Systems Program

This program provides information, training, and technical assistance to small systems, in coordination with state regulatory agencies and other organizations assisting small systems. Contact the AWWA at 6666 W. Quincy Avenue, Denver, CO 80235 (303-794-7711) for the name of a contact for the small systems program in your area.

National Rural Water Association (NRWA)

This organization provides training and technical assistance to small systems. Contact the NRWA office at P.O. Box 1428, Duncan, OK 73534 (405-252-0629) for national information and the name of your local contact.

Rural Community Assistance Program (RCAP)

This program consists of six regional agencies formed to develop the capacity of rural community officials to solve local water problems. It provides onsite technical assistance, training, and publications, and works to improve federal and state government responsiveness to the needs of rural communities. Table C-3 lists the six RCAP regional agencies.

Farmers Home Administration (FmHA)

The Farmers Home Administration provides grants and loans for rural water systems and communities with populations less than 25,000. Contact FmHA at: USDA/FmHA, 14th and Independence Avenue, SW, Washington, DC 20250; 202-447-4323.

Publications

A wide variety of publications on specific topics of concern to water systems is available from the American Water Works Association and the National Rural Water Association. EPA's Center for Environmental Research Information (CERI) Forms and Publications Distribution Center (513-569-7562) distributes research reports from the Office of Research and Development. Call for a catalogue and to be added to their mailing list. The Safe Drinking Water Hotline will also send a list of EPA Office of Drinking Water publications on request.

General

American Water Works Association. Basic Management Principles for Small Water Systems. 1982.

American Water Works Association. Design and Construction of Small Water Systems - A Guide for Managers. 1984.

National Rural Water Association. Water System Decision Makers: An Introduction to Water System Operation and Maintenance. Duncan, OK, 1988.

Opflow. (A monthly publication of the American Water Works Association focusing on the "nuts and bolts" concerns of treatment plant operators.)

Schautz, Jane W. The Self-Help Handbook. This manual gives specific guidelines and techniques for establishing self-help projects (projects where the community does some of the work itself to save money). Focus is on improving or creating water and wastewater systems in small rural communities. For ordering information, contact: Rensselaerville Institute, Rensselaerville, NY 12147, (518) 797-3783.

U.S. Environmental Protection Agency, Office of Ground Water and Drinking Water. Guidance Manual for Compli-

Table C-1. U.S. Environmental Protection Agency Regional Offices

EPA Region 1
JFK Federal Building
Boston, MA 02203
617-565-3424
Connecticut, Massachusetts, Maine, New Hampshire, Rhode Island, Vermont

EPA Region 2
26 Federal Plaza
New York, NY 10278
212-264-2515
New Jersey, New York, Puerto Rico, Virgin Islands

EPA Region 3
841 Chestnut Street
Philadelphia, PA 19107
215-597-9370
Delaware, Maryland, Pennsylvania, Virginia, West Virginia, District of Columbia

EPA Region 4
345 Courtland Street, NE
Atlanta, GA 30365
404-347-3004
Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee

EPA Region 5
230 South Dearborn Street
Chicago, IL 60604
312-353-2000
Illinois, Indiana, Ohio, Michigan, Minnesota, Wisconsin

EPA Region 6
1445 Ross Avenue
Dallas, TX 75202
214-655-2200
Arkansas, Louisiana, New Mexico, Oklahoma, Texas

EPA Region 7
726 Minnesota Avenue
Kansas City, KS 66101
913-236-2803
Iowa, Kansas, Missouri, Nebraska

EPA Region 8
One Denver Place
999 18th Street, Suite 1300
Denver, CO 80202
303-293-1692
Colorado, Montana, North Dakota, South Dakota, Utah, Wyoming

EPA Region 9
215 Fremont Street
San Francisco, CA 94105
415-974-8083
Arizona, California, Hawaii, Nevada, American Samoa, Guam, Trust Territories of the Pacific

EPA Region 10
1200 Sixth Avenue
Seattle, WA 98101
206-442-1465
Alaska, Idaho, Oregon, Washington

EPA Headquarters
401 M Street, SW
Washington, DC 20460
202-382-5043

ance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources. October 1989.

U.S. Environmental Protection Agency, Office of Ground Water and Drinking Water. Manual of Individual Water Supply Systems. EPA-570/9-82-004. October 1982.

U.S. Environmental Protection Agency, Office of Water. Self Assessment for Small Investor-Owned Water Systems. EPA-570/9-89-011. September 1989.

U.S. Environmental Protection Agency, Office of Water. Self Assessment for Small Publicly-Owned Water Systems. EPA-570/9-89-014. September 1989.

Sampling

U.S. Environmental Protection Agency, Office of Ground Water and Drinking Water. Pocket Sampling Guide for Operators of Small Water Systems. EPA-814/B-92-001. April 1992.

U.S. Environmental Protection Agency, Office of Research and Development. Handbook for Sampling and Sample Preservation of Water and Wastewater. EPA-600/4-82-029. September 1982.

Filtration

Huisman, L. and Wood, W.E. Slow Sand Filtration. World Health Organization, Geneva. 1974.

Slezak, L.A. and Sims, R.C. The Application and Effectiveness of Slow Sand Filtration in the United States. *Journal AWWA* 76:1238-43. 1984.

Visscher, J.T., Paramasivam, R., Raman, A., and Heijnen, H.A. Slow Sand Filtration for Community Water Supply. Technical Paper 24. International Reference Centre for Community Water Supply and Sanitation, The Hague, The Netherlands. 1987.

Disinfection

American Water Works Association. AWWA Standard for Disinfecting Water Mains. AWWA C651-86. Denver, CO. 1986.

American Water Works Association. Water Chlorination Principles and Practices (M20). 1973.

American Water Works Association. Water Quality and Treatment, 4th ed. McGraw-Hill, Inc., New York. 1990.

SMC Martin, Inc. Microorganism Removal for Small Water Systems. EPA-570/9-83-012. Valley Forge, PA. June 1983.

U.S. Environmental Protection Agency, Office of Water. Protecting Our Drinking Water from Microbes. EPA-570/9-89-008. September 1989.

Corrosion Control

American Water Works Association. Cleaning and Lining Water Mains. Denver, CO. 1987.

American Water Works Association Research Foundation. Economic and Engineering Services. Lead Control Strategies. Denver, CO. 1989.

U.S. Environmental Protection Agency, Office of Ground Water and Drinking Water. Corrosion Manual for Internal Corrosion of Water Distribution Systems. EPA 570/9-84-001. September 1984.

U.S. Environmental Protection Agency, Office of Water. Cross-Connection Control Manual. EPA-570/9-89-007. September 1989.

Costs/Financial Management

American Water Works Association. Water Utility Capital Financing (M 29). 1988.

Gumerman, R.C., Burris, B.E., Hansen, S.P., Culp/Wesner/Culp. Estimation of Small System Water Treatment Costs. Final Report. Municipal Environmental Research Lab, Cincinnati, OH. 1984.

U.S. Environmental Protection Agency, Office of Water. A Water and Wastewater Manager's Guide for Staying Financially Healthy. EPA 430-09-89-004. July 1989.

Consultants

Directory—Professional Engineers in Private Practice. Published by the National Society of Professional Engineers. Contact SPE Order Department, 1420 King Street, Alexandria, VA 22314. Who's Who in Environmental Engineering. Published by the American Academy of Environmental Engineers. Contact the American Academy of Environmental Engineers, 132 Holiday Court, Suite 206, Annapolis, MD 21401.

The Federal Register

The Federal Register is published daily to make available to the public regulations and legal notices issued by federal agencies. It is distributed by the U.S. Government Printing Office, Washington, DC 20402. To order copies, call 1-202-783-3238.

Table C-2. State Drinking Water Agencies

Region 1

Connecticut Department of Health Services
Water Supplies Section
150 Washington Street
Hartford, CT
203-566-1251

Division of Water Supply
Department of Environmental Protection
One Winter Street, 9th Floor
Boston, MA 02108
617-292-5529

Drinking Water Program
Division of Health Engineering
Maine Department of Human Services
State House (STA 10)
Augusta, ME 04333
207-289-3826

Water Supply Engineering Bureau
Department of Environmental Services
P.O. Box 95, Hazen Drive
Concord, NH 03302-0095
603-271-3503

Division of Drinking Water Quality
Rhode Island Department of Health
75 Davis Street, Cannon Building
Providence, RI 02908
401-277-6867

Water Supply Program
Vermont Department of Health
60 Main Street
P.O. Box 70
Burlington, VT 05402
802-863-7220

Region 2

Bureau of Safe Drinking Water
Division of Water Resources
New Jersey Department of
Environmental Protection
P.O. Box CN-029
Trenton, NJ 06825
609-984-7945

Bureau of Public Water Supply Protection
New York State Department of Health
2 University Place
Western Avenue, Room 406
Albany, NY 12203-3313
518-458-6731

Water Supply Supervision Program
Puerto Rico Department of Health
P.O. Box 70184
San Juan, PR 00936
809-766-1616

Planning and Natural Resources
Government of Virgin Islands
Nilky Center, Suite 231
St. Thomas, Virgin Islands 00802

Region 3

Office of Sanitary Engineering
Delaware Division of Public Health
Cooper Building
P.O. Box 637
Dover, DE 19903
302-736-4731

Water Supply Program
Maryland Department of the Environment
Point Breeze Building 40, Room 8L
2500 Broening Highway
Dundalk, MD 27224
301-631-3702

Water Hygiene Branch
Department of Consumer and Regulatory Affairs
5010 Overlook Avenue, SW
Washington, DC 20032
202-767-7370

Division of Water Supplies
Pennsylvania Department of Environmental Resources
P.O. Box 2357
Harrisburg, PA 17105-2357
717-787-9035

Environmental Engineering Division
Office of Environmental Health Services
State Department of Health
Capital Complex Building 3, Room 550
1900 Kanawha Blvd., East
Charleston, WV 25305
304-348-2981

Division of Water Supply Engineering
Virginia Department of Health
James Madison Building
109 Governor Street
Richmond, VA 23219
804-786-1766

Region 4

Water Supply Branch
Department of Environmental Management
1751 Congressman W.L. Dickinson Drive
Montgomery, AL 36130
205-271-7773

Drinking Water
Department of Environmental Regulation
Twin Towers Office Building
2600 Blair Stone Road
Tallahassee, FL 32399-2400
904-487-1779

Drinking Water Program
Georgia Environmental Protection Division
Floyd Towers East, Room 1066
205 Butler Street, S.E.
Atlanta, GA 30334

Drinking Water Branch
Division of Water
Department of Environmental Protection
18 Reilly Road, Frankfort Office Park
Frankfort, KY 40601
502-564-3410

Table C-2. State Drinking Water Agencies (continued)

Division of Water Supply
State Board of Health
P.O. Box 1700
Jackson, MS 39215-1700
601-354-6616/490-4211

Public Water Supply Section
Division of Environmental Health
Department of Environment, Health, and
Natural Resources
P.O. Box 27687
Raleigh, NC 27611-7687
919-733-2321

Bureau of Drinking Water Protection
Department of Health and Environmental Control
2600 Bull Street
Columbia, SC 29201
803-734-5310

Division of Water Supply
Tennessee Department of Health and Environment
150 Ninth Avenue, North
Terra Building, 1st Floor
Nashville, TN 37219-5404
615-741-6636

Region 5

Division of Public Water Supplies
Illinois Environmental Protection Agency
2200 Churchill Road
P.O. Box 19276
Springfield, IL 62794-9276
217-785-8653

Public Water Supply Section
Office of Water Management
Indiana Department of Environmental Management
105 South Meridian
P.O. Box 6015
Indianapolis, IN 46206
317-633-0174

Division of Water Supply
Michigan Department of Public Health
P.O. Box 30195
Lansing, MI 48909
517-335-8318

Section of Water Supply and Well Management
Division of Environmental Health
Minnesota Department of Health
925 S.E. Delaware Street
P.O. Box 59040
Minneapolis, MN 55459-0040
612-627-5170

Division of Public Drinking Water
Ohio Environmental Protection Agency
1800 WaterMark Drive
P.O. Box 1049
Columbus, OH 43266-0149
614-644-2752

Bureau of Water Supply
Department of Natural Resources
P.O. Box 7921
Madison, WI 53707
608-267-7651

Region 6

Division of Engineering
Arkansas Department of Health
4815 West Markham Street - Mail Slot 37
Little Rock, AR 72205-3867
501-661-2000

Office of Public Health
Louisiana Department of Health and Hospitals
P.O. Box 60630
New Orleans, LA 70160
504-568-5105

Drinking Water Section
New Mexico Department of Health and
Environment Department
1190 St. Francis Drive
Room South 2058
Santa Fe, NM 87503
505-827-2778

Water Quality Service
Oklahoma State Department of Health
P.O. Box 53551
Oklahoma City, OK 73152
405-271-5204

Bureau of Environmental Health
Texas Department of Health
1100 W. 49th Street
Austin, TX 78756-3199
512-458-7533

Region 7

Surface and Ground-Water Protection Bureau
Environmental Protection Division
Iowa Department of Natural Resources
Wallace State Office Building
900 East Grand Street
Des Moines, IA 50319
515-281-8998

Public Water Supply Section
Bureau of Water
Kansas Department of Health and Environment
Forbes Field, Building 740
Topeka, KS 66620
913-296-1500

Public Drinking Water Program
Division of Environmental Quality
Missouri Department of Natural Resources
P.O. Box 176
Jefferson City, MO 65102
314-751-5331

Division of Drinking Water and
Environmental Sanitation
Nebraska Department of Health
301 Sentenial Mall South
P.O. Box 95007, 3rd Floor
Lincoln, NE 68509
402-471-2541

Table C-2. State Drinking Water Agencies (continued)

Region 8

Drinking Water Program
Colorado Department of Health
4210 East 11th Avenue
Denver, CO 80220
303-320-8333

Water Quality Bureau
Department of Health and Environmental Sciences
Cogswell Building, Room A206
Helena, MT 59620
406-444-2406

Division of Water Supply and Pollution Control
ND State Department of Health and
Consolidated Laboratories
1200 Missouri Avenue
P.O. Box 5520
Bismark, ND 58502-5520
702-224-2370

Office of Drinking Water
Department of Water and Natural Resources
Joe Foss Building
523 East Capital Avenue
Pierre, SD 57501
605-773-3151

Bureau of Drinking Water/Sanitation
Utah Department of Health
P.O. Box 16690
Salt Lake City, UT 84116-0690
801-538-6159

Water Quality Division
Wyoming Department of Environmental Quality
Herschler Building, 4 West
122 West 25th Street
Cheyenne, WY 82002
307-777-7781

Region 9

Field Services Section
Office of Water Quality
2655 East Magnolia Street
Phoenix, AZ 85034
602-257-2305

Office of Drinking Water
California Department of Health Services
714 P Street, Room 692
Sacramento, CA 95814
916-323-6111

Safe Drinking Water Branch
Environmental Management Division
P.O. Box 3378
Honolulu, HI 96801-9984
808-548-4682

Public Health Engineering
Nevada Department of Human Resources
Consumer Health Protection Services
505 East King Street, Room 103
Carson City, NV 89710
702-885-4750

Guam Environmental Protection Agency
Government of Guam
Harmon Plaza Complex Unit D-107
130 Rojas Street
Harmon, Guam 96911

Division of Environmental Quality
Commonwealth of the Northern Mariana Islands
P.O. Box 1304
Saipan, CM 96950
670-322-9355

Marshall Islands Environmental Protection Authority
P.O. Box 1322
Majuro, Marshall Islands 96960
VIA HONOLULU

Government of the Federated States of Micronesia
Department of Human Resources
Kolonia, Pohnpei 96941

Palau Environmental Quality Protection
Board
Hospital
Koror, Palau 96940

Region 10

Alaska Drinking Water Program
Wastewater and Water Treatment Section
Department of Environmental Conservation
P.O. Box O
Juneau, AK 99811-1800
907-465-2653

Bureau of Water Quality
Division of Environmental Quality
Idaho Department of Health and Welfare
Statehouse Mail
Boise, ID 83720
208-334-5867

Drinking Water Program
Department of Human Resources
Health Division
1400 S.W. 5th Avenue, Room 608
Portland, OR 97201
503-229-6310

Drinking Water Section
Department of Health
Mail Stop LD-11, Building 3
Airdustrial Park
Olympia, WA 98504
206-753-5954

Table C-3. Rural Community Assistance Program (RCAP) Agencies

Community Resources Group, Inc.
2705 Chapman
Springdale, AR 72764
501-756-2900

Great Lakes Rural Network
109 South Front Street
Freemont, OH 43420
419-334-8911

Midwest Assistance Program, Inc.
P.O. Box 81
New Prague, MN 56071
612-758-4334

Rural Community Assistance Corporation
2125 19th Street, Suite 203
Sacramento, CA 95818
916-447-2854

Rural Housing Improvement, Inc.
218 Central Street, Box 429
Winchendon, MA 01475-0429
617-297-1376

Virginia Water Project, Inc.
Southeastern Rural Community
Assistance Program
702 Shenandoah Avenue, NW
P.O. Box 2868
Roanoke, VA 24001
703-345-6781

United States
Environmental Protection Agency
Center for Environmental Research Information
Cincinnati, OH 45268

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