Water Quality Deterioration in Distribution Systems
Part 1: Recognition of the Role of Microorganisms

Thomas L. O'Connor and John T. O'Connor
H_2O'C, Limited, Columbia, Missouri

Summary

Beginning over a century ago, studies have been conducted to address the broad range of drinking water quality problems which originate in water distribution systems. Many of these problems involve the growth of microorganisms which may contribute to the formation of accumulations on pipe surfaces, create tastes and odors, consume disinfectant residuals or accelerate corrosion.

Much of the pioneering work of leaders in the waterworks profession have been lost or clouded by the veil of antiquity. Still, most of the remedial measures in general use today originated from their observations or were originally recommendations of these leaders. This series is an attempt to recreate and refresh the images of those whose work has led to our current understanding of microbially-mediated corrosion and water quality deterioration during distribution.

Historical Assessment of Microbial Growths in Drinking Water Systems

Very early in the history of water supply, the involvement of microorganisms in water quality deterioration during transmission was noticed. Leeds (1897) reported that problems of 'taste-and-odor' affecting the Brooklyn, New York, water supply were related to bacterial growths in the distribution system. Subsequently, other early investigators also related the development of tastes-and-odors to microbial growth (Baylis, 1922; Kofoid, 1923; Moses, 1933).

To confirm the diverse, sporadic reports of microbial regrowth in water distribution systems, Powell (1921) surveyed 32 municipal water systems and found that 92 percent had reported increases in the number of bacteria at the consumer's tap. In addition, the quality of water at the tap showed signs of degradation.

Addressing problems related to microbial growths in the Baltimore, Maryland, drinking water supply, Baylis (1922) observed a wide variety of organisms, including algae, diatoms, protozoa and bacteria in the distribution system. He pointedly expressed concern for the lack of attention being given to microbial growths in water systems. Noting a significant increase in bacterial concentrations in *winter* months, he concluded that decaying algae and diatoms penetrating the distribution system had provided nutrients for "scavenger" bacteria. Even at this early date, Baylis was apparently aware that microbiotic cycling of nutrients between algae, diatom and bacteria took place within water distribution systems. He concluded that taste-and-odor problems may have been caused by both algal by-products and subsequent bacterial growth.

Similarly, Kofoid (1923) attributed the development of tastes-and-odors to the growth of algae in reservoirs. He emphasized the maintenance of high quality source water to mitigate distribution system problems.

Transmission of Disease, Need for Maintenance of Disinfectant Residual

The principal concern over the observed increases in the number of microorganisms during distribution was related to fear of disease transmission. Reflecting this concern, a Committee on Water Supply established by the Public Health Engineering Section of the American Public Health Association (1930) reported, on the basis of a survey, that a number of cities exhibited severe bacterial aftergrowths in their distribution systems.

Schaut (1929) attributed high bacterial growth in the Philadelphia, Pennsylvania, water system to cold water temperature when chlorination was least efficient. The fact that organisms in polluted river water were penetrating treatment barriers in the winter underscored concern over the potential for transmission of disease.

The first experiments to evaluate the control of "bacterial aftergrowths" were conducted by Baylis (1930). Utilizing two parallel, continuously-flowing taps, significant aftergrowths were observed where the pipe system received unchlorinated water while low bacterial plate counts were observed when a 0.5 g Cl/ m^3 (0.5 ppm) chlorine residual was maintained.

Observing high counts of *B. coli* in the sediments deposited in pipes, Baylis concluded that pipe sediment accumulations interfere with the destruction of bacteria even though the water may contain high levels of chlorine. Reasoning that there would be regions of chlorine-free water within the sediment in which bacteria could grow abundantly, he recommended that a systematic flushing of dead-end water mains was necessary to control bacterial activity and maintain disinfectant residuals in a distribution system.

Organism Diversity

Shannon and Wallace (1944) sampled the water supply system of Detroit, Michigan and isolated 495 bacterial colonies. Samples were taken of the chlorinated water plant effluent, at distribution system 'dead-ends' and in consumer complaint areas. Forty-two of the colonies isolated were Gram positive cocci; five were Gram positive rods and 448 (91%) were Gram negative rods. Of the 448 Gram negative rods, 32.5 percent were of the coliform group; 20.5 percent *Alcaligenes*; 12.7 percent *Pseudomonas*, 12.3 percent *Proteus*; 9.5 percent *Eberthella*; 4.4 percent *Salmonella* and 6.9 percent unidentified species. The researchers postulated that either these bacteria had survived chlorine disinfection or were recruited during distribution through system defects, such as main breaks, back-siphonage and cross-connections.

Alexander (1944) emphasized the importance of maintaining chlorine residuals throughout a distribution system in order to control the development of slime-forming (attached) organisms on pipe surfaces. Even if introducing a "sterile" finished water, he hypothesized that organism growth within a distribution system could only be partially controlled. In addition, Alexander recognized the presence and effects of diverse microbial interrelationships. He observed *Bacillus, Sarcina, Micrococcus, Flavobacterium, Achromobacter, Alcaligenes, Pseudomonas* and *Proteus* genera in distributed water. Based on his observations, he suggested that the source water was the principal factor in determining the organisms subsequently found in the distribution system.

Alexander concluded *"that because of the new U.S. Public Health Service requirement of distribution system sampling, many water works men are just beginning to find out what we have known for many years, that is, that all kinds of growing organisms will thrive in the distribution pipe systems though an apparently perfect water has been produced at the plant".*

Microbial Growth and Predation, Red Water and Tubercle Formation

Based on a long-term study of Boston Water Works surface water reservoirs plus two distribution system locations, Whipple (1897) reported *decreases* in organism densities during distribution. He examined tubercles as well as a large, thick brownish mat removed from a section of water main removed from service. The brownish mat was identified as the sponge, *Polyzoa*. Whipple hypothesized that bacterial densities had declined during distribution due to cell sedimentation and 'decomposition' or consumption by the *Polyzoa* specie. This observation introduced the complication of predation in assessing changes in bacterial populations during distribution.

Shortly after the identification of *Crenothrix polyspora* in water distribution piping by E.G. Smith (1903), O.T. Smith (1904) reported a case study at Freeport, Illinois, where yellowish-brown solids were identified as a *Crenothrix* species. Since water flushed from system 'dead-ends' exhibited very high total iron concentrations, main flushing was proposed as a remedial measure.

A succession of investigators (Laux, 1926; Baylis, 1926a, 1926b; Speller and Chappell, 1929; Williams, 1930; Redington et al., 1931; Van Giesen, 1932; Larson, 1939; Alexander, 1940; Starkey, 1945) addressed the range of problems related to the transformation of iron by bacteria. The causes, costs and measures for control of corrosion, 'red water', tubercle formation and loss of hydraulic capacity were systematically addressed. Chlorination, the use of chemical 'sequestering' agents and systematic main flushing were recommended control measures.

Baylis (1926) conducted original, scientific studies to determine the role of bacteria in iron corrosion and tubercle formation. He determined that, whereas the pH of the distributed water was 7.9, the pH within a microbially-active tubercle was about 6.0. In a "dormant" tubercle, the pH ranged from 6.4 to 6.8. Moreover, chloride and sulfate ions were concentrated inside active tubercles. Baylis also determined that the black, columnar, porous fibers formed within the tubercle were magnetic ferrous-ferric oxides. The predominant iron-precipitating bacteria in the tubercles were identified as *Gallionella, Crenothrix, Clonothrix, Leptothrix,* and *Sphaerotilus*. Subsequently, Olsen and Szybalski (1949) conducted studies which showed that sterile water did not cause tubercle formation whereas water containing *Leptothrix* caused both accelerated iron corrosion and tubercle formation.

Iron- and Manganese-Precipitating Bacteria

Repeatedly, filamentous iron bacteria became associated with 'red water', foul-tasting water and loss of pipeline hydraulic capacity. Wilson (1950) described "water calamities" in California caused by accumulations of *Crenothrix*. A three-year program of chlorination and flushing was required to remediate the problems. San Francisco's Hetchy tunnels lost as much as 20 percent of their carrying capacity to surface accumulations of gelatinous, light-brown slime growths (Wilson, 1945). Palo Alto received over 1,200 'red water' complaints attributed to *Crenothrix* (Blair, 1954). Although they found no relation to iron concentrations, Lueschow and Mackenthun (1962) detected *Gallionella* and *Leptothrix* in 35 Wisconsin well waters.

While various species of *Eubacteriales* were found to precipitate iron, *Hyphomicrobium* and *Gallionella* species have been most commonly associated with manganese deposits in water pipelines (Zappfe, 1931; Griffin, 1960; Tyler and Marshall, 1967a, 1967b). *Clonothrix* and *Crenothrix* species were found capable of precipitating both iron and manganese oxides.

Wolfe (1960) observed large sheathed bacteria which concentrated iron and manganese in their sheaths from a water supply containing no detectable manganese and less than 0.02 g Fe/m^3 of iron. Hairlike aggregations in dark gray-brown flocculent clumps were identified as *Clonothrix putealis*. Dried deposits were found to contain 69 percent organic matter, 10 percent ferric oxide, 12 percent manganese oxide, 9 percent silicon oxlde and 0.08 percent phosphate. Wolfe concluded that sessile organisms can concentrate iron and manganese from dilute suspensions of metals.

Alternately, saprophytic, slime-forming bacteria were reported to have caused a 10 percent decrease in hydraulic carrying capacity in a 2.4 meter diameter main (Wilson, 1950). In Santa Rosa, California (Brown, 1950), the use of well water resulted in prolific growths of non-filamentous bacteria. These bacteria formed heavy accumulations of brown to gray-to-black slime and caused severe discoloration and septic odors. Dissolved oxygen was completely depleted within 15 minutes of contact with distribution system piping. The application of 3 g Cl/m^3, followed by main flushing, reportedly alleviated the problem within three weeks.

The corrosion of iron during distribution is of special importance because the generation of ferrous ion results in the reduction of chlorine and chloramine residuals. With the loss of these bacteriostatic agents, both microbial growth and iron corrosion rates increase (Williams, 1953; Schneider and Stumm, 1964).

In 1964, Mulder reviewed the behavior of slime-forming bacteria and summarized information on the isolation, cultivation and ecology of iron bacteria. Miller and Litsky (1976) classified bacteria found in natural waters and distribution systems as sheathed higher bacteria, stalk or caulobacteria, the spiral forms, the pigmented and non-pigmented rods, the cocci, the nitrogen-fixing and nitrifying bacteria. Touvinen (1980, 1982) recovered a wide range of organisms from tubercles in the Columbus, Ohio, distribution system. These included sulfate reducers, nitrate reducers, nitrite oxidizers, ammonium ion oxidizers, sulfur oxidizers as well as various unidentified heterotrophic microorganisms. By this time, it was clear that distribution systems routinely serve as hosts to an exceptionally large and diverse population of microorganisms.

The Concept of Microbial Ecology in Distribution Systems

Confirming and extending the work of Baylis (1922), Wilson (1945) suggested that bacteria originating in source waters penetrated treatment facilities and, thereafter, became attached to pipe walls. Microbial colonization resulted in the formation of surface slimes and, ultimately, in the formation of encrusting tubercles. Because of extensive microbial growth on pipe surfaces and within tubercles, he concluded that it would be impossible to accurately enumerate all the bacteria present in the distribution system.

Wilson was among the first to articulate the concept of microbial ecology within a drinking water distribution system. He suggested that the types and numbers of bacteria which develop in a water distribution system depend upon the ecological niches available. He also recognized that many organisms which are unable to flourish in a particular environment may survive in a dormant state for indefinite periods. Subsequently, with a change to a less inhibitory environment, the dormant organisms may again become active, particularly, in response to seasonal temperature changes. He suggested that different symbiotic microbial forms become active from season to season and place to place within a single water distribution system.

Wilson also contributed to the early understanding of the microbially-mediated transformation of iron, manganese, sulfur, carbon, nitrogen and phosphorus compounds by a mixed population of bacteria, fungi and protozoans. With respect to bacterial growth at distributed water temperature, he reported higher colony counts on plates incubated at 20°C than on plates incubated at 35°C.

Noting aesthetic concerns resulting from the formation of taste-and-odor-producing compounds during water distribution, Wilson cited *Beggiatoa, Thiobacillus, Crenothrix* and sulfate-reducing bacteria among those responsible for aesthetic degradation, corrosion of pipes and the production of tubercles.

Summary of Early Investigations of Microbial Growths in Water Systems

From the wide range of investigations conducted by early investigators, distribution system problems have long been associated with microbial growths. The changes investigated included:

- precipitation and agglomeration of iron and manganese precipitates,
- chemical changes resulting from the activity of nitrifying and heterotrophic organisms,
- tastes-and-odors originating from sulfate reduction or organic metabolites,
- biologically-mediated corrosion and tubercle formation,
- bacterial involvement in deposition and accumulation of materials on pipe walls and
- the reduction in flow rates due to tuberculation, slime growths and depositions on pipe walls.

By mid-century, the scientific underpinnings of the microbial processes leading to water quality deterioration had been clearly articulated. In addition, these early researchers identified both the organisms involved and the methods of control most commonly used today. Many articulated the need for maintaining a bacteriostatic disinfectant residual to control the adverse effects of microbial growths in distribution systems.

Part 2 of this four-part series will summarize studies directed at understanding and controlling tastes-and-odors as well as the assessing the role of microorganisms in the corrosion of distribution mains. It also summarizes studies directed at understanding the sources of microorganisms found within the distribution system and at consumers taps.

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