Water Quality Deterioration in Distribution Systems

Part 2: Microbial Processes in Distribution Mains

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

Summary:

Part 1 of this series summarized the early development of scientific understanding of the role of microorganisms in water distribution systems. The earliest concerns were for the transmission of disease by organisms which penetrated the distribution system. By mid-century, an understanding of need for the maintenance of a bacteriostatic disinfectant residual in the distribution system was well established.

Part 2 of this series deals with efforts to understand and control tastes-and-odors as well as 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.

Aesthetic Concerns: Tastes and Odors

Commonly, consumer dissatisfaction with water quality is expressed in terms of unpleasant taste-and-odor. The results of a comprehensive survey of taste-and-odor problems related to algal growths were reported by Lendall (1946). He proposed activated carbon treatment, breakpoint chlorination and chlorine dioxide as remedial measures.

The significance of algae and other interference organisms in water supplies was further detailed and illustrated in a series of reviews by Palmer and Tarzwell (1955) and Palmer (1960, 1961). In addition to algae of importance in water supplies, these reviews depicted iron bacteria and protozoans associated with water quality deterioration in distribution systems.

Reviews and studies suggesting possible taste-and-odor problems involving actinomycetes were reported by Waksman (1959), Silvey and Roach (1959, 1964) and Silvey (1963, 1966). Silvey and Roach (1959) concluded that both algae and actinomycetes were responsible for taste-and-odor problems in water supplies. Subsequently, Silvey and Roach (1964) reported increases in Gram negative organisms, confirming Baylis's earlier observations regarding the Baltimore water system (1930). While *Alcaligenes, Aerobacter* and *Pseudomonas* groups were found in water with little pollution, field data suggested that microbiotic cycles involving blue-green algae, actinomycetes and heterotrophic bacteria were responsible for the development of taste-and-odor-producing compounds in source waters.

Tastes-and-odors originating from sulfate reduction or organic metabolites were also reported (Mackenthun and Keup, 1970; Lin, 1976). A review of the literature on the sources of taste-and-odors in waters, including anthropogenic sources, was published by Lin (1976).

An extensive update of more recent studies, many of which relate to the identification and classification of the chemical and sensory nature of the taste-and-odor-producing compounds found in water, was published by AWWARF (1987).

Microorganisms Associated with Corrosion

As early as 1891, Garrett (Iverson, 1974) suggested the rate of lead corrosion might be influenced by the ammonium ion, nitrite and nitrate formed by bacterial action.

In 1910, Gaines (Iverson, 1974) postulated that the corrosion of iron in both soil and aqueous environments might be caused by sulfate-reducing, sulfur-oxidizing and iron bacteria since *Gallionella ferruginea* was isolated from corrosion products on a buried steel conduit. High concentrations of sulfur and organic matter were also noted. Gaines proposal of biologically-mediated corrosion was not accepted initially.

In 1923, von Wolzongen Kuhr (Iverson, 1974) reported that sulfate-reducing bacteria corroded iron in the absence of oxygen. Further evidence of anaerobic corrosion was presented by von Wolzongen Kuhr and Van der Vlugt (1938). They attributed the ‘graphitization’ of cast iron pipes to the activities of sulfate-reducing bacteria.

In the United States, confirmation of the role of anaerobic bacteria in the corrosion of iron pipes resulted from the studies of Hadley (1939), Pomeroy (1941) and Starkey and Wright (1945). In addition to sulfate-reducing bacteria, the researchers found large masses and encrustations of iron sulfides clogging cast iron pipe. Pomeroy (1945) also reported more rapid corrosion when iron pipe was exposed to oxygen-bearing water intermittently as opposed to constantly. This result implied that additional periods of anoxia accelerated corrosion of cast iron pipe.

Bunker (1939), Butline (1955) and Lewis (1965) isolated sulfate-reducing bacteria from tubercles. The latter two investigators enumerated 10^3 and 280 x 10^3 organisms per gram of tubercle, respectively. Lewis reported no detectable sulfate-reducing organisms in the water.

Sulfur bacteria range from complex filamentous *Beggiatoa* and *Thiothrix* species to the rod-shaped *Thiobacillus* species. Their involvement in sulfuric acid formation and corrosion of iron piping was reported by Booth et al.(1966).

Sources of Microorganisms Found in Water Distribution Systems

Aftergrowth: Contamination of Finished Water by Distribution System Piping

Early bacteriologists noted that organisms found in the distribution system reflected those present in the source waters (Alexander, 1944). Over the past half-century, confidence has grown in the ability of current water treatment processes to remove or inactivate organisms initially present in the source water. Increases in organism populations during distribution, as indicated by turbidity, coliform and heterotrophic plate count measurements, are now generally believed to result from the recruitment of organisms from colonized distribution system piping. The distribution system is generally believed to be contaminating the virtually organism-free, treated water.

Serious distribution system problems were detailed by Larson et al. (1960) in a paper describing remedial actions taken in the Hammond, Illinois, water system. The authors expressed confidence that *"treatment practices commonly employed can produce any quality of water that may be desired"* but lamented that *"a perfectly clear, soft and safe water entering the distribution system may be unrecognizable as such at the household tap"*.

Geldreich et al. (1972) concluded that *"once microorganisms enter the distribution system, they may be harbored in protective slime and sediments that develop in portions of the system"*. They reported that this population could be controlled by maintaining a residual chlorine level in the distribution system. A subsequent report by Geldreich et al. (1977) noted the *"potential for bacterial regrowth during warm water periods"* and recommended a systematic flushing program in addition to the maintenance of a chlorine residual. A third report reaffirmed earlier observations that *"whereas the water quality is excellent as it leaves the treatment plant, the consumer may be using tap water of considerably lower quality"* (Allen and Geldreich, 1985).

Despite finding relatively low surface populations of bacteria on distribution piping, Nagy and Olson (1985) concluded that *"a likely explanation for the similarity between microorganisms on pipe surfaces and in drinking waters is that detachment of microorganisms from the pipe surface and their re-entrainment into the passing water may account for the majority of bacteria in potable water"*.

Overall, biological growths ('biofilms') embedded in sediments or entrained in accumulations on the surface of distribution system piping have long been viewed as a major source of subsequent microbial contamination of treated waters (Baylis, 1930; APHA, 1930; Howard, 1940; Jewell, 1942; Olson and Ridgeway, 1981; McCoy and Olson, 1986.) As a result, remedial programs, such as flushing and chlorination, have primarily been directed at controlling attached growths on the internal surfaces of the distribution system.

Exogenous Dormancy

Microbiologists have hypothesized that a significant portion of the bacterial community in most aquatic environments are in exogenous dormancy - a state of neither activity nor death (Stevenson, 1978; Novitsky and Morita, 1978; Wright, 1978). Exogenous dormancy is defined as a condition in which development is delayed because of unfavorable chemical or physical conditions of the environment. It is an adaptation in which enzyme activity is minimal, thereby contributing to the survival of the organism. Starvation, for example, may cause bacteria to decrease in both size and activity. Release of the stress would permit normal development. Conceivably, disinfectants would have significantly less effect on dormant cells than on metabolically active cells whose enzyme systems are more susceptible to inactivation. Since bacteria attached to larger particles occupy a microenvironment higher in nutrient concentrations than the surrounding water, epibacteria are both more active (Wright, 1978; Hodson et al., 1981; Kirchman and Mitchell, 1982; Paerl and Merkel, 1982) as well as more susceptible to removal by the physical processes of a filtration plant.

If the exogenous dormancy hypothesis is correct, the numerous source water planktonic cells which penetrate filtration plants may be the very cells which have survived disinfection owing to their low level of metabolic activity. Their slow recovery and growth rates on culture media may also cause them to tend to escape enumeration as heterotrophic plate count colonies.

As an example, previous studies on both *Legionella pneumophila* (Kuchta et al., 1985) and *Pseudomonas aeruginosa* (Carson et al., 1972) have demonstrated that slowly-growing cells cultured in tap water were far more resistant to inactivation by a disinfectant than rapidly-growing active cells cultured in a rich medium.

Recovery and Regrowth of Organisms Penetrating Treatment Facilities

'Aftergrowth' was the term used to describe microbial contamination of distributed water by organisms detached from the surface of distribution system piping or by other organisms external to the source water (Baylis, 1930). Where aftergrowth is the main source of cells reaching the consumer, treated water which may be virtually organism-free would exhibit increases in cell numbers during distribution as cells were recruited from pipe surfaces or entered from cross-connections. *Aftergrowth* may operationally be defined as *microbial contamination of distributed water during distribution by recruitment of organisms from internal pipe surfaces or cross–connections*.

In order to describe the concept and develop the rationale for more scientifically delineating the origin of organisms found in distributed drinking water, the term *'regrowth'* was defined (Brazos and O'Connor, 1987) to distinguish organisms whose growth had been arrested during treatment, but were capable of growing again in distributed waters *after chlorine dissipation and time for metabolic repair of the cells passing through the plant.*

The distinction between regrowth and aftergrowth should be of particular importance to water utilities seeking to monitor and mitigate microbial problems in distribution systems. Since regrowth involves the passage of source water organisms through the treatment plant, control of regrowth is achieved by consistently maintaining effective physical removal. This is accomplished, primarily, by ensuring the entrainment of source water organisms during floc formation and providing adequate time for floc growth and sedimentation (Brazos and O'Connor, 1990).

Alternately, since aftergrowth occurs within the distribution system, control measures must be directed toward arresting the microbial activity of the organisms present in the distribution system. Conventional methods for the control of aftergrowth, such as flushing, swabbing ('pigging'), main disinfection and periodic breakpoint chlorination, would be expected to have a limited effect on regrowth where significant numbers of planktonic organisms are constantly being passed into the system through the treatment plant.

Part 3 of this four-part series will summarize studies directed at controlling microbial growths in distribution systems supplied by ground waters containing ferrous ion and naturally-occurring microbial nutrients, such as methane and ammonium ion.

References

Alexander, L.J. (1944) "Control of Iron and Sulfur Organisms by Superchlorination and Dechlorination: Experiences and Conclusions since 1940," J. AWWA 36:1349.

Allen, M.J. and E.E. Geldreich (1985) “Distribution Line Sediments and Bacterial Regrowth,” Proc. AWWA WQTC.

APHA Committee on Water Supply (1930) "Bacterial Aftergrowth on Water Distribution Systems" Am. J. Public Health 20:485.

AWWA Research Foundation (1987) Identification and Treatment of Tastes and Odors in Drinking Water.

Baylis, J.R. (1930) "Bacterial Aftergrowths in Water Distribution Systems," Water Works and Sewage 77:335.

Booth, G.H., P.M. Cooper and G.S. Wakerley (!966) “Corrosion of Mild Steel by Actively Growing Cultures of Sulphate-Reducing Bacteria,” Brit. Corrosion J. !:345

Brazos, B.J. and J. T. O'Connor (1987) "Relative Contributions of Regrowth and Aftergrowth to the Number of Bacteria in a Drinking Water Distribution System," Proc. AWWA WQTC, 433-467

Brazos, B.J., and J. T. O'Connor (1990) "Seasonal Effects on the Generation of Particle-Associated Bacteria during Distribution," ASCE, Journal of Environmental Engineering 122:12.

Bunker, H.J. (1939) “Microbiological Experiments in Anaerobic Corrosion,” J. Soc. Chem Ind. 58:93.

Butline, K.R., M.E. Adams and M. Thomas (1955) “Sulfate-Reducing Bacteria and Internal Corrosion of Ferrous Pipe Conveying Water,” Nature 163:26.

Carson, L.A., M.S Favero, W.W. Bond,., and N.J. Petersen (1972) "Factors Affecting Comparative Resistance of Naturally Occurring and Subcultured Pseudomonas aeruginosa to Disinfectants" Appl. Microbiol. 23:863.

Gaines, R.H. (1910) J. Eng Ind. Chem. 2:128. (cited by Iverson, W.P. (1974) “Microbial Corrosion of Iron,” Microbial Iron Metabolism, Academic Press.)

Geldreich, E.E., H.D. Nash, D.J. Reasoner and R.H. Taylor (1972) “The Necessity of Controlling Bacterial Populations in Potable Waters: Community Water Supplies,” J. AWWA 64:596.

Geldreich, E.E., H.D Nash and D. Spino. (1977) "Characterizing Bacterial Populations in Treated Water Supplies: A Progress Report" Proc. AWWA WQTC.

Hadley (1939)

Hodson, R.E., A.E Maccubbin and L.R Pomeroy (1981) "Adenosine Triphosphate Utilization by Free-Living and Attached Bacterioplankton," Mar. Biol. 64:43.

Howard, N.J. (1940) “Bacterial Depreciation of Water Quality in Distribution Systems,” J. AWWA 32:1501

Iverson, W.P. (1974) “Microbial Corrosion of Iron,” Microbial Iron Metabolism, Academic Press

Jewell, A. B. (1942) "Bacterial After-Growths in the Distribution System," Southwest Water Works J. 23:13.

Kirchman, D. and R. Mitchell (1982) "Contribution of Particle–Bound Bacteria to Total Microheterotrophic Activity in Five Ponds and Two Marshes," Appl. Environ. Microbiol. 43:200–209.

Kuchta, J.M., S.J. States, J.E. McGlaughlin, J.H. Overmeyer, R.M. Wadowsky, A.M. McNamara, R.S. Wolford and R.B. Yee (1985) "Enhanced Chlorine Resistance of Tap Water Adapted Legionella pneumophila as Compared with Agar Medium–Passed Strains," Appl. Environ. Microbiol.

Larson, T.E., J. C. Guillou and L.M. Henley (1960) "Circulation of Water in the Hammond Distribution System," J. AWWA 52:1059.

Lendall, H.N. (1946) "Comprehensive Survey of Taste and Odor Problems," Water Works Engr. 99:1237.

Lewis (1965)

Lin, S.D. (1976) "Sources of Tastes and Odors in Water: Parts I & II" Water and Sewage Works 121:101:122:64.

Mackenthun, K.M., and L.E. Keup (1970) "Biological Problems Encountered in Water Supplies," J. AWWA 62:520 .

McCoy, W.F. and B.H. Olson (1986) "Relationship Among Turbidity, Particle Counts and Bacteriological Quality Within Water Distribution Lines," Water Research 20:1023.

Nagy, L.A. and B.H. Olson (1985) “Occurrence and Significance of Bacteria, Fungi and Yeasts associated with Distribution Pipe Surfaces,” Proc. AWWA WQTC.

Novitsky, J. A., and R.Y. Morita (1978), "Possible Strategy for the Survival of Marine Bacteria under Starvation Conditions" Mar. Biol, 48:289.

Olson, B.H. and H.F. Ridgeway (1981) "Bacterial Colonization of Mortar-Lined and Galvanized Iron Water Distribution Mains," Proc. AWWA Ann. Conf.

Paerl, H.W. and S.M. Merkel (1982) "Differential Phosphorous Assimilation in Attached vs. Unattached Microorganisms," Arch. Hydrobiol. 93:125.

Palmer, C.M. and C.M. Tarzwell (1955) "Algae of Importance in Water Supplies," Public Works 86:107.

Palmer, C.M (1960) "Algae and Other Interference Organisms in Waters of South Central United States," J. AWWA 52:897.

Palmer, C.M. (1961) "Algae and Other Interference Organisms in Water Supplies in California," J. AWWA 53:1297.

Pomeroy, R. (1941) “Corrosion of Iron by Sulfides,” California Sewage Works J. 13:31.

Pomeroy, R. (1945) “Corrosion of Iron by Sulfides,” Water Works and Sewerage 92:133.

Silvey, J.K.G. (1963) "The Relationship between Aquatic Organisms and Tastes-and-Odors,” Public Works: 94:106

Silvey, J.K.G. (1966) "Taste-and-Odor Effect of Organisms," J. AWWA 58:706.

Silvey, J.K.G. and A.W. Roach, (1959) "Laboratory Culture of Taste-and-Odor-Producing Aquatic Actinomycetes," J. AWWA 51:20.

Silvey, J.K.G. and A.W. Roach (1964) "Studies on Microbiotic Cycles in Surface Waters," J. AWWA 56:60.

Starkey, R.L., (1945) "Transformation of Iron by Bacteria in Water," J. AWWA 37:963.

Starkey, R.L. and K.M. Wright (1945) “Anaerobic Corrosion of Iron in Soils,” Amer. Gas Assn., New York

Stevenson, L.H. (1978) "A Case for Bacterial Dormancy in Aquatic Systems" Microbial Ecology 4:127.

von Wolzongen Kuhr, C.A.H. (1923) Water 7:277 (cited by Iverson, W.P. (1974) “Microbial Corrosion of Iron,” Microbial Iron Metabolism, Academic Press.)

von Wolzongen Kuhr, C.A.H. (1938) Water 22:33 (cited by Van der Vlugt (1961) “Unity of Anaerobic and Aerobic Iron Corrosion Process in the Soil,” Corrosion 17:294.)

Waksman, S.A. (1959) Actinomycetes; Nature, Occurrence and Activities, Williams and Wilkins Co., Baltimore, MD.

Wright, R.T. (1978) "Measurement and Significance of Specific Activity in the Heterotrophic Bacteria of Natural Waters" Appl. Environ. Microbiol. 36:297.