Water Quality Deterioration in Distribution Systems
Part 4: Microbially-Mediated Deterioration in Surface Water Supplies

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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 firmly established.

Part 2 dealt with efforts to understand and control tastes-and-odors as well as the role of microorganisms in the corrosion of distribution mains. It also summarized studies directed at understanding the sources of microorganisms found within the distribution system.

Part 3 summarized 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.

The final part in this series evaluates studies of microbial growths in distribution systems supplied by surface waters. Surface water supplies are subject to sporadic variations in microbial water quality resulting from rainfall and runoff as well as seasonal variations due to temperature. Low influent water temperatures may significantly impair the effectiveness of removal and inactivation of microbial pathogens.

Seasonal Temperature Effects

While temperature is acknowledged to be an important factor in water treatment, remarkably little study has been made of the adverse influence of low temperatures on physical treatment process effectiveness. An early study concluded that *"there is no preventative or retarding effect on alum floc formation with low raw water temperatures"* (Leipold, 1934).

This conclusion prompted Camp et al. (1940) to further evaluate the effect of temperature on the rate of floc formation. Camp utilized the direct measurement of iron or aluminum in lieu of turbidity. He concluded that temperature did not have a measurable effect on the *time* of floc formation.

However, pilot plant studies of aluminum sulfate-coagulated river water demonstrated the overall adverse effect of low temperatures on sedimentation and filtration (Hannah et al.,1967). These researchers advised that, *"where raw water temperature is low, the jar tests must be run on samples held at the same temperature, if results are to be used in plant control"*.

It was not until 1984 that a systematic evaluation of the adverse effects of low temperature on water treatment plant performance was undertaken (Morris and Knocke, 1984). The investigators reported significant temperature effects on coagulation which accounted for observed decreases in *turbidity removal efficiency*, particularly when aluminum sulfate was used. Using decreases in alkalinity and measurements of the metal coagulant in solution, the researchers determined that the reduction in turbidity removal efficiency was not due to reduced metal hydroxide precipitation rate, but to retardation of the floc growth. Under equivalent conditions, iron salts produced larger flocs than aluminum salts and

resulted in lower residual turbidity values. The implications of these results became more significant in light of observed major temperature effects on *organism removals* (Brazos et al., 1987).

While low water temperatures have been shown to severely impair microorganism removals by physical water treatment processes (Brazos et al., 1987-1990, 1996), microbiological violations due to coliform or heterotrophic plate count organisms were found to be most commonly reported by U. S. water utilities during summer months (O'Connor and Brazos, 1992). Alternately, for 14 of the 21 large water distribution systems studied, summer was the season when finished water turbidities were lowest. In most systems *'percent positive total coliform samples'* and *turbidity* were either unrelated or inversely related. More significantly, based on five years of water utility data, those water utilities employing chloramine as a residual recovered 8.6 times *fewer* positive total coliform samples than those using chlorine.

While these observations are seemingly inconsistent, it would appear that the penetration of increased numbers of organisms into the distribution system in winter is not evidenced by distribution sampling for total coliform because their influx is not accompanied by the subsequent regrowth that is experienced in the summer. These water utility data further indicate the need to directly monitor the total number of microorganisms entering a distribution system throughout the year so that appropriate remedial actions can be taken (O'Connor and Brazos, 1990).

Bactericidal or Bacteriostatic Disinfectant Residuals in Distribution Systems

Microscopic total bacterial cell counts (total bacteria) in both surface water sources and water distribution systems may exceed HPC colony counts by several orders of magnitude (O'Connor et al., 1984, 1985). Are these cells, in fact, alive? In defining bacterial death, Mason, Hamer and Bryers (1986) have suggested that a *"likely scenario is that cell lysis and cell death are synonymous such that the cell dies as a result of lysis"*. By this definition, all cells enumerated by direct microscopic count in the distribution system would be classed as *"alive"*.

The exact mechanism for the destruction of bacteria with chloramine is still under study. However, the observation that the cells do not die or lyse following chloramination but are able to recover and multiply would indicate that low levels of chloramine may be bacteriostatic rather than bactericidal. This observation would support the theory that chloramine affects respiratory enzymes associated with the cell membrane (Venkobaschar et al., 1977) and causes little or no damage to nucleic acids.

Exogenously dormant bacteria have little enzymatic activity to be affected by chloramine. Those cells that have been lethally injured do not lyse since chloramine has reversibly inhibited the autolytic enzymes associated with the cell wall. Alternately, it has been shown that free chlorine (hypochlorous acid) caused a 50 percent reduction in total bacteria during distribution (Maki et al., 1986). These two observations partly explain the difference in the bactericidal activity between the disinfectant species.

Following disinfection, of the total population of organisms entering the distribution system, some have been irreversibly inactivated (killed), some are injured or exogenously dormant and some, which are disinfectant-tolerant, are still active. However, since organisms which are more metabolically active prior to the addition of disinfectant are more readily killed than inactive cells, there are few active, culturable cells in the treated water.

Generation Times

Data on the generation times for both HPC and total bacteria following dechlorination (Brazos et al., 1985) add information to the limited data on growth rates of HPC (Frankland and Frankland, 1894; Whipple, 1901; Ellison et al., 1932; Baylis, 1938; Castel and McDermott, 1941) and of specific genera of bacteria (Van der Kooij and Hijnen, 1985; Van der Kooij et al., 1982, 1980) in drinking water. In addition, they provide insight into the effect of treatment processes on the generation (doubling) times of bacteria entering the distribution system.

Studies have shown that reductions in the initial populations of bacteria by filtration or centrifugation result in increased generation times (Butterfield, 1933; Potter, 1960). By reducing the initial population of cells, the physical removal processes of drinking water treatment may be constantly selecting for increased generation times of bacteria in the distributed water. However, the growth curves of bacteria following dechlorination closely resemble those of bacteria in lake and river water (Butterfield, 1933; ZoBell and Stadler, 1940; Taylor and Collins, 1949). The rapid changes in the bacterial populations that occur after confinement were investigated by Ferguson et al. (1984).

Case Studies of Contributions of Periphytic Bacteria to Aftergrowth

Columbia, Missouri

Far less is known about the numbers of bacteria colonizing pipe surfaces. Qualitative observations by electron microscopy have shown colonization of pipe surfaces (Allen et al., 1980; Ridgeway et al., 1981; Ridgeway and Olson, 1981). Studies characterizing the bacterial content of tubercles have been reported (Baylis, 1926; Olsen and Szybalski,1949; Tuovinen and Hsu, 1982; Tuovinen et al., 1980). However, until 1988, only two studies had attempted to quantitate the population per unit surface area (Nagy and Olson, 1985; Le Chevallier et al., 1987). Based on those results, 10^3 colony forming units/cm^2 appeared to be a representative value for HPC.

Using that value for HPC and the Columbia, Missouri water system as a case study source of basic data since the total distribution system volume (60,000 m^3) and internal pipe surface area (4.8×10^5 m^2) were known, the periphytic HPC population in the water system was calculated as 4.8×10^{12} cfu (Brazos et al., 1985). Assuming that all of the attached bacteria were released simultaneously into the water stored in the distribution system, this would result in an average increase in HPC of only 80 cfu/ml. This rate of detachment would correspond to a 48 hour generation time since the calculated retention time of stored water in the Columbia system was two days.

Representative generation times of periphytic bacteria in fresh waters are strongly affected by temperature and range from 42 to 51 hours at temperatures from 0 to 5°C to 3 to 6 hours at temperatures from 15 to 22°C (Bott, 1975). Considering the adverse conditions in distribution systems due to the presence of a disinfectant, generation times would be expected to be notably slower than those observed in natural fresh waters (Bott and Brock, 1970; Bott, 1975; Hossell and Baker, 1979).

Finally, if it were assumed that periphytic bacterial generation times ranged from 12 hours in the summer to 48 hours in the winter, calculated steady-state average increases in HPC values would vary from a high of 320 cfu/ml under summer conditions to a low of 80 cfu/ml in the winter. Since such high values were not observed, these calculations imply a minimal contribution to the distributed water from periphytic aftergrowth in the Columbia, Missouri, distribution system.

Philadelphia, Pennsylvania

Alternately, a study of the Philadelphia (Pennsylvania) Suburban Water Company (PSWC) by Donlan and Pipes (1988) provided an example of a distribution system experiencing aftergrowth. HPC populations which developed on cast iron test specimens suspended in PSWC water mains were measured and related to the distribution system (planktonic) HPC values. No statistically significant relationships were found between HPC attached to the cast iron specimens and measured water quality parameters, including total organic carbon, ammonium ion, phosphate and pH. However, temperature was found to have a major influence.

Both the attached and distribution system (planktonic) HPC were most abundant at higher temperatures. The density of HPC organisms attached to the cast iron test specimens ranged from 10^2 cfu/cm^2 at 5°C to

3.7×10^7 cfu/cm^2 at 23°C. The highest reported values were 10^4 times those previously reported (Nagy and Olson, 1985; LeChevallier, 1987). They also corresponded to high planktonic HPC in the distribution system. Direct microscopic cell counts, made of the bacteria scraped from some of the cast iron specimens, were 3 to 134 times greater than the HPC enumerated.

In the PSWC distribution system, HPC increased markedly as water temperatures rose. Increased water temperatures also led to the more rapid depletion of chloramine. HPC was highest (8,318 cfu/ml) at *Cheltenham* where the chloramine residual was almost totally depleted. Alternately, at *Secane*, where chloramine was maintained at 1.31 g Cl/m^3, only 10 cfu per millilitre were observed at 24°C.

Jefferson City, Missouri

Although the 35°C standard pour plate counts made in the Jefferson City, Missouri, distribution system are not directly comparable to the 20°C spread plate counts measured in the PSWC system, it is evident that the smaller Jefferson City distribution system exhibited far lower and more uniform HPC populations throughout the year (Brazos and O'Connor, 1987). The most significant difference between the Jefferson City and Philadelphia data was the effect of seasonal temperature change on the HPC. In the Jefferson City distribution system, HPC *decreased* as temperature increased, probably reflecting the significantly increased total bacterial removals at the Jefferson City water treatment plant.

The results of the Jefferson City distribution system evaluation indicated that the HPC bacterial populations found throughout the distribution system remained close to the numbers (≈30 cfu/ml) discharged from the plant clear well. Chloramine residuals were maintained with little depletion during distribution while initially low finished water turbidities remained relatively unchanged. HPC declined at near-plant locations and increased slightly at remote locations.

From microscopic count, the Jefferson City study also showed that, seasonally, large numbers (10^4 to 10^6 cells/ml) of planktonic bacteria from the raw water passed through a well-operated, multi-stage, lime softening, rapid sand filtration plant meeting existing microbiological standards. The number of bacterial cells which passed through the plant correlated strongly with the number found throughout the distribution system.

These results suggest that, in a distribution system where a bacteriostatic disinfectant residuals can be maintained throughout the year, HPC and bacterial cell count may vary primarily with the efficiency of total bacterial removal during treatment so that little aftergrowth will be observed. Conversely, where the disinfectant residual is depleted, aftergrowth will add significantly to the total microbial population observed in the distribution system.

Biologically Stable Water

From these results, there appear to be three methods which might be applied to the control of bacteria in the distribution system. First, an attempt may be made to treat water to remove nutrients thereby producing a *"biologically stable water"*, defined as a water which does not support microbial growth. Second, a bacteriostatic disinfectant residual may be maintained at all points in the distribution system, including household plumbing. Third, the number of bacteria entering the distribution system may be reduced by effective physical removal to levels which minimize the penetration of organisms which undergo regrowth.

Ideally, the production of a 'biologically stable' water which would preclude subsequent growth would be desirable. However, the cost of producing such a water, perhaps superior to distilled water, could be prohibitive. Alternately, the maintenance of a bacteriostatic residual is reasonably effective and practical. However, not all water utilities may be able to maintain an effective residual at all points, particularly, in a large distribution system.

Perhaps most important from the standpoint of protection of public health, the optimization of treatment plant performance for physical bacterial removal would readily reduce the number of bacteria penetrating and propagating through the distribution system. Based on microscopic observations relative to bacterial removals, other, larger organisms of concern would be removed with still greater efficiency (Brazos and O'Connor, 1996).

The complete text of this four-part series can be obtained at www.h2oc.com*. Comments and questions may be directed to* tom@h2oc.com

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