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Biofouling

in Raw Water Supply Wells and Its Impact

Many coastal water utilities across the United States are striving to find additional sources of water to meet the demands of burgeoning populations and have limited freshwater availability. In many cases, this freshwater is threatened by saltwater intrusion from development that has reduced historical aquifer heads. Surficial aquifer sources also may have water quality concerns caused by a high organic content and the potential for pollution. This is especially problematic in coastal Florida.

In order to meet drinking water standards, many utilities have pursued membrane processes for organic and hardness removal. The finished water quality of membrane softened water (nanofiltration) is significantly better than the quality of water from more traditional lime softening treatment processes. Comparisons of recent bids have indicated that the construction costs for membrane systems have reduced substantially, while more traditional treatment costs have increased to meet drinking water regulations. However, as the membrane systems have become operational, it has become clear that more care needs to be taken in well construction and in the review of microbiological contaminants.

Raw Water Quality Concerns

For years, US EPA and other agencies have been concerned with contamination of water supplies by industrial users or commercial carrier accidents. Extensive efforts are ongoing to protect watersheds and provide for wellfield protection zones. As a result of findings concerning well contamination and the introduction of pathogenic bacteria in watersheds over the past 40 years, engineers and scientists have found that better raw water quality contributes to less expensive, better quality finished water.

Other investigations have indicated that while many wellfields may not be threatened by chemical contaminants, other concerns exist. For example, plugging and fouling problems occur. These plugging and fouling problems are caused by a number of hydrogeologic, geologic, engineering and construction related factors including the following.

- **Hydrogeologic constraints** that are unassessed at the time of design and/or change over time. For example, sand, clay or rock layers that are unstable and collapse into the well bores; naturally occurring and/or man-made fracturing/faulting; long term water quality changes caused by changes to the hydraulic regime such as dams; water hammer to the aquifer/formation; man-induced influences (mining the aquifer, introduction of chemicals and/or microorganisms); and naturally occurring phenomena (sinkholes, karst terrain features and/or faulting).
- **Poor well design and/or construction practices** including insufficient placement of grout, improper design of pumps, valves and fittings; and excessive drawdown allowances.
- **Poor operating and/or maintenance procedures.**
- **Mechanical failures** including failures of electrical motors, pumps and valves.
- **High silt or sand content** caused by failure to develop the wells fully, or interfingered sand or silt layers that have not or cannot be sealed off from the borehole or corrected in well design.
- **Microbiological fouling problems.**

Many coastal water utilities across the United States are striving to find additional sources of water to meet the demands of populations and have limited fresh water availability.
Photo courtesy of South Florida Water Management District.

Despite the number of systems using wells, the focus of operations personnel is more on the mechanical and electric failures that routinely plague operations than on root causes of long-term deterioration.
Photo courtesy of South Florida Water Management District.

The first five contribute to sand, silt and other physical deterioration in the wells and the downstream treatment system. In developing water sources for membrane processes, engineers typically have been concerned with the ability of membranes to remove impurities such as organics and hardness with concerns about the levels of iron, sand and silt in the raw water. ASTM has developed standards for conducting water quality analyses for reverse osmosis applications (ASTM D4195-88) and for measuring the silt density index (SDI) of the raw water (ASTM D4189-94). AWWA also has developed a 5 mg/L standard for sand content during new well development.

The issue with iron is the potential for the iron to deposit on the membrane surface. Generally, this level must be kept below 1 mg/L. Sand and silt are clogging agents that impair pretreatment processes as well as damage membranes via clogging and physical surface damage (e.g., perforations). Membrane designs have considered these problems and have specified lesser sand and silt contents than required by AWWA standards (Missimer). However, few designs have recognized the potential for microbiological fouling problems. All of the problems mentioned may contribute toward or be early signs that biofouling is a concern. As a result, the operation/start-up of the plant often is complicated with microbiological fouling problems.

Microbiological Issues

In stark contrast to public perception that aquifers are "pristine" environments, bacteria exist naturally in many aquifer systems. Almost any aquifer with an organic content will have some degree of bacteriological activity. The typical agents for microbiological fouling include iron, sulfur-reducing and slime producing organisms, although many others exist. An additional concern is that some of these organisms are opportunistic pathogens.

Iron bacteria such as *Gallionella* are common in aerobic environments where iron and oxygen are present in the groundwater and where ferrous materials exist in the formation (e.g., steel or cast iron wells). These bacteria attach themselves to the steel and create differentially charged points on the surface, which in turn create cathodic corrosion problems. The iron bacteria then metabolize the iron that is solublized in the process. Iron bacteria tend to be rust colored or cause rust colored colonies on the pipe surfaces.

Sulfur reducing bacteria often are responsible for the hydrogen sulfide smell released when raw water is aerated. These bacteria are common where sulfur naturally exists in the formation, and will tend to form black colonies on pipe surfaces. While anaerobic, they will exist in environments where aerobic conditions that can lead to symbiotic relationships with aerobic organisms exist.

Slime producing bacteria are found in surface waters and in soil. Members of this genre often are used to protect farm crops from fungal growth, and as a result are to be expected in groundwater that has organics. However, these bacteria are highly adaptive. Research several years ago indicated that the bacteria would grow in any environment into which they were introduced. The *Pseudomonas genera* are facultative anaerobes that can persist in oxygen depleted environments by breaking down complex hydrocarbons for the oxygen. In some circumstances, they will use nitrogen in the absence of oxygen.

Pseudomonas bacteria can permanently affix themselves to laser-polished 316L stainless steel in a matter of hours, so attaching to steel or lower grades of stainless steel is easily accomplished. Given that the *Pseudomonas sp.* are adhering bacteria, they are capable of producing a polysaccharide matrix (biofilm) that can act as a barrier protecting the bacteria incorporated in the films from harmful substances such as disinfectants and, in some cases, oxygen. Biofilms also act to protect the bacteria from the shearing effect of turbulent flow, and can provide an environment for other species. Periodic sloughing occurs when the biofilm gets too thick.

The microbiological accumulations/biofilms pose several significant concerns. First, the accumulations on the metallic surfaces create anodes and, in conjunction with reactions caused by dissimilar metals, can lead to a steady cathodic deterioration over time (with or without iron bacteria). Since the *Pseudomonads* are acid formers, ferrous materials are particularly vulnerable to deterioration, especially in the presence of iron bacteria.

The sloughing events pose a significant fouling concern for both the membrane softening and reverse osmosis membranes and could lead to some breaching of the membranes by the bacteria, whereby the bacteria could subsequently enter the distribution system. Because of the size of the openings in the membranes, it has been assumed that the membranes will filter out the bacteria, but the seals in the system may allow some leakage, allowing the permeate to be exposed to the raw water.

The accumulation of bacteria in the concentrate causes concern from the standpoint of a point source discharge, as well as the potential for severe corrosion caused by concentration of inorganic salts and organic acids caused by the bacteria. The corrosion of the steel pipe at lime softening plants also could be partially attributed to the bacteria being brought in with the raw water.

Analysis of treatment processes indicates that lime softening does a relatively good job at removing the bacteria because of the mixing of lime and raw water that occurs and the "sticky" constituency of the bacteria. However, the proposed membrane softening process would not be as effective in the removal of the bacteria.

How to See If You Have the Problem

Routine monitoring of background bacteria, especially iron and slime-producing species, should be performed by all utilities, whether water is obtained from a groundwater source or a surface water source. Raw water samples must be collected and analyzed to determine the speciation of bacteria, fungi and other organisms. This cannot be done by simply using BART or other tests (although they can provide a preliminary indication of species of concern being present); it must be done in a microbiological lab. The samples should be collected using one gallon sterilized plastic bottles. The wells should be shut down for several days. The sample tap must be sterilized in a manner similar to distribution system samples, since many of the organisms are common on the hands of people. The wells then should be turned on and samples collected. The samples must be placed on ice and sent to a laboratory within four hours of sampling.

Sampling protocol is important. If samples are collected from wells that have been running, the samples will be less representative of the bacterial matrix because of the potential for not obtaining a sloughing event.

Once delivered to the microbiological lab, the samples are analyzed for heterotrophic bacteria plate count, fecal and nonfecal coliform bacteria plate count and identification of species and algae. The standard industry practice for water distribution systems is that the presence of coliform bacteria is an indicator of a sanitary hazard. However, this ignores other bacteria that are known pathogens, and also are extremely detrimental to functions of the membrane process.

If undesirable bacteria are found in the wells, distribution system sampling should occur to provide some comfort that the problem has not moved beyond the plant itself. The presence or relative absence of microorganisms should determine the frequency of testing, but utilities must monitor this problem.

If You Have It, Then What?

All parties must understand that as utilities move toward more advanced treatment methods, more knowledge must be gained about the quality of the raw water. Where bacteria exist, nonferrous materials should be used for the wells and the raw water lines where possible. If ferrous materials are used, it is vital that dissimilar metal conditions not exist, as these will encourage fouling or lead to deterioration due to cathodic reactions, and may encourage biological growth.

It is recommended that utilities that are in the process of designing or constructing new production wells or plants study the raw water quality, potential plugging and fouling problems, and the geologic formations prior to completing design and construction of the new facility. Test wells should be checked for microorganisms and colloidal, sand and silt production. Use of sand separators, well disinfection programs and conversion of well construction materials from ferrous products to polyvinyl chloride (PVC), fiberglass and bronze must be factored into the life-cycle cost of the treatment process and the capital program. The need to make major modifications to the wellfield often is overlooked in the life-cycle cost of a new membrane facility.

Choosing the correct materials in the design of the plants, wells and pipelines is essential to save considerable maintenance costs in the future. Careful start-up of new facilities and the acknowledgment (and investigation) of the potential for biofouling will help engineers avoid the traditional startup fouling problems encountered by many membrane facilities in the past.

If changes to the wells cannot be made, you can change the plant design or attend to the bacteria problem in-situ. Changing the design may be the less expensive option, but will come with a time and treatment quality penalty. In-situ treatment may be the next best option. Treatment is routinely conducted using high concentrations of acid and chlorine, with the intent to shock the bacteria, by causing rapid changes in their environment via pH changes and oxidants. High concentrations of acid, in conjunction with high chlorine concentrations (up to 6,000 mg/L), have been found to be effective, but the heat generated limits the applicability to non-ferrous wells. A review of the cement grout also should be undertaken.

Other treatment methods have included lining wells (with lesser disinfection frequency), hydrogen peroxide (in some circumstances) and variations of the pH adjustment. They all have met with varying degrees of success in controlling microbiological growth. Oxygenated compounds should be used with caution given the ability of the bacteria to metabolize the oxygen from the chemical compounds.

City of Hollywood

A 30 mgd membrane treatment plant recently was constructed for the City of Hollywood (Fla.) to house 16 mgd of softening membranes to treat Biscayne aquifer water (currently 14 mgd is installed), and 14 mgd of reverse osmosis membranes to treat the brackish raw water from the Floridan Aquifer System (4.0 mgd of reverse osmosis membranes currently are installed). These processes exist on the same site as the City's mgd lime softening facility that uses Spiractor treatment units (with a sand catalyst) to treat relatively good quality Biscayne water for many years. All three processes are combined onsite to produce high quality water.

The Biscayne Aquifer is significantly affected by rainfall. In addition, at one time, most of the surface was covered with the Everglades, so significant quantities of organics are found. As a result, it should be no surprise that the City's raw water and wells contain aerobic iron bacteria, anaerobic sulfur-reducing bacteria and slime producing bacteria that cause substantial damage to well equipment and column pipes, necessitating frequent maintenance. The environment within the aquifer causes these bacteria to be extremely aggressive toward iron pipe, including Type 304 and Type 316L stainless steel. The City first noticed severe corrosion problems in its wells during the 1995 expansion of its water treatment plant. Because the lime softening reactions do a good job at removing the bacterial colonies, this was not an issue that the operations staff had focused on previously.

Additional damage was noted during investigations of the older iron well casings, pipes, pump bodies and fittings. In addition, iron bacteria staining and pitting were found on the stainless steel piping used for the raw water line on the plant site and for the membrane intakes. Testing of the cartridge filters showed effects from the bacteria in the City's wells.

Thus, the City has embarked on a program to minimize the impact of the bacteria. The City first initiated a program to treat all the wells with acid and 6,000 mg/L of chlorine. It was determined that growth in the existing wells would occur within 90 days, so oxygen treatment was necessary. The program went on to include new material specifications, pump changeouts, disinfection of the wells, replacement of iron-based parts, sliplining, abandonment and drilling of new wells. Several fiberglass column pipes were installed to correct corrosion problems. While no observable damage was evident to the fiberglass, these column pipes showed a bright orange slime layer when withdrawn from the wells after several years. The City found that the orange slime was caused by an iron bacterial growth, with the consistent presence of *Pseudomonas sp.*

Collier County

In 1990, the Collier County Water-Sewer District decided to proceed with the design of a 12 mgd membrane softening (nanofiltration) facility located five miles north of its existing 12 mgd lime softening plant. Finished water from the two plants was proposed to be manifolded together prior to entering the distribution system. Both treatment plants were to use the same wellfield (a Lower Tamiami aquifer wellfield that had served the utility system for over ten years). The production zone is a semi-confined zone between 60 and 140 feet. Except for the first five wells, all wells were of polyvinyl chloride (PVC) construction with bronze pumps and stainless steel column pipes. However, severe deterioration of the stainless steel column pipes installed in the late 1980s indicated the presence of a significant quantities of *Pseudomonas*, iron and sulfur-reducing bacteria. A wellfield disinfection program was initiated in 1990.

Toward the end of the construction of the membrane water treatment plant, the disinfection program was discontinued for nine months. The operation staff immediately found that the failure to treat the problem at the wells resulted in a significant quantity of bacteria being passed into the membrane units, causing a fouling problem. Extensive cleaning of the membranes with a bisulfite, citric acid and hydrogen peroxide was required to restore membrane efficiency in the County's plant. The use of these strong chemicals is not desirable in a new membrane facility. New membranes are expected to have a life of five to seven years and the facility is expected to have a life in excess of 30 years. The cleaning process may cause damage to the membranes and reduce the life of the membranes and/or the plant.

Conclusions

Plugging and biofouling problems in wells are prevalent throughout South Florida and other areas of the country. Unfortunately, despite the number of systems utilizing wells, the focus of operations personnel is more on the mechanical and electrical failures that routinely plague operators than on root causes of long-term deterioration such as colloidal, silt, sand, pump and well design and installation and biofouling.

Conclusions from the case studies are that long-term microbiological problems may go unnoticed, undiagnosed or improperly diagnosed. Cathodic reactions from dissimilar metals pose significant risk to the long-term maintenance of the wellfield and may be enhanced and exacerbated by microbiological action. A complete investigation and proper analysis of the raw water supply including silt, sand and microbiological analyses are required prior to design of membrane processes.

Geologic problems can go unnoticed during the initial startup of the wells. However, geologic problems, sand, silt or microbiological clogging of a gravel pack (or open hole) are significant issues that are generally ignored by design engineers, construction engineers and contractors, leaving the operations staff with a problem shortly after start-up of the facility.

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