CASE HISTORY

Copper Pipe Failure by Microbiologically Influenced Corrosion

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After a detailed investigation on the failure of copper water service pipes in a water distribution system, microbiologically influenced corrosion (MIC) was found to be the cause. Increased system disinfection appears to have remedied the problem. MIC is often overlooked in corrosion investigations of drinking water systems. This case history is a good example of telltale signs of MIC and the water environments in which this can occur.

Thirty copper water service failures occurred between 1998 and 2003 in the distribution system of the Brown Deer Water Utility (Brown Deer, Wisconsin). The pipes failed by pinhole leaks that developed as pits from the interior of the pipe and eventually broke through to the exterior. The first pipe leak was discovered in November 1998 from a complaint of a continuously running sump pump. This began a series of pipe leak discoveries. With these uncharacteristic pipe failures evident, the Brown Deer Water Utility initiated a more aggressive program of leak detection in water service lines. During the same time period that pipe leaks were discovered, a dramatic increase in unaccounted-for water loss from the water system was noted.

General Investigation

An investigation into the cause of the pipe failures began in the spring of 2002. A number of possible corrosion factors were investigated and eliminated. The eliminated factors included pipe manufacturing flaws, pipe installation and workmanship, soil interactions, stray electrical currents, electrical grounding, and water chemistry (dissolved inorganic carbonate, carbon dioxide, dissolved oxygen, chloride, sulfate, and orthophosphate).

Microbiologically Influenced Corrosion Investigation

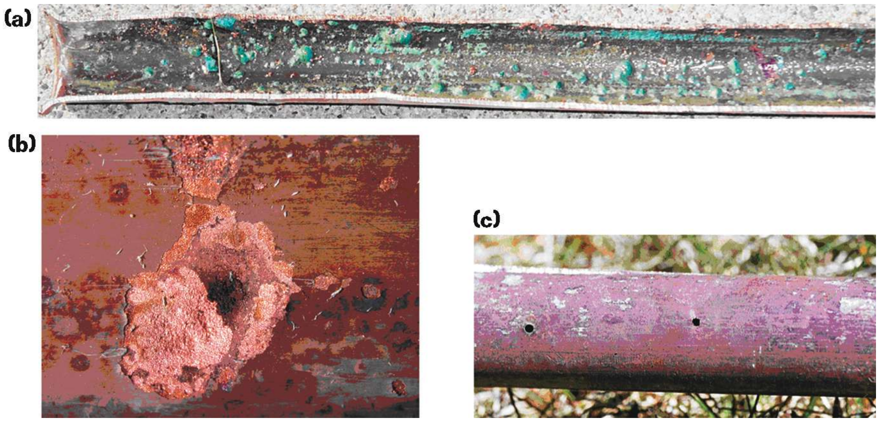
Further investigation found evidence that microbiologically influenced corrosion (MIC) was occurring. Reports of case studies and research on the biocorrosion of copper water pipe are scattered throughout the technical literature.[1] More abundant are studies concerning microbiological growth in water distribution systems. Many of these studies mention corrosion as a possible repercussion of microbiological growth but do not cite references or discuss specific characteristics of MIC.

The characteristics of MIC found in this study and substantiated in the technical literature can be grouped into the categories of visual identification, piping configurations, and biological stability of the water.

VISUAL IDENTIFICATION OF MICROBIOLOGICALLY INFLUENCED CORROSION

Greenish tubercles and areas of greenish film were typically seen on the interiors of the corroded pipes (Figure 1[a]). Similar pipe interiors can be seen in other reports of copper biocorrosion.[1] Pits were

FIGURE 1



Typical corroded copper water service pipes. (a) Tubercles found on the interior of corroded copper pipes; (b) underneath tubercles, pipe interior patterns of sharp-edged pits; (c) interior pits break through the pipe exterior as pinholes.

found underneath the tubercles. Corroded pipes must be handled very carefully, or the nuances of the pit morphology can be destroyed. For this reason, the corroded pipes were cleaned using a gentle electrolytic cleaning process.[2] Similar to cathodic protection (CP), the cleaning process applies a direct current using the pipe sample as the cathode in an electrolytic cell. However, the current is much higher than would be used in CP. This causes a large quantity of hydrogen gas to form at the metal surface of the cathode underneath any loose nonmetallic corrosion debris and dirt. The gas lifts debris off the surface of the pipe without destroying the metallic structure of the pits. Figure 1(b) shows an example of the jagged pit morphology with undermined copper flakes typical of the utility's corroded copper pipes. Pits with this jagged morphology have been identified as caused by MIC.[3] The pits progress to pinholes when the exterior of the pipe is broken through (Figure 1[c]).

In addition, corroded and non-corroded pipes were sent to the Wisconsin State Lab of Hygiene. There, microbiologists inspected the corrosion debris and interior pipe surfaces for microorganisms. In tests using nucleic material stains and microscopy, no microorganisms were observed on noncorroded pipe samples, while "microbe-laced" biofilms were identified in the pitted areas and debris of the corroded pipes.[4] It is known that microorganisms overcome the toxicity of copper by binding the copper ions in an excretion called extracellular polysaccharides (EPS).[1] The acidic EPS promotes localized dissolution of copper in the form of pitting.

PIPING CONFIGURATIONS

Another clue fitting the idea that microorganisms were active in the system is the location of the pitting problems. Microorganisms usually first colonize in a distribution system in locations where water stagnates, sediment accumulates, and disinfection residuals drop to low levels. These locations are at the farthest reaches of a distribution system, at dead ends, and at the lowest points in a line.[1]

The corrosion problem first manifested itself in the northern third of the village, which is the farthest section of the distribution system from the two water entry points. Also, pinhole leaks first occurred in the lowest points in the pipeline as observed in failed water service lines retrieved for inspection. Finally, a hydraulic model of the distribution system showed locations with the lowest water usage coinciding with the areas of failed copper pipe.[5]

BIOLOGICAL STABILITY OF WATER

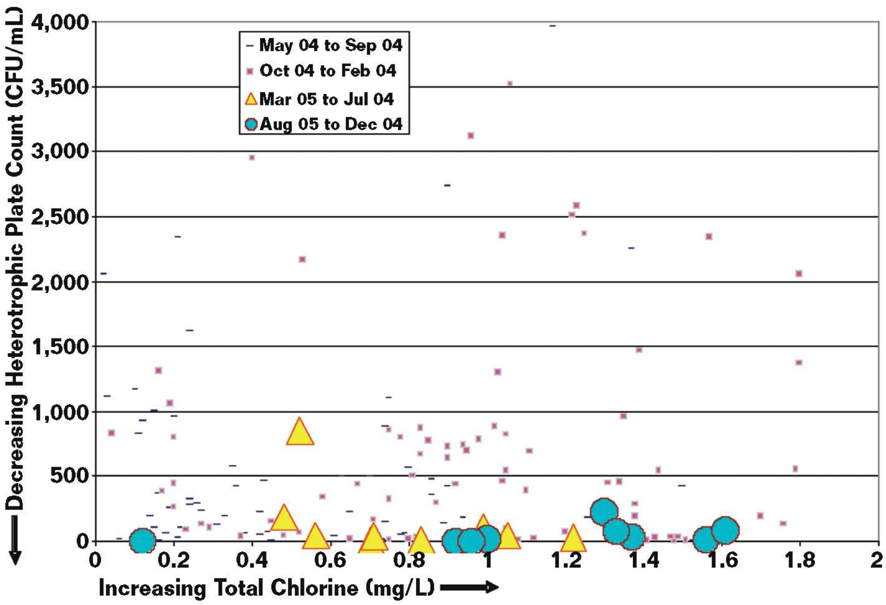
Biological stability (biostability) refers to the ability of water to support the growth of microorganisms.[6] One nutrient that supports the growth of microorganisms in water systems is assimilable organic carbon (AOC) from smaller organic compounds that are readily accessible to microorganisms for food.[7]

AOC is a fraction of the naturally occurring organic matter in the water. It can be increased as the water is treated, even as the total organic carbon is decreased. For instance, AOC is known to increase dramatically in the ozonation process used for primary disinfection.[7-8] A side effect of the added ozone is to break up larger organic carbon molecules into smaller ones; in effect, increasing AOC. As an example, one study showed that AOC increased from 70 to ~140 μg/L in an ozonation process.[7] Processes downstream of ozonation are typically installed to remove the increased AOC.

Nutrients must be counter-balanced by disinfection to have biologically stable water. Two studies are predominantly quoted in the literature as an estimate for the balance of nutrients vs disinfection. One study shows that if no disinfection is present, the AOC level must be <10 μg/L to prevent growth of microorganisms in the distribution system.[9] A second study found that the probability of microorganism growth greatly increases when the AOC is >100 μg/L and the disinfection residual is <1.0 mg/L total chlorine when monochloramines are used.[10]

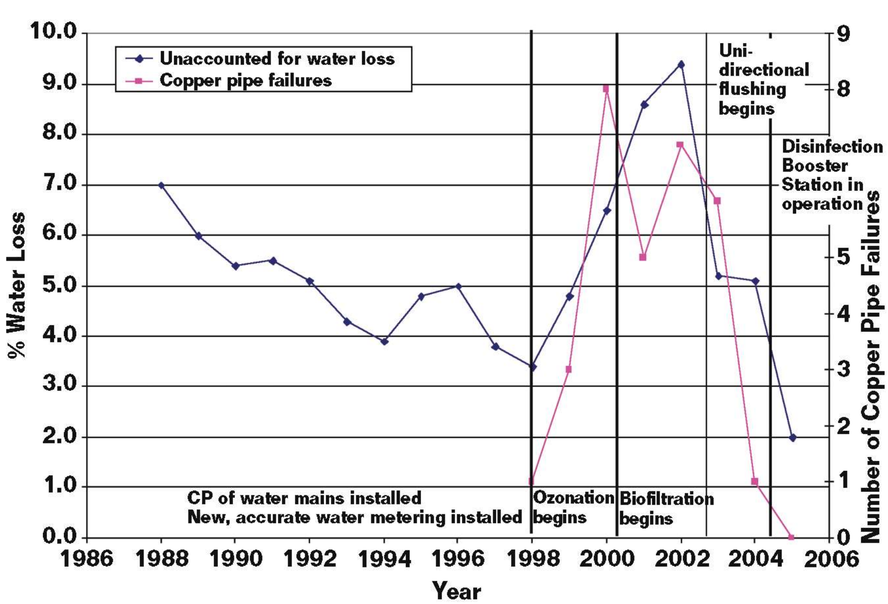
Using the perspective of the previous discussion, the AOC levels in the Brown Deer water were conducive to the growth of microorganisms in the distribution system. The water is purchased from a larger water utility, which draws and treats water from Lake Michigan. In 1998, an ozonation process was added for primary disinfection. Downstream at the treatment plant, the existing sand filters were retrofitted as a dual media filter of anthracite and sand. Chlorination was continued after the ozonation and before the filters until 2000. When the chlorination was discontinued, the filters began to function as "biofilters" where microorganisms grow on the filtration media and consume the AOC. In effect, when the

FIGURE 2



Microorganisms and disinfection in Brown Deer, Wisconsin.

FIGURE 3



Unaccounted-for water loss and copper pipe failures in Brown Deer, Wisconsin.

ozonation process was initiated in 1998, AOC probably increased in the water. Because biofiltration was not in place at the time, AOC removal efficiency was probably very low and high AOC levels were introduced into the distribution system. In 2000 when biofiltration was initiated, the AOC removal efficiency probably improved but medium concentrations of AOC most likely continue to be routinely introduced into the distribution system.

The AOC measured at the entry point to the Brown Deer system was 100 µg/L. To counteract this concentration of nutrients, the technical literature suggests a disinfection dosage of 2.0 to 2.4 mg/L total chlorine when using monochloramine as a disinfectant.[6,10] The annual average monochloramine disinfection measured throughout the distribution system from 1992 to 2002 was 0.3 to 0.4 mg/L total chlorine. Total chlorine levels in the northern one-third of the system have often been found to be at negligible concentrations. Therefore, it appears that the level of disinfection was inadequate to balance not only the surge of AOC that may have entered the system in 1998 when ozonation was added as a water treatment process, but also remained inadequate after biofilters lowered the AOC to ~100 µg/L.

Solution to the Problem

This corrosion investigation has been described in more detail elsewhere.[11-13] When MIC was suspected during the investigation, a program of the efficient distribution system cleaning technique called uni-directional flushing was implemented. Following the investigation's recommendations, a disinfection booster station was constructed and placed in operation in September 2004. Improvements have since been seen in the distribution system. Figure 2 shows the measured presence of microorganisms (heterotrophic plate count [HPC] in colony-forming units per mL [CFU/mL]) plotted against total chlorine concentration. These data were obtained at various points throughout the water system in flowing water.

The HPC values are representative of microorganisms from the adjacent water main. The HPC tests were performed using R2A media, which gives a higher HPC reading than other methods. This method is a useful tool for corrosion investigations as it is more sensitive to the presence of microorganisms. HPC is seen to vary greatly before September 2004. For five months after this point when disinfection was boosted, the variance continued to be seen. By around March 2005, the HPC had decreased greatly. In addition for

2005, unaccounted-for water loss dropped to 2% and the number of copper water service line failures dropped to zero. Figure 3 displays the history of water loss and pipe failures in the system.

Recommendations

These copper water service line failures are an example of MIC. Because MIC should be considered more often in drinking water system investigations, it is recommended that corrosion investigators look for the telltale signs of MIC to determine whether it is relevant to any given corrosion problem. The corroded pipes should be visually inspected for microorganism activity, looking for the presence of microorganisms and characteristic pit morphology. The site of corroded pipes should be studied for piping configurations conducive to MIC—low points in pipelines, extremes of distribution systems, and low water usage. Finally, the biostability of the water should be considered. Biostability involves balancing disinfection with possible nutrients in the water. In this case, the available nutrient was AOC. In other cases, there could be other available nutrients, such as nitrogen or phosphorus.

Acknowledgments

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