Evaluating In-Plant Infrastructure Corrosion After Replacing Lime Softening With Nanofiltration and Blending With Reverse Osmosis and Ion-Exchange Process Water

Rebecca J. Wilder and Steven J. Duranceau

The Town of Jupiter (Town) recently changed its water treatment operations from a combination of reverse osmosis (RO), ion-exchange (IX), and lime softening (LS), to a combination of RO, IX, and nanofiltration (NF). A change from the older LS technology to NF technology was implemented to enhance consumer water quality; however, the Town was concerned that the change in treatment could result in secondary impacts on corrosion rates of in-plant infrastructure, such as piping, joints, clearwell structures, pumps, and other related appurtenances. Prior to implementation of the NF facility, the RO, IX, and LS process streams were blended in a common clearwell. Currently, this common clearwell serves as a blend point for only the RO and IX treated waters, as the LS process has been retired from service. This intermediate blend travels through the existing pipe network to a newly constructed clearwell where final blending occurs with the NF product water to produce a stabilized finished water that is suitable for distribution to consumers.

The Town has expressed concerns with the corrosivity of the intermediate RO-IX blend, and its effects on the existing clearwell and pipe network. Permeate water from a membrane process is characteristically unstable because of its low mineral content and fairly high concentration of dissolved gases including oxygen[1]. Without proper post-treatment or chemical addition, the water can be corrosive, especially towards pipe components and appurtenances[2,3,4,5]. Previously, the blend of the three process streams (RO, IX and LS) in the clearwell provided a fairly stable, finished water that achieved equilibrium with the plant's hydraulic conveyance system. However, the removal of the LS system has changed this blend's water quality, thus increasing possibility for secondary corrosive impacts. The extent of the corrosive nature of the new RO-IX blend and it impact on hydraulic components is relatively unknown.

This article presents the results from a portion of an ongoing corrosion monitoring study that was developed by the University of Central Florida (UCF) at the request of the Town, specifically as it relates to corrosion impacts of in-plant infrastructure after process changes had been implemented by the Town. Information obtained from two study evaluations completed by UCF is also presented.

Corrosion monitoring was accomplished through analyzing the corrosion rates of three metal components: mild steel, lead, and copper. A corrosion rack was designed and constructed to house the metal components and monitor their corrosion activities as specific blended waters were passed through the system. Phase I of the corrosion study includes an evaluation of two different blends of water produced by the Town: RO-IX intermediate blend and RO-IX-NF finished water blend. Phase II of the corrosion study assesses the benefit of a low dose of a potassium orthophosphate corrosion inhibitor at controlling in-plant corrosion.

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Background

Many communities throughout the United States and its territories face a variety of environmental infrastructure challenges and often find it difficult to comply with the multitude of environmental regulations, not the least of which is the U.S. Environmental Protection Agency's (EPA) Safe Drinking Water Act (SDWA). As the SDWA has matured, the requirements have become increasingly more stringent and more complicated, and are based on best-available science and technology at the time of promulgation.

Continuing advances in regulatory constraints and aesthetic criteria for consumer water quality have driven the water community to seek new technologies that meet these criteria. Foremost among regulatory constraints are disinfection requirements, disinfection by-product formation, and corrosion control regulations. Consumers have become aware of regulatory violation through mandated public notification and Consumer Confidence Reports, and they have always been aware of the appearance, taste, and odor in their drinking water.

As water is transported through the drinking water distribution system, physical, chemical, and/or microbiological transformations may occur, resulting in degraded water quality[1,6]. These interactions occur in the bulk water phase and on surfaces in contact with the water column. There are many causal factors that contribute to the corrosion in drinking water treatment facilities, distribution systems, and the customer home plumbing systems the water provider serves. Internal corrosion of drinking water distribution and home plumbing systems occurs when water chemistry and physical conditions combine to allow one or more of the following corrosion scenarios[2,7,8]:

a) Uniform Corrosion – Water freely dissolves metal from the pipe surface.
b) Concentration Cell Corrosion – Local-

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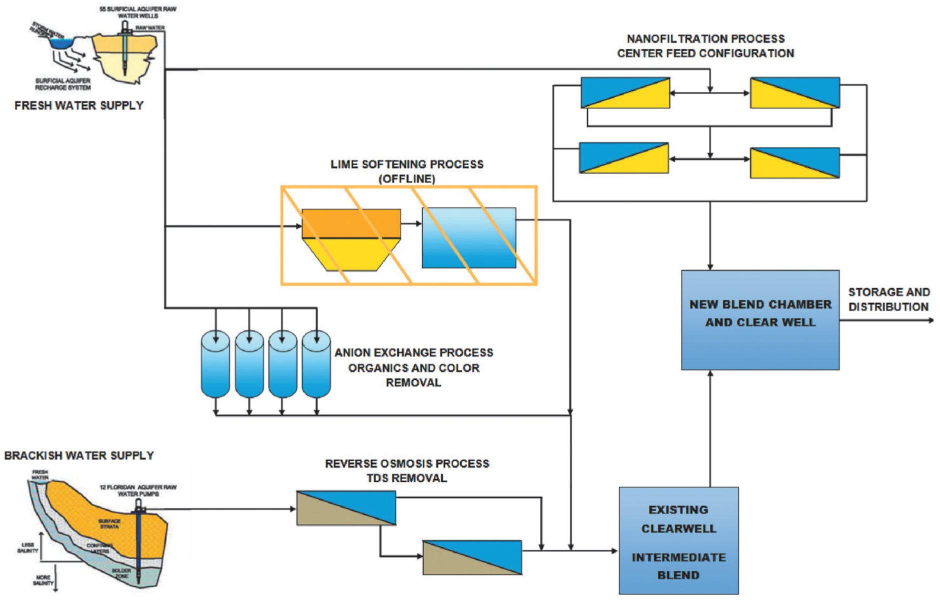

Figure 1. Schematic of Existing Facility Layout

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ized anodes (negative charge) and cathodes (positive charge) become established along the pipe wall surface, resulting in the sacrifice of metals at the anodes (formation of dissolved metal species) and redeposition of less-soluble metal compounds at the cathodes.

c) Galvanic Corrosion – Contact of two dissimilar metal pipe materials, which accelerates the dissolution of the material with the greatest tendency to corrode.

d) Stray Current Corrosion – The practice of using underground water piping as part of the grounding system of a building has been in place for more than 80 years, and alternating voltages and currents on metallic water services are common. Electrical resistance, if present in the metal pipe, will force some fraction of current (albeit small) to flow through the parallel water path. The discharge of current on the inside of the pipe increases metal release.

Treatment for corrosion control is typically intended to inhibit dissolution by altering water characteristics such that chemical reactions between the water and the pipe surface favor the formation of a protective layer on the interior pipe walls[2,8]. The ideal protective coating would be present throughout the distribution and home plumbing systems, be relatively impermeable and resistant to abrupt changes in water velocity and/or flow direction, and be less soluble than the pipe material.

Existing System and Facility Layout

Testing has been conducted at the Town's water treatment plant (WTP). The Town WTP is capable of producing approximately 30 million gallons per day (mgd) of drinking water. Currently, the Town's drinking water system blends three treatment methods: NF, IX, and RO. The NF facility has recently been integrated into the Town's system and replaced the previous LS process. The fresh water Surficial Aquifer and the brackish water Floridian Aquifer supply the WTP processes.

The fresh water from the Surficial Aquifer is characterized as being high in hardness, color, and turbidity, with appreciable levels of total organic carbon (TOC) or disinfection by-product (DBP) precursors and iron. This fresh water feeds the current NF and IX systems, as well as the former LS process. The IX process uses anion exchange resins to remove color and TOC. The NF process provides increased removal of turbidity, color, iron, and TOC producing a higher quality product water than that of the retired LS process. The brackish water from the Floridian Aquifer contains high levels of total dissolved solids (TDS) and dissolved gases. This water feeds the RO membrane process, which utilizes high pressure to force the brackish water through the membranes. The membrane rejects dissolved salts and impurities, but allows passage of water through a diffusion controlled process. The RO process produces a high-quality permeate that lacks mineral content, alkalinity, and buffering capacity, thus requiring stabilization. This is achieved by blending the RO water with the IX and NF to achieve stabilization before distribution to the community.

Prior to integration of the NF process into the existing system, water produced from the LS, RO, and IX processes were historically blended into a common clearwell where remaining post-treatment and disinfection occurred prior to storage and distribution. After the LS process was retired and replaced with the NF facility, the RO- and IX-produced waters were intermediately blended in this existing clearwell prior to downstream transport and final blending with the NF treated water. A schematic of this system is illustrated in Figure 1.

Test Methods

A corrosion control study was developed by UCF to identify and assess the secondary impacts related to corrosion as a result of implementation of an NF process into the Town's existing system. A test apparatus was constructed and was operated at the Town's facilities to monitor corrosion activity, demonstrate the relative impact of select blending ratios, and assess the performance of possible treatment strategies. The test apparatus consisted of PVC pipe connected in a series of loops that houses electrochemical probes fitted with metal electrodes and plugs fitted with metals coupons; this apparatus is also referred to as corrosion loops. The metal electrodes were used to obtain instantaneous corrosion rate measurements through an electrochemical technique, and metal coupons were used to gravimetrically determine corrosion rates through traditional weight loss measurements. The test methods presented herein relate to the evaluation of the corrosivity of the intermediate RO-IX blend.

Material Selection

Criteria for selecting the types of metal materials were based on typical metal components used in the manufacturing of in-plant hydraulic infrastructure, piping, plumbing appurtenances, and fixtures. Three types of metals chosen for evaluation were mild steel, 50/50 lead/tin solder, and copper. Figure 2(a), (b), and (c) depicts the mild steel, lead solder, and copper electrodes, respectively. Figure 3(a), (b) and (c) similarly shows the metal components as coupons.

Mild steel was selected for analysis because it provides a good baseline of corrosion activity. In addition, in-plant infrastructure such as rebar used to construct concrete structures or plumbing fixtures may contain mild steel components. Evaluation of the extent of corrosion of this particular metal may provide insight as to what facility personnel could expect with regard to degradation of these materials over time and the associated impacts to maintenance costs and/or water quality.

Copper was selected for analysis because many piping materials and plumbing appurtenances such as meters and valves are made of or contain copper components. Corrosion of these fixtures can affect their performance, leading to maintenance issues. In addition, copper release in water systems is important to consider because it affects the utility's ability to comply with the SDWA's Lead and Copper Rule (LCR).

A lead solder was selected for analysis because it is not uncommon for hydraulic components to contain lead, as well as piping that contains leaded solders. Like the considerations made for the copper selection, lead release in water systems as a result of corrosion of pipes and fixtures containing lead components can affect the utility's ability to comply with SDWA's LCR.

Corrosion Monitoring Loops

The corrosion loops were constructed so that instantaneous corrosion rate measurements, through use of electrodes, could be obtained at the same time as corrosion rate assessment through the use of coupons. Thus, a section of pipe loops was fitted with electrodes and another section of pipe loops was fitted with coupons. The entire arrangement was referred to as a corrosion rack. This setup was also mirrored by an additional corrosion rack so that two different test conditions could be evaluated simultaneously. Selected blends of water flowed through the corrosion loops and its corrosivity evaluated through electrochemical activity and metal weight loss of the materials caused by the water. The probes containing the metal electrodes were used to monitor electrochemical activity through instantaneous electrochemical monitoring equipment using the linear polarization resistance (LPR) method. Corrosion activity was also evaluated using a traditional method of monitoring the weight loss of metal coupons.

Each corrosion rack houses three electrochemical probes and coupon holders to mount the respective mild steel, lead/tin solder, and copper metal components. In addition, the corrosion racks were fitted with various valves, chemical injection ports, and appurtenances for flow control, rack maintenance, chemical addition, and water sampling. The two study phases evaluated for this portion of the corrosion monitoring study looked at various water blends, operational flow rates, and flow schedules, with and without the use of chemical addition.

Water Quality Monitoring

Instantaneous corrosion rate measurements of each metal component can be obtained from the electrochemical probes mounted with mild steel, lead solder, and copper electrodes. Therefore, daily corrosion rate measurements were taken with the use of a handheld data logger that took corrosion rate measurements using the LPR technique. Corrosion rate measurements are given in units of mils per year (mpy), which indicates the thickness of metal that is being lost over time. Daily measurements were taken to observe the trend of corrosion over time for each metal component. The instantaneous measurements obtained can also be compared with those corrosion rate measurements calculated based on the weight loss of the metal coupons.

In addition to corrosion rate measurements, water quality parameters were tested on a daily and weekly basis. The following lists the analyzed water quality parameters:

- Temperature
- Turbidity
- pH
- P-, M-, and total alkalinity
- Conductivity
- Chlorides
- Dissolved oxygen
- Calcium and total hardness

The frequency of monitoring varied in each test phase. Phase II of the evaluation also analyzed for phosphate, as a phosphate-based corrosion inhibitor was used during the test phase. These parameters were monitored for each blend in order to assess the impact of subtle or significant water quality changes on the corrosion rate of the metals.

RESULTS

Phase I Evaluation: Baseline Conditions Assessment

This portion of the study looked at the relative corrosion rates of the RO-IX blended water (intermediate blend) and the RO-IX-NF finished water (final blend) as produced by the plant in order to establish baseline corrosion rates. This study was accomplished using the corrosion rack constructed from looped, 1-in. PVC piping that was fitted with necessary flow meters, flow control valves, and sampling ports. The corrosion rack was comprised of two separate but identical racks so that each side could be fed its own source water. For this phase of study, one side received the intermediate blend and the other side received the final blend. Each side of the corrosion rack was fitted with mild steel, lead and copper electrodes, and coupons.

Water Quality

Water quality monitoring for this phase of study was initially collected on a daily

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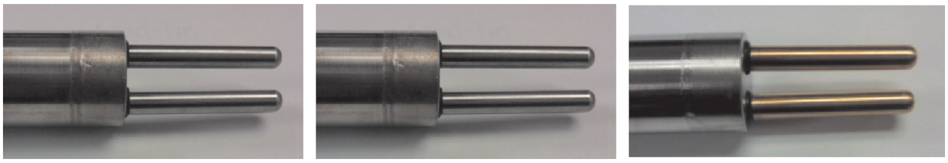

Figure 2. (a) Mild Steel, (b) Lead Solder, and (c) Copper Electrodes

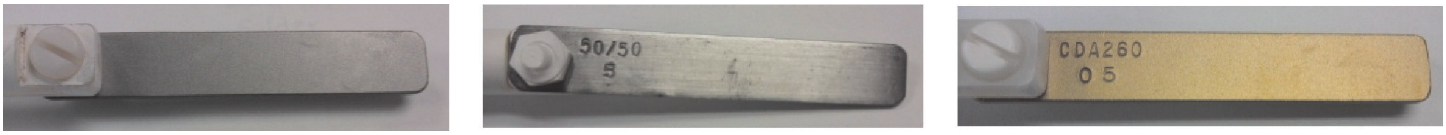

Figure 3. (a) Mild Steel, (b) Lead Solder, and (c) Copper Coupons

Table 1. Phase I Average Water Quality for Each Test Blend

Parameter	Intermediate Blend	Final Blend
pH	8.86	8.45
Conductivity	0.48	0.47
Dissolved Oxygen	3.7	3.8
Turbidity (NTU)	0.11	0.17
P-Alkalinity (mg/L as $CaCO_3$)	10.5	5.4
M-Alkalinity (mg/L as $CaCO_3$)	54.8	74.8
Total Alkalinity (mg/L as $CaCO_3$)	65.2	80.2
Chloride (mg/L)	104	94.1
Calcium Hardness (mg/L as $CaCO_3$)	44.1	69.7
Total Hardness (mg/L as $CaCO_3$)	46.7	72.9

Table 2. Summary of Phase I Corrosion Rates

Flow Regime	Average Corrosion Rate (mpy)					
	Intermediate Blend			Final Blend		
	Mild Steel	Lead	Copper	Mild Steel	Lead	Copper
On	11.4	0.23	1.2	2.8	0.17	2.4
Off	11.2	0.29	0.77	2.4	0.25	0.67
Percent Difference	1.8	25.3	35.8	14.0	45.7	71.8

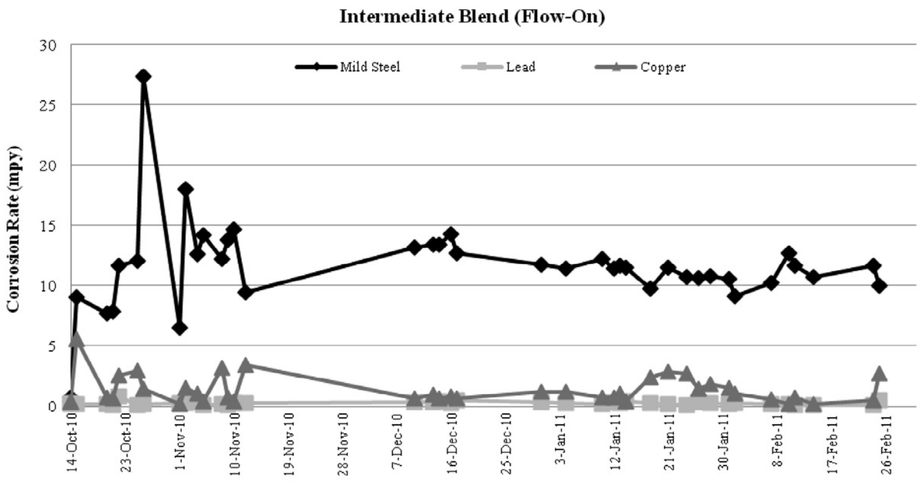

Figure 4. Average Corrosion Rate Measurements of Each Metal Component for the Intermediate Blend

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basis. It was then decided that biweekly water quality monitoring would be sufficient to collect enough data for the purposes of this study. The average water quality for the listed parameters is shown in Table 1 for each test blend.

Based on the water quality in Table 1, it can be inferred that stability of the final blend water is greater than that of the test blend by examining the total alkalinity and calcium hardness concentrations. The concentrations of these parameters are greater in the final blend than the test blend. Previous research has shown that sufficient alkalinity and hardness in the finished water contribute most to the relative water stability, thus reducing the potential for corrosion[2,3,5,9].

Corrosion Monitoring

Water flow to the corrosion rack was controlled with an on/off timer in order to approximate variations in water demand. Thus, the corrosion rack was exposed to both flowing and stagnate water. The average flow rate to each side of the corrosion rack was approximately 4 gallons per minute (gpm). Corrosion rates were measured for the flowing and stagnant waters in order to evaluate any differences that may have occurred. Table 2 summarizes the average corrosion rate of each metal for both source waters during the flow-on and flow-off cycles.

Based on the results of Phase I of the corrosion study, the following conclusions can be inferred from Table 2:

- Mild steel corrosion rates are consistently higher in flowing water for both blends; however, the differences among the corrosion rates are less than 15 percent.
- Lead corrosion rates are consistently higher in stagnant water for both blends, where the percent difference ranges from 25 percent to as high as 46 percent.
- Copper corrosion rates are consistently higher in flowing water for both blends, where the percent difference ranges from 36 percent to as high as 72 percent.
- The percent difference among corrosion rates for flowing versus stagnate water is consistently greater for all three metal types exposed to the final blend when compared with the intermediate blend.
- The intermediate blend is significantly more corrosive toward mild steel when compared to the final blend. This blend produces a corrosion rate that is approximately 75 percent greater than the finished water blend

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- The intermediate blend is more corrosive toward lead.
- The final blend is more corrosive toward copper for the flow-on condition when compared with the intermediate blend.
- For both blends, the same pattern is observed with respect to the relative ranking of corrosion rates: mild steel > copper > lead.

The following figures illustrate the variations in corrosion rates throughout the duration of this phase of study. For simplicity, only the corrosion rate measurements taken during the flowing water condition are shown. Although differences in corrosion rates were observed among flowing and stagnant waters, the data portrays a similar pattern and shape.

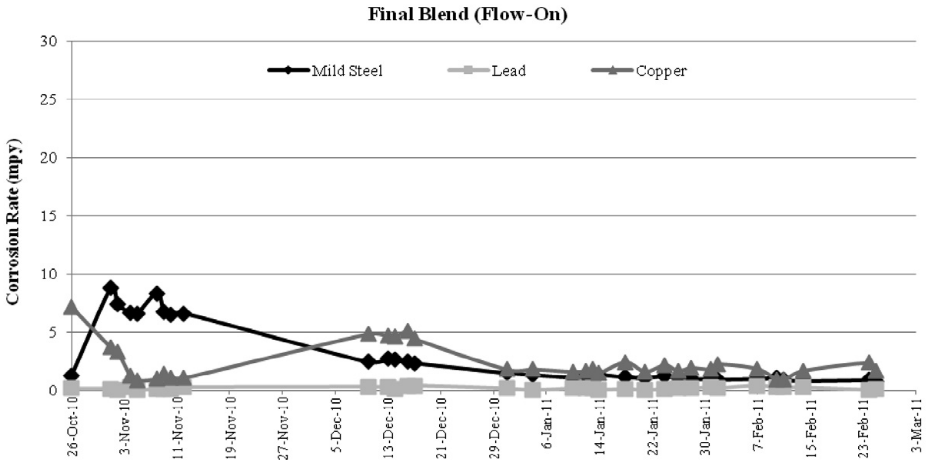

Figure 5. Average Corrosion Rate Measurements of Each Metal Component for the Final Blend

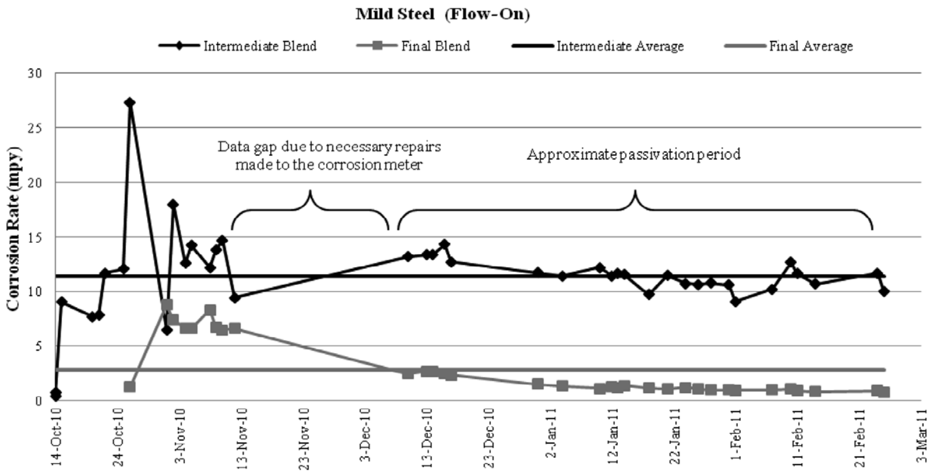

Figure 6. Mild Steel Corrosion Rate Curves for RO-IX Blend and RO-IX-NF Finished Water Blend

Table 3. Mild Steel Corrosion Rate Summary

	Mild Steel Corrosion Rate (mpy)		**Percent Difference**
	Intermediate Blend	Final Blend	
Maximum	27.3	8.8	67.8
Passivation Average	11.5	1.4	87.8
Average	11.4	2.8	75.4

Figures 4 and 5 illustrate the relative difference among corrosion rates for the three metals tested. The same plot is shown for each blend tested and the same range was set for the horizontal axis (corrosion rate) of each figure to illustrate the relative difference among the corrosion rates.

The mild steel corrosion rates for the intermediate and final blends are shown in Figure 6. The figure shows both plots to further illustrate the higher corrosion rate observed for the mild steel exposed to the intermediate blend relative to the final blend.

The shape of the curves shown in Figure 6 is characteristic of what is typically observed for a corrosion rate curve. When the virgin metal is initially exposed to the source water, high corrosion rates are observed as the outer layer of the metal surface is corroded. In addition, corrosion rate measurements can also vary significantly within the first few weeks of exposure as the metal equilibrates with the surrounding environment. After sufficient time, the corroded layer grows in thickness and then serves as a protective layer for the metal underneath. This occurrence is often termed “passivation.” At this point, the observed corrosion rate decreases to a relatively consistent value, which typically indicates that passivation is occurring.[7]

The maximum mild steel corrosion rates observed for the RO-IX and RO-IX-NF blends were 27.3 mpy and 8.8 mpy, respectively. The average corrosion rate during the passivation period for the RO-IX and RO-IX-NF blends were 11.5 mpy and 1.39 mpy. Table 3 summarizes this information. Based on the collected data, it appears that the intermediate blend is significantly more corrosive toward mild steel relative to the final blend. This observation coincides with the water quality results where it was observed that the alkalinity and hardness of the final blend, on average, was higher than that of the test blend. Sufficient alkalinity and hardness in water can contribute to a stabilized finished water, hence being less corrosive to hydraulic components. This demonstrates the need for a stabilized intermediate water blend as it relates to the water treatment plant infrastructure.

Figure 7 depicts the lead corrosion rate for the intermediate and final blends. As shown in this figure, the corrosion rates among the different source waters are not significantly different. In addition, the shape of the corrosion curve does not correspond to the typical curve shape previously discussed; thus, a passivation region is not observed.

The range of corrosion measurements only varies from 0 to 0.77 mpy, which indicates that the lead corrosion rates are not high enough to form a protective corroded metal layer for either source water. However, the lead metal does not appear to be as sensitive to corrosion; thus, a passivating layer may not be necessary for the lead exposed to these blended waters.

Figure 8 represents the copper corrosion rate for the intermediate and final blends. From the figure, it can be observed that the corrosion rates for both blends are sporadically similar to what was observed for the lead corrosion rate curves. Therefore, the typical shape for a corrosion rate curve is not clearly observed in this study for copper corrosion. However, unlike lead, the range of corrosion measurements is wider and varies from 0 to 7.2 mpy.

Still, interesting observations arise from the data obtained for the copper corrosion rates. The copper corrosion rate resulting from the final blend is higher, on average, then the corrosion rate for the RO-IX blend. For the previous metals, the intermediate blend appeared to be the more corrosive water as it produced higher mild steel and lead corrosion rates. In addition, Figure 8 indicates that the corrosion rate of the copper metal exposed to the final blend increased significantly, indicated by the red dashed line. According to water quality data obtained for the final blend, the calcium hardness concentration increased from 48 to 97 mg/L as $CaCO_3$ and the total alkalinity concentration increased from 60 to 104 mg/L as $CaCO_3$ during this time period.

Figure 9 depicts the trend in calcium hardness and total alkalinity, along with the copper corrosion rate for the final blend. Figure 9 illustrates that the copper corrosion rate may increase if there is a sudden change in the hardness and alkalinity content of the water. In this case, the change was not favorable, resulting in an increased rate. As conditions stabilized, the copper corrosion rate also appeared to stabilize (reduce). Thus, based on the testing conditions experienced in this evaluation, it appears that copper corrosion is sensitive to changes in hardness and alkalinity concentrations. This

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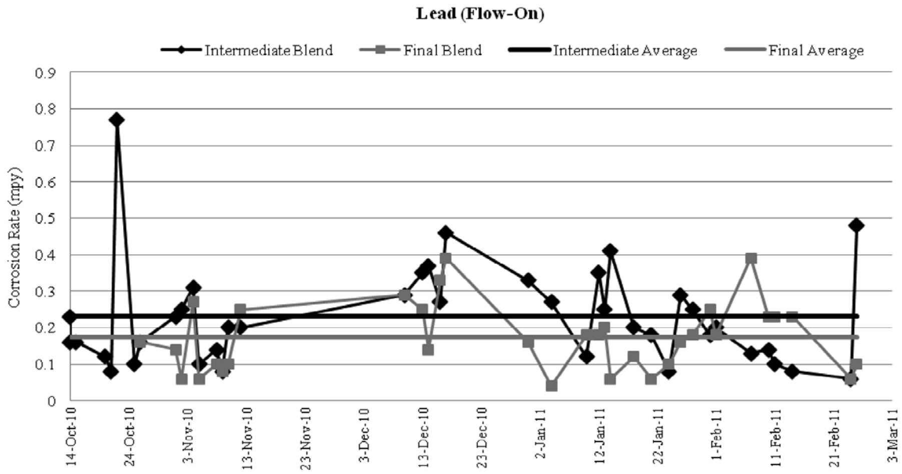

Figure 7. Lead Corrosion Rate Curves for RO-IX Blend and RO-IX-NF Finished Water Blend

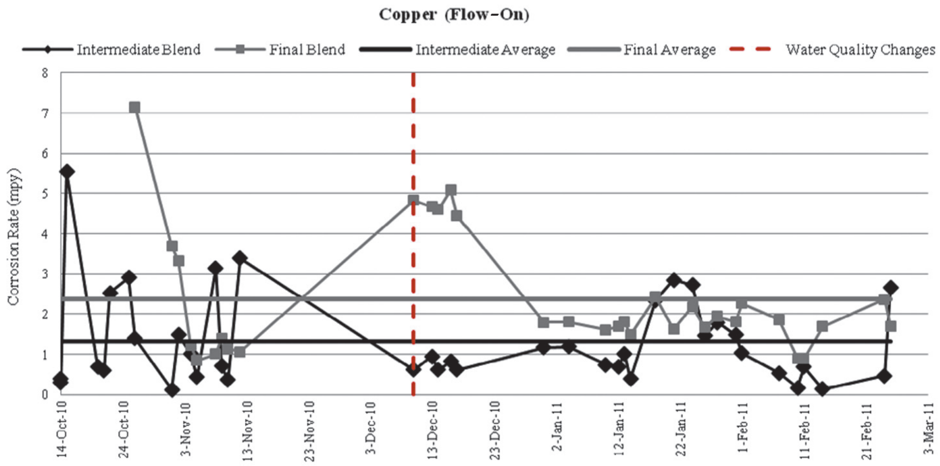

Figure 8. Copper Corrosion Rate Curves for RO-IX Blend and RO-IX-NF Finished Water Blend

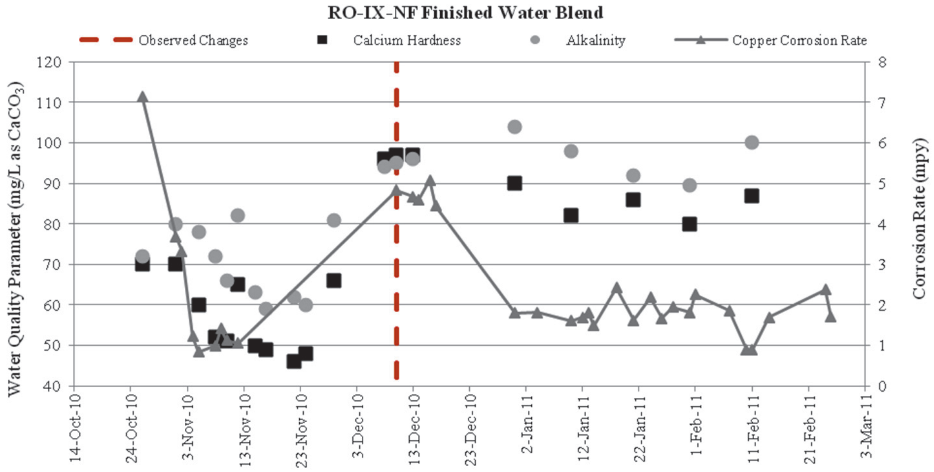

Figure 9. Calcium Hardness Concentration and Corrosion Rate of the RO-IX-NF Finished Water Blend

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demonstrates the need for a stable finished water quality as it relates to copper corrosion, as well as the need to maintain consistent and non-variable water quality conditions.

Phase II Evaluation: Potassium Ortho-Phosphate Inhibitor Assessment

This phase of the corrosion study looked at the corrosivity of the intermediate blend (RO-IX water) in the presence of an orthophosphate corrosion inhibitor. Based on the data and observations from the first phase of study, it was apparent that the intermediate blend was considerably more corrosive toward mild steel components relative to the final blend. Furthermore, data from the previous study phase suggested that the intermediate blend was generally corrosive, and corrosion control measures were necessary to stabilize the water supply in order to preserve the integrity of the in-plant infrastructure and hydraulic conveyance components. This served as the motivation for the second phase of study where chemical addition in the form of a corrosion inhibitor was assessed to determine its effectiveness at reducing the corrosivity of the intermediate blend.

The same corrosion rack was used for this phase of study; however, the metal electrodes and coupons from Phase I were removed and replaced with a new set of materials. The same three metals were analyzed in this phase (mild steel, lead. and copper) and the corrosion rates were analyzed using the same methods--instantaneous and gravimetric corrosion rate measurements. Water quality parameters were also monitored for this phase of study. The analyzed parameters are the same as listed above with the addition of phosphate because of the use of a phosphate based corrosion inhibitor.

Both sides of the rack received the same source water—the intermediate blend. However, the metal components on one side of the corrosion rack were exposed to this blend for a period of time necessary to form a sufficient corrosion layer without the presence of any corrosion inhibitor chemical. This side was referred to as the "corroded metal."

After the elapsed time period, the feed water was then dosed with the inhibitor to expose the already corroded metal to the corrosion inhibitor. This test blend will be referred to as corroded metal blend. Assessing the benefit of a corrosion inhibitor with a corrosion rack is not typically done in this way; however, this arrangement was chosen because rarely is a corrosion inhibitor chemical fed into a system where new, virgin metal components are in place. Often, the existing system contains metal components that have previously been exposed to the historical water for a period of time sufficient to build a corrosion layer on the inside of hydraulic conveyance components. Introduction of a corrosion inhibitor, and thus a different water supply to the system, may disrupt the existing equilibrium that was present before the changes in treatment occurred, resulting in unforeseen secondary impacts.

The metal components on the other side of the corrosion rack were only exposed to the intermediate blend in the presence of the corrosion inhibitor. This side was referred to as the "virgin metal," and the test blend will be referred to as "virgin metal blend." A corrosion inhibitor is typically evaluated in this way to determine if its presence in the test water supply decreases the corrosion rate of the metal components; however, results may not be representative of what could occur in a full-scale system. Nonetheless, this setup was chosen in order to compare the results with those obtained from the corroded metal blend.

Table 4. Phase II Average Water Quality of Intermediate Blend

pH	8.78
Conductivity	0.46
Dissolved Oxygen	3.9
Turbidity (NTU)	0.25
P-Alkalinity (mg/L as $CaCO_3$)	13.0
M-Alkalinity (mg/L as $CaCO_3$)	51.3
Total Alkalinity (mg/L as $CaCO_3$)	64.3
Chloride (mg/L)	94.4
Calcium Hardness (mg/L as $CaCO_3$)	43.2
Total Hardness (mg/L as $CaCO_3$)	45.6

Table 5. Average Outlet Phosphate Concentrations From the Corrosion Rack

	Average Phosphate Concentration (mg/L as PO_4^{3-})	
	Initial (low dose)	Final (elevated dose)
Corroded Metal Blend	0.23	0.84
Virgin Metal Blend	0.26	0.83

Water Quality

Table 4 presents the results of the average water quality for the intermediate blend, which is comparable to the Phase I average water quality for the intermediate blend. For this test phase, both corrosion racks received that same water (intermediate blend) and the only difference among the test conditions was the corroded metal versus the virgin metal; thus, the water quality of both test racks was the same. These measurements were taken biweekly to allow for sufficient data collection in order to observe any significant water quality changes and assess if any observed changes would affect the corrosion of the metal components.

Corrosion Inhibitor

The chemical feed system to deliver the corrosion inhibitor to the intermediate blend was dosed upstream of the metal components to allow for sufficient mixing. The inhibitor chemical used is referred to as CARUS™ 4200, which is a potassium orthophosphate manufactured by the Carus Corporation. The concentration of the corrosion inhibitor in the water was measured in terms of mg/L as phosphate (PO_4^{3-}). The chemical was initially dosed so that the out-

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Table 6. Phase II Average Corrosion Rate Measurements

	Average Corrosion Rate (mpy)		
	Mild Steel	Lead	Copper
Corroded Metal	9.3	0.39	2.6
Virgin Metal	8.1	0.51	2.2
Percent Difference	12.5	30.8	16.4

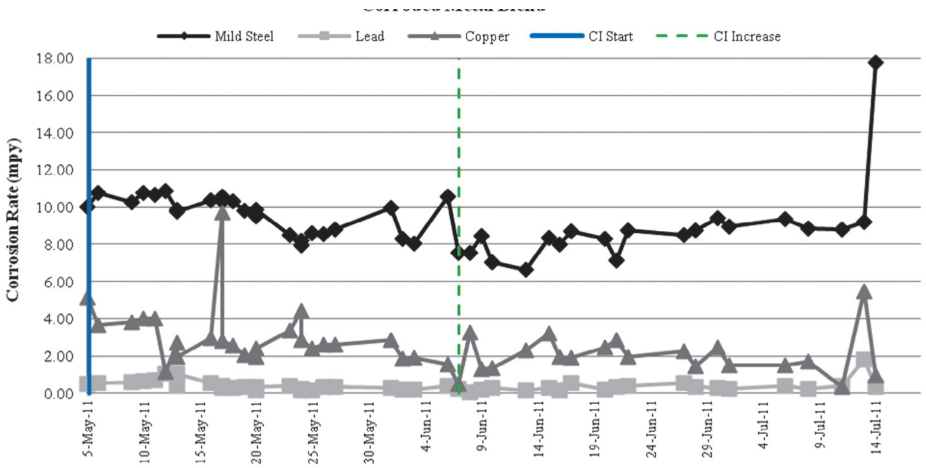

Figure 10. Average Corrosion Rate Measurements of Each Metal Component for the Corroded Metal Blend

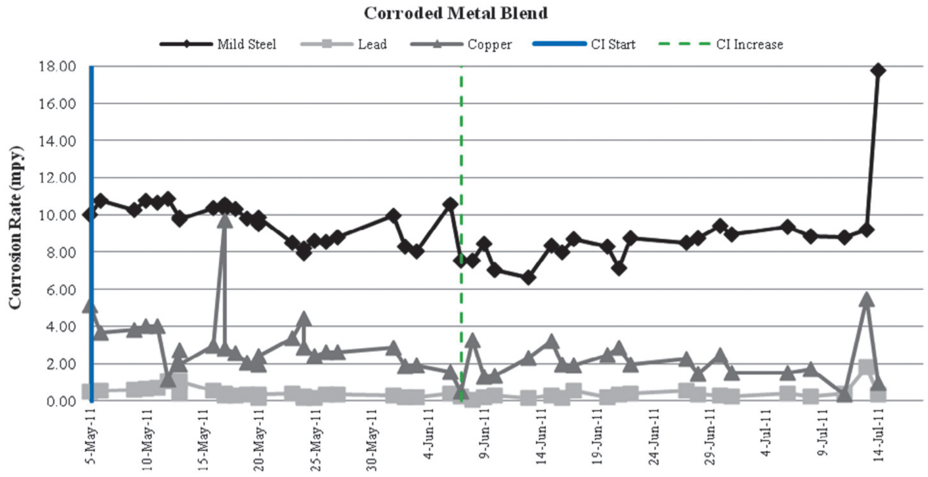

Figure 11. Average Corrosion Rate Measurements of Each Metal Component for the Virgin Metal Blend

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let concentration was approximately 0.25 mg PO_4^{3-}/L; then the chemical feed system was adjusted so that the outlet concentration was approximately 1.0 mg PO_4^{3-}/L. The feed concentrations of the corrosion inhibitor are less than what was recommended by the chemical manufacturer and are also less than what is typically practiced when using an inhibitor chemical for corrosion control. However, the dose of corrosion inhibitor was only intended to resolve the corrosivity of the intermediate blend primarily in the blending clearwell. It was not desired to carry a residual concentration to other portions of the plant where final blending with NF product water occurred, nor was it desired to carry a residual inhibitor concentration into the distribution system.

Table 2 presents the average outlet phosphate concentrations for the initial dose and elevated dose. Phosphate concentrations were monitored on a daily basis in order to observe that the chemical feed system was operating correctly. As shown in Table 5, the initial average lower dose of phosphate was approximately equal to target concentration of 0.25 mg/L as PO_4^{3-}. However, the final elevated dose of phosphate was, on average, less than the target concentration of 1.0 mg/L as PO_4^{3-}, as shown in Table 5. Reasons for this discrepancy are unknown, but the performance of the feed system is suspect.

Corrosion Monitoring

For this phase of study, the flow rate to the corrosion rack was continuous and set at approximately 1.5-2.0 gpm. The purpose of a continuous, lower flow rate was to better simulate the conditions that occur within the existing clearwell where the RO and IX treated waters are blended, which is where the corrosive impacts on this intermediate blend are more realized. Instantaneous corrosion rate measurements were taken daily from both sides of the test rack.

First, the corrosion rate measurements were compared between the corroded metal and virgin metal to determine if there was a significant difference between the corrosion rates. Then the corrosion rates in the presence of the inhibitor chemical were compared to the corrosion rates obtained in the first phase of study for the intermediate blend to assess the corrosion inhibitor's ability to decrease the corrosion rates of the mild steel, lead, and copper metals.

Table 6 provides a summary of the average instantaneous corrosion rate measurements obtained in Phase II of experimentation. The relative difference between the measurements has been shown through a percent difference calculation.

The following observations can be made from the data shown in Table 6:

- The corrosion rate of the components exposed to the corroded metal blend is higher for two of the three metals: mild steel and copper. The corrosion rate of the lead is greater for the virgin metal blend.
- The relative difference among the mild steel corrosion rates for the corroded and virgin metals is 12.5 percent.
- The relative difference among the copper corrosion rates for the corroded and virgin metals is slightly greater at 16.4 percent.
- The relative difference among the lead corrosion rates for the corroded and virgin metals is the greatest at 30.8 percent.
- For both test conditions, the same pattern is observed with respect to the relative ranking of corrosion rates: mild steel > copper > lead.

Figures 10 and 11 illustrate the relative difference among corrosion rates for the three metals tested for each test blend. The same plot is shown for each blend tested and the same range was set for the horizontal axis (corrosion rate) of each figure to illustrate the relative difference among the corrosion rates.

Figure 12 illustrates the variations in the mild steel corrosion rate throughout the Phase II of study. The corroded and virgin metal test conditions have been plotted on the same figure to compare corrosion rate trends. The presentation of the results from this study phase will focus on the mild steel corrosion rates as they can give a good indication of the general corrosivity of the water. Detailed figures for the lead and copper metals are not shown; however, the results are discussed and compared.

As shown in Figure 12, the corrosion rate measurements do not initially vary significantly between the test conditions; however, following the increase in corrosion inhibitor addition, the corrosion rate of the virgin metal blend begins to decrease, while the corrosion rate of the corroded metal blend remains fairly constant. This observation suggests that the increased corrosion inhibitor concentration was effective at reducing the corrosivity of the virgin metal blend towards the mild steel metal component. However, the increased corrosion inhibitor concentration did not show an added benefit towards significantly reducing the corrosion rate of the mild steel exposed to the corroded metal blend.

It can also be seen that the corrosion rate curve does not adhere to the characteristic shape described previously: initially high observed corrosion rates, followed by stabilized, lower, and consistent corrosions rates. This observation is likely a result of the differences in the buildup of the corrosion layer due to the presence of the corrosion inhibitor chemical. The chemical is intended to form a stable, evenly distributed film of the metal surface. This is happening in conjunction with the corrosion layer formation from metal oxidation.

In addition, Figure 12 does not show initial elevated corrosion rates; they remain relatively stable. Thus, the presence of the corrosion inhibitor may assist in dampening initial high corrosion rates typically observed as a metal substance equilibrates with the surrounding environment. Sporadic, el-

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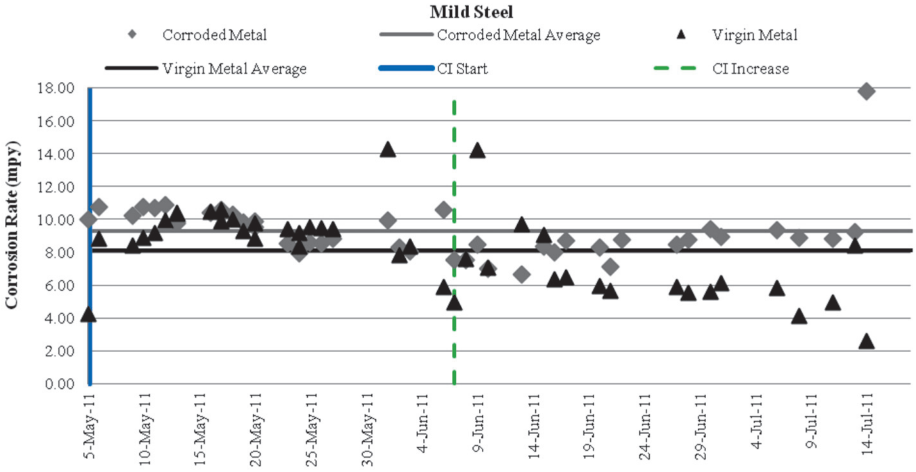

Figure 12. Phase II Mild Steel Corrosion Rate

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evated measurements are observed following the increase in the corrosion inhibitor concentration, as shown in Figure 12. However, this is likely due to the subtle changes in the water environment due to the increased inhibitor concentration and the mild steel having to reacclimate with these changes.

Another important observation made from this phase of study that is not shown in the last figure were episodes of red water (brown, discolored water that typically results from an abundance of iron in the water) occurring in the corrosion rack containing the corroded metal blend. During routine water quality monitoring, the presence of red water was observed coming from the sample port of the corrosion rack when water quality analyses were done on the corroded metal blend. Since the red water was only observed in the corroded metal blend, it most likely resulted from the mild steel coupon mounted within the rack. The oxidized iron metal that forms the corroded layer on this coupon may have deposited in the water, causing the discoloration.

These observations occurred after the corrosion inhibitor was placed online and the mild steel had already formed a sufficient corrosion layer being exposed to the intermediate blend. Thus, the presence of the corrosion inhibitor may have disturbed the existing corrosion layer, causing the release of iron into the water. Although no significantly elevated corrosion rates were observed for the corroded mild steel metal, the introduction of a corrosion inhibitor to an existing corroded metal surface may disrupt the equilibrium, resulting in iron release and red water observations.

Comparison with Results of Study Phase I

Table 7 provides a comparison of the average corrosion rates obtained from Phase I and Phase II for the RO-IX blend. From Phase I, the corrosion rates listed are from the flowing water condition for each metal tested. From Phase II, the average corrosion rates are shown for virgin metal condition.

Recall that from Phase I of the corrosion study, new mild steel, lead, and copper metal components were mounted in the corrosion rack and exposed for a length of time to the intermediate blend, without the presence of any chemical addition. The corrosion rate measurements obtained were based upon the extent of corrosion of the metal surface occurring as a result of the exposure to the source water. From Phase II of experimentation for the virgin metal blend, the new metal components were mounted into the corrosion rack and exposed to the intermediate blend only in the presence of the corrosion inhibitor chemical. The corrosion rates obtained resulted from corrosion of the metal surface and mitigation of corrosion through the presence of the chemical inhibitor. Thus, the Phase I intermediate blend could represent the control within the experiment and best represents the extent of corrosion currently occurring to in-plant infrastructure exposed to this blend. Likewise, the virgin metal blend can represent the test condition within the experiment and represents the potentially reduced corrosion rates due to the presence of the corrosion inhibitor. The true benefit of the inhibitor in the water supply can be realized by comparing these two blends, and thus assess the ability of the corrosion inhibitor to reduce the corrosion rate of the metal components.

The following observations can be made from Table 7:

- The mild steel corrosion rate in Phase II is less than the corrosion rate in Phase I. The presence of the corrosion inhibitor in Phase II of experimentation reduced the corrosion rate of the mild steel by 28.9 percent.
- The lead corrosion rate in Phase II is greater than the corrosion rate in Phase I. The presence of the corrosion inhibitor increased the corrosion rate of lead by 122 percent.
- The copper corrosion rate in Phase II is greater than the corrosion rate in Phase I. The presence of the corrosion inhibitor increased the corrosion rate of copper by 83.3 percent.

Table 7. Comparison of Average Corrosion Rates Between Phase I and Phase II

	Average Corrosion Rate (mpy)		
	Mild Steel	Lead	Copper
Phase I Intermediate Blend (without corrosion inhibitor)	11.4	0.23	1.2
Phase II Virgin Metal Blend (with corrosion inhibitor)	8.1	0.51	2.2
Percent Difference	28.9	122	83.3

Summary of Findings

Phase I Summary

Based on the data obtained from the Phase I experimentation, it appears that the intermediate blend is significantly more corrosive towards mild steel when compared with mild steel corrosion rates resulting from exposure to the final blend. The average mild steel corrosion rates for the intermediate and final blends for the flowing water condition are 11.4 mpy and 2.80 mpy, respectively. The final blend produces a mild steel corrosion rate that is 75 percent less than intermediate blend.

Phase I data also show that the corrosion of lead is greater when exposed to the intermediate blend, as compared with the final blend. However, the average lead corrosion rate for the intermediate and final blends were 0.23 mpy and 0.17 mpy, respectively, which are relatively much less than the corrosion rates observed for the other metal components. Therefore, the extent of lead corrosion is relatively low in the blended waters studied.

Unlike mild steel and lead, average copper corrosion rates were greater in the final blend when compared with the intermediate blend. The final blend produced an average copper corrosion rate of 2.36 mpy while the intermediate blend produced a rate of 1.20 mpy. It is suspected that the primary cause for elevated copper corrosion rates observed in the final blend was primarily due to variations in hardness and alkalinity concentrations. Therefore, a stabilized finished water quality is necessary to alleviate issues related to copper corrosion.

Phase II Summary

The second phase of study compares the relative effectiveness of an orthophosphate corrosion inhibitor at reducing the corrosion rates of previously corroded and virgin mild steel, lead, and copper. Results indicate that the previously corroded mild steel component had a higher corrosion rate than the virgin mild steel component. The corrosion rate of the virgin mild steel component was 12.5 percent less than the corroded metal. This was also observed for the copper components, where the corrosion rate of the virgin metal was 16.4 percent less than the corroded copper metal. However, the corrosion rate of the virgin lead component was greater than that of the corroded metal component. The corroded lead component's corrosion rate was 30.8 percent less than the virgin metal. Therefore, the corrosion inhibitor results in an added benefit with respect to reducing the corrosivity of the intermediate blend for the virgin mild steel and copper components. On the other hand, the inhibitor is more effective at reducing the corrosivity of the intermediate blend when exposed to the previously corroded lead component.

In general, the corrosion rate of the mild steel was relatively much greater than that of the copper and lead metals. The lead components resulted in the lowest observed corrosion rates. The average mild steel corrosion rates for the corroded and virgin metal blends were 9.3 and 8.1 mpy, respectively. The average copper and lead corrosion rates for the corroded and virgin metal blends were 2.6 and 2.2 mpy, and 0.39 and 0.51 mpy, respectively. These are relatively much less than the corrosion rates observed for the mild steel components. Therefore, the extent of the lead and copper corrosion is relatively low in the intermediate blend. Furthermore, lead and copper corrosion are of greater concern with respect to finished water quality as they impact the utility's ability to comply with the SDWA's LCR.

Based on the summary data of average corrosion rates of Phase I and Phase II data, shown in Table 7, it appears that the presence of the corrosion inhibitor can be beneficial for reducing mild steel corrosion rates, but adversely affects the corrosion rates of lead and copper. However, the extent of corrosion of lead and copper and subsequent effects on their release into the water is of greater concern for finished water distributed to consumers. The intermediate blend does not represent finished water and will not be used for distribution to consumers.

Although the presence of the corrosion inhibitor does reduce the extent of mild steel corrosion, the percent reduction is only 28.9 and the corrosion rate is still approximately 8 mpy. Recall from Phase I the experimentation for the final blend, where the average mild steel corrosion rate for the flowing water condition was 2.8 mpy, which is approximately 75 percent less than the Phase I mild steel corrosion rate of 11.4 mpy. Based on the results of experimentation from Phase I and Phase II of the corrosion study, it appears that the final blend provides the greatest reduction in the mild steel corrosion rate.

In addition, Phase II experimentation indicated that introduction of a corrosion inhibitor to a previously corroded metal surface containing iron may cause release or deposition of the iron corrosion products and result in discolored or red water. Furthermore, the percent reduction in the corrosion rate of the mild steel represents the virgin metal condition, which is not representative of the existing system. The hydraulic conveyance components of the in-plant infrastructure contain various metal parts that have previously been corroded, forming a quasi-equilibrium with the intermediate blend. Introduction of the corrosion inhibitor to reduce in-plant corrosion may disrupt the existing equilibrium, creating unintentional and secondary impacts, such as red water release.

Future Work

The data obtained from the second phase of study revealed that corrosion inhibitor addition only provides limited benefit in terms of decreasing the corrosivity of the intermediate blend towards metal components. However, results for Phase I of the corrosion study demonstrated that the final blend of water was the least corrosive towards metal components. These observations now serve as the motivation for the continued corrosion monitoring study. Currently, work is being done to evaluate the benefit of blending the three process streams (RO, IX, and NF) in a common clearwell prior to distribution, thus eliminating the intermediate blend from the existing system. The third phase of study is intended to evaluate the feasibility and benefit of resolving in-plant corrosion control issues through modification of the blend location for the three product waters.

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