Use of Precorroded Linear Polarization Probes and Coupons for Conducting Corrosion Control Studies

Steven J. Duranceau, Angela B. Rodriguez, Carlyn J. Higgins, Rebecca Wilder, Samantha Myers-O'Farrell, Samantha J. Black, and Benjamin A. Yoakum

As water is transported through the drinking water distribution system, physical, chemical, and microbiological transformations may occur, possibly resulting in degraded water quality. These interactions occur in the bulk water phase and surfaces in contact with the water column. There are many causal factors that contribute to corrosion and tuberculation within drinking water distribution systems and customer home plumbing. Corrosion in water distribution systems typically involves the internal corrosion of pipe materials due to flow velocity, dissolved oxygen, pH, and minerals in the near neutral solution of potable water. Internal corrosion occurs either by abrasion, metabolic activity, electrochemical processes, dissolution, or a combination of these mechanisms.

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. 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 be less soluble than the pipe material. The objective of corrosion control treatment is to inhibit the dissolution (release) of metals (such as lead and copper) from the pipe material to the potable water. Alteration of the water quality characteristics by a treatment method can extensively reduce some forms of corrosion activity, and to a lesser extent, the impact from other factors. Adjustments made to pH, alkalinity, calcium content, and use of proprietary inhibitors are commonly used to effectively reduce corrosion rates in water systems.

Often it's common for water purveyors to feed a blended orthophosphate-polyphosphate inhibitor prior to the distribution system; silicates are less commonly used. The role of inhibitors is to form a protective film and to sequester metal ions. Excessive doses of inhibitors could create a build-up of metal complexes on the pipe wall causing the release of corrosion byproducts into the potable water or a combination of these two circumstances. Testing is typically required to evaluate the plethora of available formulations.

In this work, the use of precorroded linear polarization resistance (LPR) probes and coupons for conducting accurate and rapid corrosion control inhibitor screening studies is discussed. A corrosion control testing rack apparatus using two identical parallel flow loops was designed and constructed to house mild steel and lead and copper coupons used for weight loss analysis, as well as mild steel, lead solder, and copper electrodes used for LPR analysis. Unlike other studies, coupons and electrodes were precorroded to simulate existing distribution system conditions.

Water Distribution System Regulatory Considerations

The U.S. Environmental Protection Agency (EPA), pursuant to the requirements of the 1986 Safe Drinking Water Act (SDWA), promulgated the Lead and Copper Rule (LCR) on June 7, 1991, which established an action level (AL) of 0.015 mg/L for lead and 1.3 mg/L for copper in public water supplies[1,2,3]. The Code of Federal Regulations (CFR) Title 40 Parts 141 and 142 present the requirements for the control of lead and copper in potable water systems (PWS). The rule was intended to minimize lead and copper in drinking water, primarily by reducing water corrosivity. This regulation required utilities to apply treatment techniques to meet the action levels in order to control lead and copper release from distribution systems into drinking water at the tap. The state of Florida administers the LCR per federal requirements specified under Title 40 CFR Part 141 (Subpart I) through the Florida Department of Environmental Protection (FDEP). The FDEP has published rules that adopt the national primary and secondary drinking water standards of the federal government, as well as create additional rules to fulfill state requirements. They are contained in Chapters 62-550, 62-555, and 62-560, Florida Administrative Code (F.A.C.). Chapter 62-550.800, F.A.C. (Control of Lead and Copper) presents details related specifically to the LCR requirements (detailed at the website (http://www.dep.state.fl.us/water/drinkingwater/docs/62-550_800_1.pdf) as follows:

- In-home tap sampling for large, medium, and small systems
- Source water and water quality parameters sampling
- Lead and copper action levels
- Corrosion control treatment
- Public education and notification

The PWSs that are subject to compliance must demonstrate that either an "optimal" treatment technology has been implemented for the control of lead and copper, or existing concentrations of lead and copper at residential taps are below the respective action levels mandated by the LCR. It's important to note that exceeding the lead or copper AL is not a violation of the LCR, although an exceedance does require that a utility take additional action to reduce lead and copper concentrations with its water distribution system and notify consumers. Under the LCR there are two major corrosion control treatment measures: water chemistry control or the use of corrosion inhibitors in water treatment.

Steven J. Duranceau, Ph.D., P.E., (to whom correspondence should be addressed) is professor in environmental engineering at the University of Central Florida (UCF) in Orlando. Angela B. Rodriguez, M.S., E.I., and Carlyn J. Higgins, M.S., E.I., are graduate research assistants at UCF. Rebecca Wilder, P.E., is assistant facilities manager for Jupiter Water and Stormwater Utilities. Samantha Myers-O'Farrell, M.S., E.I., is a project engineer at Jacobs in Jacksonville. Samantha J. Black, Ph.D., is a water/wastewater engineer with HDR in Raleigh, N.C. Benjamin A. Yoakum, Ph.D., E.I., is a project engineer with Wright-Pierce in Orlando. At the time this work was conducted, the co-authors were graduate research assistants at UCF.

Corrosion Study Methods and Techniques

Coupons

The most fundamental method for evaluating corrosion studies has been the "cook and look" method using metal coupons that can be manufactured in a number of shapes[4,5,6]. Metal coupons can be fabricated into any size, shape, or material required for testing. In the use of coupons, preweighed metal samples are exposed to a fluid medium (usually potable drinking water), and after the desired exposure period, are removed, cleaned of corrosion products, and reweighed. Weight loss can be converted to average corrosion rate of mils per year (mpy) using Faraday's law. Using corrosion coupons for weight loss (corrosion rate) measurements are advantageous as they are simple and inexpensive, allowing analysis of corrosion products that can easily be done in a laboratory or on service equipment. This method, however, requires long-term exposures to be more accurate, as short-term tests can yield misleading information.

Electrochemical Methods

Alternative electrochemical methods have been evaluated for use since World War II to overcome the length of testing requirements in performing corrosion control studies. Today, linear polarization techniques used to rapidly study uniform corrosion represent one of the more widespread technologies used in the application of electrochemical measurements, both in the laboratory and the field[5,6,7,8,9,10,11].

The LPR is one type of electrochemical method used to monitor corrosion, as well as other processes, such as material polarization resistance. The LPR involves the monitoring of the existing relationship between the current and the electrochemical potential, allowing the measurement of corrosion rates. This method is widely employed in liquid solutions, where it has been found to be effective. The measurement of the corrosion rate provides a means for operators to generate immediate feedback and has been used for more than 50 years due to its efficiency.

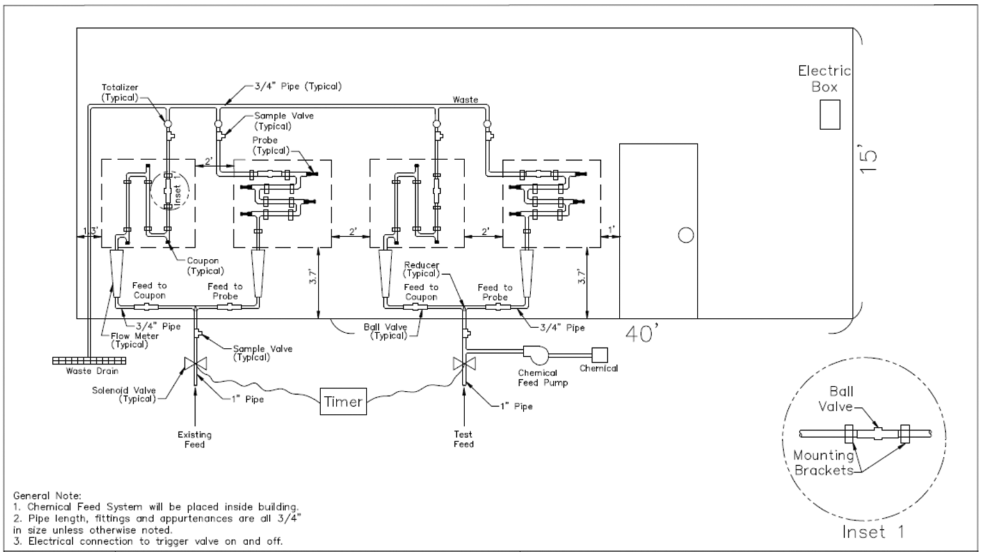
The use of the "polarization resistance" for measuring corrosion rates has one particularly important advantage: The potential range investigated is close to the corrosion potential and the applied currents are generally smaller than the corrosion current. Thus, the nature of the surface is not changed significantly, and the reactions that proceed during polarization are those that actually occur during the corrosion process. This is not necessarily the case when a corroding surface is markedly polarized, since under such conditions,

Continued on page 24

Table 1. Metal Alloys and Respective Unified Numbering System Numbers

Metal	UNS Number	Material Number and Name
Mild Steel	G10100	C1010 Mild Steel
Lead	L55030	50/50 Tin/Lead
Copper	C23000	CDA 230 Red Brass
	C26000	CDA 260 Cartridge Brass

Figure 1. Corrosion Loop Test Rack Design Example (Maui, Hawaii)
(photo: Angela Rodriguez)



General Note:
1. Chemical Feed System will be placed inside building.
2. Pipe length, fittings and appurtenances are all 3/4" in size unless otherwise noted.
3. Electrical connection to trigger valve on and off.

Figure 2. Example of Corrosion Loop Test Rack Design Schematic

Figure 3. Metal Coupon Test Rack Component
Use of coupons provides an average weight loss value. Coupons can also be analyzed for surface characteristics ["cook and look"].
(photo: Benjamin A. Yoakum)

Figure 4. Linear Polarization Probe Test Rack Component
The change in resistance of the electrochemical probe over time is measured; the rate of change is directly proportional to the corrosion rate in mils per year.
(photo: Benjamin A. Yoakum)

Continued from page 23

the subsequent corrosion rate may be affected for some time after polarization has been discontinued. The use of these electrochemical techniques does not mean that they are without complications; the effects of scan rate, solution resistance, and changing surface conditions must be controlled using sophisticated equipment to minimize complications.

Corrosion Testing Applications

The U.S. Army Corps of Engineers (USACE) developed a pipe loop system for determining the effectiveness of corrosion control chemicals in potable water[12,13]. The USACE used the recommended design demonstrated at the Aberdeen Proving Ground in Maryland (circa 1990), several years prior to the promulgation of the SDWA's LCR. In addition, the Water Research Foundation (WRF) had developed a soldered copper tubing test loop for use in conducting corrosion control studies[14]. Few utilities have relied to any great extent on the USACE and WRF methods to conduct corrosion studies since the implementation of the LCR. Moreover, municipal water supply corrosion control studies have typically focused on the water distribution system and not within the actual water treatment process clearwells, process transfer stations, and appurtenances.

Duranceau and colleagues investigated the use of electrochemical noise corrosion monitoring for water purveyors[15]. Electrochemical noise (EN) involves the monitoring of instantaneous fluctuations in corrosion current and corrosion potential normally observed between nominally identical electrodes of the material of interest in the environment of interest. The EN corrosion monitoring estimates corrosion rates from naturally occurring fluctuations of potential and current where no applied voltages or currents are used; however, EN methods (like the USACE and WRF methods) are not uniformly used or accepted by mainstream municipal water purveyors due to cost, complexity, and application limitations. The LPR methods are more commonly accepted by a far wider audience.

Additionally, prior municipal corrosion control studies have historically relied on virgin components during implementation of the studies. These methods do not account for existing system conditions and rely on "cook and look" or "concentration" data to ascertain corrosion methods. Corrosion testing by weight loss methods generally requires extended testing periods that do not necessarily produce satisfactory results. This is particularly true when the corrosion rate changes with time. Consequently, the University of Central Florida (UCF) has conducted research that has focused on overcoming some of the challenges posed when conducting chemical-based treatment evaluations used for internal corrosion control evaluations[16].

A corrosion control testing program that served as the basis for the development of the testing rack methods is described herein. The results of initial corrosion control assessments for one municipal water supply has been reported elsewhere, and since that time, UCF has further enhanced the testing rack concept, modifying the design and procedures for intent and focused implementation[16,17,18]. This article describes the testing apparatus and methods used, and reviews applications as case studies.

Methods and Materials

Corrosion Test Rack

A corrosion control testing rack apparatus was designed and constructed for use in research conducted by UCF, as depicted as an example in Figure 1. The testing apparatus housed mild steel, lead and copper coupons, and LPR electrode probes. Coupons and probes were inserted in the order of least noble to most noble. Electrodes were fastened to LPR probes, which were inserted into the corrosion apparatus. To evaluate corrosion control chemicals in a comparison mode, one side of the apparatus, referred to as the "control condition," was supplied potable water that did not contain corrosion control chemicals, while the identical parallel side of the corrosion apparatus, termed the "test condition," was supplied potable water that had been dosed with a corrosion control chemical (i.e., pH adjustment, calcium, alkalinity, or inhibitor addition). Water flow to the apparatus was controlled with an on/off timer to represent variations in the system and in homes. Test conditions were maintained by controlling flow and chemical dosage within a predetermined target range. The corrosion rates of mild steel, lead, and copper electrodes are measured routinely (typically twice per day) using a portable corrosion data logger. This data logger instrument measures the change in resistance of the electrochemical probe over time and displays the result in mpy. The rate of change is directly proportional to the corrosion rate.

The test apparatus is comprised of two parallel flow-through pipe loops equipped with chemical injection ports, in-line static mixers, LPR probes, flow meters, sampling ports, LPR data loggers and transmitters, precision flow control valves, and automatic flow on/off control. The LPR data are monitored with two identical sets of probes; one set of probes is for mild carbon steel, lead, and copper monitoring that are installed on each side of the test rack. Lead probe tips for this application are manufactured by applying a thin film of 50:50 tin:lead solder over a copper elec-

Continued on page 26

Continued from page 24

trode to simulate soldered joints in a copper water line. Coupons are typically comprised of cartridge brass, while electrodes are manufactured using red brass. Probe tips and coupons can be acquired from several corrosion vendors; however, for the work described in this article, Metal Samples Company (P.O. Box 8, 152 Metal Samples Rd., Munford, Ala. 36268) was used[19]. After the assessment of each chemical treatment method (in this case, an inhibitor) is completed, coupons and electrodes can be shipped to Metal Samples Company (or a similar entity) to conduct a post analysis evaluation.

Table 1 presents the metal materials used in the testing rack. The metal types shown represent distribution system materials of construction found in homes and residential service lines. Figure 2 presents a layout of a wall-mounted rack design to illustrate an example layout of piping components[16,17,18], although mobile designs can be made available. Figure 3 presents a pipe loop showing placement of metal coupons within the apparatus. Figure 4 presents a pipe loop showing placement of linear polarization probes so that the metal component is in the middle of the flow pattern, representing home piping.

Operating Procedures

After installation of the corrosion rack, the test rack is flushed with potable water at a rate of 8 to 10 gal per minute (gpm) to remove any material debris that may be attached to the interior surface of the piping and appurtenances. While the system is flushing, the rack is checked for proper operation of flow meters, timers, and valves, as well as pipe leaks. The chemical metering pumps are frequently checked and calibrated for proper dosage operation. After flushing and calibration, LPR probes and metal coupons are inserted into the test rack. The timer is programmed for proper operation. The LPR probes and metal coupons are handled using latex gloves to avoid leaving fingerprint residues that could influence the corrosion activity and the accuracy of the corrosion measurement. The LPR probes and electrodes are securely placed in the racks in the order of iron, copper (or brass), and lead (based on metal nobility).

The LPR is the key tool used to obtain "instantaneous" corrosion rate data, which are collected using a handheld meter (MS1500E) that plugs into each probe installed on each rack. The device reads corrosion rate and pitting index. The corrosion rate is determined by measuring the current from a small applied electrical potential difference between two measurement electrodes of each material. The pitting index is a qualitative measurement of an alloy's tendency to corrode uniformly across its surface. Approximately 20 millivolts (mV) are applied between the test and auxiliary electrodes, for a predetermined time cycle, and the polarizing current at the end of the cycle is stored. The applied potential is then automatically reversed, and the equilibrium polarizing current value is again stored. The average value of the polarizing current, in the forward and reverse polarizations, is then automatically used to calculate and display the corrosion rate as mpy.

Measuring Techniques

The gravimetric method, or weight loss method, analyzes the net average effect of corrosion over a specific time period, but does not directly determine the corrosion rate. Stern and Geary[8,9] found that a region of linear dependence of potential on an applied current can be described for a corroding electrode by treating it in a manner analogous to that for a noncorroding electrode. According to Porter and Ferguson[20], the LPR technique measures electrochemical current of an electrode surrounded with the water under consideration. When using the gravimetric method, as shown in Equation 1, it can be used to calculate the corrosion rate[18].

(Equation 1)

$$Corrosion\ Rate\ \left(\frac{mils}{year}\right) = \frac{(W)(K)}{(D)(A)(T)}$$

where,
W=weight loss (g)
D=density of the metal (g/(cm^3)
A=area of test specimen (in^2)
T=exposure time (hours)
K=5.34 x 10^5

The LPR method allows corrosion rates to be measured directly[19], and is based on the principle that, at relatively low corrosion potentials, the rate of corrosion is a linear function of polarization resistance[20]. Equation 2, a modified version of Faraday's law, can be used to calculate the corrosion rate[8,9,18,20].

(Equation 2)

$$C = \frac{(I_{CORR})(E)}{(A)(D)}(128.67)$$

where,
C=corrosion rate (mpy)
I_{CORR}=corrosion current generated by the flow of electrons
E=equivalent weight of the corroding material (g)
A=area of corroding electrode (cm^2)
D=density of corroding metal (g/cm^3)

A linear polarization measurement involves a single short-duration (less than 60 seconds) polarization offset close to the freely corroding surface potential (E_{corr}) within the linear response range between the current versus voltage curve. Polarization resistance is measured from the slope of this line and has resistance units.

The measured polarization resistance is converted to a corrosion rate by application of a conversion constant derived from the Stern and Geary equation, as shown in Equation 3.

(Equation 3)

$$i_{corr} = [1/(2.303\ R_p)][\beta_a{*}\beta_c)/(\beta_a+\beta_c)]$$

where,
i_{corr} = corrosion current density, A/cm^2
R_p = polarization resistance (Ep/i)
E_p = polarization offset (<0.01 V)
i = measured current density, A/cm^2
B_a = anodic Tafel constant
B_c = cathodic Tafel constant

Wilcoxon-Signed Ranks Test

According to Wysock and colleagues[22], utilizing the Wilcoxon-signed ranks test for corrosion monitoring can statistically show if one treatment method is more effective than another. Consequently, the Wilcoxon-signed ranks test was conducted on the corrosion rates measured for corrosion research performed by UCF. The Wilcoxon-signed ranks test was used to compare test and control conditions prior to and after treatment (chemical or proprietary inhibitor).

(Equation 4)

$$Z = \frac{T^{+} - \frac{n(n+1)}{4}}{\sqrt{\frac{n(n+1)(2n+1)}{24}}}$$

where:
T^+= sum of the ranks of positive differences between test and control conditions
n = number of observations

If the Z-value falls outside of the critical region determined by a 95 percent confidence interval, the null hypothesis can be rejected. Alternatively, if the calculated Z-value falls within the range specified by a 95 percent confidence interval, then the null hypothesis will not be rejected. Two Wilcoxon-signed ranks tests are recommended to be conducted on each metal for the assessment of each inhibitor: one during the precorrosion phase (a two-tailed test), and another during the inhibitor-effectiveness phase of testing (a one-tailed test). The null hypothesis for each metal before inhibitor addition is that the test and control conditions corroded at equal rates. Failure to reject the null hypothesis implied that the corrosion rates in the test and control conditions were equal. The alternative hypothesis of the precorrosion phase was that the test and control corrosion rates were different. As both sides of the corrosion apparatus received the same water, it was not expected that corrosion rates should differ. In theory, if one condition was corroding at a faster rate than the other prior to inhibitor addition, it would be difficult to compare results after inhibitor addition. The Wilcoxon-signed ranks test was found useful when evaluating corrosion rack data.

Results and Discussion

Corrosion control within the water treatment facility and distribution system is imperative to the long-term performance of a water purveyor's infrastructure. Internal corrosion can lead to deterioration of the system infrastructure and water quality, leading to taste, odor, and microbial growth problems. Changes in water conditions without changes in corrosion control treatment can impact lead, copper, and iron release, thus compliance, and operating and maintenance costs; if not properly selected, use of an incompatible corrosion control treatment method may result in regulatory noncompliance. Because corrosion is an electrochemical process, monitoring methods that take advantage of electrochemical processes are typically very rapid, as compared to the traditional methods of weight loss coupons, and include electrical resistance probes or direct inspection by visual or surface analytical means.

Although existing distribution system plumbing materials are already at least partially corroded, many corrosion studies cited in the literature evaluated corrosion rates using virgin coupons and electrodes. Subsequently, the method developed in research conducted by UCF assessed the corrosion inhibitors' ability to reduce mild steel, lead, and copper corrosion rates under precorroded conditions. At the start-up of each inhibitor evaluation, mild steel, lead, and copper components experienced high corrosion rates, eventually stabilizing to a relative steady state (corrosion fluctuations remain; however, a baseline can be statistically determined). Use of parallel test racks allows a direct comparison of test versus control conditions. It's acknowledged that the use of coupons provides limited value when conducting screening studies of short duration. Although mpy measurements in these cases may not be accurate, evaluation of surfaces using X-ray spectrophotometric techniques may provide beneficial perspectives on corrosion morphologies.

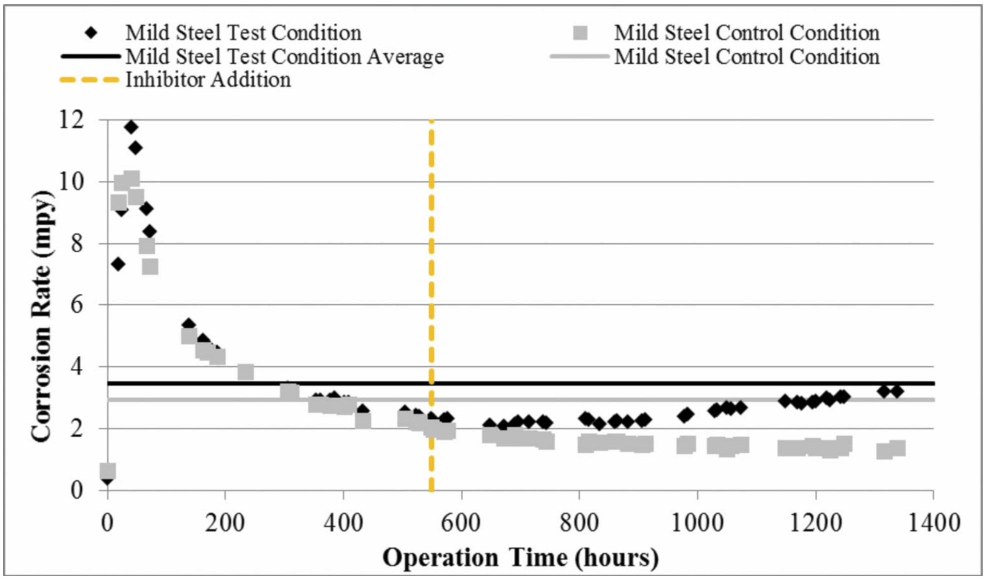


Figure 5. Example Graph Displaying Corrosion Rate (mils per year) Versus Time [10,11]

Water Plant Infrastructure Corrosion Control Example

Unlike previous studies, this research assessed the corrosion inhibitors' ability to reduce mild steel, lead, and copper concentrations under precorroded conditions. Prior research indicates that corrosion inhibitors are a viable option to reduce mild steel, lead, and copper release within the distribution system[22]. Findings demonstrate that orthophosphate- and polyphosphate-blended inhibitors are largely successful in inhibiting and sequestering lead and copper in home taps. Duranceau and colleagues[24] indicated that corrosion inhibitors can be added to membrane permeate to prevent scaling and corrosion in pipes and other appurtenances. Phosphate-based inhibitors, including blended orthophosphate:polyphosphate (ortho:poly) inhibitors, are available in a variety of compositions. According to Cantor and researchers[23], polyphosphates are used to minimize the sequestering of metals, while orthophosphate is added to protect against scale formation. These researchers[22,23,24] recommended that water purveyors conduct controlled monitoring evaluations of corrosion inhibitors prior to implementation.

Figure 5 provides a representative graphical display of corroding mild steel probes, followed by a stabilization period, then a response after chemical treatment for permeate water blends of nanofiltration and reverse osmosis processes[16,17]. The graphical display illustrates mild steel corrosion rates before and after the addition of a phosphate-based chemical corrosion control inhibitor as a function of operating time. In this example, it is noted that during the precorrosion phase, mild steel corrosion rates decreased in both the test and control conditions. Subsequently, after the inhibitor was added to the test side of the corrosion apparatus, mild steel corrosion rates began to increase in the test condition, yet continued to decrease in the control condition. Although not shown, this water supply responded favorably to corrosion control treatment for copper and lead materials, and hence was recommended for use in this example water system[16,17,18]. This example serves to demonstrate that inhibitor use for lead and copper may have slight adverse effects on iron-based components (such as cast iron pipe) in the distribution system.

Distribution System Infrastructure Corrosion Control Example

Figure 6 provides another example, in a graphical display, for groundwater supply and corroding copper probes. As in Figure 5, the initial corrosion period is followed by a stabilization period, then a negative response after chemical treatment. The graphical display illustrates copper corrosion rates before and after the addition of a phosphate-based chemical corrosion control inhibitor as a function of operating time. In this example, it's noted that during the precorrosion phase, copper corrosion rates decreased in both the test and control conditions. Subsequently, after the inhibitor was added to the test side of the corrosion test rack, copper corrosion rates began to increase in the test condition, but decreased in the control condition. In this example the corrosion rates for copper were low, without the need for chemical treatment. For this water, a phosphate-based corrosion control inhibitor would not be recommended.

Continued on page 28

Continued from page 27

Figure 7 provides a representative graphical display of the corrosion rate response of mild steel probes, exposed to changing disinfectant cycles, in a surface water chloramine system. Average baseline-measured corrosion rates were 1.5 mpy for mild steel, 0.3 mpy for copper, and 0.4 mpy for lead solder. Conversion to chlorine disinfection did not have an effect on copper and lead solder corrosion rates, but did increase the mild steel corrosion rate significantly. The increase in the mild steel corrosion rate under chlorine disinfection was positively correlated to the total chlorine residual concentration. The threshold total chlorine residual concentration, past which mild steel corrosion rates did not return to baseline after switching back to chloramines from chlorine, was 5.0 mg/L as Cl_2. In addition, the unusual mild steel and copper baseline corrosion curve shape (logarithmic instead of exponential) was theorized to be due to high organic acid content forming a protective layer on the metal surface. The weight-loss-based calculated corrosion rates for the copper and lead solder coupons were found to be lower than the LPR measurements.

Scanning electron microscopy and energy dispersive X-ray analysis of the mild steel coupon tuberculation layer found that its structure and appearance could be attributed to organic/biological influences. The findings from this one example study shed light on the morphological and elemental differences of tuberculation layers from a chlorine and chloramine system, and also elucidated the sensitivity of corrosion rates to changes in disinfectant type. This is particularly important for chloramine systems that practice regular chlorine maintenance cycles to control nitrification problems in their distribution systems.

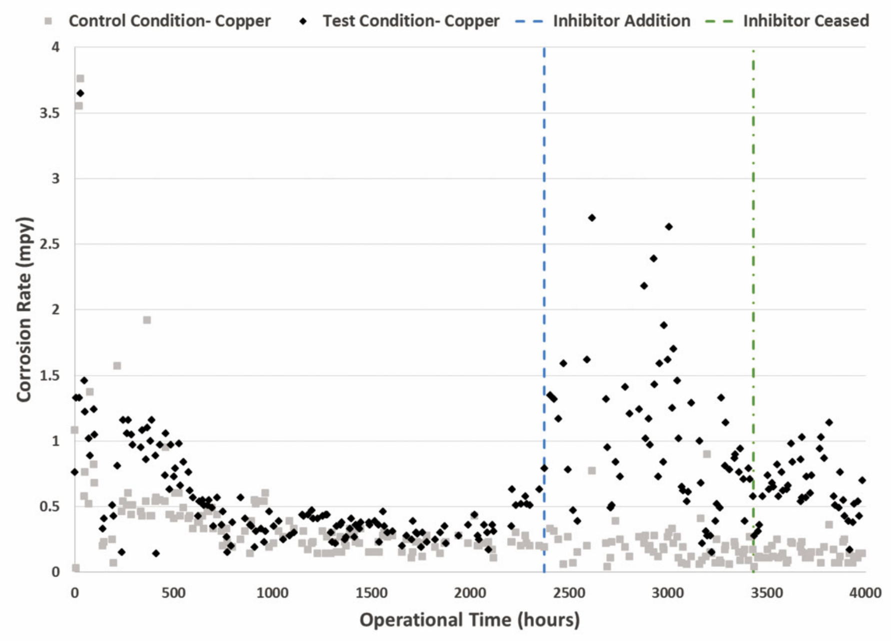


Figure 6. Representative Plot Illustrating Metal Release for Incompatible Inhibitor Type

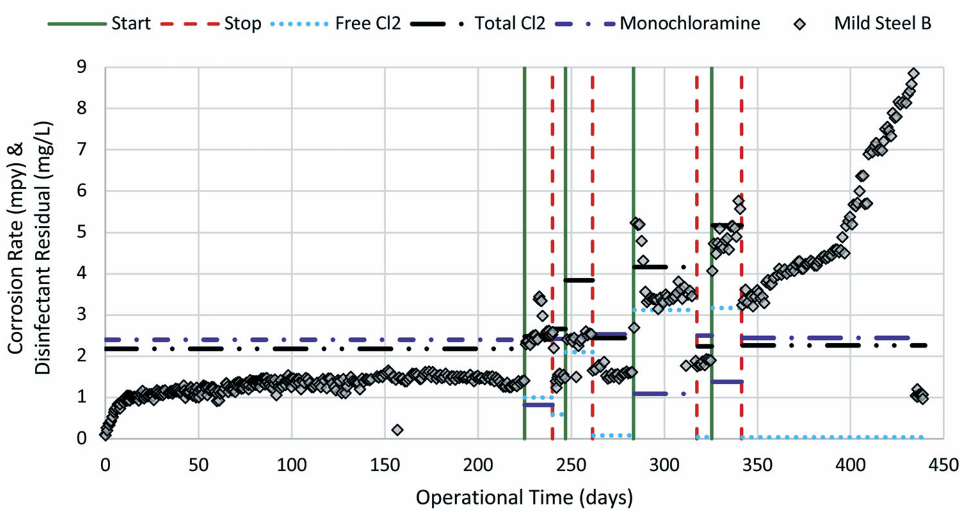


Figure 7. Representative Plot Illustrating Metal Release for Changing Disinfectant Type

Opinion of Probable Corrosion Test Rack Cost and Water Quality

One complete set of replacement probe tips and coupons approximated $2,500, with testing period intervals that approximate two months. Metal coupons, holders, probes, and other miscellaneous wands approximated $3,900, while an LPR probe, handheld meter approximated $1,400, providing an opinion of probable construction costs of close to $11,000. Water quality parameters evaluated in this research include pH, temperature, conductivity, dissolved oxygen, turbidity, alkalinity, total chlorine, chloride, calcium and total hardness, and orthophosphate. Also, pH, temperature, chlorine, and orthophosphate are recommended to be measured twice per weekday, while other water quality parameters can be evaluated twice per week (or at a different frequency, as desired).

Findings Summary

The use of precorroded LPR probes and coupons for conducting accurate and rapid corrosion control inhibitor screening studies has been demonstrated. A corrosion control testing rack apparatus using two identical parallel flow loops was designed and constructed to house mild steel, lead, and copper coupons used for weight loss analysis, as well as mild steel, lead solder, and copper electrodes used for LPR analysis. Coupons and electrodes were precorroded to simulate existing distribution system conditions. Although existing distribution system plumbing materials are already partially corroded, many corrosion studies cited in the literature evaluated virgin coupons and electrodes. The test rack was found useful for conducting studies for corrosion control chemical selection, distribution system blending studies, and clearwell and process infrastructure studies. Alkalinity addition, pH adjustment, and use of inhibitors were found to be beneficial for lowering corrosion rates in water system infrastructure.

Additional findings included:

- Different water supplies may respond differently to differing corrosion control chemicals; consequently, corrosion control pipe loop testing is recommended prior to selection of an appropriate chemical control method, whether for permeate or any water supply.

- At times a change in disinfectant type can cause a permanent and negative corrosion rate change, and in one of the studies presented herein, the threshold parameter was found to be the total chlorine residual concentration that was exposed to the metal.
- Blended orthophosphate-polyphosphate corrosion inhibitors were found to reduce lead and copper corrosion in the distribution system, but varied by manufacturer, blend formulation, and water supply; mild steel rates were at times adversely affected. Silicate inhibitor addition offered mixed results and altered pH significantly.
- It's important to compare average corrosion rates prior to and after inhibitor addition, where applicable, to evaluate the performance of a selected inhibitor; note however that corrosion rates as a function of time should also be evaluated to observe how corrosion rates change throughout inhibitor assessments.
- The use of precorroded LPR samples allows for the rapid evaluation of changes and can screen alternative treatments comparatively. Studies can be completed in as little as 10 weeks using LPR. The use of coupons provides limited value when conducting short duration studies, and although mpy measurements in these cases may not be accurate, evaluation of surfaces using X-ray spectrophotometric techniques may provide beneficial perspectives on corrosion coupon morphologies.
- A comparison between the control and test conditions can be analyzed statistically using the Wilcoxon-signed ranks test, which compares control and test conditions since the distribution of data are dependent and nonparametric. The use of the test for statistical analysis during corrosion monitoring is found to be a useful technique.
- Metal coupons, holders, probes, and other miscellaneous wands approximated $3,900, while an LPR probe, handheld meter approximated $1,400, providing an opinion of probable construction cost of close to $11,000. A set of replacement probe tips and coupons approximated $2,500, with testing period intervals that approximate two months.

Acknowledgments

This work would not have been possible without the support of Jupiter Water Utilities (Jupiter, Fla.), RosTek Associates Inc. (Tampa, Fla.), Kimley Horn & Associates Inc. (West Palm Beach, Fla.), Pulama Lanai Utilities (Honolulu, Hawaii), Aqua Engineers Inc. (Kalaheo, Hawaii), Brown & Caldwell (Wailuku, Hawaii), and the County of Maui Department of Water Supply (Wailuku, Hawaii). Funding was provided through UCF Contracts 16208083, 16208114, 16208134, 16208138 and 16208168 with the aforementioned agencies. Special thanks go to the UCF drinking water research team members who supported the graduate students in conducting corrosion control research over the years. Reference to any specific commercial product, process, or service, or the use of any trade, firm, or corporation name is for the information and convenience of the public, and does not constitute endorsement, recommendation, or favoring by UCF or its board of governors.

References

[1] Code of Federal Regulations. Title 40 CFR Part 141 (Subpart I). 56 Federal Register, 26548, June 7.

[2] USEPA (2003) Revised Guidance Manual for Selecting Lead and Copper Control Strategies. EPA-816-R-03-001, Office of Water, Washington, D.C.

[3] USEPA (2008) Lead and Copper Rule: A Quick Reference Guide. EPA816-F-08-018, Office of Water.

[4] Banerji, S.K., J.E. Bauman, and J.T. O'Conner (1987). Evaluation of Silicate and Phosphate Compounds for Corrosion Control. EPA/600/s2-87/031, June 1987. USEPA Water Engineering Research Laboratory, Cincinnati, Ohio 45268.

[5] Ahmad, Z. (2006). Principles of Corrosion Engineering and Corrosion Control. Elsevier.

[6] Roberge, P.R. (2000). Handbook of Corrosion Engineering, McGraw-Hill, 1140 pages.

[7] NACE. (1999). Techniques for Monitoring Corrosion and Related Parameters in Field Applications. NACE International Publication 3T199; Item No. 24203.

[8] Stern, M. and A.L. Geary (1957). Electrochemical Polarization: I. A Theoretical Analysis of the Shape of Polarization Curves. *Journal of the Electrochemical Society*, Vol. 104, No. 1, 56-63.

[9] Stern, M. (1958). A Method for Determining Corrosion Rates from Linear Polarization Data. Corrosion, Vol. 14, No. 9, 440t-444t.

[10] Mansfield, F. (1976). "The Polarization Resistance Technique for Measuring Corrosion Currents." Advances in Corrosion Science and Technology, Vol. 6, ed. by M.G. Fontana and R.W. Staehle, Plenum Press, New York.

[11] ASTM International. (2015). ASTM G59 - 97(2014) Standard Test Method for Conducting Potentiodynamic Polarization Resistance Measurements. ASTM Int., 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, Penn. 19428-2959.

[12] Prakash, T.M., et al. (1988). Development of the Pipe Loop System for Determining the Effectiveness of Corrosion Control Chemicals in Potable Water Systems. Technical Report N-88/12/ADA200105, U.S. Army Construction Engineering Research Labs (USACERL), August 1988.

[13] Scholze, R.J., K.A. Pontow, G. Kanchibhatia, and B.T. Ray (1994). Using the CERL Pipe Loop System (PLS) to Evaluate Corrosion Inhibitors That Can Reduce Lead in Drinking Water. Fort Belvoir, Va.: U.S. Army Corp of Engineers Facilities Engineering Applications Program.

[14] Water Research Foundation. (1990). Lead Control Strategies. Denver, Colo.: AWWA.

[15] Duranceau, S.J., D. Townley, and G.E.C. Bell (2004). Optimizing Corrosion Control in Water Distribution Systems. Denver, Colo.: Awwa Research Foundation and AWWA. 271 pages.

[16] Wilder, R. (2012). Evaluating Corrosion Control Alternatives for a Reverse Osmosis, Nanofiltration, and Anion Exchange-Blended Water Supply. Orlando, Fla.: University of Central Florida (Thesis).

[17] Jeffery, S. (2013). In-Plant and Distribution System Corrosion Control for Reverse Osmosis, Nanofiltration, and Anion Exchange Process Blends. Orlando, Fla.: University of Central Florida (Thesis).

[18] Wilder, R.J. and S.J. Duranceau. (2012). Evaluating In-Plant Infrastructure Corrosion After Replacing Lime Softening With Nanofiltration and Blending with Reverse Osmosis and Ion-Exchange Process Water. *Florida Water Resources Journal*. 64(10); 42-55.

[19] Metal Samples Company. P.O. Box 8, 152 Metal Samples Rd., Munford, Ala. 36268.

[20] Porter, R.; Ferguson, J. (1995). Improved Monitoring of Corrosion Proc. *Journal American Water Works Association*, 87(11), 85-95.

[21] Crittenden, J.C., R.R. Trussell, D.W. Hand, K.J. Howe, and G Tchobanoglous. Water Treatment Principles and Design, 3rd ed., New Jersey: John Wiley & Sons Inc., 2012.

[22] Wysock, B. M., Sandvig, A. M., Schock, M.R., Frebis, C. P., and Prokop, B. (1995). Statistical Procedures for Corrosion Studies. *Journal American Water Works Association*, 87 (7), 99-112.

[23] Cantor, A.F., Denig-Chakroff, D., Vela, R.R., Oleinik, M.G., and Lynch, D.L. (2000). Use of polyphosphate in corrosion control. *Journal American Water Works Association*, 92 (2), 95-102.

[24] Duranceau, S.J., Wilder, R.J. & Douglas, S.S. (2012). Guidance and Recommendations for Post-Treatment of Desalinated Water. *Journal American Water Works Association*, 104 (9), E510-E520.