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CONTROL OF METAL-RELEASE AND TUBERCULATION IN A SILICA-LADEN GROUNDWATER DISTRIBUTION SYSTEM ON THE VOLCANIC ISLAND OF LANA'I

by

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A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Civil, Environmental, and Construction Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
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Major Professor: Steven J. Duranceau

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ABSTRACT

In August of 2014, the University of Central Florida's (UCF's) Civil, Environmental, and Construction Engineering Department was retained to conduct a corrosion control study for Pulama Lana'i Water Company, a private water utility on the Hawaiian island of Lana'i. The aim of this project was to evaluate several corrosion inhibitors at two locations to treat corrosion and tuberculation within the distribution systems. The island measures just over 140 square miles and is historically arid, receiving approximately ten inches of rainfall per year. Non-native Cook Island Pine trees supplement the groundwater supply via fog-drip infiltration.

Two distinct distribution systems were studied: (1) the Manele Bay distribution system and (2) the Lana'i City distribution system. The utility provides water to a steady population of approximately 3100 residents. In some parts of the island, the distribution system is upwards of 50 years old. An expansion in residency would require the development of alternative water sources, thus knowing baseline corrosion rates within the current system is highly beneficial. Additional alternative water supply introduced to the distribution system may unintentionally impact compliance with the Safe Drinking Water Act's (SDWA's) Lead and Copper Rule (LCR).

The Manele Bay system is supplied by one well, while the Lanai City system relies on water supplied by three wells. The well water on the island is generally of high quality; therefore, the historical treatment method has been limited to disinfection (as free chlorine) prior to distribution. However, well water quality varies between wells. The distribution systems consist of several materials of construction, the majority of which is galvanized iron. Valves and pipes in both systems were experiencing visible corrosion and tuberculation believed to be responsible for variable pressure drop throughout portions of the system.

The research presented herein focused on performing a corrosion control study for both the Lana’i City and Manele Bay water systems. Two corrosion racks, each consisting of two parallel loops, were installed at each site; one loop was maintained as a control while the other loop was used for testing the effect of corrosion inhibitors. Each loop contained sections for sample coupons and linear polarization probes for analysis of corrosion rate of selected metals of interest. Coupons were utilized for weight loss (gravimetric) measurement while probes were used to obtain linear polarization resistance (electrochemical) measurements.

Results indicate that the water in Manele Bay experienced little to no change between the test loop and control loop when inhibitor was added. Baseline testing at Manele Bay showed that the corrosion rate for mild steel, lead, and copper coupons after 4,008 hours of exposure were 0.70 mils per year (mpy), 0.20mpy, and 0.14mpy respectively. The addition of 1.0 mg/L of blended phosphate inhibitor did not reduce nor increase the corrosion rates of the mild steel, lead, and copper coupons after an exposure time of approximately 2,700 hours. A second round of baseline testing indicated that after 2,232 hours of exposure mild steel, lead, and copper corrosion rates were stable at 0.60mpy, 0.18mpy, and 0.17mpy respectively. The addition of 1.0 mg/L of a silica inhibitor did not reduce nor increase the corrosion rate of mild steel, lead, and copper coupons after an exposure time of approximately 1,000 hours.

Results from Lana’i City indicate that inhibitors offer little to no positive effect between the control condition and test condition corrosion rates. Baseline testing at Lana’i City showed that the corrosion rate for mild steel, lead, and copper coupons after 2,376 hours of exposure were 0.40mpy, 0.19mpy, and 0.35mpy respectively. The addition of 1.0 mg/L blended phosphate inhibitor did not reduce nor increase the corrosion rates of mild steel and lead. However, the corrosion rate of copper increased to an average corrosion rate of 1.0mpy during blended phosphate inhibitor addition. Following the termination of inhibitor feed, the average corrosion rate for copper was 0.73mpy. A second round of baseline testing indicated that after 1,416 hours of exposure mild steel, lead, and copper rates were stable at 2.0mpy, 0.22mpy, and 0.85mpy respectively. The addition of 1.0 mg/L of silica inhibitor did not reduce nor increase the corrosion rate of mild steel, lead, and copper coupons after an exposure time of approximately 600 hours.

Since the waters in both locations do not benefit from adding corrosion inhibitor, UCF recommended a valve exercise and replacement program for the Pulama Lana’i Water Company’s assets. The objectives of the valve exercise and replacement program included: (1) a detailed asset inventory, (2) specific operation and maintenance tasks for individual valves as well as for the entire distribution system, and (3) the establishment long-range financial planning for the utility. In general a valve exercise and replacement program will help to extend the life of the utility’s assets and keep the system in operation for continued service and emergency needs. With an initial investment in an automatic valve exerciser, the approximate operation and maintenance budget for the valve exercise program is estimated to be $19,000 during the first year, and $8,000 in subsequent years (for the expected life of the exercise equipment). An opinion of probable replacement cost for 200 new valves was conceptually estimated to approximate $3.3 million expended over a 20 year time period.

This thesis is dedicated to my family. Thank you for your love and support.

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This work was only possible because of the support provided by several individuals. I would like to thank Dr. Steven J. Duranceau for providing the opportunity to work on this research project and serve as my advisor and mentor throughout my time at UCF. In addition, I would like to thank my committee members, Dr. Woo Hyoung Lee and Dr. Anwar Sadmani for time they took to review this manuscript and serve on my committee. I would also like to express my sincerest appreciation to Mrs. Maria Real-Robert, the Civil, Environmental, and Construction Engineering Laboratory coordinator, for her guidance, assistance, and patience.

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LIST OF ABREVIATIONS

AL	Action Level
ALSPI	Alabama Specialty Products Inc.
AQUA	Aqua Engineering Inc.
CEI	Chromatic Elemental Imaging
CFR	Code of Federal Regulations
CL	Control Limit
CWL	Control Warning Limit
DOH	Department of Health
EDX	Energy Dispersive X-Ray
EPDM	Ethylene Propylene Diene Monomer (Rubber)
GIS	Geographic Positioning System
GPS	Geographic Positioning System
IBBM	Iron Body- Brass Mount
IC	Ion Chromatograph
ICP	Inductively-Coupled Plasma
LCR	Lead and Copper Rule
LPR	Linear Polarization Resistance
LR	Larson Ratio
LSI	Langelier Saturation Index
MCLG	Maximum Contaminant Level Goal
MDL	Maximum Detection Limit
MGD	Million Gallons per Day
PVC	Polyethylene Vinyl Chloride
QA	Quality Assurance
QC	Quality Control
RPD	Relative Percent Difference

RSI	Ryznar Saturation Index
SEM	Scanning Electron Microscope
TDS	Total Dissolve Solids
UCF	University of Central Florida
UCF-MCF	University of Central Florida Materials Characterization Facility
UNS	Unified Number System
USEPA	United States Environmental Protection Agency
UWL	Upper Warning Limit
WL	Warning Limit
WWTF	Wastewater Treatment Facility
XPS	X-Ray Photoelectron Spectroscopy

CHAPTER 1: INTRODUCTION

Water distribution systems historically have been made from various materials. Most recently these materials have included metals, concrete, and plastics. The internal corrosion of drinking water distribution pipelines is of particular concern to both utilities and consumers. When pipelines fail in the distribution system due to corrosion and tuberculation, this can affect water quality, pose a risk to public health, and increase the cost of providing safe drinking water. The internal corrosion of metals in drinking water systems is specific to the water source; therefore, it is prudent of utilities to conduct corrosion control studies focused on their particular water and treatment processes.

Corrosion cannot be completely controlled, it is usually only slowed and rarely entirely stopped. Because corrosion is inevitable within a water system, the replacement of metal pipelines and components is required. Many utilities across the United States are facing aging distribution systems that require high maintenance, replacement, and operations costs. The fact that pipes of different materials within these distribution systems can experience variable rates of corrosion would suggest that protection measures are warranted.

Utilities producing potable water from groundwater often have consistent water quality throughout the year; therefore, treatment of such water is predictable and steady. In addition to having predictable effluent water quality, the corrosion rates can also be easily predicted. Hence, replacement of aging components can be forecasted and a long-term cost analysis and goal can be developed.

Corrosion studies are often linked to compliance with the Lead and Copper Rule (LCR) as well as with red water concerns. This project focused on the corrosion of two distribution systems on the

Hawaiian island of Lana’i. Of particular concern was the corrosion and tuberculation of iron components in their already aging system. The research in this document is focused on two separate distribution systems. Therefore, the document chapters herein are organized in two sections:

1) The Manele Bay Distribution System
2) The Lana’i City Distribution System

Corrosion control experiments were conducted within each distribution system to determine real-time corrosion rates and to find a solution to reduce the existing corrosion occurring in the system. The corrosion control experiments involved the assessment of two inhibitors and their effect on mild steel, lead, and copper release of each distribution system.

CHAPTER 2: LITERATURE REVIEW

Corrosion Fundamentals

Corrosion is the interaction of an electrochemical species with a metal surface (AWWA, 2011a); in a drinking water system these interactions usually occur between potable water and the surface of a pipe. The process of corrosion involves the oxidation of a metal by constituents in the water such as dissolved oxygen or chlorine (Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2012). The release of metal into a drinking water system may result in decreased water quality that could include potential health concerns, discoloration, and/or adverse taste and odor problems (AWWA, 2011a). In addition to the possibility of decreased water quality, distribution system infrastructure can also be severely impacted by corrosion resulting in plumbing or valve failures. In 2008 AWWA stated that a majority of drinking water infrastructure required replacement over the next 30 years due to end of service life and corrosion of the pipe lines (AWWA, 2008).

For corrosion to occur, four components which compose a corrosion cell are necessary: (1) the anode, (2) the cathode, (3) a conductor, and (4) a conducting electrolyte. Figure 2-1 depicts a corrosion cell on an iron metal surface and the reactions that occur at each interface. Anodes and cathodes can develop on the surface of a metal pipe for a variety of reasons including: characteristics of the metal, characteristics of the water, sediment accumulation, impurities in the metal, and accumulation of the products of corrosion (AWWA, 2011b).

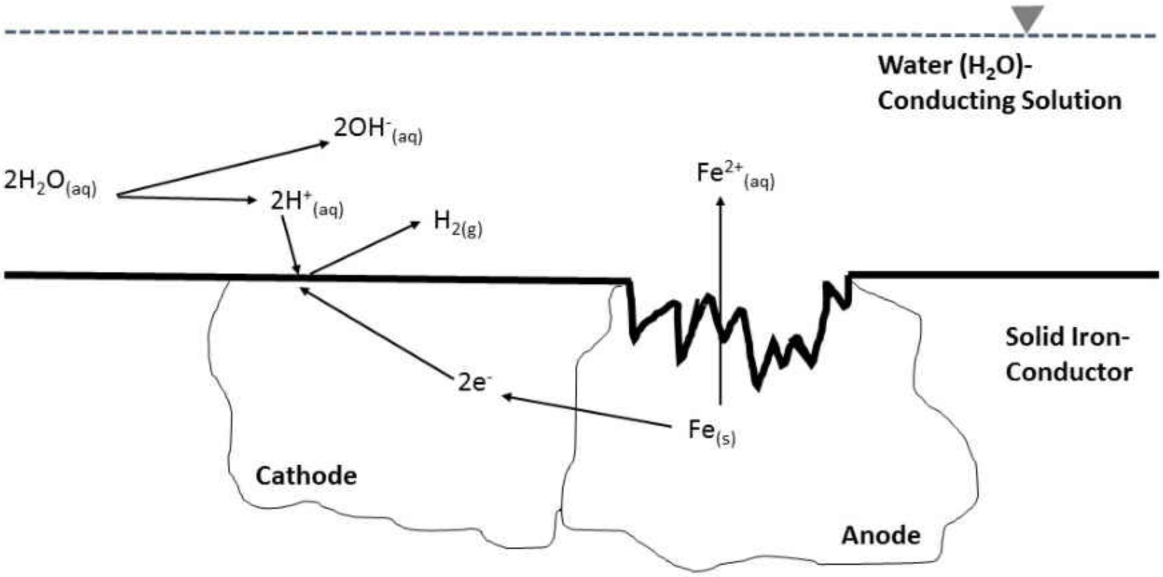


Figure 2-1: A Simple Diagram of a Corrosion Cell in an Iron Pipe

Corrosion is an oxidation reaction and occurs at the anode where electrons from the metal are generated and metal cations are released to the conducting solution. In Figure 2-1, the iron pipe releases ferrous iron (Fe^{2+}) into the surrounding water solution. Electrons generated at the anode travel through the metal conductor to the cathode. At the cathode, these electrons react with water and hydrogen to form hydroxide ions (OH^-) and hydrogen gas (H_2). In this example, the reaction occurs in an acidic solution and hydrogen ions are the electron acceptor, thus H_2 is formed. If the reaction were to occur in a basic solution, electrons accepted by the cathode react with oxygen in the surrounding water to form hydroxide ions. Furthermore, metal cations released at the anode can react with hydroxide ions to create rust, or iron hydroxide ($Fe(OH)_2$). Cations produced at the anodic site tend to attract negative particles in the water; the opposite is true of the cathodic site where anions produced attract positively charged particles. Ion movement is a result of changing concentration gradients which retains electro-neutrality in the solution (AWWA, 2011b).

Drinking water is typically devoid of metals in the bulk solution and therefore not in equilibrium with the metal materials within the distribution system. As a result of this gradient, an oxidation reaction occurs with the metal going into solution in an attempt to reach equilibrium with the bulk solution (AWWA, 2011b). The oxidation reaction occurring in the metal is represented in equation 2-1 where M represents the metal (measured in volts), z represents the charge, and e^- represents the electrons.

$$\mathbf{Me} \leftrightarrow \mathbf{Me^{z+}} + \mathbf{ze^{-}} \qquad (2\text{-}1)$$

As equation 2-1 proceeds to the right, oxidation is occurring and the resulting current is referred to as anodic exchange current (AWWA, 2011b). In this direction, the rate can be characterized by metal or weight loss. If the equation proceeds to the left, a reduction reaction in which the metal ions combine with electrons occurs and is referred to as cathodic exchange current (AWWA, 2011b). At equilibrium both directions of the reaction are occurring simultaneously and the metal experiences no net corrosion (AWWA, 2011b).

The type of metal and variable water quality parameters can influence the rate at which corrosion will occur. Water quality parameters affecting corrosion rates may include: (1) dissolved oxygen concentration, (2) pH, (3) temperature, (4) water velocity, (5) chlorine, chloride, and sulfate concentrations, and (6) calcium (AWWA, 2011b; Volk, Dundore, Schiermann, & LeChevallier, 2000). There are three steps which control the rate of corrosion:

1) Transport of dissolved reactants to the metal surface.
2) Electron transfer at the surface.
3) Transport of dissolved products from the reaction site.

When one of these steps is the slowest, this is known as the rate-limiting step.

Types of Corrosion

Where and how corrosion occurs is dependent on a number of factors. These may include imperfections on metal surface, bacterial presence, temperature, concentration of oxidants, and the solubility of the metal (AWWA, 2011a, 2011b; AWWARF & DVGW, 1996; Crittenden et al., 2012; Hill & Cantor, 2011).

Corrosion can take one of two forms: uniform or localized. Table 2-1 describes uniform and localized corrosion. Table 2-2 presents common forms of localized corrosion. Corrosion types pertinent to this project are further described following the tables. More information on corrosion types can be found in: Crittenden, 2012; Singley et. al, 1985, Duranceau et. al, 1996 and AWWA 2011b.

Table 2-1: Description of Forms of Corrosion

Forms of Corrosion	Description
Uniform	Corrosion that occurs uniformly over a metal's surface. Typically, a thin film will develop protecting the metal from further corrosion
Localized	Refers to corrosion that is not uniform. Localized corrosion is often a function of metal characteristics and water quality.

Table 2-2: Description of Types of Localized Corrosion

Type of Localized Corrosion	Description
Galvanic	Corrosion occurring when two dissimilar metals are next to each other where one metal serves as the anode and the other serves as the cathode. The anodic metal experiences corrosion.
Pitting	Corrosion that occurs on one small part of the pipe surface and causes pits or holes. One part of the metal surface becomes the anode and surrounding areas act as the cathode.
Tuberculation	Corrosion products precipitate out of solution forming tubercles. Tuberculation typically occurs in conjunction with pitting corrosion.
Erosion	Corrosion of the protective scales and films that have formed on the metal surface. This type of corrosion is common where there is high water velocity as in beds or elbows of pipes.
Stray Current	Grounding of electrical systems to underground piping is a common practice. Stray current corrosion occurs when the electrical current exits a pipe, causing corrosion on the outside of the pipe.

Pitting Corrosion

Unlike uniform corrosion, pitting corrosion occurs on one small part of the pipe surface and causes pits or holes on the metal surface (AWWA, 2011b). Pitting occurs when one part of the surface becomes the anode and the surrounding surface serves as the cathode (Crittenden et al., 2012). Factors contributing to pitting include: (1) oxidizing potential of the conducting solution, (2) the presence of aggressive ions, and (3) the condition of the surface (Crittenden et al., 2012). Pitting does not cause high quantities of metal release; therefore, it is difficult to predict using water quality measurements (AWWA, 2011b).

Initial detection of pitting corrosion is inherently difficult due to the size of the corrosion location. Pits continue to grow over time and the corresponding pinhole leaks that develop make pitting corrosion a destructive and costly form of corrosion (Kirmeyer & Logsdon, 1983).

Tuberculation

Products of corrosion often combine with other available constituents in the conducting solution and precipitate out of solution forming tubercles (AWWA, 2011b). Tubercles often form on steel and iron piping exposed to oxygenated water sources at locations experiencing pitting corrosion. Tubercles can be a substantial problem in distribution systems since they can constrict water flow and cause red water. Red water can occur when changing water quality causes iron particles from the tubercle to dissolve into the solution, causing a change in water color and quality (Clement, 2002).

In flowing water systems where oxygen is present, as those seen in drinking water distribution systems, an iron ion that is released reacts with oxygen forming ferrous and ferric compounds creating a crust layer (Clement, 2002). Tubercles are made of five distinct layers: (1) Outer crust, (2) Inner shell, (3) Core material, (4) fluid filled cavity, and (5) Corroded floor (Davis, 2000). Figure 2-2 is a schematic depicting these layers on mild steel.

The outer hard layer of the tubercle is typically composed of magnetite, lepidocrocite and goethite, and acts as a semiconductor that electrons can travel to from the metal (Crittenden et al., 2012). Often the migration of oxygen to inside the tubercle is inhibited by the outer crust. The inner layers of the tubercle are soluble and porous. The inner crust is composed of mainly ferrous phases of iron including iron, hydroxide ($Fe(OH)_2$) and iron carbonate ($FeCO_3$) (Clement, 2002).

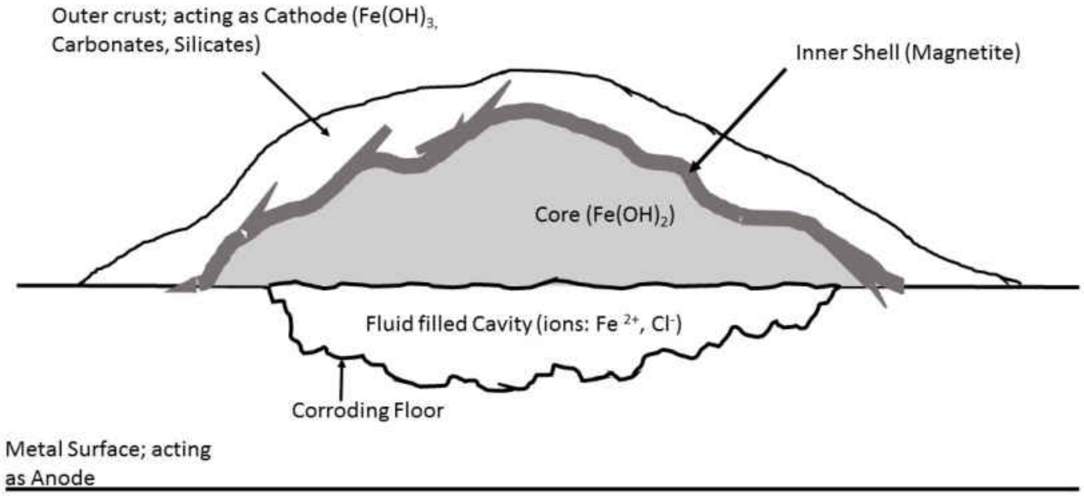


Figure 2-2: A Simple Diagram Depicting the Layers of an Iron Tubercle

Corrosion Measurement and Monitoring

Corrosion monitoring is an important component of water quality for many utilities. Corrosivity of water within a distribution system can affect the performance of protect pipes, storage tanks, and valves. In addition to protecting valuable assets, corrosion monitoring can help utilities understand the impact their water quality may have on the lead and copper rule (LCR) compliance.

Indirect Measurement: Corrosion Indices

Although it is very difficult to predict when corrosion will occur or how quickly it will occur, several empirical equations or indices have been developed. Water quality characteristics including pH, alkalinity, hardness, and calcium, are used to calculate various indices. The results can then be used to compare the corrosivity of similar waters. The following common corrosion indices are based on the solubility of calcium carbonate species. In theory, the development of a protective layer of calcium carbonate scale will provide barrier protection to corrosion of various metals. Calculation of the saturation of the carbonate systems and other ions can be used predict the corrosivity of certain waters.

Langelier Saturation Index (LSI)

At the time Langelier (1936) developed his saturation index, pH measurement was becoming more precise and calcium carbonate saturation was a popular means of controlling iron corrosion. The LSI optimizes alkalinity and calcium equilibrium within a water source. Langelier (1936) developed a mathematical means to determine the "saturated pH" (pH_s) as presented in equation 2-2. The minimum information required for the LSI calculation is: (1) total alkalinity, (2) calcium concentration, (3) ionic strength (i.e. by total dissolved solids concentration), (4) pH, (5) temperature, and (6) saturated pH (pH_s). The LSI is reported by many utilities throughout the United States as a means of compliance (AWWA, 2011b).

$$pH_s = pk_2' - pk_{so}' - \log[Ca^{2+}] - logAlk \qquad (2\text{-}2)$$

Where,

pk'_2 = acidity constant for dissociation of bicarbonate

pk'_{so} = solubility constant for dissolution of calcium carbonate

$\log[Ca^{2+}]$ = log value of calcium concentration

log *Alk* = log value of alkalinity concentration

In equation 2-2 it is pertinent to note that $[Ca^{2+}]$ and *Alk* be in the units of moles/L. When the pH is between 6.5 and 8.5 the alkalinity component can be ignored (Crittenden et al., 2012). The LSI is defined as the difference between pH and pH_s, and is most applicable to waters with a pH range of 7.0 to 9.5. The LSI equation is given in equation 2-3.

$$\boldsymbol{LSI = pH - pH_s} \qquad (2\text{-}3)$$

LSI can be either positive or negative (Crittenden et al., 2012): If the LSI is < 0, the solution is under-saturated with calcium carbonate ($CaCO_3$); thus, $CaCO_3$ can dissolve and corrosion may occur. If the LSI is > 0 the solution is supersaturated with $CaCO_3$; thus, $CaCO_3$ precipitates and scale is formed. If the LSI $= 0$, the solution is at equilibrium with $CaCO_3$. While the LSI can be used to assess the corrosive tendencies of a water, it does not quantify a corrosion rate (J.E. Singley et al., 1985).

In theory, if the LSI value is positive the precipitation of $CaCO_3$ will create a "protective scale" that prevents corrosion on metal surfaces in contact with water. Thus, it is sometimes desirable to have a slightly positive LSI value to form a thin scale on the pipe. Protective scales are usually formed when high precipitation of $CaCO_3$ and other dissolved constituents can create a thick scale layer, restricting flow. Since pH and solubility of $CaCO_3$ are dependent on temperature, changing water supply temperatures can greatly affect scale layers. Higher temperature cause higher precipitation of $CaCO_3$, thus contributing to scale. Water utilities should therefore be cognizant of the scale buildup caused by differing water qualities throughout the distribution system.

Researchers have noted reasons behind inaccuracies of the LSI (Schock, 1984; Sontheimer, Kolle, & Snoeyink, 1981). Among these reasons is the presence of dissolved solids other than calcium can provide resistance to corrosion and have variable interactions with pH and alkalinity (AWWARF & DVGW, 1996). In general, LSI should not be the only predictor used to indicate corrosivity or non-corrosivity of a water supply (AWWA, 2011b; AWWARF & DVGW, 1996; Crittenden et al., 2012).

Ryznar Stability Index (RSI)

Ryznar utilizes the same pHs developed in the Langelier equation to produce positive values for his stability index. The larger the Ryznar Stability Index (RSI), the more corrosive the water (J Edward Singley, 1981). This equation was developed empirically from field results on encrusted and/or corroded steel mains. Equation 2-4 represents the Ryznar Stability Index equation.

$$\boldsymbol{RSI = 2pH_s - pH} \qquad (2\text{-}4)$$

RSI values between 6.5 and 7.0 indicate that the water is at saturation equilibrium with calcium carbonate (AWWA, 2011b; J Edward Singley, 1981). Thus, water with an RSI value >7.0 are under-saturated and tend to dissolve existing solid calcium carbonate, while water with an RSI value <6.5 tends to have scaling formation potential (AWWA, 2011b).

Larson Ratio (LR)

The Larson Ratio (LR) is based on chloride, sulfate, and bicarbonate (alkalinity) concentrations in a bulk water sample. Larson and Skold performed a series of experiments on the corrosion of mild steel to determine the (LR) as presented in equation 2-5. The bracketed values (chloride [Cl^-], sulfate [SO_4^{2-}], and bicarbonate [HCO_3^-]) are expressed in units of moles per liter.

$$LR = \frac{[Cl^-]+2[SO_4^{2-}]}{[HCO_3^-]} \qquad (2\text{-}5)$$

The calculated LR values attempt to predict the corrosivity of a water source; ideal values for LR should be less than 0.2 to 0.3 (AWWA, 2011a). Like the Langelier Index, the Larson Index is reliant on bicarbonate and ion concentrations to predict the corrosivity of water.

Calcium Carbonate Precipitation Potential (CCPP)

The Calcium Carbonate Precipitation Potential (CCPP) predicts the amount of $CaCO_3$ that will precipitate as a solution moves towards equilibrium (AWWA & DVGW, 1996).The desired value range to predict chemical stability using this index is between 3 and 10 (Duranceau et. al., 2011). Two principles are considered in the calculation of CCPP of a water (Snoeyink et al., 1980):

1) The total acidity remains constant as calcium carbonate precipitates or dissolves
2) As precipitation or dissolution occurs, the total alkalinity (eq/L) – calcium (eq/L) = constant.

Since the longhand calculation of CCPP is tedious, it is typically calculated by a computer program. Equation 2-6 presents the iterative CCPP calculation.

$$\boldsymbol{CCPP = 50{,}045 * [TALK_i - TALK_{eq}]} \qquad (2\text{-}6)$$

Where,

$CCPP = Calcium\ Carbonate\ Precipitation\ Potential\ (\frac{mg\ as\ CaCO_3}{L})$

$TALK_i = Total\ Alkalinity\ of\ water\ (\frac{eq}{L})$

$TALK_{eq} = Total\ Alkalinity\ of\ Water\ at\ Equilibrium\ (\frac{eq}{L})$

Chloride:Sulfate Mass Ratio (CSMR)

The chloride:sulfate mass ratio (CSMR) is used in particular to predict lead metal release in water distribution systems. CSMR is calculated using the mol/L effluent concentrations of chloride and sulfate as shown in equation 2-7.

$$\boldsymbol{CSMR} = \frac{[Cl^-]}{[SO_4^{2-}]} \tag{2-7}$$

Utilities should use the CSMR in conjunction with alkalinity concentrations to determine if there may be a potential corrosion issue, especially if the utility may change its water treatment practices. High CSMR has been linked to lead leaching problems which manifest through galvanic corrosion between lead and copper (Edwards & Triantafyllidou, 2007).

Direct Measurement: Corrosion Rate Techniques

There are several established methods to directly measure the corrosion of metals in various environments and industries. Of these, the most popular method for water distribution corrosion studies are the gravimetric and electrochemical methods. Corrosion rate of metal is a measurement of the metal loss in mils per year (mpy), where 1mil is equivalent to 1/1000 inch. Overall, this measurement expresses the rate at which the metal surface mass decreases over time due to corrosion-caused material loss (AWWARF & DVGW, 1996).

Corrosion experiments utilizing pipe segments or test loops can be used by utilities to determine current corrosion rates within the water system. Pipe segments are typically pulled directly from the system being tested as they are a direct representation of the distribution materials (AWWARF & DVGW, 1996). These pipe segments are then submerged in constant flowing water for a specified time; at completion of the experiment, the submerged segments can then be removed and evaluated for corrosion rates. The advantage of using actual materials from the distribution system is that scales and inhibitor films formed on the pipe surface are tangible and easily reported.

Corrosion test loops are usually constructed of non-corrosive PVC pipe. Representative metal coupons and linear polarization (LPR) probes are inserted into the pipe and evaluated. In this study, PVC pipes and fittings were used with three representative metal coupons and LPR probes that were then evaluated for corrosion rates. Coupons were inserted to obtain a corrosion rate by the gravimetric method, while LPR electrode probes were inserted to obtain the corrosion rate electrochemically.

Gravimetric Method

The gravimetric method describes an analytical method where the measurement collected is based on a change in mass or weight loss. For drinking water systems this method is also known as the coupon testing method. Typically, multiple metal samples can be tested for corrosion rates at the same time. However, attention to metal nobility is important when determining the order of installation of various metal materials within a pipe loop. In general, metals of greater nobility are placed downstream of less noble metals to avoid unwanted interactions between metals. Flow velocities in the test loop should simulate velocities in the system being evaluated. Additionally, the intermittent flow characteristics of a municipal water system, as well as commercial and residential uses, should be considered.

Virgin coupons experience high initial corrosion rates for the first four to seven days before long-term stabilization of corrosion rates occur (AWWARF & DVGW, 1996). Therefore, it is prudent to allow coupons to come to steady- state flow conditions prior to evaluating the rates. Gravimetric analysis of coupon corrosion rates can be evaluated using equation 2-8 (Metals Samples, 2016).

$$Corrosion\ Rate\ \left(\frac{mils}{year}\right) = \frac{(W)(K)}{(D)(A)(T)} \tag{2-8}$$

Where,

$W = weight\ loss\ (g)$

$D = density\ of\ the\ metal\ (\frac{g}{cm^3})$

$A = area\ of\ test\ specimen\ (in^2)$

$T = exposure\ time\ (hours)$

$K = 5.34\ \times 10\text{^}5$

The advantages to using the gravimetric method for evaluation coupon corrosion rates include: (1) coupons can be placed directly into the distribution system, (2) specific metals can be monitored with specified locations and times that are suitable for operating conditions, and (3) coupons and test loops are relatively inexpensive to analyze. However, there are also several disadvantages to using the gravimetric method on coupons: (1) determining a corrosion rate can take several months, (2) the method cannot distinguish between uniform and localized corrosion, and (3) the reaction between a coupon and the source water may not be similar with that of the distribution pipes and the source water.

Linear Polarization Resistance (LPR) Method

Linear polarization resistance (LPR) method is a way of measuring corrosion rates directly and instantaneously. The LPR method relies on the principle that at low corrosion potentials, the rate of corrosion is a linear function of polarization (Crittenden et al., 2012). While this monitoring system is limited to corrosion monitoring of metals immersed in electrolytically conducting liquids, it is a valuable measurement technique for many industries (Metals Samples, 2016). The LPR method is an electrochemical form of measurement for monitoring corrosion by monitoring the current between two probes and the electrochemical potential (J.E. Singley et al., 1985). Commercially available equipment will read the corrosion rate as a function of corrosion current with a fixed corrosion potential of ±10mV (Crittenden, 2012). Stern and Geary (1957) theoretically defined the corrosion current as:

$$\boldsymbol{I_{corr}} = \left[\frac{\mathbf{1}}{\mathbf{2.303}\ \boldsymbol{R_p}}\right]\left[\frac{\boldsymbol{\beta_a * \beta_c}}{\boldsymbol{\beta_a + \beta_c}}\right] \tag{2-9}$$

Where,

$I_{corr} = corrosion\ current\ density\ (\frac{A}{cm^2})$

$R_p = polarization\ resisitance\ (E_p/i)$

$\beta_a =\ anodic\ Tafel\ constant$

$\beta_c =\ cathodic\ Tafel\ constant$

The polarization resistance (R$_p$) is simply the corrosion potential (ΔE) divided by the corrosion current (ΔI). Hence, the equation developed by Stern and Geary (1957) can be reduced to:

$$\boldsymbol{I_{corr}} = \frac{\boldsymbol{\Delta I}}{\boldsymbol{\Delta E}}\ \boldsymbol{x\ constant} \tag{2-10}$$

Using a modified form of Faraday's law, the corrosion rate can be calculated and expressed in mils per year (mpy) as shown in equation 2-11 (Metals Samples, 2016).

$$\boldsymbol{C} = \frac{(\boldsymbol{I_{CORR}})(\boldsymbol{E})}{(\boldsymbol{A})(\boldsymbol{D})}\boldsymbol{x}(\mathbf{128.67}) \tag{2-11}$$

Where,

$C = Corrosion\ Rate\ (mpy)$

$I_{CORR} = Corrosion\ current\ (\frac{\mu A}{cm^2})$

$E = equivalent\ weight\ of\ corroding\ metal$

$A = Area\ of\ corroding\ elevtrode\ (cm^2)$

$D = Density\ of\ corroding\ metal\ (\frac{g}{cm^3})$

Direct Assessment: Microscopic and X-ray Elemental Analysis

Scanning Electron Microscope (SEM)

Scanning electron microscopes (SEM) use a focused electron beam held in a vacuum to scan the surface of a sample. When the electron beam hits the sample, x-rays and electrons are ejected from the surface. These x-rays and electrons are captured by scanning coils and a series of electron detectors which interpret them into signals which are converted to high resolution images. There are several advantages to using an SEM over a traditional microscope: (1) more than one specimen can be focused, (2) higher resolution (in some cases 5000x), and (3) more control over magnification and focus (Goldstein et al., 2003; Roomans & Dragomir, 2014). Metals are conductive and require no preparation prior to SEM analysis. Non-conductive materials are typically made conductive by covering the sample in a thin layer of conductive material. In the case of corrosion control, SEM is typically used to corroborate additional findings on how bacterial films can affect corrosion rates of variable metals (Venzlaff et al., 2013; Wang, Hu, Hu, Yang, & Qu, 2012).

Energy Dispersive X-Ray (EDX)

Energy dispersive x-ray or EDX is typically assessed in conjunction with SEM. The electron beam of the SEM causes surficial elements to release x-rays with k, l, and m atomic shells. The EDX spectrophotometer reads the “characteristic” x-rays that can be associated with specific elements (Kanda, 1991). These x-rays can then be used to calculate the composition of the specific surface area read by the SEM. EDX has the ability to detect a wide range of elements simultaneously and rapidly.

X-Ray Photoelectron Spectroscopy (XPS)

X-ray photoelectron spectroscopy (XPS) is a widely used method for surficial analysis and has in particular been used to analyze the effectiveness of inhibitors to create surface films (Swift, 1995; Vignal, Krawiec, Heintz, & Oltra, 2007; Zarrok et al., 2012). XPS has the ability to (1) determine the elemental composition of the top 10nm of any solid surface and (2) determine the speciation of respective elements observed (Van der Heide, 2012). XPS instruments use an x-ray to excite photons on the surface releasing electrons from individual elements. The release of photoelectrons allows for the kinetic energy to be measured which is element and environment specific (Van der Heide, 2012). Typically the output of such instruments can be read in one of three ways: (1) energy distribution, (2) spatial distribution, and (3) depth distribution.

XPS analysis requires an x-ray source, energy analyzer, and a detection system. The instrument where the sample is housed should have the ability to create a vacuum and not allow any external electrostatic or magnetic fields. Data collected from the instrument must be further analyzed, typically with computer software. Emissions data can be compared with known elemental signals to determine the composition of a sample, however, quantitative measurements can be difficult to calculate accurately.

Monitoring- The Lead and Copper Rule

In 1991, the USEPA promulgated the Lead and Copper Rule (LCR) to limit consumer exposure to lead and copper at the tap. 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. All community water systems and non-transient non-community water systems are subject to the LCR requirements. Lead and copper levels above a certain level may cause health-related effects that include possible gastrointestinal and cerebral impacts (USEPA, 1992).

Changes in water source or quality can cause previously stable iron, lead, and copper lines to release corrosion by-products. Utilities are required to either maintain 90% of lead and copper concentrations below established action levels (AL), or demonstrate that optimal treatment for lead and copper control has been installed. It is important to note that exceeding the AL does not mean that the maximum contaminant level (USEPA, 1992) has been exceeded. Treatment options for controlling lead and copper corrosion include the use of corrosion inhibitor and water quality control (Duranceau, Townley, & Bell, 2004). In addition, the Revised Guidance Manual for Selecting Lead and Copper Control Strategies (USEPA, 2003) directs utilities in the employment of corrosion control treatments in order to achieve compliance with the LCR. This revision makes recommendations for corrosion control including: aeration, limestone contact, pH adjustment, and iron and manganese removal.

Action levels and maximum contaminant level goals (MCLG) are presented in

Table 2-3. AL levels are based on the 90th percentile level of samples taken (USEPA, 1992). Number of samples are determined by the size of the distribution system. The LCR separates water purveyors into three categories: (1) large (2) medium and (3) small. Small utilities include any distribution system serving less than 3,300 consumers. The island of Lana'i falls into the small system category. Every six months, at least 20 samples must be collected for lead and copper concentrations unless the utility qualifies for reduced monitoring.

Table 2-3: LCR Metal Limits in Drinking Water

Metal	AL (mg/L)	MCLG (mg/L)
Lead	0.015	Zero
Copper	1.3	1.3

Corrosion Control and Prevention

The control of corrosion can be accomplished by a number of means including water quality and stability adjustments, use of corrosion inhibitors, materials selection, and distribution management (J.E. Singley et al., 1985). Corrosion control can prevent economic loss and prolong the life of materials. It is unlikely that a utility can completely eliminate corrosion; however, a simple treatment application can often reduce the corrosion potential of the water. Success of corrosion mitigation methods can often be system specific and will include many factors such as: system maintenance, system materials, and system age (AWWARF & DVGW, 1996).

Water Quality Adjustments

The control or modification of water quality can be a useful tool in the control of corrosion (Duranceau et al., 2004). Lead and copper solubility tends to be lower at higher pH levels (Brown, McTigue, & Cornwell, 2013; Cornwell, Brown, & Mctigue, 2015; Edwards, Chock, & Travis, 1996; Lee, Becker, & Collins, 1989). The reduction of corrosion in distribution systems is usually accomplished by adjustment of pH at the utility prior to distribution (AWWA, 2011a). While each water source is unique and pH is system specific, the USEPA secondary standard for pH ranges from 6.5 to 8.5 for finished water, however, it is recommended that for corrosion control, pH be >8 (AWWA, 2011b). Changing water sources can make it difficult for a utility to accurately maintain an optimal pH (Brown et al., 2013). Other water quality parameters should be monitored as scale build-up or red-water situations can develop over time (AWWA, 2011b).

In addition to pH adjustment, alkalinity adjustments can also be made to further protect utility assets against corrosion. Alkalinity in water is a measurement of a water's capacity to buffer changes in pH and is usually measured by carbonate concentrations. Sufficient amounts of alkalinity allow for a protective calcium carbonate deposit on pipe walls (AWWA, 2011b). Studies have found that copper release decreases with increased alkalinity and pH (Duranceau et al., 2004; Edwards et al., 1996). Many of the aforementioned indices utilize pH, alkalinity, and hardness characteristics to determine potential corrosivity of a water source. With LSI, RSI, and LR, as pH and alkalinity increases the potential for corrosion decreases. Alkalinity can be increased with a single chemical or combination of chemicals including: soda ash, sodium bicarbonate, and/or lime (AWWA, 2011a). In general, waters that are super-saturated with carbonate species are considered to be non-corrosive (J.E. Singley et al., 1985).

Corrosion Inhibitors

Even if pH and alkalinity adjustments are made, this may not lower the corrosion rates enough to suppress problems seen in the system. The USEPA's LCR suggests one way of preventing lead and copper corrosion is to use a chemical corrosion inhibitor in the distribution system (Duranceau et al., 2004). There are several types of inhibitors available for commercial use, but typically they contain one of the following base materials: phosphates or silicates.

Phosphate inhibitors consist of three principal types: (1) orthophosphates, (2) molecularly dehydrated polyphosphates, and (3) bimetallic phosphates (AWWA, 2011a). Commercial products often consist of a phosphate blends. Phosphates in a water system are thought to act as anodic inhibitors (Crittenden et al., 2012). Orthophosphates are believed to form insoluble films on the pipe and react with the metal directly to form these thin films (AWWA, 2011b), thus obstructing electrochemical process that cause corrosion. Ortho:poly phosphate blends are utilized to create thin films along the length of a pipe since over time, polyphosphate chains hydrolyze to form orthophosphates.

Silicate inhibitors also form a thin film on the pipe surface; this film reduces corrosion by providing a barrier (much like calcium carbonate) preventing water from reacting directly with the metal of the pipe (AWWA, 2011b). However, addition of a silica-based inhibitor increases the pH of the water due to the chemicals basicity. Hence it is unclear whether pH or silica is responsible for reducing corrosion potential of the water. Since silicate is amorphous (non-crystalline) in water, the exact chemical composition of silicate based inhibitors is indeterminate. For the purposes of this project, silica is often represented as its solid phase component, SiO_2. Dilute sodium silicate solutions allow silica to exist in an equilibrium between ionic and colloidal states. Singley (1985) suggests that an average dose of 2-8 mg/L is sufficient to achieve corrosion control. Another study suggests that while metal release does not decrease with increased silica presence, an optimum silica dose can reduce corrosion rates in iron and copper (Lintereur, 2008).

Materials Selection

Corrosion can often be mitigated by selecting proper materials during the construction phase. Some materials are more resistant to corrosion than others in specific environments (J.E. Singley et al., 1985). However, water distribution materials are not selected solely on resistance to corrosion; consideration to cost, availability, and maintenance are also made. When considering replacement or rehabilitation of old lines, it is important for utilities to evaluate their current water quality characteristics. In domestic water distribution systems, ductile iron and cast iron account for 70% of pipelines (Crittenden et al., 2012). Plastic, polyvinyl chloride (PVC), is a common alternative to metal pipelines used in residences. While PVC is non-corrosive (AWWARF & DVGW, 1996), it does not have the durability of other materials like cement, iron, and copper.

Distribution System Valve Management

Valves, pipes, and fittings are among a water utility's largest assets. To preserve this capital investment, attention to operation and maintenance is important. Valves are essential components of a water distribution system and aid in controlling water flow, pressure, and are used to isolate lines for repair. Like valves, fire hydrants are important to utilities and their serviceable communities; therefore they must maintain pressure for emergencies and be easily serviceable (Franklin, 1982). Valves and fire hydrants play an essential role in water distribution systems, their failure may further lead to failures of pumps and distribution mains. Valve failures can cause pressure loss, water loss, and loss in customer satisfaction throughout the system (Deb, Snyder, & Grayman, 2012). The resulting failures represent an additional cost burden for water purveyors.

There are two types of valves that are found in drinking water distribution systems: (1) isolation valves, and (2) control valves (USEPA, 2005). Isolation valves are used to isolate segments within a system, usually for maintenance or repair on said section. During water main breaks, isolation valves are used to minimize the number of customers without water (Deb et al., 2006). Control valves are less numerous than isolation valves and are used to control pressure or flow throughout a distribution system. Most valves consist of five components: (1) operator, (2) stem, (3) packing, (4) disk or closure member, and (5) body. Water distribution systems contain a variety of valves, the majority of which are gate valves (Deb et al., 2006).

Valve management in a water distribution system helps water utilities maintain a desired level of service from these assets at the lowest life-cycle cost (USEPA, 2008). In order that systems stay in good working order the utility maintains accurate inventories, monitors assets, and performs long-term financial planning. Many utilities around the United States are facing similar infrastructure problems as pipes and valves approach the end of their useful life (AWWA, 2008). Prudent planning and cost analyses are crucial so that drinking water distribution systems will continue to perform for several more decades.

Asset management can be achieved if attainable goals are set. Good asset management planning includes (USEPA, 2008):

1) Detailed asset inventory
2) Operation and maintenance tasks
3) Long-range financial planning

There are variable factors that contribute to asset failure. In particular, for valves, these factors could include: end-of-service life, excessive pressure in the distribution system, tuberculation and corrosion. There are many benefits to creating and implementing an asset management plan (USEPA, 2008):

1) Prolongs the life of capital investments by focusing investments on maintenance, rehabilitation, and/or replacement.
2) Allows for budgeting, financial planning, and determining rates based on future replacement and maintenance costs.
3) Keeps system operational, therefore, meeting continued service and regulatory expectations.

CHAPTER 3: EXISTING TREATMENT AND DISTRIBUTION SYSTEM

Overview

The Hawaiian island of Lana'i was created by a single shield volcano and consists of three rift zones. Lana'i measures just over 140 square miles and is historically dry, receiving approximately fifteen inches of rainfall per year. At its highest point, the island is 3,370 feet tall. The island consists of nine aquifers, where only the central aquifer is believed to have freshwater. The central aquifer of the island can be divided into two sections: (1) the windward and (2) the leeward. Recharge of the aquifers and springs is from precipitation; however, since Lana'i is a relatively dry island, non-native Cook Island pine trees supplement the groundwater supply via fog-drip infiltration. The island's aquifer system consists of a series of vertical dikes. Dikes are confined spaces formed by lava flow tubes and other volcanic formations. Freshwater is found typically in the high level dikes in the center of the island.

The aquifer and well systems rely on accumulated water that has been transported through volcanic rock which is believed to impact the water chemistry. Wells are further separated by the elaborate dike system which may further diversify the water supply. Lana'i is permitted to withdraw 6 million gallons per day (MGD) of sustainable yield; however, the population pumps approximately 2.25MGD on an average daily basis.

Existing Groundwater Supply and Treatment

The two potable water systems that exist in Lana'i are regulated for quality by the Hawaii State Department of Health (DOH) under the Safe Drinking Water Act; financial rates and fiscal recovery are regulated by the Public Utilities Commission. The island is supplied by four groundwater wells that draw water from the island's central aquifer. Three of these wells supply the Lanai City distribution system while the fourth well supplies the Manele Bay water system. Table 3-1 presents the well numbers assigned to each distribution system and the respective storage tanks associated with each well.

Table 3-1: Well Supply to Distribution Systems on the Island of Lana'i

Distribution System	Well #	Depth	Storage Tank
Lana'i City	3	866	Koele Tank
	6	868	Lana'i City Tank
	8	783	Lana'i City Tank
Manele Bay	4	2,327	Hi'i Reservoir and Hi'i Tank

In the Lana'i City system, each well pumps water to one of three potable water storage tanks. Wells 3 and 8 are pumped to the Koele tank, while well 6 pumps to the Lana'i City tank, and well 4 pumps to the Hi'i Reservoir and Hi'i Tank. The Koele tank and the Lana'i City tank are connected via a ductile iron pipe; water can be pumped up from the Lana'i City tank to the Koele Tank if required. Well 6 pumps from a pump elevation of 868 feet and is the primary source of water serving Lana'i City and the surrounding area; the water is further pumped to a ground level of 1,910 feet where it is then transferred to the Lana'i City tank. Well 8 is located in the Koele Project District at a ground elevation of 1,902 feet; the pump elevation is located at 783 feet. Well 3 was replaced and put into online service in 2010. It is located at an elevation of 1,850 feet and has an approximate pump elevation of 866 feet. Well 3 has an emergency interconnect with the Manele Bay water system and is typically used as a supplementary source for Lana'i City, for redundancy. Well 4 is the primary water source supply for potable water to Manele Bay. The pump elevation for well 4 is at 1,316 feet; the water is pumped to a ground elevation of 2,327 feet.

The groundwater is of high quality, therefore, treatment is limited to disinfection. Prior to entering the storage tank, the water supply pumped from the well is directly treated with free chlorine as hypochlorous acid for disinfection. Figure 3-1 depicts the typical treatment process for the island of Lana'i.

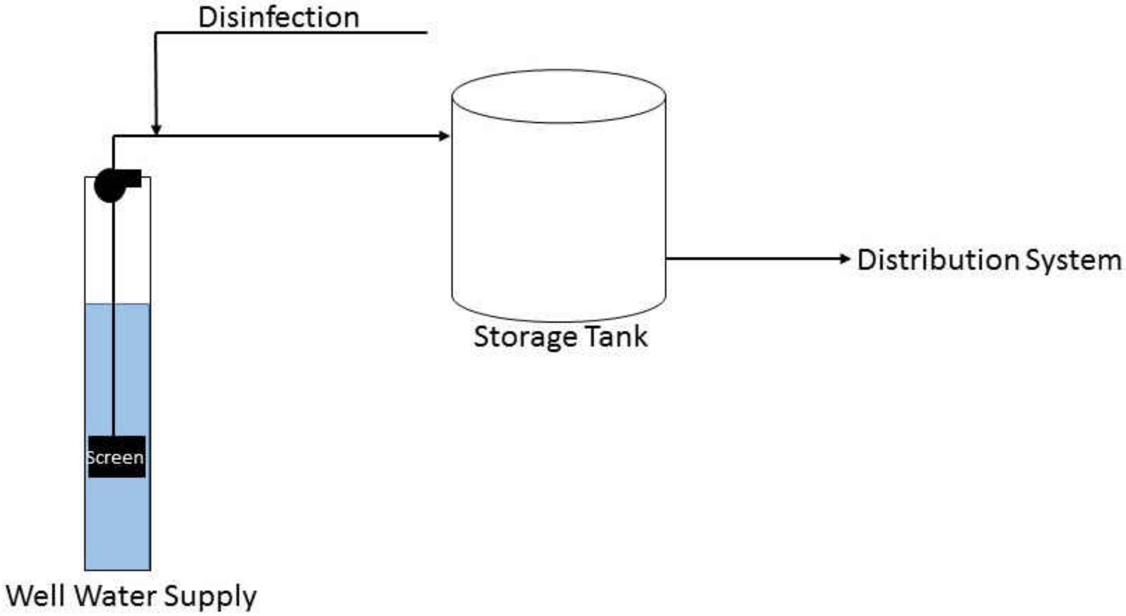


Figure 3-1: Schematic of Water Treatment Process

Table 3-2 presents average raw water quality results for each well and were determined from a limited sampling and analysis effort conducted prior to project implementation. Temperature, pH, conductivity, and turbidity were collected on-site. Bulk water samples were sent to UCF for analysis of total dissolved solids (TDS), alkalinity, hardness, chloride, sulfate, and silica.

Table 3-2: Raw Water Quality for each Well Feeding the Distribution System

Water Quality Parameter	Lana'i City			Manele Bay
	Well 3	Well 6	Well 8	Well 4
pH	8.50	8.70	8.60	9.20
Temperature (ºC)	21.6	20.5	21.5	19.9
Conductivity (µS/cm at 25ºC)	353	256	400	209
Turbidity (mg/L)	0.243	0.498	0.133	0.165
Total Dissolved Solids (mg/L)	179	141	253	124
Alkalinity (mg/L as $CaCO_3$)	90.7	65.8	94.3	57.2
Hardness (mg/L as $CaCO_3$)	100	64.6	118	57.0
Chloride (mg/L)	37.2	26.5	46.7	22.4
Sulfate (mg/L)	7.25	6.01	9.42	3.9
Silica (mg/L)	62.5	44.6	59.9	48.3

Water Distribution System

A survey of the island found that Lana'i has approximately 93 miles of water pipeline; 78 miles of this pipeline are active while 15 miles are abandoned or not in use (LWAC, 2011). Many of the newer pipelines installed since 1995 are made of PVC pipe, however older lines installed in previous decades consist of ductile iron, galvanized iron, and asbestos-concrete.

Lana'i City composes of approximately 1,400 service connections that provide water to three service areas: Koele, Lana'i City, and Kaumalapau. The Lana'i City service area consists largely of small businesses and residential housing. The Koele area includes residential housing, as well as, an upscale Four Seasons Resort including a golf course and irrigation system. Kaumalapau refers to a harbor on the west side of the island and the airport. The Kaumalapau water supply first flows through the Lana’i City distribution system before reaching the harbor. The harbor is fed water through a 2-1/4 inch pipe to a storage tank where the water is further disinfected. There are approximately 35 miles of potable water pipelines in the Lana’i City service area. The Manele Bay water distribution system serves the Four Seasons Manele Bay Resort, Hulopo’e Beach Park, and the Small Boat Harbor. There are also residential homes located within the Manele Bay service area. There are approximately 200 service connections in this area with 35 miles of potable and non-potable irrigation pipelines.

Much of the distribution system in the Lana’i City service areas are reaching the end of their expected and useable life. This presents an important challenge for the utility to replace large distribution mains and parts throughout the island. Increased scrutiny is hence necessary to prevent loss of service or decreased water quality to consumers. Because the Manele Bay water system is relatively new as compared to the Lana’i City service areas, Manele Bay was evaluated strictly for internal corrosion control whereas Lana’i City’s service area were evaluated for internal corrosion control as well as asset management considerations.

Public drinking water systems are required to provide annual consumer confidence reports which demonstrate the utility’s ability to meet or exceed the Safe Drinking Water Act (SDWA) regulations. The consumer confidence report includes information pertaining to lead and copper contamination and compliance with the lead and copper rule (LCR). Lead and copper concentration data reported in 2015 for the Lana’i Water System is summarized in Table 3-3.

Recent events around the United States, specifically, in Flint, Michigan have drawn attention to the significance of corrosion in distribution systems (Bernstein, 2016; Hanna-Attisha, LaChance, Sadler, & Chamney Schnepp, 2016). Baseline corrosion data can be an important tool when considering an alternative water supply. In addition, if an alternative water supply is be used, a corrosion study should be conducted to determine if adverse effects could take place in the water distribution system (Duranceau, Wilder, & Douglas, 2012). Increased corrosion caused by changing the existing water supply can be mitigated using any number of techniques as outlined in Chapter 2 and further described by the EPA (1992). Older distribution systems that are subjected to changes in water quality are especially vulnerable to variable corrosion rates. These changes may affect compliance with the LCR.

Table 3-3: 2015 Lana'i Water System Consumer Confidence Report- Lead and Copper

Contaminant	Unit	MCL	MCLG	Highest Detected Contaminant Level	Violation
Lead (at consumer's tap)	ppb	AL 15	0	90% Percentile Value NON-DETECTABLE	No
Copper (at consumer's tap)	ppm	AL 1.3	1.3	90% Percentile Value 0.0126	No

CHAPTER 4: MATERIALS AND METHODS

Monitoring the conditions within a distribution system is a critical component of studies that are implemented to determine a course of action for corrosion control in a water system. UCF developed a corrosion control monitoring program for the Pulama Lana'i Water Company in order to better understand existing corrosion conditions and to identify acceptable alternatives to resolve suspected tuberculation problems for the utility's water distribution system. To accomplish this need, a monitoring plan was developed that included the design, construction, and operation of a field-scale corrosion control test rack and loop apparatus used for data collection purposes for the two following service areas:

1) Manele Bay Distribution System
2) Lanai City Distribution System

A detailed rendering of the test rack and loop apparatus is provided in Figure 4-1. Laboratory quality assurance (QA) and quality control (QC) procedures were followed for this study in accordance with *Standard Methods for the Examination of Water and Wastewater* (2012) that addressed sample collection, analyses, and reporting activities. Because of the distance that existed between UCF and the Lana'i test sites, Pulama Lana'i Water Company directed Aqua Engineers, Inc. (3560 Koloa Rd., Kalaheo, Kauai, HI, 96741) to support UCF's corrosion studies. Aqua Engineers (AQUA) had historically served as Pulama Lana'i's wastewater treatment operations and maintenance provider, and was a critical team member in its support of UCF activities. A communication and test plan was created to facilitate on-site field data collection and off-site laboratory analysis.

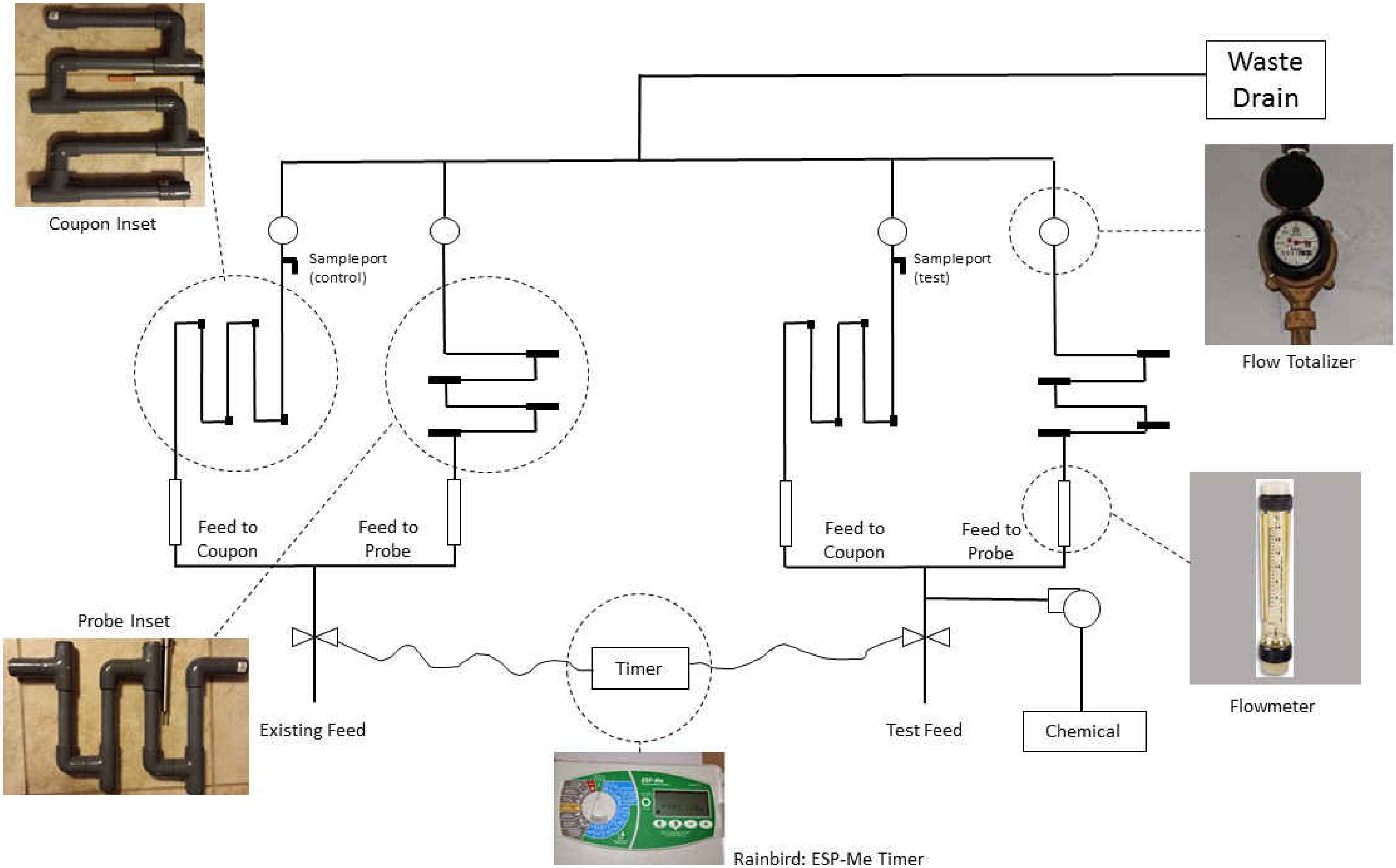


Figure 4-1: Rendering of Corrosion Control Experiment

Manele Bay Distribution System

Experimental Set-up

In order to study existing corrosion and tuberculation conditions in the distribution system, an experimental plan to determine current corrosion rates and assess tubercle formation was developed. The primary goal of this initial series of experiments was to determine corrosion rates in the distribution system and screen alternative chemical inhibitors that could be used to lower existing corrosion rates. A series of three experiments were performed for the study at Manele Bay:

1) Initial Screening (no corrosion inhibitor introduced to assess background conditions)
2) Inhibitor Type 1 Experiment (Phosphate-based chemical)
3) Inhibitor Type 2 Experiment (Silica-based chemical)

A corrosion test rack consisting of parallel pipe loops were designed, constructed, and installed within an abandoned chlorine room at the Manele Bay Wastewater Treatment Facility (WWTF). Four sections were constructed of plastic (PVC) components for this site, where two loops were used to house corrosion coupons and two loops were used to house corrosion linear polarization probes. The configuration consisted of two loops, one configured for coupons and one configured for metal probes. There were two racks at the Manele Bay test site; this pair of racks will henceforth be referred to as a skid. Figure 4-2 includes pictures of the corrosion skid utilized in Manele Bay.

(a) (b)

Figure 4-2: Manele Bay WWTF Corrosion Control Skid (a) Control rack (b) Test rack

One rack was consistently used as a control where finished water with no corrosion inhibitor was added for the entirety of the study. The second rack was used to test alternative inhibitors in the finished water for specified time periods within each experiment. Having two racks per skid allowed for the direct comparison between control and test corrosion rates. Each rack consisted of two loops; one loop contained three different metal corrosion coupons and one loop contained three different linear polarization resistance probes. Based on common materials of construction in the existing distribution system, three metals were chosen to be tested in the corrosion study, and included mild steel, lead, and copper coupon alloys; these metals are summarized in Table 4-1. Metals Samples Corrosion Monitoring Systems (Metals Samples; Munford AL), a division of Alabama Specialty Products, Inc. (ALSPI), supplied the corrosion coupons and probes. In addition, Metals Samples also supplied the corrosion monitoring equipment which included the coupon holders, linear polarization resistance (LPR) wands, and portable corrosion data logger.

For this work metals were identified using the Unified Number System (UNS) for metals and alloys. The UNS number is utilized by the portable corrosion data logger in its calculation and reporting of the corrosion rate. Specific alloys may have significant price differences between coupons and probes. This is typically due to the fact that coupons are larger than the equivalent metal probes, and was the case with the copper alloys selected for this experiment and as identified in Table 4-1. Red Brass is comprised of 85% copper and 15% zinc, while Cartridge Brass is comprised of 70% copper and 30% zinc.

Table 4-1: Metal Alloys used in Manele Bay Corrosion Monitoring Experiment

Metal Alloy	Coupon Alloy	Probe Alloy
Mild Steel	C1010 Mild Steel	C1010 Mild Steel
Lead	50-50 Tin/Lead	50-50 Tin/Lead
Copper	CDA260 Cartridge Brass	CDA230 Red Brass

Corrosion coupons were attached to individual plastic wands with plastic bolts and nuts. Corrosion probes were female grooved and fastened to linear polarization wands via an existing male screw stem on the LPR wand. Both coupons and probes were inserted into the corrosion rack. At the beginning of each experimental condition tested, new coupons and probes were installed for method consistency that allowed different inhibitors to be evaluated.

Corrosion Control Evaluation and Operating Conditions

Manele Bay Initial Screening

When virgin metal is introduced to finished drinking water, there is a short period where high corrosion rates predominate (typically uniform corrosion), during which time a corrosion layer builds on the metal's surface. This process was further described in Chapter 2. A pre-corrosion conditioning phase was implemented prior to inhibitor addition and was necessary so that the virgin components of the rack could corrode to better replicate conditions existing in the system. Once the corrosion layer had been established, the metal was considered to be "pre-corroded". The initial screening allowed the collection of baseline corrosion data representative of the Manele Bay distribution system. Data was collected over a period of 17 weeks to pre-corrode the metal test specimens. After the initial pre-corrosion phase was completed to screen existing Manele Bay distribution system conditions, the used coupons and electrodes were replaced with virgin coupons and electrodes for use in the next stage of testing. The operational time between experiments varied due to the variable logistical planning that occurs when working between Florida and Hawaii.

Manele Bay Inhibitor Type 1

The inhibitor type 1 experiments were focused on testing a phosphate type inhibitor. This specific experiment involved two phases, a pre-corrosion phase and a phosphate inhibitor test phase. Both racks of the Manele Bay skid underwent the pre-corrosion phase. A phosphate inhibitor was then added to the test rack for evaluation of its effectiveness. The phosphate inhibitor used in the study was manufactured by the Carus Corporation (315 Fifth Street, Peru, IL, 61354). The specific product tested was Aquadene SK-7641 and is a 50:50 orthophosphate and polyphosphate blend. The pre-corrosion phase lasted approximately 23 weeks. The phosphate inhibitor testing phase consisted of two dosages. Initially, a low dose of inhibitor was introduced to the test corrosion loop at approximately 0.005 mg/L. The second dose was introduced 8 weeks later and was approximately 1.0 mg/L. The high dose was applied to the test loop for 8 weeks. In total, the Manele Bay phosphate type inhibitor test phase lasted approximately 16 weeks. After the testing of the phosphate inhibitor ceased, the used coupons and electrodes were replaced with virgin coupons and electrodes for use in the next phase of experimentation.

Manele Bay Inhibitor Type 2

The inhibitor type 2 experiment included the testing of a silicate-based inhibitor. This experiment involved two phases, a pre-corrosion phase and a silicate-based inhibitor test phase. Again, both racks underwent the pre-corrosion phase prior to silicate inhibitor being added to the test rack for side-by-side comparison of test and control conditions. The sodium silicate inhibitor used in this experiment manufactured by the PQ Corporation (300 Lindenwood Drive, Malvern, PA 19355). The specific inhibitor was an N-sodium silicate solution, consisting of approximately 37.5% silica solution strength. The pre-corrosion phase lasted approximately 14 weeks. The silicate inhibitor testing phase comprised of a single silica inhibitor dose of approximately 1.0 mg/L. The silicate inhibitor test phase lasted approximately 5 weeks. After the testing of the silicate inhibitor the operation of the racks ceased, and the used coupons and electrodes were removed for analysis.

Analytical Methods and Materials

Manele Bay Water Quality

Evaluation of water quality parameters and the associated monitoring frequencies are presented in Table 4-2. Water samples were collected from each rack and analyzed for specific water quality parameters. Daily measurements were conducted by AQUA professional staff. Weekly water samples were express shipped to UCF for analysis. Sampling and collection procedures were consistent with Standard Methods (2012); Table 4-3 presents the methods and equipment used by AQUA and UCF for the analysis of water samples. It is pertinent to note that phosphate was initially analyzed using the HACH method 8048, however, it was determined that a silica interference rendered this test ineffective for the reliable measurement of orthophosphate in the water. Silica is naturally occurring in the Lana’i water sources. HACH method 8114 was used as an alternative method of analysis as it renders silica inactive, thus it can be used for more accurate phosphate measurements. Table 4-4 presents the equipment used in the UCF drinking water research laboratories for cation and anion analysis.

Table 4-2: Water Quality Parameters and Monitoring Frequency

Parameter	Testing Frequency
Flow Rate	Twice Daily
Corrosion Rate	Twice Daily
pH	Once Daily
Temperature	Once Daily
Conductivity	Once Daily
Dissolved Oxygen	Once Daily
Turbidity	Once Daily
Free Chlorine	Once Daily
TDS	Once Daily
Alkalinity	Once Weekly
Total Hardness	Once Weekly
Sulfate	Once Weekly
Chloride	Once Weekly

Table 4-3: List of Methods and Equipment for Water Quality Analysis

Test	Testing Location	Method/Equipment Description	Method Detection Limit (MDL)
pH, Temperature, Conductivity	Manele bay WWTF	HQ40d Portable Multimeter	0.01 pH Units/ 0.01 ^{o}C/ 0.01 µS/cm
Turbidity	Manele bay WWTF	Hach 2100 Q Portable Turbidimeter	0.01 NTU
Free Chlorine	Manele bay WWTF	Pocket Chlorometer II (Chlorine MR/HR System)	0.01 mg/L
Dissolved Oxygen	Manele bay WWTF	YSI 58 DO Meter	0.01 mg/L
Alkalinity	UCF Laboratory	SM:2320 B. Titration Method	5 mg/L as $CaCO_3$
Total Dissolved Solids (TDS)	UCF Laboratory	SM 2540 C. Total Dissolve Solids Dried at 180 ^{o}C	2.5 mg/L
Total Hardness	UCF Laboratory	SM 3120 B. Inductively Coupled Plasma (ICP) Method/Inductively Coupled Plasma Spectrometer	0.1 mg/L
Silica	UCF Laboratory	SM 3120 B. Inductively Coupled Plasma (ICP) Method/Inductively Couples Plasma Spectrometer	0.001 mg/L
Phosphate	UCF Laboratory	HACH DR6000/HACH Method	0.001 mg/L
Sulfate	UCF Laboratory	SM: 4110 B. Ion Chromatography	0.001 mg/L
Chloride	UCF Laboratory	SM: 4110 B. Ion Chromatography	0.001 mg/L

Table 4-4: Equipment used for Anion and Cation Analysis at UCF Drinking Water Laboratory

Analysis	Parameter	Equipment
Ion Chromatography	Anions (Cl^-, SO_4^{2-})	Dionex ICS-1100 with AS40 Automated Sampler
Inductively Coupled Plasma Spectrometer	Cations (Ca^{2+}, Mg^{2+}, SiO_2)	Perkin Elmer Optima 2100 DV

Corrosion Coupon and LPR Probe Data Analysis

Coupons were removed from each test loop following the completion of each experiment. After the initial screening and the inhibitor type 1 experiment, coupons were sent to Metals Samples (152 Metal Samples Road, Munford, AL 36268) for weight loss analysis. After the inhibitor type 2 experiment, materials characterization analysis was performed on the surface of the coupon. Surficial analysis of the coupons was completed at the UCF Materials Characterization Facility (UCF-MCF), located in Research Park (2522 Neptune Drive, Orlando, FL 32804). The following equipment was used for these analyses: (1) scanning electron microscope (SEM), (2) energy dispersive x-ray (EDX), and (3) x-ray photoelectron spectrometer (XPS). The SEM captured surface photographs of each coupon at up to 2000X resolution. EDX was used in conjunction with SEM to investigate the composition of surface materials. To further define composition of the first ten nanometers of the surface, XPS was utilized. Table 4-5 presents the analysis performed at UCF-MCF and the model of the equipment used.

Linear polarization resistance (LPR) data was collected by AQUA staff twice daily. The corrosion rates of mild steel, lead, and copper probes were measured using a corrosion data logger. The data logger measures corrosion rate between the probes by electrochemical differentiation in mils per year (mpy), corrosion rates and water quality data were recorded on daily log sheets an example of which is presented in Appendix A.

Table 4-5: Equipment used for analysis of corrosion coupons at the UCF Materials Characterization Facility

Analysis	Equipment
Scanning Electron Microscope (SEM)	JEOL JSM-6480LV
Energy Dispersive X-Ray (EDX)	EDAX Genesis
X-Ray Photoelectron Spectroscopy (XPS)	Physical Electronics 600 AES/SAM (Auger Electron Spectroscopy)

Test and control measurements for mild steel, lead, and copper were compared using statistical analysis via Wilcoxon signed ranks test. The Wilcoxon signed ranks test was used for this comparison because the distribution of the data was dependent and non-parametric. To perform this test, the difference between test and control values was first calculated. The absolute value of this difference was then ranked from lowest to highest. Positive differences are summed and then denoted as T^+; this value was further used to calculate Z in Equation 4-1.

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

A critical region is determined by a 95% confidence interval by which Z is compared. If Z falls outside the critical region, the null hypothesis is rejected; however, if Z falls within the critical region then the null hypothesis is not rejected. This analysis was first performed on the pre-corrosion phase to determine if the test and corrosion loops were corroding at the same rate prior to inhibitor addition. Secondly, the test was used to analyze the inhibitor addition phases to determine the effectiveness, if any, in reducing corrosion rates.

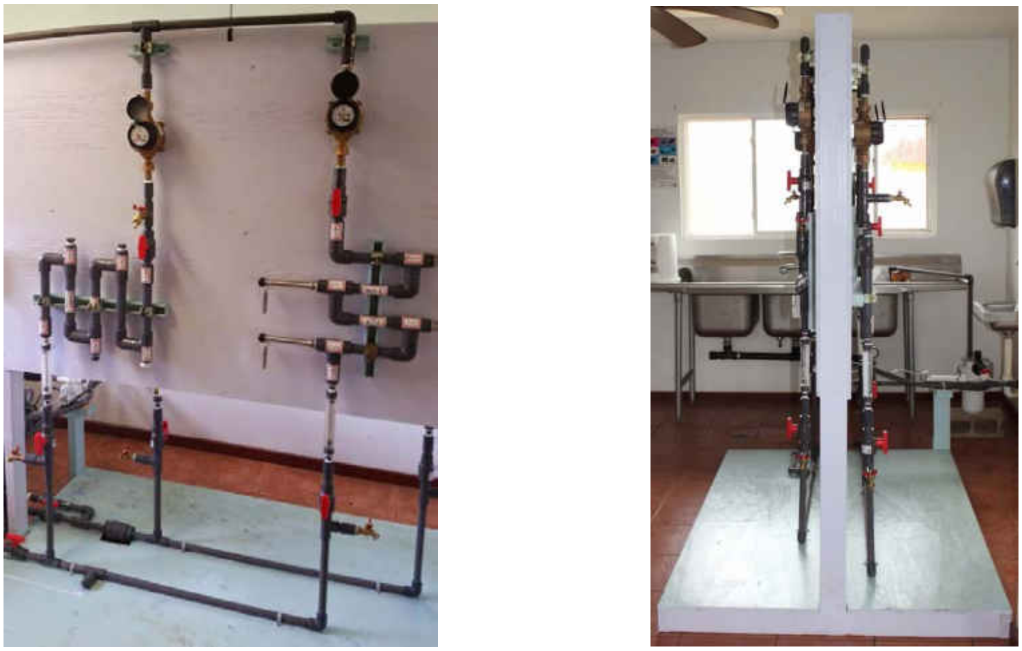
Lana’i City Distribution System

Experimental Set-up

After the development of the study in Manele Bay, Pulama Lana’i Water Company requested the same study to be reproduced in Lana’i City. Lana’i City has been experiencing visible tuberculation in its distribution system. In particular, this tuberculation affects the iron main lines and valves, thus affecting flow rate. The primary goal of the Lana’i City study was to determine baseline corrosion rates in the distribution system and identify inhibitors that could potentially lower these corrosion rates. Two experiments were performed for the study at Lana’i City:

1) Inhibitor Type 1 Experiment (phosphate-based chemical)
2) Inhibitor Type 2 Experiment (silica-based chemical)

Corrosion loops were installed at a house owned by AQUA in Lana’i City (339 Lama Street, Lana’i City, HI 96793). This skid was jointly constructed by UCF and Aqua Engineers Inc. Two racks were constructed of plastic (PVC) components for this site. Unlike Manele Bay, each loop in Lana’i City contained four place holders for coupons and four placeholders for LPR electrode probes. Figure 4-3 provides photographic representation of the corrosion skid developed for in Lana’i City. For this study, the fourth place holder was not used.



(a) (b)

Figure 4-3: Lana’i City Corrosion Experiment (a) Corrosion Racks- front view (b) Corrosion Rack- side view

Corrosion Control Phases of Operation

Lana’i City Inhibitor Type 1

The inhibitor type 1 experiment included the testing of the same phosphate inhibitor used in the Manele Bay inhibitor type 1 experiment, Aquadene SK-7641, a 50:50 orthophosphate and polyphosphate blend. This Lana’i Inhibitor Type 1 experiment involved three phases, a pre-corrosion phase, a phosphate inhibitor test phase, and a post-inhibitor phase. Both racks underwent the pre-corrosion phase prior to phosphate inhibitor being introduced to the test rack. The pre-corrosion phase duration lasted approximately 14 weeks long. The phosphate inhibitor was fed to the test loop at approximately 1.0 mg/L for 6 weeks during the inhibitor test phase. After the phosphate inhibitor feed was terminated, monitoring of the LPR probes continued for 6 more weeks. The period after inhibitor feed ceased is referred to as the “post-inhibitor phase”. At the conclusion of this experiment, the used coupons and electrodes were replaced with virgin coupons and electrodes prior to the commencement of another experiment.

Lana’i City Inhibitor Type 2

The inhibitor type 2 experiment included the testing of the same silicate-based inhibitor used in the Manele Bay inhibitor type 1 experiment. The sodium silicate inhibitor used in the Lana’i City Inhibitor Type 2 study was the N-sodium silicate solution (37.5% solution strength). This experiment involved two phases, a pre-corrosion phase and a silicate-based inhibitor test phase. The control rack and the test rack underwent a pre-corrosion phase prior to silicate inhibitor being added to the test rack flow stream. The pre-corrosion phase lasted approximately 8 weeks. The silicate inhibitor was fed to the test loop at a dose of approximately 1.0 mg/L for about 4 weeks. At the conclusion of this experiment, the used coupons and electrodes were removed for analysis and the study was concluded in Lana’i City.

Analytical Methods and Materials

Lana’i City Water Quality

Evaluation of water quality parameters and associated monitoring frequencies were analogous to the Manele Bay experiments as presented in Table 4-2 . Water samples were collected from both the control rack and the test rack. Daily measurements were conducted by AQUA staff. Weekly samples were express shipped to UCF for analysis. Sampling and collection procedures were consistent with Standard Methods (2012); Table 4-3 presents the methods and equipment used by AQUA and UCF for the analysis of water samples. Due to the discovery of silicate interference during the Manele Bay experiment, phosphate levels were measured using the HACH method 8114 on the HACH DR 6000.

Corrosion Coupon and LPR Probe Data Analysis

Coupons were removed following the completion of each experiment. After the inhibitor type 1 experiment, coupons were sent to Metals Samples (152 Metal Samples Road, Munford, AL 36268) for weight loss analysis. After the inhibitor type 2 experiment, materials characterization analysis was performed on the surface of the coupon. Surficial analysis of the coupons was completed at the UCF-MCF (Research Park, Orlando, FL) in a similar fashion to the coupons collected during the Manele bay experimentation, as presented in Table 4-5.

Linear Polarization Resistance (LPR) data was collected by AQUA staff twice daily in the same manner as in Manele Bay using the LPR data logger. This data was recorded on a data sheet similar to that of Manele Bay (Appendix A). Test and control measurements for mild steel, lead, and copper were compared using statistical analysis via Wilcoxon signed ranks test. The Wilcoxon signed ranks test was used for this comparison because the distribution of the data was dependent and non-parametric.

Field and Laboratory Quality Assurance and Control

This study involved the assessment of several of water parameters to determine its corrosive potential. Statistical analysis and quality control of samples collected were executed in accordance with the methodologies in *Standard Methods for the Examination of Water and Wastewater* 1010B. Statistics and 1020B. Quality Control (American Public Health Association et al. 2012). Quality assurance and control is necessary to show data collected throughout this experiment was reliable and accurate. First, outliers were identified as a value was more than three times the standard deviation from the mean. Outliers were removed then from the results. Duplicate and spike samples were developed for one of every five samples.

Duplicate and replicate samples were analyzed using relative percent difference (RPD) and is represented in equation 4-2. For values of RPD to be acceptable, they are required to fall within a range of 90%-100%.

$$\boldsymbol{RPD} = \frac{\boldsymbol{S-D}}{(\boldsymbol{S+D})/\mathbf{2}} \times \mathbf{100\%} \qquad (4\text{-}2)$$

Where,

$S = sample\ result\ (\frac{mg}{L})$

$D = duplicate\ sample\ result\ (\frac{mg}{L})$

Precision

Precision is a measure of reproducibility between samples and sample duplicates. A precision chart was developed from average and standard deviation values in order to monitor variations in analysis. For this experiment, precision charts for the constituents measured with ion chromatograph (IC) and inductively-coupled plasma (ICP) instruments (anion and cation analyses) were developed. The industrial statistic (I-statistic) was used evaluate data in order to create a control chart using equation 4-3.

$$\boldsymbol{I} = \frac{|\boldsymbol{S-D}|}{(\boldsymbol{S+D})} \qquad (4\text{-}3)$$

Where,

$S = sample\ result\ (\frac{mg}{L})$

$D = duplicate\ sample\ result\ (\frac{mg}{L})$

Precision charts include the use of the mean of the I-statistic in conjunction with warning limits (WL) and control limits (CL). WL and CL were calculated using equation 4-4 and 4-5, respectively.

$$\boldsymbol{WL = I_{avg} + 2\sigma} \tag{4-4}$$

$$\boldsymbol{CL = I_{avg} + 3\sigma} \tag{4-5}$$

Where,

$I_{avg} = mean\ of\ I - statistic\ values$

$\sigma = standard\ deviation\ of\ I - statitic\ values$

Data points falling above the CL were removed from the data set. If two points consecutively exceeded the warning limits the data was considered to be in violation. Samples in violation were re-analyzed and/or removed from the data set.

Accuracy

Accuracy measures the consistency of the analytical laboratory methodologies. For this experiment, accuracy charts for the constituents measured with ion chromatograph (IC) and inductively-coupled plasma (ICP) instruments (anion and cation analyses) were developed. An accuracy chart was developed from the average and standard deviation of the percent recovery between the sample and a spiked sample. The percent recovery can be found using equation 4-6.

$$\%\ \boldsymbol{Recovery = \frac{C_{sample+spike} - C_{sample}}{C_{spike}}} \tag{4-6}$$

Where,

$C_{sample} = concentration\ of\ the\ sample\ (\frac{mg}{L})$

$C_{sample+spike} = concentration\ of\ the\ spiked\ sample\ (\frac{mg}{L})$

$C_{spike} = concentration\ of\ the\ spike\ (\frac{mg}{L})$

Accuracy was assessed by plotting percent recovery results in consecutive order on the accuracy control chart. Accuracy control charts consist of the mean percent recovery, upper and lower control limits (UCL and LCL, respectively) and upper and lower warning limits (UWL and LWL, respectively). The UWL and LWL were calculated using equation 4-7. The UCL and LCL were calculated using equation 4-8.

$$\boldsymbol{UWL = \bar{r} + 2\sigma} \text{ and } \boldsymbol{LWL = \bar{r} - 2\sigma} \quad (4\text{-}7)$$

$$\boldsymbol{UCL = \bar{r} + 3\sigma} \text{ and } \boldsymbol{LCL = \bar{r} - 3\sigma} \quad (4\text{-}8)$$

Where,

$\bar{r} = mean\ of\ percent\ recovery$

$\sigma = standard\ deviation\ of\ the\ percent\ recovery$

Data points falling above or below the UCL and LCL, respectively, were removed from the data set. If two points consecutively exceeded the UWL or LWL the data was considered to be in violation. Samples in violation were re-analyzed and/or removed from the data set.

CHAPTER 5: RESULTS AND DISCUSSION

Treatment of corrosion and tuberculation within a distribution system can prolong the life of system components and appurtenances aiding to keep the system operational. Prior corrosion control research indicates that the addition of corrosion inhibitors to distribution systems can reduce the metal release of mild steel, lead, and copper (AWWA, 2011a; Crittenden et al., 2012; Duranceau et al., 2004). The research and results presented in this document may be used by the water purveyors to make decisions regarding future corrosion control within their distribution systems. There are several components to the corrosion control analysis. Water quality is one key parameter when determining the extent of water corrosivity. Coupon analysis varied by experiment, but includes weight loss analysis, SEM analysis, EDX analysis, and XPS analysis. This chapter includes a discussion of the results of a study focused on two sites:

1) Manele Bay Water Distribution System
2) Lana'i City Water Distribution System

In addition, quality control and quality assurance protocols were taken into account (where applicable) to maintain data quality.

Manele Bay Corrosion Study Results and Discussion

Results are presented for each experiment conducted during the Manele Bay corrosion control research project. Analysis of coupons differed by experiment. The initial screening and inhibitor type 1 coupon corrosion analysis consisted of only a weight loss analysis performed by Metal Samples (152 Metal Samples Road, Munford,

AL 36268). The inhibitor type 2 coupon analysis did not undergo a weight loss analysis, instead comprehensive surface analysis using SEM, EDX, and XPS was used. LPR probe analysis largely consisted of interpreting results obtained from the LPR data logger using statistics. Wilcoxon signed rank test was used to compare for symmetry between the control rack and the test rack. The program Minitab was used to perform the statistical analysis used in the Wilcoxon signed rank test. Water quality results are presented as a summary per experiment in this section.

Manele Bay Initial Screening

The purpose of this initial experiment was to obtain baseline corrosion rates for the utility, hence, no inhibitor was added. Coupons and probes were corroded for a total of 1,470 hours before the initial screening was concluded. This experiment was comprised of just the pre-corrosion phase. As described previously, the pre-corrosion phase describes the corrosion that occurs when virgin metal enters a water system until the corrosion rates reach a steady baseline. For easy comparison of corrosion rates between metals, axis bounds for corrosion rates are from 0-3.5 mils per year (mpy). Water quality analysis was limited during this experiment as the facilities did not receive adequate monitoring equipment until the inhibitor testing experiments. Water quality data that was collected is presented in Table 5-1. Temperature and pH were collected daily by AQUA staff.

Table 5-1: Average Water Quality Results for Manele Bay Initial Screening

	Concentration or Value	
Parameter	**Control**	**Test**
pH (pH Units)	7.27	7.36
Temperature (°C)	23.4	23.1

Mild Steel

Figure 5-1 illustrates mild steel corrosion rates as a function of time for the initial screening for test and control conditions. The corrosion rates continue to decrease until there is a baseline corrosion rate around hour 1,200 for both test and control conditions. The control condition corrosion rate appears to be corroding at a higher rate than the test condition. The average corrosion rate for the control condition (1.44 mpy) is higher than that of the test condition (0.96 mpy).

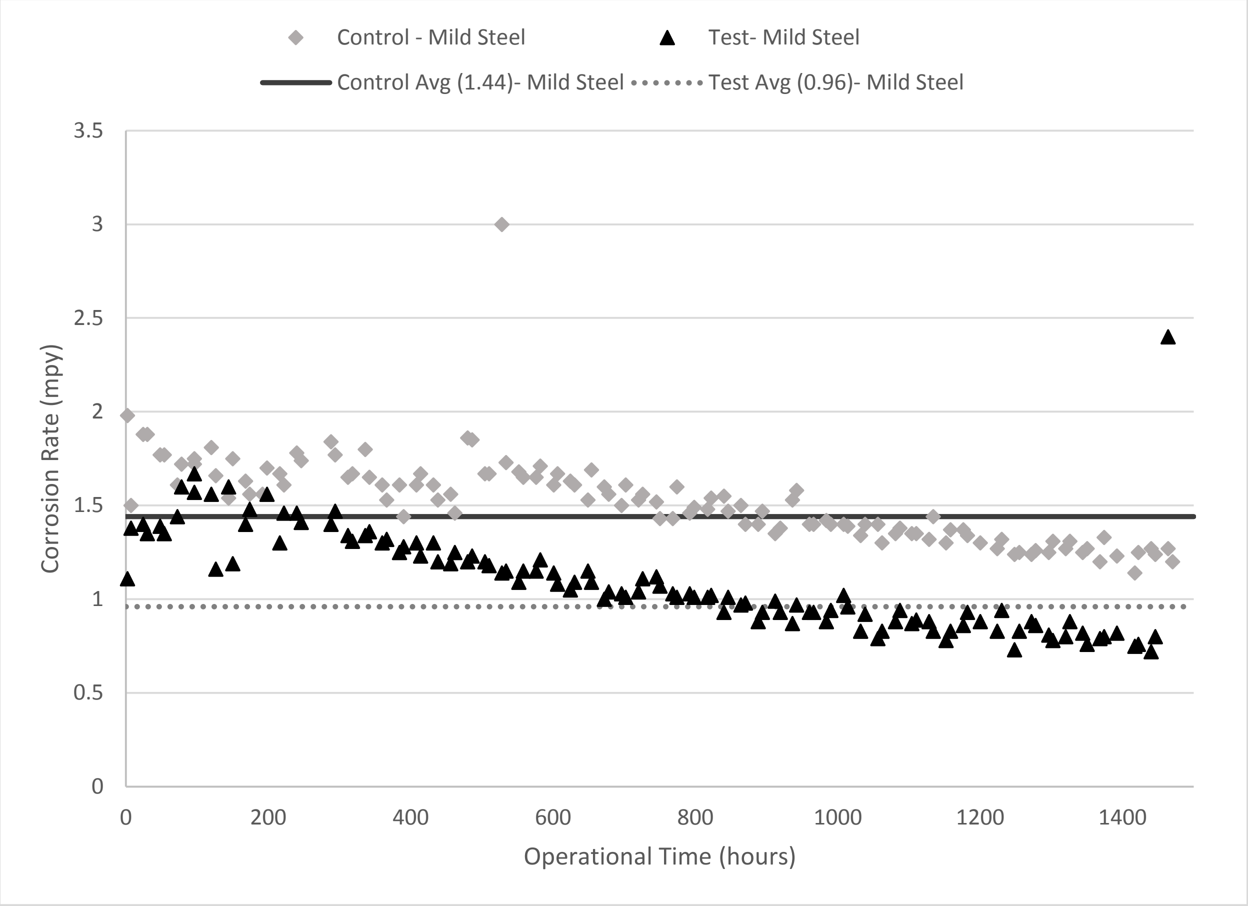


Figure 5-1: Mild Steel Corrosion Rates for Manele Bay Initial Screening

Lead

Figure 5-2 shows lead corrosion rates as a function of time for the initial screening test and control conditions. The corrosion rates for lead are very low (> 0.5mpy) throughout the initial screening data collection. There does not appear to be a difference between the test and control condition corrosion rates. The average corrosion rates for the test and control conditions are barely distinguishable at corrosion rates of 0.18 mpy and 0.19 mpy, respectively. Consequently, it will be difficult to improve the corrosion rates.

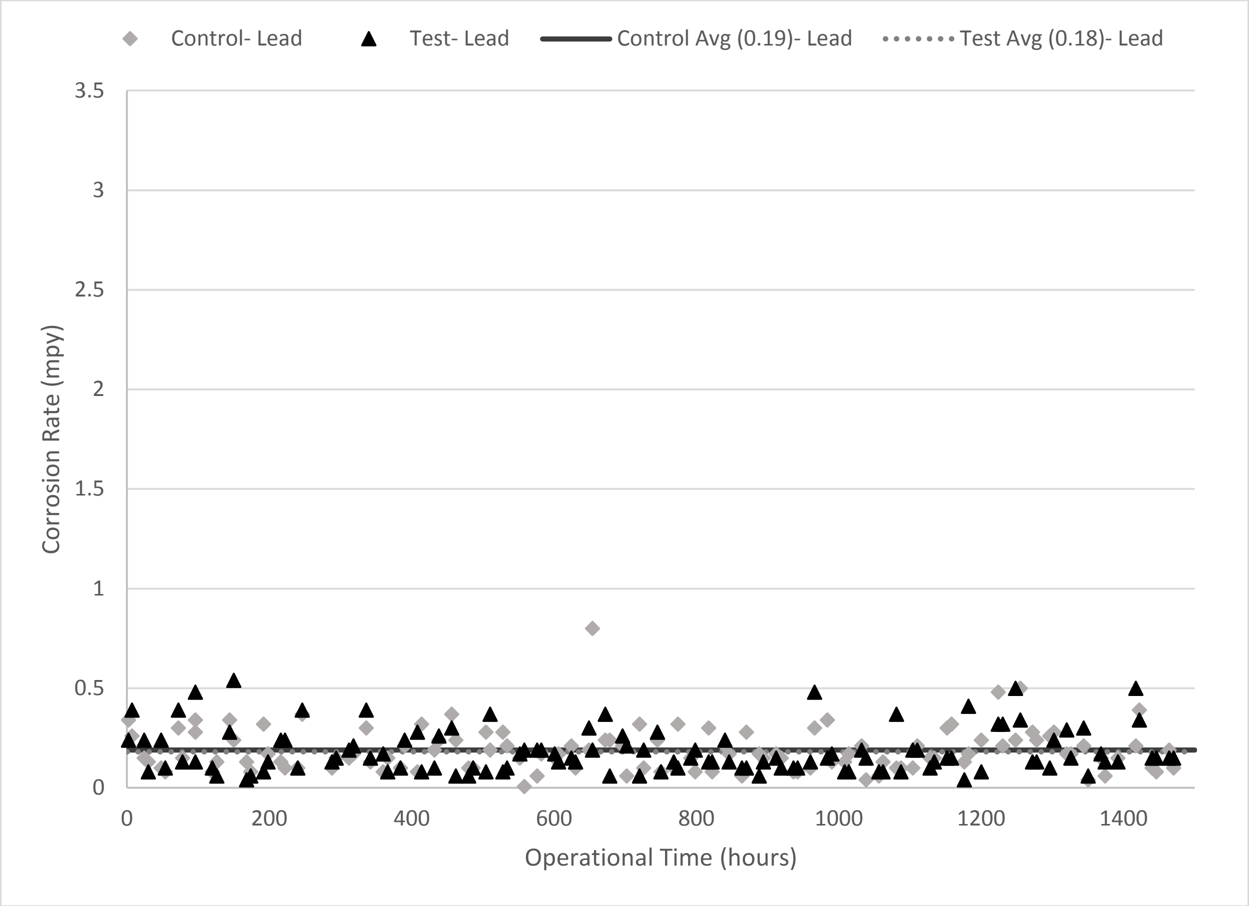


Figure 5-2: Lead Corrosion Rates for Manele Bay Initial Screening

Copper

Figure 5-3 shows copper corrosion rates as a function of time for the initial screening test and control conditions. The corrosion rates continue to decrease until there is a baseline corrosion rate around hour 600 for both test and control conditions. Test and control corrosion rates appear to be corroding at the same rate. Similar to the lead corrosion rates, the average corrosion rates between the control and test conditions are indistinguishable at 0.20 mpy and 0.18 mpy, respectively.

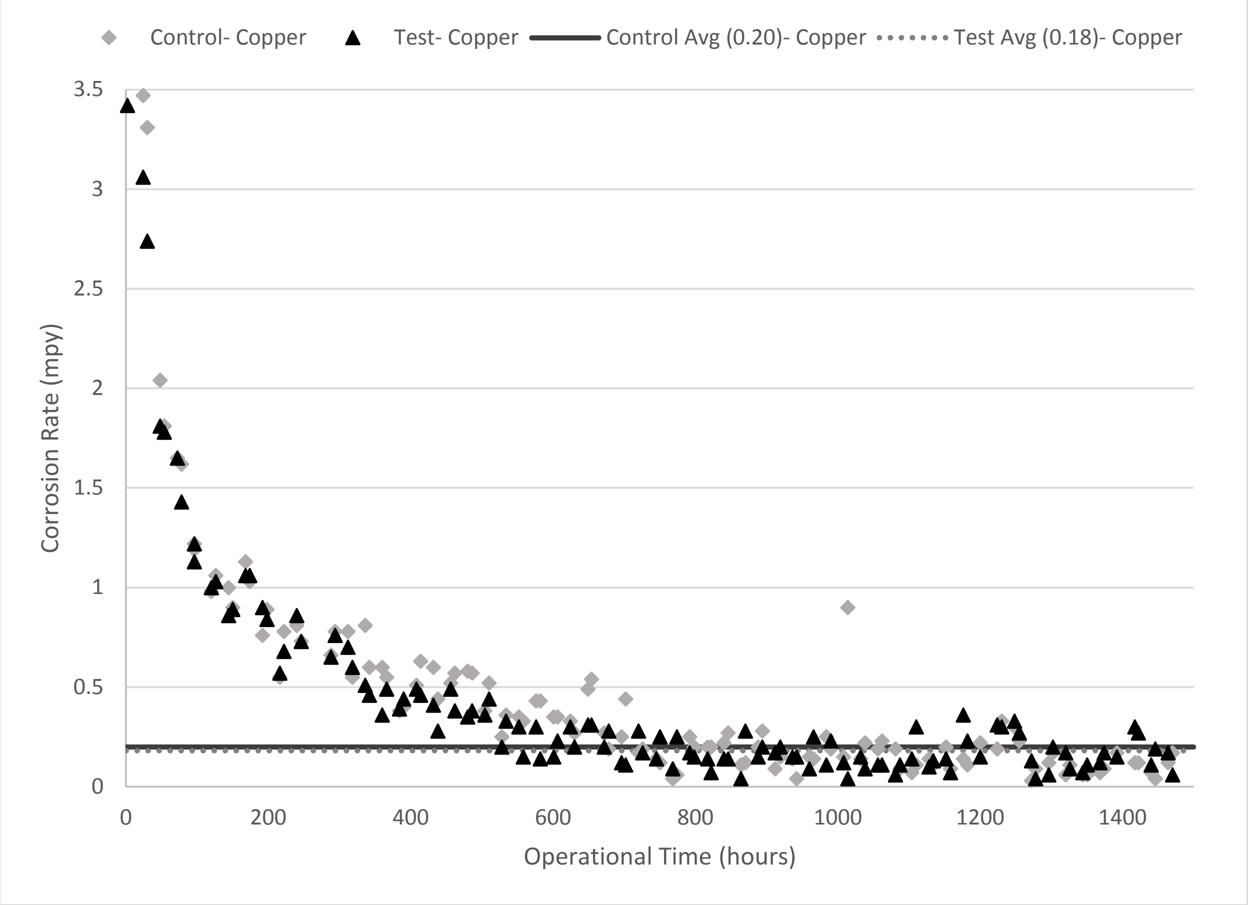


Figure 5-3: Copper Corrosion Rates for Manele Bay Initial Screening

Manele Bay Statistical Analysis- Initial Screening

In the initial screening experiment no inhibitor was added, therefore, statistical analysis was performed on the entirety of the data collected from the LPR probes. Because of the length and frequency of the measurements taken during this project, corrosion rate measurements using the LPR data logger are presented in Appendix B. Table 5-2 presents the results of the Wilcoxon signed rank applied to initial screening data. The null hypothesis postulates that corrosion occurred at equal rates under control and test conditions. The null hypothesis was rejected for mild steel, indicating that the test and control conditions were not corroding at the same rate. The null hypothesis was not rejected for lead and copper, indicating that the test and control conditions were corroding at the same rate. Table 5-2 summarizes the results obtained from Wilcoxon signed ranks test analysis for the Manele Bay initial screening experiment.

When the null hypothesis is rejected in the pre-corrosion phase, test and control conditions cannot be compared directly in the inhibitor addition phase. Since the test and control conditions are not corroding at statistically equal rates, it can be assumed that water quality characteristics differ between the two conditions. Therefore, comparisons between the test pre-corrosion and inhibitor additions phases must be made. These comparisons will be presented in the statistical analysis section for each inhibitor tested.

Table 5-2: Summary of Wilcoxon Signed Ranks Results for Manele Bay Initial Screening

Metal	Phase	H_o	H_a	n	P	Conclusion
Mild Steel	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	80	0.000	Reject the null. Test and control conditions are corroding at a different rate
Lead	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	78	0.659	Do not reject the null. Test and control conditions are not corroding at different rates
Copper	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	79	0.196	Do not reject the null. Test and control conditions are not corroding at different rates

*CR= Corrosion Rate (mpy)

Manele Bay Post-Analysis- Initial Screening

Post-analysis contains the results obtained from analysis of the corrosion coupons. For this initial screening experiment, corrosion coupons were sent to Metals Samples (Munford, AL) for weight loss (gravimetric) analysis. Results from this analysis are presented in Table 5-3. Results indicate that corrosion rates in the test conditions were higher than control conditions in lead and copper by 13% and 12% respectively.

Table 5-3: Coupon Gravimetric Analysis - Manele Bay Initial Screening

	Corrosion Rate (mpy)		
Alloy	**Control**	**Test**	**Percent Difference**
C1010 Mild Steel	6.0304	5.8211	4%
50/50 Lead/Tin Solder	0.0610	0.0695	-13%
CDA 260 Copper	0.1766	0.1995	-12%

Manele Bay Inhibitor Type 1

Inhibitor type 1 evaluated in this research is a 50:50 ortho:poly blended inhibitor. Coupons and probes were corroded for a total of 6,768 hours before the experiment was concluded. This experiment is comprised of two phases: (1) a pre-corrosion phase, and (2) phosphate inhibitor addition phase. The average water quality results for the inhibitor type 1 experiment are presented in Table 5-4. pH, conductivity, turbidity, dissolved oxygen, and free chlorine were collected daily on site. Water samples were collected for alkalinity, chloride, sulfate, hardness, and total dissolved solids weekly and shipped to UCF for analysis.

Table 5-4: Water Quality Results for Manele Bay Inhibitor Type 1 Experiment

Parameter	**Concentration or Value**	
	Control	**Test**
pH (pH units)	7.89	8.07
Conductivity (µS/cm)	252	214
Turbidity (NTU)	1.06	1.55
Dissolved Oxygen (mg/L)	7.35	7.37
Free Chlorine (mg/L)	0.69	0.74
Total Alkalinity (mg/L as $CaCO_3$)	57.6	57.4
Chloride (mg/L)	22.3	22.7
Sulfate (mg/L)	3.80	3.70
Total Hardness (mg/L as $CaCO_3$)	57.8	57.8
Total Dissolved Solids (mg/L)	120	122
Langelier Saturation Index	-0.89	-0.71
Ryznar Index	9.68	9.52
Larson Ratio	0.74	0.75

Mild Steel

Figure 5-4 illustrates mild steel corrosion rates as a function of time for the inhibitor type 1 experiment for test and control conditions. The corrosion rates continue to decrease until there is a baseline corrosion rate around hour 1,800 for both test and control conditions. The control and test conditions appear to be corroding at similar rates throughout the experiment. The average corrosion rate for the test condition is higher than that of the control condition at 0.81 mpy and 0.77 mpy, respectively. Inhibitor was added continuously starting at hour 4,008, however the dosage changed from a low dose of 0.005 mg/L to a high dose of 1.0 mg/L at hour 5,520. Consequently, it appears that the addition of inhibitor type 1 does not improve the corrosion rate of the test rack and is therefore not a viable option for corrosion control in Manele Bay.

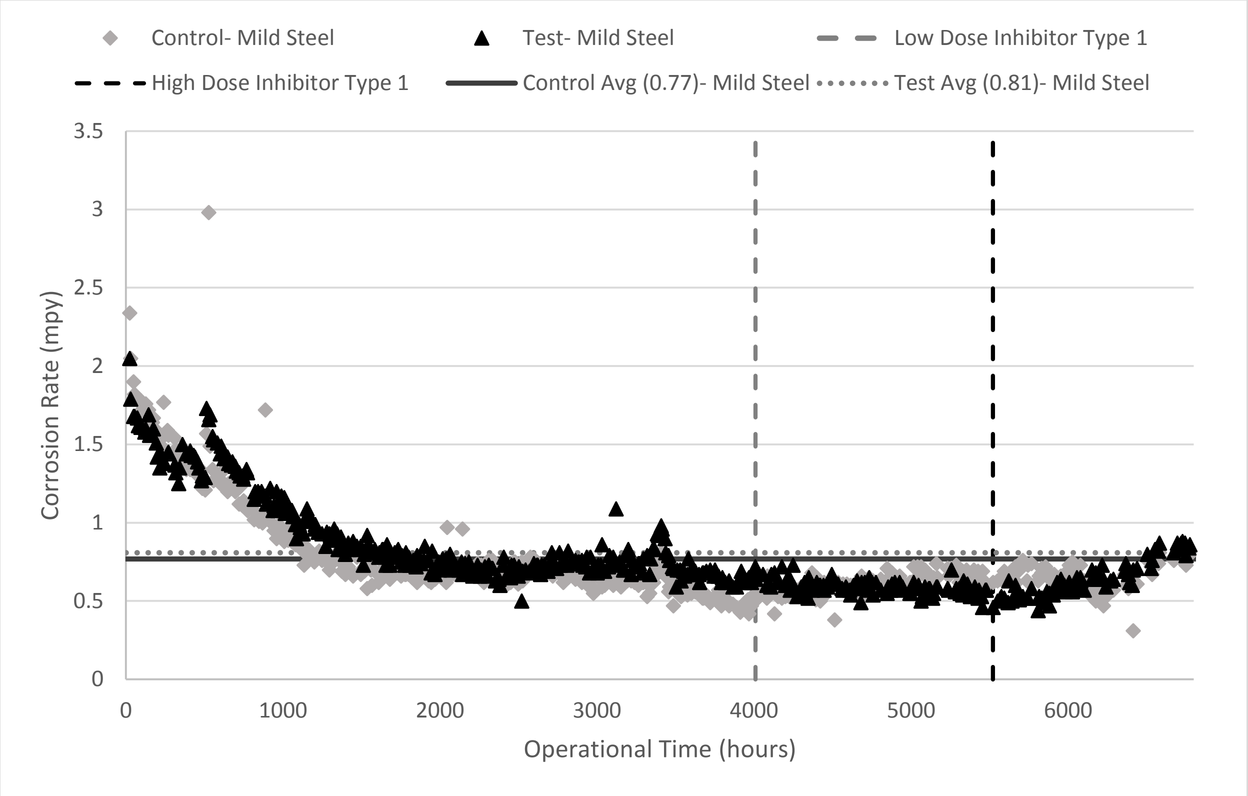


Figure 5-4: Mild Steel Corrosion Rates for Manele Bay Inhibitor Type 1

Lead

Figure 5-5 shows lead corrosion rates as a function of time for the inhibitor type 1 experiment control and test conditions. The corrosion rates for lead are fluctuating, but are also very low (< 0.5mpy) throughout data collection. There does not appear to be a difference between the test and control condition corrosion rates. The average corrosion rates for the test and control conditions are indistinguishable at 0.19 and 0.18, respectively. Consequently, there was not a discernable difference between the test and corrosion rates after inhibitor was added. It appears that addition of inhibitor type 1 does not benefit in reducing lead corrosion rates.

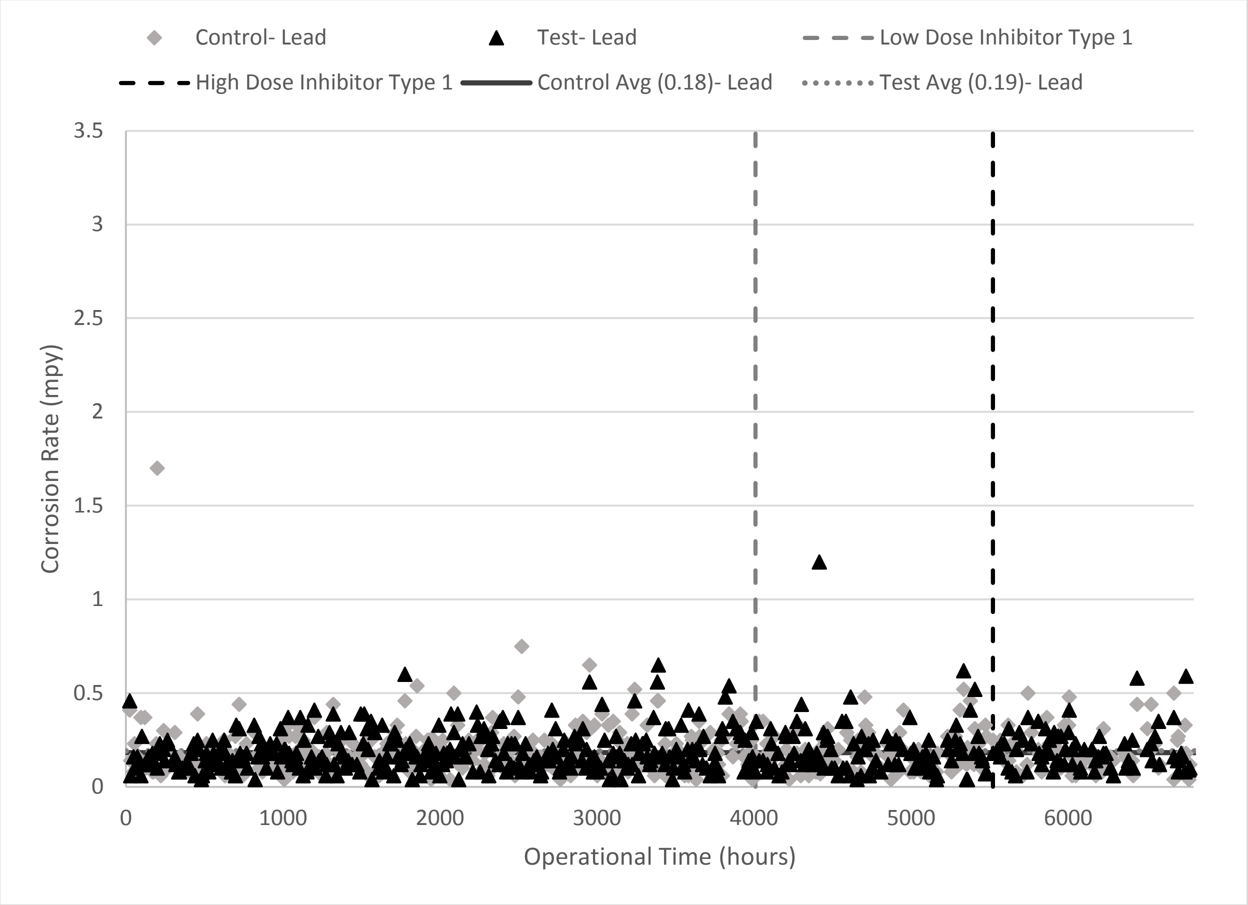


Figure 5-5: Lead Corrosion Rates for Manele Bay Inhibitor Type 1

Copper

Figure 5-6 shows copper corrosion rates as a function of time for the inhibitor type 1 experiment control and test conditions. The corrosion rates continue to decrease until there is a baseline corrosion rate around hour 800 for both test and control conditions. Test and control corrosion rates appear to be corroding at the similar rate. The average corrosion rates between the control and test conditions are comparable at 0.22 and 0.23 mpy, respectively. Similar to that of mild steel and lead, the corrosion rates do not appear to improve and the use of inhibitor type 1 is not a viable option for corrosion control in Manele Bay.

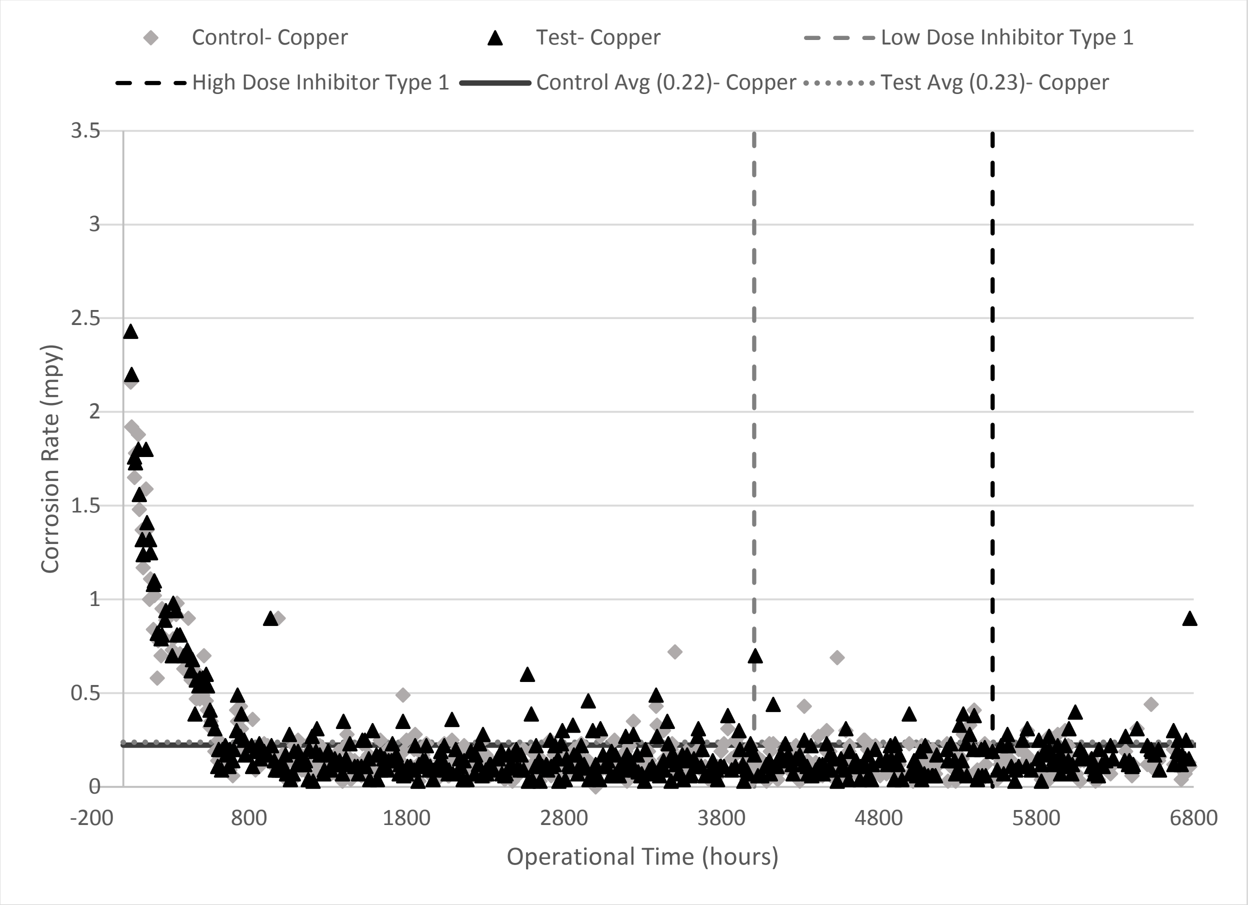


Figure 5-6: Copper Corrosion Rates for Manele Bay Inhibitor Type 1

Manele Bay Statistical Analysis- Inhibitor Type 1

The inhibitor type 1 experiment consisted of two phases: (1) pre-corrosion and (2) inhibitor type 1 Addition. Statistical analysis using Wilcoxon signed ranks test was performed on each of the phases. Because of the length and frequency of the measurements taken during this project, corrosion rate measurements using the LPR data logger are presented in Appendix C. Table 5-5 presents the results of the Wilcoxon signed ranks test applied to inhibitor type 1 data. The null hypothesis for pre-corrosion data postulates that corrosion occurred at equal rates under control and test conditions. The null hypothesis was rejected for mild steel, indicating that the test and control conditions were not corroding at the same rate. The null hypothesis was not rejected for lead and copper, indicating that the test and control conditions were corroding at the same rate.

In the inhibitor type 1 addition phase, the null hypothesis is that the test and control conditions are corroding at the same rate. The alternative hypothesis states the control condition is corroding faster than the test condition. The null hypothesis was rejected for mild steel, indicating that the control conditions are corroding faster than the test conditions. The null hypothesis was not rejected for copper and lead, therefore, it can be concluded that the corrosion rates remained equal throughout the experiment. Table 5-5 summarizes the results obtained from Wilcoxon signed ranks test analysis for the Manele Bay inhibitor 1 experiment.

Table 5-5: Summary of Wilcoxon Signed Ranks Results for Manele Bay Inhibitor Type 1

Metal	Phase	H_o	H_a	n	P	Conclusion
Mild Steel	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	305	0.000	Reject the null. Test and control conditions are corroding at a different rate
	Inhibitor Addition	Test CR = Control CR	Test CR < Control CR	167	0.001	Reject the null. Test condition is corroding at higher rate than control
Lead	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	287	0.093	Do not reject the null. Test and control conditions are not corroding at different rates
	Inhibitor Addition	Test CR = Control CR	Test CR < Control CR	160	0.190	Do not reject the null. Test and control conditions are not corroding at different rates
Copper	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	284	0.064	Do not reject the null. Test and control conditions are not corroding at different rates
	Inhibitor Addition	Test CR = Control CR	Test CR < Control CR	158	0.023	Reject the null. Test condition is corroding at higher rate than control

*CR= Corrosion Rate

If the null hypothesis in the pre-corrosion phase is rejected, it is difficult to compare control and test conditions between each other. Therefore, in the case that the pre-corrosion phase null hypothesis was rejected, comparisons between the pre-corrosion steady-state phase and inhibitor addition phase will be further analyzed. For the inhibitor type 1 experiment, steady state was reached at hour 1,800. Table 5-6 presents average corrosion rates for the pre-corrosion steady state phase and inhibitor addition phase for mild steel, copper, and lead.

Table 5-6: Average Corrosion Rates of Manele Bay Inhibitor Type 1

		Control Condition	Test Condition	Percent Difference
Mild Steel	Average During Pre-Corrosion Steady State	0.645	0.723	11%
	Average During Inhibitor Addition	0.635	0.611	-4%
Lead	Average During Pre-Corrosion Steady State	0.185	0.197	7%
	Average During Inhibitor Addition	0.182	0.197	8%
Copper	Average During Pre-Corrosion Steady State	0.135	0.140	4%
	Average During Inhibitor Addition	0.139	0.157	12%

Since the null hypothesis for mild steel pre-corrosion phase was rejected, further comparison between the pre-corrosion steady state corrosion rate and inhibitor addition phase for mild steel is made. The pre-corrosion test condition steady state average is 0.723 mpy while the inhibitor addition phase average corrosion rate is 0.611 mpy resulting in a 17% decrease in corrosion rate. The control condition pre-corrosion steady state and "inhibitor addition" phase experience a 2% decrease. This may indicate that the total decrease in corrosion rate that may have been caused by inhibitor addition was 15%.

A direct comparison between the test and control conditions can be made for lead and copper because the null hypothesis was not rejected. There is increased corrosion in both conditions for lead, however the increase is equal indicating the cause of increase is likely due to fluctuating water quality characteristics. The inhibitor does not have an impact on corrosion rate for lead.

In comparing the control and test conditions for copper, the test condition is 12% higher than that of the control condition. The comparison result for copper may indicate that inhibitor type 1 may have a negative effect on the corrosion rate. This could be due to changes in water chemistry when phosphate inhibitor is added.

Manele Bay Post Analysis- Inhibitor Type 1

Post-analysis contains the results obtained from analysis of the corrosion coupons. For the inhibitor type 1 experiment, corrosion coupons were sent to Metals Samples (Munford, AL) for weight loss (gravimetric) analysis. Results from this analysis are presented in Table 5-7. Results indicate that corrosion rates in the control conditions were higher than test conditions in copper by 9%. While post analysis of mild steel shows a 22% decrease in test condition compared to control condition, gravimetric analysis is not able to distinguish between pre-corrosion and inhibitor addition phases. Therefore, in addition to overall weight loss analysis, it is important to include other methods of analysis when monitoring corrosion rates to determine the effectiveness of an inhibitor. Figure 5-7 presents coupon photographs at the experiment conclusion.

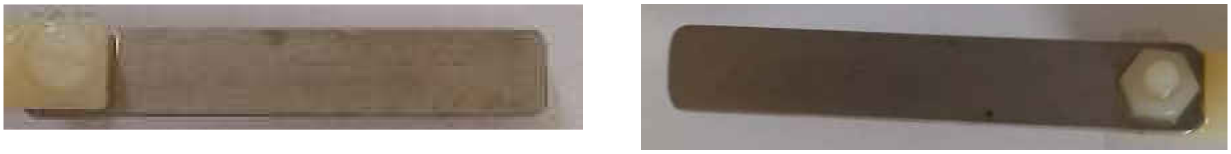
Table 5-7: Coupon Gravimetric Analysis - Manele Bay Inhibitor Type 1

	Corrosion Rate (mpy)		
Alloy	**Control**	**Test**	**Percent Difference**
C1010 Mild Steel	3.8989	3.1265	-22.0%
50/50 Lead/Tin Solder	0.1326	0.1332	0.5%
CDA 260 Copper	0.1479	0.1624	9.3%

Control **Test**

Mild Steel

Mild Steel



Lead

Lead

Copper

Copper

Figure 5-7: Manele Bay Coupon Photographs- Inhibitor Type 1

Manele Bay Inhibitor Type 2

The inhibitor type 2 evaluated in this research refers to a sodium silicate inhibitor. Coupons and probes were corroded for a total of 3,072 hours before the experiment was concluded. This experiment is comprised of two phases: (1) a pre-corrosion phase, and (2) silicate inhibitor addition phase. The average water quality results for the inhibitor type 2 experiment are presented in Table 5-8. The pH, temperature, conductivity, turbidity, dissolved oxygen, and free chlorine were collected daily on site. Water samples were collected weekly and shipped to UCF for alkalinity, chloride, sulfate, hardness, and total dissolved solids analysis.

Table 5-8: Water Quality Results for Manele Bay Inhibitor Type 2 Experiment

Parameter	**Concentration or Value**	
	Control	**Test**
pH (pH units)	8.10	8.39
Temperature (^{o}C)	26.8	26.9
Conductivity (µS/cm)	242	222
Turbidity (NTU)	0.58	0.71
Dissolved Oxygen (mg/L)	7.27	6.79
Free Chlorine (mg/L)	0.71	0.78
Total Alkalinity (mg/L as $CaCO_3$)	57.4	57.6
Chloride (mg/L)	21.0	20.8
Sulfate (mg/L)	4.40	4.30
Total Hardness (mg/L as $CaCO_3$)	55.1	55
Total Dissolved Solids (mg/L)	130	130
Langelier Saturation Index	-0.66	-0.37
Ryznar Index	9.42	9.13
Larson Ratio	0.72	0.71

Mild Steel

Figure 5-8 illustrates mild steel corrosion rates as a function of time for the inhibitor type 2 experiment for test and control conditions. The corrosion rates continue to decrease until there is a baseline corrosion rate around hour 1,400 for both test and control conditions. While the average corrosion rate for the test condition (0.65 mpy) is higher than that of the control condition (0.49 mpy), the two conditions corrode in a similar way. Inhibitor was added continuously starting at hour 2,232 at a dose of approximately 1.0 mg/L. Inhibitor addition and the experiment was concluded at operational hour 3,072. Consequently, it appears that the addition of inhibitor type 2 does not improve the corrosion rate of the test rack and is therefore not a viable option for corrosion control in Manele Bay.

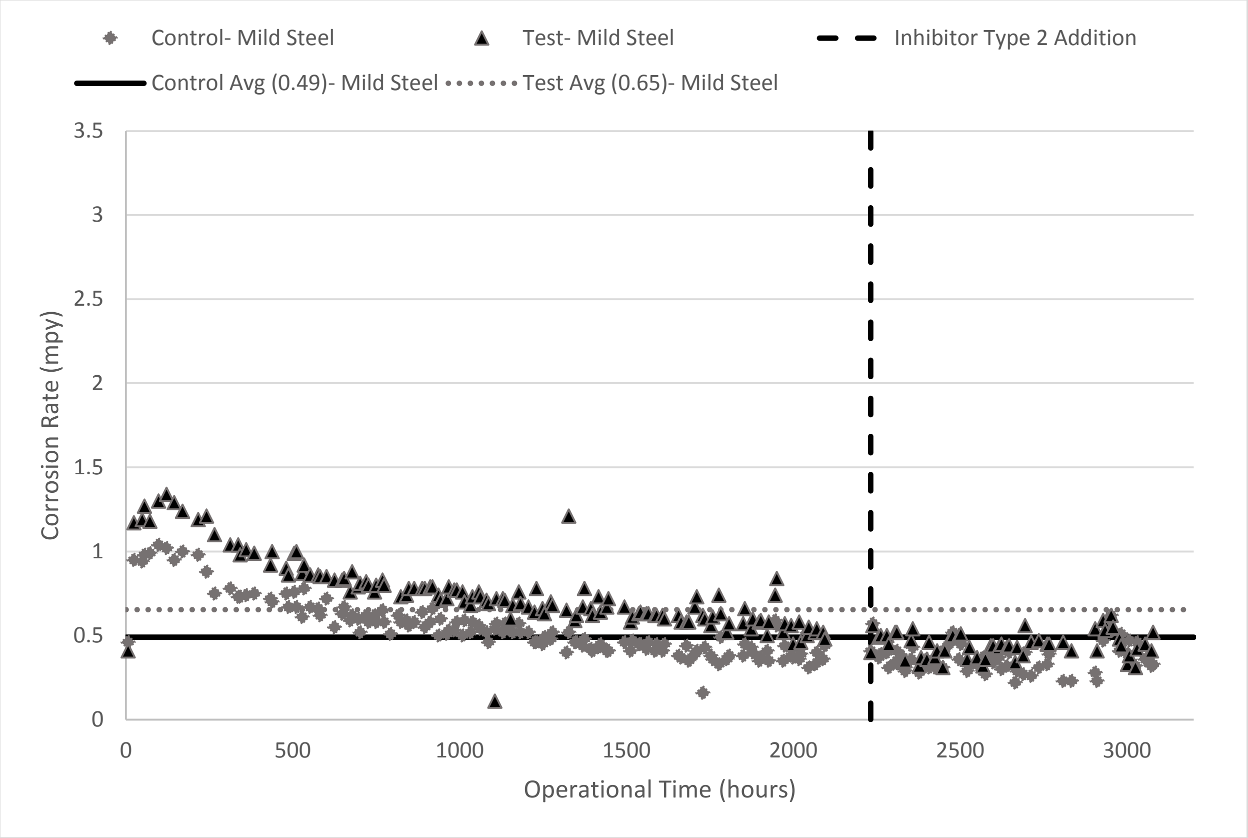


Figure 5-8: Mild Steel Corrosion Rates for Manele Bay Inhibitor Type 2

Lead

Figure 5-9 shows lead corrosion rates as a function of time for the inhibitor type 2 experiment control and test conditions. The corrosion rates for lead are fluctuating, but are also low (< 0.6 mpy) throughout data collection. There does not appear to be a difference between the test and control condition corrosion rates. The average corrosion rates for the test and control conditions are barely distinguishable. Consequently, there was not a discernable difference between the test and corrosion rates after inhibitor was added. It appears that addition of inhibitor type 2 does not benefit in reducing lead corrosion rates.

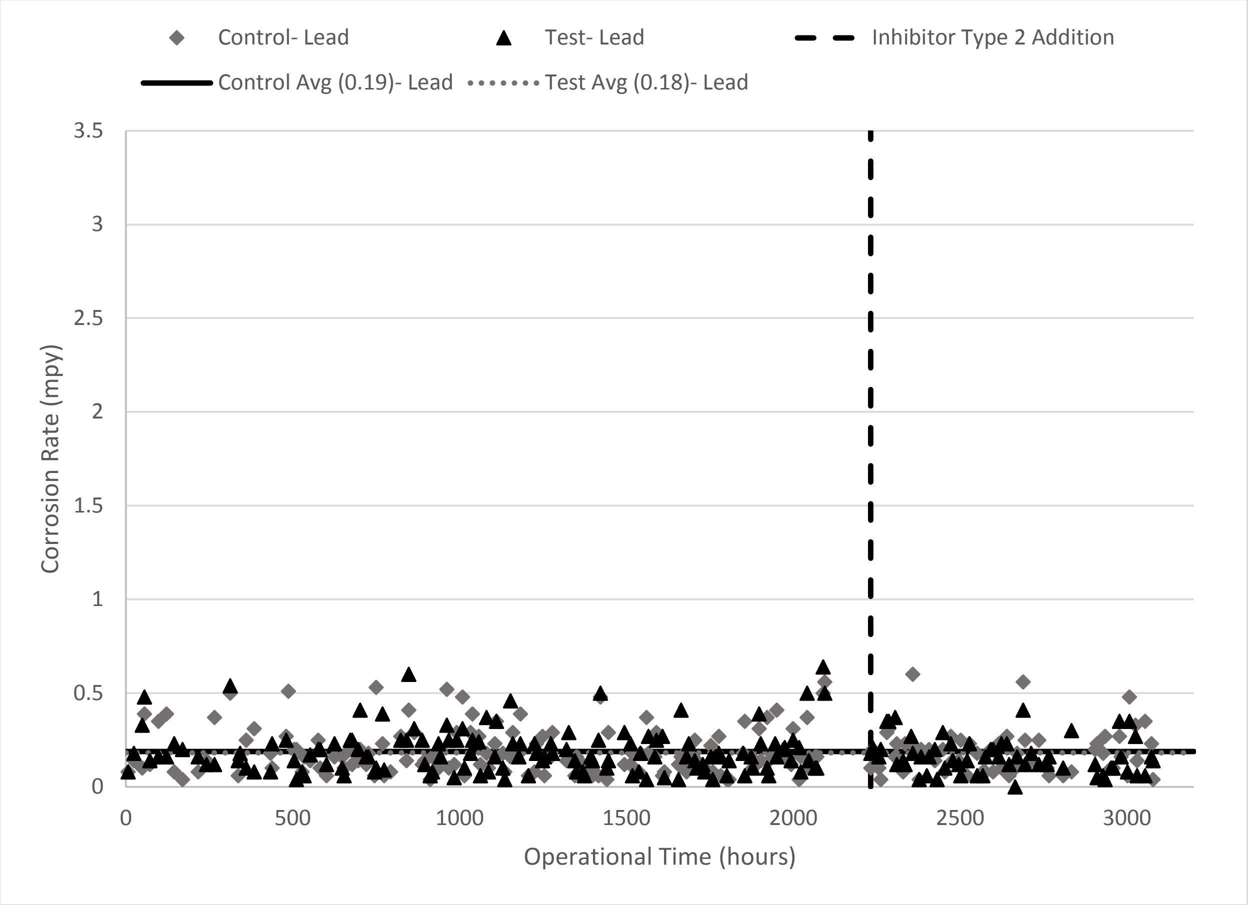


Figure 5-9: Lead Corrosion Rates for Manele Bay Inhibitor Type 2

Copper

Figure 5-10 shows copper corrosion rates as a function of time for the inhibitor type 2 experiment control and test conditions. The corrosion rates continue to decrease until there is a baseline corrosion rate around hour 800 for both test and control conditions. Test and control corrosion rates appear to be corroding at the similar rate. The average corrosion rates for the test and control conditions are 0.29 mpy and 0.3.0 mpy, respectively. Similar to that of mild steel and lead, the corrosion rates do not appear to improve and the use of inhibitor type 2 is not a viable option for corrosion control in Manele Bay.

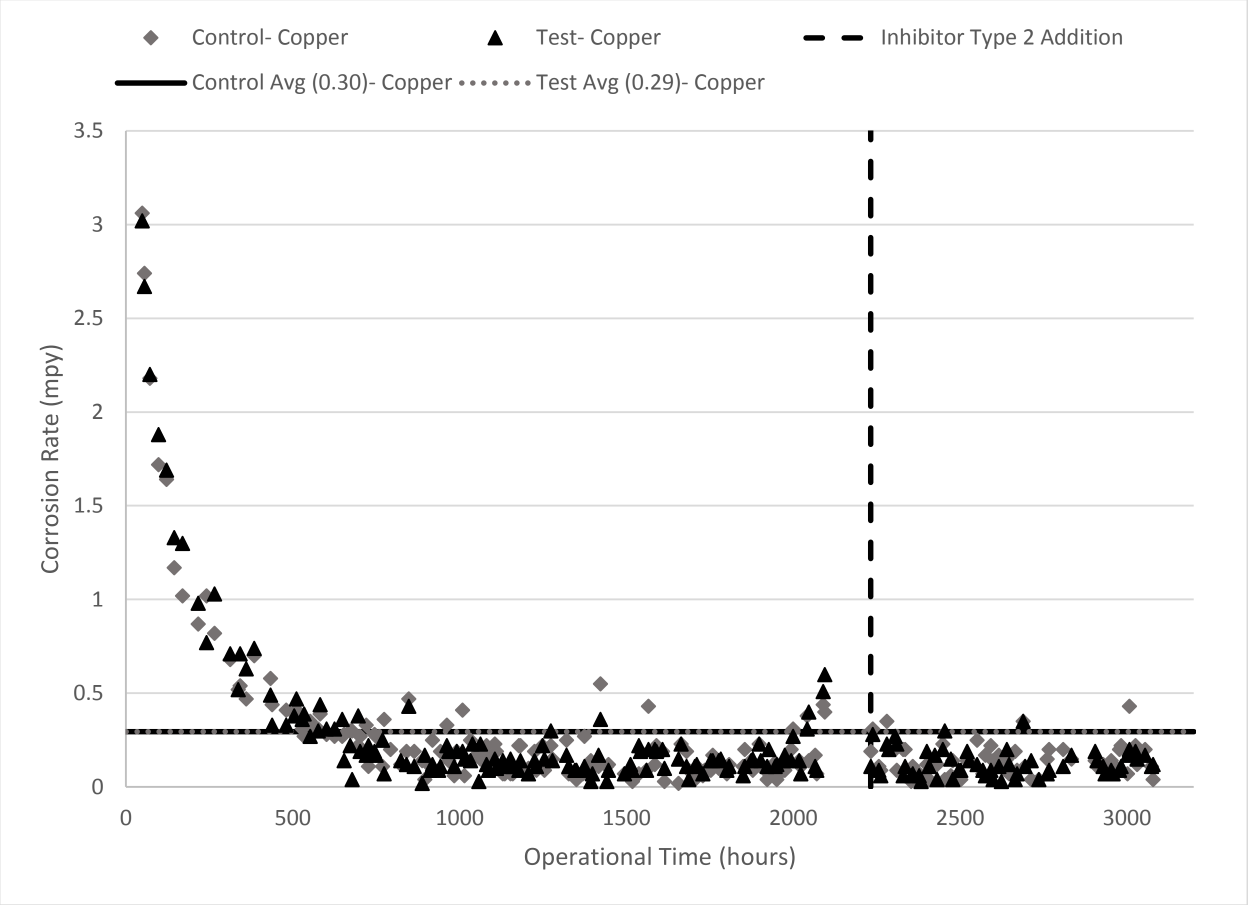


Figure 5-10: Copper Corrosion Rates for Manele Bay Inhibitor Type 2

Manele Bay Statistical Analysis- Inhibitor Type 2

The inhibitor type 2 experiment consisted of two phases: (1) pre-corrosion and (2) Inhibitor Type 2 Addition. Statistical analysis using Wilcoxon signed ranks test was performed on each of the phases. Corrosion rate measurements using the LPR data logger are presented in Appendix D. The null hypothesis for pre-corrosion data postulates that corrosion occurred at equal rates under control and test conditions. The null hypothesis was rejected for mild steel, indicating that the test and control conditions were not corroding at the same rate. The null hypothesis was not rejected for lead and copper, indicating that the test and control conditions were corroding at the same rate.

In the inhibitor type 2 addition phase, the null hypothesis is that the test and control conditions are corroding at the same rate. The alternative hypothesis states the test condition is corroding faster than the control condition for mild steel, lead, and copper. The null hypothesis was rejected for mild steel, indicating that the control conditions are corroding faster than the test conditions. The null hypothesis was not rejected for copper and lead, therefore, it can be concluded that the corrosion rates remained equal throughout the experiment. Table 5-9 summarizes the results obtained from Wilcoxon signed ranks test analysis for the Manele Bay inhibitor type 2 experiment.

Table 5-9: Summary of Wilcoxon Signed Ranks Results for Manele Bay Inhibitor Type 2

Metal	Phase	H_o	H_a	n	P	Conclusion
Mild Steel	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	139	0.000	Reject the null. Test and control conditions are corroding at a different rate
	Inhibitor Addition	Test CR = Control CR	Test CR > Control CR	59	0.000	Reject the null. Test condition rate is higher than control corrosion rate
Lead	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	138	0.590	Do not reject the null. Test and control conditions are not corroding at different rates
	Inhibitor Addition	Test CR = Control CR	Test CR > Control CR	59	0.180	Do not reject the null. Control condition corrosion rates are higher than test conditions
Copper	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	59	0.980	Do not reject the null. Test and control conditions are not corroding at different rates
	Inhibitor Addition	Test CR = Control CR	Test CR > Control CR	138	0.080	Do not reject the null. Test and control conditions are not corroding at different rates

*CR= Corrosion Rate

As stated previously, if the null hypothesis in the pre-corrosion phase is rejected, it is difficult to compare control and test conditions between each other. In the case that the pre-corrosion phase null hypothesis is rejected, comparisons between the pre-corrosion steady-state phase and inhibitor addition phase are further analyzed. For the inhibitor type 2 experiment, steady state was reached at hour 1,400. Table 5-10 presents average corrosion rates for the pre-corrosion steady state phase and inhibitor addition phase for mild steel, copper, and lead with type 2 inhibitor addition.

Table 5-10: Average Corrosion Rates of Manele Bay Inhibitor Type 2

		Control Condition	Test Condition	Percent Difference
Mild Steel	Average During Pre-Corrosion Steady State	0.396	0.582	38%
	Average During Inhibitor Addition	0.365	0.443	19%
Lead	Average During Pre-Corrosion Steady State	0.188	0.184	-2%
	Average During Inhibitor Addition	0.186	0.163	-13%
Copper	Average During Pre-Corrosion Steady State	0.142	0.166	15%
	Average During Inhibitor Addition	0.145	0.127	-13%

Since the null hypothesis for mild steel pre-corrosion phase was rejected, further comparison between the pre-corrosion steady state corrosion rate and inhibitor addition phase for mild steel is made. The test condition pre-corrosion steady state average is 0.582 mpy while the inhibitor addition corrosion rate average is 0.443 mpy resulting in a 27% decrease in corrosion rate. The control pre-corrosion steady state and inhibitor addition phases experience an 8% decrease. This may indicate that the total decrease in corrosion rate that may have been caused by inhibitor addition was 19%.

A direct comparison between the test and control conditions can be made for lead and copper because the null hypothesis was not rejected. There is decreased corrosion in both conditions for lead, and it appears that the inhibitor test condition results in an 11% decrease overall to the corrosion rate.

Comparison between the control and test conditions during the pre-corrosion phase indicates that the test condition is 15% higher than that of the control condition. In the inhibitor addition phase, the test condition corrosion rates decrease such that there is a 13% difference between test and control conditions. The difference in corrosion rate between the two phases for the control condition was 2% while the test condition resulted in a 26% difference.

Manele Bay Post Analysis- Inhibitor Type 2

Post-analysis contains the results obtained from analysis of the corrosion coupons. For the Manele Bay Inhibitor type 2 experiment, coupons were analyzed that the UCF Materials Characterization Facility (UCF-MCF) in Orlando, FL. Coupon photographs taken after the experiment concluded are presented in Figure 5-11. Three analyses were conducted to determine the surficial composition of each coupon. The first analysis involved the collection of images with a scanning electron microscope (SEM) which is capable of collecting images at 2000x zoom. Images for mild steel and copper are included. Lead corrosion rates were so low and indicate that there is little to no corrosion occurring on the surface.

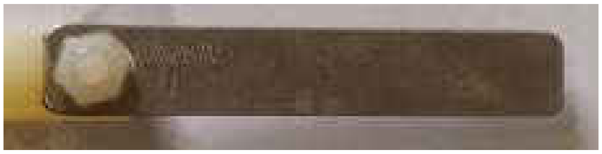
Figure 5-12 includes images of control and test condition mild steel coupon surfaces at 100x zoom. Mild steel SEM images are of tubercle surfaces. Figure 5-13 includes images of control and test condition copper coupon surfaces at 1000x zoom. Copper SEM images were taken at pitting sites on the coupon. It is difficult to have a direct comparison between the two images since tubercles and pitting have individual characteristics. While there does not appear to be a difference between the control and test mild steel coupons, the copper test condition pitting has a distinct build up when compared to the control condition.

Control **Test**

Mild Steel

Mild Steel

Lead



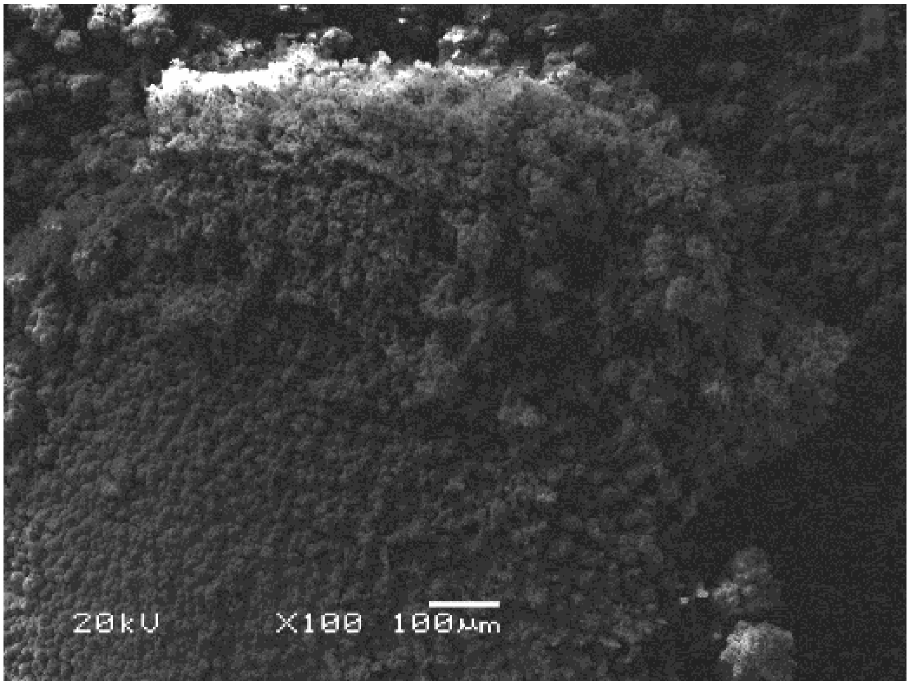
Lead

Copper

Copper

Figure 5-11: Manele Bay Coupon Photographs- Inhibitor Type 2

(a) Control Condition- Mild Steel



(b) Test Condition- Mild Steel

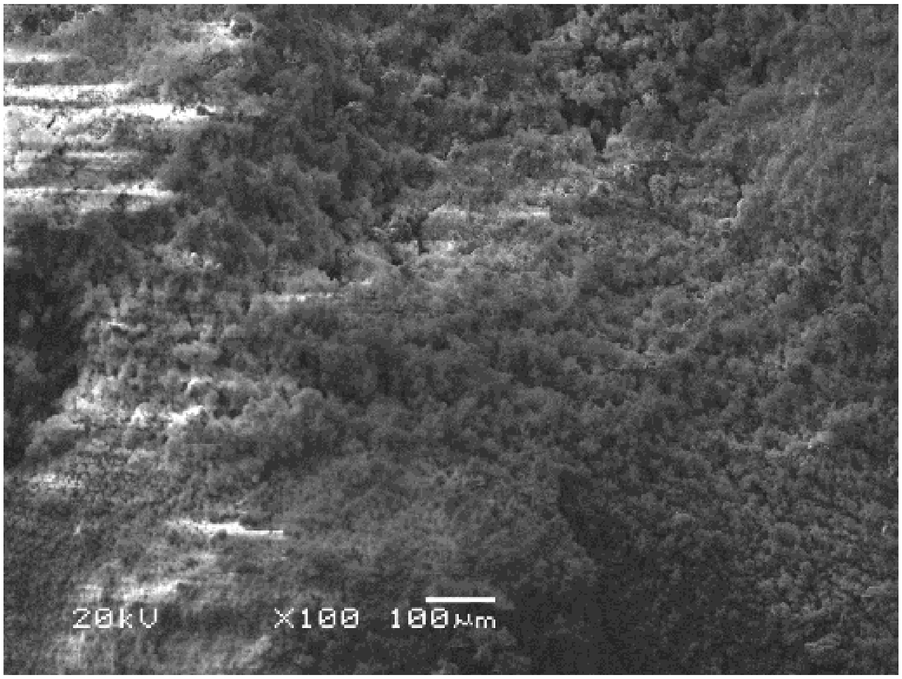
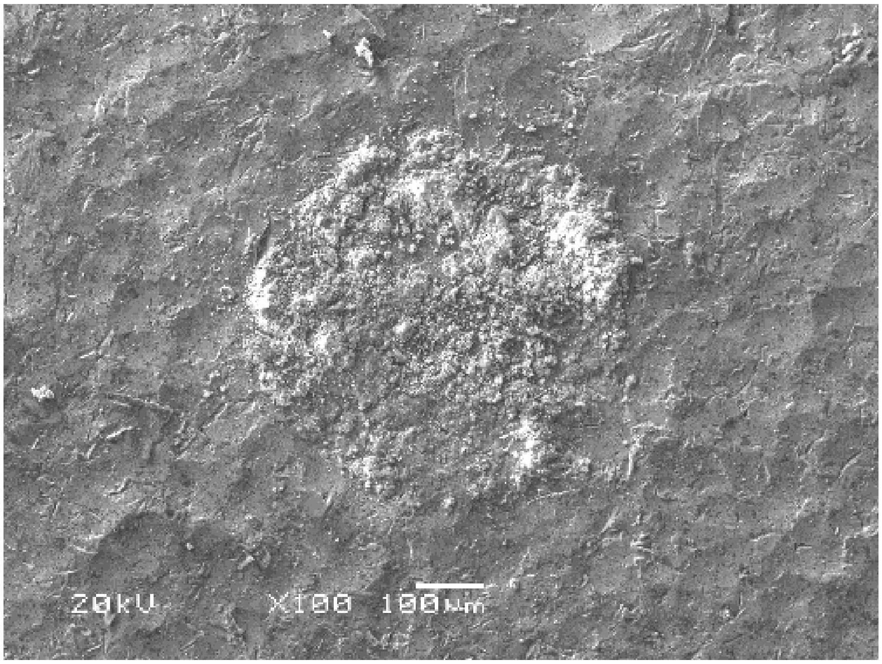


Figure 5-12: SEM imaging of Manele Bay Inhibitor Type 2 Mild Steel Coupons (100x)

(a) Control Condition- Copper



(b) Test Condition- Copper

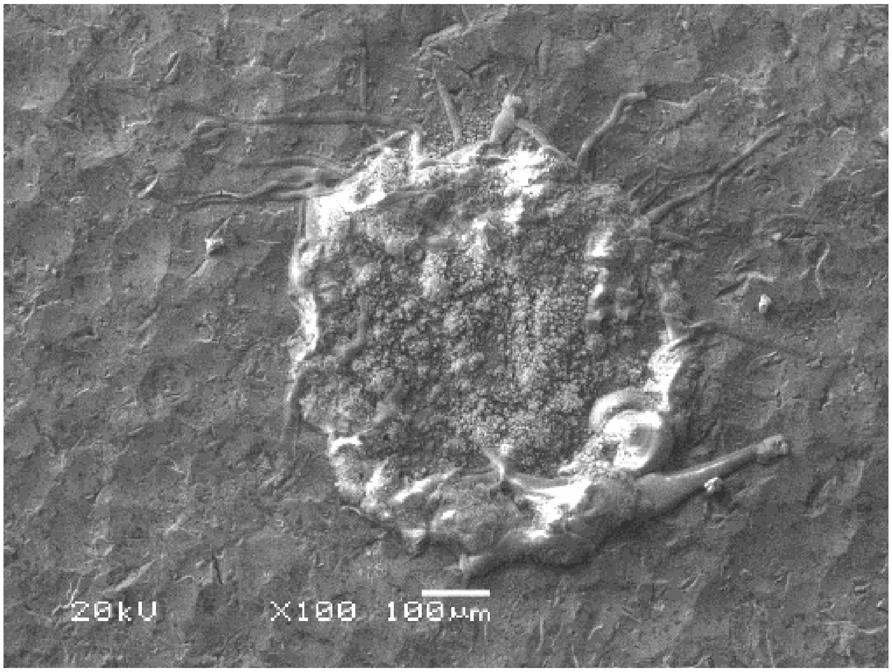


Figure 5-13: SEM Imaging of Manele Bay Inhibitor Type 2 Copper Coupons (100x)

Attached to the SEM equipment is an energy dispersive spectrometer (EDX) which measures the elemental weight and atomic percentage on the surface of an object. For this second analysis the surface of mild steel and copper coupons for each condition underwent EDX analysis at a tubercle or pit that developed on the metal surface. Table 5-11 presents EDX weight percent results for test and control mild steel tubercles. Table 5-12 presents EDX weight percent results for test and control copper coupon pits.

Table 5-11: EDX Results for Manele Bay Inhibitor 2 Experiment- Mild Steel

	Mild Steel (Weight %)		
	Control	**Test**	**% Difference**
Carbon	16.0%	5.53%	97.4%
Oxygen	24.3%	23.3%	4.37%
Silica	7.43%	9.79%	27.4%
Magnesium	0.68%	0.71%	4.32%
Iron	48.2%	57.4%	17.5%
Other	3.37%	3.28%	2.71%

Table 5-12: EDX Results for Manele Bay Inhibitor 2 Experiment- Copper

	Copper (Weight %)		
	Control	**Test**	**% Difference**
Oxygen	23.6%	17.7%	28.7%
Silica	18.2%	9.3%	65.0%
Potassium	0.37%	2.51%	149%
Chloride	1.94%	1.02%	62.2%
Calcium	0.94%	0.49%	63.0%
Copper	9.86%	3.62%	92.6%
Zinc	45.2%	65.5%	36.7%

EDX results for mild steel indicate that there are differences between the tubercles of the control coupon and tubercles of the test coupon. Most notable is the 27% difference in silica from control to test. This increase could be due to the increased silicate concentration introduced via inhibitor 2. In addition, for these particular tubercles, there is a 97% difference between the carbon levels. EDX results for copper also indicate that the pit formation has differences in silica. However, in this comparison, silica presence in the control is 65% higher than that of the test.

The third analysis conducted was x-ray photoelectron spectroscopy (XPS) such that elemental maps of the surface can help determine the spatial distribution of elements. XPS analysis is inclusive of tubercles, pits, film layer, and non-corroded surface. Table 5-13 presents XPS results for the control condition.

Table 5-13: XPS results for Manele Bay Inhibitor Type 2

Element Detected	Mild Steel		Copper	
	Control	Test	Control	Test
Carbon	13.6%	17.2%	18.1%	21.2%
Oxygen	40.8%	38.3%	49.4%	47.3%
Silica	ND*	3.86%	6.57%	7.00%
Copper	ND*	ND*	12.1%	9.74%
Zinc	ND*	ND*	13.9%	14.8%
Iron	45.6%	40.7%	ND*	ND*

*ND- Not Detected

XPS results indicate that much of the surface between the test and control for both mild steel and copper are similar. The largest difference is noted in the zinc result between test and control copper coupons. This is probably due to anomalies in how the metal sample was cut prior to analysis. Another notable observation is the silicate was detected in the test mild steel coupon and not in the control mild steel coupon.

Lana'i City Corrosion Study Results and Discussion

Results are presented for each of two experiments conducted during the Lana'i City corrosion control research project. Analysis of coupons for each experiment comprised of comprehensive surface analysis using SEM, EDX, and XPS was used. LPR probe analysis largely consisted of interpreting results obtained from the LPR data logger using statistics. Wilcoxon signed ranks test was used to compare for symmetry between the control rack and the test rack. The program Minitab was used to perform the statistical analysis used in the Wilcoxon signed rank test. Water quality results are presented as a summary per experiment in this section.

Lana'i City Inhibitor Type 1

Inhibitor type 1 evaluated in this research is a 50:50 ortho:poly blended inhibitor. Coupons and probes were corroded for a total of 4,470 hours before the experiment was concluded. This experiment is comprised of three phases: (1) a pre-corrosion phase, (2) phosphate inhibitor addition phase, and (3) post-inhibitor addition phase. The post-corrosion phase occurs after inhibitor feed has ceased (i.e. inhibitor is no longer present in the system).

The average water quality results for the inhibitor type 1 experiment are presented in Table 5-14. pH, conductivity, turbidity, dissolved oxygen, and free chlorine were collected daily on site.

Alkalinity, chloride, sulfate, hardness, and total dissolved solids were collected weekly and shipped to UCF for analysis.

Table 5-14: Water Quality Results for Lana'i City Inhibitor Type 1 Experiment

Parameter	Concentration or Value	
	Control	Test
pH (pH units)	8.20	8.38
Conductivity (µS/cm)	352	329
Turbidity (NTU)	0.29	0.25
Dissolved Oxygen (mg/L)	6.75	6.72
Free Chlorine (mg/L)	0.46	0.48
Total Alkalinity (mg/L as CaCO3)	83.1	82.7
Chloride (mg/L)	36.7	36.6
Sulfate (mg/L)	7.60	7.60
Total Hardness (mg/L as CaCO3)	94.3	94.2
Total Dissolved Solids (mg/L)	195	201
Langelier Saturation Index	-0.29	-0.11
Ryznar Index	8.78	9.08
Larson Ratio	0.87	0.86

Mild Steel

Figure 5-14 illustrates mild steel corrosion rates as a function of time for the inhibitor type 1 experiment for test and control conditions in Lana'i City. There is no distinct curve, however, the corrosion rates appear to reach baseline at hour 1,500. While the average corrosion rate for the control condition (0.73 mpy) is higher than that of the test condition (0.48 mpy), the two conditions corrode in a similar way. Inhibitor was added continuously starting at hour 2,376 at a dose of approximately 1.0 mg/L. Inhibitor feed was ceased at operational hour 3,432 and the corrosion rates continued to be monitored until the experiment was concluded at operational hour 4,464. The addition of inhibitor type 1 does not improve the corrosion rate of the mild steel test rack for and is therefore not a viable option for mild steel corrosion control in Lana'i City.

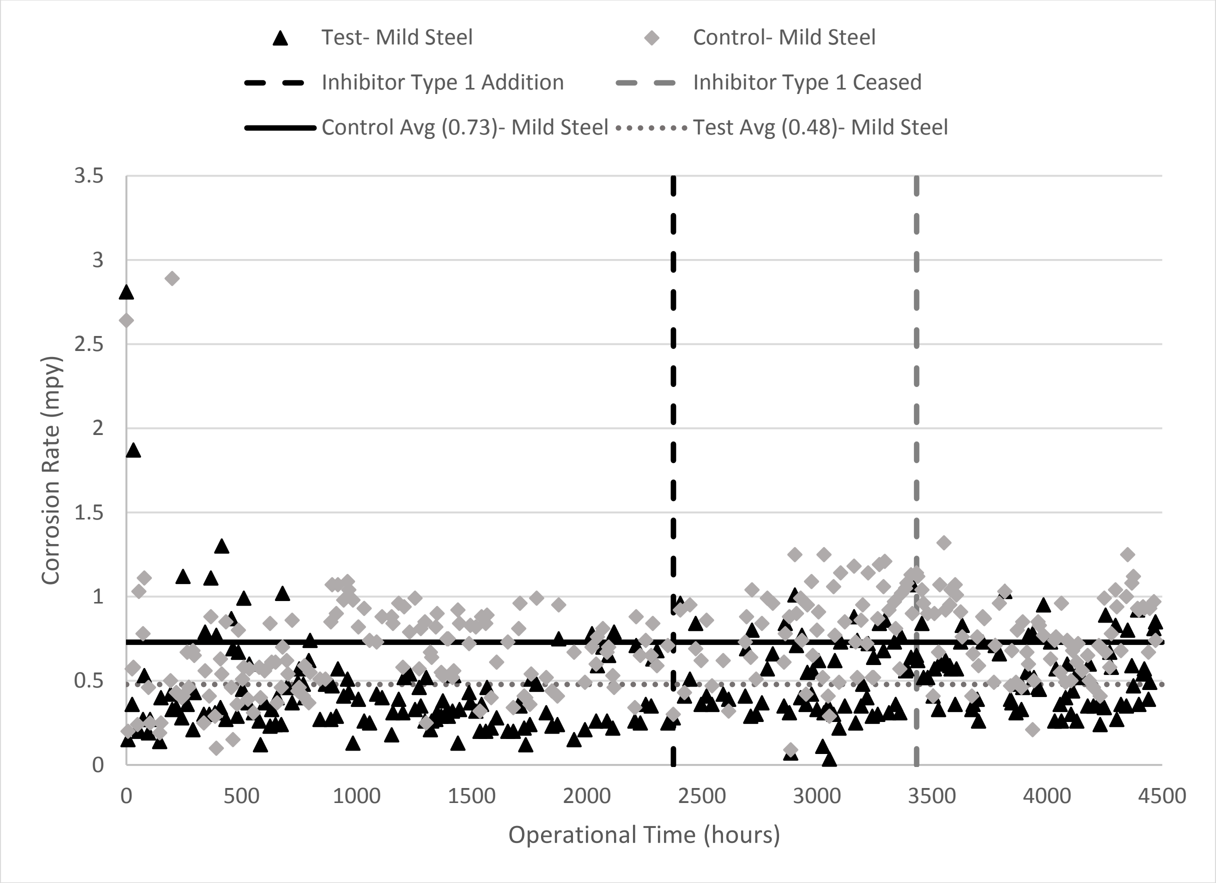


Figure 5-14: Mild Steel Corrosion Rates for Lana'i City Inhibitor Type 1

Lead

Figure 5-15 shows lead corrosion rates as a function of time for the inhibitor type 2 experiment control and test conditions. The corrosion rates for lead are fluctuating, but are also low (< 0.6 mpy) throughout data collection. There does not appear to be a difference between the test and control condition corrosion rates. The average corrosion rates for the test and control conditions are barely distinguishable (0.17 mpy and 0.18 mpy). In addition, there was not a discernable difference between the test and corrosion rates after inhibitor was added. It appears that addition of inhibitor type 2 does not benefit the distribution system in reducing lead corrosion rates in Lana'i City.

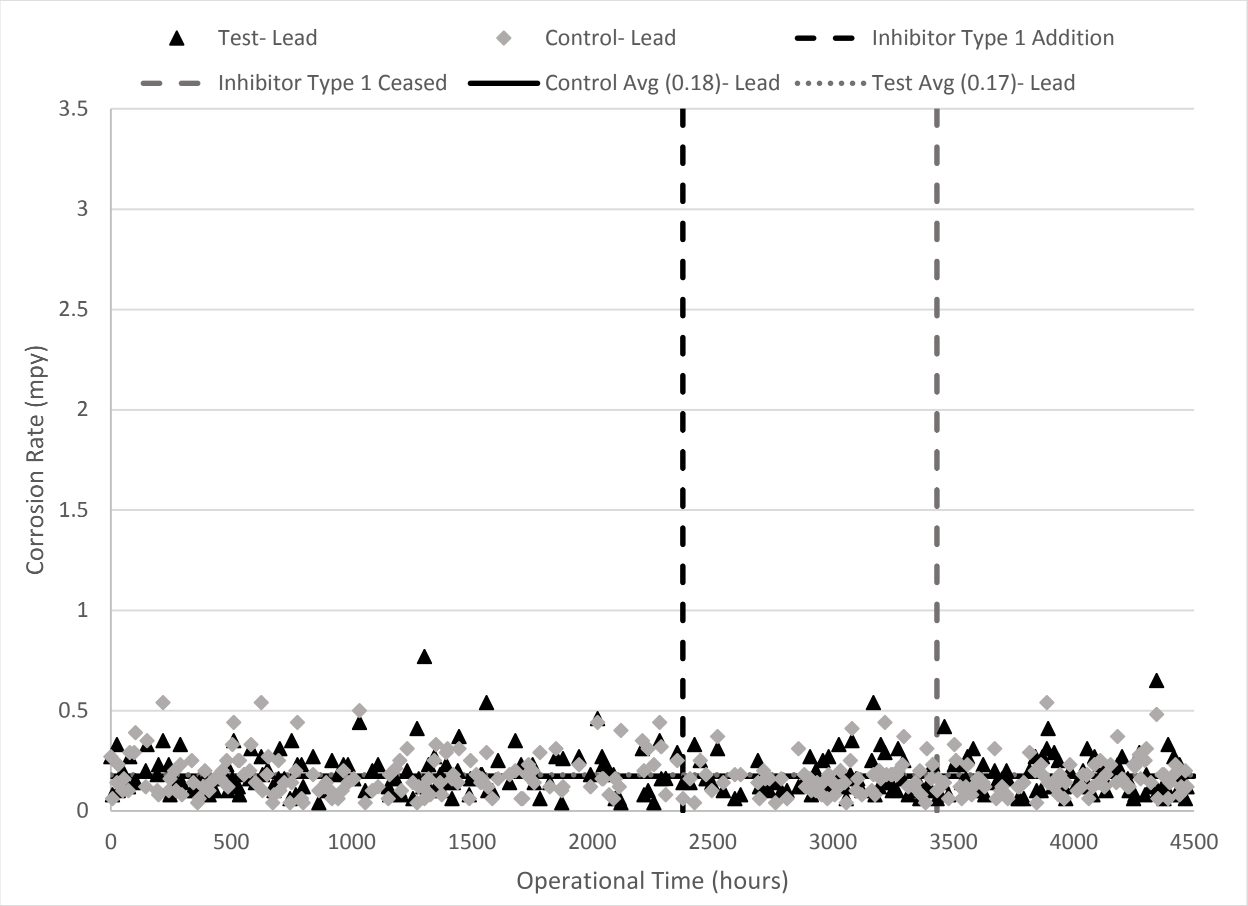


Figure 5-15: Lead Corrosion Rates for Lana'i City Inhibitor Type 1

Copper

Figure 5-16 shows copper corrosion rates as a function of time for the inhibitor type 1 experiment control and test conditions. The corrosion rates continue to decrease until there is a baseline corrosion rate around hour 1,000 for both test and control conditions. Test and control corrosion rates appear to be corroding at the similar rate until inhibitor type 1 is added. Phosphate inhibitor addition causes a spike in the test condition corrosion rates. When inhibitor type one is no longer added, monitoring continued. It appears that corrosion rates for the test condition never returned to their previous, lower corrosion rates. Note that the average corrosion rate for the test condition is higher at 0.70 mpy compared to the control condition average corrosion rate at 0.29 mpy.

Interactions between silica and phosphate could explain the copper corrosion rate increase when corrosion inhibitor was added. It has been noted that silica addition can affect the properties of phosphate coatings on iron surfaces (Stoch & Stoch, 1989). In addition, silica surfaces with a negative charge have enhanced silica-phosphate complexes in the presence of cations (Muashov & Leszczynski, 1999). While the pipe is not a silica surface, solid silica formations present in the copper corrosion scale may interact with phosphates in such a way that the scale could be compromised and degraded.

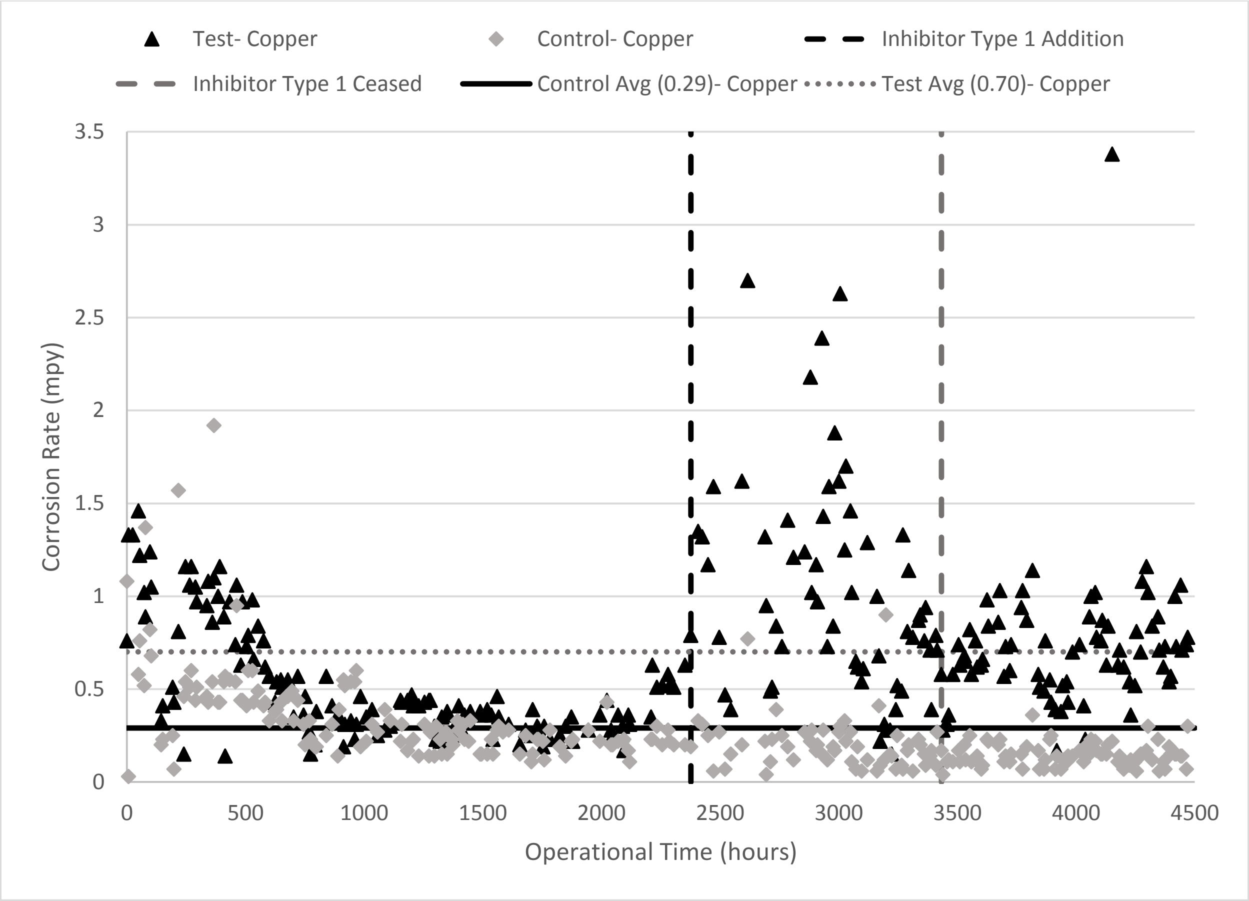


Figure 5-16: Copper Corrosion Rates for Lana’i City Inhibitor Type 1

<u>Lana’i City Statistical Analysis- Inhibitor Type 1</u>

The inhibitor type 1 experiment consisted of three phases: (1) pre-corrosion, (2) inhibitor type 2 Addition, and (3) post-inhibitor addition phase. Statistical analysis using Wilcoxon signed ranks test was performed on each of the phases. Because of the length and frequency of the measurements taken during this project, corrosion rate measurements using the LPR data logger are presented in Appendix E. As previously stated, the null hypothesis for pre-corrosion data postulates that corrosion occurred at equal rates under control and test conditions. The null hypothesis was rejected for mild steel and copper measurements, indicating that the test and control conditions were not corroding at the same rate. The null hypothesis was not rejected for lead, indicating that the test and control conditions were corroding at the same rate.

In the inhibitor type 1 addition phase, the null hypothesis is that the test and control conditions are corroding at the same rate. The alternative hypothesis states the test condition is corroding faster than the control condition for mild steel, lead, and copper. The null hypothesis was rejected for mild steel and copper, indicating that the test conditions are corroding faster than the test conditions. The null hypothesis was not rejected for lead, therefore, it can be concluded that the corrosion rates remained equal.

In the post-inhibitor addition phase, the null hypothesis is that the test and control conditions are corroding at the same rate. The alternative hypothesis states that the corrosion rates are not equal. The null hypothesis was rejected for mild steel and copper, indicating the control and test conditions are corroding at different rates. The null hypothesis was not rejected for lead and it can be concluded that the corrosion rates remained equal throughout the experiment. Table 5-15 summarizes the results obtained from Wilcoxon signed ranks test analysis for the Lana’i City inhibitor type 1 experiment.

Table 5-15: Summary of Wilcoxon Signed Ranks Results for Lana'i City Inhibitor 1 Experiment

Metal	Phase	H_o	H_a	n	P	Conclusion
Mild Steel	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	135	0.000	Reject the null. Test and control conditions are corroding at a different rate
	Inhibitor Addition	Test CR = Control CR	Test CR > Control CR	64	0.000	Reject the null. Test condition is corroding at higher rate than control
	Post-Inhibitor Addition	Test CR = Control CR	Test CR ≠ Control CR	73	0.000	Reject the null. Test and control conditions are corroding at a different rate
Lead	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	135	1.000	Do not reject the null. Test and control conditions are not corroding at different rates
	Inhibitor Addition	Test CR = Control CR	Test CR > Control CR	63	0.984	Do not reject the null. Test and control conditions are not corroding at different rates
	Post-Inhibitor Addition	Test CR = Control CR	Test CR ≠ Control CR	75	0.467	Do not reject the null. Test and control conditions are not corroding at different rates
Copper	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	132	0.000	Reject the null. Test and control conditions are corroding at a different rate
	Inhibitor Addition	Test CR = Control CR	Test CR > Control CR	61	0.000	Reject the null. Test condition is corroding at higher rate than control
	Post-Inhibitor Addition	Test CR = Control CR	Test CR ≠ Control CR	73	0.000	Reject the null. Test and control conditions are corroding at a different rate

As in the Manele Bay corrosion experiments, if the null hypothesis in the pre-corrosion phase is rejected, it is difficult to compare control and test conditions between each other. In the case that the pre-corrosion phase null hypothesis is rejected, comparisons between the pre-corrosion steady-state phase and inhibitor addition phase are further analyzed. For the inhibitor type 1 experiment, steady state was reached at hour 1,500. Table 5-16 presents average corrosion rates for the pre-corrosion steady state phase and inhibitor addition phase for mild steel, copper, and lead with type 1 inhibitor addition.

Table 5-16: Average Corrosion Rate of Lana'i City Inhibitor Type 1

		Control Condition	Test Condition	Percent Difference
Mild Steel	Average During Pre-Corrosion Steady State	0.658	0.375	-55%
	Average During Inhibitor Addition	0.807	0.512	-45%
	Average During Post-Inhibitor	0.782	0.532	-38%
Lead	Average During Pre-Corrosion Steady State	0.198	0.189	-4%
	Average During Inhibitor Addition	0.160	0.167	4%
	Average During Post-Inhibitor	0.167	0.178	7%
Copper	Average During Pre-Corrosion Steady State	0.220	0.350	45%
	Average During Inhibitor Addition	0.204	1.005	132%
	Average During Post-Inhibitor	0.147	0.729	133%

The null hypothesis for mild steel pre-corrosion phase was rejected, therefore, further comparison between the pre-corrosion steady state corrosion rate and inhibitor addition phase for mild steel is made. The test condition pre-corrosion steady state average is 0.375 mpy while the inhibitor addition corrosion rate average is 0.512 mpy resulting in a 31% increase in corrosion rate. The control pre-corrosion steady state and inhibitor addition phases experience a 20% increase. This may indicate that the total increase in corrosion rate that may have been caused by inhibitor addition was 11%. In this case, phosphate inhibitor addition does not help and may hinder the reduction of the corrosion rate of mild steel.

The null hypothesis for copper pre-corrosion phase was also rejected. As with mild steel, further comparison between the pre-corrosion steady state corrosion rate and inhibitor addition corrosion rate was made. The test condition pre-corrosion steady state average is 0.350 mpy while the inhibitor addition rate average is 1.005 mpy; a 97% increase. The control pre-corrosion steady state and inhibitor addition phases experience an 8% decrease. It is obvious from the graph that the phosphate inhibitor addition negatively impacted the corrosion rate of copper.

A direct comparison between the test and control conditions can be made for lead because the null hypothesis was not rejected. There is increased corrosion in both conditions for lead, and it appears that the inhibitor test condition results in a 3% increase overall to the corrosion rate. Phosphate inhibitor addition does not seem to affect the corrosion rates of lead.

Lana'i City Post Analysis- Inhibitor Type 1

Post-analysis contains the results obtained from analysis of the corrosion coupons. For the Lana'i City Inhibitor type 1 experiment, coupons were analyzed that the UCF Materials Characterization Facility (UCF-MCF) in Orlando, FL. Figure 5-17presents coupon photographs at the completion of the experiment. Three analyses were conducted to determine the surficial composition of each coupon. As in the Manele Bay inhibitor type 2 experiment surface analyses utilizing SEM, EDX, and XPS were conducted. SEM images at 100x zoom of mild steel are shown in Figure 5-18. Mild steel images were taken to show the iron tubercle that formed on the coupon. Figure 5-19 includes SEM images of control and test condition copper coupon surfaces at 100x zoom. Copper SEM images were taken at pitting sites on the coupon. It is difficult to have a direct comparison between the two images since tubercles and pitting have individual characteristics. While there does not appear to be a difference between the control and test mild steel coupons, the copper test condition pitting has a distinct build up when compared to the control condition.

Control **Test**

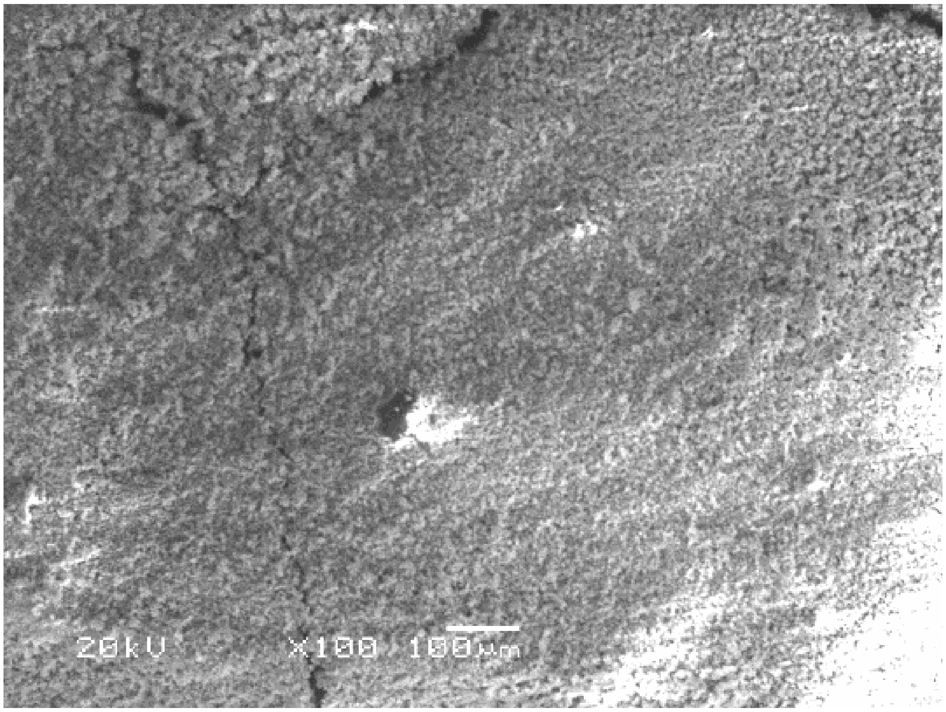
Mild Steel Mild Steel

Lead Lead

Copper Copper

Figure 5-17: Lana’i City Coupon Photographs- Inhibitor 1

(a) Control- Mild Steel



(b) Test- Mild Steel

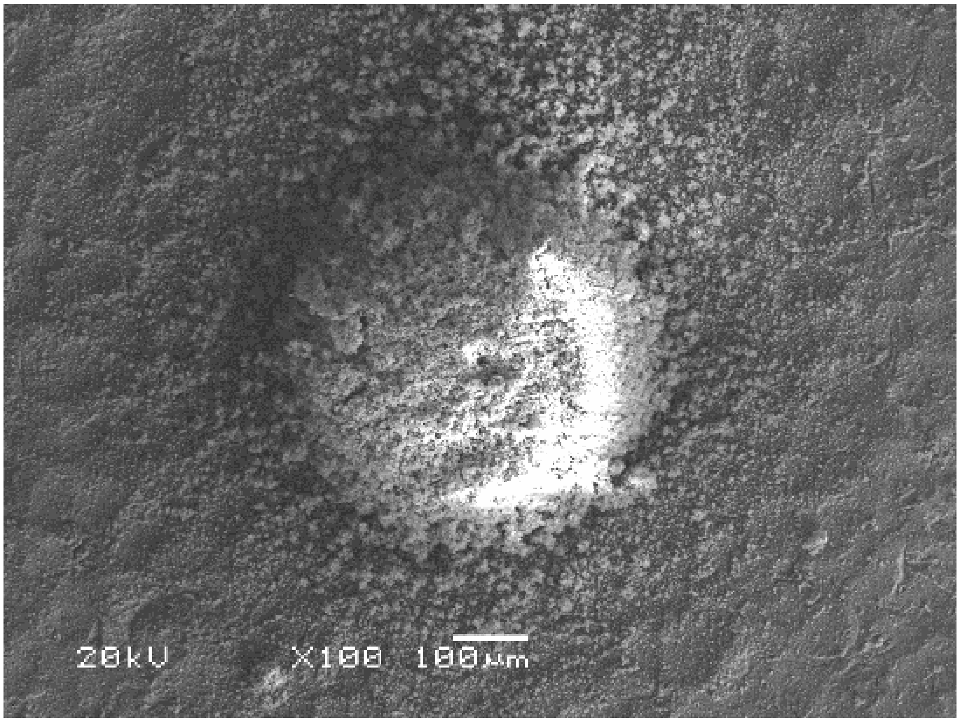
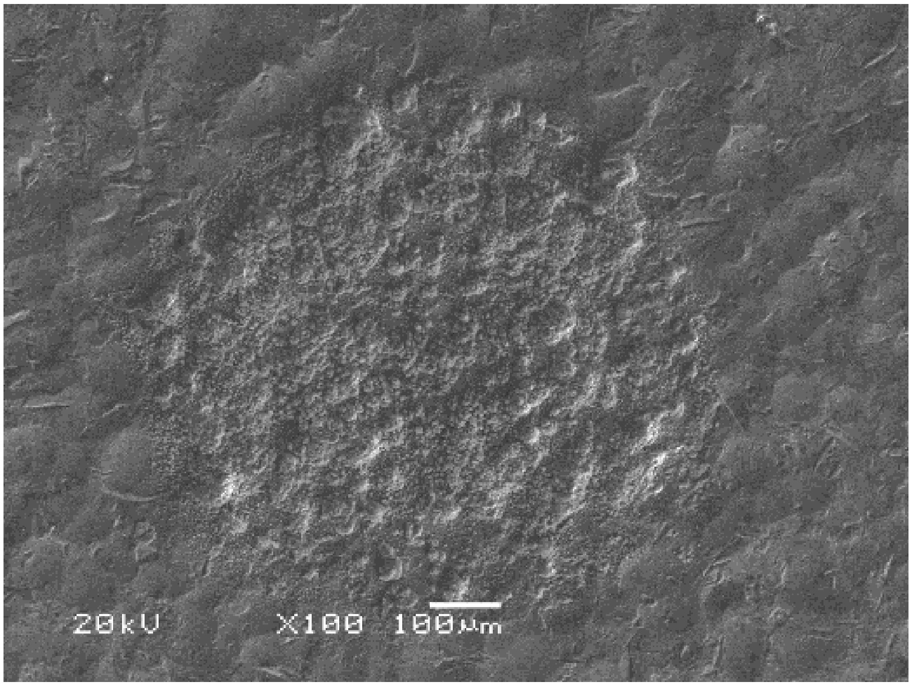


Figure 5-18: SEM Imaging of Lana'i City Inhibitor Type 1 Mild Steel Coupons (100x)

(a) Control- Copper



(b) Test- Copper

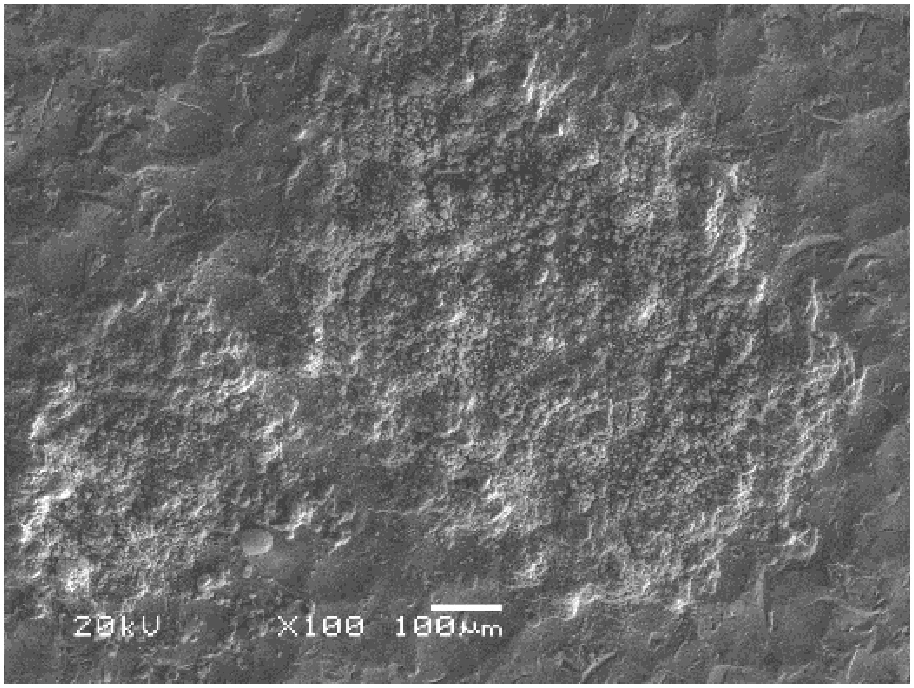


Figure 5-19: SEM imaging of Lana’i City Inhibitor Type 1 Copper Coupons (100x)

This sample was further analyzed using EDX. This second analysis of the surface of mild steel and copper coupons for each condition occurred at a tubercle or pit that developed on the metal surface. Table 5-17 presents EDX weight percent results for test and control mild steel tubercles. Table 5-18 presents EDX weight percent results for test and control copper coupon pits.

Table 5-17: EDX Results for Lana'i City Inhibitor 1 Experiment- Mild Steel

	Mild Steel (Weight %)		
	Control	Test	% Difference
Carbon	13.5%	12.9%	4.47%
Oxygen	0.00%	45.1%	200 %
Silica	8.96%	0.00%	200 %
Iron	72.8%	30.3%	82.4%
Other	4.75%	11.7%	84.4%

Table 5-18: EDX Results for Lana'i City Inhibitor 1 Experiment- Copper

	Copper (Weight %)		
	Control	Test	% Difference
Oxygen	22.2%	20.6%	7.42%
Silica	14.7%	12.8%	13.6%
Iron	1.78%	1.32%	29.7%
Copper	6.24%	3.91%	45.9%
Zinc	53.5%	58.6%	9.06%
Other	1.60%	2.76%	53.2%

EDX results for mild steel indicate that there are differences between the tubercles of the control coupon and tubercles of the test coupon. The instrument reads a high oxygen level in the test tubercle, but not on the control tubercle. The opposite is true of silica; silica is detected in the control tubercle and not in the test tubercle. The discrepancies in the elemental readings may be differences in the tubercles themselves or could be caused by differences in water chemistry experienced in each condition. EDX results for copper also indicate that the pit formation has differences, specifically in copper content. In this comparison, copper presence in the control is 45% higher than that of the test. This may indicate that the copper protection layer has decreased in the test condition.

The third analysis conducted was x-ray photoelectron spectroscopy (XPS) such that elemental maps of the surface can help determine the spatial distribution of elements. As noted previously, XPS analysis is representative of the surface of the coupon and not a particular tubercle or pit. In addition, the first 10 nm are analyzed rather than just the immediate surface as in EDX. Table 5-19 presents XPS results for the control condition.

Table 5-19: XPS Results for Lana'i City Inhibitor Type 1

	Mild Steel		**Copper**	
Element Detected	**Control**	**Test**	**Control**	**Test**
Carbon	18.1%	22.8%	23.3%	25.5%
Oxygen	64.8%	62.4%	53.3%	56.0%
Copper	ND*	ND*	1.30%	3.10%
Iron	6.00%	9.20%	ND*	ND*
Silica	11.1%	5.70%	9.30%	11.1%
Zinc	ND*	ND*	12.4%	4.20%

*ND- Not detected

XPS results indicate that much of the surface between the test and control for both mild steel and copper are similar. In addition, silica is present in both control and test conditions indicating that it is present in corrosion scale and tuberculation. The largest difference is noted in the zinc result between test and control copper coupons. This is probably due to anomalies in how the metal sample was cut prior to analysis. Another notable observation is the silicate percentage between control and test mild steel coupons.

Lana'i City Inhibitor Type 2

Inhibitor type 2 evaluated in this research is a sodium silicate inhibitor. Coupons and probes were corroded for a total of 2,016 hours before the experiment was concluded. This experiment is comprised of two phases: (1) a pre-corrosion phase and (2) silicate inhibitor addition phase. Due to time restrictions at the site, the experiment was shortened and results consistent with previous experiments associated with this project were not fully obtained. It is suspected that the LPR wands or data logger is at the end of its useable life.

Some of the results from this experiment may be hence inaccurate. The average water quality results for the inhibitor type 2 experiment are presented in Table 5-20. pH, conductivity, turbidity, dissolved oxygen, and free chlorine were collected daily on site. Water samples were collected weekly and shipped to UCF for alkalinity, chloride, sulfate, hardness, and total dissolved solids analysis.

Table 5-20: Water Quality Results for Lana'i City Inhibitor Type 2 Experiment

Parameter	Concentration or Value	
	Control	Test
pH (pH units)	8.88	8.94
Conductivity (µS/cm)	388	358
Turbidity (NTU)	0.31	0.33
Dissolved Oxygen (mg/L)	7.20	7.15
Free Chlorine (mg/L)	0.62	0.60
Total Alkalinity (mg/L as $CaCO_3$)	90.5	90.5
Chloride (mg/L)	36.5	36.5
Sulfate (mg/L)	7.90	7.80
Total Hardness (mg/L as $CaCO_3$)	101	101
Total Dissolved Solids (mg/L)	195	199
Langelier Saturation Index	+0.50	+0.57
Ryznar Index	7.88	7.80
Larson Ratio	0.79	0.79

Mild Steel

Figure 5-20 illustrates mild steel corrosion rates as a function of time for the inhibitor type 2 experiment for test and control conditions in Lana'i City. There is no distinct curve, however, the corrosion rates appear to reach baseline at hour 1,000. While the average corrosion rate for the control condition (2.5 mpy) is higher than that of the test condition (2.2 mpy), the two conditions corrode in a similar way. Inhibitor was added continuously starting at hour 1,416 at a dose of approximately 1.0 mg/L. Inhibitor feed was ceased at operational hour 2,016. The addition of inhibitor type 2 does not appear to improve the corrosion rate of the mild steel test rack and is therefore not a viable option for mild steel corrosion control in Lana'i City.

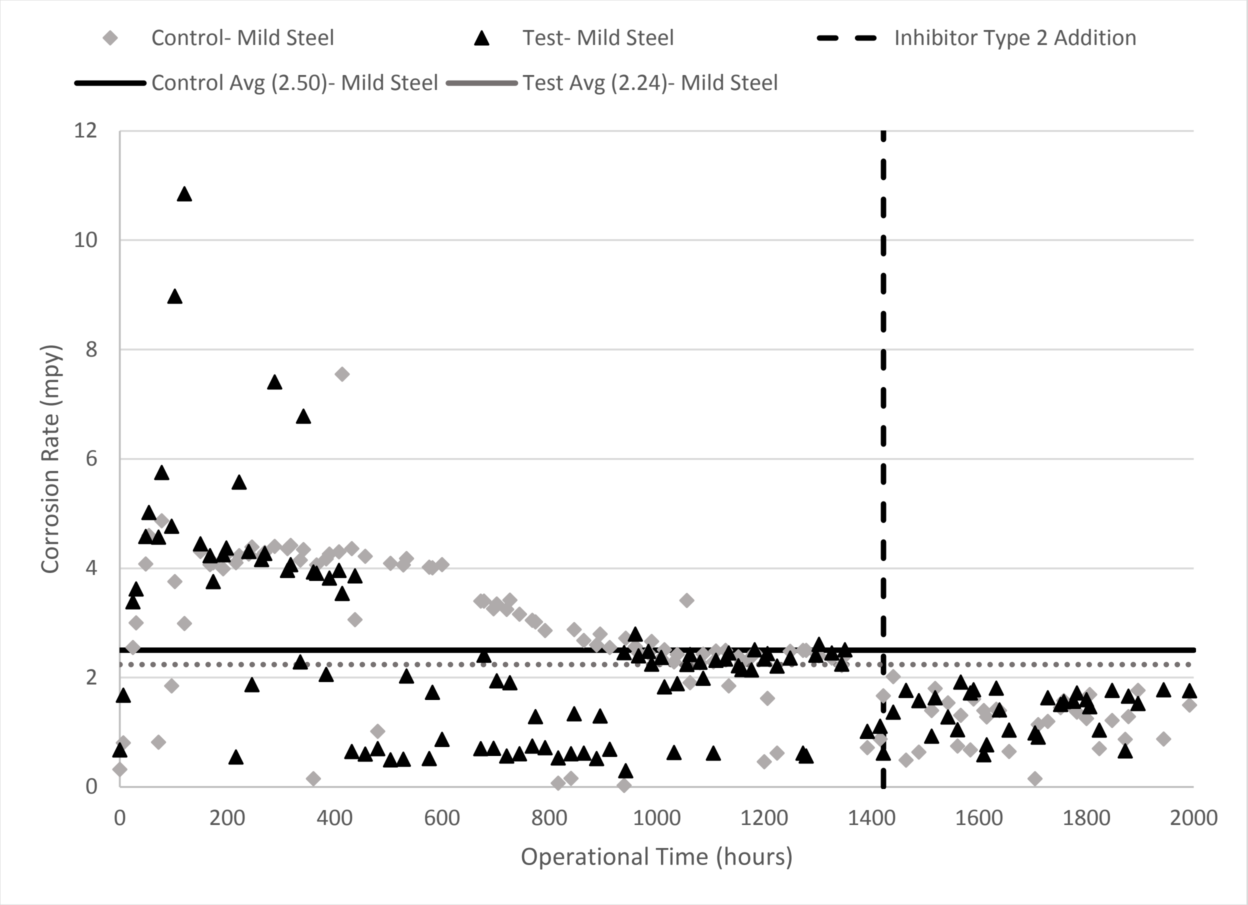


Figure 5-20: Mild Steel Corrosion Rates for Lana'i City Inhibitor Type 2

Lead

Figure 5-21 shows lead corrosion rates as a function of time for the inhibitor type 2 experiment control and test conditions. The corrosion rates for lead are fluctuating, but are also very low (< 0.6 mpy) throughout data collection. There does not appear to be a difference between the test and control condition corrosion rates at 0.18 mpy and 0.22 mpy, respectively. The average corrosion rates for the test and control conditions are barely distinguishable. Consequently, there was not a discernable difference between the test and corrosion rates after inhibitor was added. It appears that addition of inhibitor type 2 does not benefit in reducing lead corrosion rates.

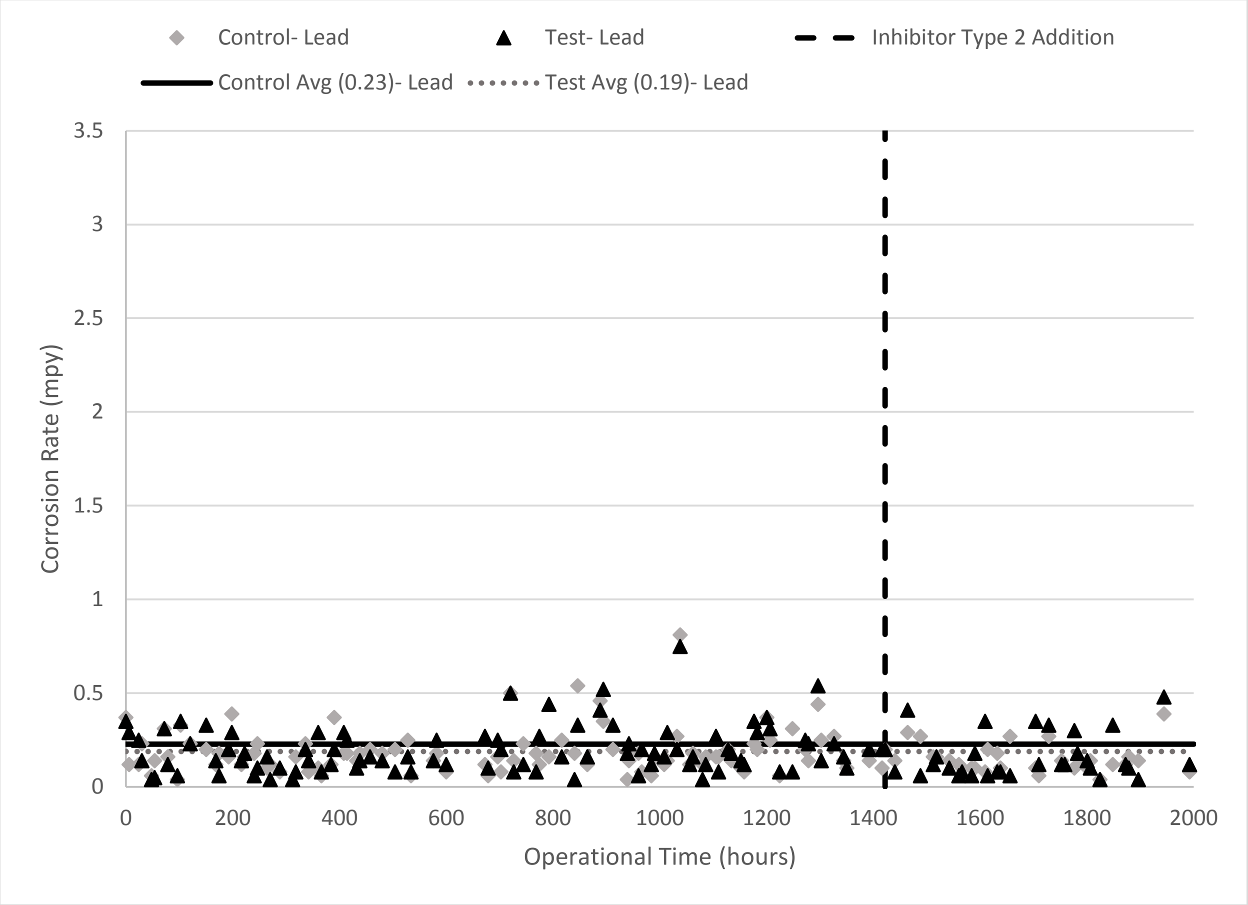


Figure 5-21: Lead Corrosion Rates for Lana'i City Inhibitor Type 2

Copper

Figure 5-22 shows copper corrosion rates as a function of time for the inhibitor type 2 experiment control and test conditions. The corrosion rates are a bit sporadic at the beginning but appear to level at hour 1,100. Test and control average corrosion rates are not corroding at the same rate. The test condition average is 86% higher than the control condition. The test and control corrosion rates are 0.95 mpy and 0.38 mpy respectively.

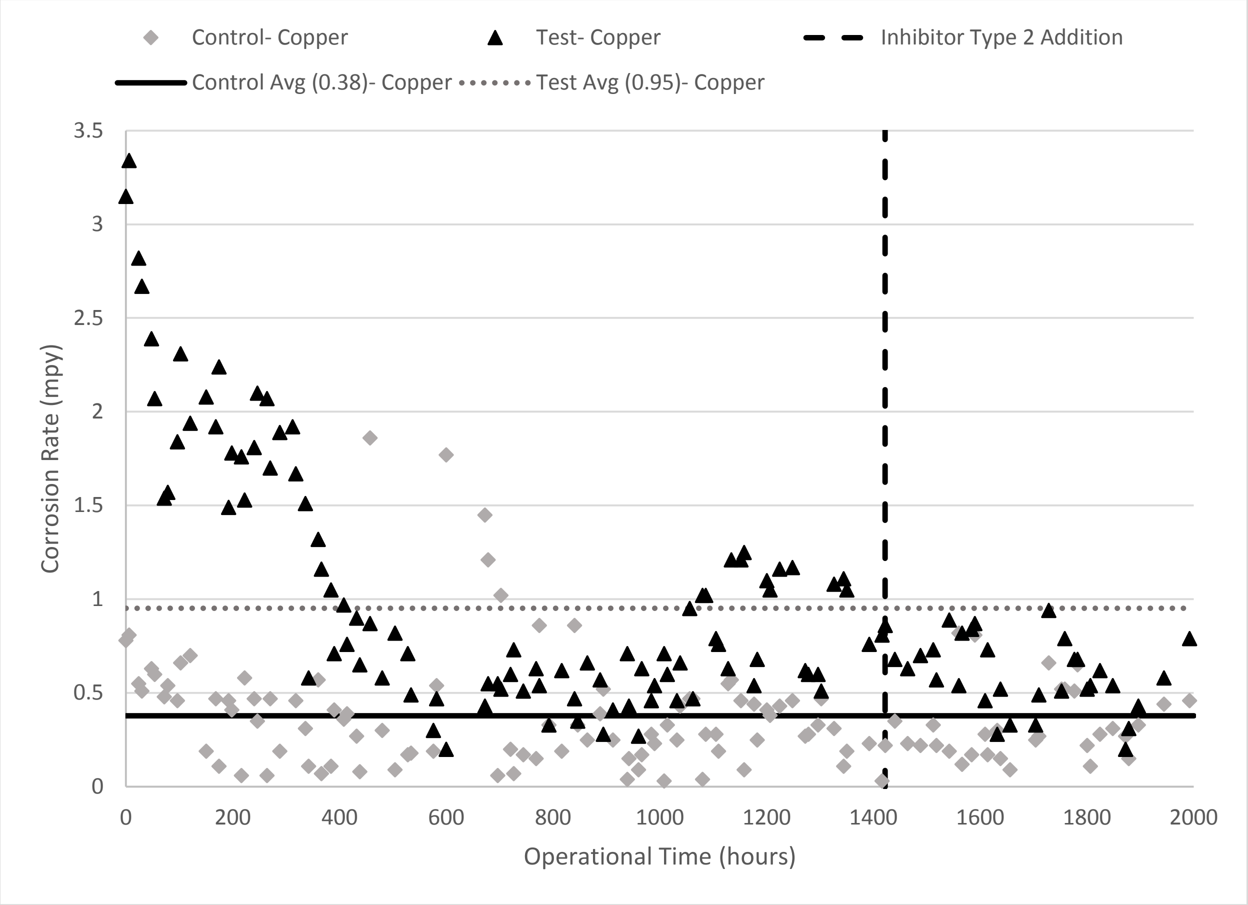


Figure 5-22: Copper Corrosion Rates for Lana'i City Inhibitor Type 2

Lana’i City Statistical Analysis- Inhibitor Type 2

The inhibitor type 2 experiment at Lana’i City consisted of two phases: (1) pre-corrosion and (2) Inhibitor Type 2 Addition. Statistical analysis using Wilcoxon signed ranks test was performed on each of the phases. Corrosion rate measurements t the LPR data logger are presented in Appendix F. The null hypothesis for pre-corrosion data postulates that corrosion occurred at equal rates under control and test conditions. The null hypothesis was rejected for mild steel and copper, indicating that the test and control conditions were not corroding at the same rate. The null hypothesis was not rejected for lead, indicating that the test and control conditions were corroding at the same rate.

In the inhibitor type 2 addition phase, the null hypothesis is that the test and control conditions are corroding at the same rate. The alternative hypothesis states the test condition is corroding faster than the control condition for mild steel, lead, and copper. The null hypothesis was rejected for copper, indicating that the control conditions are corroding faster than the test conditions. The null hypothesis was not rejected for mild steel and lead, therefore, it can be concluded that the corrosion rates remained equal throughout the experiment for lead. For mild steel the Wilcoxon signed rank test results are inconclusive. Table 5-21 summarizes the results obtained from Wilcoxon signed ranks test analysis for the Lana’i City inhibitor type 2 experiment.

Table 5-21: Summary of Wilcoxon Signed Ranks Results for Lana'i City Inhibitor Type 2

Metal	Phase	H_o	H_a	n	P	Conclusion
Mild Steel	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	95	0.017	Reject the null. Test and control conditions are corroding at a different rate
	Inhibitor Addition	Test CR = Control CR	Test CR > Control CR	33	0.077	Do not reject the null. Control condition corrosion rates are higher than test conditions
Lead	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	94	0.351	Do not reject the null. Test and control conditions are not corroding at different rates
	Inhibitor Addition	Test CR = Control CR	Test CR > Control CR	33	0.846	Do not reject the null. Control condition corrosion rates are higher than test conditions
Copper	Pre-Corrosion	Test CR = Control CR	Test CR ≠ Control CR	94	0.000	Reject the null. Test and control conditions are corroding at a different rate
	Inhibitor Addition	Test CR = Control CR	Test CR > Control CR	33	0.000	Reject the null. Test condition is corroding at higher rate than control condition

*CR=Corrosion Rate

As with previous experiments, if the null hypothesis in the pre-corrosion phase is rejected, it is difficult to compare control and test conditions between each other. In the case that the pre-corrosion phase null hypothesis is rejected, comparisons between the pre-corrosion steady-state phase and inhibitor addition phase are further analyzed. For the inhibitor type 2 experiment, steady state was reached at hour 1000. Table 5-22 presents average corrosion rates for the pre-corrosion steady state phase and inhibitor addition phase for mild steel, copper, and lead with type 2 inhibitor addition.

Table 5-22: Average Corrosion Rates of Lana'i City Inhibitor Type 2

		Control Condition	**Test Condition**	**Percent Difference**
Mild Steel	Average During Pre-Corrosion Steady State	2.13	1.98	7.61%
	Average During Inhibitor Addition	1.24	1.40	-12.5%
Lead	Average During Pre-Corrosion Steady State	0.209	0.221	-5.98%
	Average During Inhibitor Addition	0.337	0.167	67.8%
Copper	Average During Pre-Corrosion Steady State	0.321	0.852	-90.5%
	Average During Inhibitor Addition	0.329	0.602	-58.7%

Since the null hypothesis for mild steel pre-corrosion phase was rejected, further comparison between the pre-corrosion steady-state corrosion rate and inhibitor addition phase for mild steel is made. The test condition pre-corrosion steady state average is 1.98 mpy while the inhibitor addition corrosion rate average is 1.40 mpy resulting in a 53% decrease in corrosion rate. The control pre-corrosion steady state and inhibitor addition phases experience a 34% decrease. This may indicate that the total decrease in corrosion rate that may have been caused by inhibitor addition was 19%.

A direct comparison between the test and control conditions can be made for lead because the null hypothesis was not rejected. There is an increase in corrosion in the control condition and a decrease in corrosion rate in the test condition. The inhibitor test condition results in a 68% decrease overall to the corrosion rate of lead.

The null hypothesis for copper pre-corrosion phase was rejected, therefore further comparison between the pre-corrosion steady-state and inhibitor addition corrosion rates is made. The test condition pre-corrosion steady-state average is 0.852 mpy and the test condition inhibitor addition average is 0.602 mpy, resulting in a 34% decrease. The control pre-corrosion steady-state and inhibitor addition phases experience a 2% increase over the operational time of the experiment.

Lana’i City Post Analysis- Inhibitor 2

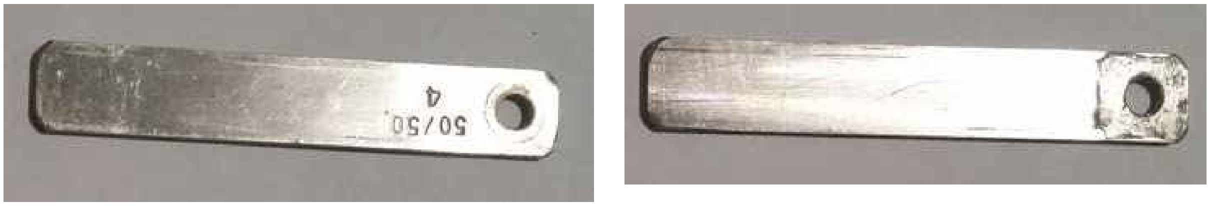
Post-analysis contains the results obtained from analysis of the corrosion coupons. For the Lana’i City Inhibitor type 2 experiment, coupons were analyzed that the UCF Materials Characterization Facility (UCF-MCF) in Orlando, FL. Figure 5-23 presents photographic images of coupons at the end of the experiment. Three analyses were conducted to determine the surficial composition of each coupon. Experiment surface analyses utilizing SEM, EDX, and XPS were conducted.

SEM images at 100x zoom of mild steel are shown in Figure 5-24. Mild steel images were taken to show the iron tubercle that formed on the coupon. Figure 5-25 includes SEM images of control and test condition copper coupon surfaces at 100x zoom. Copper SEM images were taken at pitting sites on the coupon. It is difficult to have a direct comparison between the two images since tubercles and pitting have individual characteristics. While there does not appear to be a difference between the control and test mild steel coupons, the copper test condition pitting has a distinct build up when compared to the control condition.

Control **Test**

Mild Steel Mild Steel

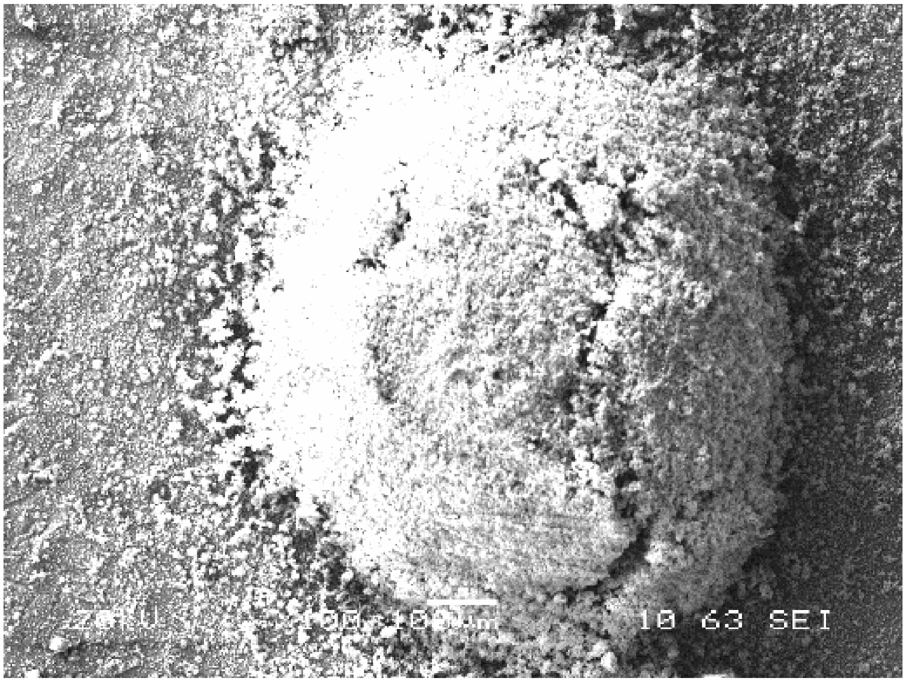
Lead Lead



Copper Copper

Figure 5-23: Lana’i City Coupon Photographs- Inhibitor 2

(a) Control Condition- Mild Steel



(b) Test Condition- Mild Steel

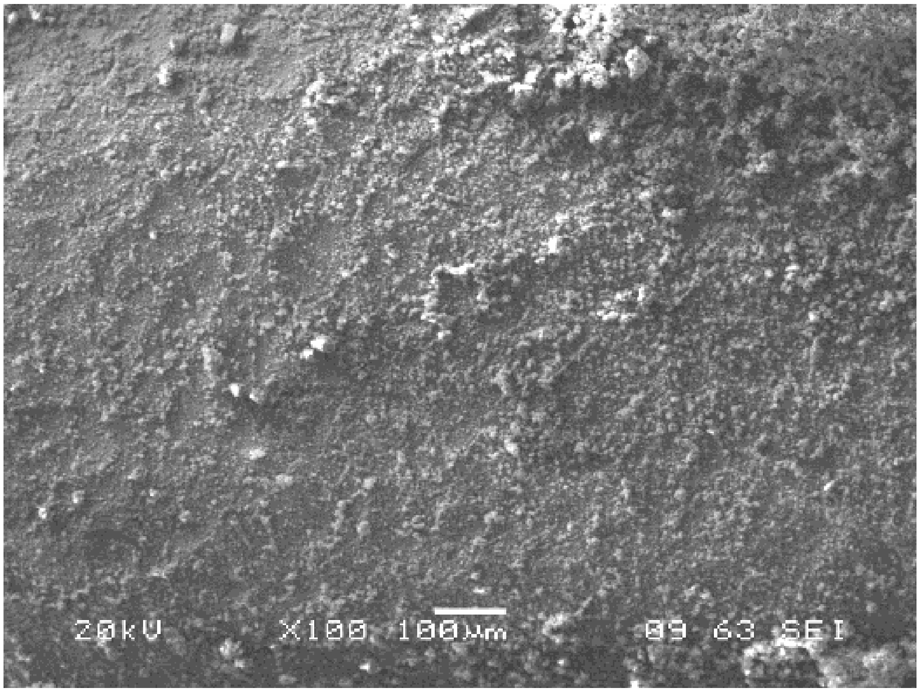
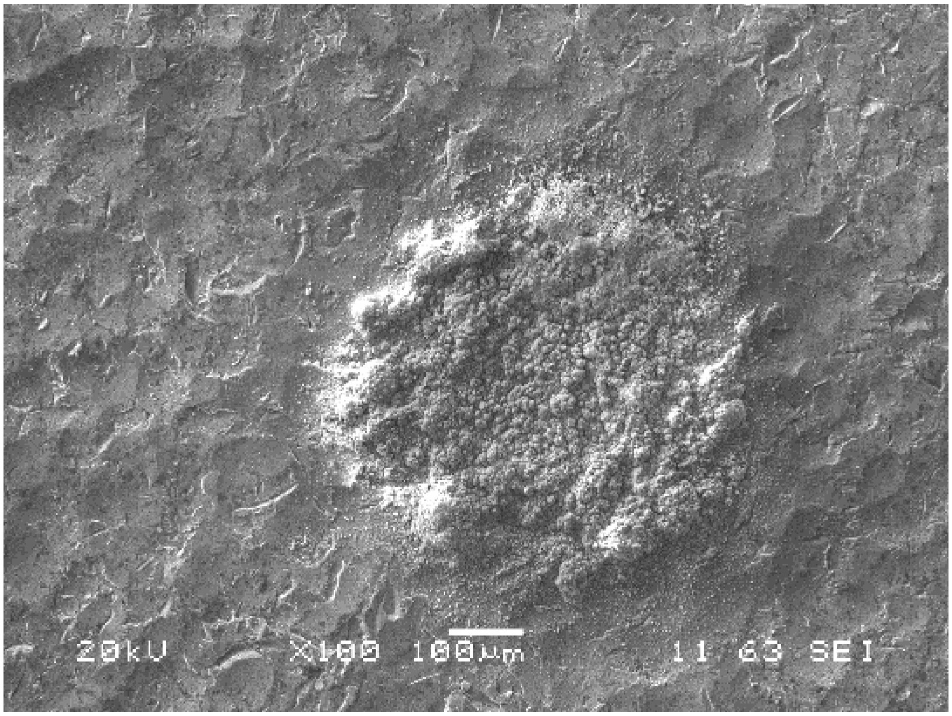


Figure 5-24: SEM Imaging of Lana'i City Inhibitor Type 2 Mild Steel Coupons (100x)

(a) Control Condition- Copper



(b) Test Condition- Copper

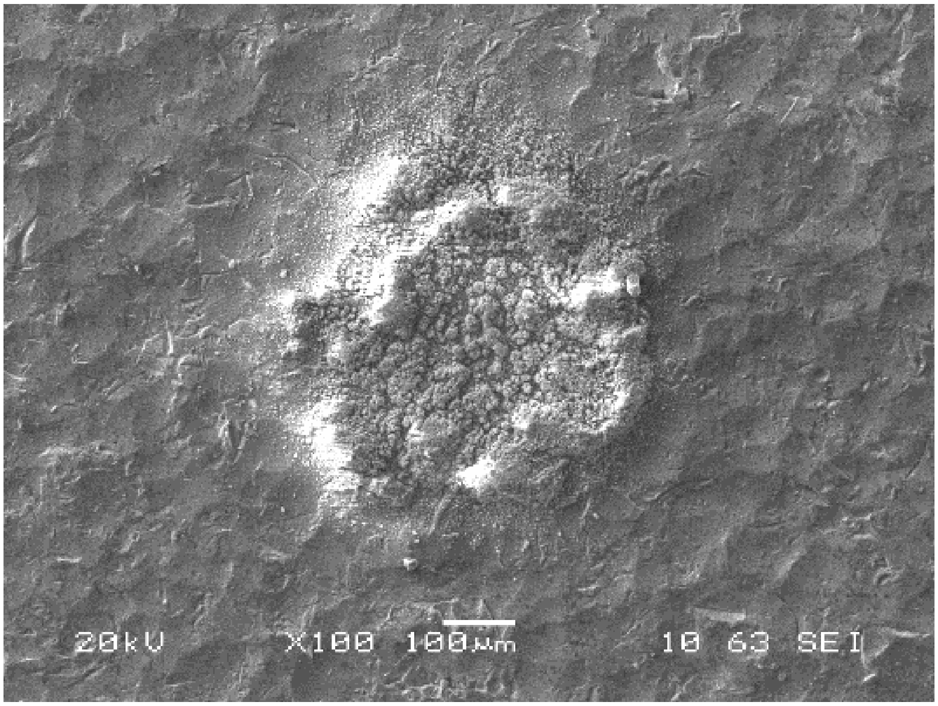


Figure 5-25: SEM Imaging of Lana'i City Inhibitor Type 2 Copper Coupons (100x)

Further analysis was done utilizing EDX analysis. This second analysis of the surface of mild steel and copper coupons for each condition occurred at a tubercle or pit that developed on the metal surface. Table 5-23 presents EDX weight percent results for test and control mild steel tubercles. Table 5-24 presents EDX weight percent results for test and control copper coupon pits.

Table 5-23: EDX Results for Lana'i City Inhibitor 2 Experiment- Mild Steel

	Mild Steel- Weight Percent		
	Control	**Test**	**% Difference**
Carbon	4.09%	0.00%	200%
Oxygen	21.8%	14.7%	39%
Silica	9.03%	4.55%	66%
Calcium	1.95%	0.09%	183%
Iron	63.1%	79.8%	23%

Table 5-24: EDX Results for Lana'i City Inhibitor 2 Experiment- Copper

	Copper- Weight Percent		
	Control	**Test**	**% Difference**
Carbon	0.00%	10.00%	200%
Oxygen	22.0%	19.6%	12%
Silica	12.0%	11.5%	4%
Copper	4.36%	3.85%	12%
Zinc	60.9%	55.0%	10%

EDX results show for mild steel that calcium and carbon deposits had the largest percent weight differences between test and control coupons. Another notable difference in the mild steel results is the 66% difference in silica with the control having the higher content than the test. This is unexpected since silica concentrations were increased with the addition of silicate inhibitor. Copper EDX results show similar elements found on the surface of each pit with the exception of carbon. Carbon is detected in the test copper coupon and not in the control copper coupon.

The third analysis conducted was x-ray photoelectron spectroscopy (XPS) such that elemental maps of the surface can help determine the spatial distribution of elements. As noted previously, XPS analysis is representative of the surface of the coupon and not a particular tubercle or pit. In addition, the first 10 nm are analyzed rather than just the immediate surface as in EDX. Table 5-25 presents XPS results for the control condition.

Table 5-25: XPS Results for Lana'i City Inhibitor Type 2

Element Detected	Mild Steel		Copper	
	Control	Test	Control	Test
Carbon	12.9%	11.5%	11.1%	10.0%
Oxygen	51.6%	51.2%	35.4%	41.4%
Silica	8.32%	7.64%	4.81%	6.22%
Copper	ND*	ND*	13.9%	12.7%
Zinc	ND*	ND*	22.6%	20.7%
Iron	27.2%	29.7%	12.2%	8.99%

*ND- Not detected

XPS results indicate that much of the surface between the test and control for both mild steel and copper are similar. Silica is detected in both the control and test samples for copper and mild steel.

Lana'i City Residential Pipe Scale Analysis

As part of the Lana'i City corrosion investigation, a screening evaluation of copper and galvanized iron pipe internal scale collected from a Pulama Lana'i employee's home was conducted. Internal scale sample was examined at Avista Technologies (140 Bosstick Boulevard, San Marcos, CA, 92069). The analyses of the pipe scale included testing for the presence of carbonates, SEM, EDX, and chromatic elemental imaging (CEI). Figure 5-26 presents photographs of the internal scale from (a) a copper pipe and (b) a galvanized iron pipe.

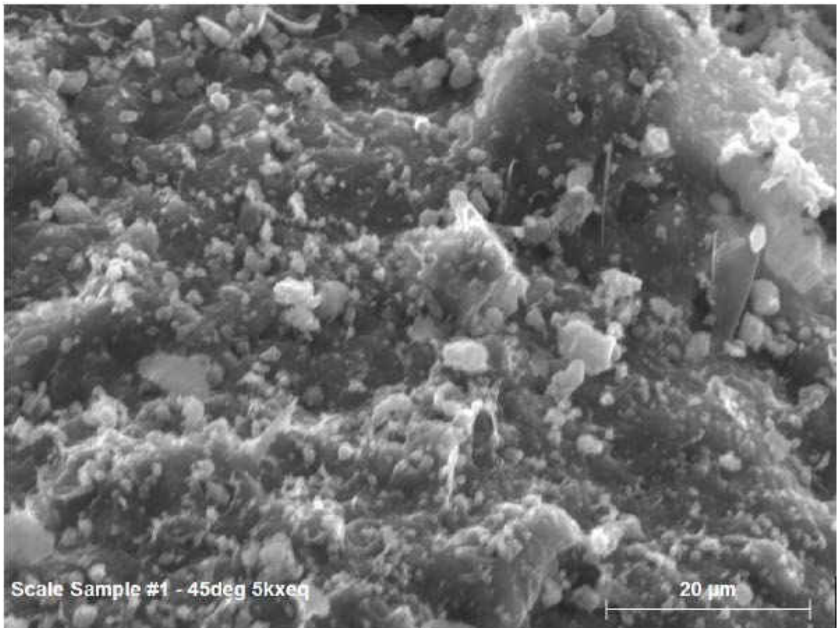

(a) Copper Pipe

(b) Galvanized Iron Pipe

Figure 5-26: Internal Pipe Scale from Copper and Galvanized Iron Pipes in Lana'i City Residence

Acid testing results for both the copper and galvanized iron scale indicated positive results for calcium carbonate presence. Calcium carbonate presence is expected as the source water contains alkalinity and hardness. Figure 5-27 presents SEM imaging of the two scale samples at 150x.

(a) Copper Pipe



(b) Galvanized Iron Pipe

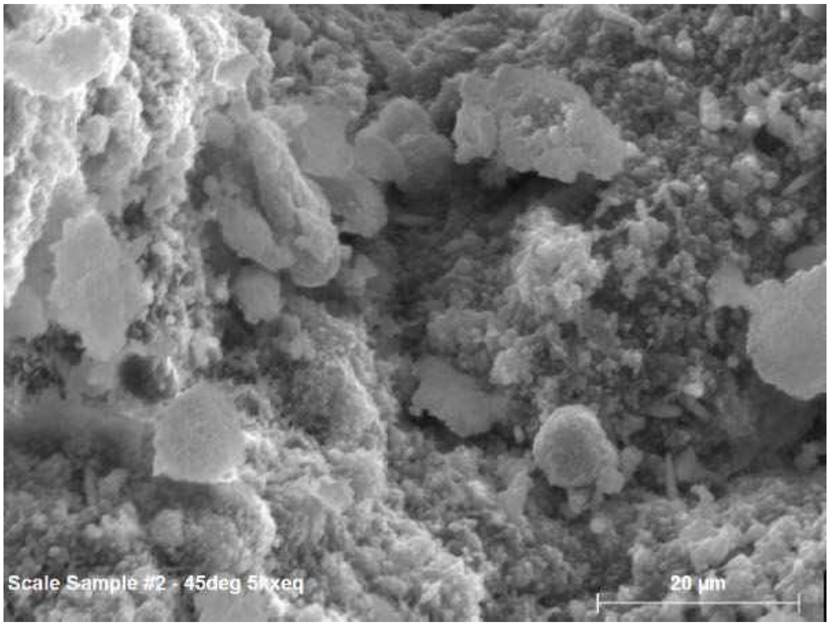


Figure 5-27: SEM Imaging of Residential Copper and Galvanized Internal Pipe Scale at 150x

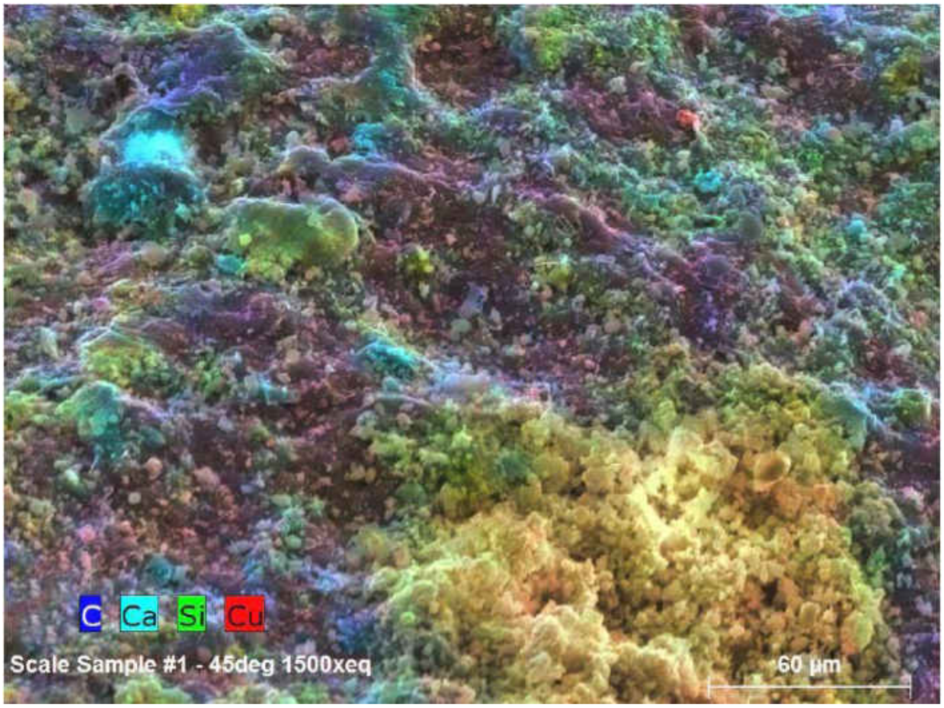
EDX analysis was performed in conjunction with SEM. EDX identifies inorganic constituents of the scale sample. Table 5-26 presents the results from EDX analysis. EDX results indicate that silica is present during corrosion layer formation. An interesting note is the amount of zinc present in the galvanized iron scale.

Table 5-26: EDX Results for Lana'i City Residential Pipe Scale

Element (weight %)	Copper Scale	Galvanized Iron Scale
Carbon	42.79	14.99
Oxygen	37.15	18.72
Silicon	5.03	17.84
Zinc	Not Detected	45.12
Calcium	2.46	0.77
Sulfur	0.46	Not Detected
Copper	8.39	Not Detected
Potassium	0.22	Not Detected
Aluminum	0.87	0.52
Magnesium	0.89	0.92
Iron	1.74	1.12

The final analysis conducted on the scale samples was CEI. CEI includes elemental analysis which is depicted in a color scheme. CEI assigns each element and color and provides an image of the exact location within the sample. The color intensity is largely influenced by the concentration of the element. CEI images at 1500x of the copper and galvanized iron pipe scales are presented in Figure 5-28. Results indicate that silica has a distinct presence in both scales; it is particularly noticeable in the galvanized iron internal pipe scale. Together, SEM, EDX, and CEI confirm that silica is an important factor in the formation of a corrosion layer in the Lana'i City water distribution system.

(a) Copper Pipe



(b) Galvanized Iron Pipe

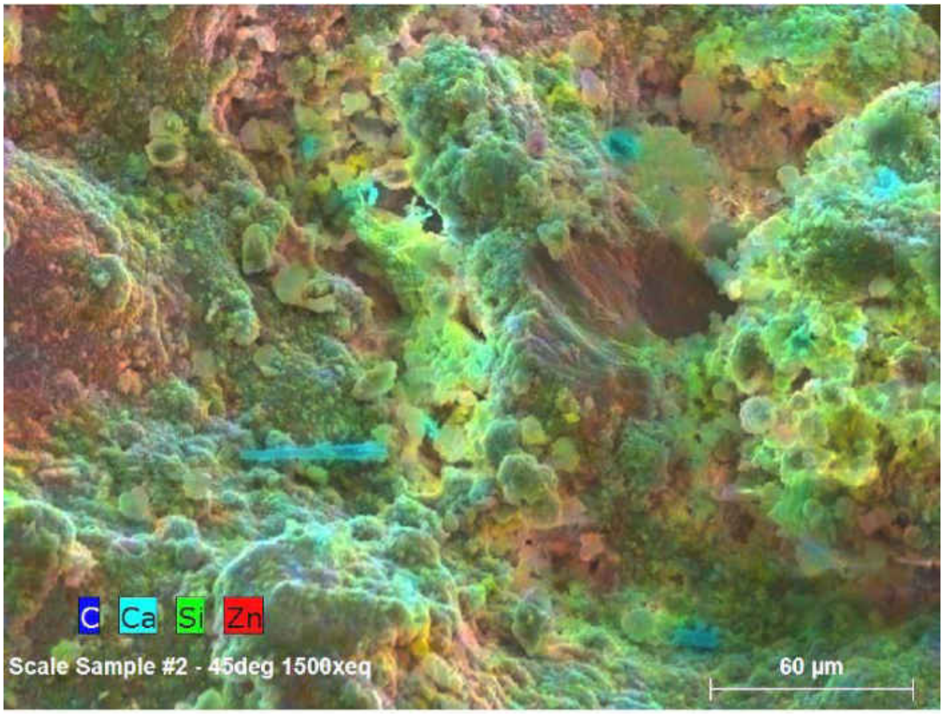


Figure 5-28: CEI Results for Residential Pipe Scale in Lana’i City

Laboratory Quality Assurance and Quality Control Results

Precision

Quality control charts for precision using I-statistic values were produced for cation (calcium, magnesium, and silica) and anion (sulfate and chloride) measurements; these charts are presented in Appendix G. None of the values calculated exceeded the UCL. There were few exceedances of the UWL across the parameters monitored. However, two consecutive points were not recorded to exceed the UWL, therefore, all values are included in water quality analyses for this project. The exceedances in the UWL are likely due to human error or contamination.

Accuracy

Quality control charts for accuracy using percent recovery were produced cation (calcium, magnesium, and silica) and anion (sulfate and chloride) measurements. These charts are presented in Appendix G. None of the values exceed the UCL or LCL. There were few exceedances of the UWL and LWL for the parameters monitored. In the exceedances of UWL or LWL, none happened consecutively, therefore, all values are included in water quality analysis for this project. The exceedances in UWL or LWL were likely due to human error or contamination.

Valve Management Plan

Current Inventory

Maintaining an accurate inventory of available assets is an important component of utility management. The inventory can be updated as valves are rehabilitated, repaired, and/or replaced. Depending on the information available, asset inventories should attain the following data for individual assets: age, location, condition, probability of failure, consequence of such a failure, and remaining useful life.

Water distribution system plans developed in 2003 for Lana'i City, Lana'i, HI were provided to UCF by Pulama Lana'i Water Company for evaluation and inventory of current assets. Table 5-27 depicts the types and number of assets that were outlined in the water distribution system plans (Pulama Lana'i Water Company, 2003). The majority of valves in the distribution system are gate valves. Table 5-28 depicts the valve sizes based on the pipeline feeding the valve as outlined in the Pulama Lana'i Water Company (2003). In addition to this initial inventory, UCF recommends that the water utility perform visual inspections of the valves, if possible. This is recommended in order to help to determine which specific valves were reaching the end of their useful life.

To increase the usefulness of the inventory, the USEPA (2005) recommends that utilities take photographs of assets and document the condition at time of repair, rehabilitation, or replacement. In addition to photographs, utilities can record the location via Global Positioning System (GPS) coordinates that can be used to create Geographic Information Systems (GIS) maps. GIS is a useful tool for the upkeep of a distribution system and can be utilized by numerous entities within the county.

Table 5-27: Current Inventory of Assets in Lana'i City, HI.

Plan #	Existing Water Valve	Existing Fire Hydrant	Existing Air Relief Valve	Existing Check Valve	Existing Pressure Reducing Valve	6" PRV-PSV-ROF Valve	PRV & Standpipe	Water Meter	Offset Water Meter
1	1	1	0	0	0	0	0	2	0
2	0	3	0	0	0	0	0	0	0
3	0	0	0	0	0	3*	0	0	1
4	9	3	0	1	0	0	0	12	0
5	10	17	0	0	1	0	2	3	0
6	5	8	0	0	1	0	0	0	0
7	9	5	0	0	0	0	0	11	0
8	61	75	1	0	0	0	0	341	0
9	72	41	0	0	0	0	0	436	0
10	1	3	0	0	0	0	0	23	0
11	0	3	0	0	0	0	0	38	0
12	33	18	0	0	0	0	0	112	0
Total (Index)	**200**	**177**	**1**	**1**	**2**	**3**	**2**	**978**	**1**

*Note: There are three valves whose symbol (▶◀) does not show on the legend for plan 3; one of these is labeled "PRV-PSV-ROF Valve"

**PRV: Pressure Relieving Valve, PSV: Pressure Safety Valve, ROF: Rate of Flow

Table 5-28: Inventory of valve sizes

		Pipe size leading to valve (inch)				
		4"	**6"**	**8"**	**10"**	**12"**
# of Valves	**Plan 1**	0	0	0	1	0
	Plan 2	0	0	0	0	0
	Plan 3	0	0	0	0	0
	Plan 4	1	4	0	0	4
	Plan 5	0	0	0	7	3
	Plan 6	0	0	5	0	0
	Plan 7	0	2	4	0	3
	Plan 8	0	7	47	0	7
	Plan 9	0	0	72	0	0
	Plan 10	0	0	0	0	0
	Plan 11	0	0	0	0	0
	Plan 12	1	0	32	0	0
	Total	**2**	**13**	**160**	**8**	**17**

Valve Exercise Plan

The USEPA (2005) recommends that valves be exercised at least once per year. Periodic turning of valves throughout a distribution systems ensures that the valves will be operational during emergency situations to isolate sections of pipe. In addition to valve exercising, fire hydrants should also experience regular exercise to maintain a working system for fire control. Typically, fire hydrants are exercised by the water utility or fire department (USEPA, 2005).

Standard of Care

In order for Pulama Lana’i Water Company to maintain the working order of the valves within its distribution system, UCF recommends that the water utility initiate a regimented valve exercise program. By testing individual valves to asses working conditions, valves in need of replacement or rehabilitation can be quickly and routinely identified.

Assuming that two valves can be exercised per day during a five day work week, the valves within the Lana'i City water distribution system can be evaluated in about 20 weeks. An approximate timeline for this exercise program is provided in Table 5-29.

Table 5-29: Approximate Timeline for Initial Valve Exercise Program

			Exercised Valves					
		Date	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Total**
Week	1	1/18/2016	2	2	2	2	2	10
	2	1/25/2016	2	2	2	2	2	10
	3	2/1/2016	2	2	2	2	2	10
	4	2/8/2016	2	2	2	2	2	10
	5	2/15/2016	2	2	2	2	2	10
	6	2/22/2016	2	2	2	2	2	10
	7	2/29/2016	2	2	2	2	2	10
	8	3/7/2016	2	2	2	2	2	10
	9	3/14/2016	2	2	2	2	2	10
	10	3/21/2016	2	2	2	2	2	10
	11	3/28/2016	2	2	2	2	2	10
	12	4/4/2016	2	2	2	2	2	10
	13	4/11/2016	2	2	2	2	2	10
	14	4/18/2016	2	2	2	2	2	10
	15	4/25/2016	2	2	2	2	2	10
	16	5/2/2016	2	2	2	2	2	10
	17	5/9/2016	2	2	2	2	2	10
	18	5/16/2016	2	2	2	2	2	10
	19	5/23/2016	2	2	2	2	2	10
	20	5/30/2016	2	2	2	2	2	10
							Total	**200**

During individual exercises, operators should take note of the location and condition of the valve. This can be recorded on a data sheet such as the one provided in Appendix A. Once the valves have been tested, rehabilitated, and/or replaced, UCF recommends that the valves continue to be exercised every year as recommended by the USEPA (2005). This can be easily accomplished by placing valves on a rotational exercise schedule of four to five valves per week. An approximate 1-year rotation schedule for the valves within the distribution system is provided in Table 5-30.

Table 5-30: One Year Valve Exercise Rotation Schedule

	Number of Valves Exercised				
Month	Week 1	Week 2	Week 3	Week 4	Monthly Total
Jan	4	4	4	4	16
Feb	4	4	4	4	16
March	4	4	4	4	16
April	4	4	4	4	16
May	4	4	4	4	16
June	4	4	4	4	16
July	4	4	4	4	16
Aug	4	4	4	4	16
Sept	4	4	4	4	16
Oct	4	4	4	4	16
Nov	4	4	4	4	16
Dec	4	4	4	4	16
			1-Year Total		**192****

**Note: While this particular schedule does not accommodate the inventory of the valves in a 1-year period, certain weeks can be modified at the utility's discretion to exercise 5 valves instead of 4 valves.

Exercise Process

Valve operation and maintenance procedures are specified by the manufacturer. In general, exercising a valve simply means closing and opening the valve to confirm that it is operational. Prior to implementing an exercise program, it is suggested that customer service personnel should be notified with the following information: why the valves are being operated on, how long the consumer may be out of service, and how many customers will be out of service (AWWARF & KIWA). Prior to exercising an individual valve, some preparations are recommended:

1) Notify staff which valves will be exercised 1-2 days in advance;
2) Notify other agencies (i.e. fire department, road, county, other utilities; if applicable);
3) Obtain necessary tools and paperwork;
4) Distribute information on valve location and history; if available.

These external guidelines are provided to serve as a general procedure to the utility for informing customers, personnel, and external agencies of work being performed. When preparations have been completed, the operator should proceed with the valve exercise protocol as determined by the water utility. These guidelines are provided to serve as a generic step-by-step procedural check for the operator. The operator should modify these checks for site specific conditions, as needed. When exercising a valve, the operator should use the normal valve operating key and it is recommended to not exceed the number of turns required to open or close each valve, as provided by the manufacturer. In general, the following guidelines from Table 5-31 should be followed when exercising a valve.

Once the initial valve exercise initiative is complete, a list of which valves need rehabilitation, replacement, and/or continued maintenance should be updated and revised. A flow chart representing how these decisions should be construed is provided in Figure 5-29. An approximate time table for a continued 1-year rotational exercise maintenance plan is provided in Table 5-29.

Table 5-31: Generic Valve Exercise Protocol (AWWARF & KIWA, 2002)

Step #	Procedure
1	Check the opening/closing directions on the valve BEFORE operation
2	If there is an electric motor is should be disabled. DO NOT perform powered operation during manual operation.
3	Note the last time of operation/exercise (choose a or b):
	a) If a valve has not been operated for longer than the specified time it needs to be exercised using a series of up and down motions. DO NOT over torque to obtain a shut off as this can cause damage to the valve. PROCEED TO STEP 4.
	b) If the valve has been exercised within the advised period, proceed with current exercise protocol. SKIP STEP 4 and PROCEED TO STEP 5
4	To exercise a valve that has not been exercised within 1 year:
	a) Begin with steady amount of torque in the "close" direction for 5-10 rotations
	b) Reverse for 2-3 rotations ("open" direction)
	c) Again, rotate the stem in the close direction for 5-10 more turns
	d) Repeat 4a through 4c until the valve is fully closed. Once the valve is fully closed, it should be opened 3-4 turns to remove the remainder of sediment in the valve with high-velocity water
	e) Fully close the valve again. PROCEED TO STEP 6
5	To exercise a valve that has been exercised within 1 year:
	a) Close the valve slowly. Closing too quickly could cause water hammer
6	After the valve is fully closed, inspect the valve to check that the water has been cut off
7	Open the valve slowly, record that the valve has been returned to the fully open position.

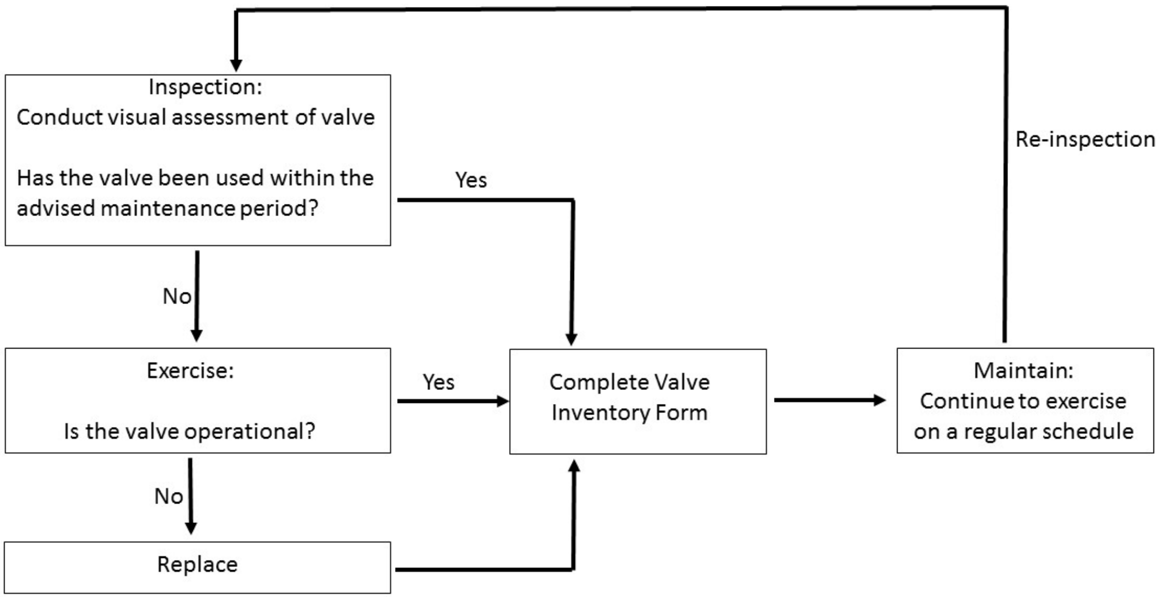


Figure 5-29: Valve Decision Flow Chart

Valve Replacement Plan

After the completion of the initial valve exercise screening, a valve replacement plan can be utilized. Replacement valves should be determined based on available water quality data and affordable materials/manufacturing for the utility.

<u>Valve Specifications</u>

Many utilities require that water distribution assets meet minimum specifications that are determined by their governing body. As an example, utilities could require that gate valves between 3 and 14 inches be tested under AWWA C509 or AWWA C1515 standards. AWWA standards can be further modified to meet individual water purveyor needs. These modifications may be necessary depending on water quality, location, and use of valves in the distribution system. In addition to providing valve standards, AWWA has standards for corrosion coatings (i.e. AWWA C550), stem alloys, body coatings, and alloys.

Because iron valves in Lana'i City are prone to tuberculation, UCF recommends that Pulama Lana'i Water Company consider three valve materials for replacement valves:

1) Iron body, brass mounted wedge gate valve
2) Epoxy coated ductile iron resilient wedge gate valve
3) Stainless Steel stem and body wedge gate valve

Creating a Priority List

The age and condition of the Lana'i City distribution system may lead to a majority of the valves needing replacement. It is recommended that the utility prioritize which valves should be replaced before others. The factors leading to a valve being placed in a priority position may include:

1) Condition of the valve;
2) Consumers affected by valve failures;
3) Location of valve.

Once priority valves have been determined, replacement of such valves can be accomplished. The excavation and replacement of valves is time consuming and labor intensive. It is expected that Pulama Lana'i Water Company will be able to replace approximately 10 valves per year. At this rate, valves can be replaced in approximately 20 years. An expected timeline of a replacement program is provided in Table 5-32.

Table 5-32: Approximate Timeline for Valve Replacement (20 year cycle)

			Number of Valves Replaced												
		Year	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	**Total**
Year	1	2017		1	1	1	1	1	1	1	1	1	1		10
	2	2018		1	1	1	1	1	1	1	1	1	1		10
	3	2019		1	1	1	1	1	1	1	1	1	1		10
	4	2020		1	1	1	1	1	1	1	1	1	1		10
	5	2021		1	1	1	1	1	1	1	1	1	1		10
	6	2022		1	1	1	1	1	1	1	1	1	1		10
	7	2023		1	1	1	1	1	1	1	1	1	1		10
	8	2024		1	1	1	1	1	1	1	1	1	1		10
	9	2025		1	1	1	1	1	1	1	1	1	1		10
	10	2026		1	1	1	1	1	1	1	1	1	1		10
	11	2027		1	1	1	1	1	1	1	1	1	1		10
	12	2028		1	1	1	1	1	1	1	1	1	1		10
	13	2029		1	1	1	1	1	1	1	1	1	1		10
	14	2030		1	1	1	1	1	1	1	1	1	1		10
	15	2031		1	1	1	1	1	1	1	1	1	1		10
	16	2032		1	1	1	1	1	1	1	1	1	1		10
	17	2033		1	1	1	1	1	1	1	1	1	1		10
	18	2034		1	1	1	1	1	1	1	1	1	1		10
	19	2035		1	1	1	1	1	1	1	1	1	1		10
	20	2036		1	1	1	1	1	1	1	1	1	1		10
														Total	**200**

Cost Analysis

In this section, a conceptual and preliminary cost estimation associated with valve replacement is presented. The cost to replace a valve goes beyond the capital cost of the valve itself; other costs include: excavation, installation, operation, and maintenance. Implementation of an asset replacement and maintenance program involves a significant investment to the utility, both in resources and labor. An evaluation of capital cost, equipment rentals, and maintenance investments is provided herein.

Operation and Maintenance Investment

In order to keep the valves working effectively for their expected life-cycle, they should be exercised regularly as discussed earlier. There are many types of valve exercisers; the most common include: (1) manual hand-held, (2) electric hand-held, (3) hydraulic hand-held, (4) pneumatic hand-held, and (5) electronic truck-mounted. Three options presented for valve exercise equipment were considered for cost analysis:

1) Manual exercise by hand-held equipment
2) Automatic exercise by hand-held equipment
3) Automatic exercise by truck mounted exercise equipment

The time required to exercise the valves varies based on the equipment used. For the purposes of this project, utility labor is evaluated on a per hour basis. The estimated hourly labor cost for one staff member is $40/hour. An estimated operation and maintenance cost was calculated using capital investment and labor required for three types of valve exercise equipment. Table 5-33 presents the estimated total operation and maintenance cost for a valve exercise program for 200 valves. During the first year of maintenance the total investment includes capital cost for equipment and labor. Subsequent yearly maintenance will consist of only labor and depreciation to the equipment.

Table 5-33: Valve Operation and Maintenance Cost

Valve Exercise Equipment	Hours Required for Operation	Staff Required for Operation	Capital Cost	Labor Cost
Manual Hand-held	4	4	$150	$128,000
Automatic Electric Hand-held	1	2	$7,000	$16,000
Automatic Electric Truck-mount	1	1	$11,000	$8,000

Operating valves manually is labor intensive and may cause operator injury or overexertion more readily than automatic valve operation. While automatic valve exercise equipment has a higher initial investment, it requires fewer operators and less operational time for task completion. In addition, to lower operational costs, automatic valve exercisers often have torque restrictions that reduce the likelihood of damaging the valve stem.

Capital and Excavation Investment

The capital investment for this project is limited to the cost of wedge gate valves within the Manele Bay water distribution system. Several valve materials were researched for pricing estimates; it was assumed that the valve material used during the initial construction phase is either solid brass or brass mount with cast iron. The materials researched for this project were (1) cast iron body brass mount (IBBM), (2) epoxy coated ductile iron (EPDM), and (3) stainless steel. List prices from manufactures for each material were obtained from the manufacturers. These prices, however, may not reflect the actual amount paid by the utility. Distributor prices were provided by ISI Water Solutions TDG (368 Lehuakona Street, Kahului, Maui, Hawaii, 96732) for EPDM valves. An adjusted cost ratio was calculated between the distributer price and list price of the EPDM valves. This ratio was further applied to the list price for IBBM valves and stainless steel valves such that more accurate distributer prices could be compared. List price, distributer price, and the resulting adjusted cost ratio are presented in Table 5-34. It should be noted that IBBM valves are included strictly for cost comparison. As of January 4, 2014, IBBM valves are no longer allowed to be used in drinking water systems per section 1417 of SDWA.

Table 5-34: EPDM Gate Valve Adjusted Price Ratio

Valve Diameter (in)	List Price	Distributer Price	Adjusted Cost Ratio
4	\$1,160	\$560	2.07
6	\$1,550	\$725	2.14
8	\$2,423	\$1,101	2.20
10	\$3,850	\$1,748	2.20
12	\$4,649	\$2,282	2.04

A comparison between the distributer cost and valve diameter for each material is presented in Figure 5-30. The most expensive material found in this study was stainless steel followed by

EPDM and IBBM. The cost of IBBM, EPDM, and stainless steel materials increases exponentially with valve diameter as can be seen with the R^2 values 0.99, 0.99, and 0.99, respectively. Establishing the growth rate for each material allows for quick and efficient calculations to size similar valves.

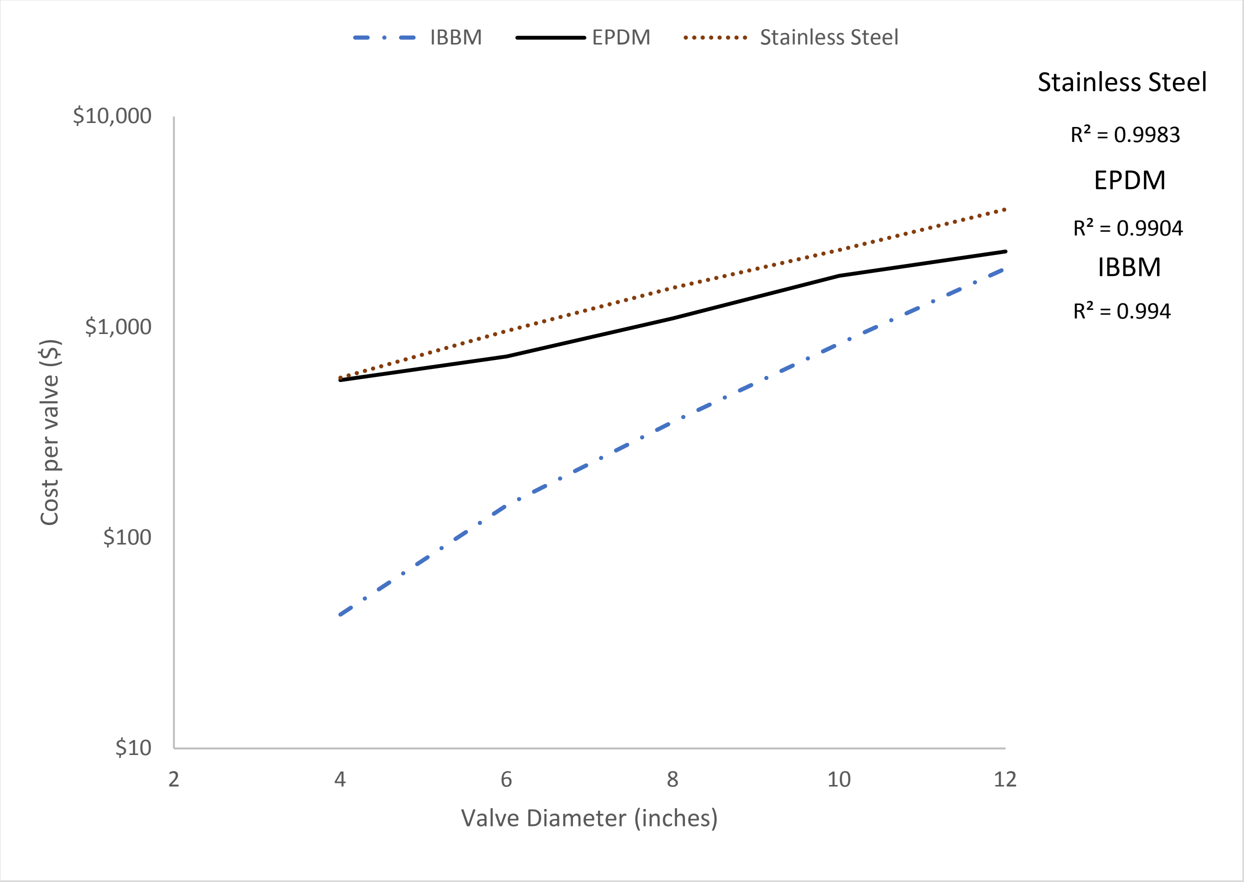


Figure 5-30: Distributer price and Valve Diameter Comparison for 3 Valve Materials

Inventoried valve replacement cost present value is conceptually approximated to be $240,000 if EPDM valves are selected. Recall from Table 5-32, a replacement plan spanning 20 years was developed for Pulama Lana’i Water Company. Using EPDM valves with inflation estimated at 2% the future capital cost is approximately $425,000; assuming that 10 valves are replaced each year.

To reduce cost, the amount of time required to complete the valve replacement plan can also be reduced. Figure 5-31 presents estimated cost assuming 2% inflation each year over 30 years for several valve replacement plans. These valve replacement plans vary the number of valves replaced in a given year. The replacement plans are as follows: (1) 7/yr: 7 valves replaced annually, (2) 10/yr: 10 valves replaced annually, (3) Escalating +1/yr: Starting with 5 valves in the first year, 6 valves the second year, 7 valves the third year, and so on, and (4) Escalating +2/yr: Starting with 5 valves in the first year, 7 valves the second year, 9 valves the third year, and so on.

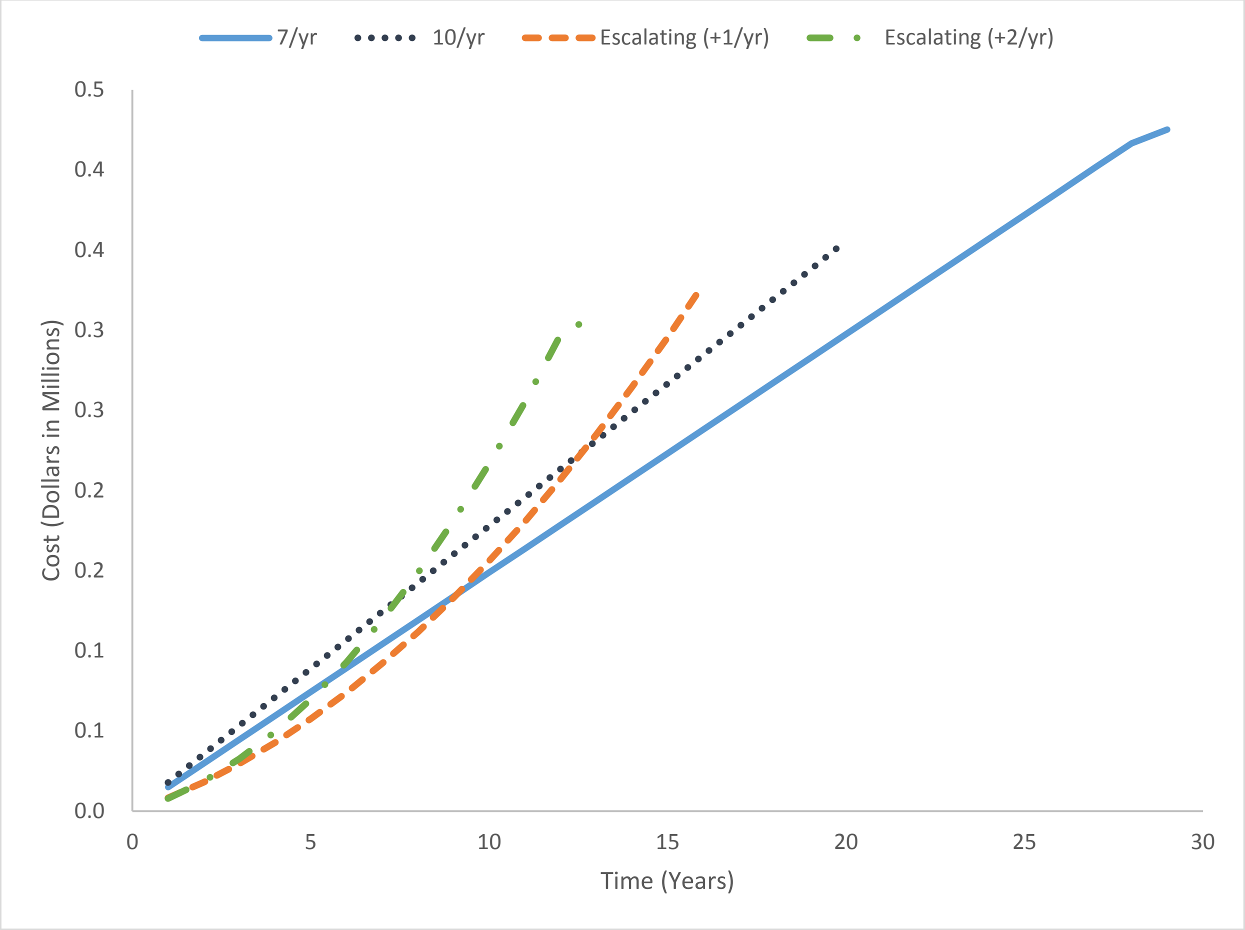


Figure 5-31: Capital Cost of EPDM Valve over Time

Excavation, construction, and labor costs were considered to determine an overall cost for valve replacement. The estimated valve extraction cost will be approximately $10,000 for equipment rental, labor, and contingency per valve. Present value for replacement excavation of 200 valves is approximately $2,000,000. Future worth evaluations using an estimated 2% inflation rate were calculated for four valve replacement plans (the same as used in Figure 5-31) and are presented in Figure 5-32. Note, there is a noticeable cost increase when considering the excavation costs associated with valve replacement.

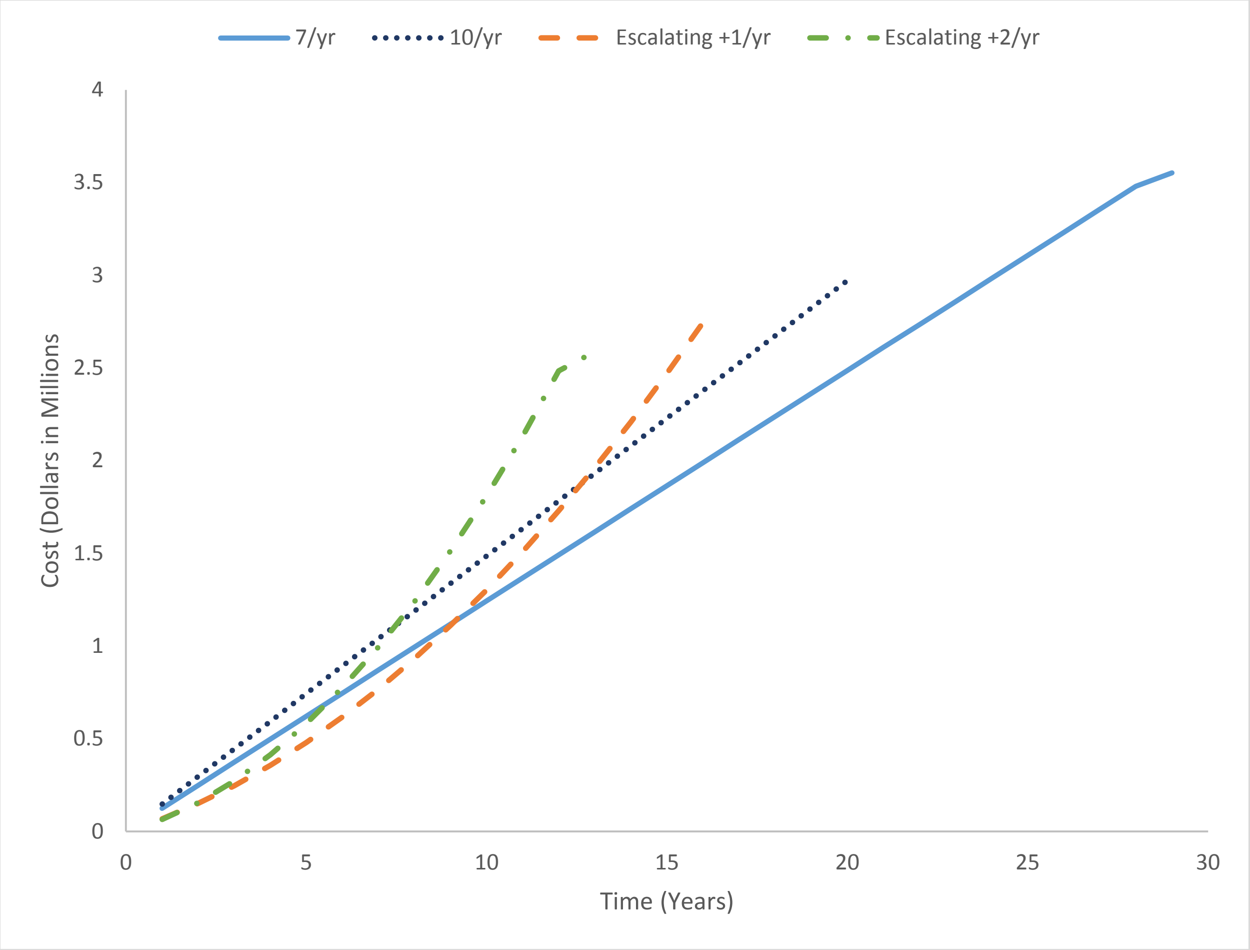


Figure 5-32: Cost of Valve Excavation over Time

To gain a better understanding of the overall cost associated with replacing the valves in the Manele Bay water distribution system, the probable capital cost and excavation cost were combined. The total cost estimates to replace 200 wedge gate valves for several time periods are presented in Table 5-35. Again, by reducing the amount of time required to replace the valves from 29 to 16 years, the utility can save nearly $1million.

Table 5-35: Total Valve Replacement Cost Estimation

Years to Replace	Total Cost
29	$3,980,000
20	$3,330,000
16	$3,070,000
13	$2,900,000

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

At the request of the Pulama Lana'i Water Company, a series of corrosion control experiments were conducted on their two distribution systems: (1) Manele Bay and (2) Lana'i City. The primary objective of this research was to determine if corrosion and tuberculation issues could be mitigated with the introduction of corrosion inhibitors into the distribution systems. An initial screening of the corrosion rates was conducted at Manele Bay; following this screening phase, two inhibitors were then tested at each location.

Conclusions

Manele Bay Corrosion Control

- Initial Screening: Stable corrosion rates were obtained at approximately 1,000 operational hours. A reasonable time frame was established in which steady-state corrosion rates would occur for this water source for the three metals tested that was used in subsequent studies.
- Inhibitor Type 1: Stable corrosion rates were obtained at approximately 1,800 operational hours. A 50:50 ortho:poly phosphate inhibitor blend was found to have little, if any, effect on the corrosion rates of mild steel, lead, or copper. The data collected indicates that Manele Bay potable water is non-corrosive toward lead and copper.
- Inhibitor Type 2: Stable corrosion rates were obtained at approximately 1,400 operational hours. Sodium silicate inhibitor was found to have little, if any, effect on the corrosion rates of mild steel, lead, or copper. The data collected confirmed that Manele Bay potable water is non-corrosive. SEM, EDX, and XPS findings for the copper coupons indicate that

silicate inhibitor may have affect the copper to zinc ratio of the coupon. The test coupon has a lower percent weight of copper than the control coupon.

Lanai City Corrosion Control

- Inhibitor Type 1: Stable corrosion rates were reached at approximately 1,500 operational hours, a 50:50 ortho:poly phosphate blended inhibitor was found to have little, if any, effect on the corrosion rates of mild steel and lead. However, copper corrosion rates increased when inhibitor was added. After inhibitor addition ceased, corrosion rates did not return to background values indicating the copper had been permanently altered. SEM and EDX results indicate that there is a higher iron content in the control tubercle than that of the test tubercle.
- Inhibitor Type 2: Stable corrosion rates for lead were reached nearly immediately. However, mild steel and copper rates had uncharacteristic corrosion rates at the beginning of the experiment. Regardless of the uncharacteristic trend, corrosion rates seemingly leveled out at operational hour 1,000 and a sodium silicate inhibitor was introduced. Sodium silicate inhibitor was found to have little, if any, effect on the corrosion rates of mild steel, lead, or copper. Similar to the Manele Bay experiment in which silica-based inhibitor was applied, EDX results at the corrosion pit show that the copper to zinc weight by percent is also lower in the test coupon than the control coupon. This could signify that the silica based inhibitor is causing higher copper release to the water.
- Residential Pipe Scale Analysis: SEM, EDX, and CEI provide results that indicate silica is present in pipe scale formation for both copper and galvanized iron. However, this chemistry is complex and the form silica has taken has not been identified.

Valve Management Plan

- To mitigate the effects of tuberculation on water distribution assets, an asset management plan was developed to assist in providing Pulama Lana'i a long-term maintenance and replacement program.
- Valve Exercise: It is recommended that valves be exercised on a yearly basis in order to identify faulty valves and maintain working valves. A valve inventory found that there are approximately 200 gate valves, 2 pressure reducing valves, and 3 PRV-PSV-ROF valves. The cost of operation and maintenance is largely dependent on the equipment used for exercising valves. Automatic valve exercisers that reduce staff number and time to exercise are cost effective by paying themselves off within one year. A conceptual cost analysis indicates that the labor costs to exercise 200 valves for a manual hand-held exerciser and an automatic electric truck-mount exerciser are $128,000 and $8,000, respectively. While initial costs are higher, investment in automatic valve exercise equipment will reduce labor costs and lower the water purveyor's overall maintenance budget.
- Valve Replacement: Based on the cost analysis for three valves, EPDM coated valves are the most cost effective and adhere to AWWA regulations. Conceptual cost analysis has shown that the purchase cost of 200 EPDM valves over 20 years is approximately $425,000, the excavation cost for 200 valves over 20 years is approximately $2.9 million, and the total cost to replace 200 EPDM valves in 20 years is approximately $3.3 million. In addition, cost analysis indicates that reducing the time allotted for replacement will reduce the overall cost. Manufacturer specifications for EPDM coated valves are presented in Appendix H.

Recommendations

1) It is not recommended that a phosphate or silicate based inhibitor be added to either the Manele Bay or Lana'i City water distribution systems.
2) If the water supply is changed in the future to an alternative water supply then a corrosion study for this water source is highly recommended.
3) It is recommended that Pulama Lana'i Water Company move forward with the implementation of a valve maintenance and replacement plan.
4) It is recommended that Pulama Lana'i Water Company consider investing in an automatic electric truck-mount valve exerciser to reduce labor costs over time.
5) As part of Pulama Lana'i Water Company's asset management program, it is recommended that an engineering evaluation be performed regarding the utility's fire hydrants taking into account existing conditions, existing exercise requirements, and cooperation with the fire authorities.
6) Continued monitoring of water meter inspections and testing is recommended. In addition an inventory of water meters should be kept to include location, condition, and age of water meters throughout the water distribution systems.

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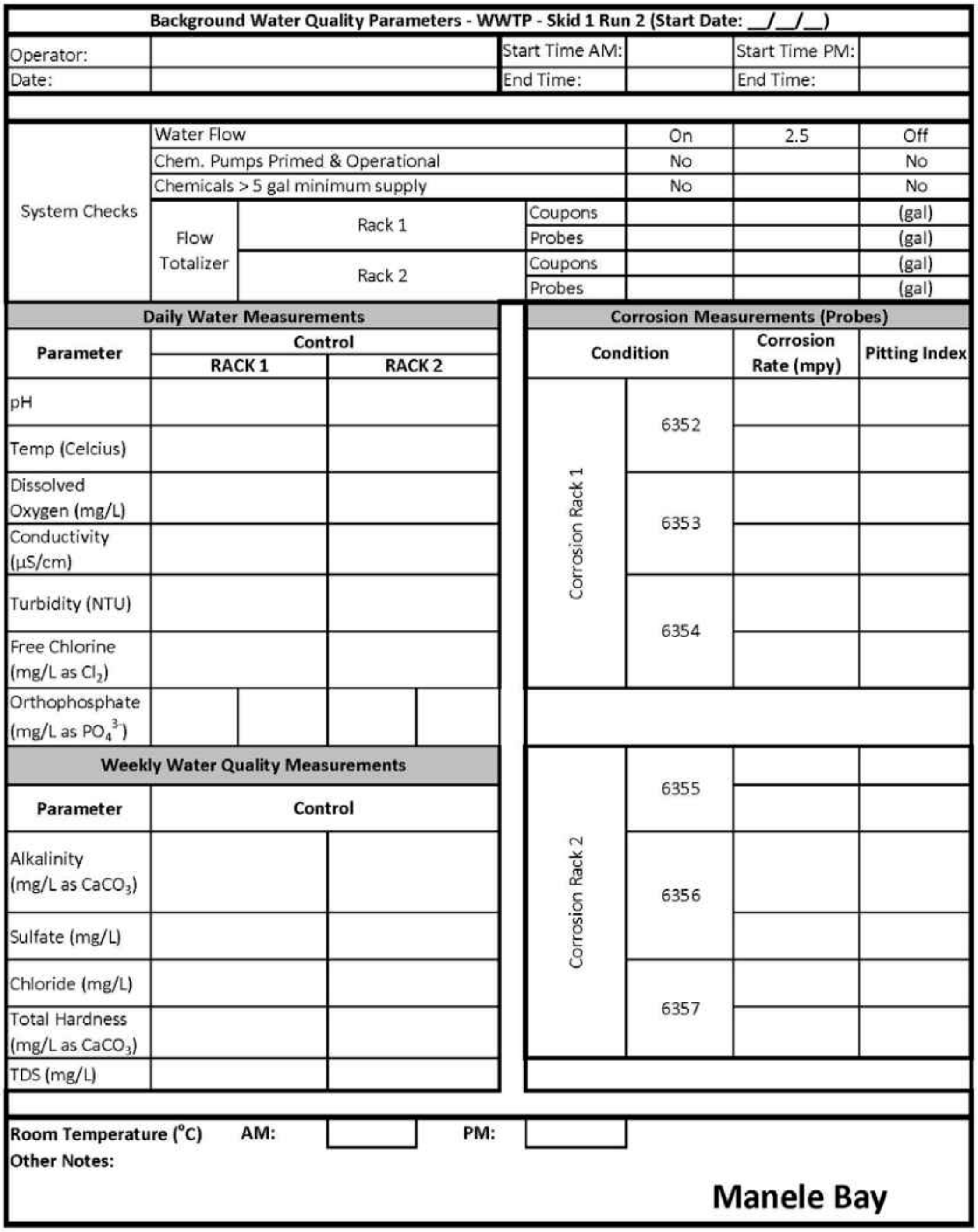
APPENDIX A: LOG SHEETS AND MATERIALS USED IN CORROSION CONTROL EXPERIMENTS



Background Water Quality Parameters - WWTP - Skid 1 Run 2 (Start Date: __/__/__)

Operator:		Start Time AM:		Start Time PM:	
Date:		End Time:		End Time:	

System Checks	Water Flow			On	2.5	Off
	Chem. Pumps Primed & Operational			No		No
	Chemicals > 5 gal minimum supply			No		No
	Flow Totalizer	Rack 1	Coupons			(gal)
			Probes			(gal)
		Rack 2	Coupons			(gal)
			Probes			(gal)

Daily Water Measurements

Parameter	**Control**	
	RACK 1	**RACK 2**
pH		
Temp (Celcius)		
Dissolved Oxygen (mg/L)		
Conductivity (µS/cm)		
Turbidity (NTU)		
Free Chlorine (mg/L as Cl_2)		
Orthophosphate (mg/L as PO_4^{3-})		

Weekly Water Quality Measurements

Parameter	**Control**	
Alkalinity (mg/L as $CaCO_3$)		
Sulfate (mg/L)		
Chloride (mg/L)		
Total Hardness (mg/L as $CaCO_3$)		
TDS (mg/L)		

Corrosion Measurements (Probes)

Condition		**Corrosion Rate (mpy)**	**Pitting Index**
Corrosion Rack 1	6352		
	6353		
	6354		
Corrosion Rack 2	6355		
	6356		
	6357		

Room Temperature (°C) **AM:** ____ **PM:** ____

Other Notes:

Manele Bay

Figure A-1: Log Sheet Used to Record Daily Corrosion Measurements and Water Quality Data

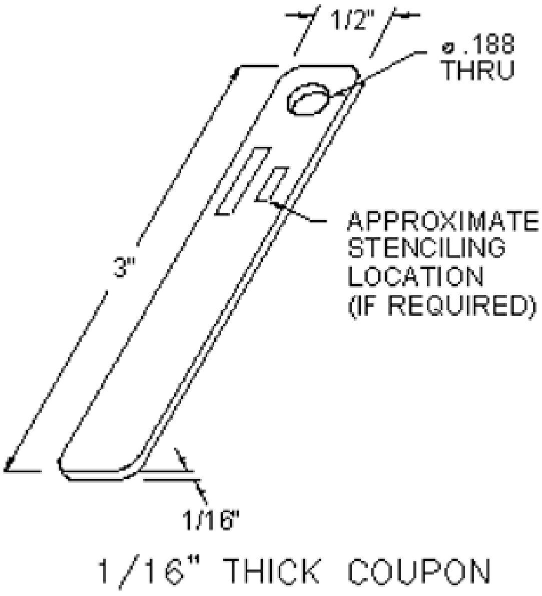


Figure A-2: Coupon Schematic Provided by Metal Samples (Munford, AL)

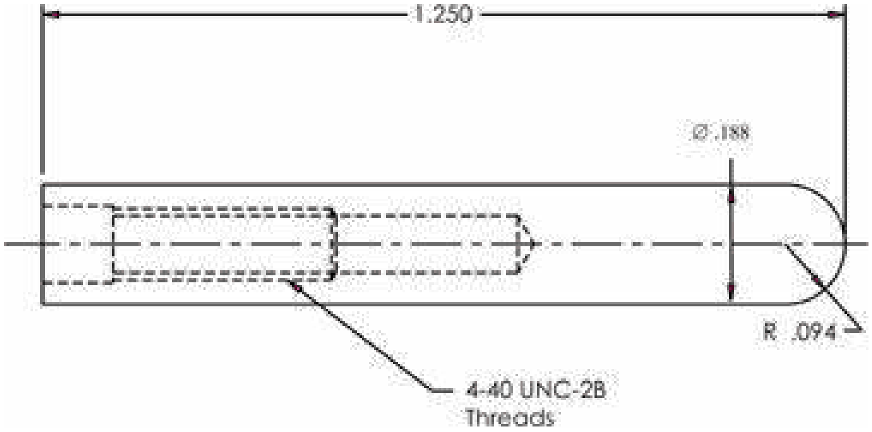


Figure A-3: Electrode Schematic Provided by Metals Samples (Munford, AL)

Valve Inventory Sheet

Date (mm/dd/yy):		**Time:**
Valve ID #:		
Installation Date:	**Last Exercise Date:**	
Flow (gpm):	**GPS**	**Latitude:**
Pressure (psi):		**Longitude:**
Location (Street Address/Intersection):		
Valve Type (i.e. Gate, Butterfly, etc.):		
Field Condition and Observations		
Further Comments		

Figure A-4: Example of Valve Inventory Log Sheet

APPENDIX B: DATA FOR MANELE BAY INITIAL SCREENING

Table B-1: Corrosion Rates for Manele Bay Initial Screening

Date	Corrosion Rate (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
5/22/2014	1.98	0.34	5.43	1.11	0.24	3.42
5/22/2014	1.50	0.26	4.73	1.38	0.39	3.53
5/23/2014	1.88	0.15	3.47	1.40	0.24	3.06
5/23/2014	1.88	0.13	3.31	1.35	0.08	2.74
5/24/2014	1.77	0.10	2.04	1.39	0.24	1.81
5/24/2014	1.77	0.08	1.81	1.35	0.10	1.78
5/25/2014	1.61	0.30	1.65	1.44	0.39	1.65
5/25/2014	1.72	0.15	1.62	1.60	0.13	1.43
5/26/2014	1.72	0.34	1.22	1.57	0.48	1.22
5/26/2014	1.75	0.28	1.19	1.67	0.13	1.13
5/27/2014	1.81	0.08	0.98	1.56	0.10	1.00
5/27/2014	1.66	0.13	1.06	1.16	0.06	1.03
5/28/2014	1.54	0.34	1.00	1.60	0.28	0.86
5/28/2014	1.75	0.24	0.90	1.19	0.54	0.89
5/29/2014	1.63	0.13	1.13	1.40	0.04	1.06
5/29/2014	1.56	0.08	1.03	1.48	0.06	1.06
5/30/2014	1.56	0.32	0.76	-	0.08	0.90
5/30/2014	1.70	0.17	0.89	1.56	0.13	0.84
5/31/2014	1.67	0.13	0.55	1.30	0.24	0.57
5/31/2014	1.61	0.10	0.78	1.46	0.24	0.68
6/1/2014	1.78	0.10	0.81	1.46	0.10	0.86
6/1/2014	1.74	0.37	0.73	1.41	0.39	0.73
6/3/2014	1.84	0.10	0.66	1.40	0.13	0.65
6/3/2014	1.77	0.15	0.78	1.47	0.15	0.76
6/4/2014	1.65	0.15	0.78	1.34	0.19	0.70
6/4/2014	1.67	0.17	0.55	1.31	0.21	0.60
6/5/2014	1.80	0.30	0.81	1.34	0.39	0.51
6/5/2014	1.65	0.13	0.60	1.36	0.15	0.46
6/6/2014	1.61	0.08	0.60	1.30	0.17	0.36
6/6/2014	1.53	0.15	0.55	1.32	0.08	0.49
6/7/2014	1.61	0.10	0.38	1.25	0.10	0.39
6/7/2014	1.44	0.21	0.40	1.28	0.24	0.44
6/8/2014	1.61	0.08	0.51	1.30	0.28	0.49
6/8/2014	1.67	0.32	0.63	1.23	0.08	0.46
6/9/2014	1.61	0.19	0.60	1.30	0.10	0.41
6/9/2014	1.53	0.24	0.44	1.20	0.26	0.28
6/10/2014	1.56	0.37	0.52	1.19	0.30	0.49
6/10/2014	1.46	0.24	0.57	1.25	0.06	0.38
6/11/2014	1.86	0.10	0.58	1.20	0.06	0.35
6/11/2014	1.85	0.10	0.57	1.23	0.10	0.38
6/12/2014	1.67	0.28	0.38	1.20	0.08	0.36
6/12/2014	1.67	0.19	0.52	1.18	0.37	0.44
6/13/2014	3.00	0.28	0.25	1.14	0.08	0.20
6/13/2014	1.73	0.21	0.36	1.15	0.10	0.33
6/14/2014	1.68	0.15	0.35	1.09	0.17	0.30
6/14/2014	1.65	0.06	0.33	1.15	0.19	0.15
6/15/2014	1.65	0.06	0.43	1.15	0.19	0.3

Date	Corrosion Rate (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
6/15/2014	1.71	0.17	0.43	1.21	0.19	0.14
6/16/2014	1.61	0.15	0.35	1.14	0.17	0.15
6/16/2014	1.67	0.17	0.35	1.08	0.13	0.23
6/17/2014	1.63	0.21	0.33	1.05	0.15	0.30
6/17/2014	1.61	0.10	0.27	1.09	0.13	0.20
6/18/2014	1.53	0.19	0.49	1.15	0.30	0.31
6/18/2014	1.69	0.80	0.54	1.09	0.19	0.31
6/19/2014	1.60	0.24	0.27	1.00	0.37	0.2
6/19/2014	1.56	0.24	0.19	1.04	0.06	0.28
6/20/2014	1.50	0.21	0.25	1.03	0.26	0.12
6/20/2014	1.61	0.06	0.44	1.01	0.21	0.11
6/21/2014	1.53	0.32	0.17	1.04	0.06	0.28
6/21/2014	1.56	0.10	0.19	1.11	0.19	0.17
6/22/2014	1.52	0.24	0.14	1.12	0.28	0.14
6/22/2014	1.43	0.08	0.12	1.07	0.08	0.25
6/23/2014	1.43	0.10	0.04	1.03	0.13	0.09
6/23/2014	1.60	0.32	0.06	1.01	0.10	0.25
6/24/2014	1.46	0.15	0.25	1.03	0.15	0.17
6/24/2014	1.49	0.08	0.20	1.01	0.19	0.15
6/25/2014	1.48	0.30	0.20	1.01	0.13	0.14
6/25/2014	1.54	0.08	0.20	1.02	0.13	0.07
6/26/2014	1.55	0.21	0.22	0.93	0.24	0.14
6/26/2014	1.47	0.17	0.27	1.01	0.13	0.14
6/27/2014	1.50	0.06	0.11	0.97	0.10	0.04
6/27/2014	1.40	0.28	0.12	0.98	0.10	0.28
6/28/2014	1.40	0.17	0.20	0.88	0.06	0.15
6/28/2014	1.47	0.15	0.28	0.93	0.13	0.20
6/29/2014	1.35	0.17	0.09	0.99	0.15	0.17
6/29/2014	1.38	0.15	0.15	0.93	0.10	0.20
6/30/2014	1.53	0.08	0.14	0.87	0.10	0.15
6/30/2014	1.58	0.08	0.04	0.97	0.10	0.15
7/1/2014	1.40	0.10	0.15	0.93	0.13	0.09
7/1/2014	1.40	0.30	0.14	0.93	0.48	0.25
7/2/2014	1.42	0.34	0.25	0.88	0.15	0.11
7/2/2014	1.40	0.13	0.19	0.94	0.17	0.23
7/3/2014	1.40	0.13	0.15	1.02	0.08	0.12
7/3/2014	1.39	0.17	0.90	0.96	0.08	0.04
7/4/2014	1.34	0.21	0.14	0.83	0.19	0.15
7/4/2014	1.40	0.04	0.22	0.92	0.15	0.09
7/5/2014	1.40	0.06	0.19	0.79	0.08	0.11
7/5/2014	1.30	0.13	0.23	0.83	0.08	0.11
7/6/2014	1.35	0.10	0.19	0.88	0.37	0.06
7/6/2014	1.38	0.10	0.09	0.94	0.08	0.11
7/7/2014	1.35	0.10	0.07	0.87	0.19	0.14
7/7/2014	1.35	0.21	0.11	0.89	0.19	0.30
7/8/2014	1.32	0.15	0.14	0.88	0.10	0.10
7/8/2014	1.44	0.15	0.11	0.83	0.13	0.13
7/9/2014	1.30	0.30	0.20	0.78	0.15	0.14
7/9/2014	1.37	0.32	0.09	0.83	0.15	0.07
7/10/2014	1.37	0.13	0.14	0.86	0.04	0.36

Date	**Corrosion Rate (mpy)**					
	Control Condition			**Test Condition**		
	MS	**L**	**C**	**MS**	**L**	**C**
7/10/2014	1.34	0.17	0.11	0.93	0.41	0.23
7/11/2014	1.30	0.24	0.22	0.88	0.08	0.15
7/12/2014	1.27	0.48	0.19	0.83	0.32	0.31
7/12/2014	1.32	0.21	0.33	0.94	0.32	0.30
7/13/2014	1.24	0.24	0.30	0.73	0.50	0.33
7/13/2014	1.25	0.50	0.23	0.83	0.34	0.27
7/14/2014	1.24	0.28	0.03	0.88	0.13	0.13
7/14/2014	1.26	0.24	0.09	0.86	0.13	0.04
7/15/2014	1.25	0.26	0.12	0.81	0.10	0.06
7/15/2014	1.31	0.28	0.17	0.78	0.24	0.20
7/16/2014	1.27	0.17	0.06	0.80	0.29	0.17
7/16/2014	1.31	0.17	0.11	0.88	0.15	0.09
7/17/2014	1.25	0.21	0.06	0.82	0.30	0.07
7/17/2014	1.27	0.04	0.06	0.76	0.06	0.11
7/18/2014	1.20	0.15	0.07	0.79	0.17	0.12
7/18/2014	1.33	0.06	0.09	0.80	0.13	0.17
7/19/2014	1.23	0.15	0.17	0.82	0.13	0.15
7/20/2014	1.14	0.21	0.12	0.75	0.50	0.30
7/20/2014	1.25	0.39	0.12	0.76	0.34	0.27
7/21/2014	1.27	0.10	0.07	0.72	0.15	0.11
7/21/2014	1.24	0.08	0.04	0.80	0.15	0.19
7/22/2014	1.27	0.19	0.12	2.40	0.15	0.17
7/22/2014	1.20	0.10	0.17	0.71	0.15	0.06

APPENDIX C: DATA FOR MANELE BAY INHIBITOR 1

Table C-1: Corrosion Rates for Manele Bay Inhibitor 1 Experiment

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
7/24/2014	2.34	0.41	3.55	2.05	0.46	3.52
7/24/2014	2.05	0.14	3.73	1.79	0.06	3.77
7/25/2014	1.90	0.08	2.16	1.68	0.16	2.43
7/25/2014	1.82	0.23	1.92	1.68	0.10	2.20
7/26/2014	1.80	0.16	1.65	1.67	0.16	1.76
7/26/2014	1.78	0.08	1.78	1.62	0.12	1.73
7/27/2014	1.78	0.37	1.88	1.61	0.06	1.80
7/27/2014	1.72	0.10	1.48	1.61	0.27	1.56
7/28/2014	1.75	0.37	1.37	1.58	0.12	1.32
7/28/2014	1.76	0.10	1.17	1.60	0.12	1.24
7/29/2014	1.72	0.14	1.59	1.69	0.16	1.80
7/29/2014	1.69	0.12	1.37	1.56	0.14	1.41
7/30/2014	1.64	0.08	1.00	1.56	0.18	1.32
7/30/2014	1.67	0.08	1.11	1.60	0.12	1.25
7/31/2014	1.59	0.23	0.84	1.51	0.18	1.08
7/31/2014	1.57	1.70	1.02	1.42	0.10	1.10
8/1/2014	1.50	0.20	0.58	1.35	0.23	0.82
8/1/2014	1.49	0.06	0.78	1.44	0.18	0.82
8/2/2014	1.77	0.30	0.70	1.39	0.20	0.79
8/2/2014	1.56	0.20	0.95	1.38	0.14	0.81
8/3/2014	1.59	0.10	0.79	1.44	0.25	0.89
8/3/2014	1.56	0.20	0.89	1.45	0.23	0.94
8/5/2014	1.54	0.29	0.73	1.37	0.16	0.70
8/5/2014	1.47	0.12	0.79	1.32	0.12	0.98
8/6/2014	1.40	0.10	0.92	1.25	0.08	0.94
8/6/2014	1.41	0.16	0.98	1.35	0.08	0.81
8/7/2014	1.40	0.10	0.71	1.50	0.10	0.81
8/8/2014	1.34	0.10	0.63	1.44	0.12	0.70
8/9/2014	1.34	0.10	0.68	1.46	0.10	0.73
8/9/2014	1.39	0.10	0.90	1.43	0.18	0.71
8/10/2014	1.35	0.06	0.57	1.43	0.23	0.62
8/10/2014	1.32	0.12	0.57	1.42	0.06	0.68
8/11/2014	1.33	0.39	0.62	1.39	0.25	0.39
8/11/2014	1.35	0.14	0.47	1.35	0.20	0.57
8/12/2014	1.28	0.08	0.57	1.27	0.04	0.54

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
8/12/2014	1.22	0.04	0.47	1.30	0.06	0.58
8/13/2014	1.21	0.20	0.49	1.29	0.14	0.58
8/13/2014	1.57	0.23	0.70	1.73	0.18	0.57
8/14/2014	2.98	0.14	0.46	1.66	0.08	0.60
8/14/2014	1.49	0.18	0.41	1.69	0.12	0.54
8/15/2014	1.34	0.16	0.32	1.55	0.25	0.41
8/15/2014	1.27	0.16	0.35	1.53	0.18	0.36
8/16/2014	1.29	0.12	0.19	1.51	0.14	0.31
8/17/2014	1.25	0.10	0.14	1.44	0.20	0.11
8/17/2014	1.32	0.18	0.25	1.49	0.10	0.20
8/18/2014	1.25	0.25	0.22	1.41	0.25	0.09
8/18/2014	1.24	0.06	0.22	1.42	0.18	0.20
8/19/2014	1.20	0.14	0.11	1.42	0.10	0.22
8/19/2014	1.25	0.18	0.14	1.38	0.14	0.17
8/20/2014	1.25	0.16	0.11	1.37	0.08	0.11
8/20/2014	1.25	0.14	0.09	1.39	0.14	0.20
8/21/2014	1.20	0.27	0.06	1.36	0.06	0.14
8/21/2014	1.22	0.10	0.20	1.33	0.33	0.20
8/22/2014	1.12	0.44	0.41	1.32	0.31	0.30
8/22/2014	1.23	0.06	0.35	1.30	0.18	0.49
8/23/2014	1.11	0.06	0.43	1.30	0.16	0.27
8/23/2014	1.14	0.14	0.31	1.28	0.14	0.39
8/24/2014	1.12	0.23	0.17	1.34	0.18	0.25
8/24/2014	1.08	0.16	0.20	1.32	0.10	0.17
8/26/2014	1.02	0.29	0.20	1.15	0.33	0.22
8/26/2014	1.07	0.16	0.36	1.20	0.04	0.11
8/27/2014	1.02	0.14	0.09	1.20	0.16	0.19
8/27/2014	1.01	0.10	0.19	1.19	0.27	0.19
8/28/2014	1.04	0.20	0.11	1.20	0.23	0.23
8/28/2014	1.00	0.08	0.19	1.17	0.16	0.15
8/29/2014	1.72	0.14	0.19	1.17	0.20	0.19
8/29/2014	1.04	0.16	0.23	1.12	0.10	0.19
8/30/2014	1.05	0.20	0.22	1.22	0.23	0.17
8/31/2014	0.99	0.12	0.15	1.08	0.18	0.90
8/31/2014	0.95	0.10	0.19	1.11	0.18	0.22
9/1/2014	0.90	0.14	0.11	1.20	0.23	0.14
9/1/2014	0.98	0.10	0.11	1.08	0.08	0.09

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
9/2/2014	0.95	0.10	0.90	1.11	0.31	0.09
9/2/2014	0.97	0.25	0.15	1.17	0.16	0.09
9/3/2014	0.88	0.04	0.17	1.16	0.20	0.09
9/3/2014	0.93	0.08	0.17	1.06	0.20	0.12
9/4/2014	0.89	0.33	0.14	1.11	0.37	0.17
9/4/2014	0.97	0.27	0.04	1.08	0.18	0.07
9/5/2014	0.88	0.12	0.14	1.08	0.14	0.28
9/5/2014	0.90	0.08	0.15	1.04	0.12	0.04
9/6/2014	0.86	0.27	0.04	0.99	0.16	0.07
9/6/2014	0.88	0.12	0.22	0.90	0.18	0.19
9/7/2014	0.88	0.20	0.14	0.99	0.10	0.12
9/7/2014	0.87	0.31	0.25	0.97	0.37	0.19
9/8/2014	0.82	0.25	0.17	0.93	0.06	0.12
9/8/2014	0.73	0.18	0.09	1.01	0.25	0.15
9/9/2014	0.84	0.12	0.09	1.09	0.08	0.12
9/9/2014	0.80	0.20	0.14	1.02	0.33	0.14
9/10/2014	0.77	0.20	0.07	1.01	0.12	0.04
9/10/2014	0.78	0.08	0.19	1.02	0.16	0.20
9/11/2014	0.75	0.37	0.25	0.96	0.41	0.27
9/11/2014	0.76	0.14	0.20	0.99	0.10	0.03
9/12/2014	0.80	0.16	0.12	0.94	0.27	0.19
9/12/2014	0.82	0.16	0.07	0.94	0.14	0.31
9/13/2014	0.76	0.06	0.22	0.93	0.16	0.17
9/14/2014	0.79	0.18	0.17	0.85	0.06	0.07
9/14/2014	0.75	0.29	0.07	0.94	0.12	0.09
9/15/2014	0.70	0.12	0.14	0.93	0.29	0.17
9/15/2014	0.76	0.06	0.11	0.92	0.25	0.19
9/16/2014	0.75	0.44	0.07	0.89	0.39	0.09
9/16/2014	0.79	0.10	0.11	0.96	0.12	0.12
9/17/2014	0.79	0.14	0.15	0.93	0.06	0.15
9/17/2014	0.77	0.20	0.07	0.83	0.23	0.12
9/18/2014	0.75	0.18	0.19	0.91	0.29	0.12
9/18/2014	0.69	0.25	0.12	0.85	0.18	0.14
9/19/2014	0.73	0.14	0.03	0.83	0.16	0.07
9/19/2014	0.67	0.10	0.06	0.80	0.10	0.35
9/20/2014	0.72	0.14	0.22	0.87	0.14	0.15
9/20/2014	0.78	0.16	0.28	0.83	0.29	0.12

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
9/21/2014	0.68	0.12	0.15	0.84	0.12	0.23
9/21/2014	0.66	0.23	0.04	0.88		
9/22/2014	0.78	0.12	0.14	0.85	0.12	0.11
9/23/2014	0.68	0.18	0.09	0.83	0.08	0.11
9/23/2014	0.67	0.12	0.12	0.85	0.39	0.07
9/24/2014	0.71	0.10	0.06	0.73	0.23	0.11
9/24/2014	0.69	0.18	0.23	0.80	0.39	0.25
9/25/2014	0.58	0.25	0.23	0.92	0.31	0.25
9/25/2014	0.73	0.06	0.15	0.86	0.20	0.11
9/26/2014	0.70	0.25	0.17	0.83	0.35	0.15
9/26/2014	0.60	0.06	0.09	0.81	0.04	0.04
9/27/2014	0.69	0.16	0.07	0.83	0.29	0.30
9/28/2014	0.62	0.10	0.07	0.78	0.10	0.17
9/28/2014	0.68	0.06	0.09	0.81	0.14	0.04
9/29/2014	0.75	0.18	0.25	0.83	0.33	0.17
9/29/2014	0.70	0.08	0.12	0.83	0.08	0.09
9/30/2014	0.67	0.18	0.11	0.73	0.10	0.15
9/30/2014	0.67	0.23	0.09	0.86	0.16	0.15
10/1/2014	0.64	0.18	0.20	0.73	0.23	0.09
10/1/2014	0.76	0.25	0.15	0.81	0.23	0.14
10/2/2014	0.72	0.20	0.14	0.78	0.06	0.14
10/2/2014	0.74	0.29	0.14	0.81	0.29	0.23
10/3/2014	0.68	0.33	0.11	0.82	0.25	0.15
10/3/2014	0.73	0.14	0.14	0.83	0.16	0.17
10/4/2014	0.66	0.18	0.07	0.75	0.12	0.07
10/4/2014	0.73	0.12	0.14	0.79	0.14	0.12
10/5/2014	0.67	0.46	0.49	0.73	0.60	0.35
10/5/2014	0.67	0.23	0.19	0.81	0.20	0.06
10/6/2014	0.67	0.16	0.25	0.78	0.18	0.07
10/6/2014	0.68	0.08	0.07	0.73	0.23	0.11
10/7/2014	0.65	0.20	0.06	0.74	0.04	0.11
10/7/2014	0.67	0.14	0.11	0.76	0.18	0.09
10/8/2014	0.68	0.27	0.20	0.72	0.16	0.09
10/8/2014	0.62	0.54	0.28	0.79	0.16	0.22
10/9/2014	0.73	0.14	0.12	0.77	0.06	0.03
10/9/2014	0.71	0.14	0.03	0.74	0.12	0.12
10/10/2014	0.77	0.12	0.19	0.76	0.16	0.11

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
10/10/2014	0.67	0.20	0.17	0.85	0.14	0.14
10/11/2014	0.65	0.25	0.14	0.76	0.18	0.14
10/11/2014	0.63	0.25	0.23	0.76	0.23	0.22
10/12/2014	0.62	0.04	0.07	0.68	0.08	0.09
10/12/2014	0.64	0.26	0.07	0.82	0.16	0.11
10/13/2014	0.64	0.08	0.07	0.67	0.10	0.04
10/13/2014	0.71	0.23	0.09	0.72	0.18	0.09
10/14/2014	0.68	0.12	0.04	0.75	0.33	0.11
10/14/2014	0.73	0.06	0.06	0.70	0.06	0.12
10/15/2014	0.71	0.25	0.14	0.77	0.12	0.19
10/15/2014	0.71	0.20	0.15	0.73	0.18	0.15
10/16/2014	0.62	0.12	0.23	0.77	0.14	0.22
10/16/2014	0.97	0.14	0.09	0.72	0.18	0.09
10/17/2014	0.68	0.04	0.06	0.80	0.20	0.07
10/17/2014	0.67	0.14	0.06	0.70	0.39	0.09
10/18/2014	0.68	0.50	0.25	0.72	0.29	0.36
10/18/2014	0.67	0.16	0.15	0.73	0.16	0.07
10/19/2014	0.67	0.33	0.19	0.71	0.39	0.20
10/19/2014	0.68	0.12	0.07	0.70	0.04	0.07
10/20/2014	0.68	0.14	0.19	0.75	0.20	0.15
10/20/2014	0.96	0.10	0.07	0.67	0.23	0.11
10/21/2014	0.70	0.14	0.12	0.74	0.16	0.04
10/21/2014	0.75	0.14	0.22	0.70	0.16	0.14
10/22/2014	0.73	0.25	0.07	0.75	0.23	0.04
10/23/2014	0.70	0.14	0.12	0.66	0.08	0.19
10/24/2014	0.70	0.20	0.06	0.70	0.40	0.07
10/24/2014	0.74	0.23	0.19	0.73	0.33	0.17
10/25/2014	0.69	0.08	0.09	0.66	0.08	0.12
10/25/2014	0.73	0.27	0.14	0.70	0.27	0.23
10/26/2014	0.62	0.12	0.17	0.68	0.31	0.06
10/26/2014	0.71	0.18	0.25	0.72	0.27	0.28
10/27/2014	0.73	0.06	0.17	0.66	0.20	0.09
10/27/2014	0.76	0.08	0.15	0.73	0.06	0.07
10/28/2014	0.71	0.29	0.06	0.71	0.23	0.12
10/28/2014	0.76	0.37	0.14	0.71	0.27	0.12
10/29/2014	0.74	0.12	0.11	0.63	0.14	0.09
10/30/2014	0.70	0.16	0.07	0.64	0.12	0.15

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
10/30/2014	0.73	0.12	0.11	0.60	0.35	0.15
10/31/2014	0.69	0.10	0.15	0.73	0.37	0.19
10/31/2014	0.73	0.23	0.06	0.78	0.18	0.07
11/1/2014	0.69	0.16	0.04	0.66	0.08	0.06
11/1/2014	0.61	0.08	0.14	0.66	0.23	0.07
11/2/2014	0.62	0.08	0.06	0.65	0.12	0.17
11/2/2014	0.69	0.20	0.07	0.73	0.23	0.11
11/3/2014	0.75	0.27	0.03	0.73	0.10	0.11
11/3/2014	0.75	0.06	0.12	0.67	0.23	0.17
11/4/2014	0.61	0.48	0.20	0.66	0.37	0.20
11/4/2014	0.73	0.14	0.06	0.72	0.12	0.10
11/5/2014	0.75	0.75	0.12	0.50	0.08	0.09
11/5/2014	0.63	0.14	0.11	0.69	0.18	0.17
11/6/2014	0.72	0.10	0.20	0.70	0.23	0.09
11/7/2014	0.72	0.18	0.11	0.69	0.12	0.60
11/7/2014	0.78	0.20	0.07	0.68	0.08	0.03
11/8/2014	0.68	0.25	0.19	0.71	0.12	0.39
11/8/2014	0.77	0.12	0.12	0.74	0.14	0.04
11/9/2014	0.67	0.10	0.07	0.73	0.16	0.11
11/9/2014	0.69	0.10	0.17	0.73	0.14	0.22
11/10/2014	0.72	0.16	0.06	0.67	0.06	0.14
11/10/2014	0.72	0.10	0.03	0.73	0.08	0.03
11/11/2014	0.67	0.25	0.14	0.73	0.14	0.11
11/12/2014	0.69	0.12	0.12	0.69	0.18	0.12
11/12/2014	0.68	0.12	0.11	0.73	0.14	0.09
11/13/2014	0.67	0.23	0.25	0.81	0.41	0.25
11/13/2014	0.66	0.10	0.06	0.75	0.20	0.11
11/14/2014	0.75	0.10	0.17	0.72	0.31	0.12
11/14/2014	0.73	0.18	0.12	0.71	0.16	0.22
11/15/2014	0.77	0.12	0.14	0.81	0.08	0.15
11/15/2014	0.67	0.04	0.06	0.73	0.10	0.03
11/16/2014	0.62	0.14	0.17	0.74	0.20	0.23
11/16/2014	0.75	0.23	0.06	0.77	0.25	0.30
11/17/2014	0.67	0.23	0.09	0.73	0.12	0.04
11/17/2014	0.65	0.16	0.07	0.82	0.14	0.15
11/18/2014	0.67	0.06	0.11	0.74	0.10	0.12
11/18/2014	0.67	0.18	0.14	0.74	0.16	0.11

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
11/19/2014	0.67	0.23	0.19	0.75	0.27	0.33
11/19/2014	0.64	0.33	0.20	0.76	0.23	0.17
11/20/2014	0.68	0.16	0.17	0.75	0.25	0.17
11/20/2014	0.69	0.10	0.11	0.75	0.25	0.07
11/21/2014	0.62	0.31	0.11	0.76	0.14	0.12
11/21/2014	0.69	0.35	0.23	0.73	0.31	0.22
11/22/2014	0.65	0.14	0.09	0.72	0.10	0.12
11/22/2014	0.67	0.29	0.14	0.78	0.20	0.10
11/23/2014	0.59	0.65	0.14	0.68	0.56	0.46
11/23/2014	0.60	0.12	0.07	0.78	0.14	0.04
11/24/2014	0.55	0.12	0.11	0.70	0.08	0.07
11/24/2014	0.67	0.33	0.11	0.72	0.16	0.30
11/25/2014	0.66	0.06	0.00	0.68	0.08	0.12
11/25/2014	0.68	0.08	0.03	0.73	0.10	0.07
11/26/2014	0.64	0.14	0.12	0.73	0.10	0.04
11/26/2014	0.59	0.39	0.27	0.86	0.44	0.31
11/27/2014	0.60	0.08	0.10	0.69	0.25	0.17
11/28/2014	0.67	0.33	0.11	0.72	0.14	0.11
11/28/2014	0.68	0.08	0.09	0.79	0.04	0.14
11/29/2014	0.63	0.08	0.11	0.74	0.06	0.06
11/29/2014	0.60	0.35	0.11	0.78	0.18	0.19
11/30/2014	0.62	0.06	0.25	1.09	0.27	0.06
11/30/2014	0.69	0.10	0.07	0.73	0.16	0.17
12/1/2014	0.64	0.29	0.15	0.75	0.18	0.09
12/1/2014	0.59	0.23	0.09	0.74	0.04	0.06
12/2/2014	0.63	0.14	0.11	0.70	0.14	0.12
12/2/2014	0.65	0.16	0.09	0.70	0.14	0.11
12/3/2014	0.63	0.23	0.19	0.79	0.10	0.27
12/3/2014	0.64	0.08	0.03	0.83	0.12	0.17
12/4/2014	0.63	0.16	0.22	0.67	0.23	0.09
12/4/2014	0.68	0.39	0.25	0.76	0.12	0.14
12/5/2014	0.62	0.52	0.35	0.73	0.46	0.28
12/5/2014	0.62	0.14	0.11	0.72	0.25	0.09
12/6/2014	0.60	0.10	0.07	0.74	0.06	0.17
12/6/2014	0.69	0.12	0.09	0.74	0.18	0.08
12/7/2014	0.62	0.12	0.14	0.68	0.23	0.06
12/7/2014	0.62	0.16	0.11	0.77	0.23	0.07

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
12/8/2014	0.62	0.18	0.15	0.77	0.25	0.03
12/8/2014	0.53	0.33	0.14	0.79	0.16	0.20
12/9/2014	0.55	0.20	0.19	0.67	0.12	0.07
12/9/2014	0.62	0.10	0.14	0.77	0.14	0.09
12/10/2014	0.62	0.12	0.07	0.84	0.37	0.11
12/10/2014	0.73	0.06	0.09	0.83	0.18	0.09
12/11/2014	0.78	0.46	0.43	0.93	0.56	0.49
12/11/2014	0.68	0.46	0.33	0.92	0.65	0.27
12/12/2014	0.81	0.08	0.07	0.98	0.16	0.06
12/12/2014	0.80	0.12	0.11	0.96	0.18	0.09
12/13/2014	0.72	0.23	0.30	0.90	0.12	0.14
12/13/2014	0.66	0.06	0.15	0.81	0.31	0.09
12/14/2014	0.56	0.14	0.20	0.79	0.31	0.35
12/14/2014	0.59	0.08	0.11	0.76	0.16	0.23
12/15/2014	0.63	0.08	0.20	0.72	0.04	0.03
12/15/2014	0.47	0.08	0.23	0.71	0.10	0.17
12/16/2014	0.56	0.23	0.72	0.59	0.20	0.15
12/16/2014	0.67	0.20	0.07	0.70	0.18	0.12
12/17/2014	0.57	0.12	0.09	0.70	0.16	0.07
12/17/2014	0.53	0.18	0.12	0.63	0.33	0.07
12/18/2014	0.56	0.14	0.17	0.69	0.12	0.17
12/18/2014	0.55	0.06	0.09	0.66	0.08	0.04
12/19/2014	0.54	0.10	0.19	0.67	0.20	0.14
12/19/2014	0.60	0.06	0.17	0.77	0.41	0.17
12/20/2014	0.55	0.27	0.09	0.70	0.16	0.06
12/20/2014	0.63	0.25	0.11	0.71	0.20	0.07
12/21/2014	0.56	0.10	0.11	0.69	0.14	0.15
12/21/2014	0.56	0.04	0.11	0.67	0.20	0.11
12/22/2014	0.58	0.35	0.17	0.67	0.39	0.27
12/22/2014	0.64	0.27	0.20	0.62	0.20	0.31
12/23/2014	0.52	0.10	0.09	0.68	0.12	0.11
12/23/2014	0.52	0.25	0.09	0.68	0.27	0.20
12/24/2014	0.54	0.10	0.11	0.69	0.10	0.06
12/25/2014	0.49	0.29	0.04	0.70	0.06	0.07
12/26/2014	0.52	0.20	0.09	0.66	0.12	0.14
12/26/2014	0.53	0.18	0.04	0.70	0.18	0.11
12/27/2014	0.52	0.18	0.09	0.66	0.10	0.09

Date	**Corrosion Rates (mpy)**					
	Control Condition			**Test Condition**		
	MS	**L**	**C**	**MS**	**L**	**C**
12/27/2014	0.57	0.12	0.11	0.66	0.06	0.04
12/28/2014	0.47	0.25	0.07	0.62	0.27	0.11
12/28/2014	0.51	0.06	0.19	0.65	0.31	0.11
12/29/2014	0.52	0.27	0.23	0.62	0.48	0.11
12/30/2014	0.47	0.39	0.31	0.63	0.54	0.38
12/31/2014	0.48	0.16	0.15	0.59	0.35	0.09
1/1/2015	0.46	0.23	0.25	0.59	0.31	0.11
1/2/2015	0.43	0.39	0.27	0.65	0.29	0.30
1/2/2015	0.46	0.35	0.19	0.69	0.27	0.20
1/3/2015	0.46	0.16	0.09	0.62	0.08	0.12
1/3/2015	0.49	0.16	0.12	0.62	0.25	0.03
1/4/2015	0.51	0.12	0.04	0.64	0.10	0.09
1/4/2015	0.42	0.18	0.15	0.65	0.14	0.07
1/5/2015	0.47	0.25	0.22	0.62	0.29	0.23
1/5/2015	0.52	0.04	0.03	0.66	0.16	0.20
1/6/2015*	**0.55**	**0.12**	**0.11**	**0.72**	**0.08**	**0.17**
1/6/2015	0.51	0.16	0.17	0.64	0.35	0.70
1/7/2015	0.55	0.35	0.14	0.67	0.14	0.06
1/8/2015	0.55	0.35	0.14	0.67	0.14	0.06
1/9/2015	0.52	0.23	0.11	0.60	0.08	0.11
1/9/2015	0.66	0.18	0.03	0.61	0.12	0.12
1/10/2015	0.57	0.14	0.23	0.59	0.31	0.14
1/10/2015	0.64	0.20	0.19	0.67	0.23	0.07
1/11/2015	0.42	0.27	0.23	0.68	0.10	0.44
1/12/2015	0.53	0.06	0.07	0.63	0.18	0.11
1/12/2015	0.57	0.06	0.04	0.62	0.06	0.14
1/13/2015	0.52	0.06	0.14	0.72	0.08	0.17
1/14/2015	0.53	0.12	0.20	0.60	0.29	0.14
1/14/2015	0.54	0.20	0.11	0.63	0.27	0.23
1/15/2015	0.53	0.04	0.11	0.65	0.14	0.17
1/15/2015	0.53	0.12	0.11	0.57	0.12	0.15
1/16/2015	0.54	0.29	0.17	0.73	0.27	0.12
1/16/2015	0.55	0.14	0.07	0.59	0.18	0.07
1/17/2015	0.57	0.18	0.22	0.53	0.35	0.15
1/18/2015	0.57	0.06	0.03	0.55	0.14	0.17
1/18/2015	0.59	0.31	0.20	0.59	0.44	0.15
1/19/2015	0.56	0.12	0.11	0.62	0.12	0.12

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
1/19/2015	0.55	0.20	0.43	0.56	0.31	0.25
1/20/2015	0.61	0.14	0.06	0.52	0.18	0.11
1/20/2015	0.56	0.06	0.14	0.65	0.20	0.07
1/21/2015	0.68	0.12	0.06	0.58	0.16	0.22
1/21/2015	0.62	0.16	0.12	0.57	0.12	0.06
1/22/2015	0.51	0.08	0.07	0.59	0.14	0.07
1/22/2015	0.65	0.08	0.13	0.62	0.18	0.09
1/23/2015	0.51	0.20	0.27	0.60	1.20	0.11
1/23/2015	0.50	0.07	0.06	0.60	0.12	0.12
1/24/2015	0.53	0.16	0.06	0.60	0.29	0.12
1/24/2015	0.62	0.25	0.09	0.57	0.10	0.07
1/25/2015	0.56	0.14	0.19	0.60	0.25	0.09
1/25/2015	0.59	0.31	0.30	0.59	0.27	0.23
1/26/2015	0.59	0.10	0.19	0.61	0.20	0.17
1/26/2015	0.59	0.18	0.06	0.67	0.10	0.09
1/27/2015	0.38	0.14	0.12	0.63	0.10	0.15
1/28/2015	0.62	0.20	0.69	0.61	0.06	0.03
1/29/2015	0.57	0.08	0.06	0.58	0.35	0.15
1/29/2015	0.61	0.06	0.07	0.57	0.10	0.11
1/30/2015	0.58	0.10	0.14	0.59	0.35	0.09
1/30/2015	0.61	0.29	0.30	0.58	0.10	0.31
1/31/2015	0.57	0.06	0.19	0.57	0.06	0.04
1/31/2015	0.60	0.25	0.22	0.54	0.48	0.19
2/1/2015	0.58	0.08	0.09	0.60	0.23	0.11
2/2/2015	0.62	0.16	0.07	0.63	0.04	0.14
2/2/2015	0.60	0.25	0.09	0.58	0.16	0.11
2/3/2015	0.51	0.08	0.06	0.49	0.06	0.04
2/3/2015	0.66	0.20	0.06	0.62	0.27	0.11
2/4/2015	0.62	0.48	0.25	0.62	0.20	0.12
2/4/2015	0.60	0.33	0.25	0.60	0.20	0.12
2/5/2015	0.57	0.29	0.20	0.57	0.23	0.17
2/5/2015	0.65	0.20	0.07	0.65	0.06	0.06
2/6/2015	0.57	0.08	0.06	0.62	0.10	0.04
2/6/2015	0.63	0.16	0.09	0.54	0.25	0.12
2/7/2015	0.62	0.18	0.22	0.62	0.14	0.20
2/8/2015	0.64	0.10	0.06	0.57	0.08	0.14
2/10/2015	0.71	0.23	0.07	0.55	0.27	0.15

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
2/10/2015	0.62	0.16	0.12	0.59	0.12	0.12
2/11/2015	0.66	0.04	0.15	0.57	0.23	0.22
2/11/2015	0.68	0.20	0.22	0.61	0.23	0.15
2/12/2015	0.66	0.20	0.15	0.62	0.12	0.04
2/12/2015	0.58	0.20	0.06	0.60	0.25	0.23
2/13/2015	0.64	0.08	0.09	0.57	0.12	0.12
2/13/2015	0.66	0.29	0.12	0.62	0.23	0.17
2/14/2015	0.62	0.20	0.07	0.59	0.20	0.04
2/14/2015	0.62	0.41				
2/16/2015	0.62	0.08	0.23	0.55	0.37	0.39
2/16/2015	0.62	0.08	0.07	0.55	0.18	0.07
2/17/2015	0.72	0.08	0.03	0.62	0.20	0.07
2/17/2015	0.57	0.14	0.11	0.59	0.10	0.14
2/18/2015	0.72	0.12	0.09	0.58	0.12	0.06
2/18/2015	0.66	0.20	0.09	0.60	0.12	0.11
2/19/2015	0.72	0.08	0.11	0.50	0.10	0.19
2/19/2015	0.68	0.16	0.22	0.53	0.16	0.04
2/20/2015	0.70	0.08	0.07	0.59	0.12	0.07
2/20/2015	0.69	0.14	0.15	0.54	0.18	0.22
2/21/2015	0.57	0.14	0.20	0.58	0.25	0.06
2/21/2015	0.63	0.06	0.15	0.58	0.08	
2/22/2015	0.64	0.10	0.12	0.52	0.10	0.06
2/22/2015	0.65	0.16	0.20	0.55	0.16	0.06
2/23/2015	0.74	0.08	0.07	0.59	0.04	0.06
2/23/2015	0.65	0.18	0.11	0.59	0.06	0.17
2/26/2015	0.71	0.27	0.23	0.58	0.25	0.20
2/26/2015	0.66	0.18	0.03	0.57	0.20	0.14
2/27/2015	0.71	0.08	0.11	0.70	0.14	0.23
2/28/2015	0.72	0.27	0.20	0.56	0.25	0.14
2/28/2015	0.73	0.20	0.03	0.58	0.33	0.07
3/1/2015	0.62	0.12	0.15	0.58	0.20	0.09
3/1/2015	0.65	0.41	0.12	0.55	0.23	0.33
3/2/2015	0.69	0.20	0.15	0.54	0.18	0.14
3/2/2015	0.63	0.52	0.28	0.63	0.62	0.39
3/3/2015	0.70	0.12	0.06	0.57	0.04	0.23
3/3/2015	0.65	0.21	0.07	0.61	0.04	0.06
3/4/2015	0.64	0.46	0.33	0.53	0.41	0.28

Date	**Corrosion Rates (mpy)**					
	Control Condition			**Test Condition**		
	MS	**L**	**C**	**MS**	**L**	**C**
3/5/2015	0.70	0.12	0.20	0.54	0.18	0.20
3/5/2015	0.69	0.31	0.41	0.59	0.52	0.38
3/6/2015	0.69	0.14	0.09	0.52	0.27	0.04
3/6/2015	0.62	0.23	0.07	0.57	0.18	0.06
3/7/2015	0.61	0.10	0.07	0.53	0.16	0.20
3/7/2015	0.69	0.12	0.04	0.46	0.14	0.06
3/8/2015	0.62	0.33	0.23	0.57	0.07	0.21
3/8/2015	0.60	0.27	0.12	0.57	0.08	0.06
3/10/2015**	**0.62**	**0.25**	**0.19**	**0.46**	**0.18**	**0.19**
3/11/2015	0.63	0.16	0.04	0.50	0.20	0.09
3/12/2015	0.64	0.25	0.12	0.52	0.16	
3/12/2015	0.65	0.16	0.14	0.53	0.23	0.22
3/13/2015	0.69	0.14	0.11	0.52	0.23	0.07
3/14/2015	0.66	0.33	0.19	0.49	0.10	0.28
3/14/2015	0.67	0.14	0.14	0.63	0.31	0.22
3/15/2015	0.66	0.23	0.14	0.50	0.08	0.11
3/16/2015	0.72	0.20	0.09	0.60	0.06	0.03
3/16/2015	0.62	0.08	0.09	0.56	0.20	0.09
3/17/2015	0.70	0.25	0.20	0.51	0.29	0.11
3/18/2015	0.76	0.06	0.12	0.53	0.25	0.25
3/19/2015	0.63	0.12	0.17	0.52	0.08	0.11
3/19/2015	0.73	0.50	0.30	0.52	0.37	0.31
3/20/2015	0.74	0.29	0.14	0.58	0.23	0.09
3/22/2015	0.63	0.20	0.14	0.44	0.35	0.15
3/22/2015	0.66	0.18	0.15	0.53	0.18	0.25
3/23/2015	0.71	0.14	0.06	0.52	0.12	0.03
3/23/2015	0.68	0.08	0.04	0.52	0.16	0.12
3/24/2015	0.72	0.20	0.19	0.49	0.31	0.20
3/24/2015	0.66	0.37	0.17	0.56	0.20	0.17
3/25/2015	0.67	0.18	0.04	0.55	0.18	0.20
3/25/2015	0.68	0.23	0.27	0.47	0.25	0.27
3/26/2015	0.61	0.18	0.07	0.54	0.08	0.12
3/26/2015	0.67	0.23	0.09	0.57	0.29	0.15
3/27/2015	0.65	0.12	0.07	0.62	0.14	0.14
3/27/2015	0.57	0.20	0.28	0.59	0.27	0.22
3/28/2015	0.66	0.10	0.07	0.57	0.27	0.17
3/28/2015	0.60	0.12	0.14	0.64	0.12	0.07

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
3/29/2015	0.65	0.33	0.09	0.60	0.12	0.11
3/29/2015	0.66	0.31	0.30	0.56	0.20	0.22
3/30/2015	0.70	0.33	0.22	0.57	0.29	0.14
3/30/2015	0.73	0.48	0.17	0.62	0.41	0.31
3/31/2015	0.69	0.06	0.12	0.59	0.20	0.07
3/31/2015	0.75	0.16	0.12	0.56	0.12	0.12
4/1/2015	0.71	0.06	0.06	0.59	0.23	0.40
4/1/2015	0.67	0.18	0.07	0.65		
4/2/2015	0.73	0.14	0.03	0.65	0.10	0.20
4/2/2015	0.60	0.10	0.14	0.63	0.08	0.15
4/3/2015	0.63	0.14	0.14	0.57	0.20	0.17
4/5/2015	0.56	0.14	0.15	0.70	0.20	0.15
4/5/2015	0.53	0.14	0.15	0.64	0.20	0.11
4/6/2015	0.60	0.10	0.06	0.67	0.08	0.07
4/6/2015	0.50	0.06	0.03	0.68	0.14	0.09
4/7/2015	0.51	0.16	0.04	0.64	0.16	0.06
4/7/2015	0.57	0.12	0.09	0.66	0.27	0.20
4/8/2015	0.59	0.08	0.12	0.73	0.16	0.12
4/8/2015	0.47	0.31	0.12	0.64	0.18	0.11
4/9/2015	0.53	0.12	0.12	0.59	0.18	0.14
4/10/2015	0.58	0.16	0.07	0.63	0.10	0.22
4/11/2015	0.57	0.14	0.12	0.64	0.06	0.15
4/13/2015	0.70	0.25	0.11	0.35	0.20	0.19
4/14/2015	0.67	0.18	0.12	0.69	0.23	0.14
4/14/2015	0.60	0.16	0.19	0.74	0.10	0.27
4/15/2015	0.58	0.14	0.14	0.67	0.14	0.12
4/15/2015	0.69	0.15	0.12	0.62	0.12	0.14
4/16/2015	0.63	0.14	0.06	0.60	0.25	0.11
4/16/2015	0.31	0.06	0.12	0.70	0.10	0.12
4/17/2015	0.61	0.44	0.31	0.71	0.58	0.31
4/20/2015	0.76	0.31	0.12	0.80	0.20	0.22
4/21/2015	0.72	0.44	0.44	0.71	0.23	0.20
4/21/2015	0.67	0.20	0.14	0.76	0.14	0.19
4/22/2015	0.76	0.23	0.09	0.83	0.27	0.17
4/23/2015	0.74	0.10	0.14	0.82	0.35	0.20
4/23/2015	0.81	0.12	0.16	0.87	0.12	0.09
4/27/2015	0.78	0.50	0.20	0.81	0.37	0.30

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
4/27/2015	0.76	0.04	0.12	0.81	0.16	0.12
4/28/2015	0.83	0.25	0.20	0.87	0.14	0.19
4/28/2015	0.78	0.27	0.15	0.83	0.08	0.25
4/29/2015	0.84	0.08	0.04	0.87	0.18	0.12
4/29/2015	0.80	0.18	0.09	0.88	0.16	0.17
4/30/2015	0.83	0.33	0.07	0.87	0.08	0.15
4/30/2015	0.73	0.18	0.11	0.79	0.59	0.25
5/1/2015	0.79	0.04	0.13	0.84	0.09	0.15
5/1/2015	0.82	0.12	0.11	0.86	0.10	0.90
5/4/2015	0.86	0.12	0.03	0.88	0.14	0.03
5/4/2015	0.84	0.16	0.12	0.87	0.18	0.12
5/5/2015	0.86	0.12	0.14	0.90	0.06	0.25
5/5/2015	0.82	0.12	0.04	0.87	0.18	0.09
5/6/2015	0.88	0.04	0.12	0.86	0.08	0.03
5/6/2015	0.98	0.14	0.15	0.83	0.10	0.11
5/7/2015	0.73	0.20	0.09	0.83	0.12	0.17
5/8/2015	0.80	0.06	0.11	0.85	0.31	0.09
5/8/2015	0.81	0.29	0.22	0.79	0.58	0.14
5/9/2015	0.73	0.27	0.07	0.88	0.16	0.11
5/11/2015	0.81	0.18	0.09	0.87	0.14	0.12

* Indicates low-dose inhibitor addition

** Indicates high-dose inhibitor addition

APPENDIX D: DATA FOR MANELE BAY INHIBITOR 2

Table D-1: Corrosion Rates for Manele Bay Inhibitor 1 Experiment

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
5/12/2015	0.46	0.08	4.14	0.41	0.08	4.71
5/13/2015	0.95	0.14	3.93	1.17	0.18	4.08
5/14/2015	0.94	0.10	3.06	1.19	0.33	3.02
5/14/2015	0.98	0.39	2.74	1.27	0.48	2.67
5/15/2015	0.99	0.12	2.18	1.18	0.14	2.20
5/16/2015	1.04	0.35	1.72	1.30	0.16	1.88
5/17/2015	1.02	0.39	1.64	1.34	0.16	1.69
5/18/2015	0.95	0.08	1.17	1.29	0.23	1.33
5/19/2015	1.00	0.04	1.02	1.24	0.20	1.30
5/21/2015	0.98	0.08	0.87	1.19	0.16	0.98
5/22/2015	0.88	0.14	1.02	1.21	0.12	0.77
5/23/2015	0.75	0.37	0.82	1.10	0.12	1.03
5/25/2015	0.78	0.50	0.68	1.04	0.54	0.71
5/26/2015	0.73	0.06	0.52	1.04	0.14	0.52
5/26/2015	0.73	0.14	0.54	0.98	0.18	0.71
5/27/2015	0.74	0.25	0.47	1.01	0.10	0.63
5/28/2015	0.75	0.31	0.70	0.99	0.08	0.74
5/30/2015	0.72	0.18	0.58	0.92	0.08	0.49
5/30/2015	0.70	0.10	0.44	1.00	0.23	0.33
6/1/2015	0.75	0.27	0.41	0.90	0.25	0.33
6/1/2015	0.67	0.51		0.86		
6/2/2015	0.76	0.20	0.39	0.99	0.14	0.38
6/2/2015	0.67	0.20	0.41	1.00	0.04	0.47
6/3/2015	0.61	0.08	0.31	0.87	0.08	0.36
6/3/2015	0.78	0.16	0.27	0.92	0.06	0.39
6/4/2015	0.67	0.14	0.35	0.86	0.17	0.27
6/5/2015	0.66	0.25	0.31	0.86	0.20	0.30
6/5/2015	0.62	0.10	0.39	0.85	0.20	0.44
6/6/2015	0.72	0.06	0.28	0.85	0.12	0.31
6/7/2015	0.55	0.16	0.27	0.83	0.23	0.31
6/8/2015	0.63	0.16	0.27	0.83	0.10	0.36
6/8/2015	0.67	0.10	0.28	0.84	0.06	0.14
6/9/2015	0.59	0.20	0.30	0.76	0.25	0.22
6/9/2015	0.62	0.12	0.30	0.88	0.25	0.04
6/10/2015	0.60	0.14	0.22	0.79	0.20	0.38

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
6/10/2015	0.52	0.20	0.27	0.81	0.41	0.19
6/11/2015	0.62	0.12	0.33	0.82	0.16	0.17
6/11/2015	0.58	0.18	0.11	0.80	0.16	0.22
6/12/2015	0.62	0.06	0.28	0.76	0.08	0.19
6/12/2015	0.58	0.53	0.27	0.80	0.10	0.17
6/13/2015	0.65	0.23	0.11	0.83	0.39	0.25
6/13/2015	0.58	0.06	0.36	0.80	0.09	0.07
6/14/2015	0.51	0.08	0.20			
6/15/2015	0.58	0.27	0.12	0.73	0.25	0.14
6/16/2015	0.59	0.14	0.19	0.74	0.25	0.12
6/16/2015	0.56	0.41	0.47	0.78	0.60	0.43
6/17/2015	0.58	0.29	0.19	0.78	0.31	0.11
6/18/2015	0.64	0.12	0.14	0.78	0.25	0.02
6/18/2015	0.55	0.14	0.04	0.78	0.12	0.17
6/19/2015	0.58	0.04	0.11	0.79	0.06	0.09
6/19/2015	0.66	0.16	0.25	0.79	0.08	0.12
6/20/2015	0.50	0.10	0.09	0.74	0.23	0.09
6/20/2015	0.60	0.20	0.19	0.71	0.16	0.11
6/21/2015	0.51	0.52	0.33	0.72	0.33	0.22
6/21/2015	0.53	0.10	0.14	0.79	0.25	0.19
6/22/2015	0.53	0.12	0.06	0.77	0.05	0.11
6/22/2015	0.58	0.29	0.19	0.77	0.25	0.19
6/23/2015	0.50	0.48	0.41	0.76	0.31	0.19
6/23/2015	0.59	0.06	0.06	0.70	0.10	0.15
6/24/2015	0.52	0.29	0.25	0.68	0.18	0.14
6/24/2015	0.58	0.39	0.15	0.73	0.25	0.23
6/25/2015	0.56	0.27	0.19	0.76	0.24	0.03
6/25/2015	0.54	0.12	0.15	0.73	0.06	0.23
6/26/2015	0.52	0.18	0.22	0.71	0.37	0.12
6/26/2015	0.46	0.10	0.17	0.69	0.08	0.09
6/27/2015	0.54	0.23	0.23	0.11	0.16	0.15
6/27/2015	0.57	0.35	0.19	0.72	0.35	0.10
6/28/2015	0.52	0.18	0.07	0.72	0.10	0.14
6/28/2015	0.57	0.08	0.07	0.71	0.04	0.11
6/29/2015	0.53	0.16	0.07	0.60	0.46	0.15
6/29/2015	0.52	0.29	0.07	0.68	0.23	0.11
6/30/2015	0.57	0.18	0.22	0.76	0.16	0.09

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
6/30/2015	0.52	0.39	0.22	0.69	0.23	0.14
7/1/2015	0.52	0.06	0.10	0.67	0.06	0.07
7/2/2015	0.46	0.08	0.19	0.64	0.23	0.14
7/2/2015	0.46	0.23	0.09	0.78	0.18	0.11
7/3/2015	0.45	0.27	0.22	0.66	0.14	0.22
7/3/2015	0.49	0.06	0.09	0.63	0.16	0.15
7/4/2015	0.48	0.16	0.22	0.70	0.23	0.30
7/4/2015	0.52	0.29	0.15	0.68	0.18	0.14
7/6/2015	0.40	0.14	0.25	0.65	0.20	0.17
7/6/2015	0.52	0.14	0.07	1.21	0.29	0.11
7/7/2015	0.46	0.06	0.06	0.59	0.14	0.09
7/7/2015	0.46	0.16	0.04	0.62	0.08	0.09
7/8/2015	0.44	0.12	0.07	0.67	0.08	0.09
7/8/2015	0.48	0.08	0.27	0.78	0.06	0.11
7/9/2015	0.42	0.10	0.14	0.66	0.16	0.03
7/9/2015	0.41	0.06	0.11	0.62	0.14	0.07
7/10/2015	0.43	0.06	0.11	0.73	0.25	0.17
7/10/2015	0.45	0.48	0.55	0.64	0.50	0.36
7/11/2015	0.41	0.04	0.11	0.67	0.10	0.03
7/11/2015	0.41	0.29	0.12	0.72	0.14	0.09
7/13/2015	0.46	0.12	0.07	0.67	0.29	0.07
7/14/2015	0.41	0.12	0.09	0.58	0.23	0.12
7/14/2015	0.47	0.18	0.03	0.61	0.06	0.09
7/15/2015	0.45	0.08	0.07	0.63	0.08	0.22
7/15/2015	0.45	0.18	0.19	0.64	0.18	0.19
7/16/2015	0.42	0.37	0.09	0.63	0.04	0.09
7/16/2015	0.46	0.18	0.43	0.63	0.27	0.20
7/17/2015	0.41	0.16	0.12	0.62	0.16	0.20
7/17/2015	0.45	0.29	0.22	0.62	0.25	0.19
7/18/2015	0.41	0.06	0.19	0.62	0.27	0.20
7/18/2015	0.45	0.08	0.03	0.60	0.05	0.10
7/20/2015	0.38	0.12	0.02	0.62	0.04	0.15
7/20/2015	0.37	0.16	0.23	0.58	0.41	0.23
7/21/2015	0.44	0.08	0.19	0.58	0.16	0.11
7/21/2015	0.35	0.18	0.09	0.58	0.23	0.04
7/22/2015	0.39	0.25	0.04	0.67	0.14	0.11
7/22/2015	0.41	0.14	0.11	0.73	0.10	0.12

Date	Corrosion Rates (mpy)					
	Control Condition			**Test Condition**		
	MS	**L**	**C**	**MS**	**L**	**C**
7/23/2015	0.16	0.10	0.06	0.62	0.12	0.07
7/23/2015	0.43	0.10	0.09	0.60	0.08	
7/24/2015	0.38	0.22	0.09	0.56	0.16	0.14
7/24/2015	0.36	0.08	0.17	0.61	0.04	0.14
7/25/2015	0.33	0.27	0.10	0.74	0.18	0.14
7/25/2015	0.49	0.06	0.10	0.63	0.16	0.15
7/26/2015	0.36	0.04	0.07	0.52	0.06	0.09
7/26/2015	0.38	0.04	0.12	0.57	0.14	0.11
7/28/2015	0.38	0.18	0.11	0.57	0.18	0.06
7/28/2015	0.45	0.35	0.20	0.66	0.06	0.11
7/29/2015	0.43	0.16	0.14	0.54	0.16	0.14
7/29/2015	0.40	0.10	0.09	0.60	0.10	0.15
7/30/2015	0.35	0.31	0.23	0.58	0.39	0.23
7/30/2015	0.37	0.14	0.11	0.59	0.23	0.14
7/31/2015	0.41	0.37	0.04	0.50	0.10	0.11
7/31/2015	0.35	0.14	0.07	0.58	0.06	0.20
8/1/2015	0.59	0.18	0.13	0.74	0.23	0.11
8/1/2015	0.56	0.41	0.04	0.84	0.16	0.12
8/2/2015	0.35	0.16	0.09	0.52	0.20	0.14
8/2/2015	0.44	0.16	0.09	0.57	0.21	0.17
8/3/2015	0.38	0.12	0.20	0.56	0.14	0.14
8/3/2015	0.37	0.31	0.31	0.45	0.25	0.27
8/4/2015	0.36	0.04	0.14	0.58	0.21	0.14
8/4/2015	0.39	0.16	0.11	0.46	0.08	0.07
8/5/2015	0.52	0.37	0.38	0.50	0.50	0.31
8/5/2015	0.31	0.10	0.14	0.55	0.14	0.40
8/6/2015	0.33	0.16	0.17	0.52	0.10	0.11
8/6/2015	0.40	0.16	0.07	0.54	0.10	0.09
8/7/2015	0.36	0.50	0.44	0.52	0.64	0.51
8/7/2015	0.44	0.56	0.40	0.48	0.50	0.60
8/17/2015*	**0.41**	**0.10**	**0.19**	**0.40**	**0.18**	**0.11**
8/17/2015	0.57	0.20	0.31	0.56	0.21	0.28
8/18/2015	0.37	0.10	0.11	0.49	0.16	0.09
8/18/2015	0.39	0.04	0.09	0.50	0.20	0.06
8/19/2015	0.40	0.29	0.35	0.50	0.35	0.23
8/19/2015	0.31	0.31	0.20	0.45	0.35	0.20
8/20/2015	0.34	0.16	0.20	0.52	0.37	0.27

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
8/20/2015	0.41	0.23	0.09	0.52	0.12	0.23
8/21/2015	0.37	0.08	0.20	0.34	0.14	0.06
8/21/2015	0.29	0.23	0.20	0.35	0.12	0.11
8/22/2015	0.36	0.23	0.03	0.47	0.27	0.06
8/22/2015	0.43	0.60	0.11	0.54	0.18	0.07
8/23/2015	0.28	0.04	0.07	0.32	0.04	0.06
8/23/2015	0.31	0.20	0.06	0.37	0.16	0.03
8/24/2015	0.36	0.18	0.12	0.36	0.06	0.19
8/24/2015	0.31	0.20	0.04	0.46	0.16	0.11
8/25/2015	0.31	0.14	0.12	0.37	0.20	0.17
8/25/2015	0.31	0.18	0.12	0.41	0.04	0.04
8/26/2015	0.31	0.20	0.23	0.31	0.29	0.20
8/26/2015	0.42	0.08	0.04	0.41	0.10	0.30
8/27/2015	0.46	0.27	0.06	0.49	0.23	0.15
8/27/2015	0.52	0.14	0.14	0.50	0.14	0.04
8/28/2015	0.36	0.14	0.07	0.50	0.12	0.09
8/28/2015	0.45	0.25	0.04	0.51	0.06	0.09
8/29/2015	0.29	0.06	0.14	0.36	0.14	0.19
8/29/2015	0.32	0.23	0.14	0.43	0.23	0.14
8/30/2015	0.33	0.18	0.25	0.37	0.06	0.12
8/31/2015	0.37	0.08	0.07	0.32	0.06	0.09
8/31/2015	0.27	0.08	0.17	0.36	0.16	0.06
9/1/2015	0.40	0.20	0.22	0.44	0.20	0.09
9/1/2015	0.34	0.08	0.14	0.44	0.20	0.04
9/2/2015	0.37	0.23	0.17	0.43	0.16	0.11
9/2/2015	0.30	0.10	0.14	0.45	0.23	0.03
9/3/2015	0.32	0.27	0.15	0.43	0.23	0.20
9/3/2015	0.40	0.06	0.07	0.44	0.12	0.12
9/4/2015	0.22	0.10	0.19	0.34	0.00	0.04
9/4/2015	0.29	0.18	0.09	0.43	0.16	0.07
9/5/2015	0.27	0.56	0.35	0.38	0.41	0.35
9/5/2015	0.40	0.25	0.11	0.56	0.12	0.11
9/6/2015	0.26	0.14	0.04	0.46	0.18	0.14
9/7/2015	0.31	0.25	0.04	0.47	0.12	0.04
9/8/2015	0.33	0.10	0.15	0.45	0.12	0.07
9/8/2015	0.39	0.06	0.20	0.45	0.16	0.09
9/10/2015	0.23	0.06	0.20	0.46	0.10	0.11

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
9/11/2015	0.23	0.08	0.15	0.41	0.30	0.17
9/14/2015	0.28	0.20	0.14	0.54	0.12	0.19
9/14/2015	0.23	0.23	0.11	0.41	0.05	0.14
9/15/2015	0.47	0.18	0.12	0.59	0.06	0.11
9/15/2015	0.57	0.27	0.11	0.53	0.04	0.07
9/16/2015	0.62	0.10	0.14	0.62	0.10	0.09
9/16/2015	0.53	0.10	0.12	0.55	0.10	0.07
9/17/2015	0.41	0.27	0.20	0.48	0.35	0.09
9/17/2015	0.51	0.16	0.22	0.44	0.16	0.11
9/18/2015	0.39	0.06	0.07	0.33	0.08	0.17
9/18/2015	0.47	0.48	0.43	0.38	0.35	0.20
9/29/2015	0.32	0.33	0.22	0.31	0.27	0.19
9/19/2015	0.46	0.14	0.12	0.42	0.06	0.15
9/20/2015	0.36	0.35	0.20	0.45	0.06	0.17
9/21/2015	0.32	0.23	0.11	0.41	0.16	0.11
9/21/2015	0.33	0.04	0.04	0.52	0.14	0.12
9/24/2015	0.36	0.10	0.09	0.50	0.12	0.12
9/24/2015	0.34	0.31	0.22	0.58	0.25	0.22

* Indicates inhibitor addition started

APPENDIX E: DATA FOR LANA’I CITY INHIBITOR 1

Table E-1: Corrosion Rates for Lana'i City Inhibitor 1 Experiment

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
2/2/2015	2.64	0.27	1.08	2.81	0.27	0.76
2/2/2015	0.20	0.06	0.03	0.15	0.08	1.33
2/3/2015	0.57	0.14	3.55	0.36	0.33	1.33
2/3/2015	0.58	0.23	3.76	1.87	0.10	3.65
2/4/2015	0.24	0.10	0.58	0.22	0.20	1.46
2/4/2015	1.03	0.16	0.76	0.20	0.14	1.22
2/5/2015	0.78	0.10	0.52	0.27	0.12	1.02
2/5/2015	1.11	0.29	1.37	0.53	0.27	0.89
2/6/2015	0.46	0.29	0.82	0.19	0.14	1.24
2/6/2015	0.25	0.39	0.68	0.27	0.15	1.05
2/8/2015	0.19	0.12	0.20	0.14	0.20	0.33
2/8/2015	0.25	0.35	0.23	0.40	0.33	0.41
2/10/2015	0.50	0.10	0.25	0.42	0.18	0.51
2/10/2015	2.89	0.08	0.07	0.33	0.23	0.43
2/11/2015	0.43	0.54	1.57	0.34	0.35	0.81
2/12/2015	0.40	0.10	0.46	0.28	0.23	0.15
2/12/2015	0.41	0.16	0.54	1.12	0.08	1.16
2/13/2015	0.67	0.20	0.51	0.36	0.10	1.06
2/13/2015	0.46	0.10	0.60	0.46	0.14	1.16
2/14/2015	0.68	0.23	0.44	0.21	0.33	1.05
2/14/2015	0.65	0.08	0.51	0.43	0.14	0.97
2/16/2015	0.25	0.25	0.46	0.30	0.10	0.95
2/16/2015	0.56	0.14	0.43	0.79	0.10	1.08
2/17/2015	0.41	0.04	0.54	0.30	0.12	0.86
2/17/2015	0.88	0.06	1.92	1.11	0.14	1.10
2/18/2015	0.29	0.12	0.43	0.31	0.12	1.00
2/18/2015	0.10	0.20	0.43	0.77	0.12	1.16
2/19/2015	0.63	0.10	0.54	0.34	0.08	0.89
2/19/2015	0.54	0.14	0.57	1.30		0.14
2/20/2015	0.85	0.16	0.55	0.27	0.10	0.97
2/21/2015	0.46	0.16	0.54	0.87	0.16	0.74
2/21/2015	0.15	0.20	0.95	0.69	0.20	1.06
2/22/2015	0.36	0.25	0.44	0.29	0.23	0.63
2/22/2015	0.80	0.12	0.44	0.67	0.10	0.97
2/23/2015	0.51	0.33	0.41	0.45	0.16	0.73

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
2/23/2015	0.58	0.44	0.60	0.99	0.35	0.79
2/24/2015	0.39	0.25	0.60	0.37	0.12	0.98
2/24/2015	0.57	0.25	0.43	0.60	0.08	0.66
2/25/2015	0.31	0.18	0.49	0.31	0.18	0.84
2/26/2015	0.58	0.20	0.41	0.26	0.16	0.76
2/26/2015	0.40	0.33	0.43	0.12	0.31	0.62
2/27/2015	0.56	0.14	0.33	0.37	0.14	0.57
2/28/2015	0.84	0.54	0.38	0.23	0.27	0.43
2/28/2015	0.61	0.10	0.39	0.33	0.18	0.54
3/1/2015	0.61	0.18	0.43	0.24	0.20	0.55
3/1/2015	0.37	0.27	0.33	0.40	0.20	0.51
3/2/2015	0.46	0.04	0.46	0.24	0.12	0.51
3/2/2015	0.70	0.08	0.46	1.02	0.10	0.55
3/3/2015	0.62	0.25	0.49	0.46	0.16	0.49
3/3/2015	0.54	0.10	0.33	0.46	0.31	0.35
3/4/2015	0.86	0.14	0.44	0.37	0.16	0.57
3/5/2015	0.44	0.04	0.31	0.49	0.06	0.36
3/5/2015	0.46	0.14	0.20	0.57	0.35	0.46
3/6/2015	0.41	0.20	0.33	0.48	0.08	0.27
3/6/2015	0.59	0.44	0.23	0.40	0.23	0.15
3/7/2015	0.37	0.06	0.19	0.62	0.23	0.20
3/7/2015	0.55	0.04	0.19	0.74	0.12	0.38
3/9/2015	0.51	0.18	0.25	0.27	0.27	0.57
3/10/2015	0.51	0.10	0.31	0.48	0.04	0.41
3/11/2015	0.85	0.12	0.14	0.27	0.10	0.36
3/11/2015	1.07	0.14	0.39	0.47	0.14	0.35
3/12/2015	0.90	0.10	0.55	0.29	0.10	0.19
3/12/2015	1.07	0.06	0.52	0.57	0.25	0.31
3/13/2015	0.98	0.06	0.54	0.41	0.18	0.33
3/14/2015	1.09	0.10	0.54	0.51	0.20	0.23
3/14/2015	1.04	0.20	0.60	0.43	0.23	0.31
3/15/2015	0.98	0.14	0.19	0.13	0.23	0.46
3/16/2015	0.82	0.16	0.22	0.39	0.16	0.35
3/17/2015	0.93	0.50	0.31	0.26	0.44	0.39
3/18/2015	0.74	0.04	0.27	0.25	0.10	0.25
3/19/2015	0.73	0.10	0.39	0.42	0.20	0.28
3/20/2015	0.88	0.12	0.33	0.40	0.23	0.30

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
3/22/2015	0.88	0.06	0.22	0.18	0.12	0.44
3/22/2015	0.84	0.18	0.31	0.31	0.08	0.43
3/23/2015	0.96	0.21	0.17	0.39	0.16	0.44
3/24/2015	0.58	0.25	0.22	0.31	0.10	0.47
3/24/2015	0.94	0.10	0.23	0.52	0.08	0.41
3/25/2015	0.79	0.31	0.14	0.54	0.20	0.41
3/26/2015	0.99	0.14	0.31	0.33	0.06	0.43
3/27/2015	0.57	0.04	0.14	0.46	0.41	0.44
3/27/2015	0.81	0.12	0.27	0.35	0.16	0.44
3/28/2015	0.85	0.12	0.14	0.26	0.12	0.30
3/28/2015	0.25	0.06	0.30	0.52	0.77	0.23
3/29/2015	0.67	0.16	0.23	0.21	0.23	0.22
3/29/2015	0.64	0.08	0.15	0.26	0.10	0.35
3/30/2015	0.82	0.25	0.27	0.27	0.27	0.36
3/30/2015	0.90	0.33	0.15	0.31	0.12	0.38
3/31/2015	0.55	0.14	0.23	0.29	0.18	0.25
3/31/2015	0.53	0.08	0.20	0.38	0.10	0.27
4/1/2015	0.75	0.29	0.33	0.32	0.23	0.33
4/1/2015	0.75	0.31	0.28	0.29	0.14	0.41
4/2/2015	0.52	0.16	0.31	0.32	0.06	0.27
4/2/2015	0.56	0.18	0.23	0.53	0.14	0.36
4/3/2015	0.92	0.14	0.22	0.13	0.20	0.33
4/3/2015	0.84	0.31	0.33	0.33	0.37	0.38
4/5/2015	0.72	0.06	0.15	0.43	0.08	0.38
4/5/2015	0.83	0.25	0.15	0.37	0.16	0.36
4/6/2015	0.82	0.18	0.15	0.32	0.16	0.39
4/7/2015	0.32	0.14	0.23	0.20	0.18	0.36
4/7/2015	0.88	0.16	0.15	0.36	0.18	0.23
4/8/2015	0.84	0.29	0.28	0.20	0.54	0.46
4/8/2015	0.89	0.12	0.30	0.46	0.10	0.35
4/9/2015	0.40	0.06	0.27	0.22	0.10	0.30
4/10/2015	0.61	0.16	0.28	0.28	0.25	0.31
4/12/2015	0.73	0.18	0.15	0.20	0.14	0.20
4/13/2015	0.34	0.20	0.25	0.20	0.35	0.28
4/14/2015	0.81	0.06	0.11	0.36	0.23	0.25
4/14/2015	0.96	0.06	0.15	0.35	0.20	0.39
4/15/2015	0.41	0.18	0.23	0.22	0.20	0.30

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
4/15/2015	0.40	0.23	0.23	0.12	0.20	0.29
4/16/2015	0.36	0.20	0.22	0.24	0.23	0.19
4/16/2015	0.54	0.14	0.12	0.51	0.14	0.30
4/17/2015	0.99	0.29	0.28	0.48	0.06	0.23
4/19/2015	0.52	0.12	0.19	0.31	0.14	0.25
4/20/2015	0.44	0.31	0.14	0.23	0.27	0.30
4/21/2015	0.41	0.10	0.22	0.24	0.04	0.35
4/21/2015	0.95	0.12	0.23	0.75	0.26	0.22
4/24/2015	0.67	0.23	0.28	0.15	0.27	0.28
4/26/2015	0.49	0.12	0.22	0.21	0.18	0.36
4/27/2015	0.70	0.44	0.43	0.78	0.46	0.44
4/28/2015	0.60	0.16	0.20	0.26	0.27	0.28
4/28/2015	0.76	0.16	0.20	0.59	0.23	0.25
4/29/2015	0.81	0.08	0.22	0.70	0.20	0.36
4/30/2015	0.67	0.06	0.22	0.26	0.18	0.30
4/30/2015	0.70	0.16	0.23	0.65	0.06	0.17
5/1/2015	0.53	0.12	0.17	0.22	0.06	0.36
5/1/2015	0.46	0.40	0.11	0.79	0.04	0.31
5/3/2015	0.60	0.04	0.25	0.29	0.10	0.43
5/4/2015	0.57	0.08	0.25	0.26	0.16	0.49
5/4/2015	0.73	0.08	0.23	0.73	0.16	0.66
5/5/2015	0.34	0.35	0.23	0.26	0.31	0.35
5/5/2015	0.88	0.20	0.23	0.71	0.08	0.63
5/6/2015	0.65	0.31	0.30	0.25	0.10	0.51
5/7/2015	0.74	0.23	0.20	0.36	0.04	0.52
5/8/2015	0.65	0.44	0.28	0.35	0.35	0.58
5/8/2015	0.84	0.32	0.22	0.63	0.16	0.52
5/9/2015	0.59	0.08	0.20	0.68	0.16	0.51
5/11/2015	0.71	0.25	0.20	0.25	0.29	0.63
5/12/2015**	**0.30**	**0.06**	**0.19**	**0.28**	**0.14**	**0.79**
5/13/2015	0.92	0.16	0.33	0.96	0.14	1.35
5/14/2015	0.43	0.04	0.31	0.41	0.33	1.32
5/15/2015	0.95	0.25	0.25	0.51	0.25	1.17
5/16/2015	0.69	0.18	0.06	0.84	0.16	1.59
5/17/2015	0.62	0.10	0.27	0.36	0.14	0.78
5/18/2015	0.86	0.37	0.07	0.41	0.31	0.47
5/19/2015	0.47	0.14	0.15	0.36	0.10	0.39

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
5/21/2015	0.62	0.18	0.20	0.42	0.06	1.62
5/22/2015	0.32	0.18	0.77	0.39	0.08	2.70
5/25/2015	0.73	0.14	0.22	0.41	0.25	1.32
5/25/2015	0.88	0.06	0.04	0.69	0.12	0.95
5/26/2015	0.64	0.20	0.11	0.29	0.18	0.49
5/26/2015	1.04	0.16	0.23	0.80	0.12	0.51
5/27/2015	0.51	0.16	0.39	0.30	0.10	0.84
5/28/2015	0.84	0.04	0.25	0.37	0.14	0.73
5/29/2015	0.99	0.16	0.19	0.57	0.10	1.41
5/30/2015	0.96	0.06	0.12	0.66	0.10	1.21
5/31/2015	0.38	0.58	0.19	0.38	0.16	0.65
6/1/2015	0.61	0.31	0.27	0.35	0.12	1.24
6/1/2015	0.78			0.84		
6/2/2015	0.88	0.18	0.22	0.31	0.15	2.18
6/2/2015	0.09	0.12	0.28	0.07	0.14	1.02
6/3/2015	1.25	0.16	0.17	1.01	0.27	1.17
6/3/2015	0.90	0.10	0.20	0.71	0.08	0.97
6/4/2015	0.99	0.10	0.15	0.40	0.20	2.39
6/4/2015	0.74	0.14	0.28	0.77	0.12	1.43
6/5/2015	0.42	0.08	0.12	0.36	0.10	0.73
6/5/2015	0.95	0.14		0.55	0.25	1.59
6/6/2015	1.09	0.06	0.19	0.42	0.10	0.84
6/6/2015	0.65	0.18	0.17	0.56	0.27	1.88
6/7/2015	0.80	0.14	0.27	0.33	0.14	1.62
6/7/2015	0.91	0.08	0.30	0.62	0.16	2.63
6/8/2015	0.52	0.12	0.33	0.11	0.33	1.25
6/8/2015	1.25	0.20	0.22	0.31	0.20	1.70
6/9/2015	0.41	0.14	0.27	0.35	0.12	1.46
6/9/2015	0.29	0.04	0.11	0.03	0.06	1.02
6/10/2015	1.06	0.25	0.07	0.30	0.18	0.65
6/10/2015	0.77	0.41	0.19	0.62	0.35	0.62
6/11/2015	0.49	0.10	0.06	0.22	0.16	0.54
6/11/2015	1.14	0.16		0.73	0.16	0.61
6/12/2015	0.85	0.08	0.12	0.35	0.10	1.29
6/13/2015	1.18	0.10	0.06	0.88	0.25	1.00
6/14/2015	0.73	0.18	0.41	0.25	0.54	0.68
6/14/2015	0.52	0.08	0.09	0.74	0.08	0.22

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
6/15/2015	0.86	0.20	0.12	0.35	0.12	0.31
6/15/2015	0.95	0.16	0.90	0.48	0.33	0.28
6/16/2015	0.72	0.44	0.15	0.40	0.29	0.28
6/16/2015	1.14	0.18	0.14	0.72	0.14	0.15
6/17/2015	0.52	0.18	0.07	0.29	0.14	0.39
6/17/2015	0.52	0.18	0.25	0.64	0.10	0.52
6/18/2015	0.87	0.18	0.09	0.30	0.10	0.49
6/18/2015	1.19	0.20	0.07	0.84	0.31	1.33
6/19/2015	1.06	0.23	0.17	0.68	0.16	0.81
6/19/2015	1.21	0.37	0.20	0.86	0.25	1.14
6/20/2015	0.92	0.12	0.06	0.31	0.08	0.78
6/21/2015	0.97	0.12	0.23	0.73	0.10	0.87
6/21/2015	0.81	0.14	0.20	0.36	0.14	0.90
6/22/2015	0.57	0.20	0.15	0.31	0.06	0.76
6/22/2015	1.02	0.08	0.09	0.76	0.12	0.94
6/23/2015	1.05	0.04	0.14	0.56	0.10	0.71
6/23/2015	1.08	0.31	0.17	0.57	0.12	0.39
6/24/2015	1.13	0.16	0.09	0.64	0.10	0.79
6/24/2015	0.90	0.23	0.27	1.07	0.23	0.71
6/25/2015**	**1.14**	**0.10**	**0.17**	**0.65**	**0.06**	**0.58**
6/25/2015	1.12	0.16	0.04	0.62	0.10	0.28
6/26/2015	1.04	0.14	0.11	0.84	0.14	0.31
6/26/2015	0.96	0.14	0.12	0.52	0.42	0.36
6/27/2015	0.90	0.06	0.11	0.52	0.08	0.58
6/28/2015	0.41	0.33	0.17	0.41	0.23	0.74
6/28/2015	0.90	0.25	0.11	0.57	0.25	0.63
6/29/2015	0.67	0.12	0.20	0.33	0.23	0.68
6/29/2015	1.07	0.06	0.12	0.61	0.14	0.65
6/30/2015	1.32	0.12	0.25	0.60	0.16	0.82
6/30/2015	0.92	0.23	0.11	0.62	0.27	0.58
7/1/2015	0.95	0.08	0.12	0.59	0.10	0.76
7/1/2015	1.04	0.12	0.14	0.57	0.31	0.62
7/2/2015	1.07	0.16	0.07	0.36	0.14	0.63
7/2/2015	1.01	0.16	0.09	0.57	0.10	0.66
7/3/2015	0.91	0.14	0.23	0.73	0.23	0.98
7/3/2015	0.76	0.12	0.22	0.83	0.08	0.84
7/5/2015	0.41	0.31	0.20	0.33	0.20	0.86

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
7/5/2015	0.66	0.06	0.23	0.36	0.14	1.03
7/6/2015	0.76	0.10	0.11	0.39	0.10	0.57
7/6/2015	0.59	0.12	0.14	0.26	0.16	0.73
7/7/2015	0.88	0.08	0.11	0.73	0.20	0.60
7/7/2015	0.87	0.06	0.15		0.16	0.74
7/9/2015	0.49	0.12	0.15		0.06	0.94
7/9/2015	0.71	0.12	0.07	0.71	0.06	1.03
7/10/2015	0.96	0.14	0.19	0.66	0.06	0.87
7/11/2015	1.03	0.29	0.36	1.03	0.20	1.14
7/12/2015	0.47	0.20	0.17	0.39	0.27	0.58
7/12/2015	0.68	0.04	0.07	0.37	0.10	0.51
7/13/2015	0.49	0.23	0.07	0.31	0.10	0.49
7/13/2015	0.80	0.18	0.12	0.48	0.27	0.76
7/14/2015	0.46	0.54	0.23	0.33	0.31	0.55
7/14/2015	0.85	0.14	0.25	0.46	0.41	0.43
7/15/2015	0.67	0.14	0.07	0.55	0.12	0.39
7/15/2015	0.60	0.12	0.14	0.77	0.29	0.17
7/16/2015	0.21	0.08	0.07	0.78	0.25	0.38
7/16/2015	0.50	0.18	0.12	0.52	0.12	0.52
7/17/2015	0.85	0.06	0.11	0.46	0.12	0.54
7/17/2015	0.83	0.14	0.14	0.45	0.06	0.43
7/18/2015	0.77	0.23	0.14	0.95	0.20	0.70
7/19/2015	0.63	0.10	0.17	0.73	0.14	0.74
7/20/2015	0.74	0.12	0.11	0.26	0.14	0.41
7/20/2015	0.76	0.18	0.19	0.57	0.20	0.23
7/21/2015	0.55	0.18	0.15	0.36	0.31	0.89
7/21/2015	0.96	0.06	0.23	0.26	0.12	1.00
7/22/2015	0.49	0.12	0.22	0.40	0.08	1.02
7/22/2015	0.74	0.23	0.17	0.60	0.27	0.78
7/23/2015	0.50	0.14	0.15	0.30	0.16	0.76
7/23/2015	0.68	0.25	0.15	0.44	0.23	0.87
7/24/2015	0.61	0.12	0.15	0.26	0.16	0.63
7/24/2015	0.72	0.18	0.20	0.56	0.10	0.84
7/25/2015	0.56	0.23	0.22	0.52	0.20	3.38
7/26/2015	0.65	0.14	0.11	0.35	0.20	0.63
7/26/2015	0.50	0.37	0.14	0.60	0.23	0.71
7/27/2015	0.46	0.16	0.07	0.35	0.27	0.62

Date	Corrosion Rates (mpy)					
	Control Condition			Test Condition		
	MS	L	C	MS	L	C
7/28/2015	0.71	0.12	0.09	0.37	0.16	0.54
7/28/2015	0.41	0.12	0.12	0.24	0.10	0.36
7/29/2015	0.99	0.23	0.11	0.34	0.06	0.52
7/29/2015	0.67	0.22	0.06	0.89	0.08	0.81
7/30/2015	0.58	0.28	0.15	0.67	0.29	0.70
7/30/2015	0.78	0.16	0.15	0.58	0.27	1.08
7/31/2015	1.04	0.25	0.17	0.83	0.08	1.16
7/31/2015	0.94	0.31	0.30	0.27	0.18	1.02
8/1/2015	0.68	0.14	0.12	0.36	0.12	0.84
8/2/2015	1.00	0.48	0.23	0.35	0.65	0.89
8/2/2015	1.25	0.06	0.06	0.80	0.10	0.71
8/3/2015	1.08	0.18	0.11	0.59	0.12	0.62
8/3/2015	1.12	0.18	0.07	0.47	0.06	0.73
8/4/2015	0.93	0.06	0.19	0.92	0.33	0.54
8/4/2015	0.92	0.14	0.15	0.36	0.08	0.57
8/5/2015	0.94	0.18	0.15	0.54	0.27	1.00
8/5/2015	0.93	0.23	0.15	0.57	0.08	0.73
8/6/2015	0.67	0.08	0.14	0.39	0.23	1.06
8/6/2015	0.93	0.12	0.14	0.49	0.18	0.71
8/7/2015	0.97	0.20	0.07	0.81	0.06	0.74
8/7/2015	0.74	0.12	0.30	0.85	0.12	0.78

* Indicates inhibitor addition started

** Indicates inhibitor addition ceased

APPENDIX F: DATA FOR LANA’I CITY INHIBITOR 2

Table F-1: Corrosion Rates for Lana’i City Inhibitor 2 Experiment

	Corrosion Rates (mpy)					
	Control Condition			Test Conditions		
Date	MS	L	C	MS	L	C
8/17/2015	0.68	0.35	3.15	0.32	0.37	0.78
8/17/2015	1.68	0.29	3.34	0.81	0.12	0.81
8/18/2015	3.39	0.25	2.82	2.55	0.12	0.55
8/18/2015	3.62	0.14	2.67	3.00	0.23	0.51
8/19/2015	4.58	0.04	2.39	4.08	0.06	0.63
8/19/2015	5.02	0.05	2.07	4.60	0.14	0.60
8/20/2015	4.57	0.31	1.54	0.82	0.31	0.48
8/20/2015	5.75	0.12	1.57	4.87	0.16	0.54
8/21/2015	4.77	0.06	1.84	1.85	0.04	0.46
8/21/2015	8.98	0.35	2.31	3.76	0.33	0.66
8/22/2015	10.80	0.23	1.94	2.99	0.23	0.70
8/23/2015	4.45	0.33	2.08	4.31	0.20	0.19
8/24/2015	4.23	0.14	1.92	4.07	0.12	0.47
8/24/2015	3.76	0.06	2.24	4.10	0.18	0.11
8/25/2015	4.25	0.20	1.49	3.99	0.16	0.46
8/25/2015	4.37	0.29	1.78	4.25	0.39	0.41
8/26/2015	0.55	0.14	1.76	4.10	0.12	0.06
8/26/2015	5.58	0.18	1.53	4.23	0.16	0.58
8/27/2015	4.31	0.06	1.81	4.26	0.18	0.47
8/27/2015	1.87	0.10	2.10	4.39	0.23	0.35
8/28/2015	4.16	0.16	2.07	4.22	0.10	0.06
8/28/2015	4.27	0.04	1.70	4.29	0.12	0.47
8/29/2015	7.41	0.10	1.89	4.40	0.08	0.19
8/30/2015	3.96	0.04	1.92	4.36		
8/30/2015	4.07	0.08	1.67	4.42	0.16	0.46
8/31/2015	2.29	0.20	1.51	4.15	0.23	0.31
8/31/2015	6.78	0.14	0.58	4.34	0.08	0.11
9/1/2015	3.93	0.29	1.32	0.15	0.10	0.57
9/1/2015	3.91	0.08	1.16	4.06	0.06	0.07
9/2/2015	2.06	0.12	1.05	4.17	0.12	0.11
9/2/2015	3.82	0.20	0.71	4.26	0.37	0.41
9/3/2015	3.96	0.29	0.97	4.30	0.18	0.36
9/3/2015	3.54	0.25	0.76	7.55	0.18	0.39
9/4/2015	0.65	0.10	0.90	4.36	0.14	0.27
9/4/2015	3.86	0.14	0.65	3.06	0.18	0.08

	Corrosion Rates (mpy)					
	Control Condition			Test Conditions		
Date	MS	L	C	MS	L	C
9/5/2015	0.60	0.16	0.87	4.22	0.20	1.86
9/6/2015	0.70	0.14	0.58	1.02	0.18	0.30
9/7/2015	0.50	0.08	0.82	4.09	0.20	0.09
9/8/2015	0.51	0.16	0.71	4.06	0.25	0.17
9/8/2015	2.03	0.08	0.49	4.18	0.06	0.18
9/10/2015	0.52	0.14	0.30	4.02	0.14	0.19
9/10/2015	1.73	0.25	0.47	4.01	0.18	0.54
9/11/2015	0.87	0.12	0.20	4.07	0.08	1.77
9/14/2015	0.70	0.27	0.43	3.40	0.12	1.45
9/14/2015	2.41	0.10	0.55	3.40	0.06	1.21
9/15/2015	0.71	0.25	0.55	3.26	0.16	0.06
9/15/2015	1.94	0.20	0.52	3.35	0.08	1.02
9/16/2015	0.57	0.50	0.60	3.25	0.50	0.20
9/16/2015	1.91	0.08	0.73	3.42	0.14	0.07
9/17/2015	0.61	0.12	0.51	3.16	0.23	0.17
9/18/2015	0.75	0.08	0.63	3.05	0.18	0.15
9/18/2015	1.29	0.27	0.54	3.02	0.12	0.86
9/19/2015	0.72	0.44	0.33	2.86	0.16	0.33
9/20/2015	0.53	0.16	0.62	0.07	0.25	0.19
9/21/2015	0.61	0.04	0.47	0.16	0.18	0.86
9/21/2015	1.34	0.33	0.35	2.88	0.54	0.33
9/22/2015	0.62	0.16	0.66	2.68	0.12	0.25
9/23/2015	0.52	0.41	0.57	2.60	0.46	0.39
9/23/2015	1.30	0.52	0.28	2.80	0.35	0.52
9/24/2015	0.69	0.33	0.41	2.55	0.20	0.25
9/25/2015	2.46	0.18	0.71	0.03	0.04	0.04
9/25/2015	0.30	0.23	0.43	2.72	0.14	0.15
9/26/2015	2.80	0.06	0.27	2.57	0.18	0.09
9/26/2015	2.40	0.20	0.63	2.45	0.08	0.17
9/27/2015	2.48	0.12	0.46	2.45	0.06	0.28
9/27/2015	2.25	0.18	0.54	2.66	0.16	0.23
9/28/2015	2.37	0.16	0.71	2.35	0.12	0.03
9/28/2015	1.83	0.29	0.60	2.51	0.14	0.33
9/29/2015	0.63	0.20	0.46	2.29	0.27	0.25
9/29/2015	1.89	0.75	0.66	2.42	0.81	0.43
9/30/2015	2.24	0.12	0.95	3.41	0.12	0.47
9/30/2015	2.42	0.16	0.47	1.91	0.18	0.47

	Corrosion Rates (mpy)					
	Control Condition			Test Conditions		
Date	MS	L	C	MS	L	C
10/1/2015	2.28	0.04	1.02	2.27	0.12	0.04
10/1/2015	1.99	0.12	1.02	2.43	0.16	0.28
10/2/2015	0.62	0.27	0.79	2.29	0.16	0.28
10/2/2015	2.32	0.08	0.76	2.49	0.16	0.19
10/3/2015	2.34	0.20	0.63	2.50	0.20	0.55
10/3/2015	2.45	0.18	1.21	1.85	0.14	0.57
10/4/2015	2.22	0.14	1.21	2.38	0.10	0.46
10/4/2015	2.15	0.12	1.25	2.28	0.08	0.09
10/5/2015	2.14	0.35	0.54	2.38	0.23	0.44
10/5/2015	2.51	0.29	0.68	2.46	0.20	0.25
10/6/2015	2.34	0.37	1.10	0.46	0.37	0.41
10/6/2015	2.44	0.31	1.05	1.62	0.25	0.38
10/7/2015	2.21	0.08	1.16	0.62	0.06	0.43
10/8/2015	2.36	0.08	1.17	2.48	0.31	0.46
10/9/2015	0.62	0.25	0.62	2.50	0.20	0.27
10/9/2015	0.57	0.23	0.60	2.50	0.14	0.28
10/10/2015	2.41	0.54	0.60	2.45	0.44	0.33
10/10/2015	2.61	0.14	0.51	2.40	0.25	0.47
10/11/2015	2.45	0.23	1.08	2.36	0.27	0.31
10/12/2015	2.25	0.16	1.11	2.23	0.14	0.11
10/12/2015	2.51	0.10	1.05	2.40	0.10	0.19
10/14/2015	1.02	0.20	0.76	0.72	0.14	0.23
10/15/2015	1.11	0.20	0.81	0.88	0.10	0.03
10/15/2015*	**0.62**	**0.20**	**0.86**	**1.67**	**0.20**	**0.22**
10/16/2015	1.37	0.08	0.68	2.02	0.14	0.35
10/17/2015	1.77	0.41	0.63	0.49	0.29	0.23
10/18/2015	1.58	0.06	0.70	0.64	0.27	0.22
10/19/2015	0.93	0.12	0.73	1.40	0.16	0.33
10/19/2015	1.63	0.16	0.57	1.80	0.16	0.22
10/20/2015	1.28	0.10	0.89	1.54	0.14	0.19
10/21/2015	1.05	0.06	0.54	0.75	0.12	0.82
10/21/2015	1.92	0.08	0.82	1.31	0.10	0.12
10/22/2015	1.72	0.06	0.84	0.68	0.10	0.17
10/22/2015	1.78	0.18	0.87	1.61	0.10	0.81
10/23/2015	0.59	0.35	0.46	1.40	0.08	0.28
10/23/2015	0.77	0.06	0.73	1.28	0.20	0.17
10/24/2015	1.81	0.08	0.28	1.42	0.18	0.30

	Corrosion Rates (mpy)					
	Control Condition			Test Conditions		
Date	MS	L	C	MS	L	C
10/24/2015	1.41	0.08	0.52	1.40	0.10	0.15
10/25/2015	1.04	0.06	0.33	0.65	0.27	0.09
10/27/2015	0.99	0.35	0.33	0.15	0.10	0.25
10/27/2015	0.91	0.12	0.49	1.14	0.06	0.27
10/28/2015	1.63	0.33	0.94	1.20	0.27	0.66
10/29/2015	1.51	0.12	0.51	1.45	0.14	0.52
10/29/2015	1.56	0.12	0.79	1.58	6.00	0.52
10/30/2015	1.57	0.30	0.68	1.44	0.10	0.51
10/30/2015	1.72	0.18	0.68	1.37	0.12	0.65
10/31/2015	1.60	0.14	0.52	1.25	0.10	0.22
10/31/2015	1.47	0.10	0.54	1.69	0.14	0.11
11/1/2015	1.04	0.04	0.62	0.70	0.04	0.28
11/2/2015	1.77	0.33	0.54	1.22	0.12	0.31
11/3/2015	0.66	0.12	0.20	0.87	0.12	0.27
11/3/2015	1.66	0.10	0.31	1.29	0.16	0.15
11/4/2015	1.53	0.04	0.43	1.77	0.14	0.33
11/6/2015	1.78	0.48	0.58	0.88	0.39	0.44
11/8/2015	1.76	0.12	0.79	1.50	0.08	0.46
11/9/2015	1.76	0.37	0.47	1.20	0.46	0.23

* Indicates inhibitor addition

APPENDIX G: QUALITY CONTROL AND QUALITY ASSURANCE

Precision Control Charts

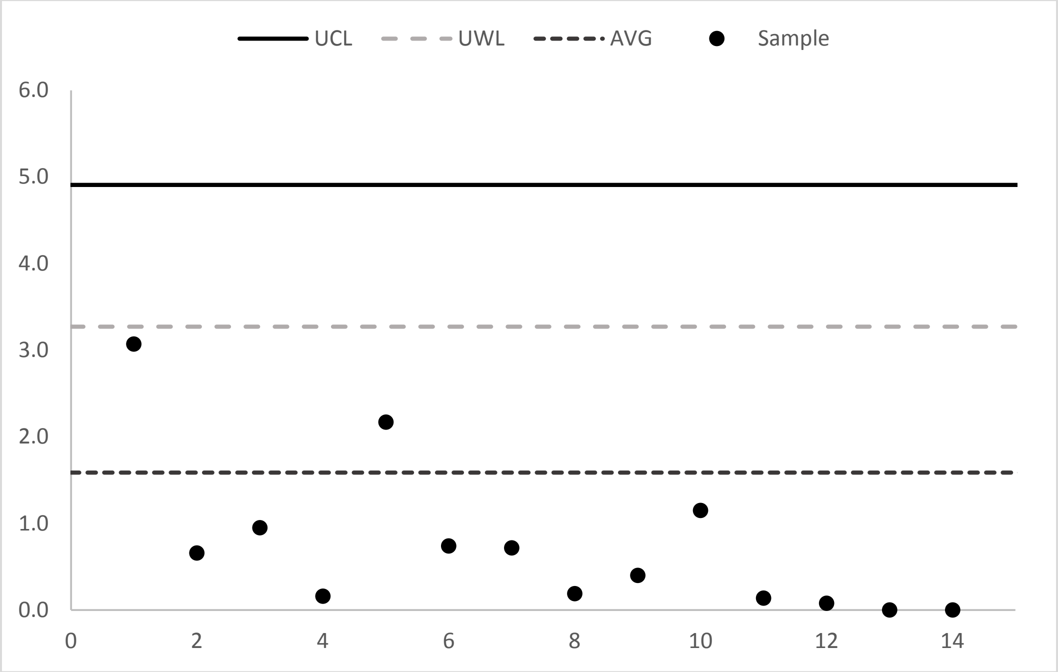


Figure G-1: Sulfate Precision Control Chart

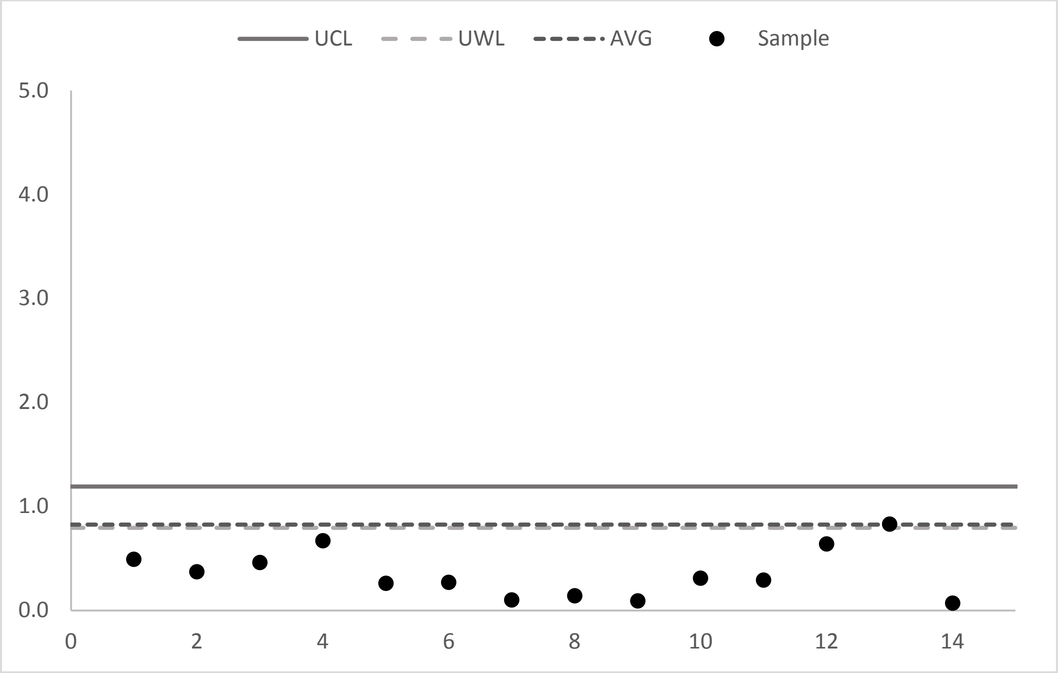


Figure G-2: Chloride Precision Control Chart

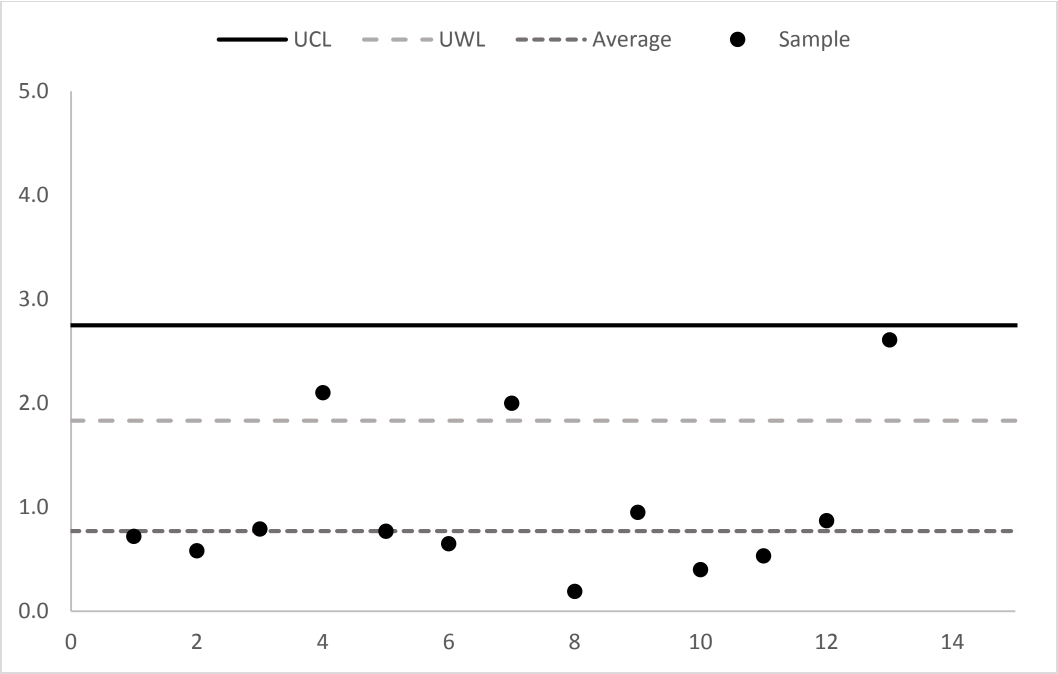


Figure G-3: Calcium Precision Control Chart

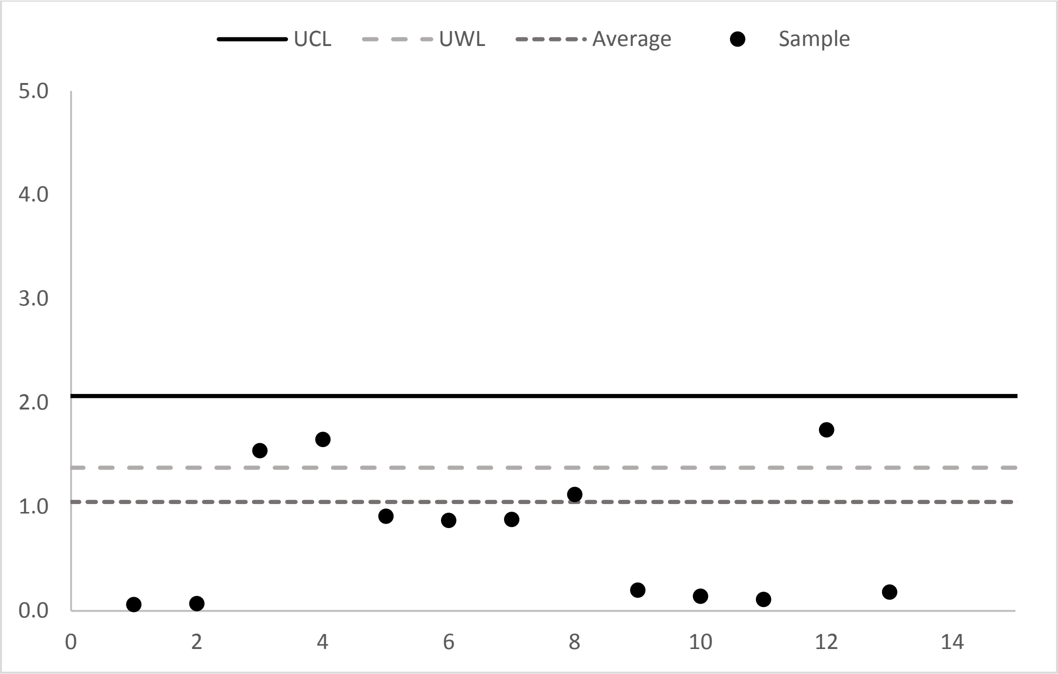


Figure G-4: Magnesium Precision Control Chart

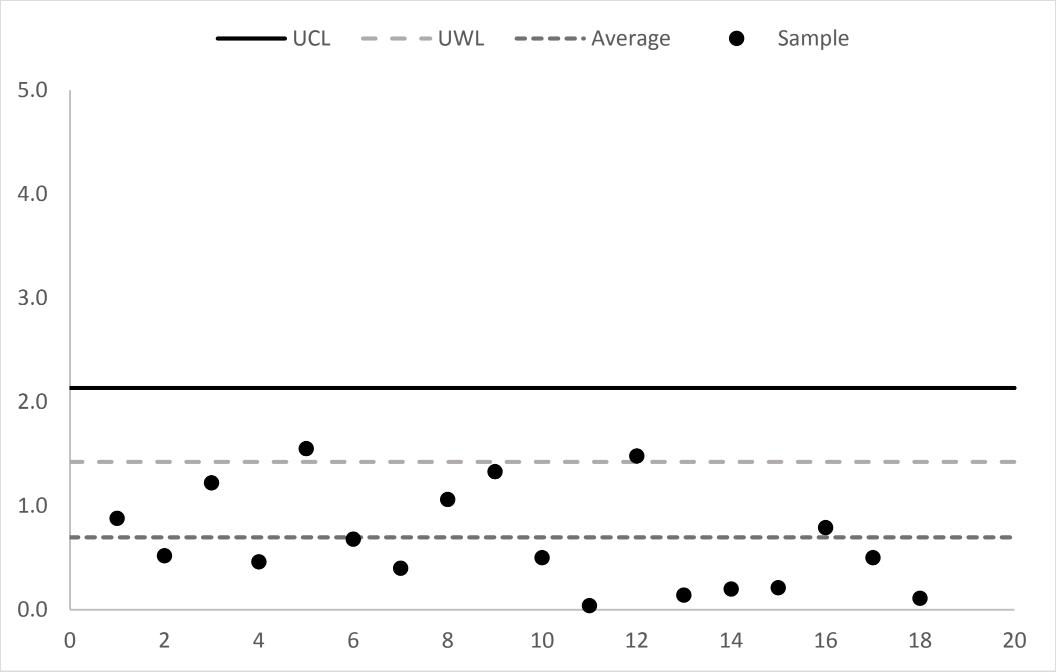


Figure G-5: Silica Precision Control Chart

Accuracy Control Charts

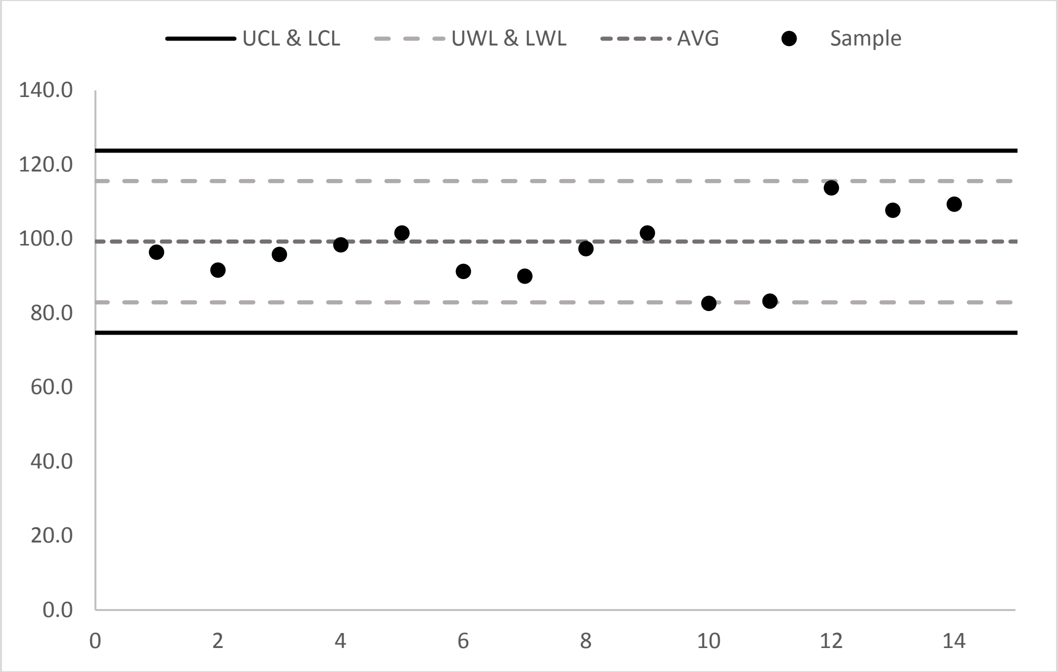


Figure G-6: Sulfate Accuracy Control Chart

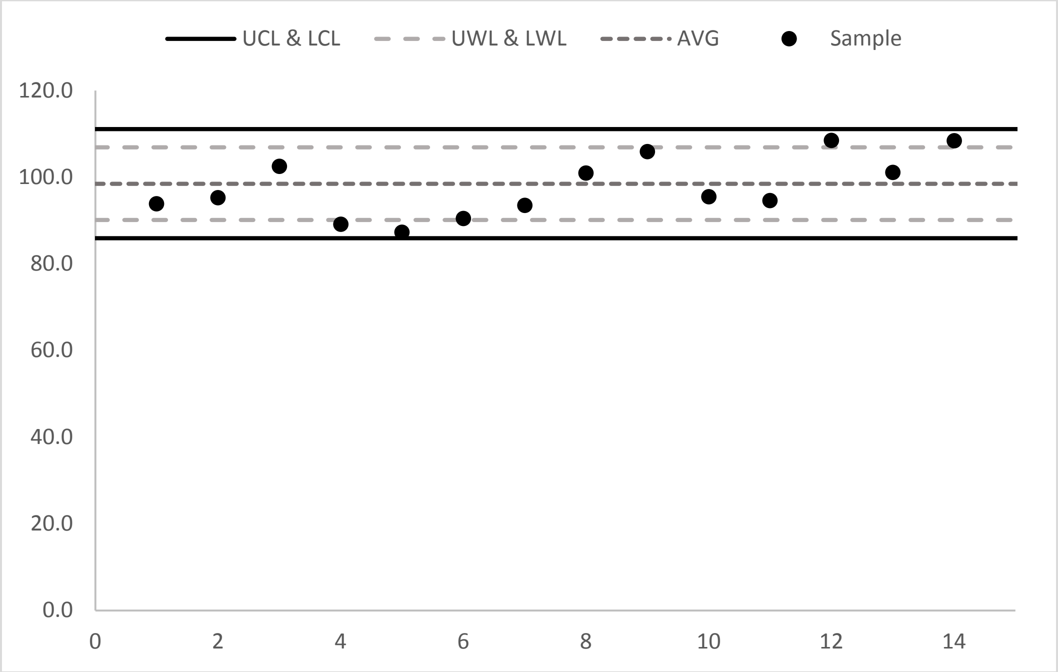


Figure G-7: Chloride Accuracy Control Chart

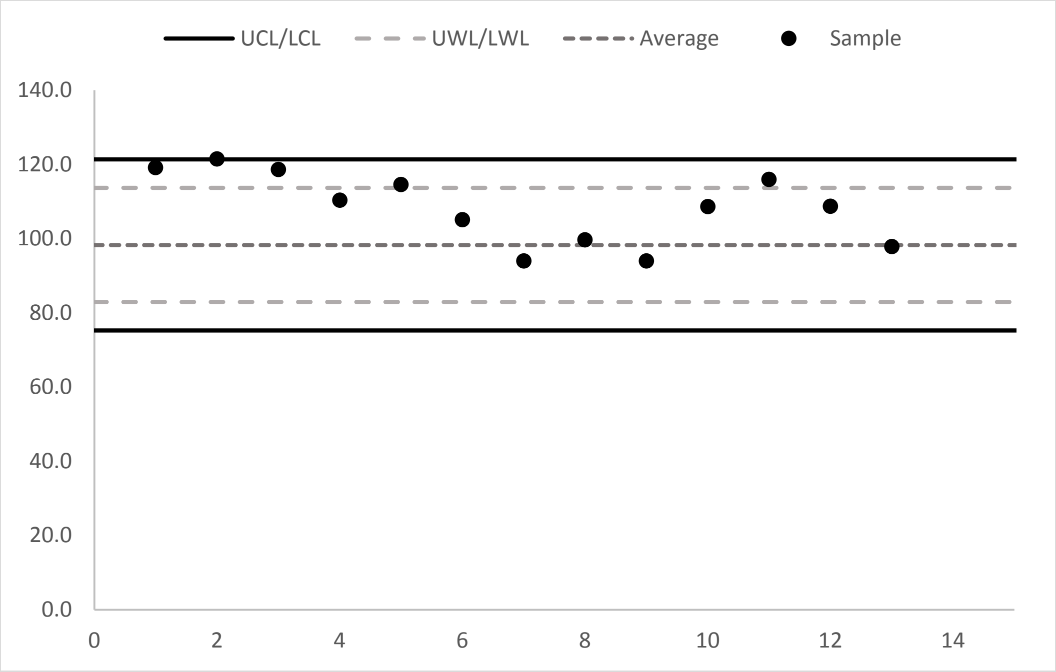


Figure G-8: Calcium Accuracy Control Chart

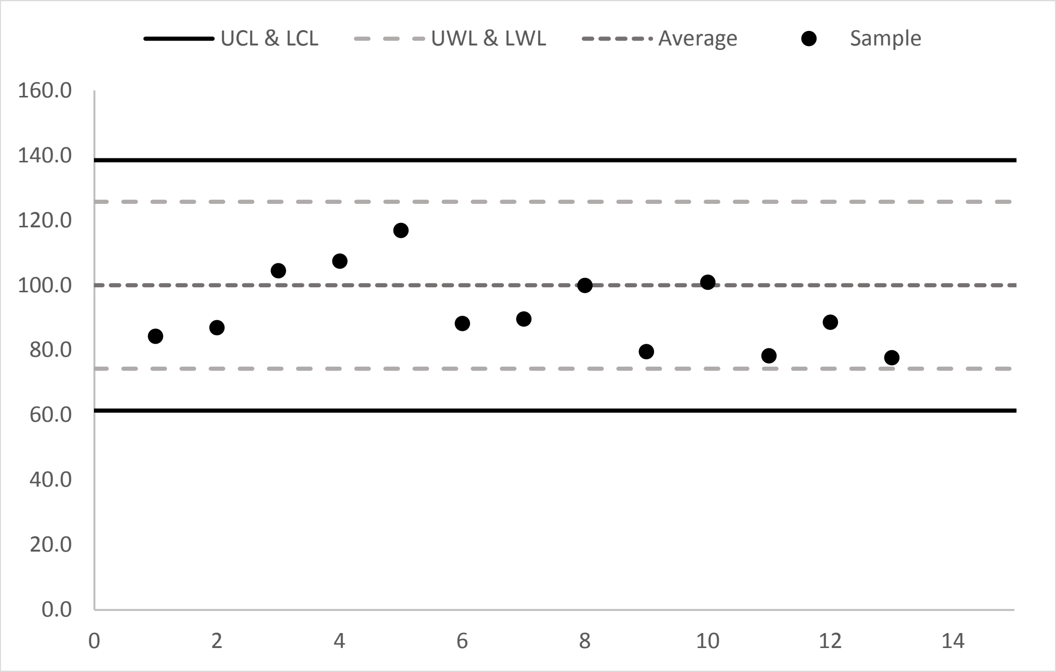


Figure G-9: Magnesium Accuracy Control Chart

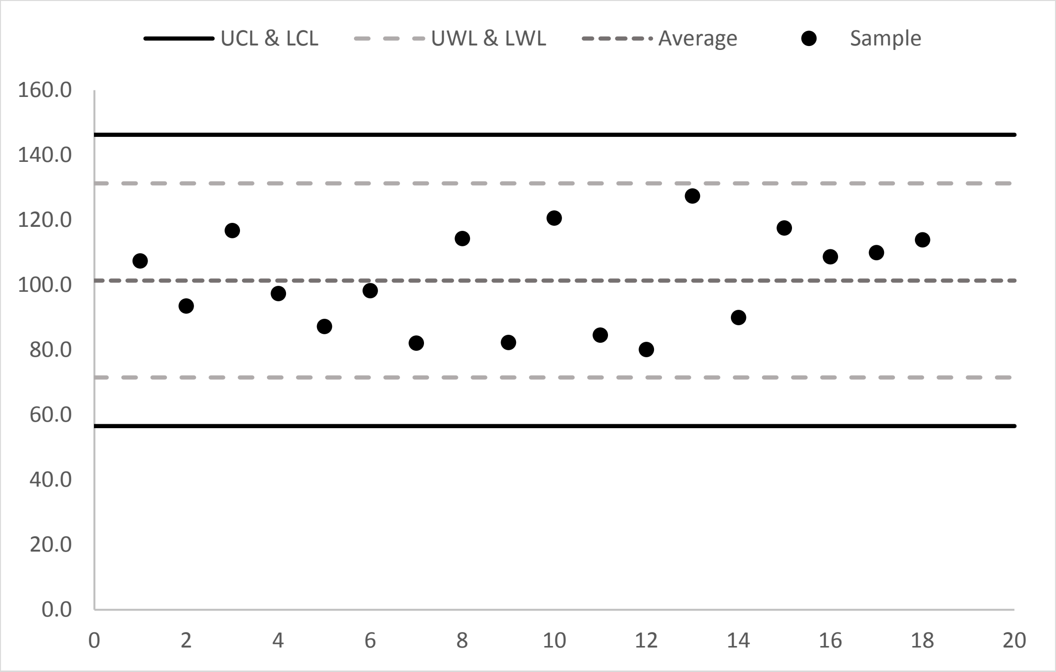
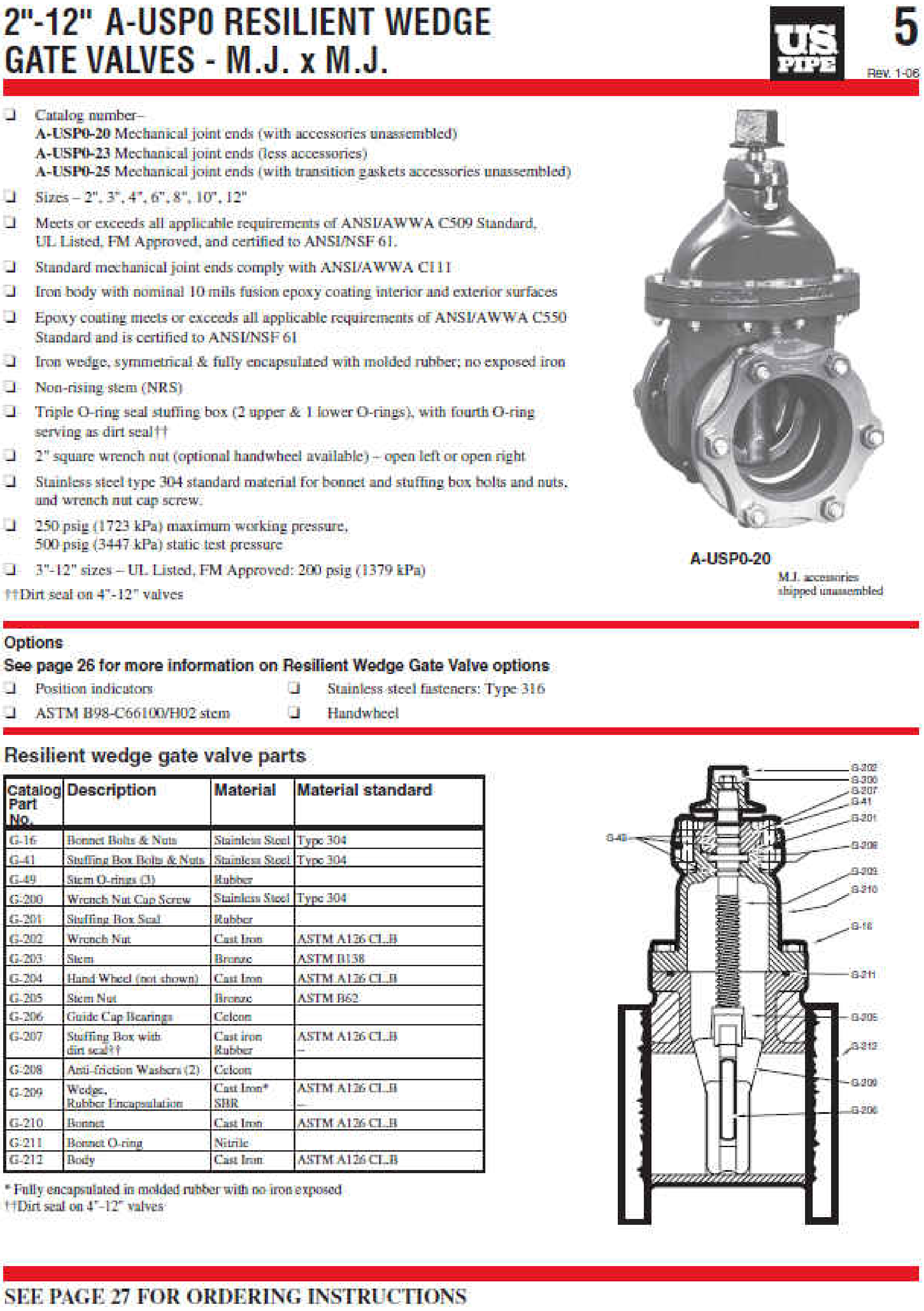


Figure G-10: Silica Accuracy Control Chart

APPENDIX H: EXAMPLE VALVE SPECIFICATIONS



2"-12" A-USP0 RESILIENT WEDGE GATE VALVES - M.J. x M.J.

US PIPE

5

Rev. 1-06

- ☐ Catalog number–
  A-USP0-20 Mechanical joint ends (with accessories unassembled)
  A-USP0-23 Mechanical joint ends (less accessories)
  A-USP0-25 Mechanical joint ends (with transition gaskets accessories unassembled)
- ☐ Sizes – 2", 3", 4", 6", 8", 10", 12"
- ☐ Meets or exceeds all applicable requirements of ANSI/AWWA C509 Standard, UL Listed, FM Approved, and certified to ANSI/NSF 61.
- ☐ Standard mechanical joint ends comply with ANSI/AWWA C111
- ☐ Iron body with nominal 10 mils fusion epoxy coating interior and exterior surfaces
- ☐ Epoxy coating meets or exceeds all applicable requirements of ANSI/AWWA C550 Standard and is certified to ANSI/NSF 61
- ☐ Iron wedge, symmetrical & fully encapsulated with molded rubber; no exposed iron
- ☐ Non-rising stem (NRS)
- ☐ Triple O-ring seal stuffing box (2 upper & 1 lower O-rings), with fourth O-ring serving as dirt seal††
- ☐ 2" square wrench nut (optional handwheel available) – open left or open right
- ☐ Stainless steel type 304 standard material for bonnet and stuffing box bolts and nuts, and wrench nut cap screw.
- ☐ 250 psig (1723 kPa) maximum working pressure, 500 psig (3447 kPa) static test pressure
- ☐ 3"-12" sizes – UL Listed, FM Approved: 200 psig (1379 kPa)

††Dirt seal on 4"-12" valves

A-USP0-20

M.J. accessories shipped unassembled

Options

See page 26 for more information on Resilient Wedge Gate Valve options

- ☐ Position indicators
- ☐ ASTM B98-C66100/H02 stem
- ☐ Stainless steel fasteners: Type 316
- ☐ Handwheel

Resilient wedge gate valve parts

Catalog Part No.	Description	Material	Material standard
G-16	Bonnet Bolts & Nuts	Stainless Steel	Type 304
G-41	Stuffing Box Bolts & Nuts	Stainless Steel	Type 304
G-49	Stem O-rings (3)	Rubber	
G-200	Wrench Nut Cap Screw	Stainless Steel	Type 304
G-201	Stuffing Box Seal	Rubber	
G-202	Wrench Nut	Cast Iron	ASTM A126 CL.B
G-203	Stem	Bronze	ASTM B138
G-204	Hand Wheel (not shown)	Cast Iron	ASTM A126 CL.B
G-205	Stem Nut	Bronze	ASTM B62
G-206	Guide Cap Bearings	Celcon	
G-207	Stuffing Box with dirt seal††	Cast iron Rubber	ASTM A126 CL.B –
G-208	Anti-friction Washers (2)	Celcon	
G-209	Wedge, Rubber Encapsulation	Cast Iron* SBR	ASTM A126 CL.B –
G-210	Bonnet	Cast Iron	ASTM A126 CL.B
G-211	Bonnet O-ring	Nitrile	
G-212	Body	Cast Iron	ASTM A126 CL.B

* Fully encapsulated in molded rubber with no iron exposed

††Dirt seal on 4"-12" valves

SEE PAGE 27 FOR ORDERING INSTRUCTIONS

Figure H-1: Specification for Resilient Wedge Gate Valve (EPDM)

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