

## A simple approach to assessing copper pitting corrosion tendencies and developing control strategies

Darren A. Lytle, Daniel Williams and Colin White

### ABSTRACT

Localized corrosion of copper premise plumbing in drinking water distribution systems can lead to pinhole leaks, which are a growing problem for many homeowners. Despite the fact that water quality is an important factor associated with localized copper corrosion, good approaches for predicting the tendency of water to support localized corrosion and for assessing water treatment options to address problems are not available. The objective of this research was to determine the effectiveness of a simple pipe loop system, installed in a drinking water distribution system, in predicting localized copper corrosion and to assess treatment alternatives in drinking water. Visual examination of the internal surface of copper pipes positioned in the loop revealed signs of localized corrosion (isolated 3 mm diameter mounds of corrosion by-products) after only 72 days. Examination of pipe sections removed from the loops after 101 days clearly showed that localized corrosion was taking place. Cross-section analysis of the pipe showed pits as deep as 0.150 mm that were covered by a thin membrane and a mound of blue-green corrosion products. An ortho- and poly-phosphate blended chemical fed to a second pipe loop, prevented pitting attack, and produced different corrosion by-products. The study showed that simple, inexpensive copper pipe loops can be useful in predicting pitting tendencies of drinking water and in assessing the effectiveness of treatment alternatives.

**Key words** | copper, drinking water, localized corrosion, pipe loop

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### INTRODUCTION

Localized corrosion of copper, or 'pitting' corrosion, is one cause of copper household plumbing failure. The cost of plumbing repair and the associated expenses of repairing water damaged materials due to pinhole leaks can be extensive. Additionally, leaks can go undetected behind walls and ceilings or in basements for months and can provide an ideal environment for the growth of mildew and mold.

Frustrated homeowners facing damage from pinhole leaks may contact their water utility for an explanation and a solution to the problem. However, because copper pitting corrosion cases are not associated with elevated copper levels in the consumers' tap water, Lead and Copper Rule ([Federal Register 1991a](#), [1991b](#), [1992](#)) (or any other drinking water standard) violations are rare. The water utility does

not have a regulatory requirement to address complaints about copper pinhole leaks. Furthermore, copper pitting corrosion is poorly understood, despite a number of research studies dedicated to the subject, and many of the reported potential causes of pitting corrosion (e.g., electrical grounding, poor quality copper tubing, lightning, bacteria) fall outside the jurisdiction of the water utility. Homeowners also look to plumbers, plumbing suppliers, builders, and other public utilities for an explanation and solution to their pinhole leak problems. Given the number of potential associated factors, identifying the responsible party and a mitigation strategy is difficult.

When the frequency of pinhole leak complaints is limited to a few random households over the course of long

time periods (years), it is reasonable to suspect that there is something unique about the plumbing configuration, pipe material, or water quality within those homes. However, as the number and frequency of pinhole leaks increase, the causative factor(s) and/or corrosion driver point to factors common to the larger group, such as water quality. Sarver & Edwards (2011a) discuss the importance of a sense of shared responsibility and action among the potential involved entities to effectively respond to pitting corrosion problems. Water utilities and others should exhibit open and timely communication with consumers and be proactive in addressing the copper pitting problem (Sarver & Edwards 2011a). A comprehensive investigation of the problem that considers water quality, field observations, geochemistry, solid and surface analysis, and observations of similar neighboring communities is important (Lytle *et al.* 2010), and experimental testing should be considered. Unfortunately, a simple, inexpensive, and representative approach for assessing pitting corrosion, which could be employed at the very onset of reported pinhole leak cases, is not available. Such a tool could ultimately save resources, frustration, and bad feelings, and avoid widespread complaints.

Pitting corrosion is complicated and accurately reproducing the phenomenon in the laboratory or pilot system is challenging. Pitting corrosion studies have been based on several experimental approaches. Given the slow nature of corrosion processes and the desire to see rapid results, electrochemical approaches have been favored because corrosion testing is accelerated. A variety of electrochemical corrosion measurements have been used to assess the tendency for copper pitting corrosion to occur. These include electrochemical noise,  $E_{\text{corr}}$  rise, and cyclic potentiodynamic polarization (Suzuki *et al.* 1983; Adeloju & Hughes 1986; Drogowska *et al.* 1987; Edwards *et al.* 1994; Souto *et al.* 1994; Duthil *et al.* 1996; Habib 2001; Schmitt & Slavcheva 2001). These methods are rapid and conclusions about pitting corrosion tendencies can be ascertained in hours or days. Obvious disadvantages include the problem that an artificial potential is applied to the copper surface to force corrosion in an 'unnatural' way in most approaches, the mechanism for pitting corrosion in the real system may not be represented in a short-term test (e.g., microbiological enhanced corrosion), and the test simply does not simulate the real conditions. Edwards *et al.* (2009) reported that all

electrochemical techniques used to characterize pitting propensity have many deficiencies and major limitations. They found, for example, that test conditions, electrode position, activating pumps, and oxidant type and concentration influenced measurements. Furthermore, conclusive physical evidence for pitting corrosion on copper surfaces is typically absent in short-term electrochemical tests.

Although pipe-loop testing has been designated as an accepted approach to studying pitting corrosion (ASTM 1983), its usefulness in studying copper pitting corrosion in drinking water has been very limited. Marshall & Edwards (2005) investigated the role of aluminum on copper pitting corrosion in drinking water. They demonstrated that water containing aluminum, high chlorine residual, and relatively high pH caused pinhole leaks in a laboratory setting. Specifically, a chlorine residual goal of 1.5 mg/L at pH 9.2 and 2 mg/L of aluminum hydroxide solids produced conditions that caused pinhole leaks. Also, the water had a low alkalinity and significant levels of chloride and sulfate, putting it in the broad category of soft water pitting corrosion. Sarver *et al.* (2011b) summarized a decade of subsequent pipe loop studies based on variations to the Marshall & Edwards (2005) conditions. Lytle & Schock (2008) showed that pitting corrosion of copper pipes was reproduced in pilot scale systems after only 91 days of operation. Pitting corrosion occurred in waters having low chlorine concentration (<0.5 mg  $\text{Cl}_2/\text{L}$  daily average) and dissolved inorganic carbon (DIC) (5 and 10 mg C/L, and possibly at 25 mg C/L), and pH 9 water in the presence of chloride. Pitting was not observed at pH 6.5 or 7 and was evident at pH 8 only when higher chlorine levels (<0.9 mg  $\text{Cl}_2/\text{L}$  daily average) were maintained. In addition, sulfate was not necessary to develop pitting corrosion; however, it did impact the composition of the corrosion by-products associated with pitting corrosion. Increasing the DIC to 50 mg C/L or adding 3 mg of  $\text{PO}_4/\text{L}$  (as orthophosphate) prevented the initiation of pitting corrosion at pH 9.

There is evidence (Marshall & Edwards 2005; Lytle & Schock 2008; Sarver *et al.* 2011b) to suggest that localized or pitting corrosion of copper pipe can be studied at the pilot scale level in reasonable timeframes (e.g., several months) in a simulated drinking water scenario. Study evaluation periods were on the same order of time as study periods needed to study uniform corrosion and metal solubility-

related work (months), and can be performed in waters having ‘realistic’ drinking water chemistries without the addition of stimulating conditions. Therefore, it is reasonable to assume that water utilities can use copper pipe-rig pilot systems to investigate the tendency for their water to induce and propagate pitting corrosion, predict the impact of water treatment or water quality changes on pitting tendency, and study techniques to reduce pitting. For example, copper pipe loops located at the treatment plant or in the distribution system operated in a single-pass, continuous water flow through mode could provide useful information at minimal cost and effort. Periodically observing the interior pipe surface of such a system could provide visual indications of localized corrosion attack and possibly lead to a better understanding of pitting corrosion. Furthermore, the past laboratory work (Marshall & Edwards 2005; Lytle & Schock 2008; Sarver *et al.* 2011b) suggests that experimental systems can be setup to systematically examine the impact of water quality variables, flow regimes, and corrosion inhibitors on pitting corrosion. Despite limited past successes, the application of copper pipe loops to evaluate pitting corrosion is limited to controlled experimental systems.

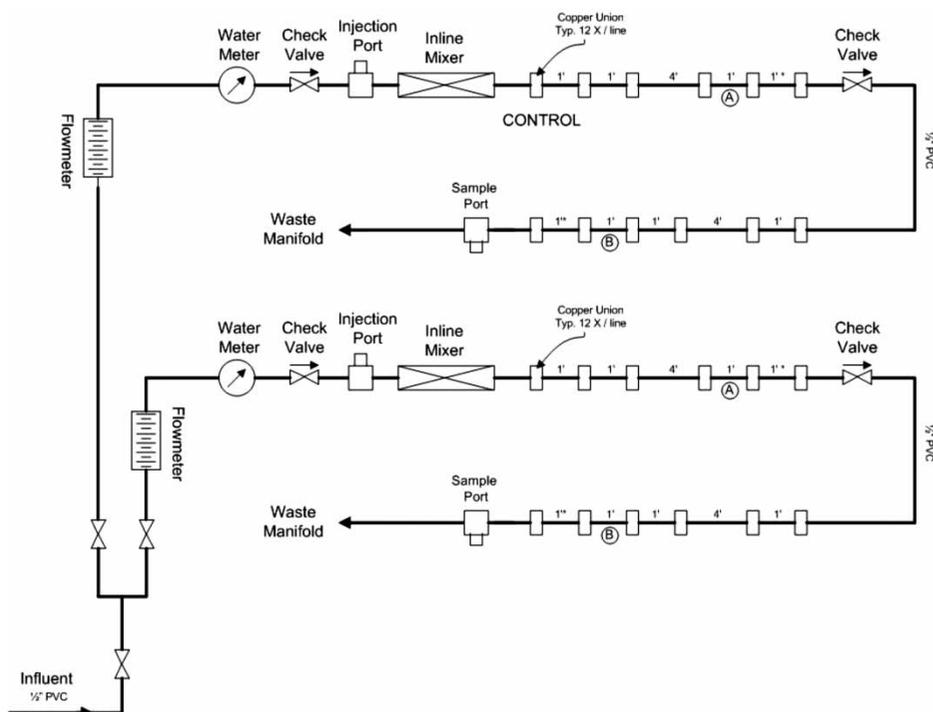
There is an obvious need for many water utilities to have a simple and inexpensive method to evaluate the tendency of their water to contribute to copper pitting corrosion and examine approaches to inhibit pitting corrosion, should it occur. The objective of this work is to describe the design and operation of a pilot-scale pipe loop system installed in the distribution system of a community that has historically had widespread complaints of copper pinhole leaks. Furthermore, the pipe loop system was also used to evaluate the use of a phosphate-based inhibitor chemical to prevent pitting corrosion attack. The pipe loop study was an extension of a comprehensive investigation (Lytle *et al.* 2010) to determine the cause of the community’s copper pinhole leak and identify a mitigation strategy. Results from monitoring the system over a period of 262 days will be discussed. These results include data from materials and solids analysis testing of the copper pipe surfaces at various times into the study. Solids collected from sampled pipes were analyzed using scanning electron microscopy (SEM). Lastly, the feasibility and usefulness of the proposed pilot system will be discussed.

## MATERIALS AND METHODS

### Experimental system design

A simple copper pipe test loop rig was used to evaluate the tendency of a community water supply to support pitting corrosion and to evaluate the effectiveness of a blended phosphate (50:50 orthophosphate: hexametaphosphate) chemical to inhibit copper pitting corrosion. The pipe loop rig was constructed of materials commonly used in household plumbing systems and materials that were purchased from a local home construction supply store. The system was constructed using trade-accepted plumbing techniques. Loops were constructed of 0.5 inch (12.7 mm) diameter type M copper pipe and 0.5 inch (12.7 mm) diameter schedule 40 polyvinyl chloride (PVC). Pipe loops were mounted on a Unistrut<sup>TM</sup> metal frame that was on casters for easy movement.

The pipe loops were installed at a pump station located in the water district’s distribution system. The test loop system was tapped into a 36 inch (914.4 mm) diameter water main that feeds the district’s distribution system. The test rig was constructed of two pipe loops, each consisting of a flow meter, on-line flow totalizer, check valve, injection port, inline mixer, 0.5 inch (12.7 mm) copper pipe, and 0.5 inch (12.7 mm) PVC pipe (Figure 1 and supplemental Figure S1). Loop 2 was considered the ‘control’ loop in that it received drinking water directly from distribution system main located in a pump station. Loop 1 received the same water, however, was treated with a 50:50 poly- and ortho-phosphate blended chemical (Calcquest, Carus Phosphates, Inc., Peru, IL, USA) at a flow rate of 1 mL/min to achieve a total phosphate concentration of 1.5 mg PO<sub>4</sub>/L. Following the phosphate injection port, an in-line mixer with six elements (Cole Parmer, Vernon Hills, IL, USA) was installed to ensure sufficient chemical mixing. Water passed through a series of ten (eight 12 inch- and two 36 inch-long) copper pipe sections that were soldered together using lead free solder (Oatey silver Safeflo<sup>TM</sup>, Cleveland, OH, USA). The eight 12 inch-long copper pipe sections were connected in series to simplify the ability to view the inside walls of each pipe loop. Threaded joints on each pipe section allowed for easy removal and replacement



**Figure 1** | Schematic of copper pitting corrosion evaluation pipe loop apparatus. Unless otherwise labeled, all runs between mixers and sample ports consist of 0.5 in diameter type M copper tubing, cut to length as noted. Lengths designated by \* are bisected and sheathed with Tygon® tubing. Pipe sections 'A' and 'B' were extracted for solids analysis.

(Figure S1, available online at <http://www.iwaponline.com/jws/061/079.pdf>). Two 12 inch (304.8 mm) sections were cut to expose the inner wall of the pipe (Figures 2(a) and (b)) and were installed in each loop. Cut sections of copper pipe were inserted into clear Tygon® tubing sleeves for viewing (Figure 2(c)). Hose clamps were used to tighten the sleeve over the pipe sections and to help to avoid leaking. Water was wasted to the on-site sanitary sewer after a single pass through each pipe loop.

### Operation

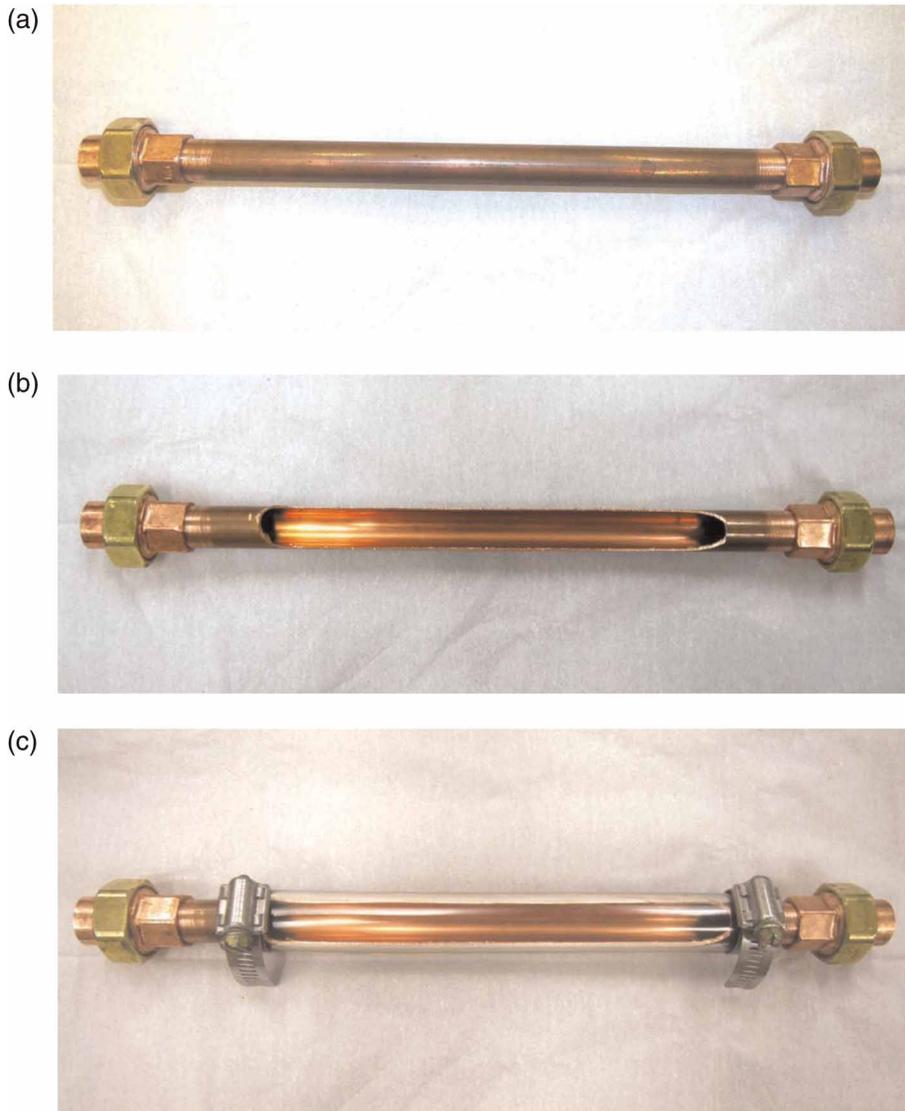
Water passed through each loop at 2.0 L/min (0.528 gpm) and was operated 24 h/day (2,880 L/day or 768 gallons/day). Flow meters were installed on each loop to maintain the flow at 2.0 L/min. The system was isolated with check valves to avoid phosphate injection into the main service line and undesirable backflow issues. Regular monitoring of the pipe loop system (flowrates, phosphate feed, rate, etc.) and water sampling were performed once a week. Since daily monitoring is not feasible, on-line flow totalizers

were installed to record cumulative flow. All monitoring records and water quality data were maintained in a log book and transferred to spreadsheets.

The system was briefly shut down once approximately every three weeks to visually inspect the inner walls of at least one copper pipe section. A flashlight was used to aid in identifying any pipe surface imperfections and suspicious areas. The pipe sections were observed quickly and carefully, and were placed back in the loops in the exact orientation as they were removed. The visible inspections allowed for comparison between loops treated and non-treated. Water samples were collected from each loop for complete metals analysis (copper, calcium, manganese, iron, etc.), total alkalinity, and phosphate. Temperature, pH, dissolved oxygen (DO), and free chlorine were also routinely monitored.

### Water and solids analysis methods

The pH was measured with a Hach Company (Loveland, CO, USA) EC40 benchtop pH/ISE meter (Model 50125), with a



**Figure 2** | Close-up photograph of copper pitting corrosion evaluation pipe loop apparatus loop test sections: (a) 1 ft long removable type M copper section (0.5 in diameter) showing connection unions for quick replacement, (b) 1 ft long removable copper section (0.5 in diameter) with a cut-out section for in-line viewing, and (c) 1 ft long removable bisected copper section with enclosed in Tygon<sup>®</sup> tubing.

Hach Company combination pH electrode (Model 48600), and a Hach Company Sension 156 portable combination pH/DO meter with temperature corrections. The instruments were standardized daily using a two-point calibration with pH 7 and 10 standard solutions (Whatman, Hillsboro, OR, USA). DO was measured with a Hach Company Model DO175 DO meter and a Model 50180 DO probe.

Total phosphorus, silicon, calcium, sulfur (sulfate), and copper were measured with a Thermo Jarrel Ash (Franklin, MA, USA) 61E<sup>®</sup> purged inductively coupled argon plasma

spectrometer (ICAPS). Chloride was analyzed using an automated potentiometric titration approach (Standard Method #4500-Cl-D) (APHA-AWWA-WEF 1995) and orthophosphate was measured using an automated colorimetric method (EPA method #365.1) (USEPA 1993). Free chlorine was analyzed according to the Hach DPD colorimetric method (APHA-AWWA-WEF 1995) using a Hach DR/2000 spectrophotometer.

SEM images and energy dispersive X-ray analyses were obtained using a JEOL 5800 scanning electron microscope

(Peabody, MA, USA) with an attached Oxford Analytical energy-dispersive X-ray spectrometer (EDS) (Madison, WI, USA). Uncoated samples of pit caps and pipe sections were mounted on 12 mm diameter aluminum studs with double-sided carbon tape, and encapsulated pipe sections were mounted directly to the sample holder. The accelerating voltage was 20 keV, and an average count time of 180 s was used to obtain EDS traces. The magnification used ranged from 100 × to 3,000 ×, and EDS results were reported as weight % unless otherwise noted. Oxygen was calculated by stoichiometry and all results were normalized to 100%. Prior to elemental analysis, the EDS system was optimized, according to the manufacturer's protocol, using an uncoated copper grid.

## RESULTS

Water chemistry data collected over the course of the study is summarized in Table 1. The water had a relatively high pH (8.72) and low alkalinity (50 mg CaCO<sub>3</sub>/L) or DIC (11.5 mg C/L), contained significant levels of chloride (69 mg/L) and sulfate (56 mg/L), and had a free chlorine residual of 0.48 mg/L. The water has been identified as one that has the potential to support copper pitting

corrosion falling under the category of the 'chlorinated, high pH and low alkalinity waters as reported by others' (Marshall & Edwards 2005; Lytle & Schock 2008). The phosphate-treated loop received water containing 1.5 mg total PO<sub>4</sub>/L of which 0.76 mg PO<sub>4</sub>/L was orthophosphate.

The tendency to develop localized or pitting corrosion of copper tubing in drinking water was based on visual examination of the internal surface of copper pipe sections and advanced solids and surface analysis approaches. The intent of the Tygon<sup>®</sup>-enclosed sections was to monitor the visual appearance of copper pipe internal surfaces with time without having to physically remove the pipe sections from the water for longer times (5–10 min) to make observations during which the pipes drained. Unfortunately, condensation developed on the outside of the tubing and a thin opaque film coated the inside of the tubing over time. This made it difficult to accurately ascertain the condition of the internal pipe sections.

The first significant pipe surface change was noted after 72 days into the study. The presence of a blue-green colored corrosion deposit mound was identified on a section of pipe on the untreated test loop (see Section A, Figure 1 for specific location where deposit was identified). Such corrosion deposit mounds are of particular interest and potentially important because they could represent a 'pit

**Table 1** | Water quality of test water passing through copper pipe loops with and without phosphate addition

		No Phosphate (2 L/min, pH 8.72, 7.78 mg O <sub>2</sub> /L)					Phosphate (2 L/min, pH 8.67, 7.95 mg O <sub>2</sub> /L)				
		N	Min	Max	Ave	Std Dev	N	Min	Max	Ave	Std Dev
<b>Ba</b>	mg/L	27	0.01	0.02	0.02	0.00	26	0.01	0.02	0.02	0.00
<b>Ca</b>	mg/L	27	20.6	30.2	25.0	2.37	26	21	29	25	2.15
<b>Cl</b>	mg/L	25	58.9	78.8	69.1	5.40	26	58	79	70	5.32
<b>Cu</b>	mg/L	27	0.00	0.12	0.01	0.02	26	0	0.05	0.01	0.01
<b>Fe</b>	mg/L	27	0.00	0.17	0.05	0.05	26	0	0.05	0.02	0.01
<b>K</b>	mg/L	27	2.66	4.23	3.66	0.37	26	2.60	4.50	3.70	0.46
<b>Mg</b>	mg/L	27	18.3	26.8	22.7	1.75	26	18	27	23	1.83
<b>Mn</b>	mg/L	27	0.001	0.009	0.002	0.002	26	0.001	0.007	0.001	0.001
<b>Na</b>	mg/L	27	27.4	38.1	33.8	3.00	26	29	38	34	2.97
<b>Total P</b>	mg PO <sub>4</sub> /L	–	–	–	–	–	26	0	2.2	1.4	0.63
<b>Ortho-P</b>	mg PO <sub>4</sub> /L	27	0.01	0.17	0.03	0.04	23	0.02	1.15	0.76	0.25
<b>SiO<sub>2</sub></b>	mg SiO <sub>a</sub> /L	27	9.06	11.4	10.1	0.70	26	9	11	10	0.73
<b>SO<sub>4</sub></b>	mg SO <sub>4</sub> /L	27	60.7	115	85.5	11.1	26	61	117	85	10.7
<b>Total Alk</b>	CaCO <sub>3</sub> /L	23	40.0	61.0	49.5	5.85	25	1	61	47	11.2

cap' that covers an active site where localized corrosion attack was occurring. The pipe was placed back into the system to monitor further pit development, if present. No solid mounds or other notable features other than a slight darkening of the pipe wall color were identified on the pipe sections subjected to phosphate treatment after 72 days.

Pipe sections were re-examined after 101 days (Section A, Figure 1). No distinct visual differences were noted between the untreated internal pipe surface at 72 and 101 days. The corrosion by-product mound discovered at day 72 on the untreated pipe section was still present and did not appear to have changed in shape or size. The pipe section exposed to phosphate treatment did not have any notable surface features or defects. The two pipe sections (one from each loop) were removed at this time for surface and solids analysis, replaced with new copper pipe sections, and the test run continued on.

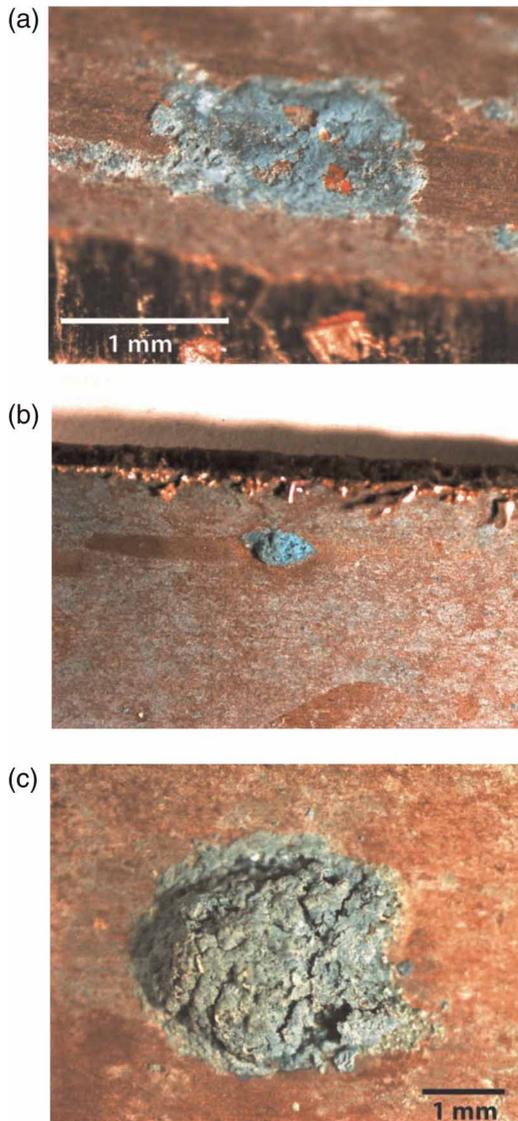
The pipe sections (101 days) were photographed then longitudinally cut while still wet with a band saw. The experience of the investigators has shown that the tendency to dislodge corrosion by-products on the interior surface of pipes during cutting is greatly reduced if pipes are cut before they are permitted to dry. The appearance of the internal surface of pipe sections showed obvious differences between the pipe exposed to phosphate (Figure 3(a)) and the

untreated pipe section (Figure 3(b)). Phosphate-exposed pipe had large patches of relatively uniformly deposited blue-green colored solids on the surface which were not as evident when the pipe was wet. The deposits were also fairly smooth and uniform in thickness. There were no obvious signs of raised, isolated mounds of corrosion by-products that resembled a pit cap or indicated localized pitting corrosion.

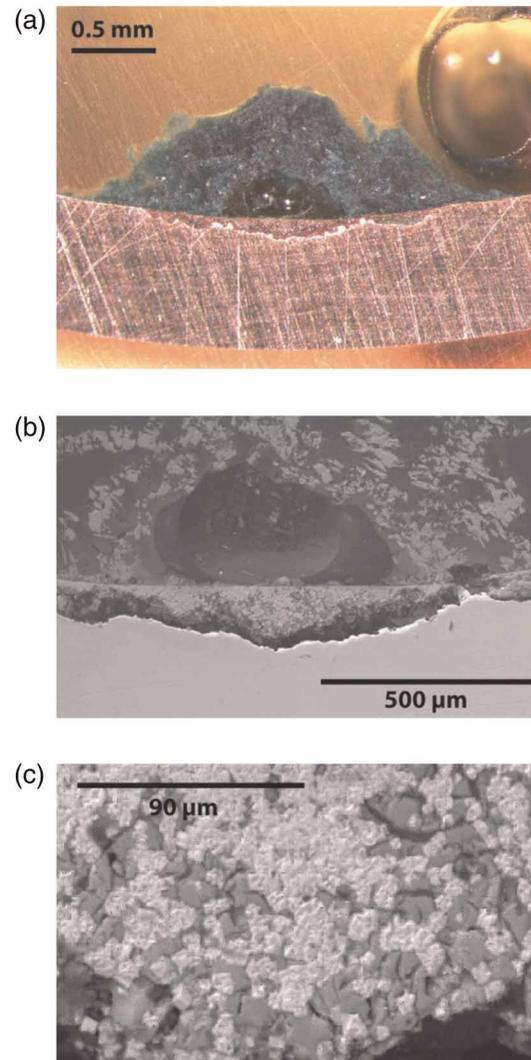
Imperfections and other areas of interest identified on the untreated pipe section surface (Figure 4) were cross-sectioned for detailed analysis. Several small mounds and dense patches of blue/green corrosion by-products were noted. Of particular interest was the large corrosion by-product mound first identified at 72 days (Figures 3(b) and 4(c)). The mound was circular and dome-shaped, had a diameter of approximately 3 mm, was blue/green in color, and appeared to be partially covered with a cream-colored solid (Figure 4(c)). A cross-sectional stereomicroscopic image through the mound clearly revealed that localized corrosion in the form of a pit was taking place below the mound (Figure 5(a)) after 101 days. All of the features of classical pitting corrosion attack: the pit cap, thin membrane, and the pit were present (Lucey 1967). The pit cap was approximately 0.75 mm thick, consisted of blue/green solids, and was dome-shaped. SEM imaging of the



Figure 3 | Interior surface of copper pipes removed after 101 days: (a) pipe exposed to an ortho- and poly-phosphate blended chemical, and (b) untreated (no phosphate) pipe.



**Figure 4** | Stereomicrographs of (a–c) areas of interest on the interior surface of the untreated copper pipe that may indicate a site of pitting corrosion (after 101 days).



**Figure 5** | Large mound of corrosion deposits on surface of untreated copper pipe. Cross-section of copper deposits imaged by (a) stereomicroscope, (b) scanning electron microscope, and (c) scanning electron microscope, focusing on pit contents (after 101 days).

cross-section revealed finer details about the area of local corrosion attack (Figure 5(c)). A generally intact thin membrane having a thickness of approximately 0.01 mm of dark orange material (likely cuprite,  $\text{Cu}_2\text{O}$ ) separated the cap from the pit. The pit was approximately 0.150 mm deep or 20% of the copper wall thickness at the cross section (Figures 5(a) and (b)). The pit was partially full of somewhat defined dark orange crystals that appeared to be cubic in shape (Figure 5(c)), having a size of approximately  $6\ \mu\text{m}$  that were most likely cuprite crystals. There were also a

few areas within the pit that contained white/green solids (not shown).

SEM imaging combined with EDS elemental mapping analysis of the cross-section of the large pit (Figure 5(b)) showed that the pit cap largely consisted of sulfur, oxygen, and copper (Figure S2, available online at <http://www.iwaponline.com/jws/061/079.pdf>). The thin membrane that separated the cap from the pit was copper rich. Chlorine (most likely a chloride compound or chloride ions) (supplemental Figure S3, available online at

<http://www.iwaponline.com/jws/061/079.pdf>) was concentrated at the base of the pit where active corrosion was occurring, indicating that it was a very important parameter with respect to pit propagation. Similar elemental mapping analysis was performed on a smaller pit on the same pipe section. The pit cap was approximately 0.8 mm wide at the base and was 0.32 mm thick, and the pit was only 50  $\mu\text{m}$  deep (Figure S3, <http://www.iwaponline.com/jws/061/079.pdf>). SEM and EDS mapping results of the pit and surrounding area showed the same features as the larger pit although the structure of the contents was not as well defined.

After 206 days of operation, a second pipe section was removed from both pipe loops. The phosphate-treated pipes looked identical to the pipe section removed at 101 days and no signs of pitting corrosion were present (not shown). The control loop had apparent small pit caps on the pipe surface (not shown). Cross-section analysis through a cap confirmed the presence of a pit with features noted earlier. Elemental analysis showed that chlorine (likely in the chloride form) nearly filled the pit (Figure S4, available online at <http://www.iwaponline.com/jws/061/079.pdf>). Two distinct silica particles, with one having a dimension of approximately 25  $\mu\text{m}$ , were in the cap and rested on the membrane. The role of the particles, if any, cannot be ascertained from this study. The work of others (Rushing & Edwards 2004) has suggested that particles are important in initiating pitting corrosion. The study was terminated after 262 days.

Phosphate treatment prevented obvious signs of pitting corrosion. Analysis of the pipe surface could provide insight as to the role of phosphate on copper corrosion and passivation. SEM images (Figure 6) of the surface of phosphate-treated pipe surfaces after 206 days showed that a relatively uniform layer of solids formed on the pipe surface. The solids appeared to be chipping away and showed signs of shrinkage, both of which were likely artifacts from drying. EDS analysis of the pipe surface showed that phosphorus was incorporated throughout the solid in a uniform distribution. The prevention of pitting corrosion of copper by phosphates in some conditions is in agreement with past works (Marshall & Edwards 2006; Lytle & Schock 2008; Lytle *et al.* 2010; Sarver *et al.* 2011b). Direct evidence of the benefit of a blended phosphate chemical on preventing copper pitting corrosion alone is important given the limited knowledge on the subject. Furthermore, the benefit of

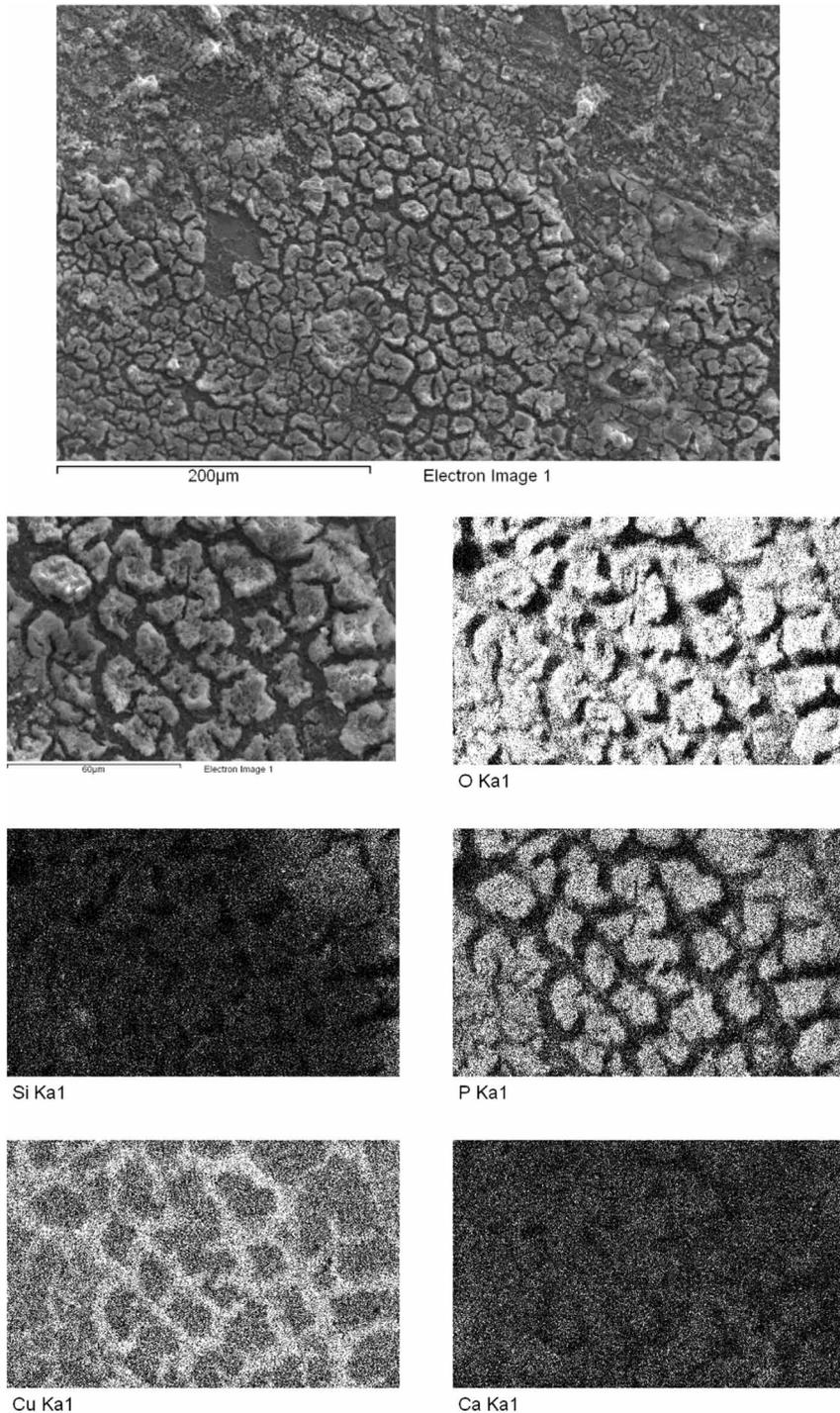
copper pipe loops in identifying pitting corrosion prevention approaches was illustrated.

The pipe loop system used in this study was simple to construct and operate, and was built from readily available materials. The system was also relatively inexpensive to build and operate. The total supply cost was \$2,638 (cost breakdown in Table 2). The largest cost was the supplies used to construct the optional chemical feed system. Also, the Unistrut<sup>TM</sup> frame, which represented approximately 10% of the total cost, is not necessary if there is space available to mount the pipe loops to walls or other structures.

## DISCUSSION AND CONCLUSIONS

This study demonstrated that, in reasonably short time periods, a simple copper pipe loop system can be used to assess the tendency of water to produce localized or pitting corrosion attack. Although pipe loops have been used to study copper pitting corrosion in the past (Marshall & Edwards 2005; Lytle & Schock 2008; Sarver *et al.* 2011b), this work is the first to successfully reproduce copper pitting corrosion using a pipe loop system with real drinking water at a field location that has a history of reports of pinhole leaks in the household copper plumbing of consumers that continued up to the time of this report. The results showed that pitting attack of copper plumbing can be largely attributed to water quality, and occurred in the absence of electrical grounding and plumbing workmanship issues that are frequently cited as the cause of household pinhole leaks.

Pipe loop rigs have been used to assess the corrosivity of water to various plumbing materials based on metal release and to evaluate the effectiveness of control strategies to reduce lead and copper levels. Cost, complexity, time of operation, and questions about how new plumbing used to construct pipe loop rigs represents old plumbing are common concerns of such systems. These issues are less of a concern when pipe loop rigs are used to evaluate pitting corrosion tendencies. The cost of materials to construct the pipe loop system used in this study was only \$2,638, with the major costs associated with an optional chemical feed pump and Unistrut<sup>TM</sup> frame. Once in operation, the costs to maintain and operate the system were small.



**Figure 6** | Scanning electron microscopy image of pipe surface exposed to phosphate treatment and corresponding elemental mapping by EDS of oxygen, silicon, phosphorus, copper, and calcium (after 206 days).

Minimal water quality sampling and analysis was necessary and little operator time was required to keep the system running.

The pipe loop system designed and used in this study was very simple. The loops were made of materials and construction supplies that can be purchased at most local

**Table 2** | Construction material costs associated with pipe loop system

Component	Cost (US \$)
Type M (red) 1/2"	60
Union compression S×S fittings	140
Miscellaneous fittings	10
Total	210
PVC	
1/2" schedule 40 pipe	15
1/2" fittings	20
1/2" valves	20
Total	55
Miscellaneous	
Check valve	220
Flow totalizer	300
In-line mixer	178
Pump drive	975
Flow meter	160
Tygon tubing	50
Pipe damps	5
Pump head	220
Total	2,638

hardware stores and detailed plans are provided in this paper (Figure 1). Signs of pitting corrosion were observed in as little as until 72 days into the study. This is a relatively short amount of time, considering it may take years from the time a water system first gets indication that a pinhole leak problem exists.

Lastly, the experience of the authors has been that pinhole leak problems are often first reported in newer homes (6–10 years old). In such cases, a pipe loop study using new copper pipes would be reasonably representative of full-scale distribution systems. The pipe loop study using the proposed pilot system and protocol proved to be useful and representative of the full-scale distribution system based on the development of pits on the pipes in the loop. The characteristics and structure of pits on the pipe loops resembled those reported (Lytle *et al.* 2010) on pipes removed from homes in the community. Specifically in this study, mounds of blue-green colored corrosion deposits on the interior surface of copper pipes and pit structure

closely resembled the properties of pits observed on pipes removed from homes in the community. Cross-sectional analysis through a pit indicated the presence of a sulfate-containing hollow pit cap over a thin membrane and a pit full of cubic crystals and chloride at the base.

The rate of attack in the experimental loops in one pit was of the order of 0.54 mm/year. The rate is likely dependent on many factors and very complicated, and must be used accordingly. Considering this, if the rate remains constant, complete penetration through the pipe wall would occur in 1.3 years. The apparent rapid rate of pit penetration observed in the pipe loop rig relative to that observed time in homes in the distribution system (4–6 years) (Lytle *et al.* 2010) could be due to many reasons. They include the continuous flow conditions and diffusion rates of important ions in and out of the pit or the assumption that pits grow at a uniform rate is incorrect. Lastly, the pipe loop system showed promise as an evaluative tool for pitting corrosion of copper and, given the low cost, operating such a system seems likely a worthwhile investment to a utility that is experiencing a pinhole leak problem. Beyond understanding the problem, the pipe loop system was also useful in identifying a potential solution to the problem. In this case, a blended phosphate chemical prevented pitting corrosion. This observation is of particular importance given the poor understanding in this area.

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no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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