Evaluation of Lead Corrosion Control Strategies in Maui Water

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INTRODUCTION

Water utilities in the US are required to comply with the 1991 Environmental Protection Agency Lead and Copper Rule. This regulation sets the action level for lead in drinking water at 15 parts per billion (ppb). In the spring of 2001, the Maui Department of Water Supply (DWS) exceeded the lead action limit. Lead is not typically detectable in the publicly owned distribution system and usually comes from lead-based solder, lead service lines, brass faucets, and bronze plumbing components installed in homes. Risk from lead is generally believed to be highest in older homes (built before 1986) where lead-based solder may have been used, or in homes where problematic leaded brass fixtures have been installed. Even new fixtures can leach high levels of lead to water.

A decision was made to control lead corrosion in the Maui system via addition of phosphates to the water. Phosphates are used for this purpose by approximately half of all public water systems in the United States, and they often form a protective film on the inside of pipes, slowing down corrosion processes and reducing lead contamination. On June 1, 2001, Maui DWS began adding zinc orthophosphates (C-9) to the Upcountry water supply. While the addition of the C-9 decreased lead levels to below the EPA action limits in many cases, concerns emerged amongst consumers regarding possible health effects arising directly or indirectly from dosing the phosphate inhibitor. Specifically, the residents were of the strong opinion that problems of itchy skin, rashes, eczema, blurring and burning eyes, respiratory problems and throat irritation were temporally linked to dosing of the zinc orthophosphate corrosion inhibitor to the water supply. Residents first contacted the second author (Dr. Marc Edwards) on December 18th, 2002 by e-mail requesting voluntary assistance and advice with the problem.

The Maui DWS serves 5 different sections of Maui County. The Upcountry Maui system includes a Lower and Upper Kula system. Both waters are relatively low pH, soft and lower alkalinity (< 30 ppm as $CaCO_3$), but the Upper Kula system has more organic matter naturally present in the surface water supply. The Lower Kula system is served by the Pi`iholo water treatment plant whereas the upper system is served by the Olinda water treatment plant. Most consumer health complaints were from the Upper Kula system.

On April 10, 2003, a decision was made to stop dosing zinc orthophosphate and to switch to orthophosphate alone. Later testing indicated that some areas in the Upper Kula system did not pass the LCR monitoring-- the 90th percentile lead was 41 ppb. Continued informal communications between Marc Edwards, Maui residents and Maui Department of Water culminated in a face to face meeting on March 1, 2004. At the meeting, significant concern was expressed by all parties regarding the possible correlation between the consumer health issues and the phosphate inhibitor addition. Many of the problems described by residents were not inconsistent with emerging understanding of problems such as "hot tub rash" or "hot tub lung." The attached reference list at the end of this document provides additional background information on these newly emerging issues.

Immediately after the productive face-to-face meetings, a proposal was made to DWS examine alternative strategies that could control corrosion without use of phosphate inhibitors. A desktop study was conducted. In water of very low alkalinity (< 30 ppm as $CaCO_3$) at the normal pH of treated Maui water (pH 7.6), the likelihood of exceeding the lead action limit was well over 60% in a study of US utilities by Dodrill et al, 1995 (Figure 1; Table 1). Utilities with low alkalinity water and pH above 8.4 had a dramatically reduced likelihood of exceeding the action limit. This fact and other considerations suggested that raising the pH to approximately 8.5 and slightly increasing the alkalinity would have a good chance to reduce lead leaching without phosphates. Because soda ash had previously been used at Maui for pH control, without any noteworthy consumer reports of itchiness, rashes and breathing difficulties, it was deemed desirable to test its effectiveness at a pH range capable of reducing lead leaching. The general goal was to determine the minimum dose of soda ash that would achieve the desired objective.

As part of the overall evaluation, it was deemed desirable to conduct some general microbial testing, since the face to face meeting raised the possibility that microbial growth contributed to the lead leaching and other problems that were being experienced. To explain this hypothesis, the following equation for heterotrophic microbial growth is useful:

Organic Matter + Nitrogen + Phosphate + Oxygen → Bacterial Re-growth

If high levels of chlorine or chloramine disinfectants are present, microbial re-growth via the above equation can be controlled almost without regard to the nutrients in the water. But once disinfectant concentrations have decreased to low levels in typical waters with oxygen, bacterial re-growth can proceed at worrisome rates if all key nutrients including phosphorus, nitrogen and organic matter are available. As mentioned previously, organic matter is known to be present in the upper Kula system at high levels relative to the lower Kula system. Due to use of chloramines, ammonia is also available in the upper system as a nitrogen source. Thus, according to the above equation (and in the absence of disinfectant), it is possible that a major factor "missing" for worrisome re-growth rates was phosphorus. If this was the case, addition of phosphorus as a corrosion inhibitor to the water could have induced more rapid rates of microbial growth than before phosphorus was used.

We note at the outset that many types of microbes are present in all potable water supplies and at appreciable concentrations. In general, growth of microbes in potable water is considered inevitable but undesirable—steps are therefore taken by utilities to minimize bacteria growth at every opportunity. Even the largest utilities in the US do not routinely sample for specific organisms that cause specific illnesses. Instead, they are required to frequently conduct simple general tests such as heterotrophic plate counts (HPC). At a 2002 expert meeting in Geneva (see also Appendix 1), the issue of using HPC values alone to judge water safety was specifically addressed. The consensus opinion is as follows:

> **"There is no evidence that HPC values alone directly relate to health risk either from epidemiological studies or from correlation with occurrence of waterborne pathogens. They are therefore unsuitable for public health target setting, or as sole justification for issuing "boil water" advisories."**

Instead, results of HPC testing are used to validate and verify effectiveness of processes such as treatment and disinfection. If HPC values are high, it is assumed that conditions are also possibly supportive to growth of pathogenic microbes, and a utility should take prompt precautionary action to control microbial growth. Since corrosion was the key focus of this study, tests were also made for other types of bacteria whose growth can make the water more corrosive to materials that contain lead. As with the HPC testing, results of these bacterial tests are not suitable for interpreting the public safety of the water supply, although high concentrations of bacteria are never desirable.

Extensive background information was provided to this report by various parties that include the Maui Coalition for Safe Water, Department of Health, Dr. Lorrin Pang and Maui Department of Water. However, the views expressed herein are exclusively those of the authors and do not necessarily represent the views of any other organization. Special thanks to the consumers who allowed sampling in their homes.

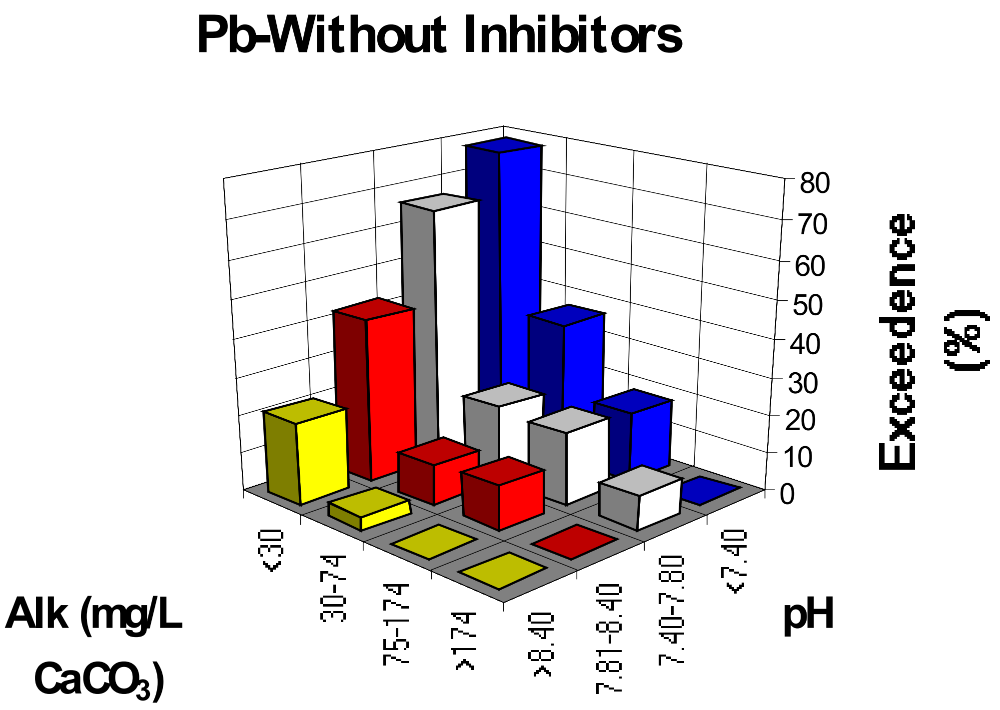

Figure 1. Average 90th percentile lead release and percentage exceedence as a function of pH and alkalinity for utilities without phosphate inhibitors.

Table 1. Average 90%tile lead release (value in ppb lead) at utilities not using inhibitors in the specified pH and alkalinity category. Typical lead leaching for a water below pH 7.4 and with alkalinity less than 30 mg/L is 33 ppb (0.033 mg/L). Above pH 8.4 in the same water, typical 90%'ile lead is 10 ppb.

Average Lead Release (ppm)

pH Range	Alkalinity Range (mg/L as $CaCO_3$)			
	0-29	30-74	75-174	>174
<7.40	0.033	0.029	0.009	0.007
7.41-7.80	0.024	0.013	0.010	0.007
7.81-8.40	0.034	0.009	0.008	0.006
>8.40	0.010	0.012	0.006	0.007

EXPERIMENTAL METHODS AND MATERIALS

Three phases of work are described in this document including 1) laboratory testing of lead leaching, 2) laboratory testing of bacterial re-growth potential, and 3) field sampling results of water collected from consumers' homes. Other data collected during the study, such as samples of lead taken from consumers' homes, are still being analyzed and those results will be discussed in later reports.

Pipe rig testing:

An experimental apparatus was constructed to simulate key features of a home plumbing system in relation to lead leaching (Figure 2). The test rig consists of a copper pipe section that is electrically connected to either leaded brass or samples of 50:50 lead tin solder. These were considered to be the key sources of lead in the Maui system.

The experiment tested the effects of different combinations of pH and phosphate levels on bacterial growth and the leaching of lead (Table 2). This experiment was completed for filtered water from both the Olinda and Pi`iholo treatment facilities in upcountry Maui. The Olinda water is the water serving consumers with the greatest number of problems. Seven different levels of pH and disinfectant were tested in each both the Olinda and Pi`iholo waters. Both lead solder and brass fixtures were tested. Thus, 14 (= 7 waters x 2 materials) experimental conditions were run for both Olinda and Pi`iholo (Figure 2, Table 2). Water was completely changed in the pipes every Monday, Wednesday, and Friday using a "dump and fill" protocol. This refreshes the water in the pipe, replenishing both nutrients and chloramine residuals. The extent of the lead problem was determined by measuring lead in the water after sitting stagnant in the pipe.

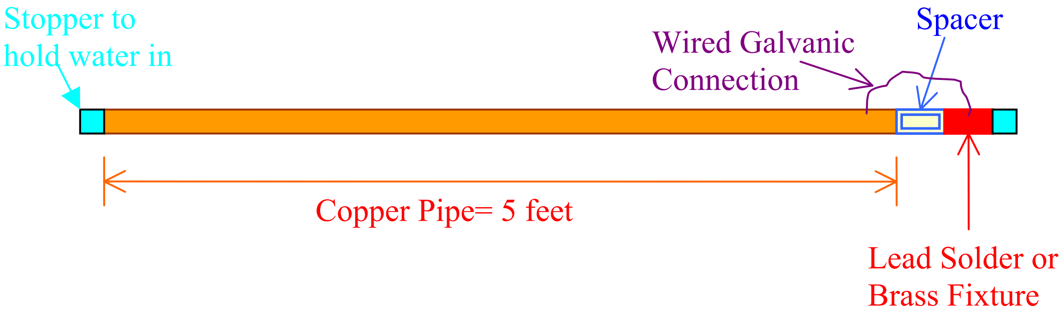

Figure 2. Experimental apparatus designed to simulate lead release as it would occur in homes.

Table 2. List of water conditions tested. Each disinfectant was present at a level of 2.4 mg/L total chlorine. Orthophosphate was present at 1 mg/L as PO4-P.

pH	**Water Quality Condition**
7.7	Chloramine
8.3	Chloramine
8.9	Chloramine
9.5	Chloramine
7.7	Chloramine and Phosphate
7.7	Free Chlorine
8.9	Free Chlorine

After 7 weeks exposure to the different test conditions, water from the copper pipe rigs was tested in triplicate for heterotrophic bacteria (HPC) counts. These bacterial counts are considered representative of what might possibly be found in homes served by waters listed in Table 2. They are not perfectly representative. For instance, the 48 hour stagnation time between water changes is likely to be longer than is typically found in many homes, but not unheard of given weekend trips. On the other hand, the disinfectant residual levels in water put into the pipe were relatively high compared to distant parts of the distribution system.

PVC Bacterial Tests:

Another experiment tested bio growth within PVC pipes for all water conditions. Water in the pipe was changed in the same way as for the pipe rig. For comparison, some testing was done with modifications of waters listed in Table 2, but without residual disinfectant. That condition was designed to be representative of re-growth conditions that might be present at homes near the end of the distribution system after chlorine residuals have disappeared.

Field Testing for Presence of Bacteria that Might Influence Corrosion:

A final set of microbial tests were conducted in consumers' homes. Eight homes total were tested, including three homes with high lead levels and four homes where consumers believed that water was adversely impacting their health. Tests were conducted for microorganisms that can influence corrosion including acid producing (APB), heterotrophic aerobic (HAB), sulfate reducing (SRB), slime forming (SLYM), and nitrifying bacteria. In general, these tests are designed to test for presence of bacteria thought to influence corrosion, and are not necessarily indicative of bacteria that would cause a public health problem. However, as mentioned previously, it is always considered desirable to minimize the number and types of bacteria present in a water supply.

RESULTS AND DISCUSSION

Lead Testing

The results from the laboratory experiments after 5 weeks of testing strongly support the hypothesis that soda ash can decrease lead leaching with the upper water system. In both Olinda and Pi’iholo water, lead leaching was minimized between pH 8.3 and 8.9 when chloramine was used as a disinfectant (Figures 3 through 6). It is worthwhile to compare the condition of phosphate plus chloramine at pH 7.6 (Figure 4) to the results obtained at pH 8.3 – 8.9 with chloramine and soda ash adjustment. Lead levels dropped by about a factor of 4X at pH 8.3 with soda ash relative to the same condition with orthophosphate and chloramine for lead solder (Figure 4). Lead leaching from brass was about the same in the system using phosphate plus chloramine at pH 7.6 versus soda ash at pH 8.3 (Figure 3). Our conclusion is that the pH target of 8.3 to 8.9 is promising for control of lead leaching in the Olinda water. In Pi’iholo water pH 8.9 resulted in better control than pH 8.3 for lead solder (Figure 6).

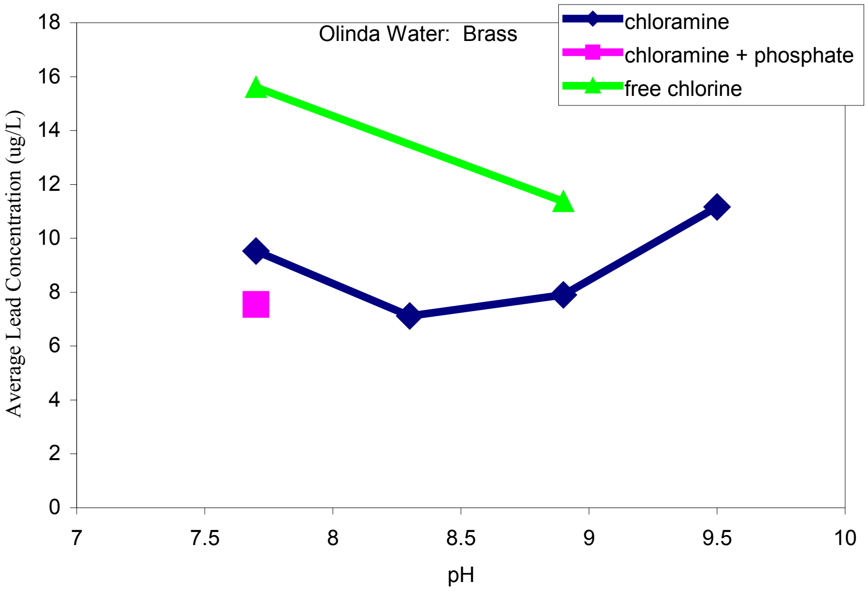

Figure 3. Lead concentrations leaching from brass fixtures for various pH conditions for Olinda

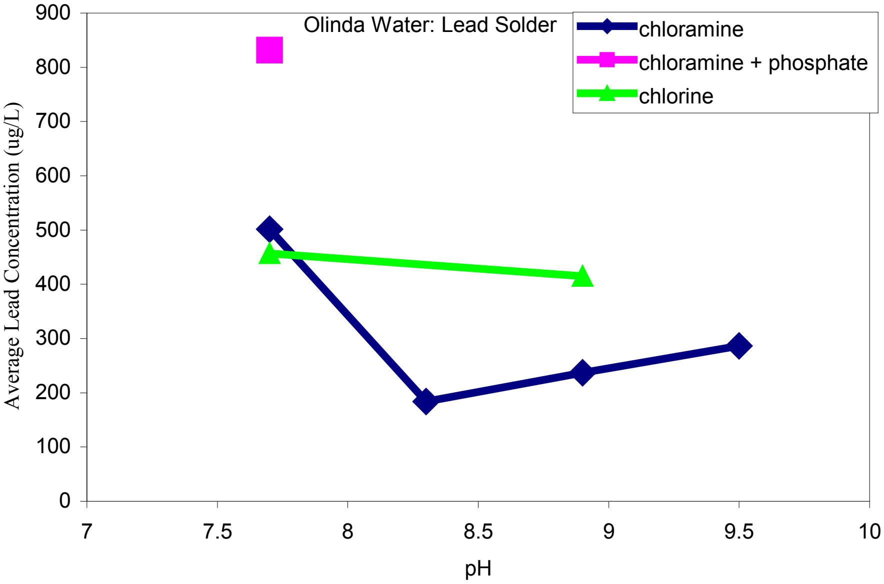

Figure 4. Lead concentrations leaching from lead solder coupons for various pH conditions for Olinda water.

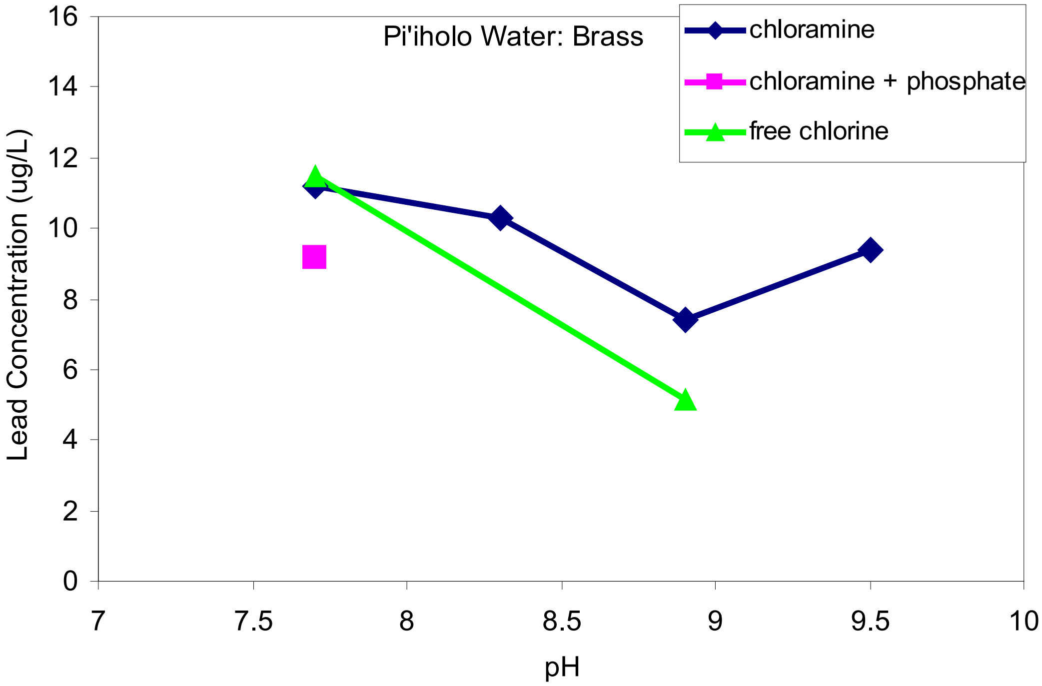

Figure 5. Lead concentrations leaching from brass fixtures for various pH conditions for Pi'iholo water.

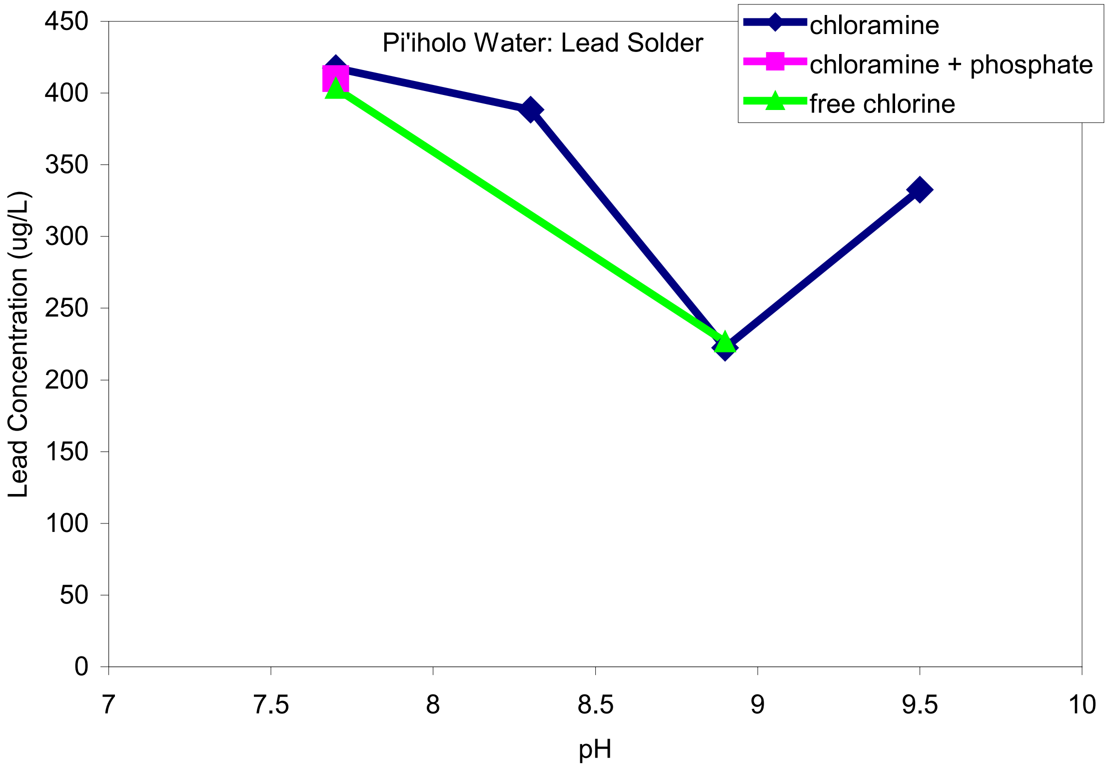

Figure 6. Lead concentrations leaching from lead solder coupons for various pH conditions for Pi'iholo water.

There was also a distinct difference in lead leaching in water with chloramines versus chlorine based on the time of exposure during the experiment. The samples containing free chlorine initially leached more lead. However, while the leaching of lead significantly decreased with time in the free chlorine samples, samples exposed to chloramine did not decrease in lead leaching, or lead levels decreased only slightly during the study (Figure 7). Thus, over the longer term effects of chlorine on lead leaching may be beneficial relative to chloramine at pH 7.7.

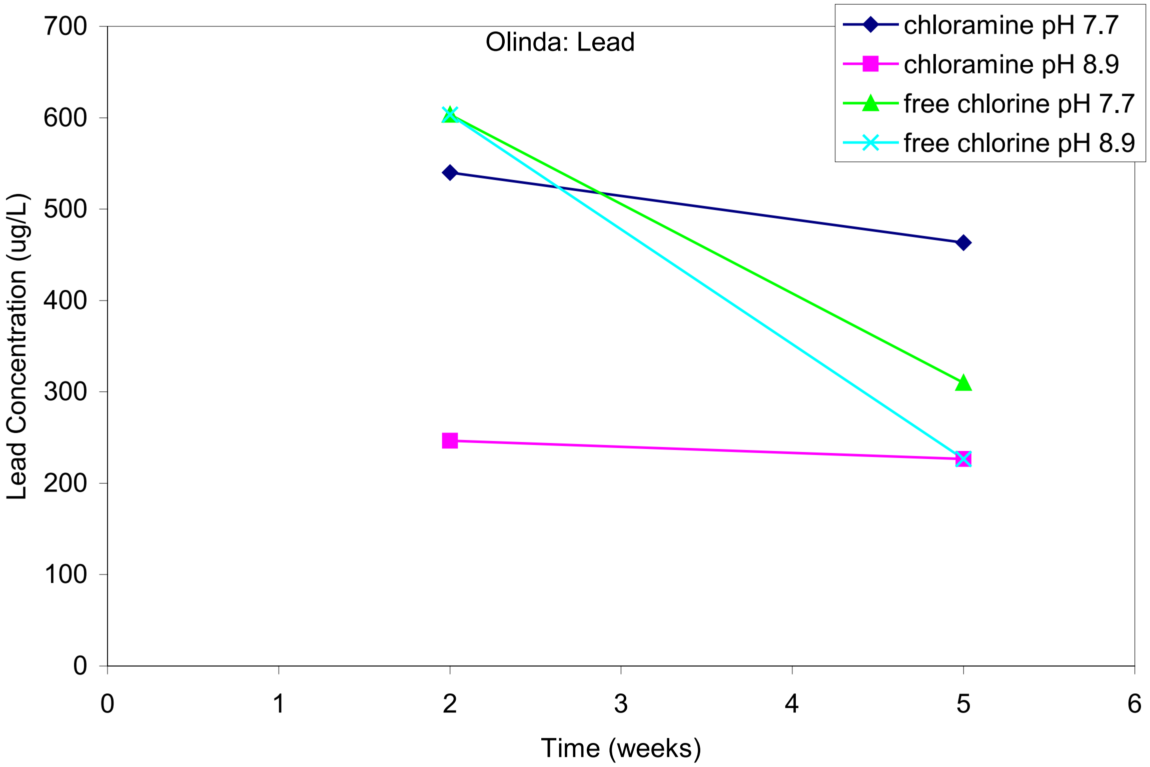

Figure 7. Lead leaching to water from pipe rigs exposed to chloramine verses those exposed to water with free chlorine. Results in the graph are averaged from triplicate samples.

Galvanic current between the copper and the brass was also measured. The galvanic current represents the rate at which the lead bearing material was being sacrificed by electrical connection to the copper. In some cases, the galvanic current between the two dissimilar metals can be a cause of high lead in water. In general, measurements of galvanic current are deemed of secondary importance to actual lead leaching data (Figure 4-7). Thus, these data are mainly provided for scientific interest at this time, although a future report will examine this issue in greater detail. For the brass fixtures, the galvanic current was significantly higher in the Pi’iholo system then in the Olinda system (Figures 8 and 9).

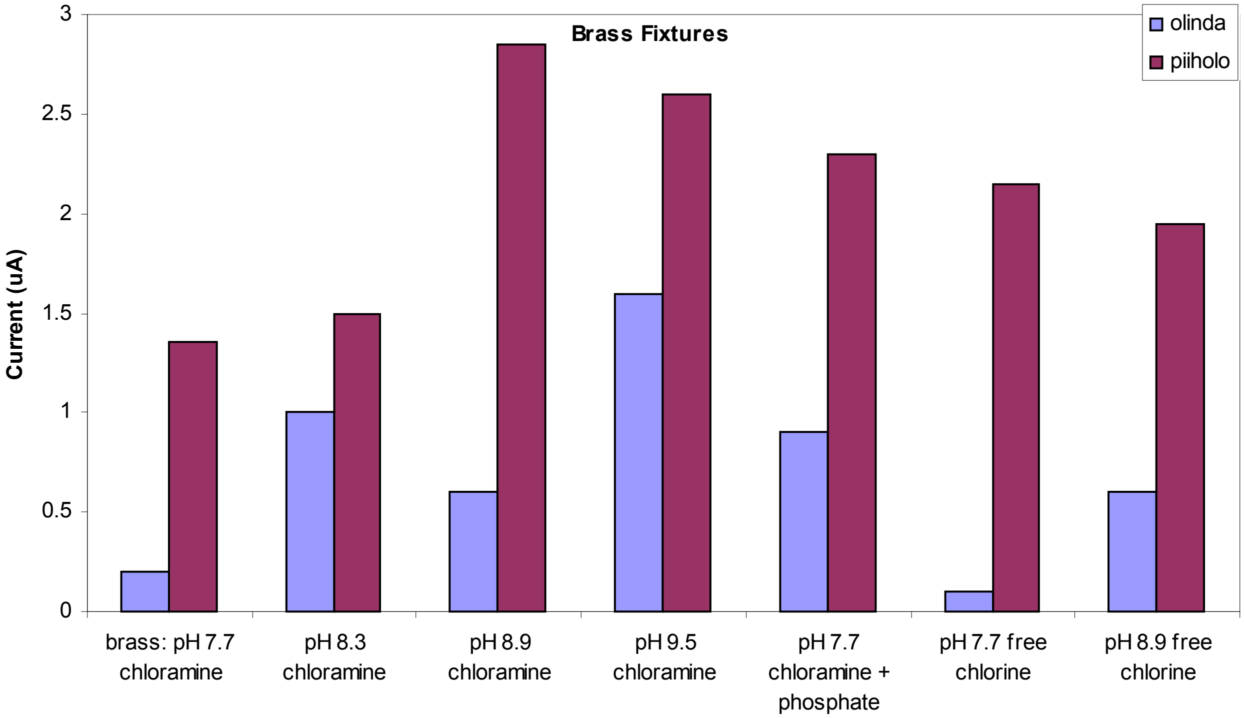

Figure 8. Galvanic current for brass fixtures exposed to Olinda and Pi'iholo water.

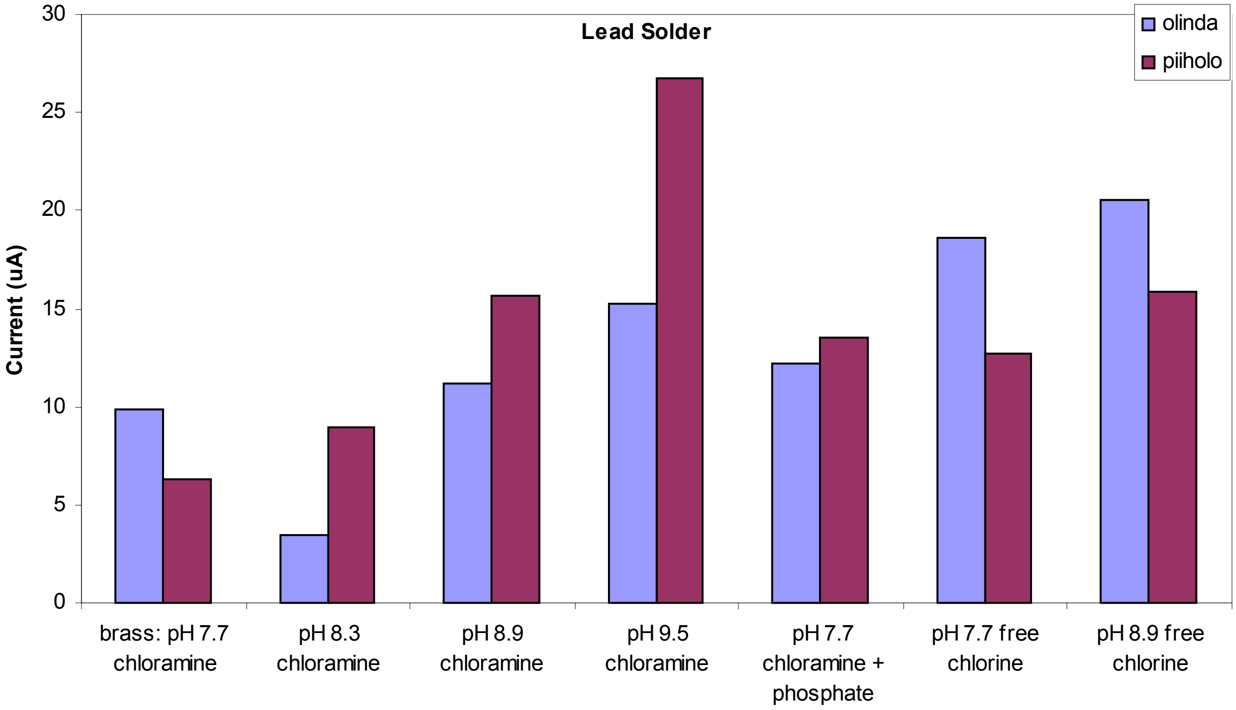

Figure 9. Galvanic current for lead solder exposed to Olinda and Pi'iholo water.

Lead samples were also taken for the Pi'iholo system both with and without the galvanic wire connections. Without the wire connecting the copper pipe to the lead bearing material, the copper pipe cannot sacrifice the lead plumbing material. The results show that without the galvanic connection, lead levels are still quite high in the case of the brass (Figure 10). This implies that the galvanic connection may not be accelerating lead leaching to the water from brass. In the case of solder, lead concentrations were consistently lower if the copper was not in electrical contact with the lead material. This implies that galvanic corrosion between the copper and solder can contribute to lead leaching in the case of solder (Figure 11). In practice, lead solder is connected to copper pipe, so the results with the wire connected are most relevant to interpreting the current lead problem.

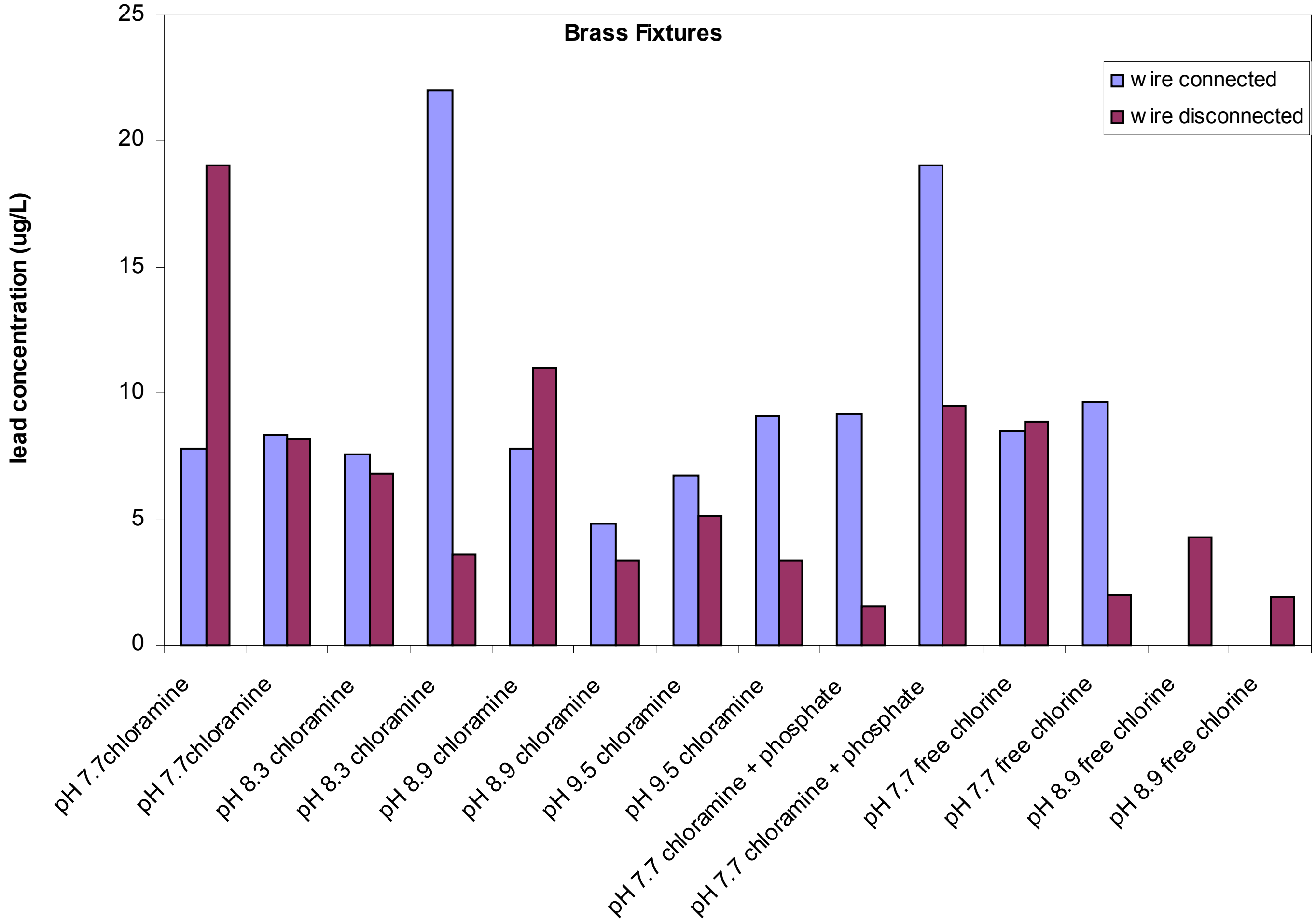

Figure 10. Lead leaching from brass fixtures both with and without galvanic connection.

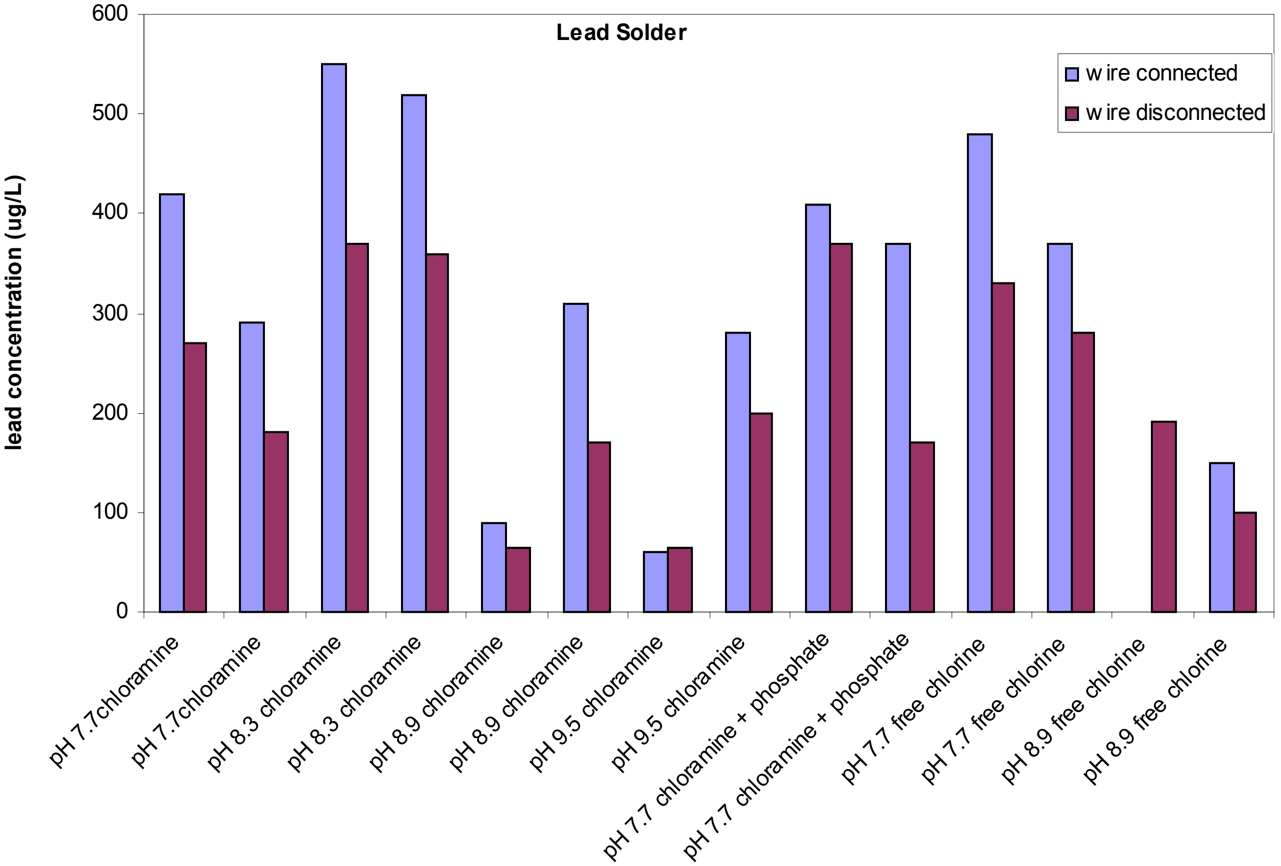

Figure 11. Lead leaching from lead solder both with and without galvanic connection.

Bacterial Testing

The field-testing demonstrated a significant presence of bacterial that influence corrosion in many consumers' homes and low chlorine residuals under at least some circumstances. Two types of water samples were collected for total chlorine residuals (upper Figure 12). In the first type of sample, total chlorine was determined in the first liter of water coming from the tap after at least eight hours stagnation. The second sample was collected after flushing water for 5 minutes. After flushing 5 minutes, chlorine residual was above 0.4 mg/L in 6 of 8 houses. But in house 2 and house 3, total chlorine was not detected at significant concentrations even after 5 minutes of flushing. House 3 is located on a private water system— this private water system initially derives their water from the Olinda system and enters a private storage system. House 2 is near the end of the county system near the Kamole tank. In the first draw sample after eight hours of stagnation, total chlorine residuals were low in all cases, except for house 5 which is actually in the Makawao Water System which uses free chlorine.

Both hot and cold water samples were collected at each of 7 homes, except for house 7 in which a hot water sample was not accessible. Only levels of bacteria detected at "aggressive" levels in the context of corrosion are discussed in the following text. The most common bacteria detected was the acid producing bacteria, testing positive in 14 of 15 samples (lower Figure 12 and Figure 13). These bacteria are heterotrophic and share a common ability to produce organic acid products when growing. These bacteria cause the pH to drop during stagnation in pipes, which could contribute to the problems with lead contamination of the water.

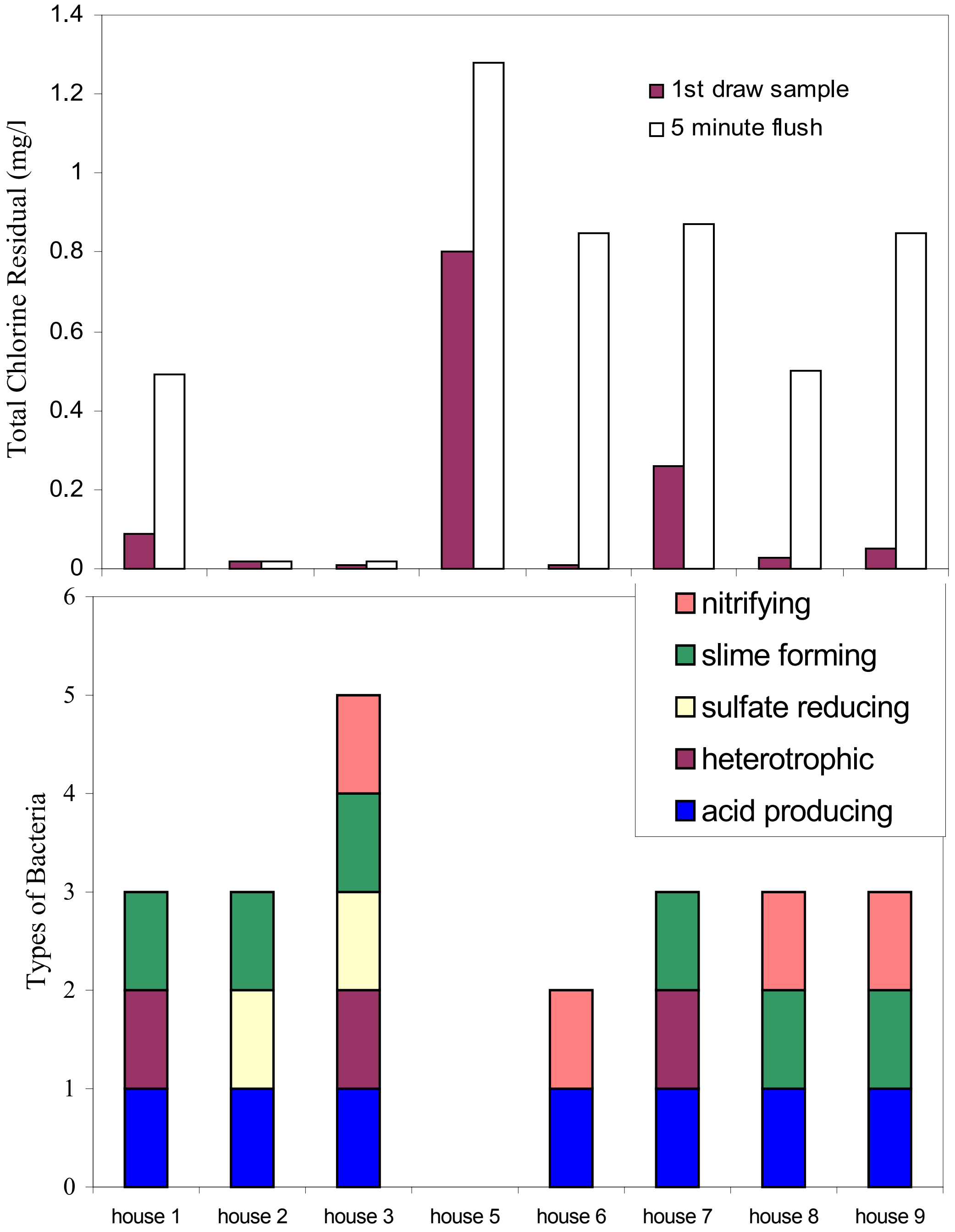

Figure 12. Types of bacteria that can influence corrosion which were identified at homes at cold water taps (below). Total chlorine detected in corresponding homes in first draw samples and after 5 minutes flushing (above) House 5 is located on the Makawao Water System and uses free chlorine. House 3 is located on a private water system— this private water system initially derives their water from the Olinda system. House 2 is at the end of the county system near the Kamole tank.

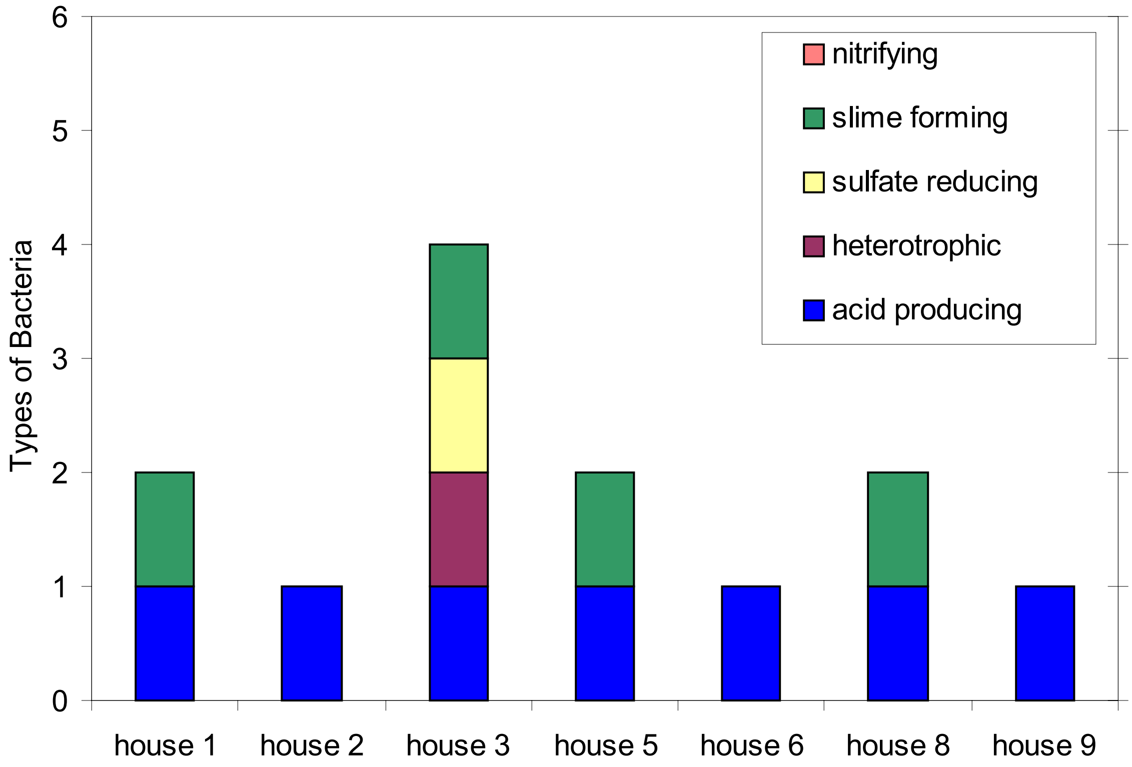

Figure 13. Types of aggressive bacteria found at each sampling location in hot water tanks.

Slime forming bacteria (SLYM) were also detected in 10 of the 15 samples. In addition to SLYM, 4 out of the 15 samples also tested positive for heterotrophic aerobic bacteria (HAB). These bacteria are known to cause several problems in water including slime formations, turbidity, taste and odor, corrosion, health and hygiene risks. Three samples (in 2 houses) also tested positive for sulfate reducing bacteria (SRB). This is a group of bacteria that generate hydrogen sulfide (H_2S). Typical problems created by these bacteria are “rotten egg” odors and corrosion of copper tube. This is high number of positive "detects" for bacteria that influence corrosion in a potable water.

Laboratory testing in PVC pipes supported the hypothesis that the addition of phosphate caused increased numbers of bacteria. Of the seven waters described in Table 2 (seven bars on the left side of Figure 14), the worst bacterial problem was in the system at pH 7.7 with phosphate and chloramine. It is very possible that lack of phosphate nutrient was somewhat limiting to bacterial growth in the Maui system, and that addition of phosphate caused increased growth of bacteria.

However, even without the addition of phosphate or ammonia from chloramine, there was rapid growth of bacteria in Olinda water once chlorine residual is gone (four right bars on the right side of Figure 14). The Olinda water is much more susceptible to the bacterial problem than the Pi`iholo system (Figures 14 and 15). Seven of the same water conditions were tested in both systems. For these seven conditions, the Pi`iholo system had only one condition over the level of 500 CFU/mL, while the Olinda system had four samples above 500 CFU/mL. This may indicate that the lower levels of organic matter in the Pi`iholo system were limiting to bacteria growth.

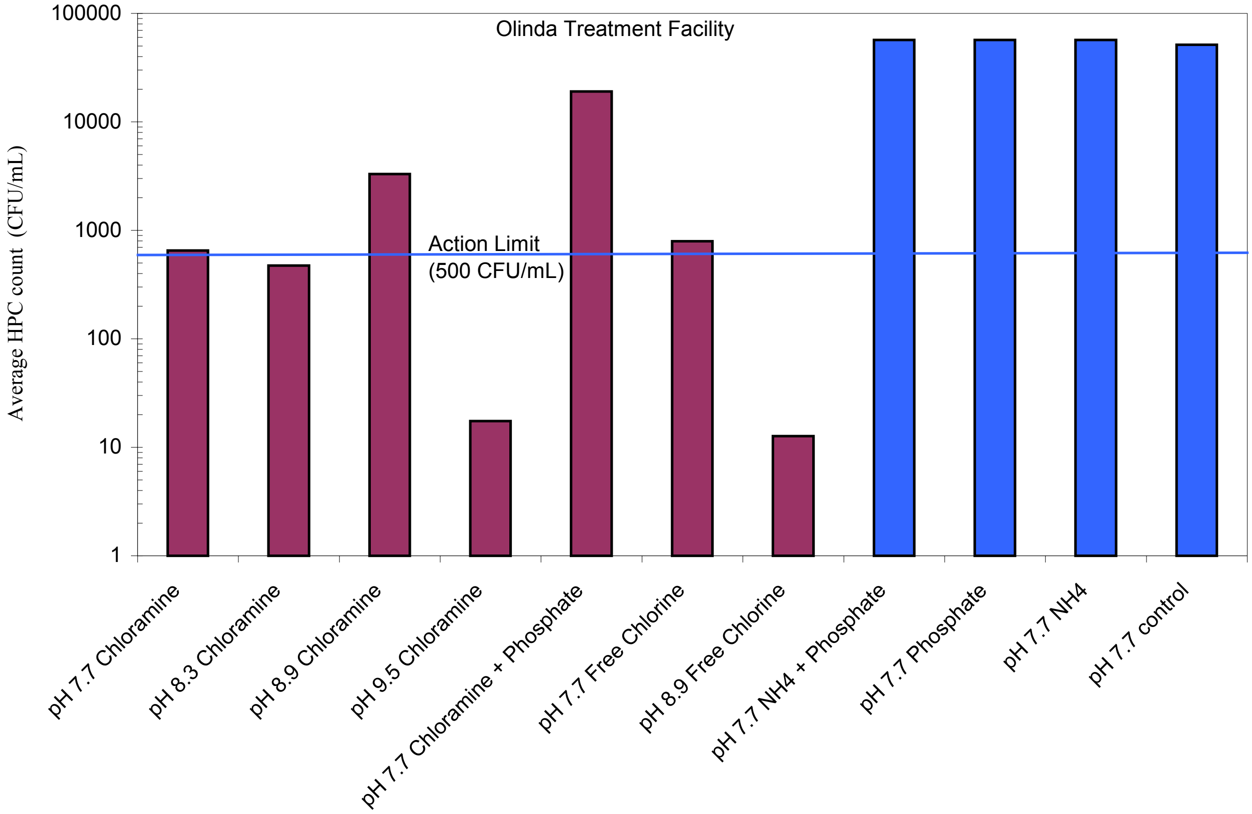

Figure 14. HPC counts for Olinda water tested in PVC pipes. The seven conditions at the left (red) had a chlorine or chloramine residual as per Table 2. The four samples at the far right (blue) did not have a chlorine residual, and are representative of what might happen if the residual disappeared in the distribution system under various circumstances. Actual bacterial levels for samples on the right were likely to be higher than indicated, since they were above the test range.

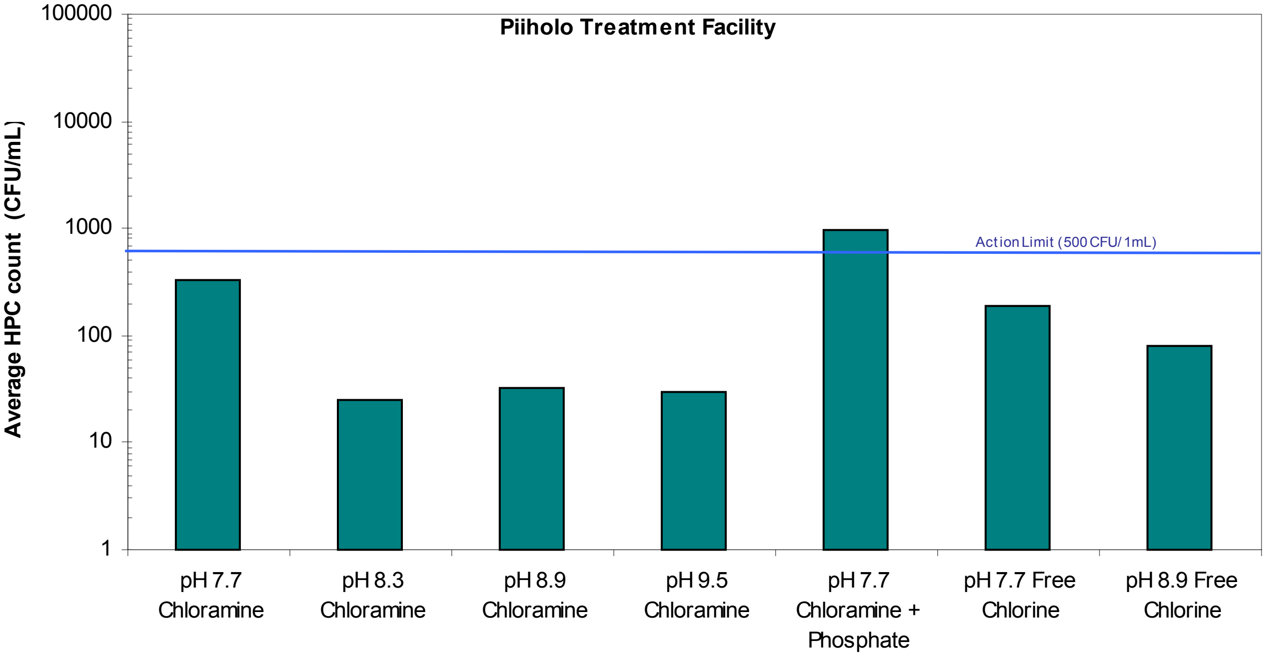

Figure 15. HPC counts for Pi`iholo water tested in PVC pipes.

Lower levels of bacteria were found in copper pipes in the Olinda water, as long as pH was maintained between 8.3 and 8.9 (Figure 16). At lower and higher pH ranges, there was a significant problem with HPC bacteria. Note that all the copper pipes were receiving water with a relatively high initial level of chlorine residual as defined in Table 2. Free chlorine also led to significantly lower bacterial counts at pH 7.7 and 8.9 when compared to the same samples containing chloramines. Thus, free chlorine is a better disinfectant in this water. However, its use might not be allowable given concerns regarding disinfection by-products.

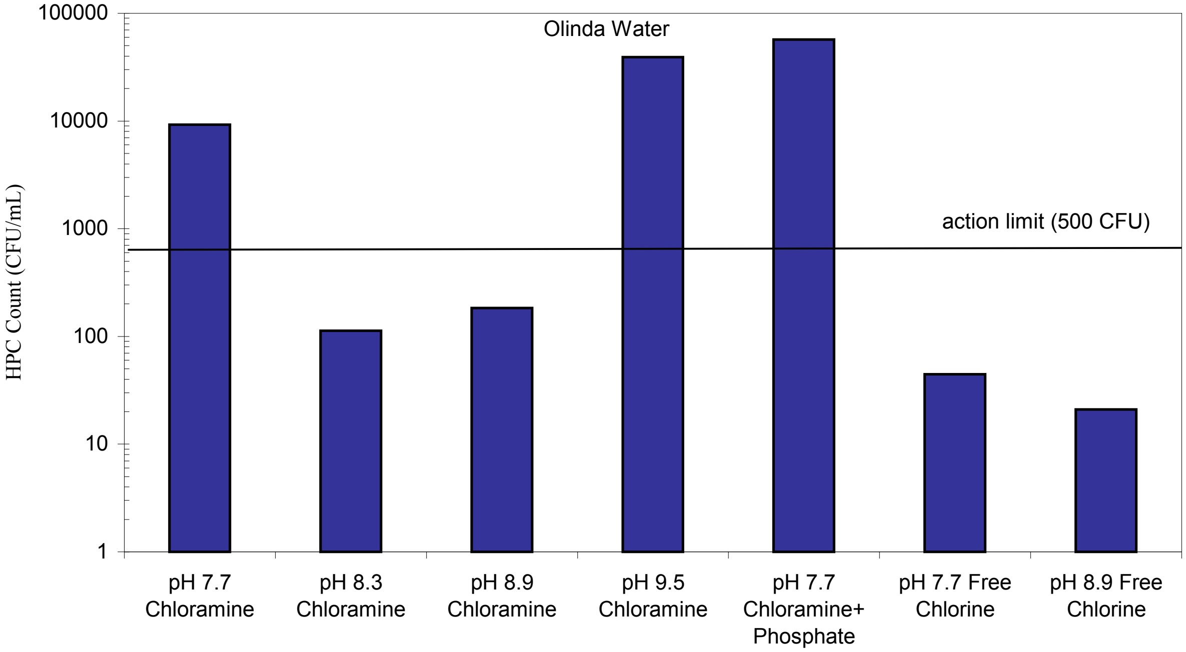

Figure 16. HPC counts for Olinda water from the copper pipes.

PRELIMINARY CONCLUSIONS

This work strongly supports the pH target of 8.3-8.9 for control of both lead and microbes in Olinda and Pi'iholo. Raising the pH to 8.3 and 8.9 with the addition of soda ash will also increase dissolved inorganic carbon, which can help control leaching of lead above and beyond that achievable with pH adjustment alone. Maintenance of a significant total chlorine residual throughout the system will be important in controlling microbial growth. Moreover, maintaining a chlorine residual will also be important to controlling lead leaching to water, since acid producing microbes could reduce pH of water in consumers homes at the surface of lead materials. Lower pH water can increase lead leaching.

Removal of the phosphate from the distribution system is likely to improve control of bacterial growth. It is possible that the switch away from phosphate and the higher pHs will gradually reduce the concentration of bacteria throughout the system and within consumers' homes.

The possible use of free chlorine should be re-evaluated in the Olinda system. At the new higher pH target, free chlorine decay was not rapid in bench testing. It is possible that the advantages of free chlorine in terms of lead control and disinfection could be achieved in this water without exceeding EPA levels of THMs. But even without a switch to free chlorine, lower levels of bacteria can be achieved as long as a chlorine residual is maintained using chloramine.

Appendix 1. Selected conclusions from expert meeting on use of **Heterotrophic Plate Count Measurement in drinking water safety management,** WHO/SDE/WSH/02.10. Report of an expert meeting, Geneva, 24-25 April 2002. Accessed 8/22/04 at: http://www.who.int/docstore/water_sanitation_health/Documents/HeterotrophicPC/HPCconcl2.htm

5. Systematic independent surveillance that verifies that the above are operating properly.

Piped water systems of large buildings may incur greater growth than encountered elsewhere (because of storage tanks and extensive internal distribution networks, and temperature-related growth). The principal health concerns in these networks are cross connections, and growth of *Legionella* bacteria, that are not detected by the HPC test procedures. General water safety is assured by maintenance protocols, regular cleaning, temperature management and maintenance of a disinfectant residual. For these reasons authorities responsible for building safety should provide advice and require specific water management safety plans.

2.2 Water quality targets

There is no evidence that HPC values alone directly relate to health risk either from epidemiological studies or from correlation with occurrence of waterborne pathogens. They are therefore unsuitable for public health target setting, or as sole justification for issuing "boil water" advisories. Abrupt increases in HPC levels might sometimes concurrently be associated with faecal contamination; tests for *E.coli* or other faecal-specific indicators and other information are essential for determining whether a health risk exists.

2.3 Validation and verification

Experience suggests that HPC monitoring can be used in drinking water supplies along with other information for validation and verification of treatment process performance and other applications. These may include:

- Monitoring of performance of filtration or disinfection processes.
- In piped distribution systems HPC measurements are assumed to respond primarily to (and therefore provide a general indication of) distribution system conditions. These arise from stagnation, loss of residual disinfectant, high levels of Assimilable Organic Carbon (AOC) in the water, higher water temperature, and availability of particular nutrients. In systems treated by chloramination or that contain ammonia in source waters, measurement of several parameters, for a variety of parameters including HPC, but especially nitrate and nitrite (which are regulated for health protection), can sometimes indicate the possible onset of nitrification.
- HPC values are also used in verification (and by some authorities also for validation) of efficacy of cleaning in diverse applications including drink vending machines, food processing and preparation facilities and medical devices. These applications of HPC have not been considered in this review.

2.4 *Aesthetic quality*

Drinking water must be aesthetically acceptable as well as safe. Aesthetic acceptability is directly relevant to health since rejection of safe, but unacceptable (undesirable) water, may lead users to consume acceptable but potentially unsafe alternative waters. HPC testing may be used in investigating aesthetic quality and it is used by some authorities as a marker for some of the underlying causes of some aesthetic problems.

3.2 Plumbed-in Devices

Bacterial growth occurs in plumbed-in domestic water devices (including water softeners, carbon filters etc.) and plumbed-in commercial devices such as beverage vending machines. HPC values in water samples typically increase in such devices. Increases of HPC (due to growth) in these devices therefore do not indicate the existence of a health risk, so long as the entry water meets acceptable water microbial quality norms (e.g. WHO Guidelines for Drinking-water Quality). Appropriate maintenance of these devices is required for aesthetic reasons (see section 2.4) e.g. per manufacturers' recommendations. Plumbed-in devices in health care facilities are considered in section 4.

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