COPPER CORROSION IN DISTRIBUTIOIN SYSTEM UNDER STAGNANT FLOW CONDITIONS

by

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LIST OF ABBREVIATIONS AND SYMBOLS

AO	Aesthetic Objective
AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
DBP	Disinfectant Byproducts
DIC	Dissolved Inorganic Carbon
DO	Dissolved Oxygen
EPS	Extracellular Polymeric Substances
FAS	Ferrous Ammonia Sulfate
GAC	Granulated Activated Carbon
HAHP	High alkalinity (100 mg/L $CaCO_3$) and high pH (8.5)
HALP	High alkalinity (100mg/L $CaCO_3$) and low pH (7.2)
HPC	Heterotrophic Plate Counts
HRWC	Halifax Regional Water Commission
ICC	Indian childhood cirrhosis
ICT	Idiopathic Copper Toxicosis
LAHP	Low alkalinity (10 mg/L $CaCO_3$) and high pH (8.5)
LALP	Low alkalinity (10 mg/L $CaCO_3$) and low pH (7.2)
LGB	Lissamine Green B
MIC	Microbiologically Induced Corrosion
NOM	Natural Organic Matter
NTU	Nephelometric turbidity unit
PBS	Phosphate Buffer Saline
PCU	platinum cobalt color unit
P-HAHP	High alkalinity (100 mg/L $CaCO_3$) and high pH (8.5) with phosphate addition
P-HALP	High alkalinity (100mg/L $CaCO_3$) and low pH (7.2) with phosphate addition
P-LAHP	Low alkalinity (10 mg/L $CaCO_3$) and high pH (8.5) with phosphate addition
P-LALP	Low alkalinity (10 mg/L $CaCO_3$) and low pH (7.2) with phosphate addition
SWTR	Surface Water Treatment Rule
THM	Trihalomethane
TOC	Total Organic Carbon
USEPA	United States Environmental Protection Agency

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ABSTRACT

Copper is the most widely used metal for household plumbing system. One of the most commonly reported adverse health effect of exposure to copper is gastrointestinal distress. Vomiting, nausea, and abdominal pain, usually occur shortly after drinking first draw water (water that sat in the pipe overnight). Lead and Copper Rule or LCR, 1991 sets action level for copper in the distribution system as 1.3 mg/L. Copper corrosion of the distribution system can cause not only health effect but also damages the water supply infrastructure.

From the literature it is known that water quality factors that have the greatest affect on lead and copper corrosion are pH, alkalinity or dissolved inorganic carbonate (DIC), orthophosphate concentration, and buffer intensity. Chlorine residual is also important consideration for copper, although its significance is poorly described in the literature. There are many other factors that affect the corrosion of copper, but they cannot be easily altered by a water system and have a lesser effect on corrosion. Alkalinity and pH are most often manipulated for controlling the corrosion of the system.

The main objective of this study is to understand the impact of secondary disinfectants on copper corrosion under stagnant flow conditions. Results show that in most of the cases the presence of disinfectant residual lowers the copper corrosion rate. This indicates that the copper corrosion may be caused predominantly by microbial activities. The corrosion inhibitor poly-phosphate also effects copper corrosion under stagnant condition. For control pipes with low alkaline water phosphate addition seems to increase the copper level in water but in case of control pipes with high alkaline water presence of phosphate reduces the copper concentration in water. In presence of free chlorine phosphate was found to have beneficial effect but in case of monochloramine pipes the effect is rather opposite. In case of chlorine dioxide dosed pipes with low pH phosphate has beneficial effect but in case of high pH it does not have that much effect. No correlation between the TOC and copper in solution was found except for the monochloramine pipes, where with increase of TOC copper concentration increased. Also under stagnant condition with higher alkalinity copper corrosion rate increases but for increase of pH it shows the reverse trends.

At low pH the monochloramine is least corrosive to copper but in case of high pH free chlorine is least corrosive. Depending upon the water quality, monochloramine can be a logical alternative to free chlorine.

1.0 Introduction

Corrosion is a physiochemical interaction between a metal and its environment that results in change in properties of metal (ISO, 1979).Corrosion control can be an important and costly issue for many water utilities as it may cause pipe leakage or blockage to flow. Corrosion can also lead to an unwanted change in water quality during distribution (Snoeyink and Wagner, 1996; Sander et al., 1996).

The factors affecting corrosion are diverse and are highly dependent on the raw water characteristics. Several of these factors can be controlled during water treatment, such as pH, alkalinity or disinfectant residual. Other parameters such as temperature are difficult to control. Often, the effect of one factor increases or reduces the relative importance of another, for example it is well known that an increase of 10^0C will double the chemical reaction rates. As a result, corrosion studies tend to be constrained by study conditions and the results are not easily extrapolated to other distribution system.

Finished water also tends to be somewhat corrosive due to the presence of disinfectant residual. The most commonly used disinfectant in North America is free chlorine (AWWA Water Quality Division Disinfection Systems Committee, 2000). Free chlorine is widely used because of its effectiveness as a disinfectants, easy to use and provide a measurable residual. The main concern with free chlorine is the formation of harmful byproducts. When free chlorine reacts with organic material in water, trihalomethanes (THM) are formed, which are known to be carcinogenic (Black et al., 1996, Cantor 1997).They have also been suspected to increase the risk of complication among the pregnant women (Gallagher 1998).

Monochloramine is another alternative disinfectant, which is gaining popularity. It is formed through combination of free chlorine and ammonia. It is not as strong a disinfectant as free chlorine but it is very stable in the distribution system.

Monochloramine produces nitrate and nitrite as byproducts which are known to cause methemoglobinemia, or "blue baby" disease (White, 1999).

As an alternative to free chlorine, several researchers have examined chlorine dioxide, which is very effective to inactivate *Cryptosporidium* and control nitrification. Chlorine dioxide has higher disinfecting capacity than free chlorine and also maintains a residual in the distribution system. As the use of ClO_2 is relatively recent, its limitations in terms of by-product formation and other water quality impacts is not well documented (Volk et al., 2002).

Copper corrosion in the distribution system increases the concentration of copper in drinking water. Excess copper in water can cause harmful toxic effect on human body and cause color and test in water. Copper can also lead to staining of cloths and premature failure of the plumbing system. Copper in drinking water ultimately accumulates in the surface water body, causing toxic effect to aquatic plants and animal.

1.1 Objectives

The objective of this research is to understand the impact of secondary disinfectants in copper corrosion under stagnant flow conditions. In particular, the specific objectives of the investigation were to:

- Compare the impact of disinfectants (free chlorine, monochloramine, ClO_2) on copper corrosion.
- Examine the effect of chemical properties of water (such as pH and alkalinity) on copper corrosion and find the appropriate properties to control corrosion;
- Examine the effect of poly-phosphate inhibitor on copper corrosion;
- Examine the effect of Natural Organic Matter (NOM) on copper corrosion;

2.0 Corrosion in Distribution Systems

Corrosion is a mechanism of returning processed metals, such as steel, copper, and zinc, to their native states as chemical compounds or minerals. For example, iron in its natural state is an oxidized compound (i.e., Fe_2O_3, FeO, Fe_3O_4), but when processed into iron and steel it loses oxygen and becomes elemental iron (Fe^0). In the presence of water and oxygen, nature relentlessly attacks steel, reverting the elemental iron (Fe^0) back to an oxide, usually some combination of Fe_2O_3 and Fe_3O_4. In the broadest sense, corrosion can be defined as the destructive attack of a metal by chemical or electrochemical reaction with its environment (Hancock, 1998). Corrosion can also be extended to other materials that are damaged by their environment: plastic swells in solvents, concrete dissolves in sewage, and wood rots in moist conditions (Bradford, 1993). Corrosion is a very common problem experienced by industries that require water or liquids to be transported through pipelines. In case of water industry, the metal that deteriorates is the pipe material into drinking water (Schock, 1999).

Most waters are corrosive to some degree, and the corrosivity of water depends on its physical and chemical characteristics (LeChevallier et al., 1993). A survey of the 100 largest member utilities of American Water Works Association Research Foundation (AWWARF) found that the most common distribution system problem was corrosion of cast-iron pipe. The majority of distribution system pipes are composed of either cast or ductile iron materials. Other metals such as copper, lead and zinc can be found in small section of this distribution systems such as in household plumbing and solder used to seal pipe joints. The corrosion characteristics of these metals are not alike. So, to find an optimum solution is very complex. For this reason, corrosion is an important problem for water utilities to overcome.

The corrosion in water distribution systems can have widespread impact. It can affect public health, public acceptance of water supply and the cost of providing safe water (Shock, 1999). The deterioration of materials resulting from corrosion can result in large expenditures for repairs and replacement. Corrosion tends to increase the concentration of metals in tap water. Some of these metals (i.e. iron) result in aesthetic changes in drinking water (Maddison et al., 2001). Potentially toxic metals such as lead can leach from pipe. Corrosion can cause leaks which will lead to loss of water and water pressure.

Corrosion byproducts can decrease the size of the pipe and thus can change the flow rate. Corrosion byproducts that attach to the pipe surface or accumulate as sediments in the distribution system can shield microorganisms from disinfectants (Shock, 1999). These microorganisms can cause problems such as bad tastes or odors, slimes, sickness, and additional corrosion. To solve this problem, higher doses of disinfectants are used. So, corrosion increases the disinfectant demand of the pipe.

2.1 Corrosion Chemistry

Although corrosion is a complicated process, it can be most easily comprehended as an electrochemical reaction involving three steps as shown in Figure 2.1:

1. Loss occurs from that part of the metal called the anodic area (anode). In this case, metal M lose n number of electron to the water solution and becomes oxidized to M^{+n} ion.
2. As a result of the formation of M^{+n}, electrons that are released flow through the metal to the cathodic area (cathode).
3. Oxygen (O_2) in the water solution moves to the cathode and completes the electric circuit by using the electrons that flow to the cathode to form hydroxyl ions (OH^-) at the surface of the metal. Chemically, the reactions are as follows:

$$\text{Anodic reaction: } M \longrightarrow M^{n+} + ne^-$$

$$\text{Cathodic reaction: } nO_2 + nH_2O + ne^- \longrightarrow 2n(OH^-)$$

Every metal surface is covered with innumerable small anodes and cathodes as shown in Figure 2.1. These sites usually develop from: (1) surface irregularities from forming, extruding, and other metalworking operations; (2) stresses from welding, forming, or other work; or (3) compositional differences at the metal surface.

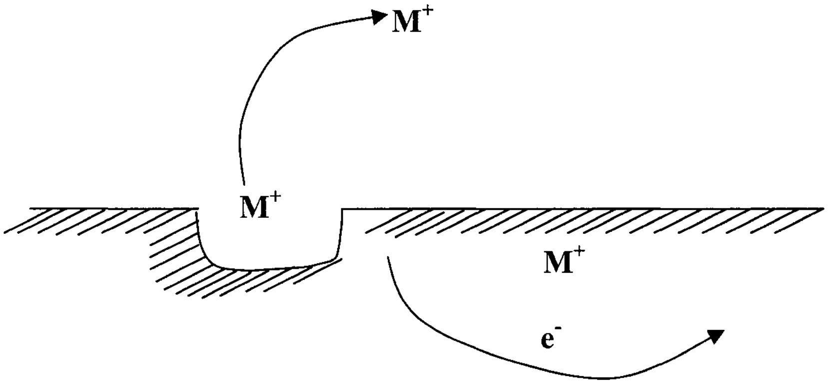

Figure 2.1 Reaction at the anode

2.2 Types of Corrosion

Corrosion can be of many different forms. It can be classified by the appearance of the corroded metal. However all types are interrelated. The kind of corrosive attack depends on the material, the construction of the system, the scale and oxide film formation, and the hydraulic conditions (Schock, 1999). The distribution of anodic and cathodic area over the corroding metal primarily influences the types of corrosion. In particular the types of corrosion that will be reviewed are uniform corrosion, pitting corrosion, galvanic corrosion, concentration cell corrosion and microbial induced corrosion.

2.2.1 Uniform Corrosion

Uniform corrosion is the most common form of corrosion. The corroding metal acts as both the anode and cathode. These areas are continually shifting, resulting in a fairly smooth surface that may or may not be covered with corrosion byproducts (Bradford, 1993). These corrosion cells can develop on these heterogeneous metals because of possible differences in crystal structure and imperfections in metal. Also, the difference in concentrations of oxidants and reductants in solutions cause momentary differences in potentials leading to this type of corrosion (Schock, 1999). Although uniform attack is the most common form of corrosion and consumes most metals, it is also the least serious as its rate can be easily predicted and thus the life of the metal can be determined (Bradford, 1993).

In the distribution system within a pipe when the anodic and cathodic areas are very small and close to one another uniform corrosion will occur. Anodic sites will shift about the surface resulting in a relatively uniform loss of metal over the surface of the pipe. Uniform corrosion results from the heterogeneous nature of the metal pipe. It results in a relatively uniform loss of metal over the surface of the pipe.

For copper tubings uniform corrosion is characterized by an unvarying surface covered with a loose, powdery blue-green scale (Cruse et al., 1985) or with tarnish like an old copper penny (Reiber. 1989). If the uniform corrosion rate in copper is excessive it will cause unacceptable levels of copper corrosion byproduct release resulting in green or blue water problem. This type of corrosion may cause coloring or straining of the cloth, metallic test water or in extreme case nausea if enough copper is consumed (Pontius F 1991). Uniform copper corrosion rates are commonly expressed as pipe penetration rates (rate of pipe wall loss) in mili-inches per year (mpy). According to Edwards et.al (1994a) if corrosion rate is more than 1mpy it is considered high and if it is less than 0.1 mpy it is low.

2.2.2 Pitting Corrosion

Pitting is a form of extremely localized attack that results in holes in the metal (Bosich, 1970). It is one of the most destructive forms of corrosion and very difficult to predict. It can cause failures with only a small percentage weight loss of the entire structure. A local cell or the formation of an anode is necessary for all corrosion by electrolytes. These cells are created because of differences in the metal surface or in the environment. Impurities, grain boundaries, nicks and rough surfaces are all metallurgical or mechanical differences, while concentration cells are environmental differences. The smaller the anodic area is relative to the cathode, the more severe the corrosion will be (Bosich, 1970).

Pitting can begin or concentrate, at a point of surface imperfections, scratches, or surface deposits in a pipe. It is frequently caused by ions of a metal higher in the galvanic series plating out on the pipe surface. Pitting occurs in an environment that offers some but not complete protection. The pit develops at a localized anodic point on the surface and continues by virtue of a large cathodic area surrounding the anode (Schock, 1999).

The initiation of pitting in copper tubing is not well understood. Lucey's (Lucy 1967) membrane theory is the most widely used explanation of this mechanism. According to this mechanism the key to pit initiation is the formation of porous cuprous oxide membrane over a cuprous chloride layer lying adjacent to the copper surface. A cuprous chloride film is formed immediately when copper is immersed in solution containing chloride ion. The cuprous chloride is removed from the surface by hydrolysis to cuprite, oxidation and formation of cupric salts, and ultimately dissolution in bulk solution. The removal of cuprous chloride forms passivating scale on the copper. However in unusual case the formation of cuprous chloride may exceed the removal which results cuprous chloride formation under the cuprite and initiation of pitting in copper.

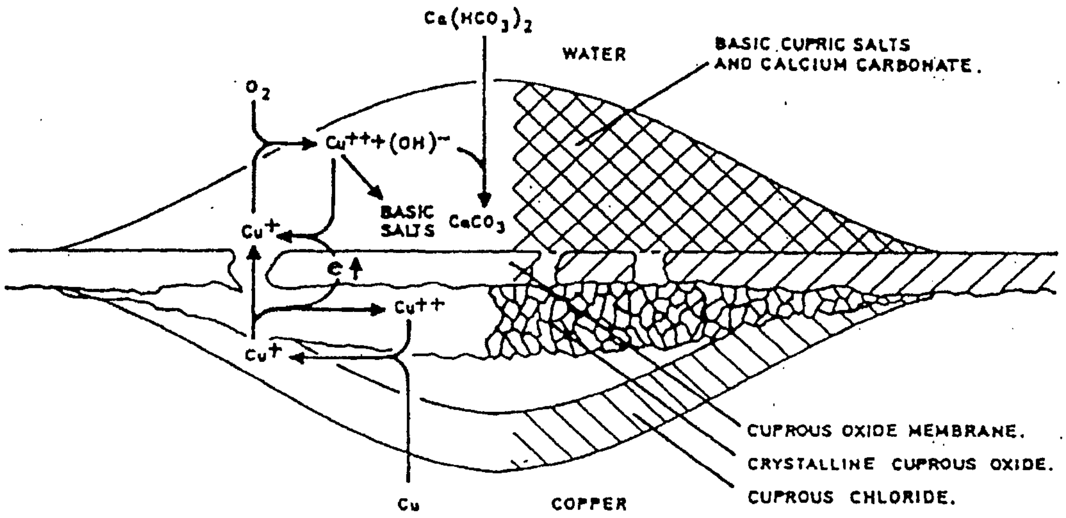

Figure 2.2: Membrane Theory (Lucey, 1967)

The galvanic couple between the copper and the carbon surface file is another factor that increases the pitting (Campbell 1950). Carbon films are cathodic to the copper metal so it stimulates the copper corrosion.

Edwards et al. (1994a) divided the copper pitting into three different groups, they are Type I pitting (cold water), Type II pitting (Hot water), Type III pitting (Soft water). The Table 2.1 on the next page summarizes the uniform and pitting corrosion of copper (after Edwards et al., 1994a)

Type I or cold water pits are relatively deep and narrow. It is characterized by a glassy film of reddish-brown cuprite (Cu_2O) sandwiched between the copper surface and the exterior scale layer of basic copper salt which is most commonly made of malachite[Cu_2 (OH_2)(CO_3)](Cruse et al., 1985; Cruse et al., 1975; Campbell et al., 1979; Campbell et al., 1950; Kasul et al., 1993). Also sometimes a deposit of copper chloride (CuCl) forms between the cuprite and the overlying layer of basic copper salts and the basic copper salts sometimes forms pipercles directly over the pit.

Table2.1 Types of copper corrosion with exacerbating and ameliorating factors (Source: Edwards et al., 1994)

Characteristics	**Uniform Corrosion**	**Type I Pitting(Cold Water)**	**Type II(Hot Water)**	**Type III (Soft Water)**
Pit Shape	No pits	Deep and narrow	Narrower than type I	Wide and shallow.
Problem	Blue or green water, high by-product release	Pipe failure	Pipe failure	Blue water, Voluminous by-product release, pipe blockage
Scale morphology on Attacked surface	Tarnished copper surface or loose powdery scale	Underlying Cu_2O with overlying malachite, calcite, or other basic copper salts, occasionally CuCl underlines Cu_2O	Underlying Cu_2O with overlying bronchantite, some malachite	Underlying Cu_2O with overlying brochantitie, some malachite
Water Quality	Soft waters of low pH(<7.2)	Hard, cold, well waters between pH 7 and 7.8,High sulfate relative to chlorides and bicarbonate, high CO_2	Hot waters, pH below 7.2,high sulfate relative to bicarbonate, occasional Mn deposits.	Soft waters, pH>8.0
Initiating factors	None noted	Stagnation early in pipe life, deposits within pipe including dirt or carbon films, high chlorine residuals, water softeners, alum coagulation.	Higher temperatures, high chlorine residuals, alum coagulation, particles	Stagnation early in pipe life, pHs>8.0,alum coagulation, low chlorine residuals
Ameliorating factors and treatments	Raise pH or increase bicarbonate	NOM ,increase bicarbonate and pH	Lower temperatures, higher pHs, increase bicarbonate and pH	NOM, avoid stagnation early in pipe life, increase hardness and alkalinity, elevate Cl_2 residual to >0.5mg/L

Cold water pitting (Type I) failure can occur within few months to few years and are the most common cause of copper pipe failure According to Edwards et al. (1994a) cold water pits are commonly formed in ground waters of relatively high conductivity, hardness, alkalinity, sulfate concentration and low TOC.

Hot water Pitting (Type II) is narrower than the cold water pits. This types of pits have film of crystalline cuprous oxide sandwiched between the copper surface and an exterior scale layer invariable containing bronchantie [$Cu_4(OH)_6(SO_4)$] (Mattsson et al., 1968; Shafer et al., 1961).According to Cruse et al., (1985) theses type of pits are generally formed in water with pH<7,temperature>60^0C, and a low bicarbonate-to-sulfate ratio. Hot water pit failures are slower than the cold water i.e. type I, and rarely produce any perforation in less than eight years (Ferguson et al., 1996). Sometimes hot soft water that contains small amount of manganese can produce a special kind of type II pitting in which pits are slightly larger and manganese dioxide forms a black deposit on the surrounding areas of the copper.

Soft water (Type III) Pitting is fairly wide and shallow. It is characterized with a film of crystalline reddish-brown cuprite sandwiched between the attacked copper surface and an exterior scale layer of bronchanite or malachite, or both (Edwards et.al.1994).Several researcher (Page G et al., 1972; Linder M et al., 1982; Gilbert P.T.1966; Potter, E.C.1984; Nicholas D 1987) characterized this types of pitting by voluminous insoluble corrosion products that contaminate the water supply or cause pipe blockage. Cold water of low conductivity, low alkalinity and relatively high pH usually causes this type of pitting (Edwards et.al.1994a).

2.2.3 Galvanic corrosion

Galvanic corrosion occurs when two different types of metals or alloys contact each other and the elements of a corrosion cell are present. One of the metals serves as the anode and deteriorates, while the other serves as the cathode. Metals can be arranged in order of their tendency to become anodic and this is called the galvanic series (Schock, 1999).An empirical galvanic series of metals is shown in Table 2.1.The further two metals in contact are apart in the galvanic series, the greatest the potential for corrosion.

Table 2.2---Empirical galvanic series (Larson, 1975)

Corroded end

Magnesium
Magnesium Alloys
Zinc
Aluminum
Cadmium
Steel or Iron
Cast Iron
Iron Alloys
Lead tin solders
Lead
Tin
Nickel
Brasses
Copper
Bronzes
Titanium
Monel
Silver solder
Silver
Carbon (Graphite)
Gold

↑ Increasingly Active

Protected end

Galvanic corrosion in distribution systems occurs where brass, bronze, or copper is in direct contact with aluminum, galvanized iron, or iron. Proper selection of materials and the order of their use in domestic hot- and cold-water plumbing systems are critical to the control of corrosion. Galvanic corrosion rates can be increased by having large cathodic areas relative to anodic areas, the physical closeness of the two metals. It also depends on how further apart the two metals are on the galvanic series. To prevent galvanic corrosion, for example, only copper tubing should be used with copper-lined water heaters. Brass valves in contact with steel and galvanized plumbing in waters with high total dissolved solids cause corrosion of the steel and galvanized pipes. Dissolved copper can attack spots on galvanized pipe, thereby causing copper-zinc galvanic cells (Kenworthy, 1943)

2.2.4 Concentration Cell Corrosion

Concentration cell corrosion is similar to uniform corrosion. However instead of dissimilar metal, a galvanic current can also be set up when a single metal is exposed to different concentrations (ionic strengths) of water solutions. As a result anodic and cathodic areas are formed, and corrosion occurs (Bosich, 1970). Differences in pH, metal-ion concentration, anion concentration, or dissolved oxygen cause differences in the solution potential of the same metal. Differences in temperature can also induce differences in the solution potential of the same metal (Schock, 1999). Concentration cells are the usual cause of the troublesome local etches or pitting type of metal loss.

Concentration cell corrosion can occur at metal-water interfaces exposed to air, such as in a full water tower, accelerating corrosion a short distance below the surface. The dissolved oxygen (DO) concentration is replaced by diffusion from air and remains high at and near the surface, but does not replenish as rapidly at lower depths because of the distance. Therefore, the corrosion takes place at a level slightly below the surface rather than at the surface.

2.2.5 Microbiologically Induced Corrosion

Microbiologically induced corrosion (MIC) results from a reaction between the pipe material and organisms such as bacteria, algae, and fungi (Schock, 1999).The corrosion in the distribution system can be affected by the microorganisms in numerous ways (Emde et al., 1992). Some microorganisms are able to metabolize corrosion inhibitors or protective coatings. Oxygen concentration cells can be created by aerobic microorganisms on the metal surface. Uneven depletion of oxygen occurs due to the variations in biofilm density and thickness which ultimately creates areas that are more anodic then others. Formation of ionic concentration cells can be enhanced by microbial activity. MIC in case of copper is very important. According to different investigators (Bremer, 2001) the developments of pitting in new hospitals in Germany and Scotland in the mid 1980s are due to the microbial activities. Taylor (1997), shows that excessive Cu corrosion by product release occurs in the extremities of the system with very low Chlorine residual. From these studies it is suspected that the dominant cause of corrosion in these cases may be microbial activities. The possible mechanism behind the MIC can be summarized as (1) Creation of a zone of lower pH surrounding the metal surface due to production of acidic metabolites on the metal surface (2) the binding of Cu by extracellular polymeric substances (EPS) of microbial origin. (3) Change of the nature and porosity of the oxide film from the incorporation of cells and polymers.

Biofilm activities can also result in changes in interfacial chemistry causing a destabilization in the passive film or prevention of formation of the passive film on the copper surface. According to Bremer and Geesey, (1993) (EPS) bind copper ions to the biofilm and accelerate the corrosion process. Davidson et al.,(1996) reported that production of acidic metabolic products is associated with increased Cu concentration in the bulk phase during the development of an *Acidivirax delafieldii* biofilm on copper. They also reported that correlation exist between the level of extractable surface-associated Cu and increase in the protein and carbohydrate concentration in the biofilms. Surprisingly dead ends and long horizontal pipe where sediment can be accumulated on the bottom are especially susceptible to MIC (Fischer et al., 1995, Page 1973).

2.3 Factors Affecting Corrosion in Water Distribution Systems

The physical, chemical and biological characteristics of drinking water affects the occurrence and rate of corrosion (Shock, 1999).These factors are interrelated so in most cases corrosion is caused or increased by a complex interaction among several factors. The corrosion in water distribution systems depends upon the water composition and composition of the pipe material.

2.3.1 Physical Characteristics

Flow velocity and temperature are the two main physical characteristics of water that affect corrosion.

2.3.1.1 Velocity

Corrosion of pipe material is always affected by the velocity of the water it carries. High velocities increase the rate at which dissolved oxygen comes in contact with the pipe materials, thus increasing the corrosion. Erosion corrosion is mainly caused by high velocities (Schock, 1999). Obrecht and Quill (1960) found that the corrosion in copper tubing by sodium zeolite softened water increases with increasing velocities. However, high velocities can have a beneficial effect on corrosion by formation of protective coating at faster rate because due to high velocity transportation of the protective material to the surfaces occurs at a higher rate.

2.3.1.2 Temperature

Increases in temperature should increase the rate of corrosion because for every 10^0C rise in temperature, chemical reaction rates tend to double. As well, the electrode potential is proportional to the absolute temperature (Schock, 1999). But in practice this rule is not always observed as there other factors playing roles in corrosion.

The effect of temperature varies depending on the water characteristics. Several researchers reported (Oberchi and Quill 1960, Kristansen 1977, Stone et al., 1987) that in the case of copper an increase of temperature usually increases corrosion. Sing and Mavinic (1991) conducted a survey on high rise residential plumbing and found that cold water copper pipe corrosion by product is about one third of that for hot water copper pipes. Also Macquarrie et al., (1997) reported lower copper corrosion at lower temperature. Edwards and Jacobs (2000). Arens et al., (1995) found that with increase of temperature the copper corrosion decreases especially when type III soft water pitting or blue water occurs. They reported that at high temperature (65^0C) copper corrosion reduced markedly. They found highest corrosion rate at temperature 30^0C.They propose that the elevated temperature may kill the microorganism that cause corrosion because most bacteria flourish at temperature range 25 to 45^0C.

2.3.2 Chemical factors Affecting Corrosion

Dissolved substances in water have an important effect on corrosion. Several of these chemical factors are closely related, and a change in one can impact another.

2.3.2.1 pH

The pH of water is a measure of acidity from H+ concentration. The pH is an important factor in corrosion because hydrogen ions (H+) are one of the major substances that accept the electrons released by a metal when it corrodes. Most drinking water's pH ranges from 6 to 10. With the increase of pH the corrosion rate decreases. One common corrosion control treatment strategy is to raise the pH of the source water. This can be done through chemical or non-chemical means. Any increase in pH within the pH range of 5 to 10 result in a decrease in copper levels. At the higher pHs, copper has less tendency to dissolve and enter drinking water. The formation or solubility of protective films is also pH dependent (Schock, 1999).

The pH of water changes significantly as water moves through the distribution system. Although the pH measured at the pump station or treatment facility may appear to be stable, as it passes through the distribution system it may increase or decrease significantly. This will depend on the size of the distribution system, flow rate, age and type of plumbing material. It is important to maintain the target pH throughout the distribution system, so that metal levels can be minimized at the tap.

2.3.2.2 Alkalinity and Dissolved Inorganic Carbon

Alkalinity is a measure of the ability of water to neutralize acids; it is a measure of buffering capacity against a pH drop (Droste, 1997).Total alkalinity is the sum of bicarbonate, carbonate and hydroxide ions. Alkalinity is typically reported as mg/L "as calcium carbonate" ($CaCO_3$). Dissolved inorganic carbon (DIC) is defined as the sum of all dissolved carbonate containing species (Schock, 1999). It is measured as milligrams of carbon per liter (mg C/L).DIC is related to alkalinity and if pH and alkalinity is known then DIC of the water can be predicted. The bicarbonates and carbonate present affect many important reactions in corrosion chemistry, including the water's ability to form a protective metallice carbonate scale or passivaiting film (Schock, 1999). At a constant pH, as the DIC increases, copper levels increases. The effect of DIC is strong as the effect of pH at high (> 30 mg C/L) levels of DIC. Increases in DIC of 3-6 mg C/L will typically have minimal impact on copper levels, particularly with respect to the regulatory action level. However recent studies (Edwards et.al 1994b) show that bicarbonate ion have a dual nature that is pH dependent. The researcher found that at $pH \leq 7.0$ it causes activation i.e. increase corrosion and at $pH \geq 8.5$ it causes passivation i.e. reduces copper corrosion. In contrast, for control of lead, as the DIC increases the lead concentration decreases or remains essentially unchanged within the pH range of about 7.0 to 8.0. The effect of DIC usually is more prominent at lower pH than at higher.

2.3.2.3 Dissolved oxygen

Oxygen is one of the most prevalent agents of corrosion. In many cases it is the substance that accepts the electrons given up by the corroding metal (Schock, 1999). However, adding dissolved oxygen can have a great effect on water quality as it oxidizes dissolved reduced iron and manganese (more slowly) and forms more soluble copper compounds than waters with no dissolved oxygen. This is a consideration for aeration for either iron oxidation or for corrosion control. The benefits of carbon dioxide removal and pH rise from aeration must be balanced against the possibility of creating soluble copper in the distribution system from increased dissolved oxygen addition.

2.3.2.4 Disinfectant Residual

Several researchers investigated the effect of disinfectant on copper corrosion. Atlas et al., (1982) tested chlorine conc. of 1,2,5,7.5,10 mg/L for 24 hour exposure and found that a higher free chlorine concentration causes more copper dissolution especially at lower pH. Stone et al., (1987) also reported similar trends. Singh and Mavinic (1991) from their field study reported about two similar buildings, where copper by-product release was higher at the building with higher chlorine level. Also Allas et al., (1982) and Reiber (1989) concluded that chlorine is dominant over oxygen as an oxidizing agent on copper. In contrast to these findings Edwards and Ferguson (1993) and Edwards et al., (1999) found that chlorine residual reduces copper corrosion. They concluded that chlorine might prevent the usual “blue water” or the soft-water pitting problem. Also several other researchers also reported that in New Zealand, Australia, and US excessive by-product release in chlorinated water supply occurs at very low residual chlorine (Cl_2) concentration.

Zhang Xiaohui et al., (2002) conducted a study on the copper corrosion behavior in mildly alkaline water in presence of monochloramine. They reported that polarization resistances (R_p) of copper increased rapidly with time for the first 6 days then slowly from 8 to 30 days. Also Macquarrie et al., (1997) reported for greater Vancouver Water

District water with the application of monochloramine the pipe metal corrosion decreased. No literature was found on the effect of chlorine dioxide on copper corrosion.

2.3.2.5 Natural Color and Organic Matter

Natural organic matter (NOM) in the water can affect corrosion in several ways. Several researchers (Broo.et al., 1998, Holmstrom et al., 1997) reported that copper release directly increases with NOM concentration. But Korshin et al., (1996) reported that very small amounts such as 0.1-0.2 mg/L levels of NOM produce significant increases(>0.8mg/L) in copper byproduct release, but further increase in NOM concentration does not change the copper release in water. They hypothesized that NOM might cause mobilization of colloidal copper via particle stabilization and detachment. Edwards et al., (2001) conducted a study on copper corrosion by product release and organic matter. They concluded that copper corrosion by-product release increases in the presence of NOM because of complexation and/or colloid mobilization/dispersion. According to this report the presence of NOM can also reduce the copper corrosion. They explained that, NOM can be used as food source for micro organism thus leading to DO depletion and subsequent re-deposition of copper onto the pipe wall in the presence of chloride or other ions. Moreover, gradual sorption of soluble NOM on to the scale on copper pipe surfaces decreases soluble copper complexation capacity of water and thus leads to reduced copper concentration.

2.3.2.6 Corrosion Inhibitor

Phosphate inhibitors are usually used for corrosion control in the distribution system. Poly phosphate or orthophosphate or a blend of these two is used as corrosion inhibitor. Though researchers have studied the effect of phosphate inhibitor on corrosion, how these inhibitors actually work is not clearly known. Bancroft (1988) reported that for tap water with low pH, alkalinity and hardness 0.5 mg/L zinc ortho phosphate reduced copper corrosion. Also Benjamin et al., (1990), Boffardi and Sherbondy (1991) and

Johnson et al., (1993) conducted copper pipe rig test with orthophosphate dosing and found a similar effect. However Edwards et al., (2002) reported that poly or orthophosphate generally reduced the soluble copper concentrations, but orthophosphate is more efficient than polyphosphate. They also reported that at pH 7.2 and alkalinity 300mg/L polyphosphate significantly increased copper release by hindering malachite formation.

2.4 EFFECT OF COPPER CORROSION

2.4.1 On human health and environment

According to Oskarsson A et.al (1998) in the US, UK, Sweden, and Norway more than 90% of the domestic plumbing material is made of copper. Also in other parts of Europe such as in Germany, Spain, France and Italy about 40 to 60% of the plumbing is made of copper. So corrosion of copper can affect a large portion of the population of these countries.

The Guidelines for Canadian Drinking Water Quality (Health and Welfare Canada 1993) has no maximum acceptable concentration (MAC) for copper but from aesthetic objective (AO) copper level should be less than 1.0mg/L. According to USEPA (1991) utilities have to take specified corrective action when copper level exceed 1.3 mg/L in more than 10% of 1.0 L standing water sample taken at the tap.

The effect of copper is more acute on the gastrointestinal system as in most cases of copper toxicity results nausea, spontaneous vomiting, abdominal pain, and diarrhea. According to different investigator except diarrhea these symptoms occurs shortly after ingestion and are not persistent (Gill and Bhagat 1999).

High level of copper can cause Liver cirrhosis such as Indian childhood cirrhosis (ICC) or Idiopathic Copper Toxicosis (ICT) (Müller et al., 1996). Normal level of copper in food and drink can also cause complication in case of Wilson's disease.

The copper in the drinking water pipe ultimately results in high concentration of copper in waste water or sludge which is harmful to the environment.

2.4.2 Economics

Copper corrosion can cause premature failure of the plumbing system. The cost of replacing the plumbing system in a typical Canadian home would be around $9400(Macquarrie et al., 1997).

2.4.3 Aesthetics

Copper salts at concentration above 1-2mg/L in water can cause blue green straining of plumbing fixtures, laundry and bleached hair. Stained bathroom ware due to copper corrosion is very common in some parts of Canada. The presence of copper can also cause taste in the water. The test threshold concentration of copper depends upon the water quality and individual difference in sensitivity. According to different literature test threshold ranged from 0.3 to 12.7 mg Cu/L depending upon water quality. Cohen et al., (1960) reported the test threshold for drinking water is 12.7 mg/L and for distilled water 6.6 mg/L of Cu.

3.0 Disinfectants Used In Distribution System

Disinfection is the destruction of pathogenic organisms in water. Disinfectants are mainly used for this purpose to limit water born disease and inactivate pathogenic organisms in water. Actually the introduction of disinfection virtually eliminated water born diseases such as typhoid and cholera. For example (White et.al 1992) in Niagara Falls NY in 1911 the number of typhoid cases was 185 deaths per 100,000 populations but after the introduction of filtration and chlorination this number drops to nearly zero. The disinfectants also do the followings (USEPA1999):

- Minimization of disinfection by produce (DBP) formation;
- Control of nuisance Asiatic clams and zebra mussels;
- Oxidation of iron and manganese;
- Prevention of re-growth in the distribution system and maintenance of biological stability;
- Removal of taste and odors through chemical oxidation;
- Improvement of coagulation and filtration efficiency;
- Prevention of algal growth in sedimentation basins and filters;
- Removal of color.

Although there are many characteristics of a good disinfectant but most important ones are (Droste, 1997) as follows:

- Effective kill of pathogenic microorganisms
- Nontoxic to human or domestic animals and
- Provides residual protection in drinking water.

Commonly used disinfectants in the portable water industry are free chlorine, chloramines, chlorine dioxide, ozone, and ultraviolet radiation (Hass, 1999). Among those, only the chlorine-based disinfectants are able to maintain a residual within the distribution system, although ozone has the greatest disinfectant capacity.

The disinfectants can be divided into two types: primary disinfection and secondary disinfection. Secondary disinfection is some times also called residual maintenance. Primary disinfection is the removal or inactivation of microbiological contaminants from the raw water supply (Trussel, 1998).The surface water treatment rule (SWTR) of 1989 in the United States has set inactivation targets for certain indicator organisms that must be met during primary disinfection (Droste, 1997).For example according to this rule surface water supplies requires 3.0-log inactivation for Giardia cysts and 4.0-log inactivation for viruses. This inactivation is based on the Ct concept, which involves the disinfectant dose and its contact time with water. Secondary disinfection is the addition of a disinfectant to the water to maintain a residual in a distribution system to prevent the re-growth of microorganisms in the distribution system. This research is focused on secondary disinfection.

3.1 Free Chlorine

The first use of chlorine in water treatment plants was reported in Belgium (White,1992) It has become the most prevalent method used for disinfection(Sawyer et.al.1994). Its popularity comes from its potency and range of effectiveness. Also, it is cost effective, easy to apply, measure, and control and maintains a good residual. Chlorine also oxidizes soluble iron manganese and sulfides, enhances removal of color test and odor (USEPA1999).It may also enhance coagulation and filtration of particulate contaminants. There are some problems with the use of chlorine such as the formation of DBP, high chlorine import test and odor, and it may induce corrosion as it is corrosive in nature. Chlorine is not effective at high pH.

Chlorine gas hydrolyzes rapidly in water according to the following equation to form hypochlorous acid.

$$Cl_2 + H_2O \longrightarrow HOCl + H^+ + Cl^-$$

Hypochlorous acid is a weak acid and tends to undergo partial dissociation as follows:

$$HOCl \longleftrightarrow H^+ + OCl^-$$

This reaction is pH dependent. Between pH 6.5 to 8.5 incomplete dissociation occurs and both HOCl and OCl^- species are present (White, 1992). Typically, bellow a pH of 5, almost all the chlorine is in the form of HOCl, while above a pH of 10, almost all is in the form of OCl^- (Hass, 1999). HOCl is a very strong disinfectant, about 80 to 200 times stronger than OCl^-(Droste 1997). Chlorination at lower pH (<5) is preferred.

3.2 Monochloramine

The disinfecting ability of monochloramine was known from the early 1900s.Initially it was used for taste and odor control. It is more stable than free chlorine.

Chloramines are formed from the reaction of chlorine and ammonia. When chlorine is dispersed in water hypochlorous acid (HOCl) is formed from rapid hydrolysis.

HOCl reacts rapidly with ammonia. Three types of chloramines can be formed according to the following equations.

$$HOCl + NH_3 \longrightarrow NH_2Cl + H_2O \quad \text{Monochloramine}$$
$$NH_2Cl + HOCl \longrightarrow NHCl_2 + H_2O \quad \text{Dichloramine}$$
$$NHCl_2 + HOCl \longrightarrow NCl_3 + H_2O \quad \text{Trichloramine}$$

The distribution of three types of chloramines is a function of pH (White, 1992).If they are prepared at a pH of 10, then they will be very stable.

In order to convert all free chlorine to monochloramine, a weight ratio of 5:1 or less chlorine to ammonia must be met. The proper pH must be maintained to successfully form chloramines (White, 1992). In the case of monochloramine less/no THM is created because ammonia is added before chlorine which prevents the reaction of chlorine with organic material. The monochloramine though not as strong as chlorine but it is the most stable.

3.3 Chlorine Dioxide

Chlorine dioxide was first used in water treatment in 1944 in Niagara Falls, New York (White 1992).Chlorine dioxide is a neutral compound of chlorine in the +IV oxidation state (Hass, 1999).Chemically, chlorine dioxide is a stable free radical that, at high concentrations reacts violently with reducing agents. Chlorine dioxide solution is extremely volatile and can not be stable in open vessels. Aqueous solutions of chlorine dioxide are also subject to photolytic decomposition. However, it is stable in dilute solution in a closed container in absence of light (Pontius, F. W, 1990). Its gaseous form has an intense greenish yellow color with a distinctive odor. Chlorine dioxide cannot be compressed or stored commercially as a gas because it is explosive under pressure.

Chlorine dioxide has more disinfecting power on *Cryptosporidium parvum* and *Giardia lamblia*. For drinking water industries Chlorine dioxide is prepared from sodium chlorite reacting with gaseous chlorine (Cl_2), hypochlorous acid (HOCl), or hydrochloric acid (HCl).The reactions are as follows:

$$2NaClO_2 + Cl_2 === 2ClO_2 + 2NaCl$$
$$2NaClO_2 + HOCl === 2ClO_2 + 2NaCl + NaOH$$
$$5NaClO_2 + 4HCl === 4ClO_2 + 5NaCl + 2H_2O$$

The principal byproducts of chlorine dioxide are chlorate (ClO_3^-) and chlorite (ClO_2^-) ions.As oxidant chlorine dioxide has a unique one-electron transfer mechanism which forms chlorite (ClO_2^-).

$$ClO_2 + e^- == ClO_2^-$$

The overall reaction that describes chlorate formation can be written as follow:

$$ClO_2^- + HOCl === ClO_3^- + Cl^- + H^+$$
$$ClO_2^- + Cl_2 + H_2O === ClO_3^- + 2Cl^- + H^+$$

There is concern for the presence of chlorite and chlorate ion in drinking water. Gonce and Voudrias, (1994) reported that chlorite can cause hemolytic anemia when fed to rats and mice via drinking water. The USEPA recommends that the combined residuals of chlorine dioxide, chlorite and chlorate do not exceed 1.0 mg/L in the distribution system (Gordon et al., 1990). According to the recently proposed Disinfectant/Disinfectant By products rule the maximum contaminant limit for chlorite is 1.0 mg/L. Therefore to comply with this regulation, chlorine dioxide dosage should be limited to 1.4mg/L, unless excess chlorite ion is removed (White, 1992).

4.0 Materials and Methods

The purpose of this chapter is to (a) describe the materials and methods use to collect, quantify and statistically evaluate data and (b) describe the facilities used to conduct the research.

4.1 Raw Water Quality

The raw water used in this project is the tap water supply in Halifax. It is characterized as low alkaline (around 10mg/L as $CaCO_3$) and low pH around 7.2.

4.2 Water qualities used in this project:

To investigate the effect of alkalinity and pH on copper corrosion water with two alkalinity (10 and 100 mg/L as $CaCO_3$) and two pH (7.2 and 8.5) was used. Four water qualities were tested as shown in the following table.

Table 4.1 pH and alkalinity of water used in this project

Water quality (WQ)	pH	Alkalinity (as mg/L of CaCO3)
LALP	7.2	10
HALP	7.2	100
LAHP	8.5	10
HAHP	8.5	100

(Here LALP=low alk low pH; HALP= Hi alk low pH; LAHP= low alk hi pH; HAHP= Hi alk hi pH)

As the raw water contains chlorine residual of approximately 0.05 mg/L to remove the residual the raw water was passed through a granular activated carbon (GAC) column. To raise the alkalinity sodium bicarbonate was added. To adjust the pH sodium hydroxide and nitric acid was used.

4.3 Corrosion inhibitor used in this project

Zinc polyphosphate is used in this project as corrosion inhibitor. Previous studies have shown that polyphosphate offers a desirable corrosion control strategy for Halifax filtered water. The Zinc polyphosphate used in this project has a brand name Dearborn 3429(Betzdearborn Wilmington DE).This is the same chemical that Halifax Regional Water Commission (HRWC) uses at the Lake Major Water Treatment Plant. This chemical was dosed to the water at a concentration of 0.8 mg/L as in Lake Major Water Treatment Plant it is typically dosed at 0.7 to 1 mg/L of concentration.

4.4 Disinfectants used in this project

Three types of disinfectants were used in this project and they are free chlorine, Monochloramine and chlorine dioxide. These three are the most common alternatives that a water treatment plant considers for disinfection. Each of these three disinfectants has its own characteristics. Chlorine is the most frequently used. The monochloramine and Chlorine dioxide are gaining popularity as alternative. Two doses of disinfectants are used in this project and they are shown in Table 4.2

Table 4.2 Disinfectants and their doses

Disinfectants	High dose	Low dose
Free Cl2	1.0ppm	0.5 ppm
ClO2	0.50 ppm	0.25 ppm
NH2Cl	2.0ppm	1.0 ppm

These low and high doses are selected based on the minimum and maximum allowable limits of disinfectants in water by the regulatory agencies. According to the Ontario Drinking water Guidelines(2001) a minimum free chlorine residual of 0.2 mg/L and a minimum combined chlorine residual of 1.0mg/L should be maintained at all point in the distribution system. Also according to the USEPA guidance manual on alternative disinfectants and oxidants typical chlorine doses at water treatment plant using sodium hypochlorite is in the range of 0.2 to 2.0 mg/L. For chlorine Dioxide USEPA maximum allowable value is 0.8mg/l.The desired concentration of the disinfectant in water was determined through dose and measurement techniques.

4.5 Total number of combination tested

Considering the water quality (four) addition of corrosion inhibitor (two) and disinfectants (seven) total number of combination tested is fifty six. For ease of representing the data each water quality is expressed symbolically such as

LALP: water with low alkalinity (10 mg/L $CaCO_3$) low pH (7.2);

P-LALP: water with low alkalinity (10 mg/L $CaCO_3$) low pH (7.2) and phosphate addition;

HALP: water with high alkalinity (100 mg/L $CaCO_3$) low pH (7.2) water;

P-HALP: water with high alkalinity (100 mg/L $CaCO_3$) low pH (7.2) water with phosphate addition;

LAHP: water with low alkalinity (10 mg/L $CaCO_3$) high pH (8.5) water;

P-LAHP: water with low alkalinity (10 mg/L $CaCO_3$) high pH (8.5) water with phosphate addition;

HAHP: water with high alkalinity (100 mg/L $CaCO_3$) high pH (8.5) water;

P-HAHP: water with high alkalinity (100 mg/L $CaCO_3$) high pH (8.5) water with phosphate addition;

4.6 Experimental Design

The experimental design matrix is shown in the Table 4.2 on next page. One of the major problems of corrosion testing in the distribution system is that it is a very slow process. Different researchers tried to set minimum duration for test. However minimum duration of previous studies was at least 3 month but most studies were 6 to 24 months (Eisnor.et al., 2003). However the duration of this experiment was 3 months. This total time is divided into two parts first 3 weeks (i.e. 21 days are termed as conditioning period), and the remaining time is taken as test period.

Table 4.3 Experimental design matrix

Water Quality	Disinfectants concentration(mg/L)			
	Free Chlorine	Monochloramine	Chlorine Dioxide	Control
LALP	0.50/1.00	1.0/2.0	0.25/0.50	0.0/0.0
P-(LALP)	0.50/1.00	1.0/2.0	0.25/0.50	0.0/0.0
HALP	0.50/1.00	1.0/2.0	0.25/0.50	0.0/0.0
P-(HALP)	0.50/1.00	1.0/2.0	0.25/0.50	0.0/0.0
LAHP	0.50/1.00	1.0/2.0	0.25/0.50	0.0/0.0
P-(LAHP)	0.50/1.00	1.0/2.0	0.25/0.50	0.0/0.0
HAHP	0.50/1.00	1.0/2.0	0.25/0.50	0.0/0.0
P-(HAHP)	0.50/1.00	1.0/2.0	0.25/0.50	0.0/0.0

4.7 Pipe Rig set up

The pipe rig consists of fifty six copper pipe sections. These pipes are 1.22 m long with diameter ¾ in type M pipes bought from a local hardware store. These types of pipes are most common in household plumbing system. Number three stoppers were used to plug the ends of each pipe. Initially the pipes were rinsed with deionized water then rinsed three times with 0.1N NaOH solution then rinsed five times with deionized water. This was done to remove any organic matter inside the pipe. These pipes are kept in horizontal position using a wooden frame. The whole pip rig is kept in the petroleum lab, room D104.

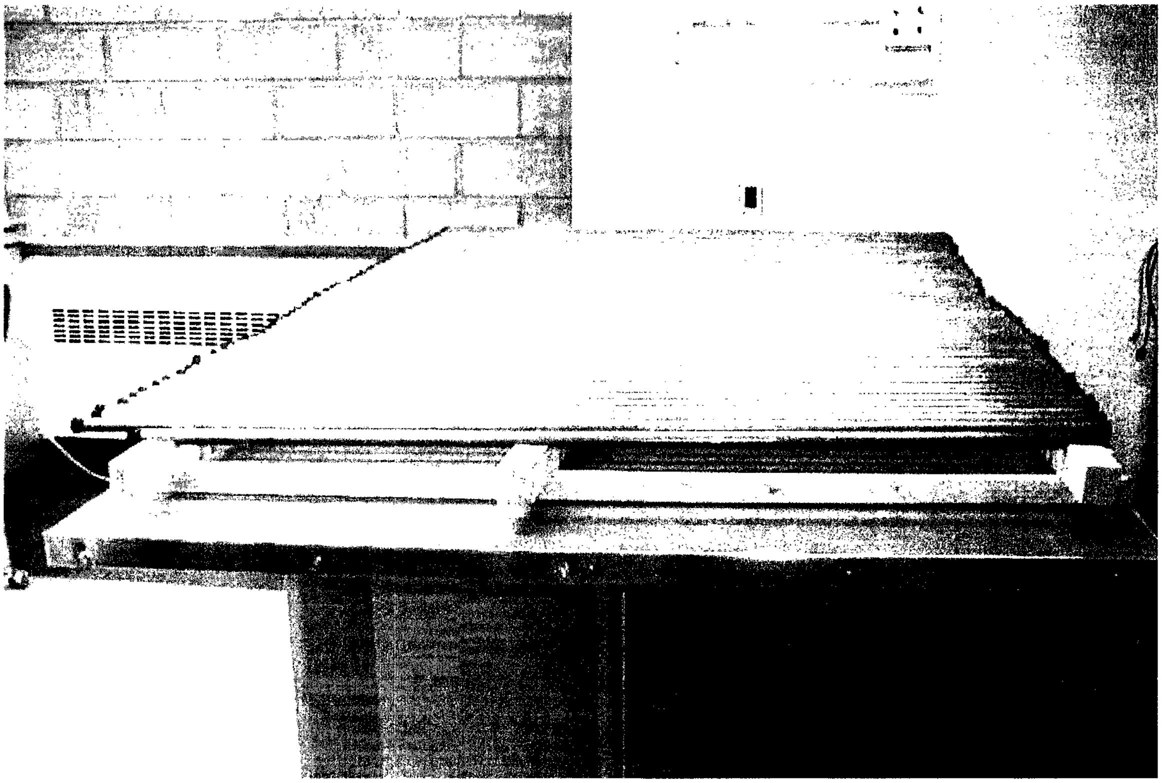

Figure 4.1-Pipe rig set up used in this project

4.8 Preparation of water used in this project

Water flowing through the granular activated carbon (GAC) column is collected in a large 29 L bucket. The GAC adsorbs the chlorine residual as well as other background organic and inorganic material. Water is then stored in eight large brown bottles. Four of these bottles were used to feed the pipes with phosphate addition and the remaining four were used for feeding pipes without phosphate addition. To raise alkalinity Sodium bicarbonate is added and to adjust the pH Sodium Hydrooxide and Hydrochloric acid was added to these bottles. After adjusting pH and alkalinity the water was poured in 56 properly labels small 500mL brown bottles. These bottles were termed as influent set. Another set of 56 bottles is used in this experiment to hold the water from the copper pipes after the stagnation is termed as the effluent set. After filling the influent set required amount of disinfectants and corrosion inhibitor poly phosphate were dosed in these bottles.

4.9 Stock Chemical Preparation

All the stock chemical solutions were prepared in Water Quality Laboratory at Dalhousie University. The following chemicals were prepared on a regular basis:

- Zinc polyphosphate
- Free chlorine
- Monochloramine,
- Chlorine Dioxide

As mentioned earlier Dearborn 3429 (Betzdearborn, Wilmington,DE) was used as the zinc polyphosphate in this project. Halifax water supply is dosed with 0.7 to 1 mg/L of this product. Researchers (Klueh K.G.et.al.1988) found that polyphosphate has a tendency to revert to orthophosphate. This phenomenon decreases polyphosphate's ability to sequester metals and increases its ability to minimize leaching of metals from the pipe wall. Several studies (Klueh K.G.et.al.1988, Koudleka, M et.al.1982, Zinder, B et.al.1984) showed that pH temperature and time have influence on this reversion. So on each sampling days fresh stock solutions of Dearborn was prepared and dosed to make a concentration of 0.8 mg/L of Dearborn in the water.

Sodium Hypo chlorite stock solution of about 60,000mg/L was used to make free chlorine solution used in this project. The highly concentrated stock solution of NaOCl was diluted to make 100mg/L of solution and fresh solutions were always used in this project.

Preparation of Monochloramine was difficult because if proper pH is not achieved it will be unstable. Previous (Eisnor 2002) researcher prepared Monochloramine by using sodium hypochlorite and ammonium chloride with phosphate buffer saline (PBS) (pH=9.5).Same process was used for this project. In this process Monochloramine was prepared by combining 1.85mL of NaOCl and 400 mg (0.4 gm) of NH_4Cl in PBS. PBS is comprised of 8gm NaCl, 0.2gm KH_2PO_4, 2.9gm Na_2HPO_4 $12H_2O$ and 0.2 gm KCl.To properly form Monochloramine, ammonium chloride was added to 500 mL of PBS (pH 9.5).Sodium hypochlorite was added to 500mL of PBS in another container. Then the sodium hypochlorite solution was added to the Monochloramine solution by slow drips while mixing. The pH of the prepared monochloramine was raised using NaOH to make it stable and stored in the refrigerator. Monochloramine prepared and stored in this process remains stable for at least 5 days.

Chlorine dioxide was generated according to a method described in *Standard methods for the Examination of Water and Waste water, 20th ed.* The experimental set up used for Chlorine dioxide generation is shown in Figure4.2 This set up consists of a bench top apparatus in which a 25% sodium chlorite solution is slowly added to an 18N sulfuric acid solution for chlorine dioxide production.

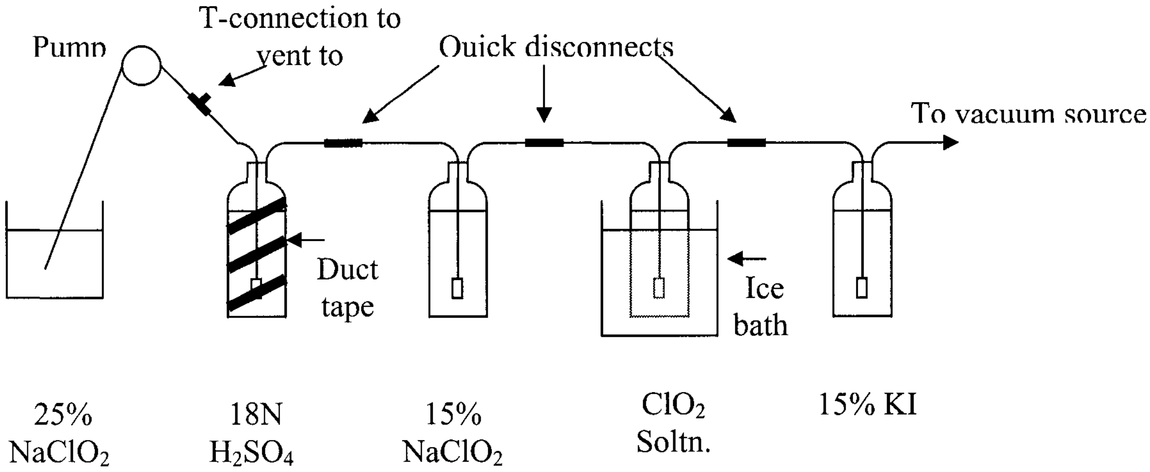

Figure 4.2-Set up used for Chlorine dioxide preparation

The produced chlorine dioxide is purged from the mixture in a gas-washing bottle, and trapped in water surrounded by an ice bath. The off-gases are removed by potassium iodide trap which prevent the release of chlorine dioxide into the air. The resulting chlorine dioxide solution is approximately 2g/L.

The produced chlorine dioxide was standardized by mixing with a potassium iodide solution, and the titrating with sodium thiosulfate, first at pH 7.6 to measure one fifth of the chlorine dioxide and any chlorine which is present, and then adding sulfuric acid to continue the titration at pH 2 to measure the remaining four-fifths of the chlorine dioxide plus any chlorite that was initially present. Past measurement indicated that the stock solution produced pure (>99%) chlorine dioxide. The stock solution prepared for this project was 2800 mg/L.

4.10 Analytical Methods

Copper, color, turbidity, pH, temperature, TOC, phosphorous, dissolve oxygen of the water samples were measured. Also the disinfection decay rate was determined. This section will discuss the methods used to determine these parameters.

4.10.1 Sampling Techniques

As described earlier two sets of bottles (Influents and Effluents) were used in sampling. The copper pipes were first inverted three times to mix the water the all the water is pour in to the effluent bottles. The pipes were immediately filled with fresh water of appropriate water quality from the Influent set.

4.10.2 Copper

Both total and dissolved copper was measured. According to *Standard Methods* the dissolved copper is operationally defined as the portion of copper which passes through a

0.45 μm pore size syringe filter. It should be noted that in the presence of colloidal species that can pass through the filter, the standard methods approach represents an upper bound to truly soluble copper. After taking out the water from the pipes pH of the sample was adjusted (pH ≤2.00) using HNO_3.For dissolve copper it was first filtered then acidified. One thing should be stated here due to large number of samples collected filtration of the sample was delayed which undoubtedly affect the copper in water. Copper was measured using IL751 atomic absorption spectrophotometer (with detection limits of 0.07±0.002 μg/L). Before measuring the sample the spectrophotometer was calibrated with five standard copper solutions. To minimize the experimental error after eight measurements standard solutions of copper was measured and if the obtained reading is outside the 90 to 110% of the standard value of the standard then the calibration was done again. This was done according to *Standard Method* 3020.

4.10.3 Color

Apparent color of the water was measured. Apparent color comes from dissolved and suspended matter in water. Apparent color was measured using HACH DR/2010 spectrophotometer (HACH Co., Loveland, CO).This instrument uses 455 ηm light source and its measurement is based on the APHA recommendation that 1 standard color unit is equal to 1mg/L of platinum as chloroplatinate ion. This instrument is capable of measuring color from 0 to 500 PCU.A 25 mL cuvet was used for this analysis. The instrument was zeroed first using deionized water.

4.10.4 Turbidity

Turbidity was measured using HACH 2100P turbidimeter. It has three ranges that can be adjusted depending on the turbidity of the water. These ranges are 2, 20, 200 NTU.

4.10.5 Temperature and pH

The temperature and pH of the sample was measured using a symphony pH meter. It was done instantly while changing the sample.

4.10.6 Dissolved Oxygen

Dissolve oxygen was measured once at the end of the test period using HACH Sension378 DO meter. The DO probe of the instrument was put in to the sample and it gives directly the dissolve oxygen concentration in mg/L. The probe was calibrated before measuring the sample.

4.10.7 Heterotrophic Plate Counts

Microbiological analysis was performed on some sample at end of the test period. Heterotrophic plate counting was done using standard microbiological methods spread plate technique on R2A agar according to *Standard Methods for the Examination of Water and Wastewater(20th Edition).*Plates were incubated at 20^0C for 7 day. Then the number of colonies in the plates was counted using a Quebec colony counter.

4.10.8 Natural Organic Matter (NOM)

The natural organic matter (NOM) is usually expressed as TOC. TOC of the sample was measured on alternate samples. After collecting the sample in TOC bottle four drops of phosphoric acid was added and put in the refrigerator for preservation. A TOC analyzer, Shemadzu TOC-VCPH was used to measure the TOC.

4.10.9 Phosphorus

Both orthophosphate (reactive) and total phosphate of the sample was measured. HACH DR/2010 was use for these measurements. Phosphorous was measured bi-weekly. The orthophosphate was measured instantly using PhosVer3 phosphate powder pillow. This method was based on standard method 4500-P-E.A light source of wavelength (λ) 890 ηm was used for measuring both ortho and total phosphorous. The total phosphorous was not measured instantly instead the sample was preserved in the refrigerator after adjusting the pH to less than 2 using H_2SO_4.For measurement of total phosphorous first all other forms of phosphorus was converted to orthophosphate. While measuring first the sample was warm to room temperature. Then 25 mL of sample was taken and one Potassium Persulfate Powder pillow was added and mixed. After that 2.00mL of 4.25 N H_2SO_4 was added. Then the sample was put in the autoclave for about 30 minutes. Then the sample was allowed to cool room temperature and 2.00mL of 4.0N NaOH solution was added and mixed. Thus all the phosphate transformed into orthophopshat form. Then volume of the sample was adjusted to 25mL and total phosphate can be measured using PhosVer3 phosphate pillow. But for total phosphate the reaction time was taken as 10 minutes instead of 2minutes as taken for orthophosphate.

4.11 Disinfectant decay analysis

As a part of the test disinfectants decay was examined, which was conducted once for the entire test period. Detail description of these tests are given bellow:

4.11.1 Chlorine

The free chlorine residual was measured using DPD colorimetric method immediately after sampling. A HACH DR/2010 spectrophotometer was used for measurement. This instrument has a 2.5 cm path length. A pair of 25 mL sample cell was used for the analysis.530ηm wavelength light was used in this measurement. The machine was zeroed first using the sample water in one cell. Then in another cell sample water was taken and free chlorine indicator reagent was added to water and shacked. The proportion of color change indicated the amount of free chlorine.

4.11.2 Monochloramine

Monochloramine was measured according to standard method #4500-Cl F DPD Ferous Titrimetric Method. In this method 5mL of PBS and 5mL of DPD were taken in a titration flask. Then 100 mL of sample was added and mixed. Due to the presence of free chlorine a light red or pink color sometime appeared. If this color appeared it was rapidly titrated with FAS (Ferrous Ammonia Sulfate) solution. Usually very small amount of FAS is needed. Then 0.1mL of KI solution was added and 2 minutes of reaction period was allowed. Then the sample was titrated with FAS until the red color disappears. The difference in volume of the FAS to make the solution colorless initially and after the addition of KI gave directly the monochloramine concentration.

4.11.3 Chlorine Dioxide

Chlorine dioxide was measured according to Chriswell B et al., (1991) using Lissamine Green B (LGB) and Ammonia Buffer Solution. The HACH HA/6000 with uv light of wave length of 616nm was used. First a calibration curve was made for the instrument using known concentration of chlorine dioxide.2mL of LGB and 10mL of buffer solution was added to 100mL of sample. The instrument was zeroed using deionized water then the absorbance of the sample was measured. With the absorbance value using the calibration curve the concentration of the ClO_2 was determined.

4.12 Statistical Analysis

Paired t-test analysis was done on the data to see if there are significant differences between two treatments. The level of significance that was used for all tests was $\alpha=0.05$.So if p-value is less than 0.05, then it indicates that there is significant difference in two treatment.

5.0 Results and discussion

5.1 Copper

5.1.1 Total Copper

The average and standard deviations for total copper concentrations for conditioning and test phase are shown in Tables 5.1. The control pipes have higher copper concentration than the disinfectant dosed pipes and the highest concentration (2.5 mg/L) was found for control pipe with high alkalinity and low pH water. The lowest copper concentration was found in case of monochloramine-dosed pipe with low alkalinity and high pH water with phosphate addition.

Table5.1 – Average total copper concentration during conditioning phase.

	Average Total Copper (mg/L)							
	LALP[1]	**P-LALP[2]**	**HALP[3]**	**P-HALP[4]**	**LAHP[5]**	**P-LAHP[6]**	**HAHP[7]**	**P-HAHP[8]**
Control	0.94±0.42	0.89±0.32	1.18±0.94	1.30±0.84	0.75±0.14	0.59±0.15	1.30±0.17	1.15±0.19
Cl_2 –Lo	0.79±0.55	1.00±1.09	0.99±0.64	0.92±0.44	0.41±0.09	0.46±0.13	0.95±0.19	0.82±0.19
Cl_2 –Hi	0.62±0.15	0.65±0.14	1.01±0.61	0.95±0.44	0.48±0.16	0.45±0.18	1.03±0.26	0.90±0.22
NH_2Cl-Lo	0.51±0.18	0.62±0.22	0.67±0.22	0.74±0.22	0.53±0.12	0.66±0.16	0.65±0.19	0.73±0.18
NH_2Cl-Hi	0.78±0.30	0.85±0.25	0.88±0.31	0.97±0.35	0.66±0.27	0.84±0.30	0.81±0.32	0.84±0.26
ClO_2-Lo	0.72±0.28	0.56±0.16	0.84±0.50	0.91±0.54	0.50±0.14	0.47±0.13	1.08±0.17	0.96±0.18
ClO_2-Hi	0.56±0.16	0.60±0.11	0.83±0.43	0.74±0.42	0.43±0.08	0.39±0.14	0.99±0.08	0.93±0.10

(1: LALP=low alk low pH, 2: P-LALP=low alk low pH with phosphate addition, 3: HALP= Hi alk low pH, 4: P-HALP= Hi alk low pH with phosphate addition, 5: LAHP= low alk hi pH, 6: P-LAHP= low alk hi pH with phosphate addition, 7: HAHP= Hi alk hi pH, 8: P-HAHP= Hi alk hi pH with phosphate addition)

Table5.2 – Average total copper concentration during test phase.

	Average Total Copper (mg/L)							
	LALP[1]	**P-LALP[2]**	**HALP[3]**	**P-HALP[4]**	**LAHP[5]**	**P-LAHP[6]**	**HAHP[7]**	**P-HAHP[8]**
Control	0.73±0.19	0.93±0.35	2.55±0.58	2.37±0.62	0.55±0.14	0.91±0.46	2.37±0.77	1.90±0.30
Cl_2 –Lo	0.58±0.12	0.51±0.11	1.26±0.31	1.23±0.24	0.29±0.09	0.26±0.07	0.59±0.12	0.59±0.17
Cl_2 –Hi	0.61±0.14	0.47±0.11	1.30±0.28	1.18±0.27	0.29±0.09	0.23±0.07	0.68±0.14	0.61±0.14
NH_2Cl-Lo	0.36±0.08	0.43±0.10	0.47±0.08	0.57±0.13	0.40±0.06	0.48±0.09	0.43±0.08	0.53±0.09
NH_2Cl-Hi	0.54±0.15	0.63±0.12	0.59±0.08	0.72±0.10	0.50±0.07	0.60±0.12	0.57±0.09	0.60±0.12
ClO_2-Lo	0.67±0.14	0.54±0.10	1.65±0.38	1.29±0.23	0.41±0.10	0.42±0.08	0.86±0.21	0.84±0.19
ClO_2-Hi	0.67±0.12	0.59±0.10	1.43±0.28	1.28±0.25	0.39±0.13	0.43±0.06	0.88±0.21	0.82±0.16

(1: LALP=low alk low pH, 2: P-LALP=low alk low pH with phosphate addition, 3: HALP= Hi alk low pH, 4: P-HALP= Hi alk low pH with phosphate addition, 5: LAHP= low alk hi pH, 6: P-LAHP= low alk hi pH with phosphate addition, 7: HAHP= Hi alk hi pH, 8: P-HAHP= Hi alk hi pH with phosphate addition)

Figure 5.1 to Figure 5.8 shows the total copper concentration for control and high disinfectants dosed pipes in a time-series fashion. The data/graph for the low dosed pipes can be found in Appendix-B.

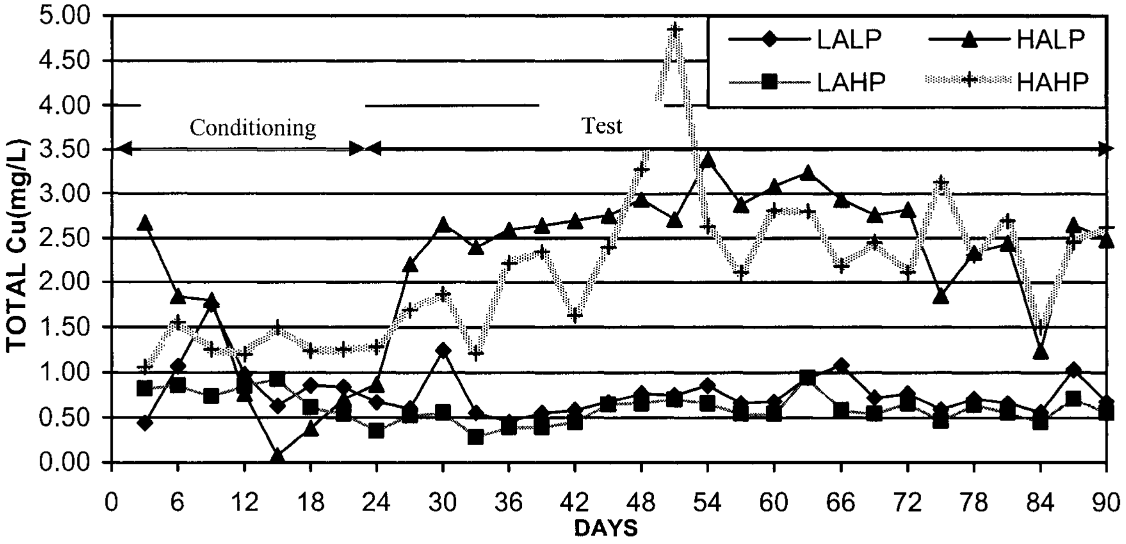

Figure 5.1 Total copper for control pipes without any phosphate addition

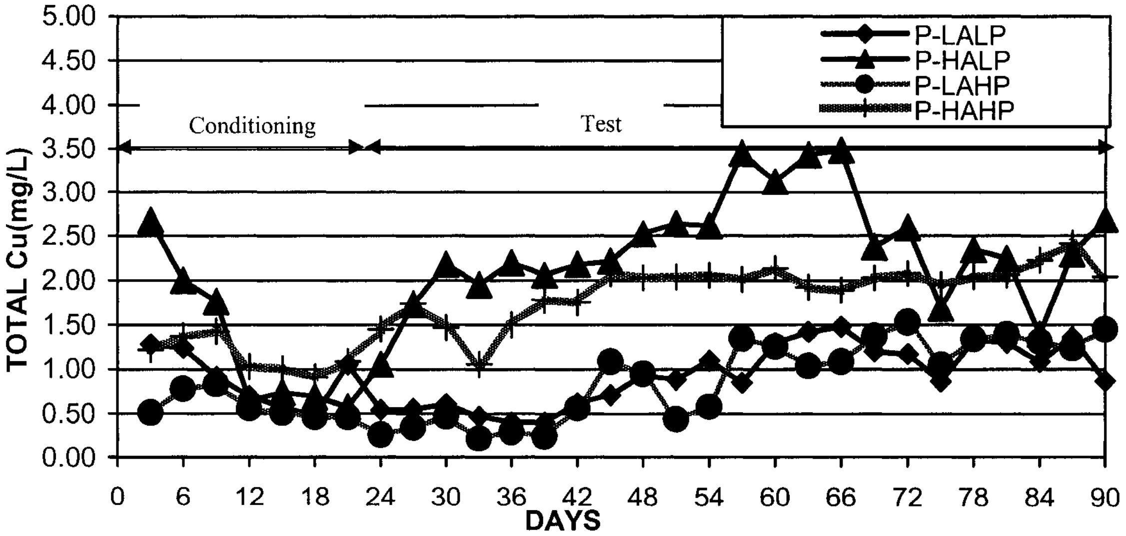

Figure 5.2 Total copper for control pipes with phosphate addition

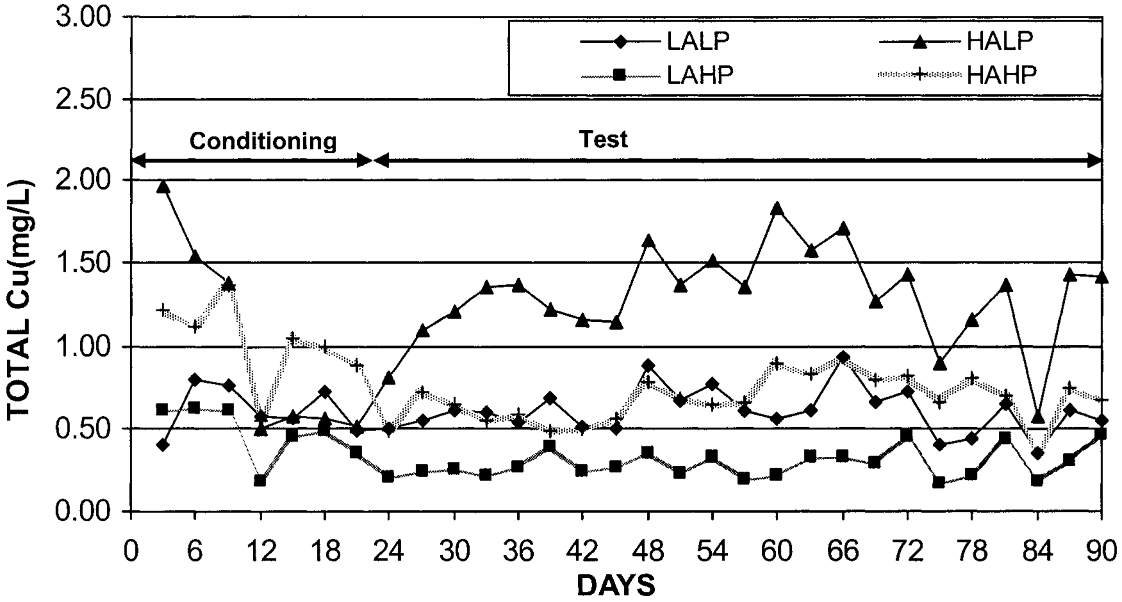

Figure 5.3 Total copper for the high dosed free chlorine pipes without phosphate addition

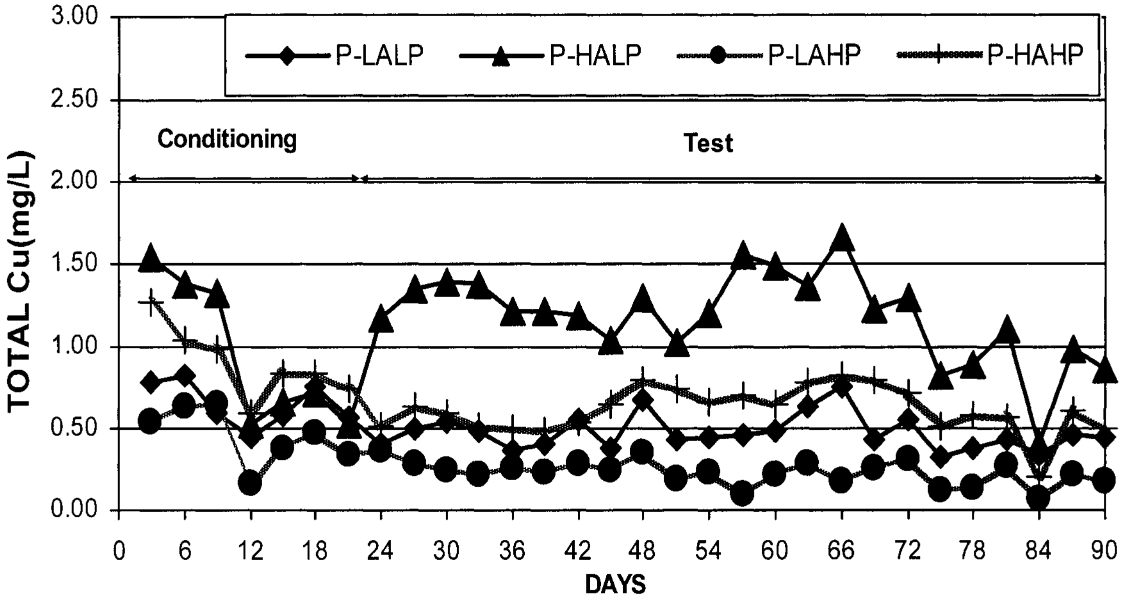

Figure 5.4 Total copper for the high dosed free chlorine pipes with phosphate addition

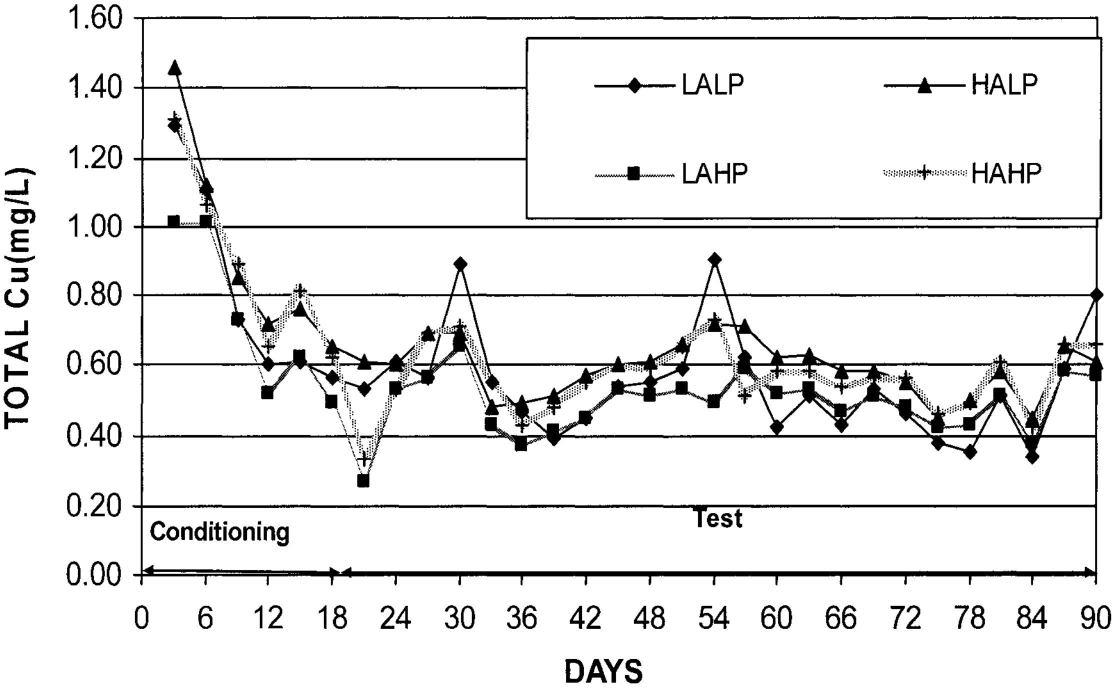

Figure 5.5 Total copper for the high dosed monochloramine pipes without phosphate addition

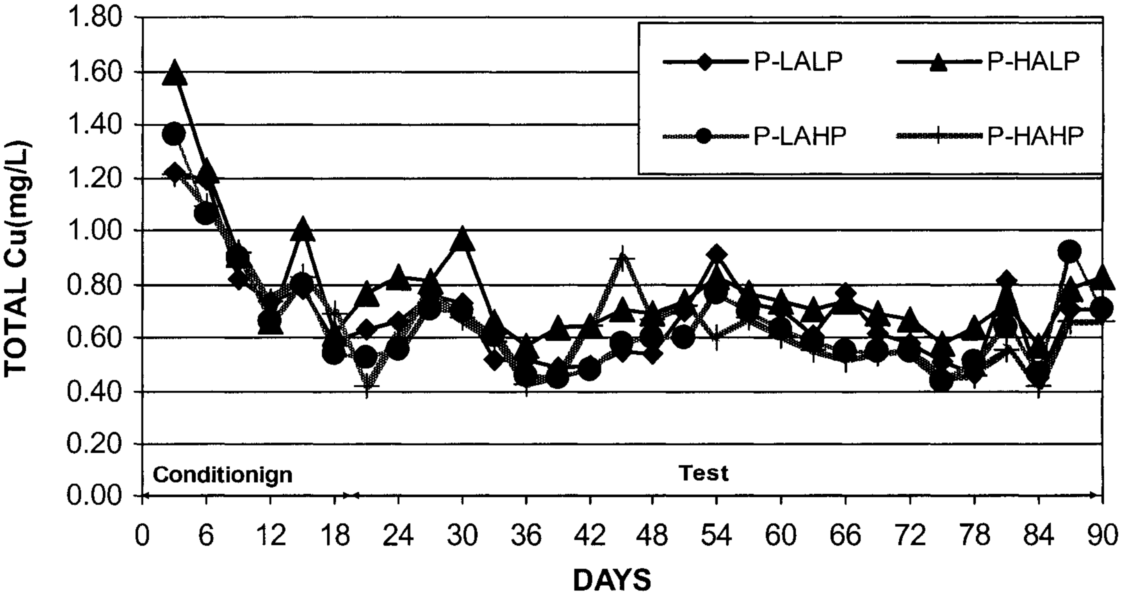

Figure 5.6 Total copper for the high dosed monochloramine pipes with phosphate addition

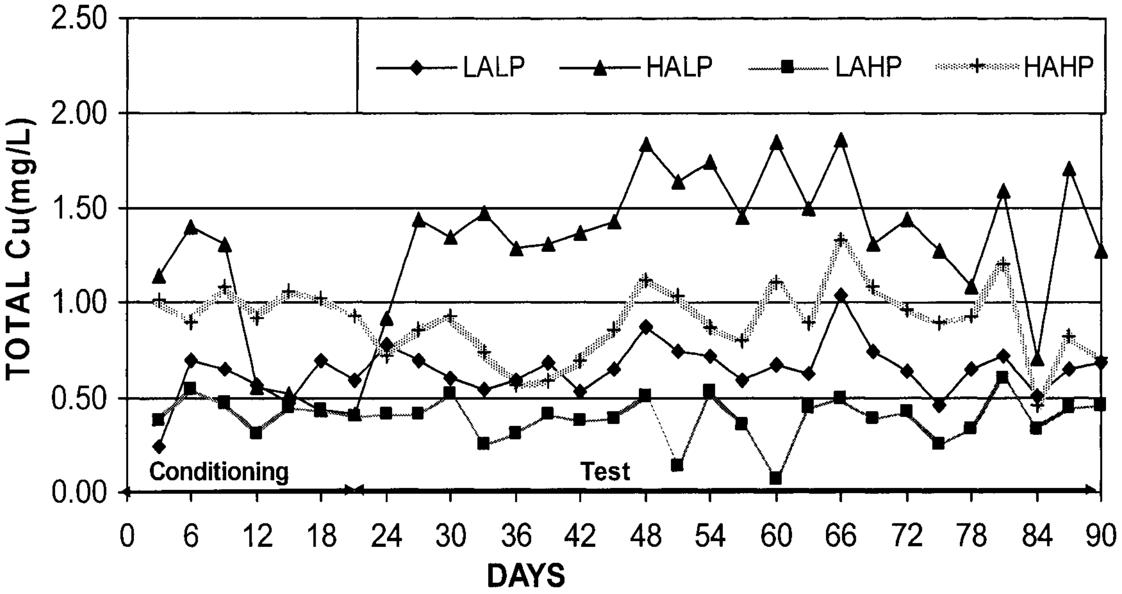

Figure 5.7 Total copper for the high dosed chlorine dioxide pipes without phosphate addition

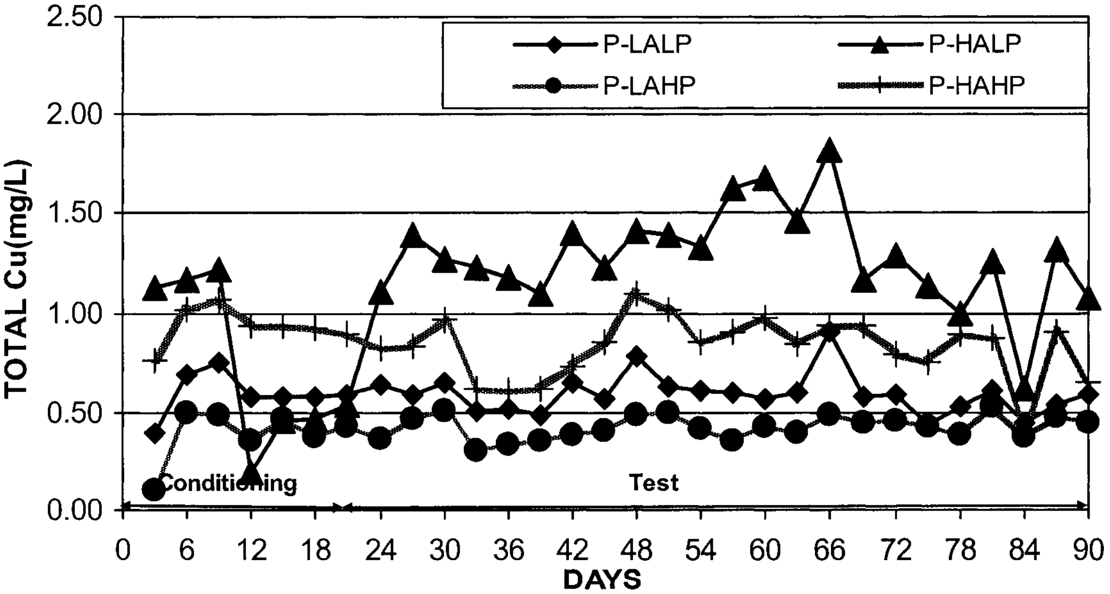

Figure 5.8 Total copper for the high dosed chlorine dioxide pipes with phosphate addition

To make a comparison between the average total copper value during the test phase bar charts showing the average concentration and standard deviation for each disinfectant are shown in Figure 5.9 to Figure 5.11.

It is observed from these figures that with the decrease of alkalinity the copper concentration decreases. Incase of control pipes with the increase of alkalinity from 10 to 100 mg/L the copper concentration in water increases about 200% or more. For control pipes without phosphate addition the effect of alkalinity is more pronounce than the phosphate added pipes. In case of chlorine and chlorine dioxide dosed pipes increase of alkalinity increases the copper concentration about 100%.But in case of monochloramine the effect of alkalinity is less pronounce. The results of the t-test on the average copper concentration from pipes are shown in appendix C. These results also support significant difference in copper level in low and high alkaline water. Most of the pipes have copper level less than the action level of 1.3 mg/L but for water with pH 7.2 and alkalinity 100 mg/l the total copper concentration more frequently exceeded the action level. With the increase of pH in most cases the copper concentration decreases. For monochloramine dosed pipes higher pH does not show noticeable beneficial effect on copper concentration.

From these figures it is found that the total copper concentrations in the disinfectant dosed pipes are lower than that in the control pipes. This trend indicates that the copper corrosion may be caused mainly by microbial activities. The disinfectants are corrosive to copper but they suppress the bio corrosion, which may cause a total decrease in the copper corrosion.

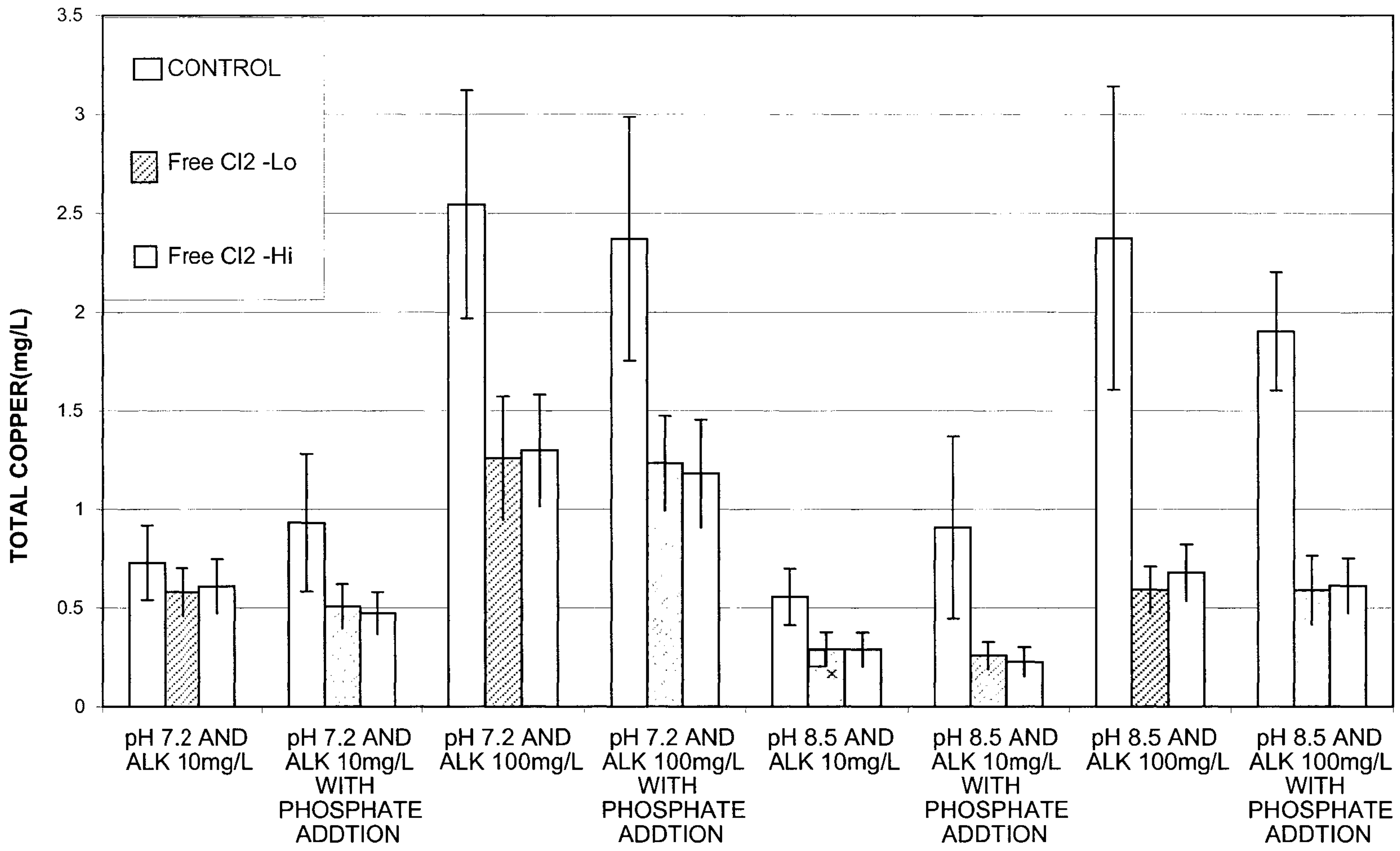

Figure 5.9 Comparison of total copper values among the control and free chlorine dosed pipes during test periods

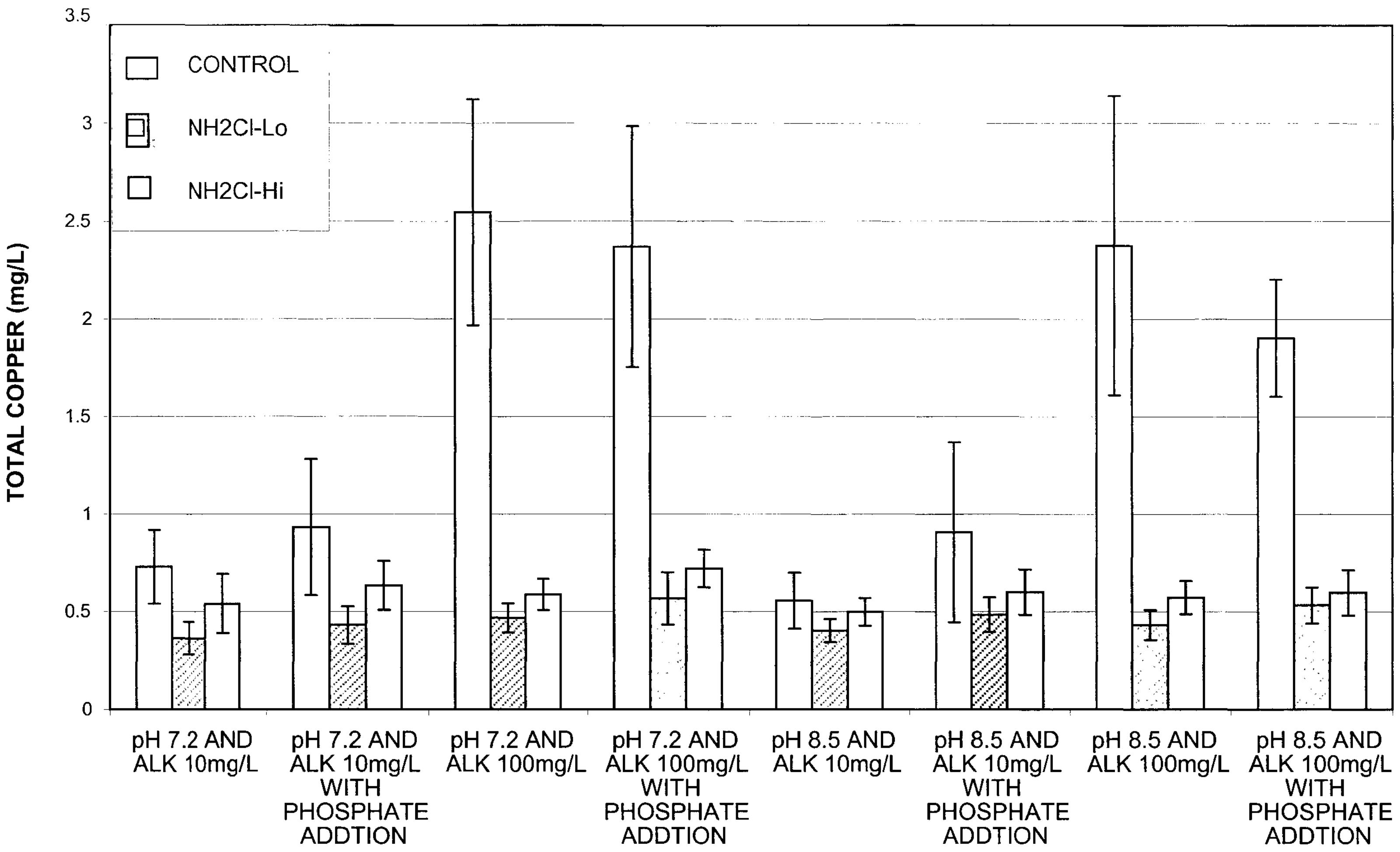

Figure 5.10 Comparison of total copper values among the control and monochloramine dosed pipes during test periods

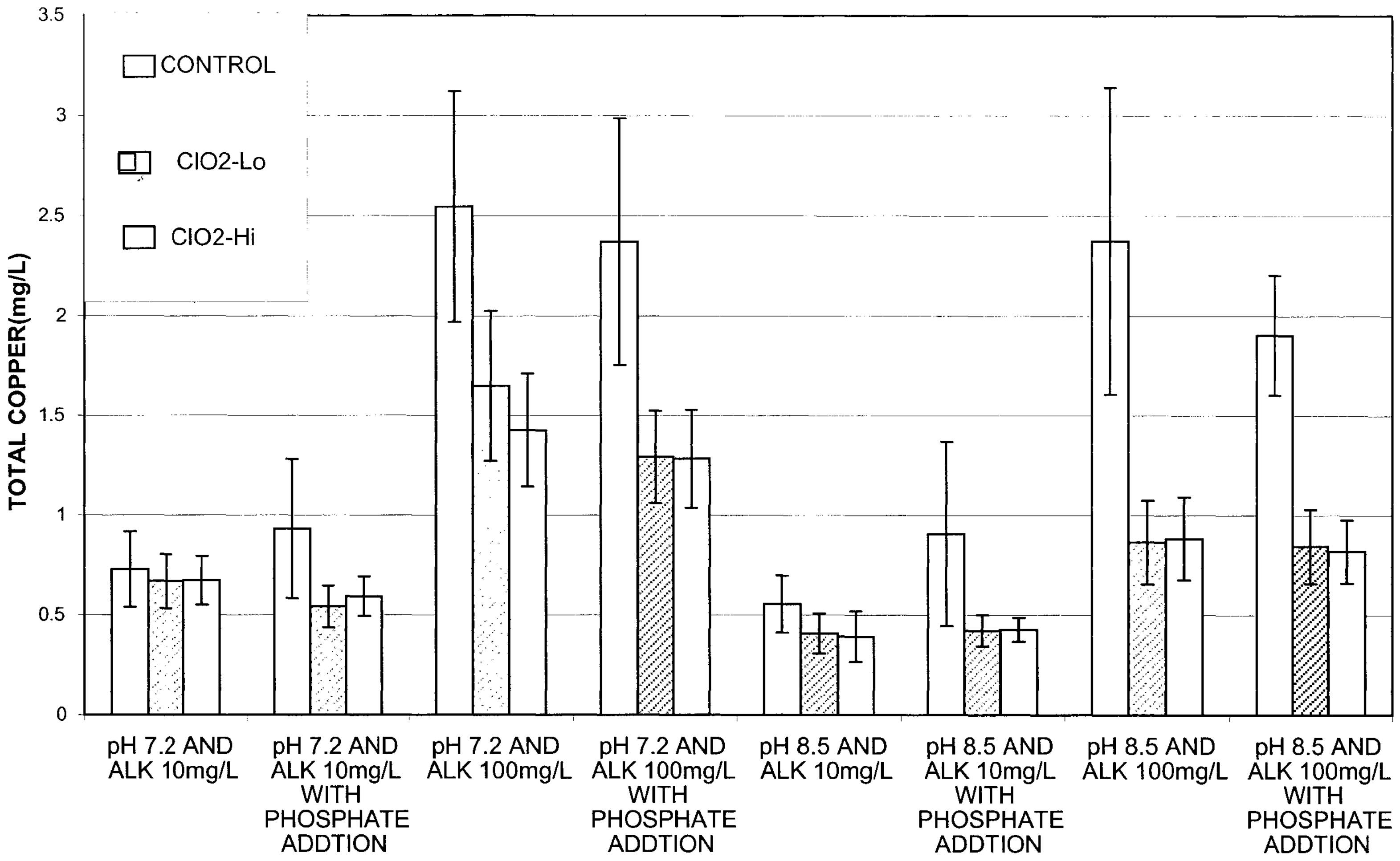

Figure 5.11 Comparison of total copper values among the control and chlorine dioxide dosed pipes during test periods

The phosphate addition also affected the total copper concentration. For the control pipes the phosphate addition found to lower the average copper in case of high alkalinity. But in case of low alkalinity the opposite results were founds. All most all the disinfectant dosed pipes with phosphate addition have average total copper concentration lower than that for without phosphate addition. But all the pipes with monochloramine and ClO_2 pipes with low alkalinity and high pH water phosphate addition results no change or slight increase in average copper concentration. To compare the effect of phosphate addition t-test was done on the total copper data. In most cases the test shows that phosphate addition has significant effect on the copper concentration. The results of this test are shown in the table in appendix C.

5.1.2 Dissolved copper

The average and standard deviations for dissolved copper concentrations for conditioning and test phase are shown in Table5.3 and Table 5.4. The control pipes have higher copper concentration than the disinfectant dosed pipes and the highest concentration (1.51mg/L) was found for control pipe with high alkalinity and low pH water. Lowest copper concentration was found in case of chlorine-dosed pipe with low alkalinity and high pH water with phosphate addition.

Table5.3 – Average dissolved copper concentration during conditioning phase.

Average Dissolved copper (mg/L)								
	LALP[1]	**P-LALP[2]**	**HALP[3]**	**P-HALP[4]**	**LAHP[5]**	**P-LAHP[6]**	**HAHP[7]**	**P-HAHP[8]**
Control	0.69±0.54	0.67±0.30	0.85±0.70	0.97±0.65	0.62±0.29	0.47±0.23	0.86±0.39	0.86±0.37
Cl_2 –Lo	0.59±0.66	0.77±1.20	0.76±0.66	0.66±0.45	0.26±0.18	0.31±0.24	0.61±0.32	0.53±0.30
Cl_2 –Hi	0.42±0.26	0.44±0.22	0.76±0.54	0.76±0.45	0.31±0.23	0.32±0.24	0.73±0.39	0.64±0.29
NH_2Cl-Lo	0.45±0.21	0.57±0.24	0.57±0.22	0.65±0.22	0.47±0.13	0.58±0.20	0.58±0.20	0.68±0.23
NH_2Cl-Hi	0.66±0.25	0.73±0.26	0.75±0.22	0.79±0.28	0.61±0.26	0.70±0.32	0.71±0.31	0.74±0.26
ClO_2-Lo	0.38±0.24	0.34±0.20	0.61±0.42	0.66±0.53	0.30±0.26	0.31±0.23	0.62±0.23	0.69±0.34
ClO_2-Hi	0.39±0.21	0.46±0.19	0.65±0.51	0.57±0.46	0.26±0.19	0.28±0.18	0.63±0.30	0.66±0.30

(1: LALP=low alk low pH, 2: P-LALP=low alk low pH with phosphate addition, 3: HALP= Hi alk low pH, 4: P-HALP= Hi alk low pH with phosphate addition, 5: LAHP= low alk hi pH, 6: P-LAHP= low alk hi pH with phosphate addition, 7: HAHP= Hi alk hi pH, 8: P-HAHP= Hi alk hi pH with phosphate addition)

Table5.4 – Average dissolved copper concentration during test phase.

Average Dissolved copper (mg/L)								
	LALP[1]	**P-LALP[2]**	**HALP[3]**	**P-HALP[4]**	**LAHP[5]**	**P-LAHP[6]**	**HAHP[7]**	**P-HAHP[8]**
Control	0.40±0.13	0.43±0.12	1.51±0.40	1.22±0.41	0.25±0.07	0.27±0.10	0.44±0.11	0.48±0.13
Cl_2 –Lo	0.31±0.08	0.31±0.07	0.85±0.20	0.85±0.19	0.14±0.07	0.15±0.06	0.38±0.11	0.40±0.12
Cl_2 –Hi	0.30±0.09	0.27±0.07	0.89±0.21	0.84±0.22	0.13±0.07	0.12±0.05	0.41±0.09	0.39±0.10
NH_2Cl-Lo	0.32±0.08	0.39±0.09	0.41±0.06	0.50±0.07	0.35±0.06	0.43±0.08	0.39±0.06	0.49±0.09
NH_2Cl-Hi	0.45±0.13	0.54±0.11	0.53±0.07	0.63±0.07	0.44±0.06	0.54±0.10	0.51±0.08	0.55±0.10
ClO_2-Lo	0.34±0.12	0.32±0.11	0.99±0.33	0.89±0.29	0.19±0.08	0.26±0.08	0.49±0.17	0.53±0.16
ClO_2-Hi	0.39±0.07	0.36±0.05	0.97±0.20	0.91±0.19	0.20±0.07	0.27±0.06	0.51±0.12	0.54±0.11

(1: LALP=low alk low pH, 2: P-LALP=low alk low pH with phosphate addition, 3: HALP= Hi alk low pH, 4: P-HALP= Hi alk low pH with phosphate addition, 5: LAHP= low alk hi pH, 6: P-LAHP= low alk hi pH with phosphate addition, 7: HAHP= Hi alk hi pH, 8: P-HAHP= Hi alk hi pH with phosphate addition)

Figure 5.12 to Figure 5.19 shows the dissolved copper concentration for control and high disinfectants dosed pipes in a time-series fashion. The data/graph for the low dosed pipes can be found in Appendix A and B.

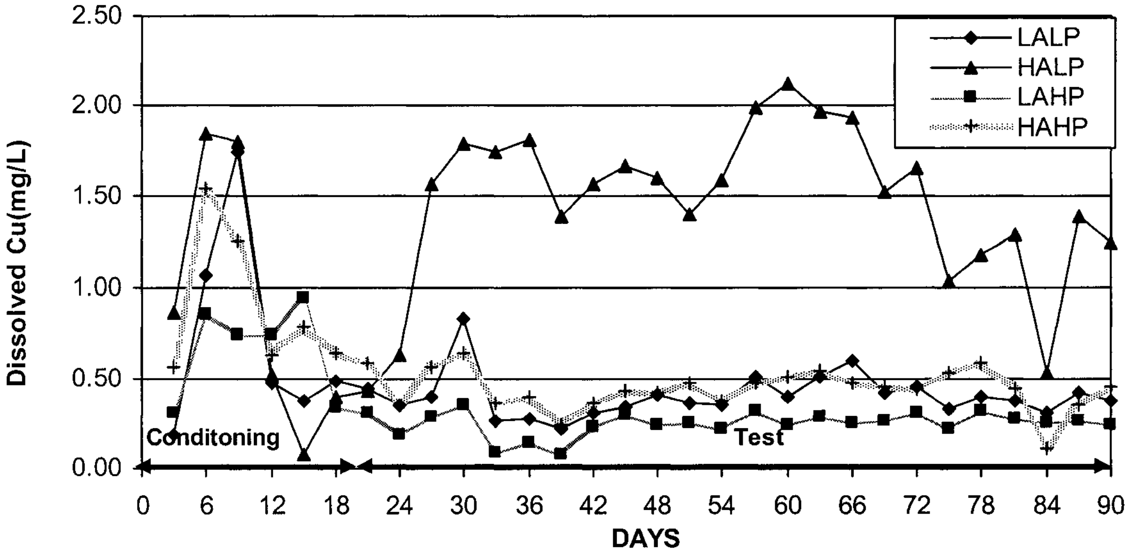

Figure 5.12 Dissolved copper for the control pipes, without phosphate addition

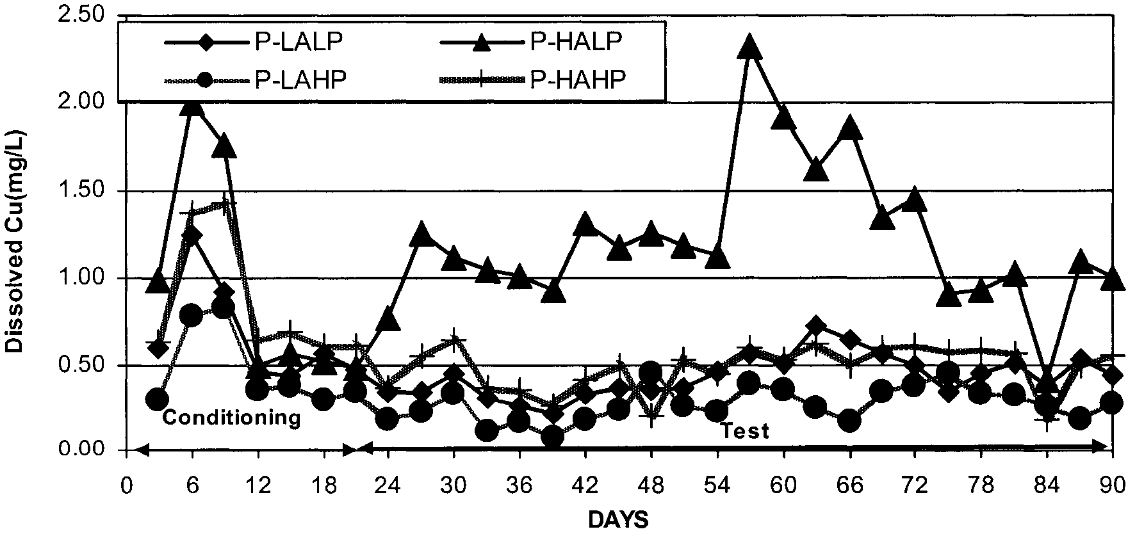

Figure 5.13 Dissolved copper for the control pipes, with phosphate addition

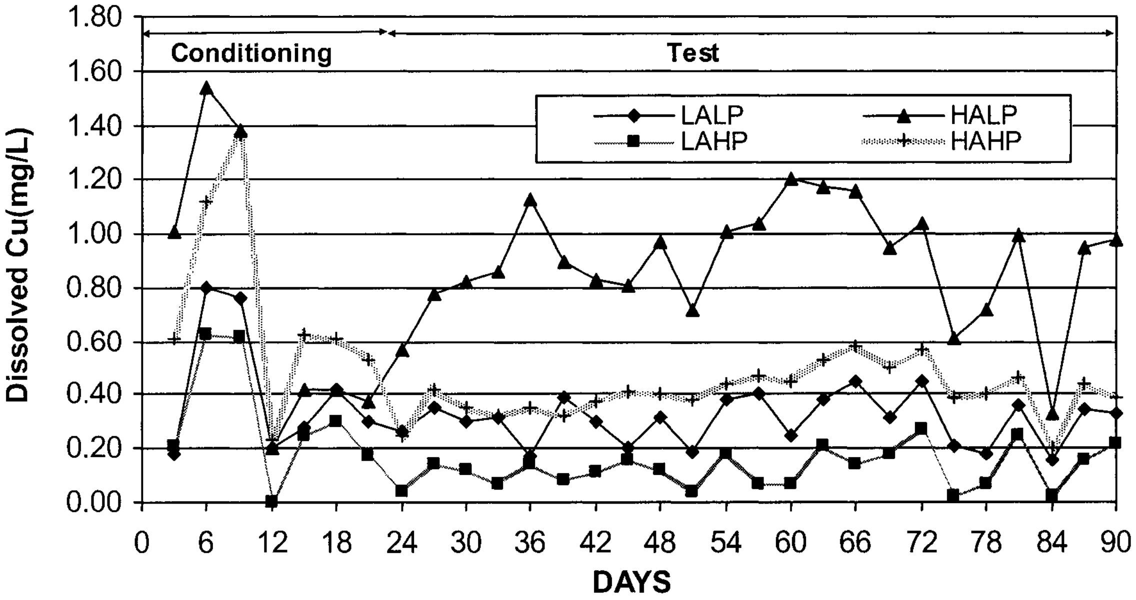

Figure 5.14 Dissolved copper for the high dosed chlorine pipes without phosphate addition

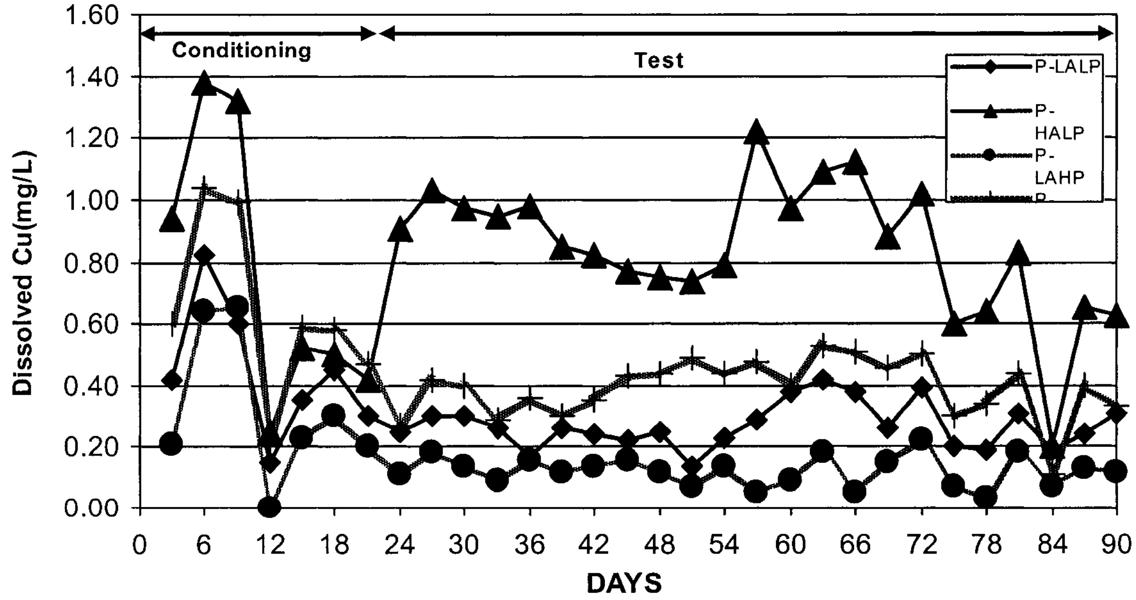

Figure 5.15 Dissolved copper for the high dosed chlorine pipes with phosphate addition

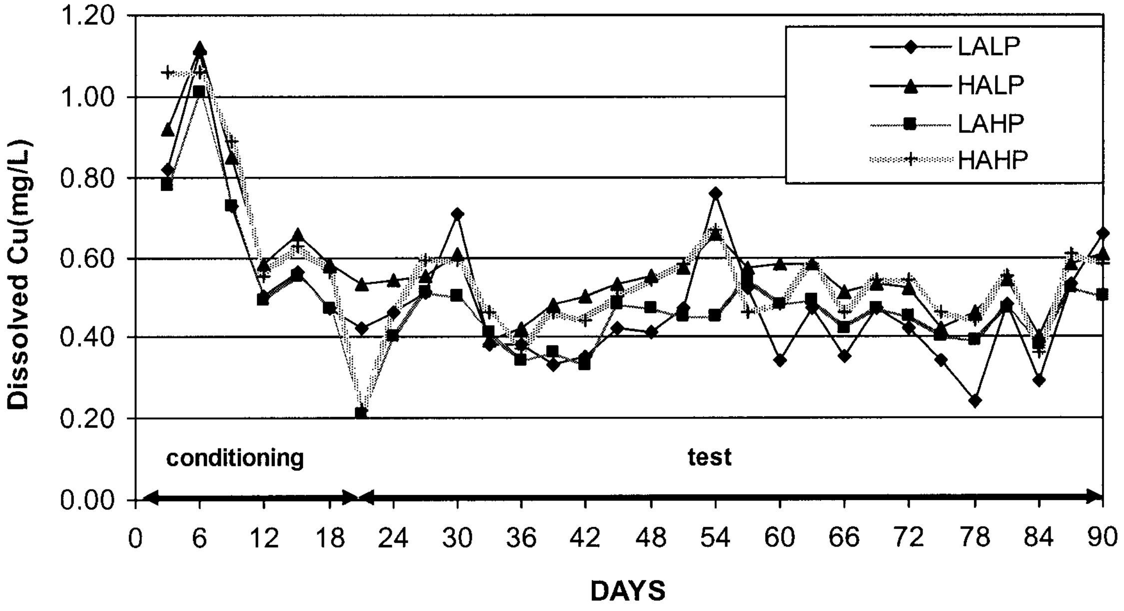

Figure 5.16 Dissolved copper for the high dosed monochloramine pipes without phosphate addition

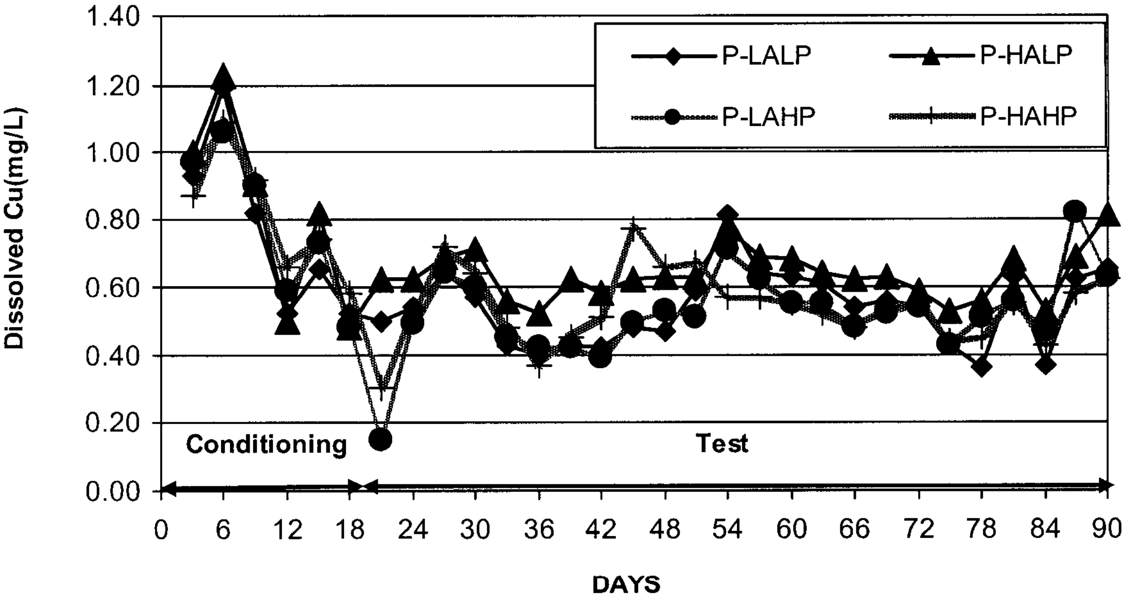

Figure 5.17 Dissolved copper for the high dosed monochloramine pipes with phosphate addition

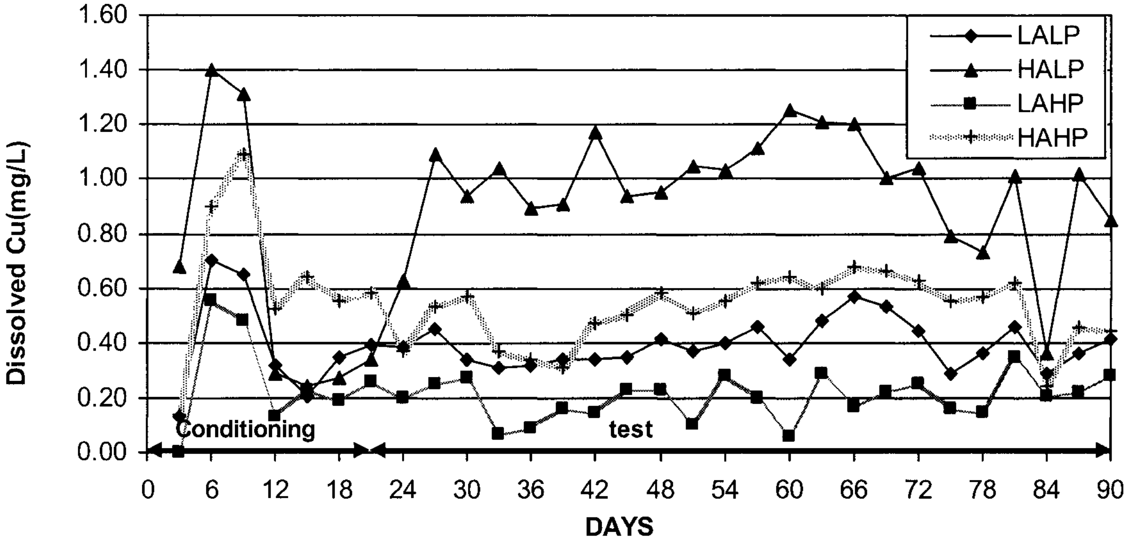

Figure 5.18 Dissolved copper for the high dosed chlorine dioxide pipes without phosphate addition

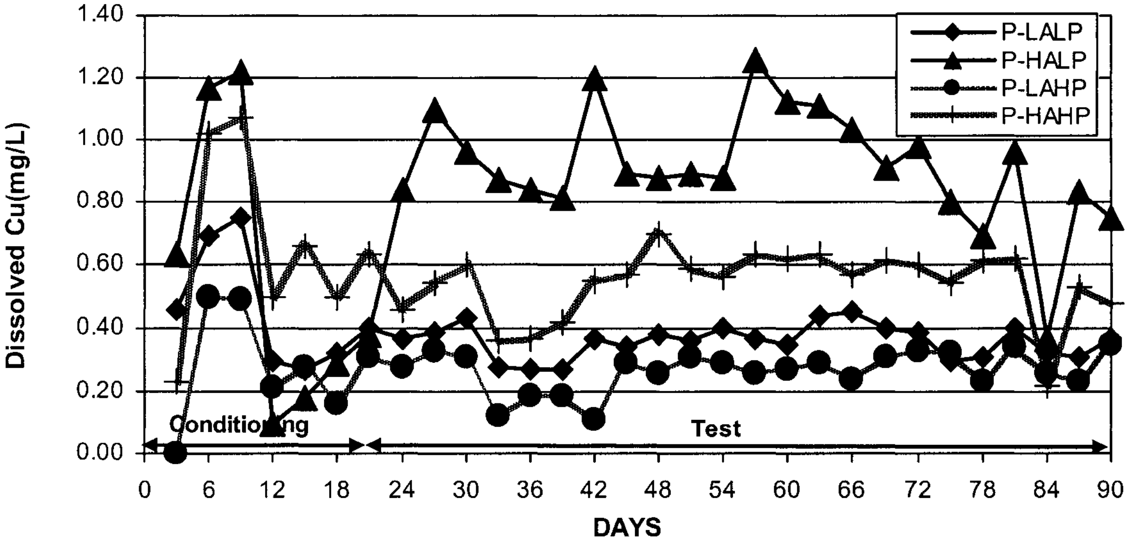

Figure 5.19 Dissolved copper for the high dosed chlorine dioxide pipes with phosphate addition

To make a comparison between the average dissolved copper value during the test phase bar charts showing the average concentration and standard deviation for each disinfectant are shown in Figure 5.20 to 5.22.

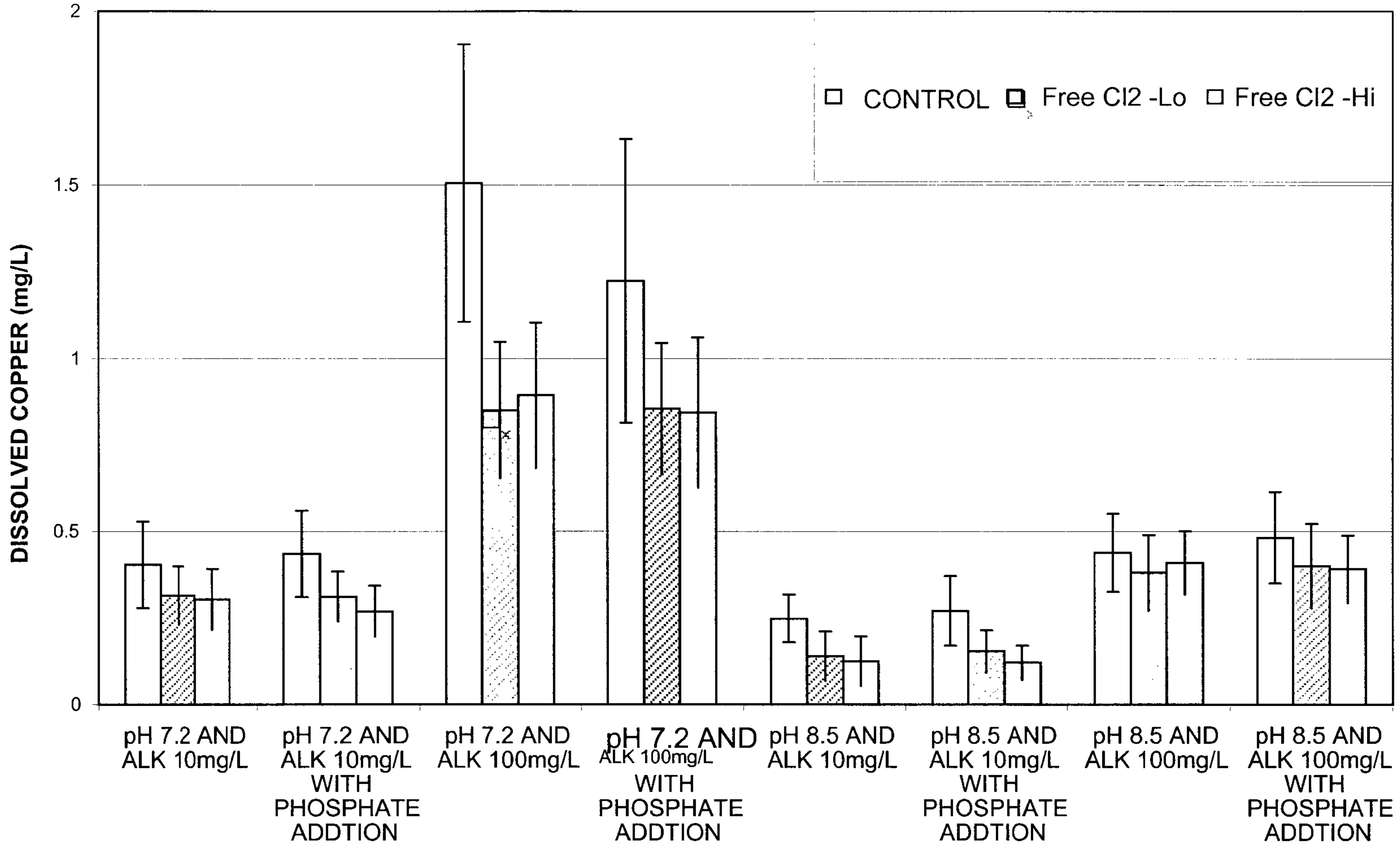

Figure 5.20 Comparison of dissolved copper values among the control and free chlorine dosed pipes during test period

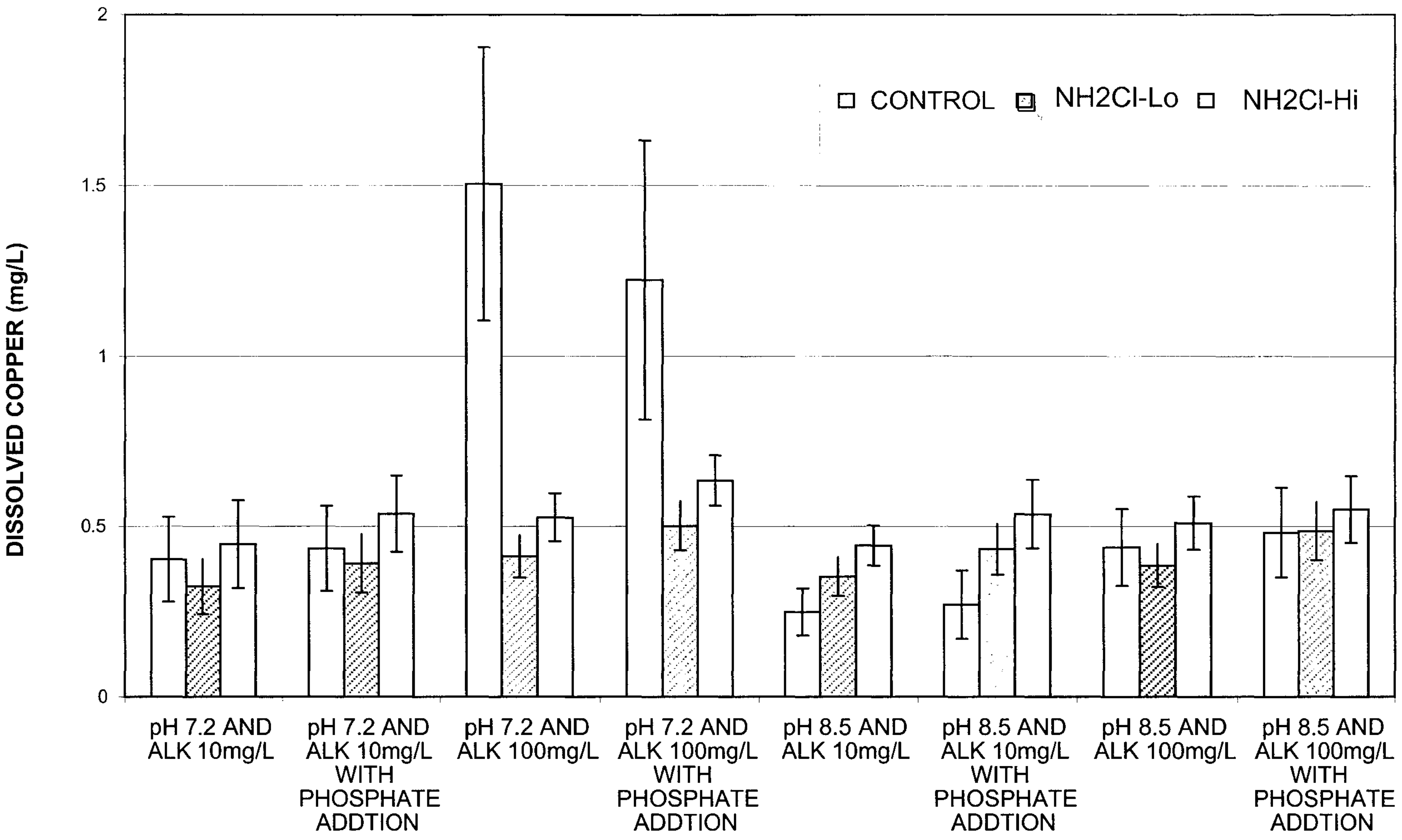

Figure 5.21 Comparison of dissolved copper values among the control and monochloramine dosed pipes during test period

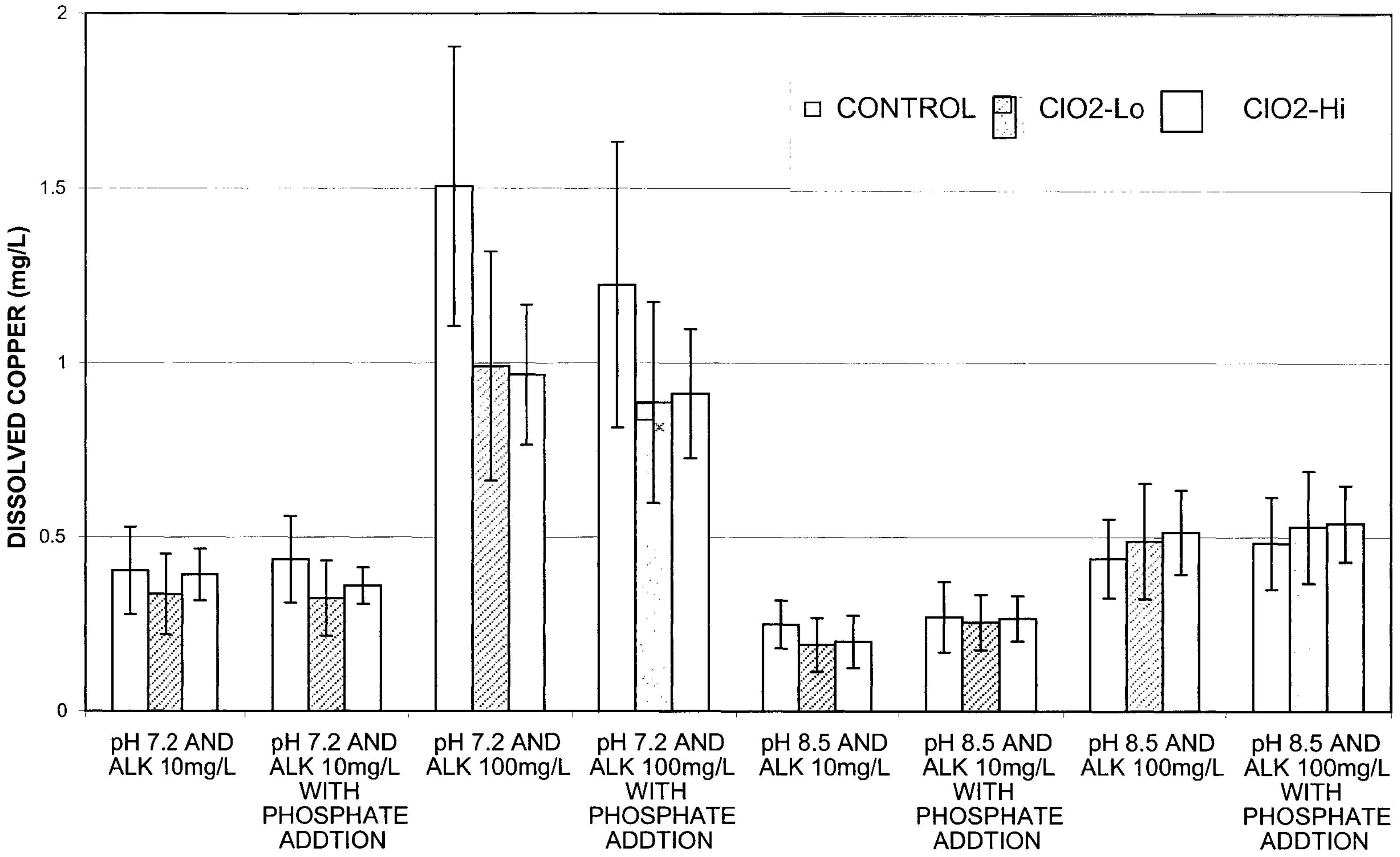

Figure 5.22 Comparison of dissolved copper values among the control and chlorine dioxide dosed pipes during test period

It is found from these figures that like the total copper in most cases average dissolved copper concentration also increases with increase of alkalinity and decrease of pH. But incase of monochloramine the affect is less prominent. In most of the cases in presence of disinfectants lowers the average dissolved copper concentration.

The phosphate addition for chlorine and chlorine dioxide dosed pipes does not cause that much impact on the dissolved copper level. But in most of the monochloramine and control pipes the phosphate addition affected significantly. The result of the t-test on the average value of dissolved copper is shown in the appendix C.

To compare the value of total and dissolved copper bar charts are shown in Figure 5.23 to Figure 5.26. From these figures it is found that most of the copper in case of monochloramine pipes are in dissolved forms and with the increase of disinfectant dose the copper concentration increases. As a result of dissociation of monochloramine ammonia is produced, that forms dissolved copper complexes in water. So the dissolved copper values in case of monochloramine pipes are higher. But in case of other pipes dissolved copper is much less and a significant part of the copper is in particulate form.

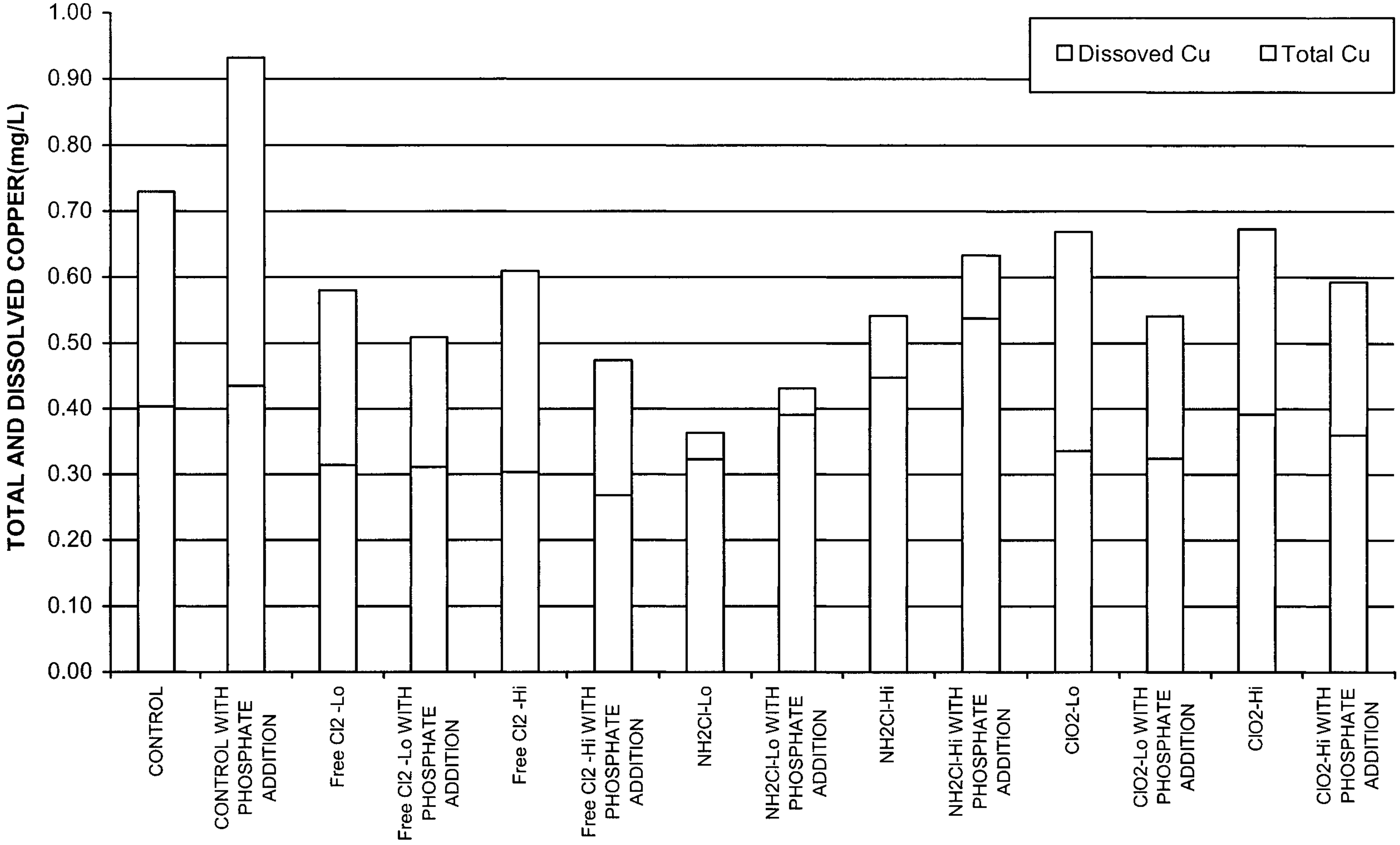

Figure 5.23 Comparison of total and dissolved copper values among the pH 7.2 and alkalinity 10 mg/L water pipes during test phase.

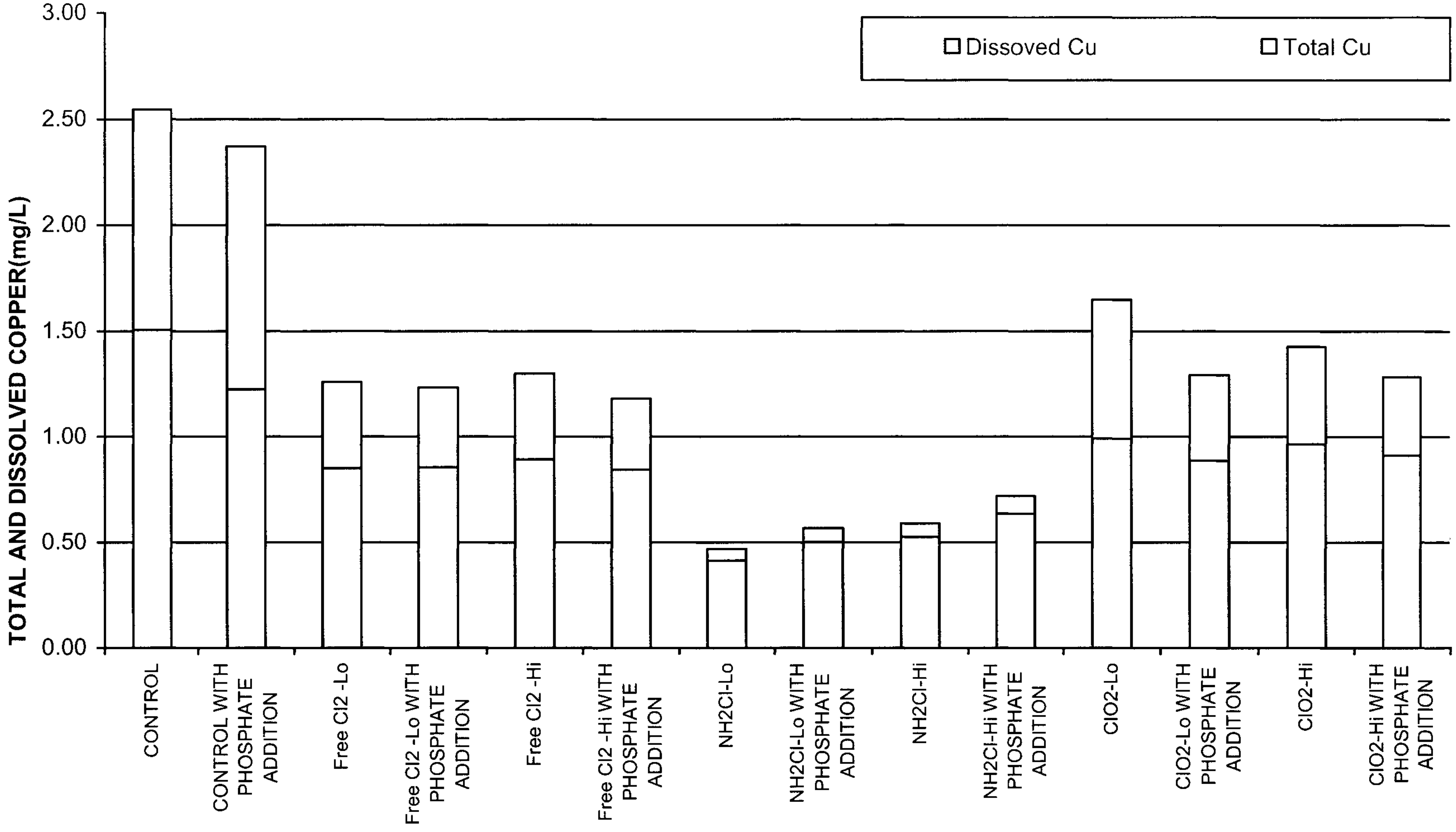

Figure 5.24 Comparison of total and dissolved copper values among the pH 7.2 and alkalinity 100 mg/L water pipes during test phase.

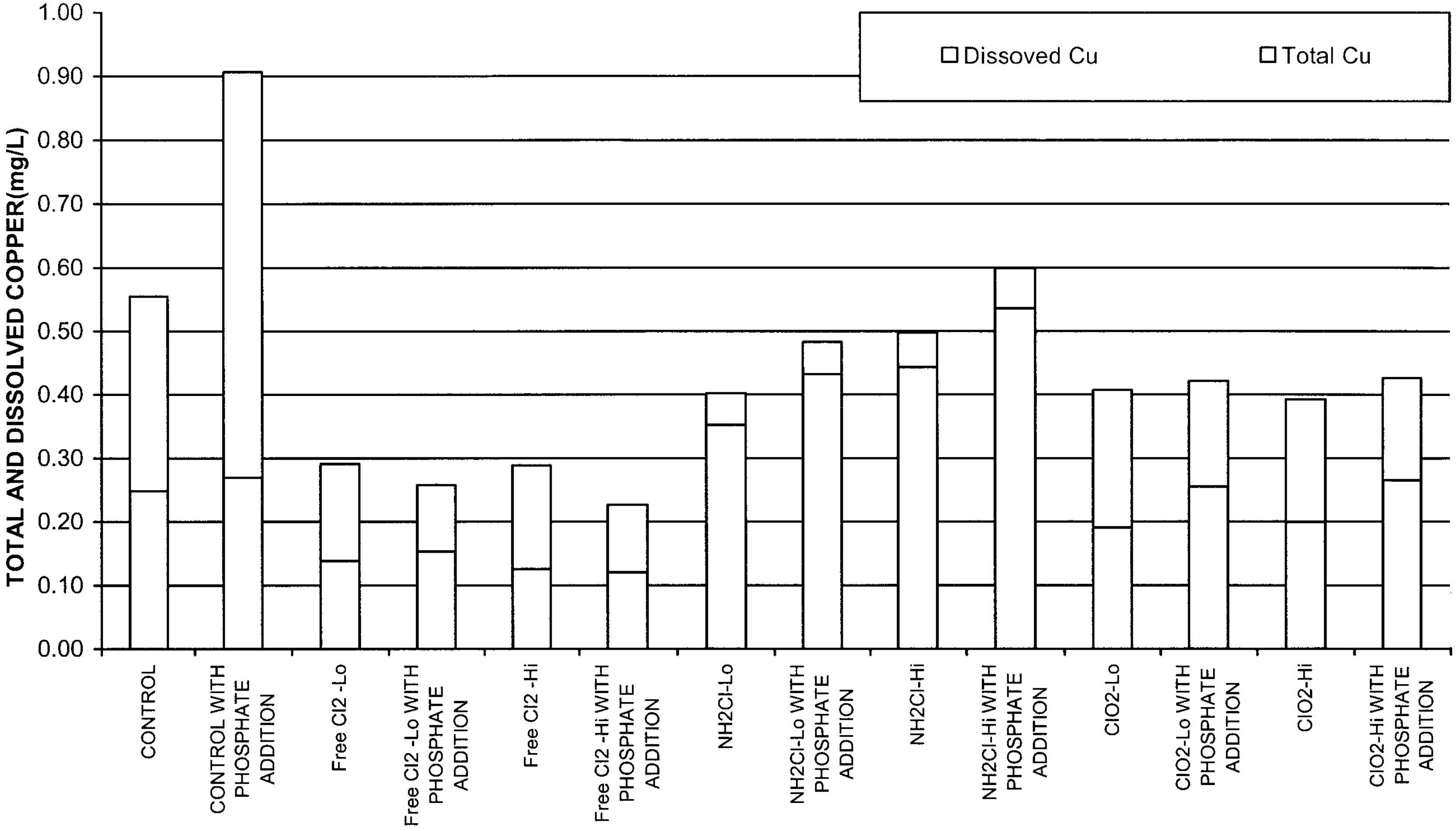

Figure 5.25 Comparison of total and dissolved copper values among pH 8.5 and alkalinity 10mg/L water pipes during test phase.

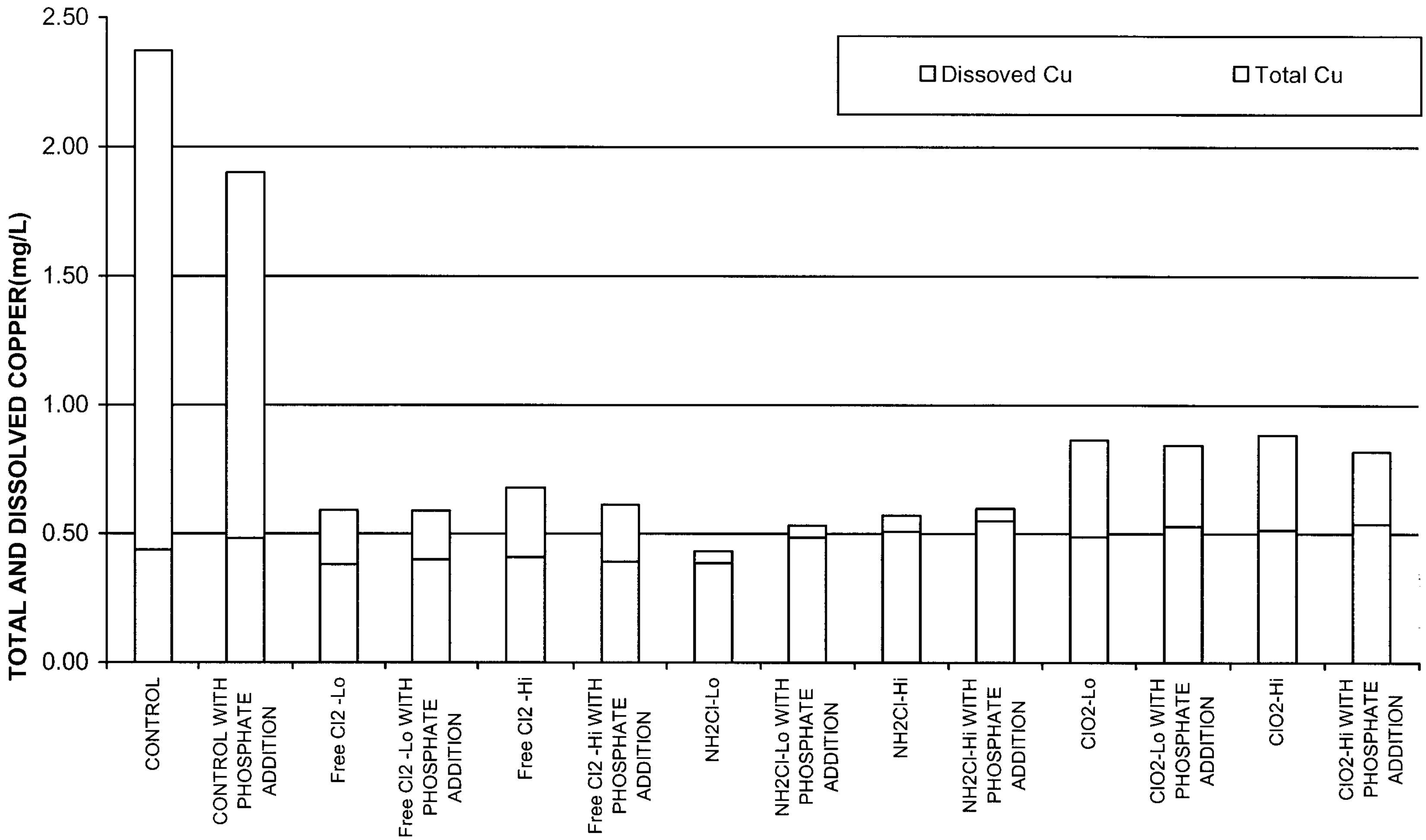

Figure 5.26 Comparison of total and dissolved copper values among pH 8.5 and alkalinity 100 mg/L water pipes during test phase

5.2 Disinfectant decay analysis

Free chlorine monochloramine and chlorine dioxide concentration in the water with pH 7.2 and alkalinity 10 mg/L was measured with time to observed the decay rate of the disinfectants in water. It was found that monochloramine decays slowly than other. It took almost 16 hours for complete monochloramine decay. In case of free chlorine and chlorine dioxide the decay time is 9 and 10 hours respectively. The disinfectants follow a 1st order decay rate. The following figures show the decay with time.

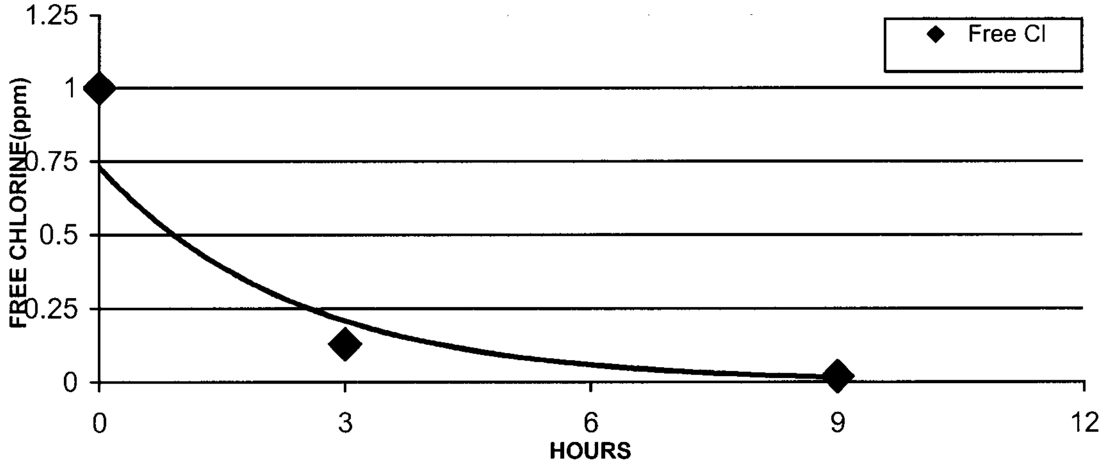

Figure 5.27 Free chlorine decay with time.

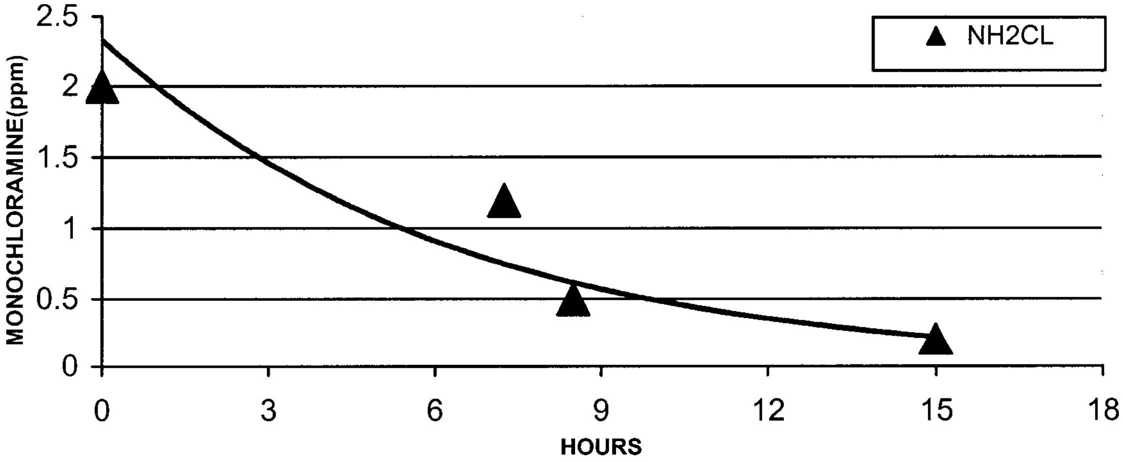

Figure 5.28 Monochloramine decay with time.

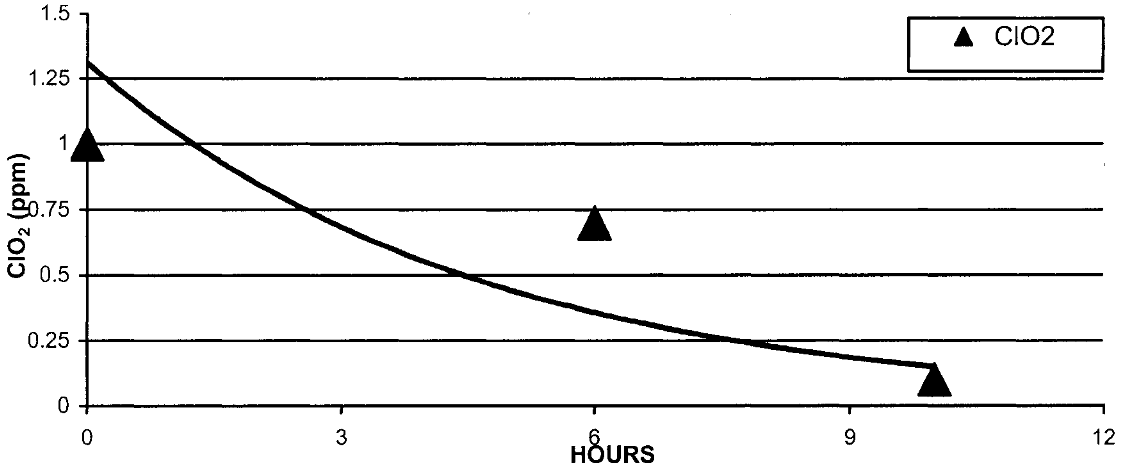

Figure 5.29 Chlorine dioxide decay with time.

5.3 Natural Organic Matter

TOC is a measure of natural organic matter present in the water. The TOC was measured in this project. The TOC values for different pipes are shown in appendix A. To compare the TOC and total Copper bar chart showing TOC and total copper for different pipes are shown in Figure5.30 to Figure5.33. No regular pattern is found in these charts except in case of monochloramine pipes where with the increase of TOC value copper level increased.

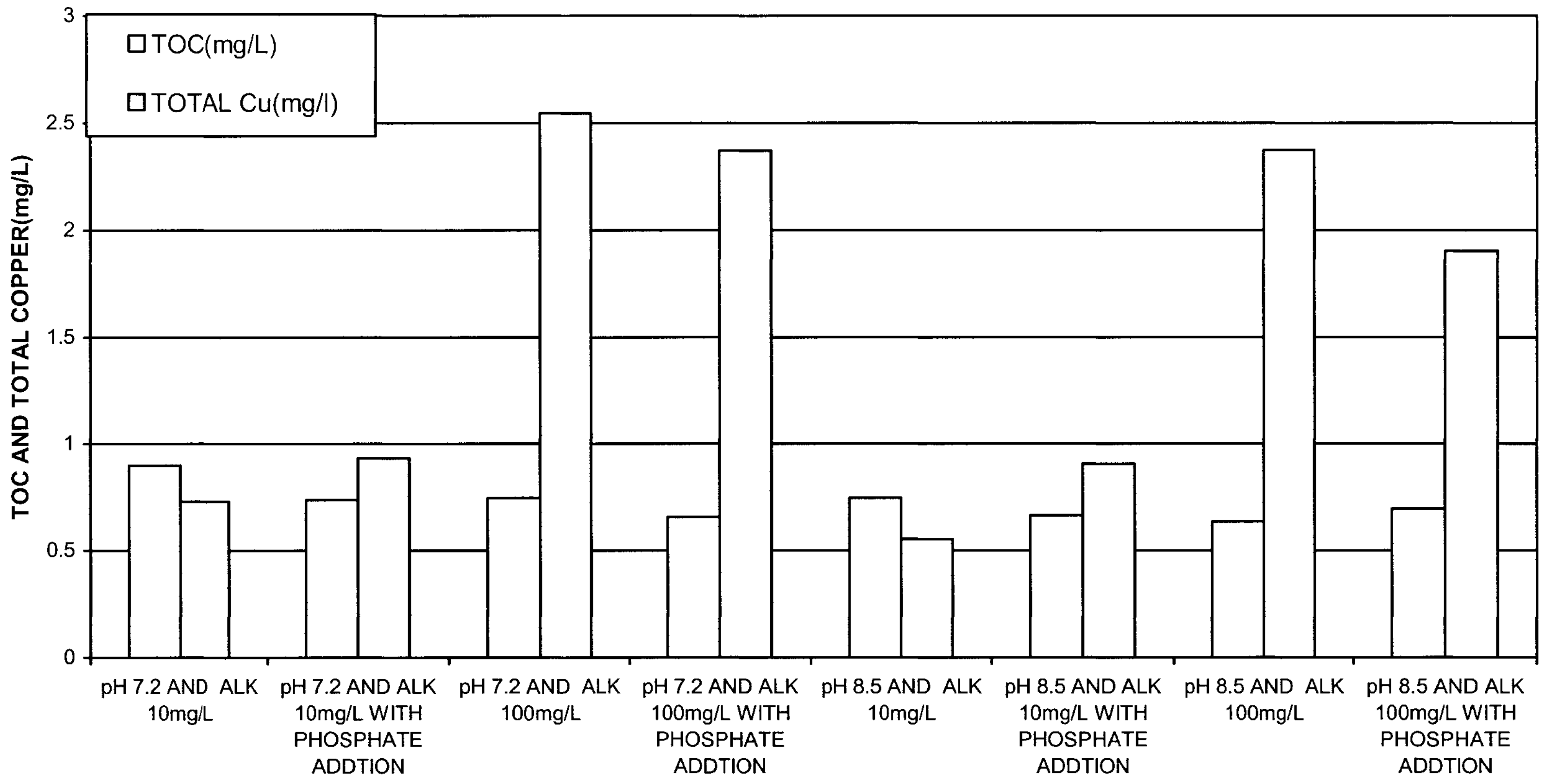

Figure 5.30 Comparison of TOC and total copper values among the controlled pipes during test phase

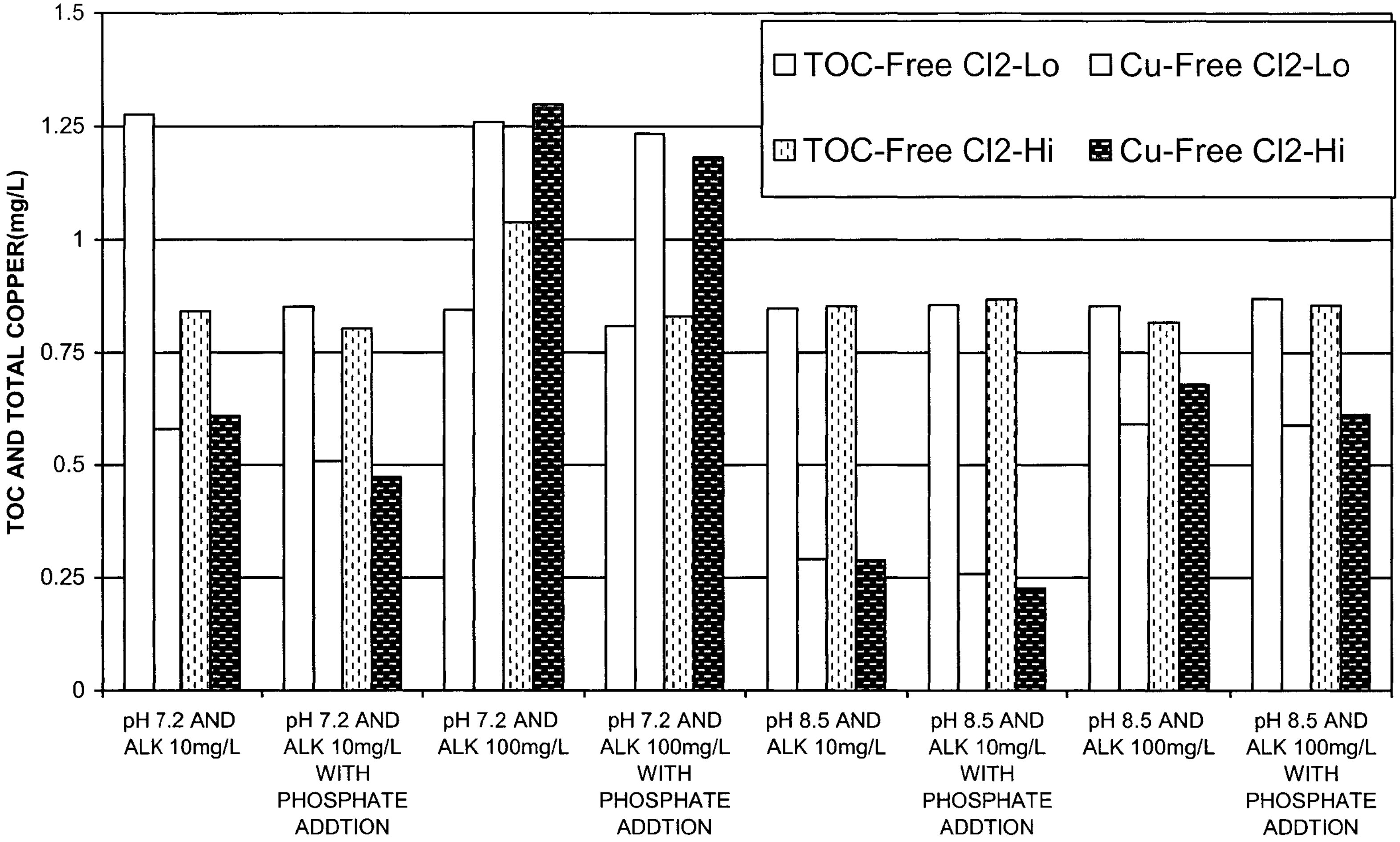

Figure 5.31 Comparison of TOC and total copper values among the free chlorine during test phase

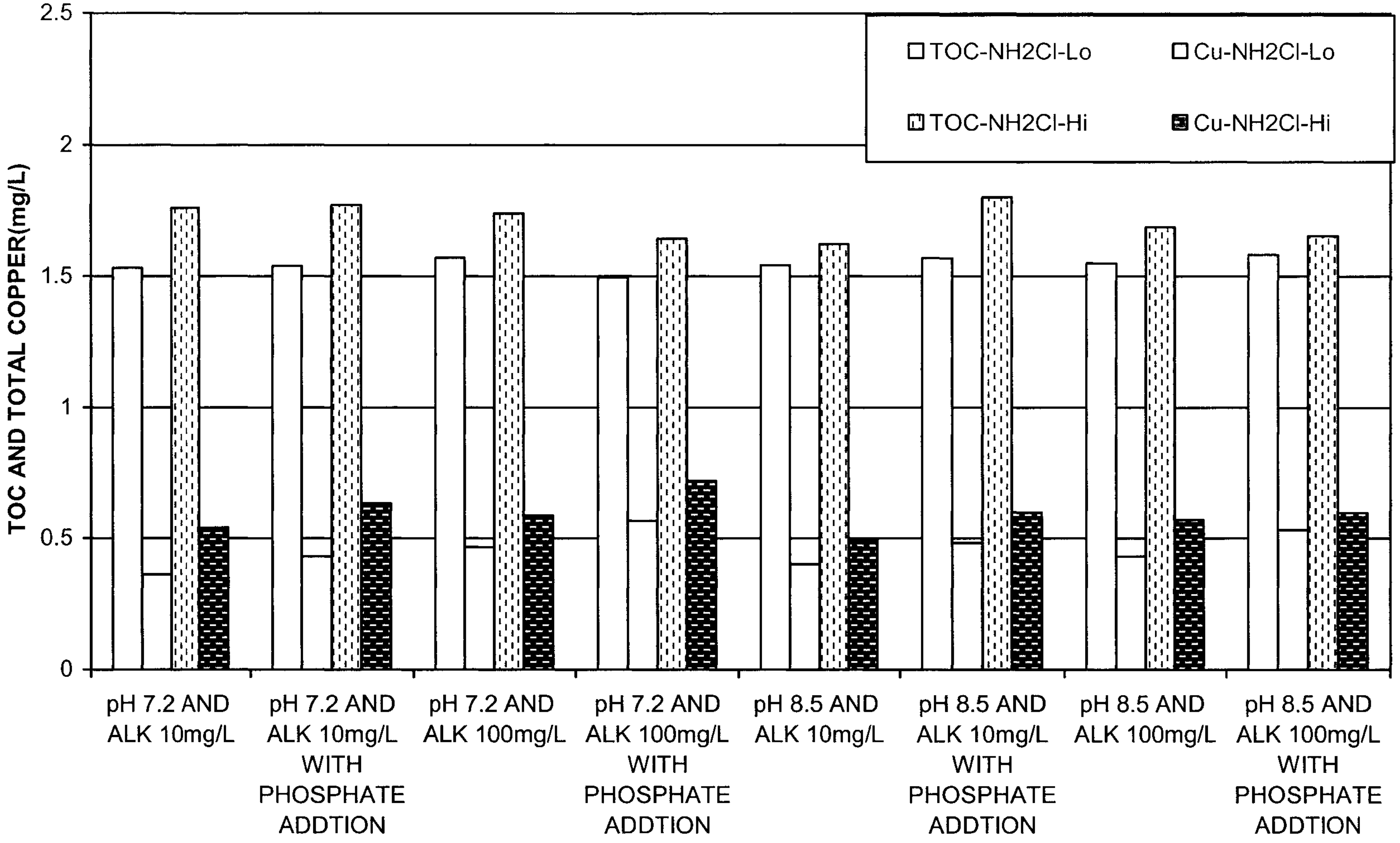

Figure 5.32 Comparison of TOC and total copper values among the monochloramine dosed pipes during test phase

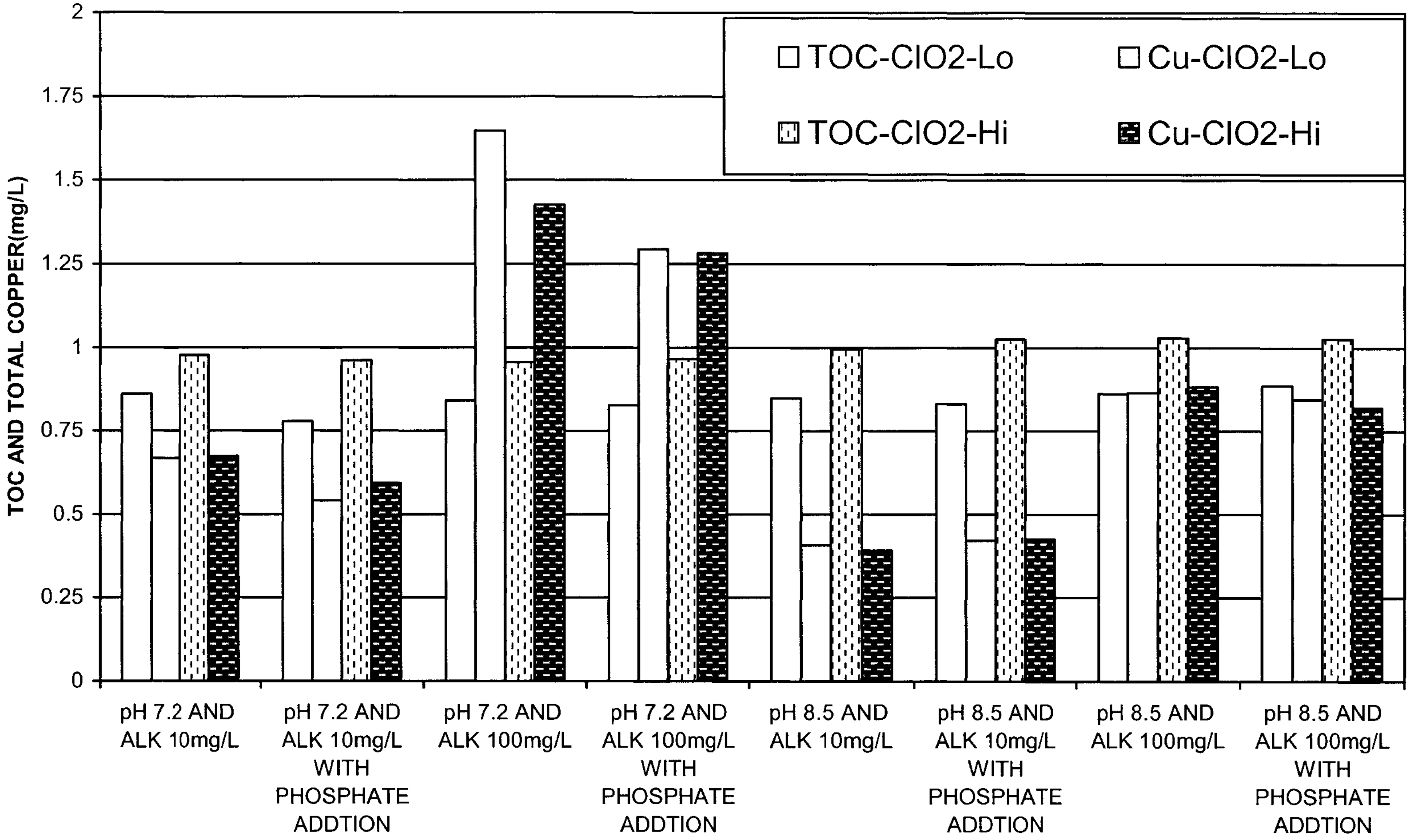

Figure 5.33 Comparison of TOC and total copper values among the chlorine dioxide dosed pipes during test phase

5.4 Residual phosphate

Ortho and total residual phosphate was measured. In most cases no correlation between the amounts of phosphate present and the total copper value was found. Only for control pipes amount of ortho-phosphate and total copper value shows good correlation (R=0.9214). The following figure shows the total copper and amount of phosphate in case of control pipes.

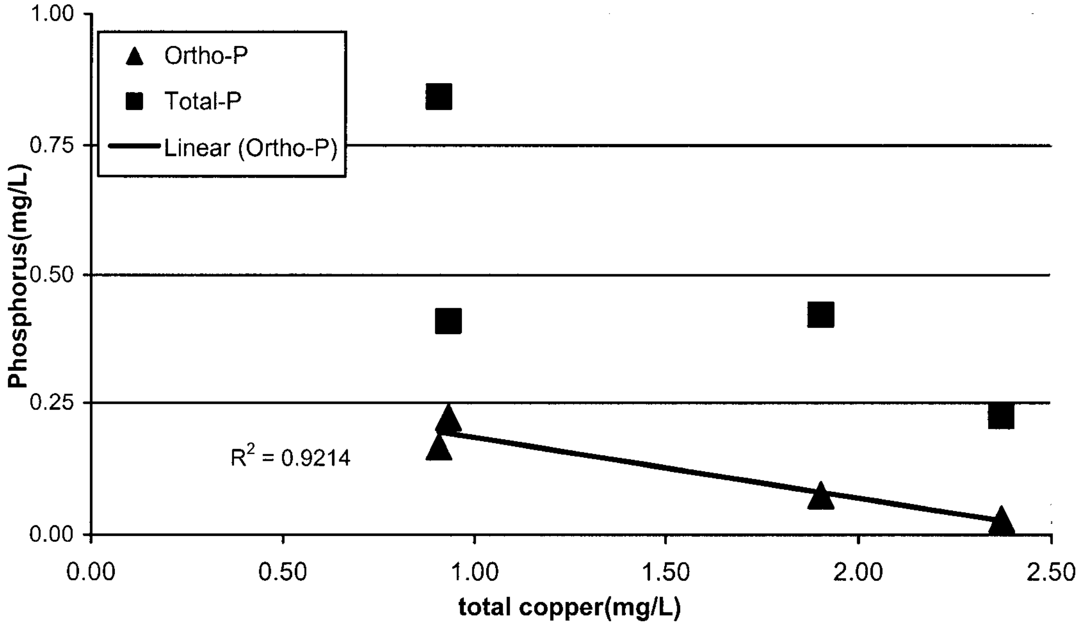

Figure 5.34 Total copper as a function of phosphorus for the control pipes.

5.5 Color and Turbidity

Color and turbidity are two important parameters of drinking water which indicate the aesthetic quality. They are also measure of clarity of water. The color and turbidity were measured in the conditioning and test phase. The average and standard deviations for turbidity are shown in the Table 5.5 to Table 5.8.

Table 5.5 – Average color during conditioning phase.

	Average Color (PCU)							
	LALP[1]	**P-LALP[2]**	**HALP[3]**	**P-HALP[4]**	**LAHP[5]**	**P-LAHP[6]**	**HAHP[7]**	**P-HAHP[8]**
Control	10.00±4.55	9.00±3.46	6.71±3.86	7.57±4.47	6.00±2.52	12.14±11.16	5.57±4.69	7.43±4.31
Cl_2 -Lo	6.71±2.81	6.00±2.89	5.71±2.21	4.86±2.19	5.43±2.99	6.14±2.91	5.86±2.85	5.57±1.90
Cl_2 -Hi	5.14±2.91	5.00±2.94	5.57±3.31	6.29±2.75	6.00±3.79	6.43±4.61	5.71±3.77	6.67±3.44
NH_2Cl-Lo	6.86±4.67	8.29±4.75	8.86±5.76	6.29±3.77	7.29±3.45	7.14±4.02	7.29±3.50	7.00±3.61
NH_2Cl-Hi	10.00±5.86	7.00±6.03	7.43±5.62	7.00±5.16	7.00±4.86	7.71±5.94	10.14±9.17	11.86±7.63
ClO_2-Lo	4.00±2.31	3.57±2.44	3.29±2.56	3.43±2.57	4.29±2.06	4.43±2.37	4.17±1.83	4.57±1.27
ClO_2-Hi	4.43±1.51	3.71±1.98	4.00±1.83	4.57±1.27	6.71±3.90	5.00±1.91	6.29±2.21	5.86±2.48

(1: LALP=low alk low pH, 2: P-LALP=low alk low pH with phosphate addition, 3: HALP= Hi alk low pH, 4: P-HALP= Hi alk low pH with phosphate addition, 5: LAHP= low alk hi pH, 6: P-LAHP= low alk hi pH with phosphate addition, 7: HAHP= Hi alk hi pH, 8: P-HAHP= Hi alk hi pH with phosphate addition)

Table 5.6 – Average color during test phase.

	Average Color (PCU)							
	LALP[1]	**P-LALP[2]**	**HALP[3]**	**P-HALP[4]**	**LAHP[5]**	**P-LAHP[6]**	**HAHP[7]**	**P-HAHP[8]**
Control	3.37±2.36	5.26±2.49	3.42±1.89	4.32±2.75	5.26±3.18	10.00±6.82	9.95±3.39	13.47±5.63
Cl_2 -Lo	3.11±1.85	3.21±1.55	2.42±1.26	2.95±2.04	3.16±1.50	2.89±2.23	2.42±1.43	2.00±1.33
Cl_2 -Hi	2.63±1.61	2.42±1.57	2.21±1.08	2.37±1.21	2.74±1.97	2.74±1.82	2.58±1.71	2.22±1.56
NH_2Cl-Lo	2.79±2.18	2.95±2.50	2.37±2.09	3.53±1.98	3.00±2.16	4.37±2.27	3.21±2.53	2.89±1.94
NH_2Cl-Hi	3.21±1.99	2.47±1.58	2.95±2.34	3.74±2.13	3.47±2.70	3.95±2.04	3.26±2.02	2.79±1.90
ClO_2-Lo	3.11±1.88	2.63±1.74	2.42±1.35	2.32±1.38	2.63±1.46	2.53±1.61	2.89±1.56	3.89±2.16
ClO_2-Hi	2.89±1.24	2.68±1.45	2.16±1.17	2.42±1.39	2.58±1.71	3.11±2.00	3.32±1.49	3.11±1.66

(1: LALP=low alk low pH, 2: P-LALP=low alk low pH with phosphate addition, 3: HALP= Hi alk low pH, 4: P-HALP= Hi alk low pH with phosphate addition, 5: LAHP= low alk hi pH, 6: P-LAHP= low alk hi pH with phosphate addition, 7: HAHP= Hi alk hi pH, 8: P-HAHP= Hi alk hi pH with phosphate addition)

Table 5.7 – Average Turbidity during conditioning phase

	Turbidity (NTU)							
	LALP[1]	**P-LALP[2]**	**HALP[3]**	**P-HALP[4]**	**LAHP[5]**	**P-LAHP[6]**	**HAHP[7]**	**P-HAHP[8]**
Control	1.24±0.82	0.92±0.34	0.79±0.38	0.92±0.49	0.92±0.44	0.86±0.41	0.90±0.42	1.16±0.38
Cl_2 -Lo	0.74±0.33	0.67±0.38	0.72±0.50	0.69±0.44	0.72±0.42	0.76±0.39	0.87±0.74	0.78±0.59
Cl_2 -Hi	0.71±0.38	0.79±0.48	0.73±0.48	0.74±0.47	0.74±0.42	0.74±0.38	0.79±0.56	0.84±0.60
NH_2Cl-Lo	1.12±1.18	1.04±0.93	1.05±0.89	0.89±0.73	0.88±0.48	0.74±0.45	0.82±0.47	0.84±0.52
NH_2Cl-Hi	1.21±1.12	1.13±1.25	1.18±1.07	0.97±0.70	1.07±1.04	1.13±1.08	1.00±0.90	1.22±1.03
ClO_2-Lo	0.62±0.32	0.64±0.30	0.61±0.26	0.63±0.35	0.71±0.30	0.68±0.36	0.84±0.37	0.70±0.34
ClO_2-Hi	0.66±0.27	0.69±0.34	0.65±0.33	0.67±0.33	0.66±0.29	0.64±0.27	0.72±0.34	0.66±0.31

(1: LALP=low alk low pH, 2: P-LALP=low alk low pH with phosphate addition, 3: HALP= Hi alk low pH, 4: P-HALP= Hi alk low pH with phosphate addition, 5: LAHP= low alk hi pH, 6: P-LAHP= low alk hi pH with phosphate addition, 7: HAHP= Hi alk hi pH, 8: P-HAHP= Hi alk hi pH with phosphate addition)

Table 5.8 – Average Turbidity during test phase

	Turbidity (NTU)							
	LALP[1]	**P-LALP[2]**	**HALP[3]**	**P-HALP[4]**	**LAHP[5]**	**P-LAHP[6]**	**HAHP[7]**	**P-HAHP[8]**
Control	0.51±0.16	0.99±0.65	0.56±0.17	0.83±0.47	0.83±0.37	1.85±1.57	1.77±0.79	2.53±1.14
Cl_2 -Lo	0.45±0.15	0.41±0.13	0.41±0.12	0.41±0.13	0.42±0.11	0.44±0.17	0.38±0.11	0.34±0.10
Cl_2 -Hi	0.42±0.11	0.37±0.08	0.34±0.07	0.36±0.08	0.43±0.15	0.42±0.14	0.40±0.06	0.40±0.08
NH_2Cl-Lo	0.38±0.09	0.44±0.12	0.39±0.07	0.49±0.15	0.44±0.14	0.44±0.11	0.43±0.13	0.39±0.06
NH_2Cl-Hi	0.43±0.10	0.40±0.08	0.39±0.10	0.44±0.14	0.47±0.22	0.47±0.12	0.43±0.12	0.44±0.07
ClO_2-Lo	0.44±0.10	0.40±0.08	0.42±0.08	0.40±0.09	0.44±0.07	0.45±0.12	0.45±0.07	0.55±0.18
ClO_2-Hi	0.45±0.09	0.41±0.10	0.41±0.07	0.43±0.08	0.45±0.08	0.45±0.11	0.48±0.07	0.48±0.08

(1: LALP=low alk low pH, 2: P-LALP=low alk low pH with phosphate addition, 3: HALP= Hi alk low pH, 4: P-HALP= Hi alk low pH with phosphate addition, 5: LAHP= low alk hi pH, 6: P-LAHP= low alk hi pH with phosphate addition, 7: HAHP= Hi alk hi pH, 8: P-HAHP= Hi alk hi pH with phosphate addition)

The color and turbidity value of the water remains within the allowable standard limit(15 PCU for color and 5 NTU for turbidity). In order to make comparison among the pipe loops bar charts of the average color and turbidity during the test phase are shown in Figure 5.35 to Figure5.40. However at higher pH values the color and turbidity values are found to be higher.

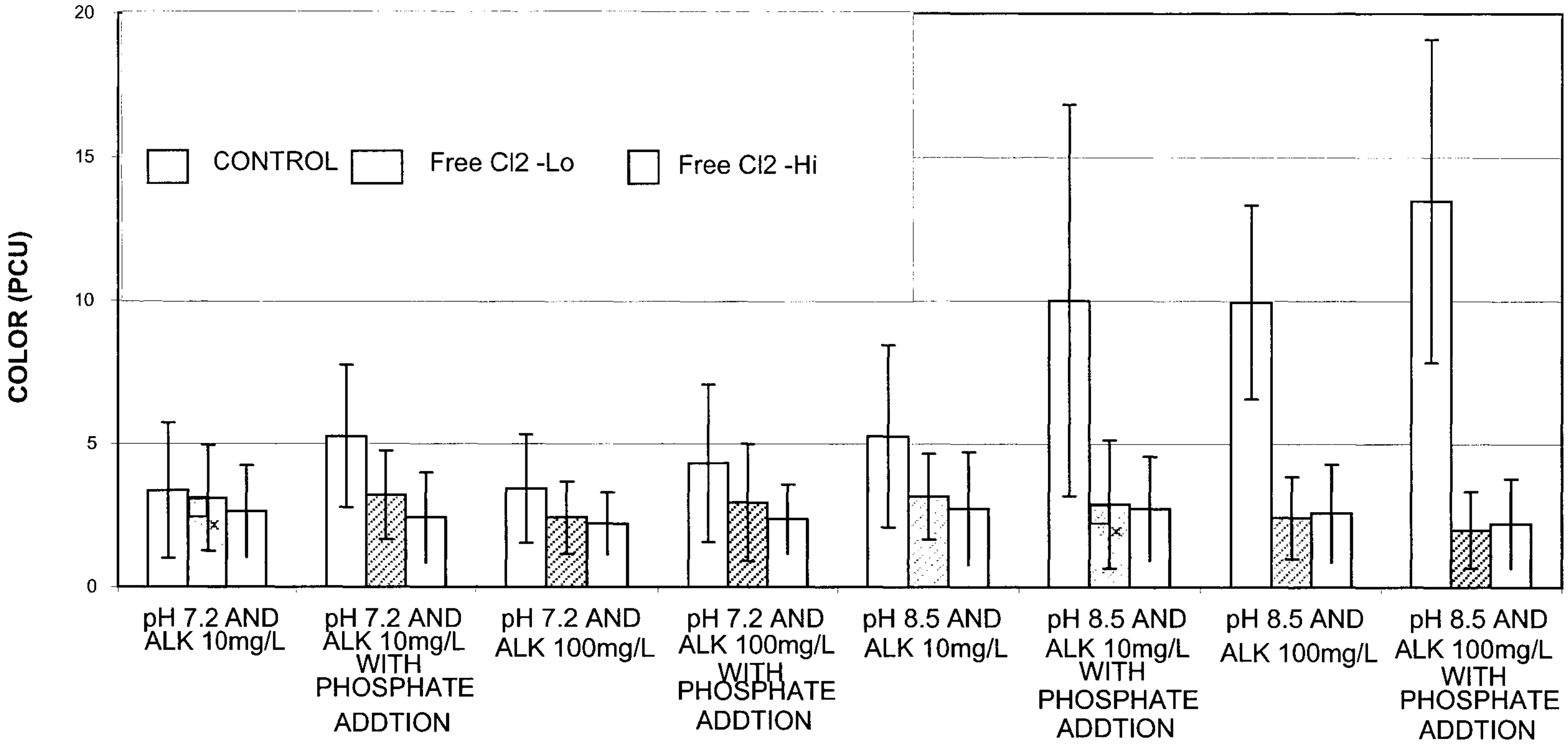

Figure 5.35 Comparison of Color values among the control and Free Chlorine dosed pipes during test periods

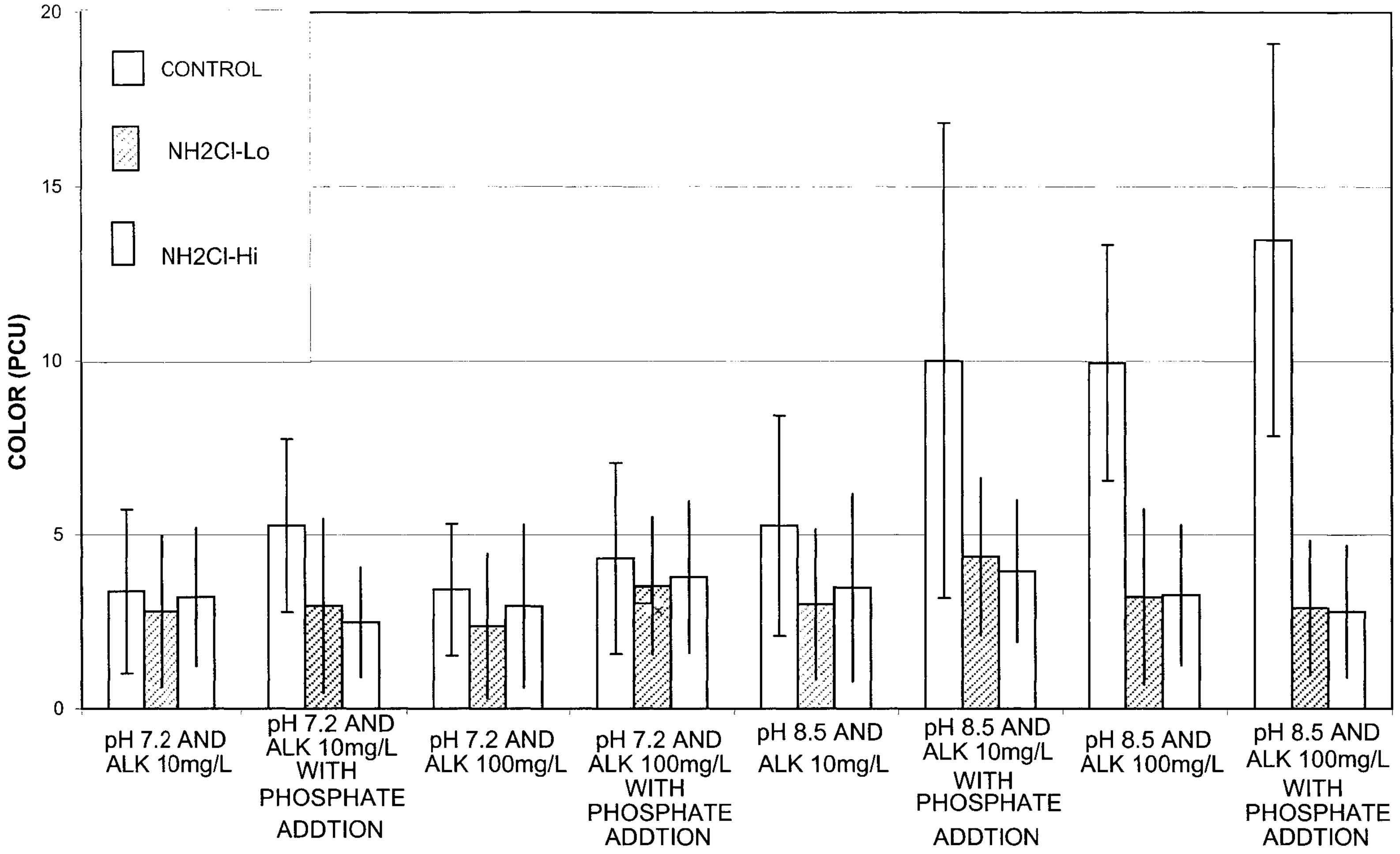

Figure 5.36 Comparison of Color values among the control and Monochloramine dosed pipes during test periods

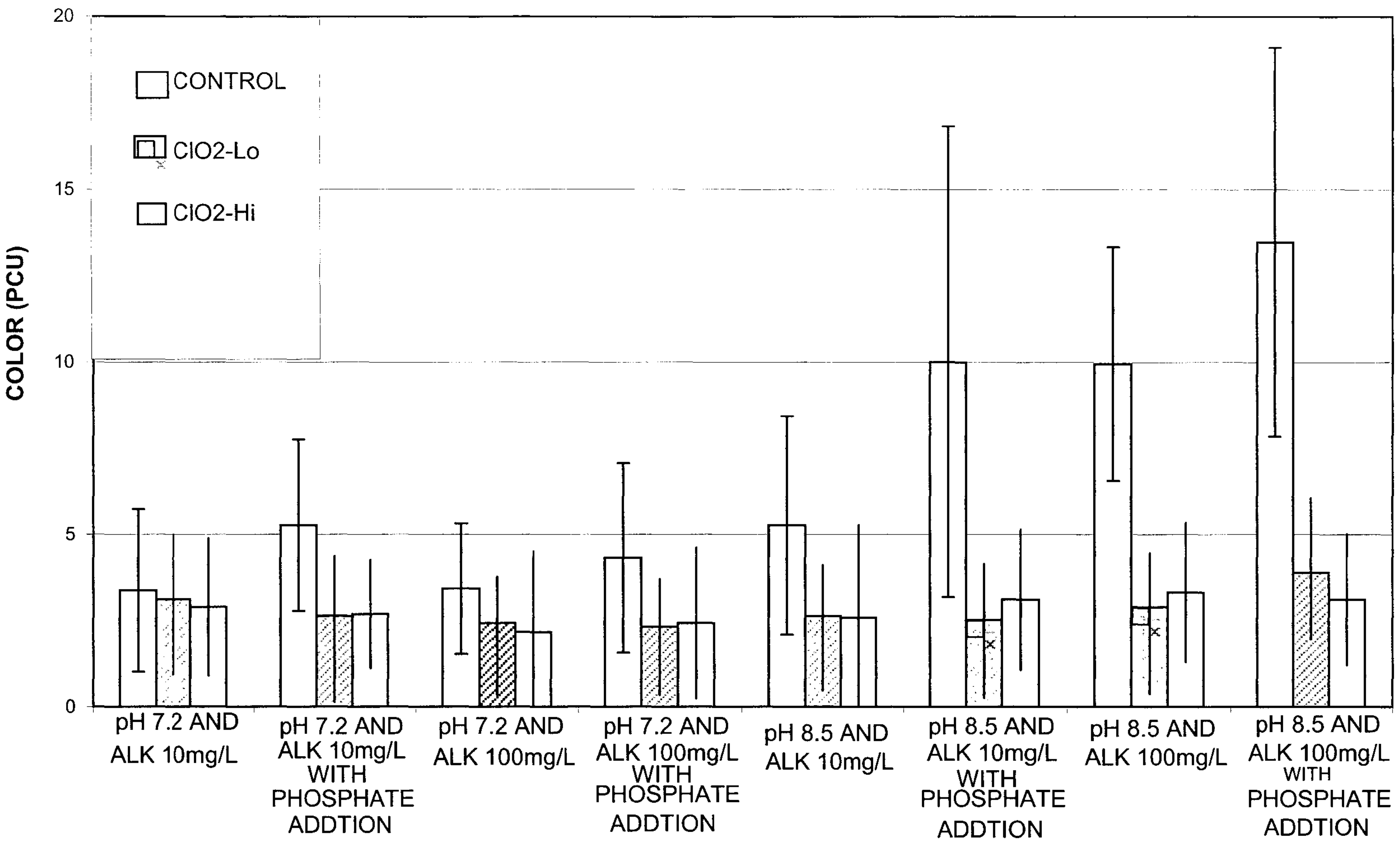

Figure 5.37 Comparison of Color values among the control and Chlorine Dioxide dosed pipes during test periods

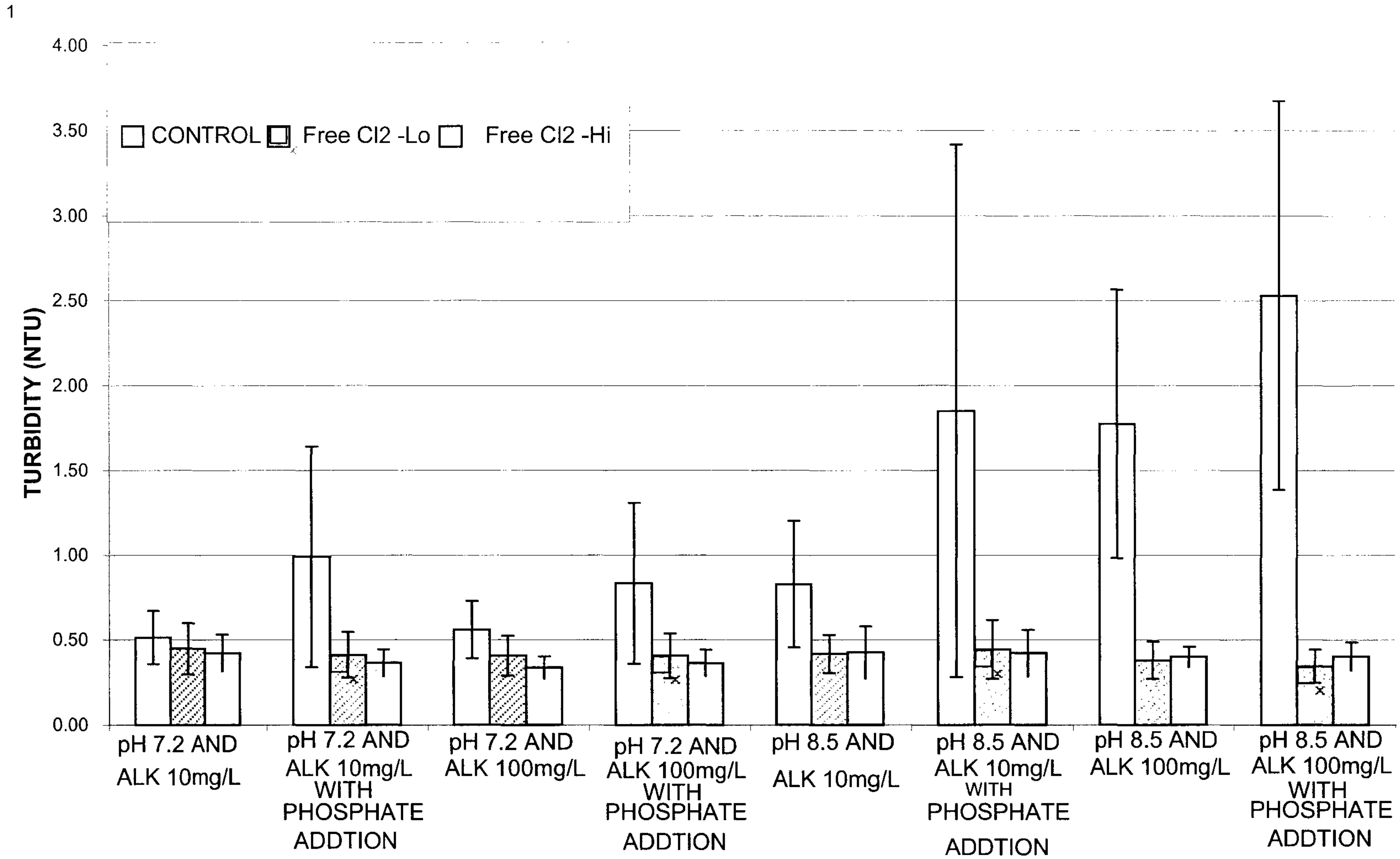

Figure 5.38 Comparison of turbidity values among the control and free chlorine dosed pipes during test period

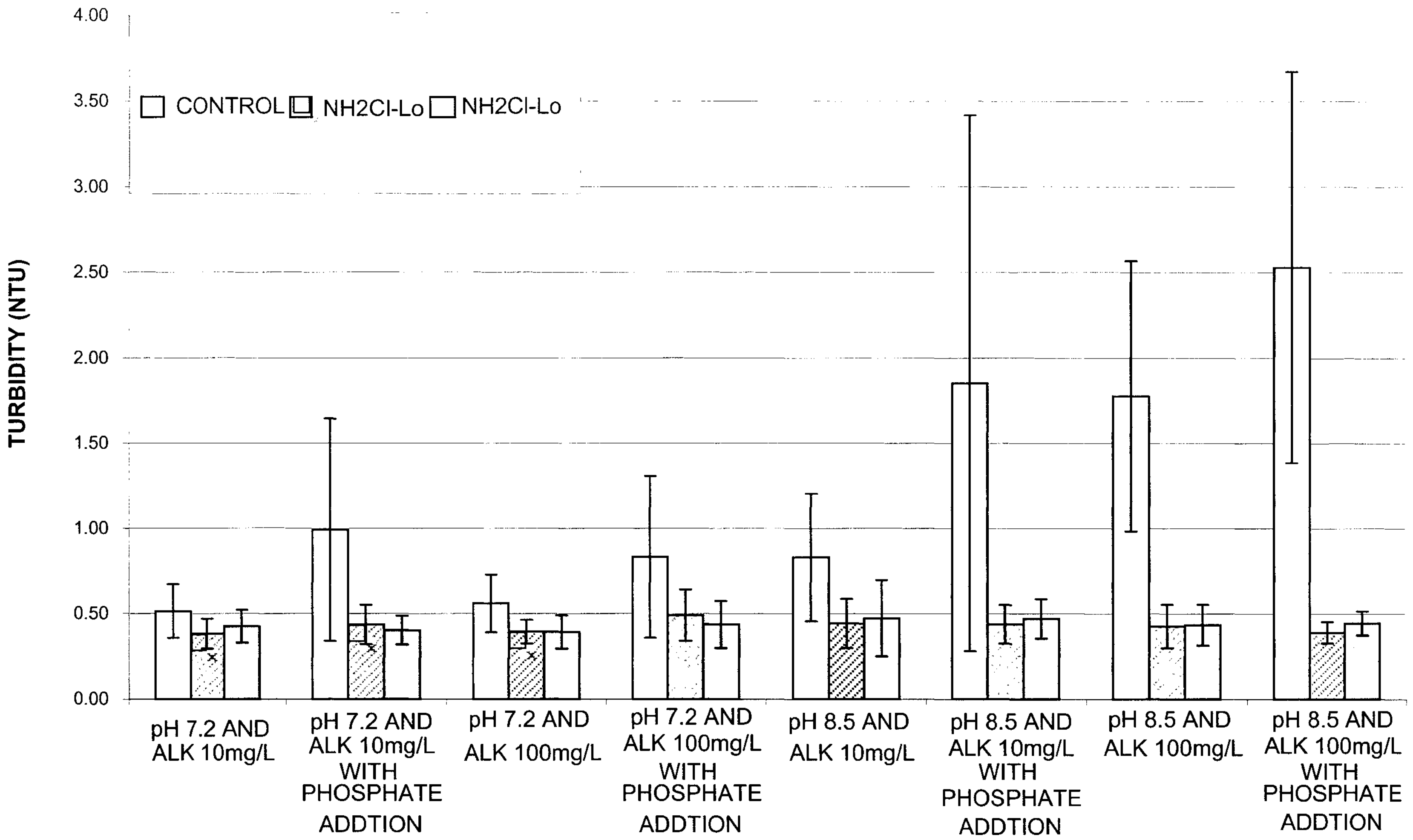

Figure 5.39 Comparison of turbidity values among the control and monochloramine dosed pipes during test period

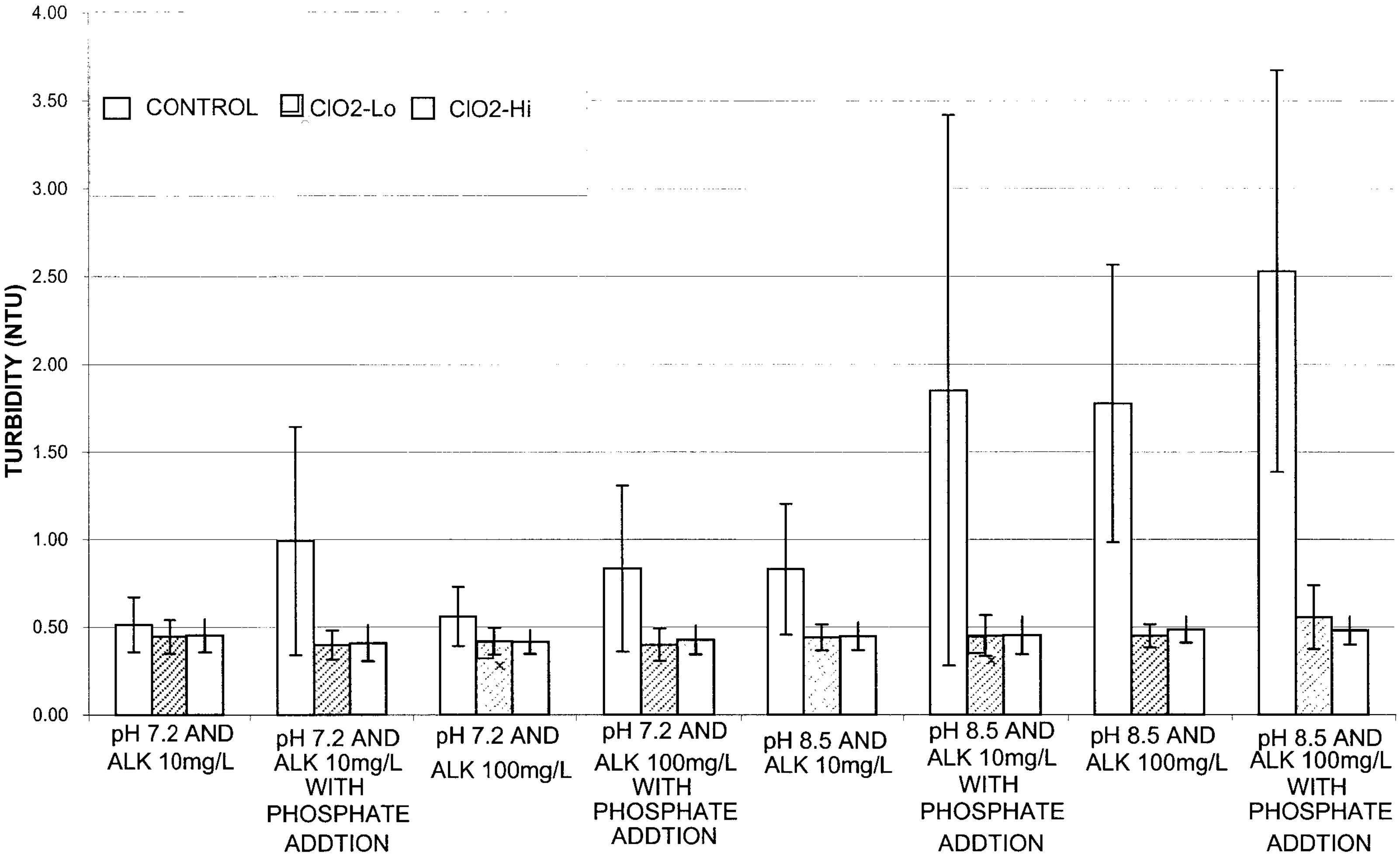

Figure 5.40 Comparison of turbidity values among the control and chlorine dioxide dosed pipes during test period

5.6 Heterotrophic Bacteria

To test the microbial quality of the stagnant water HPC test was done for few pipes. Only water with pH 7.2 and alkalinity 100 mg/L was used in these tests. The results of these test is given bellow. From these values it is found that in most cases the control has higher HPC count than the disinfectant dosed water. So bio-corrosion may be significant.

Table 5.9 HPC result of the water

Date	HPC(CFU)			
	Control	**Free chlorine-Hi**	**NH$_2$Cl-Hi**	**ClO$_2$-Hi**
09/07/2003	384,00	1700	250.00	-
09/10/2003	40000	24000	57000	-
09/13/2003	20000	-	-	10000
09/16/2003	120000	140000	30000	26000

5.7 Other physico-chemical parameter

5.7.1 pH and temperature

The final pH and temperature of the water was measured. Figure 5.41 shows the temperature of the water with time. The temperature was in the range of 24 to 30^{0}C.The average temperature is 26.83°C.

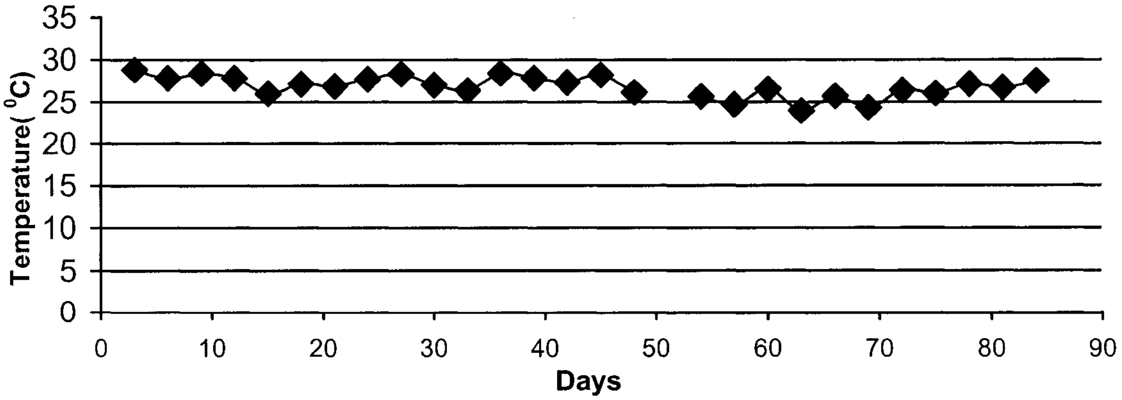

Figure 5.41 Temperature of the water during the test.

The average and standard deviations of the final pH of water are shown in Table5.9.

Table 5.10 Average final pH of the water

	Final pH							
	LALP[1]	P-LALP[2]	HALP[3]	P-HALP[4]	LAHP[5]	P-LAHP[6]	HAHP[7]	P-HAHP[8]
Control	7.64±0.13	7.63±0.13	7.75±0.18	7.85±0.19	7.89±0.19	8.04±0.26	8.62±0.29	8.59±0.27
Cl_2 -Lo	7.67±0.25	7.62±0.28	7.75±0.15	7.79±0.18	7.94±0.20	7.93±0.17	8.25±0.18	8.25±0.28
Cl_2 -Hi	7.72±0.18	7.69±0.17	7.75±0.16	7.78±0.15	7.94±0.17	7.99±0.19	8.25±0.15	8.33±0.17
NH_2Cl-Lo	7.78±0.14	7.75±0.15	7.75±0.16	7.76±0.17	7.77±0.12	7.77±0.14	7.91±0.17	7.93±0.18
NH_2Cl-Hi	7.72±0.16	7.72±0.17	7.71±0.17	7.72±0.15	7.75±0.18	7.74±0.19	7.85±0.18	7.87±0.18
ClO_2-Lo	7.58±0.17	7.55±0.18	7.68±0.18	7.71±0.20	7.82±0.21	7.84±0.16	8.15±0.26	8.20±0.25
ClO_2-Hi	7.65±0.21	7.60±0.23	7.74±0.20	7.74±0.20	7.79±0.19	7.81±0.21	8.16±0.28	8.20±0.27

(1: LALP=low alk low pH, 2: P-LALP=low alk low pH with phosphate addition, 3: HALP= Hi alk low pH, 4: P-HALP= Hi alk low pH with phosphate addition, 5: LAHP= low alk hi pH, 6: P-LAHP= low alk hi pH with phosphate addition, 7: HAHP= Hi alk hi pH, 8: P-HAHP= Hi alk hi pH with phosphate addition)

5.7.2 Dissolved Oxygen measurement

Dissolved oxygen was measured at the end of the test period. The measured DO is presented in the following table. In most cases the pipes with disinfectants have higher DO level than the control pipes. It can be explained as because of higher corrosion rate in control pipes more DO is used up making the DO level lower.

Table 5.11 Final DO of the water

	Dissolved Oxygen(mg/L)							
	LALP[1]	P-LALP[2]	HALP[3]	P-HALP[4]	LAHP[5]	P-LAHP[6]	HAHP[7]	P-HAHP[8]
Control	4.4	4.1	3.9	3.8	4.3	3.8	2.2	3.0
Cl_2 -Lo	5.5	5.6	5.0	4.9	5.3	5.0	4.9	4.8
Cl_2 -Hi	4.8	4.8	5.0	5.0	5.2	5.0	4.9	4.4
NH_2Cl-Lo	4.7	5.6	5.0	4.9	4.8	4.8	4.7	4.7
NH_2Cl-Hi	5.1	4.8	5.2	5.5	6.4	5.3	5.0	5.2
ClO_2-Lo	5.1	4.7	4.6	5.0	4.7	5.0	6.1	5.2
ClO_2-Hi	5.0	5.1	5.0	4.9	5.3	4.2	4.9	5.1

(1: LALP=low alk low pH, 2: P-LALP=low alk low pH with phosphate addition, 3: HALP= Hi alk low pH, 4: P-HALP= Hi alk low pH with phosphate addition, 5: LAHP= low alk hi pH, 6: P-LAHP= low alk hi pH with phosphate addition, 7: HAHP= Hi alk hi pH, 8: P-HAHP= Hi alk hi pH with phosphate addition)

5.8 Testing the Natural Additives

Recent studies (El-Etre, 1998, El-Etre, et al. 2000) show that honey can inhibit corrosion of copper and other metals. Also Saeed, (2003) and Al-Darbi (2002) demonstrated that some of the natural materials have anti bacterial qualities which can be used to control MIC. To test the natural additives, experiments were conducted on honey, olive oil, lemon juice and salt.

A 5 ml of a mixture of olive oil, lemon juice and 10% salt solution mixed together in 1:1:1 proportions (volume basis), were added to diluted sewage water in an Erlenmeyer flask. In a second flask, the olive oil was replaced by honey, while everything else was the same as that of the first flask. A third flask serves as control, in which only the sewage water was kept without addition of any natural materials.

The bacteria populations in these three flasks were monitored with time, using the heterotrophic plate count method (HPC). The time scale graph of the bacterial population is shown in the following figures.

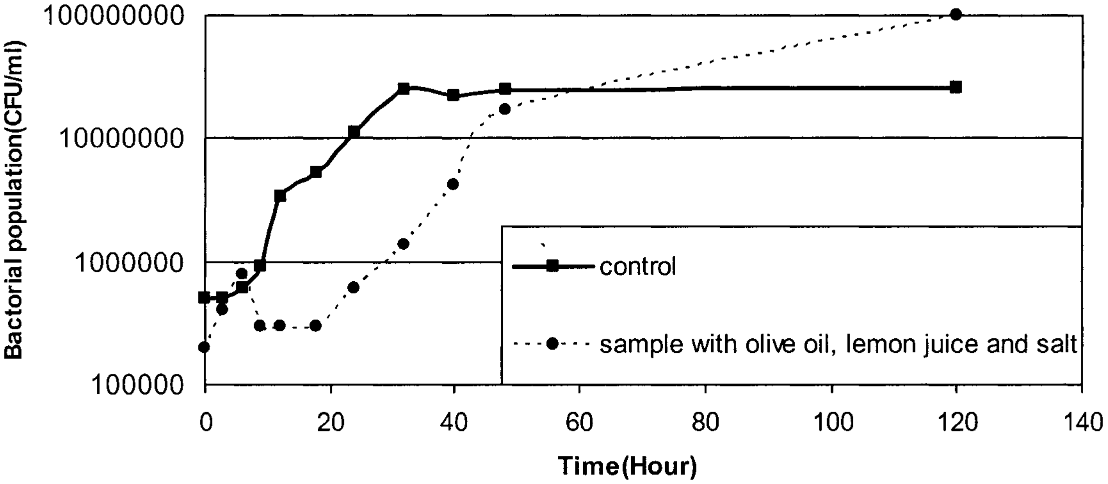

Figure5.42 HPC results on the control and natural additive (olive oil, lemon juice and salt) dosed sample.

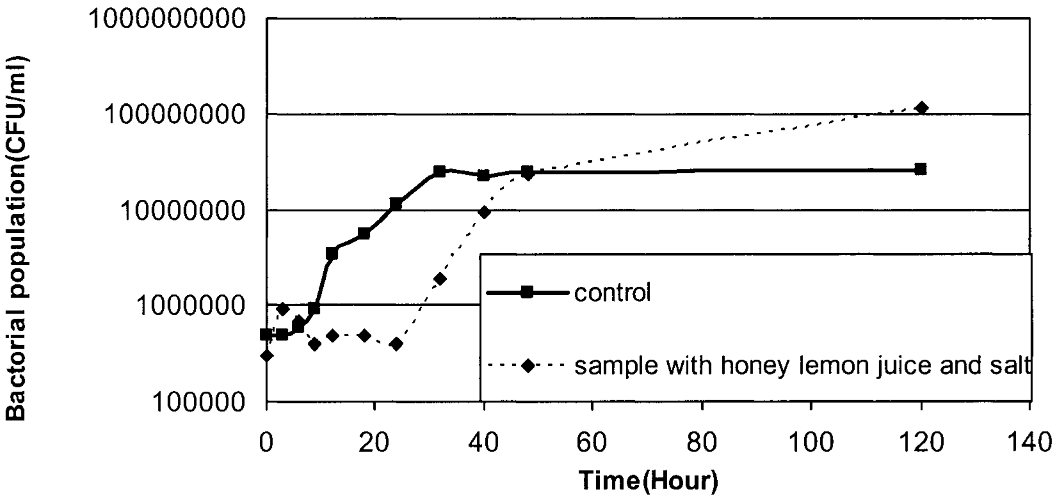

Figure5.43 HPC results on the control and natural additive (honey, lemon juice and salt) dosed sample.

From these Figures, it is found that for the first 40 hours the samples with natural additives have lower bacterial population than the control. After 120 hours the bacterial population of both honey and olive oil added sample become higher than the control sample.

The microbial growth inhibition in the samples containing natural additives, during the initial period of the experiments, might be related to effect of lemon juice as it lower the pH of the sample, or the high salt concentrations. The other possibility is that, the natural materials added to the sample have antibacterial effects, and that was the reason behind the reduction in bacteria numbers in those environments compared to the ones without any natural additives in them.

Depending on the previous studies (El-Etre, 1998, El-Etre, et al. 2000, Saeed, 2003) by different researchers on those and many other natural additives, the second possibility and explanation mentioned above, sound to be more convincing.

After two days from the start of the experiment, the bacteria numbers in the samples containing natural additives started to increase faster than those in the control samples without any additives. The reason behind this might be attributed to the decomposition of those natural additives, reduction in their concentration below the effective value, and the microbe's adaptation to the antibacterial effects of those materials.

6.0 Conclusions

6.1 Impact of Disinfectants

Comparing average copper values it is found that disinfectant dosed pipes have lower copper concentration. From the HPC test results also it is strongly suspected that major cause of copper corrosion was MIC. Monochloramine pipes have lowest copper concentration for low pH water. But in case of high pH water free chlorine pipes have lowest copper level.

Also the presence of disinfectants decrease the color and turbidity level of water, thus it improves the water quality.

6.2 Impact of pH and alkalinity

It was found that higher pH level (8.5) and lower alkalinity (10mg/L) reduced the copper level in water. Caustic (sodium or potassium hydroxide), soda ash, limestone contactors (calcite filters) and aeration (air stripping) are the principal methods that can be used for increasing the pH. Aeration is the only pH adjustment method that does not add a chemical to the water and the only one that can reduce excess alkalinity. But in deciding the final pH and alkalinity of water corrosion characteristics of other metal (such as cast iron and lead) should be considered and an optimum pH and alkalinity should be selected.

6.3 Impact of phosphate addition

The phosphate dosed as corrosion inhibitor does not have a straight forward relation with the copper concentration in water. For control pipes low alkaline water phosphate addition seems to increase the copper level in water. However with high alkaline water presence of phosphate reduces the copper concentration in water in control pipes. This relationship may have been due to MIC. Pipes dosed with free chlorine the phosphate was found to have beneficial effect, by lowering the Copper concentration. For monochloramine pipes phosphate additions have an antagonistic effect. In case of chlorine dioxide dosed pipes with low pH phosphate has beneficial affect but in case of high pH it does not have that much effect.

Also in presence of disinfectant no correlation between the residual phosphorous and copper concentration was found. In the absence of disinfectants (i.e. control pipes) strong correlation between ortho-P and total copper was found.

6.4 Impact of NOM

Considering the average value of the TOC and copper found that in case of monochloramine pipes with increase of TOC copper concentration increase. But in case of other pipes no pattern was found.

7.0 Recommendations

7.1 Longer Study Time

Due to the shorter duration of the study some parameters have large variability. So longer study time should be used to examine the corrosion in distribution system. According the American Water Works Research Foundation (AWWARF,1996) experimental duration between 6 and 12 months is recommended to draw conclusions.

7.2 Use of other corrosion inhibitor

Only poly-phosphate inhibitor is used in this project. Other types of inhibitor that are mostly used are ortho-phosphate, blend of ortho and poly phosphate, silicate inhibitor. These inhibitors may be tested for comparing their relative effectiveness.

7.3 Control dosing of organic matter

Organic matters have significant effect on copper corrosion. Their effect depends on their nature. In this project amount of NOM was not controlled. To examine the effect of organic matter on copper corrosion controlled dosing of different types of organic matter such as sodium alginate(representing EPS), soluble NOM and particulate NOM may be used.

7.4 Improved setup

To represent the household distribution system pipe loop instead of pipes may be used. Also intermittent flowing and stagnant condition may be introduced to make it more representative.

7.5 Temperature effect

To examine the temperature effect test should be conducted both on summer and winter. Also chemical analysis of the corrosion deposits on the pipe wall should be done to find if there is any difference in chemical composition of the deposits forms in these two times.

7.6 Identification of the microbes present in water

Test should be conducted to determine the species of the microbes present in water. This will help to draw a conclusion about whether MIC is mainly responsible for corrosion or not.

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APPENDIX A- RAW DATA

Table A.1. Total Copper for pH 7.2 and alkalinity 10mg/L water

Date	CONTROL	Cl2 –Lo	Cl_2 -Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	0.44	0.36	0.40	0.60	1.29	1.34	0.25
6/7/03	1.07	2.02	0.80	0.84	1.11	0.71	0.70
9/7/03	1.75	0.69	0.76	0.58	0.73	0.70	0.65
12/7/03	0.98	0.66	0.58	0.40	0.60	0.64	0.57
15/07/03	0.63	0.61	0.57	0.47	0.61	0.54	0.48
18/07/03	0.86	0.68	0.73	0.29	0.56	0.59	0.70
21/07/03	0.84	0.51	0.49	0.38	0.53	0.51	0.59
24/07/03	0.67	0.50	0.50	0.42	0.61	0.65	0.78
27/07/03	0.60	0.51	0.55	0.45	0.56	0.62	0.7
30/07/03	1.24	0.58	0.61	0.39	0.89	0.60	0.61
2/8/03	0.55	0.48	0.6	0.29	0.55	0.52	0.55
5/8/03	0.45	0.51	0.54	0.31	0.47	0.48	0.59
8/8/03	0.55	0.65	0.69	0.27	0.39	0.54	0.69
11/8/03	0.58	0.57	0.52	0.30	0.45	0.61	0.54
14/08/03	0.67	0.54	0.51	0.33	0.54	0.70	0.65
17/08/03	0.77	0.71	0.89	0.36	0.55	0.79	0.88
20/08/03	0.75	0.57	0.68	0.43	0.59	0.72	0.75
23/08/03	0.86	0.76	0.77	0.54	0.90	0.66	0.72
26/08/03	0.66	0.45	0.62	0.45	0.62	0.66	0.59
29/08/03	0.68	0.51	0.57	0.28	0.42	0.74	0.68
1/9/03	0.94	0.64	0.61	0.40	0.51	0.66	0.63
4/9/03	1.08	0.97	0.94	0.31	0.43	1.11	1.04
7/9/03	0.72	0.61	0.66	0.40	0.53	0.75	0.75
10/9/03	0.77	0.64	0.73	0.35	0.46	0.68	0.64
13/09/03	0.59	0.41	0.41	0.27	0.38	0.49	0.47
16/09/03	0.71	0.47	0.44	0.25	0.35	0.59	0.65
19/09/03	0.66	0.63	0.65	0.42	0.51	0.87	0.72
22/09/03	0.56	0.44	0.36	0.23	0.34	0.56	0.51
25/09/03	1.03	0.59	0.62	0.45	0.59	0.70	0.65
28/09/03	0.68	0.60	0.55	0.46	0.80	0.68	0.69

Table A.2. Total Copper for pH 7.2 and alkalinity 10mg/L water with phosphate addition

Date	CONTROL	Cl2 -Lo	Cl_2-Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	1.28	0.79	0.79	0.86	1.22	0.84	0.4
6/7/03	1.24	3.47	0.82	0.93	1.19	0.68	0.69
9/7/03	0.92	0.54	0.6	0.74	0.82	0.59	0.75
12/7/03	0.7	0.59	0.44	0.47	0.74	0.45	0.58
15/07/03	0.58	0.6	0.58	0.56	0.78	0.43	0.58
18/07/03	0.48	0.59	0.76	0.35	0.59	0.53	0.58
21/07/03	1.06	0.44	0.57	0.46	0.63	0.38	0.59
24/07/03	0.54	0.48	0.41	0.52	0.66	0.55	0.64
27/07/03	0.55	0.46	0.5	0.6	0.76	0.53	0.59
30/07/03	0.61	0.48	0.54	0.49	0.73	0.54	0.65
2/8/03	0.47	0.37	0.48	0.38	0.52	0.43	0.51
5/8/03	0.4	0.33	0.36	0.32	0.52	0.39	0.52
8/8/03	0.4	0.6	0.41	0.36	0.49	0.46	0.49
11/8/03	0.62	0.51	0.55	0.35	0.5	0.6	0.65
14/08/03	0.71	0.45	0.38	0.39	0.55	0.5	0.57
17/08/03	0.93	0.61	0.67	0.4	0.54	0.65	0.78
20/08/03	0.89	0.53	0.43	0.51	0.7	0.63	0.63
23/08/03	1.1	0.51	0.45	0.6	0.91	0.56	0.61
26/08/03	0.85	0.53	0.46	0.54	0.73	0.46	0.6
29/08/03	1.3	0.56	0.48	0.35	0.71	0.55	0.57
1/9/03	1.42	0.64	0.64	0.44	0.61	0.59	0.6
4/9/03	1.48	0.87	0.76	0.42	0.77	0.88	0.9
7/9/03	1.2	0.51	0.43	0.46	0.62	0.62	0.58
10/9/03	1.17	0.58	0.55	0.41	0.58	0.58	0.59
13/09/03	0.86	0.35	0.33	0.3	0.51	0.42	0.44
16/09/03	1.33	0.43	0.38	0.27	0.47	0.47	0.53
19/09/03	1.3	0.49	0.43	0.46	0.81	0.61	0.61
22/09/03	1.09	0.4	0.34	0.29	0.45	0.42	0.45
25/09/03	1.36	0.51	0.46	0.51	0.71	0.49	0.54
28/09/03	0.87	0.5	0.45	0.54	0.71	0.52	0.59

Table A.3. Total Copper for pH 7.2 and alkalinity 100mg/L water

Date	CONTROL	Cl2 -Lo	Cl_2-Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	2.67	1.56	1.97	0.99	1.46	1.7	1.14
6/7/03	1.84	2.03	1.54	0.92	1.12	1.1	1.4
9/7/03	1.8	1.32	1.38	0.75	0.85	1.23	1.31
12/7/03	0.76	0.56	0.5	0.53	0.72	0.52	0.56
15/07/03	0.08	0.58	0.58	0.57	0.76	0.49	0.53
18/07/03	0.38	0.56	0.56	0.43	0.65	0.5	0.44
21/07/03	0.71	0.35	0.52	0.48	0.61	0.36	0.42
24/07/03	0.87	0.67	0.81	0.54	0.6	0.84	0.92
27/07/03	2.2	1.12	1.1	0.58	0.69	1.41	1.44
30/07/03	2.65	0.98	1.21	0.55	0.69	1.46	1.34
2/8/03	2.4	1.31	1.35	0.53	0.48	1.67	1.47
5/8/03	2.59	1.18	1.36	0.4	0.49	1.27	1.29
8/8/03	2.64	1.08	1.22	0.42	0.51	1.52	1.31
11/8/03	2.69	1.04	1.16	0.38	0.57	1.56	1.37
14/08/03	2.75	1.09	1.14	0.45	0.6	1.69	1.42
17/08/03	2.94	1.61	1.63	0.48	0.61	1.99	1.83
20/08/03	2.71	1.48	1.36	0.52	0.66	1.94	1.63
23/08/03	3.39	1.5	1.51	0.63	0.72	2.08	1.74
26/08/03	2.87	1.36	1.35	0.51	0.71	1.75	1.45
29/08/03	3.08	1.62	1.83	0.49	0.62	2.37	1.85
1/9/03	3.24	1.48	1.57	0.47	0.63	1.81	1.5
4/9/03	2.93	1.76	1.71	0.45	0.58	2.08	1.86
7/9/03	2.76	1.24	1.27	0.44	0.58	1.73	1.31
10/9/03	2.82	1.53	1.43	0.43	0.55	1.75	1.44
13/09/03	1.85	0.96	0.9	0.32	0.45	1.38	1.27
16/09/03	2.34	1.05	1.15	0.4	0.5	1.5	1.09
19/09/03	2.44	1.5	1.37	0.45	0.58	2.1	1.59
22/09/03	1.24	0.54	0.58	0.33	0.45	0.85	0.71
25/09/03	2.65	1.66	1.43	0.5	0.65	1.79	1.71
28/09/03	2.49	1.2	1.42	0.48	0.61	1.37	1.27

Table A.4. Total Copper for pH 7.2 and alkalinity 100mg/L water with phosphate addition

Date	CONTROL	Cl2 -Lo	Cl_2-Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	2.68	1.53	1.54	1.01	1.6	1.65	1.13
6/7/03	2	1.38	1.38	1.03	1.23	1.56	1.17
9/7/03	1.76	1.25	1.32	0.72	0.91	1.21	1.22
12/7/03	0.65	0.58	0.53	0.66	0.66	0.53	0.19
15/07/03	0.74	0.66	0.66	0.73	1.01	0.51	0.46
18/07/03	0.69	0.62	0.72	0.47	0.62	0.51	0.47
21/07/03	0.58	0.454	0.53	0.53	0.77	0.41	0.54
24/07/03	1.06	1.24	1.18	0.58	0.83	1.29	1.11
27/07/03	1.73	1.2	1.35	0.67	0.81	1.31	1.39
30/07/03	2.18	1.11	1.39	0.61	0.97	1.25	1.27
2/8/03	1.95	1.25	1.38	1.05	0.66	1.32	1.23
5/8/03	2.2	1.16	1.21	0.45	0.57	1.07	1.18
8/8/03	2.06	1.31	1.22	0.54	0.64	1.11	1.1
11/8/03	2.18	1.2	1.19	0.5	0.65	1.45	1.4
14/08/03	2.22	1.07	1.04	0.52	0.71	1.25	1.23
17/08/03	2.53	1.36	1.3	0.53	0.69	1.41	1.41
20/08/03	2.64	1.34	1.03	0.63	0.74	1.28	1.39
23/08/03	2.62	1.12	1.2	0.72	0.83	1.44	1.33
26/08/03	3.45	1.5	1.55	0.62	0.77	1.58	1.63
29/08/03	3.12	1.61	1.49	0.59	0.74	1.66	1.68
1/9/03	3.43	1.36	1.37	0.57	0.71	1.42	1.46
4/9/03	3.49	1.81	1.66	0.6	0.74	1.78	1.82
7/9/03	2.38	1.27	1.23	0.49	0.69	1.24	1.17
10/9/03	2.6	1.4	1.3	0.48	0.67	1.47	1.29
13/09/03	1.69	0.96	0.83	0.37	0.58	1.06	1.14
16/09/03	2.35	1.01	0.89	0.48	0.64	1.08	1
19/09/03	2.25	1.28	1.11	0.54	0.73	1.33	1.26
22/09/03	1.4	0.58	0.4	0.39	0.57	0.71	0.62
25/09/03	2.3	1.18	0.99	0.56	0.78	1.21	1.32
28/09/03	2.69	1.06	0.86	0.56	0.83	1.02	1.08

Table A.5. Total Copper for pH 8.5 and alkalinity 10mg/L water

Date	CONTROL	Cl2 -Lo	Cl_2-Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	0.82	0.45	0.62	0.72	1.01	0.42	0.38
6/7/03	0.86	0.45	0.63	0.59	1.01	0.48	0.55
9/7/03	0.74	0.48	0.62	0.65	0.73	0.79	0.48
12/7/03	0.85	0.24	0.19	0.46	0.52	0.35	0.31
15/07/03	0.93	0.46	0.45	0.45	0.62	0.49	0.46
18/07/03	0.61	0.43	0.49	0.44	0.49	0.51	0.44
21/07/03	0.54	0.34	0.36	0.39	0.27	0.47	0.41
24/07/03	0.35	0.16	0.21	0.41	0.53	0.39	0.42
27/07/03	0.52	0.22	0.24	0.49	0.56	0.38	0.42
30/07/03	0.55	0.3	0.26	0.4	0.65	0.41	0.53
2/8/03	0.28	0.2	0.22	0.37	0.43	0.26	0.26
5/8/03	0.39	0.27	0.27	0.27	0.37	0.29	0.31
8/8/03	0.39	0.3	0.39	0.37	0.41	0.34	0.42
11/8/03	0.45	0.32	0.25	0.34	0.45	0.4	0.38
14/08/03	0.65	0.34	0.27	0.38	0.53	0.43	0.4
17/08/03	0.66	0.44	0.36	0.42	0.51	0.63	0.51
20/08/03	0.7	0.24	0.23	0.45	0.53	0.43	0.14
23/08/03	0.66	0.34	0.33	0.52	0.49	0.57	0.54
26/08/03	0.54	0.29	0.2	0.44	0.59	0.35	0.36
29/08/03	0.54	0.24	0.22	0.43	0.52	0.48	0.07
1/9/03	0.94	0.3	0.33	0.44	0.53	0.43	0.46
4/9/03	0.58	0.39	0.33	0.39	0.47	0.51	0.5
7/9/03	0.54	0.23	0.29	0.41	0.51	0.38	0.4
10/9/03	0.66	0.45	0.45	0.39	0.48	0.48	0.43
13/09/03	0.46	0.14	0.17	0.31	0.42	0.21	0.26
16/09/03	0.64	0.22	0.22	0.36	0.43	0.35	0.34
19/09/03	0.55	0.39	0.44	0.4	0.51	0.55	0.61
22/09/03	0.45	0.2	0.18	0.33	0.38	0.29	0.34
25/09/03	0.71	0.31	0.31	0.48	0.58	0.38	0.46
28/09/03	0.55	0.4	0.47	0.45	0.57	0.44	0.47

Table A.6. Total Copper for pH 8.5 and alkalinity 10mg/L water with phosphate additions

Date	CONTROL	Cl2 -Lo	Cl_2-Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	0.51	0.43	0.54	0.74	1.36	0.3	0.1
6/7/03	0.78	0.69	0.64	0.89	1.06	0.45	0.5
9/7/03	0.83	0.53	0.65	0.8	0.9	0.72	0.49
12/7/03	0.56	0.26	0.16	0.53	0.66	0.35	0.36
15/07/03	0.51	0.44	0.38	0.65	0.8	0.46	0.47
18/07/03	0.46	0.48	0.47	0.52	0.54	0.49	0.38
21/07/03	0.46	0.37	0.34	0.48	0.53	0.52	0.43
24/07/03	0.26	0.16	0.36	0.56	0.56	0.37	0.37
27/07/03	0.34	0.22	0.29	0.63	0.71	0.45	0.47
30/07/03	0.47	0.27	0.24	0.57	0.7	0.44	0.51
2/8/03	0.22	0.16	0.21	0.42	0.61	0.23	0.3
5/8/03	0.29	0.26	0.26	0.34	0.46	0.32	0.34
8/8/03	0.24	0.21	0.23	0.39	0.45	0.34	0.36
11/8/03	0.56	0.28	0.28	0.4	0.48	0.47	0.39
14/08/03	1.09	0.32	0.24	0.46	0.58	0.42	0.41
17/08/03	0.95	0.33	0.35	0.47	0.6	0.58	0.49
20/08/03	0.44	0.27	0.19	0.52	0.6	0.56	0.5
23/08/03	0.58	0.29	0.23	0.63	0.77	0.42	0.42
26/08/03	1.35	0.21	0.1	0.56	0.7	0.35	0.36
29/08/03	1.26	0.28	0.22	0.5	0.63	0.45	0.43
1/9/03	1.04	0.36	0.28	0.51	0.59	0.43	0.4
4/9/03	1.09	0.31	0.17	0.48	0.55	0.44	0.49
7/9/03	1.37	0.29	0.26	0.48	0.55	0.45	0.45
10/9/03	1.53	0.42	0.31	0.31	0.55	0.48	0.46
13/09/03	1.05	0.16	0.12	0.38	0.44	0.38	0.43
16/09/03	1.34	0.18	0.14	0.42	0.51	0.37	0.39
19/09/03	1.39	0.3	0.27	0.53	0.64	0.53	0.53
22/09/03	1.31	0.15	0.07	0.41	0.47	0.39	0.38
25/09/03	1.24	0.27	0.22	0.57	0.92	0.38	0.48
28/09/03	1.45	0.24	0.17	0.58	0.71	0.45	0.45

Table A.7. Total Copper for pH 8.5 and alkalinity 100mg/L water

Date	CONTROL	Cl2 -Lo	Cl_2-Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	1.06	1.22	1.22	0.84	1.31	1.42	1.02
6/7/03	1.55	0.82	1.12	0.93	1.06	1.05	0.9
9/7/03	1.26	1.12	1.37	0.76	0.89	1.03	1.09
12/7/03	1.2	0.7	0.55	0.51	0.65	1.1	0.92
15/07/03	1.5	1.07	1.05	0.56	0.81	1.05	1.06
18/07/03	1.24	0.94	0.99	0.5	0.62	1.06	1.03
21/07/03	1.26	0.81	0.89	0.48	0.33	0.86	0.93
24/07/03	1.28	0.37	0.49	0.53	0.53	0.7	0.73
27/07/03	1.69	0.61	0.73	0.58	0.69	0.86	0.87
30/07/03	1.87	0.54	0.65	0.53	0.71	0.81	0.93
2/8/03	1.22	0.49	0.55	0.45	0.55	0.8	0.75
5/8/03	2.22	0.57	0.59	0.33	0.43	0.65	0.57
8/8/03	2.35	0.47	0.49	0.37	0.48	0.65	0.6
11/8/03	1.63	0.54	0.5	0.4	0.55	0.75	0.7
14/08/03	2.4	0.59	0.57	0.42	0.6	0.87	0.86
17/08/03	3.28	0.55	0.79	0.47	0.59	1.21	1.12
20/08/03	4.85	0.61	0.69	0.48	0.65	1	1.04
23/08/03	2.63	0.6	0.65	0.56	0.73	0.91	0.88
26/08/03	2.11	0.59	0.66	0.44	0.51	0.87	0.81
29/08/03	2.81	0.61	0.9	0.44	0.58	1.26	1.11
1/9/03	2.8	0.73	0.84	0.44	0.58	0.85	0.9
4/9/03	2.19	0.91	0.93	0.38	0.54	1.21	1.33
7/9/03	2.45	0.68	0.8	0.42	0.56	0.98	1.09
10/9/03	2.11	0.78	0.82	0.39	0.56	1.05	0.97
13/09/03	3.13	0.55	0.66	0.36	0.46	0.84	0.9
16/09/03	2.31	0.61	0.81	0.35	0.49	0.99	0.94
19/09/03	2.69	0.66	0.7	0.43	0.61	0.86	1.2
22/09/03	1.5	0.35	0.36	0.25	0.42	0.3	0.47
25/09/03	2.46	0.56	0.75	0.46	0.66	0.79	0.83
28/09/03	2.62	0.62	0.68	0.44	0.66	0.68	0.71

Table A.8. Total Copper for pH 8.5 and alkalinity 100mg/L water with phosphate addition

Date	CONTROL	Cl2 -Lo	Cl_2 -Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	1.22	1.15	1.27	0.93	1.21	1.11	0.76
6/7/03	1.37	0.78	1.04	0.97	1.09	1.14	1.02
9/7/03	1.43	0.94	0.99	0.79	0.92	1.18	1.07
12/7/03	1.03	0.56	0.6	0.64	0.74	0.7	0.93
15/07/03	1.01	0.79	0.84	0.68	0.83	0.86	0.94
18/07/03	0.91	0.79	0.84	0.55	0.69	0.89	0.92
21/07/03	1.09	0.7	0.75	0.52	0.42	0.87	0.89
24/07/03	1.45	0.35	0.52	0.63	0.6	0.75	0.82
27/07/03	1.74	0.46	0.64	0.74	0.77	0.79	0.83
30/07/03	1.47	0.49	0.6	0.57	0.68	0.89	0.97
2/8/03	1.06	0.35	0.52	0.44	0.59	0.69	0.62
5/8/03	1.5	0.45	0.5	0.36	0.43	0.64	0.61
8/8/03	1.78	0.38	0.48	0.6	0.46	0.66	0.62
11/8/03	1.75	0.56	0.54	0.55	0.65	0.8	0.73
14/08/03	2.08	0.59	0.65	0.51	0.9	0.92	0.85
17/08/03	2.03	0.58	0.8	0.59	0.67	1.22	1.1
20/08/03	2.04	0.76	0.74	0.56	0.72	0.97	1.02
23/08/03	2.06	0.64	0.66	0.67	0.6	0.92	0.85
26/08/03	2.01	0.64	0.7	0.57	0.68	0.83	0.9
29/08/03	2.13	0.76	0.65	0.53	0.61	1.05	0.98
1/9/03	1.92	0.82	0.78	0.54	0.56	0.85	0.84
4/9/03	1.89	0.88	0.82	0.5	0.52	1.09	0.93
7/9/03	2.03	0.77	0.8	0.56	0.54	0.97	0.94
10/9/03	2.08	0.82	0.71	0.47	0.56	1.02	0.79
13/09/03	1.95	0.49	0.52	0.4	0.45	0.77	0.75
16/09/03	2.04	0.61	0.58	0.43	0.46	0.95	0.89
19/09/03	2.06	0.68	0.57	0.54	0.56	0.79	0.87
22/09/03	2.23	0.22	0.2	0.36	0.42	0.33	0.41
25/09/03	2.42	0.73	0.61	0.57	0.66	0.87	0.9
28/09/03	2.04	0.52	0.5	0.55	0.66	0.65	0.65

Table A.9. Dissolve Copper for pH 7.2 and alkalinity 10mg/L water

Date	CONTROL	Cl2 -Lo	Cl_2 -Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	0.19	0.00	0.18	0.52	0.82	0.09	0.13
6/7/03	1.07	2.02	0.80	0.84	1.11	0.71	0.70
9/7/03	1.75	0.69	0.76	0.58	0.73	0.70	0.65
12/7/03	0.48	0.36	0.20	0.35	0.50	0.34	0.32
15/07/03	0.38	0.36	0.28	0.38	0.56	0.23	0.21
18/07/03	0.49	0.41	0.42	0.21	0.47	0.29	0.35
21/07/03	0.45	0.26	0.30	0.30	0.42	0.27	0.39
24/07/03	0.36	0.24	0.26	0.36	0.46	0.33	0.38
27/07/03	0.40	0.25	0.35	0.42	0.51	0.37	0.45
30/07/03	0.83	0.33	0.30	0.34	0.71	0.37	0.34
2/8/03	0.27	0.30	0.31	0.24	0.38	0.28	0.31
5/8/03	0.28	0.20	0.17	0.28	0.38	0.27	0.32
8/8/03	0.22	0.35	0.39	0.24	0.33	0.06	0.34
11/8/03	0.31	0.30	0.30	0.25	0.35	0.30	0.34
14/08/03	0.35	0.26	0.20	0.31	0.42	0.31	0.35
17/08/03	0.41	0.33	0.31	0.29	0.41	0.36	0.41
20/08/03	0.37	0.34	0.19	0.35	0.47	0.32	0.37
23/08/03	0.36	0.34	0.38	0.47	0.76	0.36	0.40
26/08/03	0.51	0.35	0.40	0.39	0.52	0.45	0.46
29/08/03	0.40	0.24	0.25	0.25	0.34	0.33	0.34
1/9/03	0.51	0.38	0.38	0.37	0.47	0.40	0.48
4/9/03	0.60	0.54	0.45	0.27	0.35	0.11	0.57
7/9/03	0.42	0.31	0.31	0.37	0.47	0.67	0.53
10/9/03	0.46	0.42	0.45	0.33	0.42	0.42	0.44
13/09/03	0.33	0.19	0.21	0.24	0.34	0.27	0.29
16/09/03	0.40	0.24	0.18	0.18	0.24	0.32	0.36
19/09/03	0.38	0.42	0.36	0.42	0.48	0.42	0.46
22/09/03	0.31	0.19	0.16	0.21	0.29	0.28	0.29
25/09/03	0.42	0.32	0.34	0.42	0.53	0.34	0.36
28/09/03	0.38	0.39	0.33	0.44	0.66	0.38	0.41

Table A.10. Dissolve Copper for pH 7.2 and alkalinity 10mg/L water with phosphate addition

Date	CONTROL	Cl2 -Lo	Cl_2 -Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	0.60	0.00	0.42	0.75	0.93	0.18	0.46
6/7/03	1.24	3.47	0.82	0.93	1.19	0.68	0.69
9/7/03	0.92	0.54	0.60	0.74	0.82	0.59	0.75
12/7/03	0.46	0.28	0.15	0.41	0.52	0.24	0.30
15/07/03	0.44	0.42	0.35	0.50	0.65	0.23	0.27
18/07/03	0.56	0.38	0.45	0.27	0.52	0.23	0.32
21/07/03	0.47	0.28	0.30	0.39	0.50	0.26	0.40
24/07/03	0.34	0.29	0.25	0.45	0.54	0.32	0.37
27/07/03	0.35	0.26	0.30	0.55	0.64	0.36	0.39
30/07/03	0.45	0.28	0.30	0.45	0.57	0.34	0.43
2/8/03	0.31	0.29	0.26	0.29	0.43	0.25	0.28
5/8/03	0.26	0.19	0.17	0.30	0.40	0.24	0.27
8/8/03	0.22	0.29	0.26	0.35	0.43	0.09	0.27
11/8/03	0.33	0.28	0.24	0.35	0.42	0.28	0.37
14/08/03	0.37	0.27	0.22	0.36	0.48	0.32	0.34
17/08/03	0.36	0.28	0.25	0.35	0.47	0.31	0.38
20/08/03	0.37	0.29	0.14	0.43	0.59	0.36	0.36
23/08/03	0.46	0.29	0.23	0.54	0.81	0.37	0.40
26/08/03	0.57	0.39	0.29	0.45	0.64	0.35	0.37
29/08/03	0.51	0.33	0.38	0.32	0.63	0.31	0.35
1/9/03	0.73	0.43	0.42	0.42	0.61	0.41	0.44
4/9/03	0.65	0.49	0.38	0.38	0.54	0.13	0.45
7/9/03	0.57	0.33	0.26	0.45	0.56	0.67	0.40
10/9/03	0.50	0.44	0.39	0.38	0.54	0.39	0.39
13/09/03	0.34	0.24	0.20	0.28	0.43	0.29	0.30
16/09/03	0.45	0.24	0.19	0.24	0.36	0.33	0.31
19/09/03	0.51	0.36	0.31	0.44	0.63	0.39	0.40
22/09/03	0.38	0.25	0.19	0.26	0.37	0.27	0.32
25/09/03	0.53	0.28	0.24	0.47	0.62	0.30	0.31
28/09/03	0.44	0.37	0.31	0.48	0.65	0.38	0.37

Table A.11. Dissolve Copper for pH 7.2 and alkalinity 100mg/L water

Date	CONTROL	Cl2 -Lo	Cl_2 -Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	0.87	0.51	1.01	0.67	0.92	0.78	0.68
6/7/03	1.84	2.03	1.54	0.92	1.12	1.10	1.40
9/7/03	1.80	1.32	1.38	0.75	0.85	1.23	1.31
12/7/03	0.52	0.32	0.20	0.45	0.58	0.32	0.29
15/07/03	0.08	0.46	0.42	0.49	0.66	0.25	0.24
18/07/03	0.40	0.42	0.42	0.31	0.58	0.29	0.27
21/07/03	0.43	0.26	0.37	0.40	0.53	0.33	0.34
24/07/03	0.63	0.57	0.57	0.43	0.54	0.57	0.63
27/07/03	1.57	0.81	0.78	0.48	0.55	0.95	1.09
30/07/03	1.79	0.76	0.82	0.45	0.61	0.94	0.94
2/8/03	1.75	0.89	0.86	0.44	0.39	1.14	1.04
5/8/03	1.81	0.89	1.13	0.32	0.42	0.97	0.89
8/8/03	1.39	0.79	0.90	0.36	0.48	0.25	0.91
11/8/03	1.57	0.78	0.83	0.32	0.50	1.15	1.17
14/08/03	1.67	0.77	0.81	0.40	0.53	1.09	0.94
17/08/03	1.60	0.85	0.97	0.44	0.55	1.19	0.95
20/08/03	1.40	0.84	0.72	0.45	0.57	1.08	1.05
23/08/03	1.59	0.97	1.01	0.56	0.66	1.23	1.03
26/08/03	1.99	0.99	1.04	0.45	0.57	1.35	1.11
29/08/03	2.12	1.13	1.20	0.45	0.58	1.45	1.25
1/9/03	1.97	1.20	1.17	0.44	0.58	1.40	1.21
4/9/03	1.93	1.13	1.16	0.41	0.51	0.27	1.20
7/9/03	1.52	0.92	0.95	0.40	0.53	1.09	1.00
10/9/03	1.66	0.98	1.04	0.39	0.52	1.16	1.04
13/09/03	1.03	0.62	0.61	0.31	0.42	0.81	0.79
16/09/03	1.18	0.60	0.72	0.36	0.46	0.87	0.73
19/09/03	1.29	0.95	0.99	0.44	0.54	1.14	1.01
22/09/03	0.53	0.32	0.33	0.30	0.40	0.44	0.36
25/09/03	1.39	0.89	0.95	0.45	0.58	1.20	1.02
28/09/03	1.25	0.91	0.98	0.43	0.61	1.04	0.85

Table A.12. Dissolve Copper for pH 7.2 and alkalinity 100mg/L water with phosphate addition

Date	CONTROL	Cl2 -Lo	Cl_2-Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	0.99	0.51	0.94	0.77	1.00	0.73	0.63
6/7/03	2.00	1.38	1.38	1.03	1.23	1.56	1.17
9/7/03	1.76	1.25	1.32	0.72	0.91	1.21	1.22
12/7/03	0.50	0.32	0.25	0.54	0.50	0.30	0.10
15/07/03	0.56	0.46	0.52	0.63	0.82	0.23	0.18
18/07/03	0.52	0.43	0.50	0.36	0.48	0.25	0.29
21/07/03	0.48	0.29	0.42	0.47	0.62	0.32	0.38
24/07/03	0.77	0.83	0.91	0.52	0.62	0.82	0.84
27/07/03	1.26	0.87	1.03	0.63	0.69	0.96	1.10
30/07/03	1.12	0.75	0.97	0.52	0.71	0.94	0.96
2/8/03	1.05	0.96	0.95	0.52	0.56	0.98	0.87
5/8/03	1.01	0.91	0.98	0.39	0.52	0.85	0.84
8/8/03	0.93	0.82	0.85	0.50	0.62	0.30	0.81
11/8/03	1.31	0.80	0.82	0.48	0.58	1.12	1.20
14/08/03	1.18	0.77	0.77	0.49	0.62	0.93	0.89
17/08/03	1.26	0.83	0.75	0.46	0.63	0.91	0.88
20/08/03	1.19	0.81	0.74	0.56	0.63	0.91	0.89
23/08/03	1.13	0.79	0.79	0.65	0.77	0.99	0.88
26/08/03	2.33	1.19	1.22	0.56	0.69	1.24	1.26
29/08/03	1.92	1.11	0.97	0.56	0.68	1.12	1.12
1/9/03	1.62	1.07	1.09	0.54	0.64	1.12	1.11
4/9/03	1.87	1.20	1.12	0.54	0.62	0.23	1.03
7/9/03	1.35	0.94	0.88	0.47	0.63	1.53	0.91
10/9/03	1.45	0.97	1.02	0.48	0.59	1.02	0.98
13/09/03	0.91	0.64	0.60	0.36	0.53	0.76	0.80
16/09/03	0.93	0.69	0.64	0.45	0.56	0.66	0.69
19/09/03	1.03	0.88	0.83	0.52	0.68	0.94	0.96
22/09/03	0.42	0.31	0.20	0.35	0.53	0.42	0.37
25/09/03	1.10	0.77	0.65	0.49	0.69	0.85	0.83
28/09/03	1.00	0.75	0.63	0.49	0.81	0.78	0.75

Table A.13. Dissolve Copper for pH 8.5 and alkalinity 10mg/L water

Date	CONTROL	Cl2 -Lo	Cl_2 -Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	0.31	0.00	0.21	0.59	0.78	0.01	0.00
6/7/03	0.86	0.45	0.63	0.59	1.01	0.48	0.55
9/7/03	0.74	0.48	0.62	0.65	0.73	0.79	0.48
12/7/03	0.75	0.08	0.00	0.36	0.49	0.09	0.13
15/07/03	0.94	0.31	0.25	0.40	0.55	0.24	0.23
18/07/03	0.35	0.29	0.30	0.35	0.47	0.20	0.19
21/07/03	0.31	0.22	0.17	0.35	0.21	0.31	0.26
24/07/03	0.19	0.00	0.04	0.36	0.40	0.19	0.20
27/07/03	0.29	0.10	0.14	0.45	0.51	0.22	0.25
30/07/03	0.36	0.15	0.12	0.36	0.50	0.21	0.27
2/8/03	0.09	0.06	0.07	0.31	0.41	0.09	0.07
5/8/03	0.15	0.14	0.14	0.25	0.34	0.14	0.09
8/8/03	0.08	0.12	0.08	0.28	0.36	0.05	0.16
11/8/03	0.23	0.15	0.11	0.30	0.33	0.18	0.15
14/08/03	0.30	0.18	0.16	0.33	0.48	0.19	0.23
17/08/03	0.25	0.22	0.12	0.35	0.47	0.21	0.23
20/08/03	0.26	0.08	0.04	0.35	0.45	0.23	0.10
23/08/03	0.22	0.18	0.18	0.48	0.45	0.24	0.28
26/08/03	0.32	0.18	0.07	0.41	0.54	0.19	0.20
29/08/03	0.25	0.11	0.07	0.36	0.48	0.17	0.06
1/9/03	0.29	0.20	0.21	0.40	0.49	0.25	0.29
4/9/03	0.26	0.15	0.14	0.31	0.42	0.03	0.17
7/9/03	0.27	0.14	0.18	0.39	0.47	0.33	0.22
10/9/03	0.31	0.24	0.27	0.35	0.45	0.33	0.25
13/09/03	0.22	0.03	0.02	0.28	0.40	0.13	0.16
16/09/03	0.32	0.07	0.07	0.32	0.39	0.12	0.15
19/09/03	0.28	0.22	0.25	0.37	0.47	0.29	0.35
22/09/03	0.26	0.03	0.02	0.29	0.38	0.15	0.21
25/09/03	0.27	0.16	0.16	0.41	0.52	0.19	0.22
28/09/03	0.24	0.28	0.22	0.40	0.50	0.25	0.28

Table A.14. Dissolve Copper for pH 8.5 and alkalinity 10mg/L water with phosphate addition

Date	CONTROL	Cl2 -Lo	Cl_2-Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	0.30	0.00	0.21	0.63	0.97	0.00	0.00
6/7/03	0.78	0.69	0.64	0.89	1.06	0.45	0.50
9/7/03	0.83	0.53	0.65	0.80	0.90	0.72	0.49
12/7/03	0.36	0.11	0.00	0.43	0.59	0.16	0.21
15/07/03	0.38	0.33	0.23	0.52	0.73	0.29	0.28
18/07/03	0.30	0.28	0.30	0.41	0.48	0.24	0.16
21/07/03	0.34	0.23	0.20	0.40	0.15	0.28	0.31
24/07/03	0.18	0.07	0.11	0.48	0.49	0.28	0.28
27/07/03	0.23	0.11	0.18	0.57	0.64	0.32	0.33
30/07/03	0.33	0.14	0.14	0.48	0.60	0.29	0.31
2/8/03	0.11	0.06	0.09	0.37	0.45	0.09	0.12
5/8/03	0.17	0.18	0.16	0.31	0.42	0.17	0.19
8/8/03	0.08	0.12	0.12	0.38	0.42	0.11	0.19
11/8/03	0.19	0.15	0.14	0.37	0.39	0.19	0.11
14/08/03	0.24	0.22	0.16	0.41	0.49	0.28	0.29
17/08/03	0.45	0.16	0.12	0.41	0.53	0.29	0.26
20/08/03	0.26	0.14	0.07	0.43	0.51	0.33	0.31
23/08/03	0.23	0.19	0.14	0.56	0.71	0.27	0.29
26/08/03	0.39	0.10	0.05	0.50	0.62	0.26	0.26
29/08/03	0.36	0.17	0.09	0.45	0.55	0.25	0.27
1/9/03	0.25	0.26	0.18	0.47	0.55	0.30	0.29
4/9/03	0.17	0.15	0.05	0.41	0.48	0.08	0.24
7/9/03	0.35	0.20	0.15	0.46	0.52	0.38	0.31
10/9/03	0.38	0.28	0.22	0.27	0.54	0.32	0.33
13/09/03	0.45	0.11	0.07	0.34	0.43	0.29	0.32
16/09/03	0.33	0.07	0.03	0.38	0.51	0.22	0.23
19/09/03	0.32	0.23	0.18	0.49	0.56	0.35	0.34
22/09/03	0.27	0.06	0.07	0.41	0.47	0.26	0.26
25/09/03	0.19	0.17	0.13	0.50	0.82	0.23	0.23
28/09/03	0.28	0.18	0.12	0.50	0.63	0.31	0.35

Table A.15. Dissolve Copper for pH 8.5 and alkalinity 100mg/L water

Date	CONTROL	Cl2 -Lo	Cl_2-Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	0.57	0.14	0.61	0.65	1.06	0.4	0.14
6/7/03	1.55	0.82	1.12	0.93	1.06	1.05	0.9
9/7/03	1.26	1.12	1.37	0.76	0.89	0.75	1.09
12/7/03	0.63	0.39	0.23	0.43	0.55	0.44	0.52
15/07/03	0.79	0.73	0.63	0.49	0.63	0.63	0.64
18/07/03	0.65	0.57	0.61	0.42	0.56	0.48	0.55
21/07/03	0.59	0.52	0.53	0.39	0.22	0.57	0.58
24/07/03	0.36	0.15	0.25	0.41	0.46	0.42	0.37
27/07/03	0.57	0.33	0.42	0.48	0.59	0.53	0.53
30/07/03	0.64	0.32	0.35	0.45	0.59	0.49	0.57
2/8/03	0.37	0.25	0.32	0.35	0.46	0.4	0.37
5/8/03	0.4	0.32	0.35	0.29	0.37	0.34	0.34
8/8/03	0.25	0.28	0.32	0.32	0.46	0.13	0.31
11/8/03	0.37	0.33	0.37	0.35	0.44	0.48	0.47
14/08/03	0.43	0.39	0.41	0.36	0.5	0.51	0.5
17/08/03	0.42	0.38	0.4	0.42	0.54	0.56	0.58
20/08/03	0.48	0.39	0.38	0.45	0.58	0.53	0.51
23/08/03	0.38	0.43	0.44	0.51	0.67	0.51	0.55
26/08/03	0.48	0.43	0.47	0.39	0.46	0.55	0.62
29/08/03	0.51	0.46	0.45	0.42	0.48	0.58	0.64
1/9/03	0.54	0.5	0.53	0.43	0.58	0.64	0.6
4/9/03	0.48	0.6	0.58	0.32	0.46	0.2	0.68
7/9/03	0.46	0.51	0.5	0.4	0.54	0.92	0.66
10/9/03	0.44	0.55	0.57	0.39	0.54	0.62	0.63
13/09/03	0.53	0.35	0.39	0.32	0.46	0.47	0.55
16/09/03	0.59	0.39	0.4	0.31	0.44	0.57	0.57
19/09/03	0.44	0.45	0.46	0.41	0.55	0.61	0.62
22/09/03	0.11	0.17	0.2	0.25	0.36	0.19	0.24
25/09/03	0.36	0.38	0.44	0.42	0.61	0.48	0.46
28/09/03	0.46	0.38	0.39	0.41	0.58	0.48	0.44

Table A.16. Dissolve Copper for pH 8.5 and alkalinity 100mg/L water with phosphate addition

Date	CONTROL	Cl2 -Lo	Cl_2 -Hi	NH_2Cl-Lo	NH_2Cl-Hi	ClO_2-Lo	ClO_2-Hi
3/7/03	0.63	0.02	0.6	0.98	0.87	0.31	0.23
6/7/03	1.37	0.78	1.04	0.97	1.09	1.14	1.02
9/7/03	1.43	0.94	0.99	0.79	0.92	1.18	1.07
12/7/03	0.65	0.32	0.22	0.53	0.66	0.44	0.5
15/07/03	0.69	0.65	0.59	0.61	0.74	0.62	0.66
18/07/03	0.61	0.51	0.58	0.43	0.58	0.52	0.5
21/07/03	0.61	0.48	0.47	0.45	0.3	0.6	0.63
24/07/03	0.37	0.2	0.27	0.54	0.53	0.47	0.46
27/07/03	0.55	0.31	0.42	0.68	0.72	0.54	0.54
30/07/03	0.65	0.35	0.4	0.56	0.64	0.57	0.6
2/8/03	0.37	0.19	0.29	0.43	0.48	0.4	0.36
5/8/03	0.36	0.33	0.36	0.36	0.37	0.4	0.37
8/8/03	0.27	0.29	0.3	0.56	0.45	0.19	0.42
11/8/03	0.41	0.35	0.35	0.42	0.51	0.49	0.55
14/08/03	0.49	0.45	0.43	0.44	0.77	0.56	0.57
17/08/03	0.21	0.32	0.44	0.53	0.66	0.68	0.7
20/08/03	0.53	0.48	0.49	0.51	0.67	0.64	0.59
23/08/03	0.45	0.48	0.44	0.63	0.57	0.61	0.56
26/08/03	0.6	0.51	0.48	0.5	0.57	0.64	0.63
29/08/03	0.53	0.47	0.4	0.5	0.55	0.63	0.62
1/9/03	0.62	0.57	0.53	0.49	0.52	0.64	0.63
4/9/03	0.49	0.58	0.51	0.43	0.48	0.21	0.57
7/9/03	0.6	0.51	0.46	0.55	0.54	0.87	0.61
10/9/03	0.61	0.54	0.5	0.47	0.55	0.62	0.6
13/09/03	0.58	0.32	0.3	0.36	0.44	0.47	0.54
16/09/03	0.59	0.4	0.34	0.38	0.45	0.58	0.61
19/09/03	0.57	0.5	0.44	0.5	0.55	0.64	0.62
22/09/03	0.19	0.16	0.11	0.33	0.43	0.23	0.22
25/09/03	0.49	0.5	0.4	0.5	0.58	0.58	0.53
28/09/03	0.55	0.38	0.33	0.51	0.62	0.5	0.48

APPENDIX B- CHARTS.

LINE GRAPH FOR TOTAL COPPER

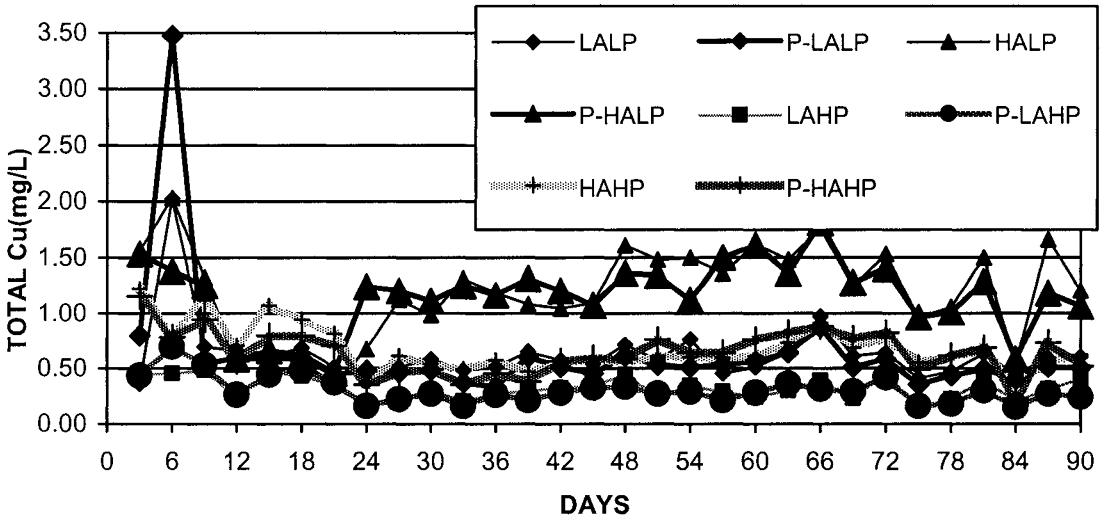

Figure B.1 Total copper for the low dosed free chlorine pipes

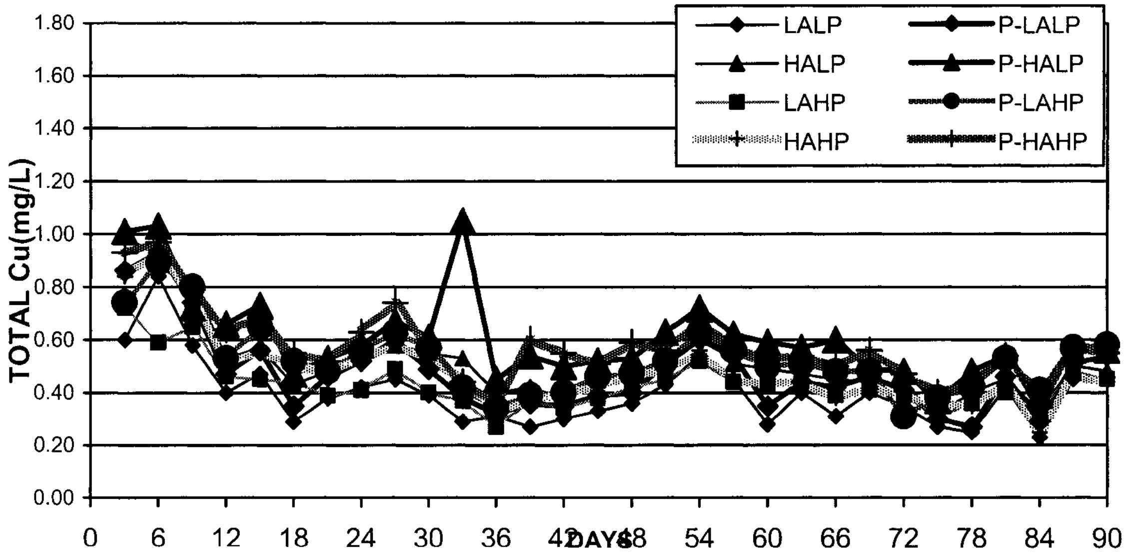

Figure B.2 Total copper for the low dosed monochloramine pipes

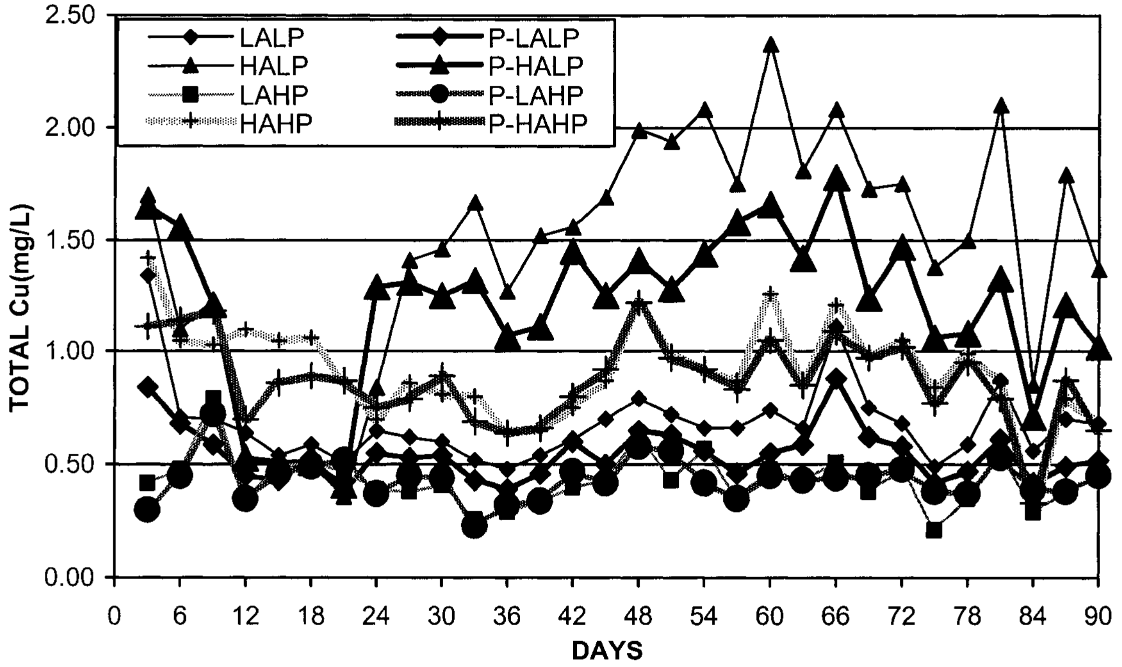

Figure B.3 Total copper for the low dosed Chlorine Dioxide pipes

LINE GRAPH FOR DISSOLVED COPPER

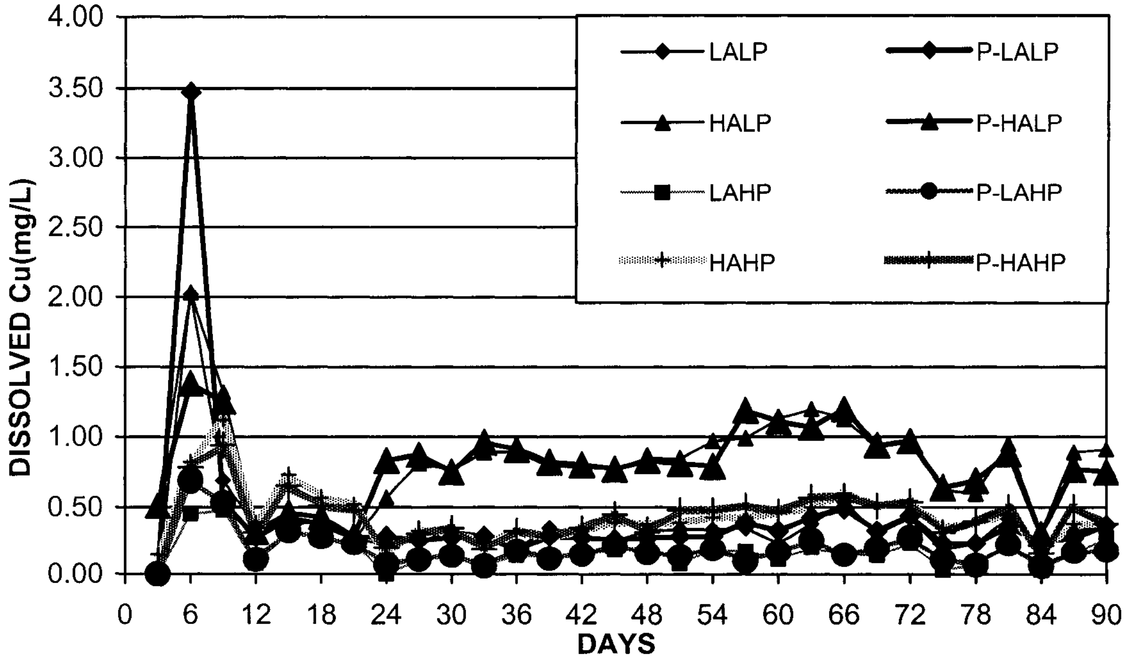

Figure B.4 Dissolved copper for the low dosed free chlorine pipes

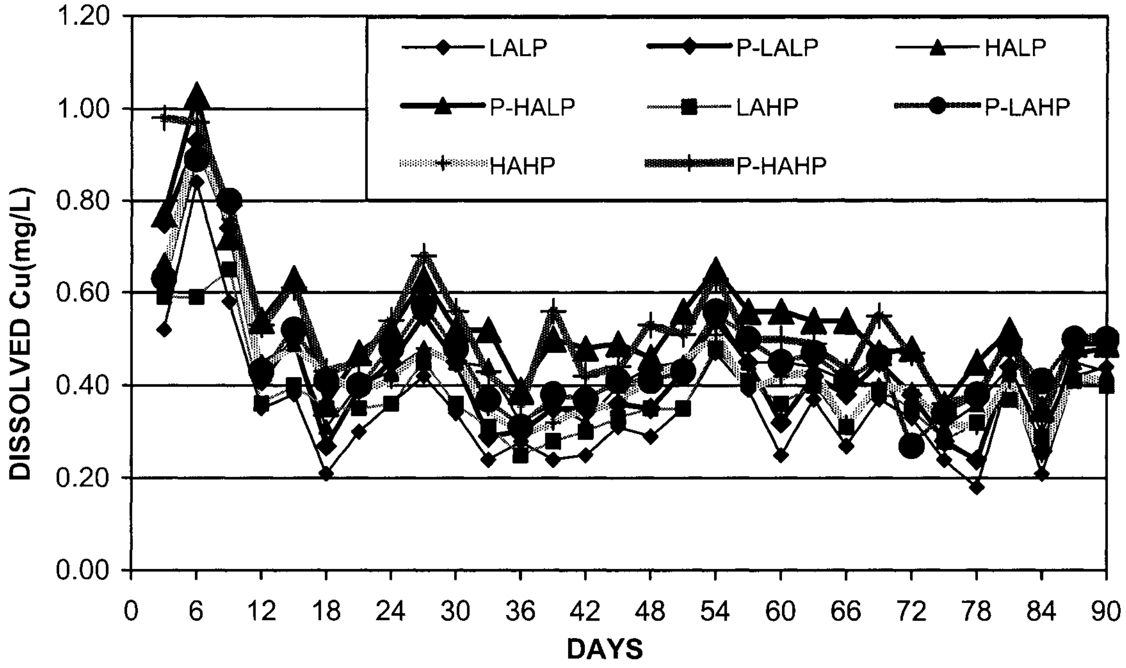

Figure B.5 Dissolved copper for the low dosed monochloramine pipes

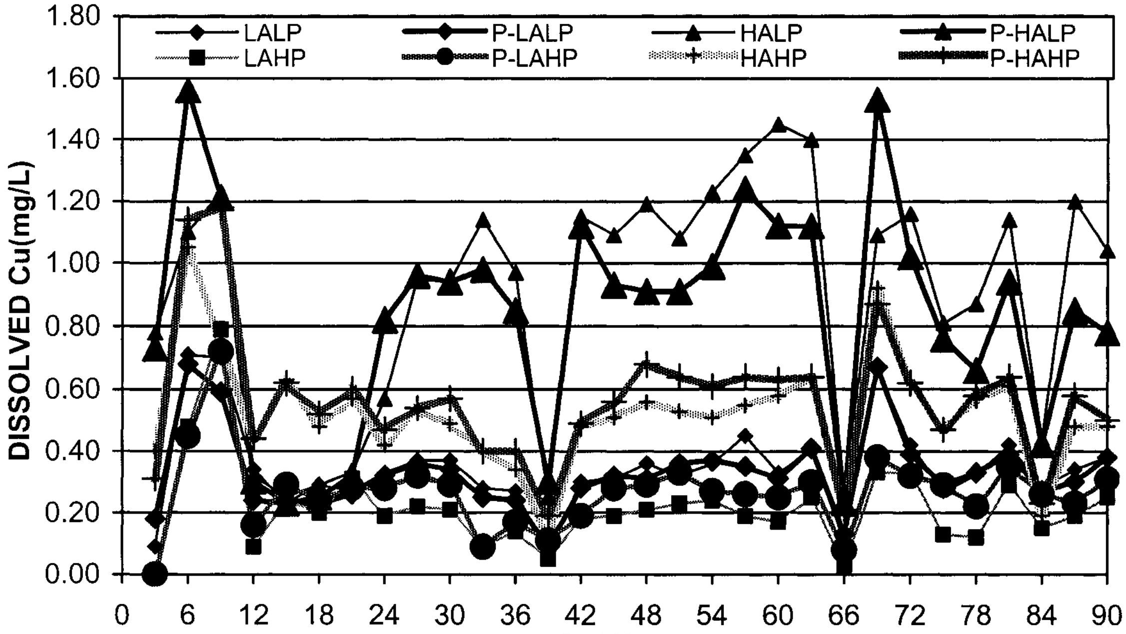

Figure B.6 Dissolved copper for the low dosed chlorine dioxide pipes

APPENDIX C-STATISTICAL ANALYSIS

Table C.1-Results of t-test Comparing Average Total Copper Concentration for different pH and alkalinity during conditioning phase (without phosphate addition) (α=0.05).

Free Cl2 LOW			
p-values	HALP	LAHP	HAHP
LALP	0.338	0.112	0.529
HALP		0.041	0.867
LAHP			$3.80*10^{-5}$
Free Cl2 HIGH			
p-values	HALP	LAHP	HAHP
LALP	0.153	0.093	0.007
HALP		0.028	0.912
LAHP			$2.046*10^{-5}$
NH2Cl-Lo			
p-values	HALP	LAHP	HAHP
LALP	0.007	0.703	0.0008
HALP		0.021	0.629
LAHP			0.014
NH2Cl-Hi			
p-values	HALP	LAHP	HAHP
LALP	0.001	0.043	0.521
HALP		0.004	0.149
LAHP			0.003
ClO2-Lo			
p-values	HALP	LAHP	HAHP
LALP	0.298	0.136	0.0005
HALP		0.114	0.161
LAHP			0.0007
ClO2-Hi			
p-values	HALP	LAHP	HAHP
LALP	0.184	0.049	0.0009
HALP		0.039	0.357
LAHP			$5.82*10^{-6}$
CONTROL			
p-values	HALP	LAHP	HAHP
LALP	0.543	0.352	0.068
HALP		0.281	0.766
LAHP			0.0002

Table C.2-Results of t-test Comparing Average Total Copper Concentration for different pH and alkalinity during conditioning phase (with phosphate addition) (α=0.05).

Free Cl2 LOW			
p-values	HALP	LAHP	HAHP
LALP	0.834	0.196	0.671
HALP		0.016	0.404
LAHP			0.002

Free Cl2 HIGH			
p-values	HALP	LAHP	HAHP
LALP	0.066	0.004	0.002
HALP		0.004	0.617
LAHP			$9.48*10^{-5}$

NH2Cl-Lo			
p-values	HALP	LAHP	HAHP
LALP	0.006	0.369	0.005
HALP		0.138	0.687
LAHP			0.036

NH2Cl-Hi			
p-values	HALP	LAHP	HAHP
LALP	0.081	0.666	0.821
HALP		0.013	0.127
LAHP			0.862

ClO2-Lo			
p-values	HALP	LAHP	HAHP
LALP	0.056	0.370	0.0001
HALP		0.088	0.738
LAHP			0.0003

ClO2-Hi			
p-values	HALP	LAHP	HAHP
LALP	0.390	0.0001	$1.56*10^{-8}$
HALP		0.087	0.263
LAHP			$7.98*10^{-7}$

CONTROL			
p-values	HALP	LAHP	HAHP
LALP	0.140	0.034	0.022
HALP		0.051	0.598
LAHP			$4.076*10^{-6}$

Table C.3-Results of t-test Comparing Average Total Copper Concentration for different pH and alkalinity during test phase (without phosphate addition) (α=0.05).

Free Cl2 LOW			
p-values	HALP	LAHP	HAHP
LALP	$1.59*10^{-11}$	$2.32*10^{-13}$	0.617
HALP		$4.00*10^{-14}$	$6.56*10^{-12}$
LAHP			$2.13*10^{-12}$
Free Cl2 HIGH			
p-values	HALP	LAHP	HAHP
LALP	$1.53*10^{-13}$	$6.28*10^{-12}$	0.026
HALP		$4.15*10^{-15}$	$7.49*10^{-13}$
LAHP			$9.69*10^{-12}$
NH2Cl-Lo			
p-values	HALP	LAHP	HAHP
LALP	$7.60*10^{-9}$	0.0008	$5.15*10^{-6}$
HALP		$4.09*10^{-7}$	$1.47*10^{-5}$
LAHP			0.008
NH2Cl-Hi			
p-values	HALP	LAHP	HAHP
LALP	0.0494	0.088	0.162
HALP		$8.25*10^{-10}$	0.133
LAHP			$2.78*10^{-6}$
ClO2-Lo			
p-values	HALP	LAHP	HAHP
LALP	$4.95*10^{-13}$	$6.80*10^{-12}$	$1.16*10^{-5}$
HALP		$6.23*10^{-15}$	$3.11*10^{-13}$
LAHP			$1.28*10^{-11}$
ClO2-Hi			
p-values	HALP	LAHP	HAHP
LALP	$8.23*10^{-13}$	$3.52*10^{-9}$	$2.17*10^{-6}$
HALP		$8.33*10^{-14}$	$1.78*10^{-11}$
LAHP			$6.72*10^{-10}$
CONTROL			
p-values	HALP	LAHP	HAHP
LALP	$9.81*10^{-14}$	$2.73*10^{-5}$	$6.71*10^{-10}$
HALP		$5.36*10^{-15}$	0.687
LAHP			$1.82*10^{-11}$

Table C.4-Results of t-test Comparing Average Total Copper Concentration for different pH and alkalinity during test phase (with phosphate addition) (α=0.05).

Free Cl2 LOW

p-values	HALP	LAHP	HAHP
LALP	$1.36*10^{-15}$	$1.28*10^{-11}$	0.009
HALP		$2.56*10^{-16}$	$3.74*10^{-14}$
LAHP			$3.27*10^{-11}$

Free Cl2 HIGH

p-values	HALP	LAHP	HAHP
LALP	$2.32*10^{-13}$	$1.57*10^{-10}$	$3.42*10^{-6}$
HALP		$1.11*10^{-14}$	$5.63*10^{-12}$
LAHP			$1.79*10^{-12}$

NH2Cl-Lo

p-values	HALP	LAHP	HAHP
LALP	$4.30*10^{-5}$	$5.63*10^{-5}$	$3.67*10^{-8}$
HALP		0.005	0.225
LAHP			0.0012

NH2Cl-Hi

p-values	HALP	LAHP	HAHP
LALP	0.012	0.083	0.227
HALP		$2.98*10^{-7}$	$6.87*10^{-6}$
LAHP			0.955

ClO2-Lo

p-values	HALP	LAHP	HAHP
LALP	$1.30*10^{-15}$	$5.15*10^{-7}$	$7.94*10^{-10}$
HALP		$5.54*10^{-15}$	$5.75*10^{-12}$
LAHP			$1.08*10^{-11}$

ClO2-Hi

p-values	HALP	LAHP	HAHP
LALP	$4.17*10^{-14}$	$5.48*10^{-9}$	$1.64*10^{-8}$
HALP		$2.26*10^{-14}$	$5.21*10^{-11}$
LAHP			$8.82*10^{-13}$

CONTROL

p-values	HALP	LAHP	HAHP
LALP	$5.48*10^{-12}$	0.687	$1.00*10^{-14}$
HALP		$6.58*10^{-11}$	0.001
LAHP			$2.83*10^{-13}$

Table C.5- Results of t-test Comparing Average Total Copper Concentration of water with different treatment during conditioning phase. (Without phosphate addition and α=0.05).

For water with pH 7.2 and alkalinity 10mg/L($CaCO_3$)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.533	0.041	0.034	0.474	0.353	0.025
Free Cl2 -Lo		0.367	0.141	0.945	0.785	0.263
Free Cl2 -Hi			0.193	0.283	0.508	0.128
NH2Cl-Lo				0.010	0.085	0.582
NH2Cl-Hi					0.373	0.212

For water with pH 7.2 and alkalinity 100mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.400	0.299	0.118	0.297	0.116	0.183
Free Cl2 -Lo		0.904	0.097	0.512	0.299	0.141
Free Cl2 -Hi			0.064	0.369	0.028	0.159
NH2Cl-Lo				0.003	0.184	0.145
NH2Cl-Hi					0.702	0.655

For water with pH 8.5 and alkalinity 10mg/L (CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.0005	0.006	0.005	0.303	0.017	0.0009
Free Cl2 -Lo		0.080	0.024	0.028	0.063	0.285
Free Cl2 -Hi			0.286	0.042	0.711	0.341
NH2Cl-Lo				0.088	0.656	0.104
NH2Cl-Hi					0.198	0.052

For water with pH 8.5 and alkalinity 100mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.019	0.056	0.0003	0.013	0.101	0.006
Free Cl2 -Lo		0.264	0.008	0.178	0.089	0.475
Free Cl2 -Hi			0.002	0.075	0.618	0.698
NH2Cl-Lo				0.066	0.0007	0.004
NH2Cl-Hi					0.012	0.170

Table C.6-Results of t-test Comparing Average Total Copper Concentration of water with different treatment during conditioning phase. (With phosphate addition and α=0.05).

For water with pH 7.2 and alkalinity 10mg/L(CaCO$_3$)

p-values	Free Cl2 -Lo	Free Cl2 –Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.777	0.066	0.010	0.605	0.011	0.063
Free Cl2 -Lo		0.396	0.338	0.690	0.298	0.350
Free Cl2 -Hi			0.716	0.039	0.062	0.472
NH2Cl-Lo				0.0004	0.237	0.763
NH2Cl-Hi					0.001	0.062

For water with pH 7.2 and alkalinity 100mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.052	0.073	0.065	0.167	0.019	0.026
Free Cl2 -Lo		0.196	0.121	0.631	0.776	0.032
Free Cl2 -Hi			0.095	0.866	0.461	0.006
NH2Cl-Lo				0.013	0.248	0.972
NH2Cl-Hi					0.629	0.088

For water with pH 8.5 and alkalinity 10mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.030	0.047	0.095	0.058	0.071	0.014
Free Cl2 -Lo		0.932	0.001	0.010	0.831	0.288
Free Cl2 -Hi			0.002	0.006	0.814	0.456
NH2Cl-Lo				0.059	0.039	0.011
NH2Cl-Hi					0.038	0.023

For water with pH and alkalinity 100mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.004	0.013	0.0001	0.009	0.002	0.016
Free Cl2 -Lo		0.026	0.193	0.718	0.021	0.242
Free Cl2 -Hi			0.010	0.321	0.202	0.781
NH2Cl-Lo				0.032	0.002	0.032
NH2Cl-Hi					0.145	0.438

Table C.7-Results of t-test Comparing Average Total Copper Concentration of water with different treatment during test phase. (Without phosphate addition and α=0.05).

For water with pH 7.2 and alkalinity 10mg/L($CaCO_3$)

p-values	Free Cl2 -Lo	Free Cl2 –Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.029	0.179	$1.59*10^{-9}$	$4.92*10^{-5}$	0.103	0.148
Free Cl2 -Lo		0.021	$7.53*10^{-8}$	0.320	0.0002	$3.71*10^{-5}$
Free Cl2 -Hi			$1.37*10^{-8}$	0.078	0.016	0.002
NH2Cl-Lo				$2.21*10^{-8}$	$5.83*10^{-10}$	$7.00*10^{-11}$
NH2Cl-Hi					0.005	0.002

For water with pH 7.2 and alkalinity 100mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	$1.14*10^{-13}$	$1.03*10^{-13}$	$1.53*10^{-14}$	$3.00*10^{-14}$	$1.76*10^{-11}$	$3.75*10^{-12}$
Free Cl2 -Lo		0.135	$1.27*10^{-11}$	$1.98*10^{-10}$	$1.45*10^{-10}$	$9.26*10^{-7}$
Free Cl2 -Hi			$5.36*10^{-13}$	$8.77*10^{-12}$	$1.90*10^{-8}$	0.0002
NH2Cl-Lo				$4.65*10^{-11}$	$1.82*10^{-13}$	$1.79*10^{-14}$
NH2Cl-Hi					$9.29*10^{-13}$	$1.62*10^{-3}$

For water with pH 8.5 and alkalinity 10mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	$2.31*10^{-9}$	$8.67*10^{-9}$	$6.04*10^{-6}$	0.047	$1.18*10^{-5}$	0.0001
Free Cl2 -Lo		0.836	$7.20*10^{-6}$	$8.11*10^{-10}$	$2.83*10^{-8}$	$8.96*10^{-5}$
Free Cl2 -Hi			$5.70*10^{-6}$	$2.20*10^{-9}$	$1.03*10^{-6}$	$5.41*10^{-5}$
NH2Cl-Lo				$6.38*10^{-9}$	0.751	0.715
NH2Cl-Hi					0.0002	0.0005

For water with pH 8.5 and alkalinity 100mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	$8.01*10^{-11}$	$1.28*10^{-10}$	$2.96*10^{-11}$	$8.66*10^{-11}$	$6.63*10^{-10}$	$6.34*10^{-10}$
Free Cl2 -Lo		$3.70*10^{-5}$	$1.65*10^{-5}$	0.475	$3.41*10^{-8}$	$3.87*10^{-7}$
Free Cl2 -Hi			$6.55*10^{-8}$	0.001	$1.52*10^{-7}$	$1.73*10^{-5}$
NH2Cl-Lo				$1.87*10^{-12}$	$6.60*10^{-10}$	$7.32*10^{-9}$
NH2Cl-Hi					$5.40*10^{-7}$	$1.67*10^{-6}$

Table C.8-Results of t-test Comparing Average Total Copper Concentration of water with different treatment during test phase (with phosphate addition and α=0.05).

For water with pH 7.2 and alkalinity 10mg/L($CaCO_3$)						
p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	$1.41*10^{-6}$	$1.09*10^{-6}$	$1.20*10^{-6}$	0.0003	$4.94*10^{-6}$	$8.20*10^{-5}$
Free Cl2 -Lo		0.020	0.009	0.0002	0.017	$1.26*10^{-5}$
Free Cl2 -Hi			0.127	$1.9*10^{-5}$	0.0001	$2.70*10^{-9}$
NH2Cl-Lo				$3.46*10^{-12}$	0.0003	$7.04*10^{-7}$
NH2Cl-Hi					0.001	0.126
For water with pH 7.2 and alkalinity 100mg/L(CaCO3)						
p-values	Free Cl2 –Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	$1.42*10^{-10}$	$1.94*10^{-10}$	$1.85*10^{-12}$	$8.34*10^{-12}$	$5.79*10^{-10}$	$1.57*10^{-10}$
Free Cl2 -Lo		0.073	$4.09*10^{-12}$	$6.38*10^{-10}$	0.017	0.052
Free Cl2 -Hi			$2.84*10^{-11}$	$1.46*10^{-8}$	0.0007	0.003
NH2Cl-Lo				$1.49*10^{-5}$	$1.69*10^{-13}$	$1.22*10^{-12}$
NH2Cl-Hi					$1.59*10^{-11}$	$6.91*10^{-11}$
For water with pH 8.5 and alkalinity 10mg/L(CaCO3)						
p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	$5.21*10^{-7}$	$1.14*10^{-6}$	0.0003	0.004	$3.08*10^{-5}$	$3.52*10^{-5}$
Free Cl2 -Lo		0.046	$3.87*10^{-9}$	$6.49*10^{-12}$	$5.38*10^{-11}$	$2.38*10^{-11}$
Free Cl2 -Hi			$2.01*10^{-10}$	$4.39*10^{-12}$	$3.78*10^{-10}$	$1.82*10^{-10}$
NH2Cl-Lo				$8.53*10^{-8}$	0.009	0.004
NH2Cl-Hi					$1.71*10^{-6}$	$1.09*10^{-7}$
For water with pH 8.5 and alkalinity 100mg/L(CaCO3)						
p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	$3.28*10^{-17}$	$1.41*10^{-15}$	$4.27*10^{-16}$	$1.48*10^{-15}$	$1.13*10^{-13}$	$3.34*10^{-14}$
Free Cl2 -Lo		0.270	0.154	0.830	$2.63*10^{-9}$	$4.11*10^{-8}$
Free Cl2 -Hi			0.008	0.627	$2.16*10^{-11}$	$1.32*10^{-10}$
NH2Cl-Lo				0.004	$2.76*10^{-8}$	$1.74*10^{-9}$
NH2Cl-Hi					$1.46*10^{-6}$	$2.81*10^{-7}$

Table C.9- Results of t-test Comparing Average total copper Concentration at water with and without phosphate addition during the test phase (α=0.005).

	p-values	LALP	HALP	LAHP	HAHP
FOR Free Cl2 LOW	P-LALP	$5.64*10^{-5}$			
	P-HALP		0.576		
	P-LAHP			0.0092	
	P-HAHP				0.930
FOR Free Cl2 HIGH	P-LALP	$5.30*10^{-7}$			
	P-HALP		0.023		
	P-LAHP			0.003	
	P-HAHP				0.002
FOR NH2Cl LOW	P-LALP	$9.73*10^{-10}$			
	P-HALP		$5.33*10^{-5}$		
	P-LAHP			$1.15*10^{-7}$	
	P-HAHP				$1.41*10^{-9}$
FOR NH2Cl HIGH	P-LALP	0.001			
	P-HALP		$6.20*10^{-11}$		
	P-LAHP			$2.96*10^{-6}$	
	P-HAHP				0.1509
FOR ClO2-LOW	P-LALP	$1.80*10^{-9}$			
	P-HALP		$1.58*10^{-6}$		
	P-LAHP			0.3353	
	P-HAHP				0.1667
FOR ClO2-HIGH	P-LALP	$1.38*10^{-5}$			
	P-HALP		0.0003		
	P-LAHP			0.1821	
	P-HAHP				0.0230
FOR CONTROL	P-LALP	0.0045			
	P-HALP		0.0308		
	P-LAHP			0.0006	
	P-HAHP				0.0030

Table C.10-Results of t-test Comparing Average Dissolve Copper Concentration for different pH and alkalinity during conditioning phase (without phosphate addition) (α=0.05).

Free Cl2 LOW			
p-values	HALP	LAHP	HAHP
LALP	0.145	0.175	0.901
HALP		0.053	0.486
LAHP			0.0009
Free Cl2 HIGH			
p-values	HALP	LAHP	HAHP
LALP	0.049	0.011	0.004
HALP		0.014	0.747
LAHP			0.0005
NH2Cl-Lo			
p-values	HALP	LAHP	HAHP
LALP	$7.54*10^{-5}$	0.750	0.0005
HALP		0.056	0.528
LAHP			0.028
NH2Cl-Hi			
p-values	HALP	LAHP	HAHP
LALP	0.0007	0.122	0.378
HALP		0.003	0.484
LAHP			0.022
ClO2-Lo			
p-values	HALP	LAHP	HAHP
LALP	0.074	0.190	0.002
HALP		0.034	0.982
LAHP			0.004
ClO2-HI			
p-values	HALP	LAHP	HAHP
LALP	0.112	0.002	0.005
HALP		0.037	0.919
LAHP			0.0004
CONTROL			
p-values	HALP	LAHP	HAHP
LALP	0.330	0.688	0.202
HALP		0.388	0.931
LAHP			0.071

Table C.11-Results of t-test Comparing Average Dissolve Copper Concentration for different pH and alkalinity during conditioning phase (with phosphate addition) (α=0.05).

Free Cl2 LOW			
p-values	HALP	LAHP	HAHP
LALP	0.774	0.283	0.583
HALP		0.015	0.321
LAHP			0.004
Free Cl2 HIGH			
p-values	HALP	LAHP	HAHP
LALP	0.020	0.008	0.001
HALP		0.003	0.173
LAHP			$1.49*10^{-5}$
NH2Cl-Lo			
p-values	HALP	LAHP	HAHP
LALP	0.011	0.687	0.005
HALP		0.116	0.359
LAHP			0.072
NH2Cl-Hi			
p-values	HALP	LAHP	HAHP
LALP	0.072	0.573	0.931
HALP		0.209	0.387
LAHP			0.229
ClO2-Lo			
p-values	HALP	LAHP	HAHP
LALP	0.061	0.464	0.001
HALP		0.079	0.820
LAHP			0.0005
ClO2-HI			
p-values	HALP	LAHP	HAHP
LALP	0.319	0.021	0.040
HALP		0.087	0.487
LAHP			0.0002
CONTROL			
p-values	HALP	LAHP	HAHP
LALP	0.072	0.011	0.022
HALP		0.023	0.366
LAHP			0.0003

Table C.12-Results of t-test Comparing Average Dissolve Copper Concentration for different pH and alkalinity during test phase (without phosphate addition) (α=0.05).

Free Cl2 LOW			
p-values	HALP	LAHP	HAHP
LALP	$7.73*10^{-14}$	$1.92*10^{-11}$	0.0009
HALP		$4.90*10^{-16}$	$3.49*10^{-14}$
LAHP			$5.22*10^{-12}$

Free Cl2 HIGH			
p-values	HALP	LAHP	HAHP
LALP	$1.15*10^{-13}$	$1.15*10^{-10}$	$1.41*10^{-6}$
HALP		$6.23*10^{-16}$	$5.50*10^{-13}$
LAHP			$3.46*10^{-15}$

NH2Cl-Lo			
p-values	HALP	LAHP	HAHP
LALP	$1.32*10^{-7}$	0.004	$6.25*10^{-6}$
HALP		$1.22*10^{-8}$	0.0002
LAHP			$7.52*10^{-5}$

NH2Cl-Hi			
p-values	HALP	LAHP	HAHP
LALP	0.0002	0.874	0.001
HALP		$1.07*10^{-7}$	0.094
LAHP			$1.50*10^{-5}$

ClO2-Lo			
p-values	HALP	LAHP	HAHP
LALP	$7.29*10^{-11}$	$2.07*10^{-10}$	$5.76*10^{-9}$
HALP		$5.71*10^{-12}$	$8.00*10^{-10}$
LAHP			$2.06*10^{-11}$

ClO2-Hi			
p-values	HALP	LAHP	HAHP
LALP	$2.74*10^{-13}$	$6.11*10^{-11}$	$1.44*10^{-6}$
HALP		$4.93*10^{-14}$	$2.41*10^{-12}$
LAHP			$3.07*10^{-11}$

CONTROL			
p-values	HALP	LAHP	HAHP
LALP	$1.32*10^{-12}$	$4.33*10^{-8}$	0.133
HALP		$3.70*10^{-13}$	$1.44*10^{-12}$
LAHP			$2.73*10^{-9}$

Table C.13-Results of t-test Comparing Average Dissolve Copper Concentration for different pH and alkalinity during test phase (with phosphate addition) (α=0.05).

Free Cl2 LOW			
p-values	HALP	LAHP	HAHP
LALP	3.98*10^{-14}	2.38*10^{-10}	0.0001
HALP		4.91*10^{-15}	1.58*10^{-12}
LAHP			6.53*10^{-12}
Free Cl2 HIGH			
p-values	HALP	LAHP	HAHP
LALP	4.91*10^{-13}	1.95*10^{-9}	1.51*10^{-6}
HALP		7.07*10^{-14}	9.57*10^{-12}
LAHP			2.26*10^{-12}
NH2Cl-Lo			
p-values	HALP	LAHP	HAHP
LALP	1.17*10^{-8}	0.0009	3.01*10^{-9}
HALP		1.62*10^{-5}	0.176
LAHP			0.0003
NH2Cl-Hi			
p-values	HALP	LAHP	HAHP
LALP	1.00*10^{-7}	0.932	0.574
HALP		3.07*10^{-7}	5.51*10^{-5}
LAHP			0.521
ClO2-Lo			
p-values	HALP	LAHP	HAHP
LALP	1.49*10^{-11}	2.65*10^{-5}	1.66*10^{-10}
HALP		4.16*10^{-11}	1.22*10^{-9}
LAHP			9.31*10^{-11}
ClO2-Hi			
p-values	HALP	LAHP	HAHP
LALP	1.61*10^{-13}	1.53*10^{-7}	2.59*10^{-9}
HALP		2.40*10^{-13}	2.18*10^{-11}
LAHP			1.59*10^{-11}
CONTROL			
p-values	HALP	LAHP	HAHP
LALP	2.55*10^{-10}	6.93*10^{-6}	0.065
HALP		8.46*10^{-11}	2.36*10^{-9}
LAHP			1.12*10^{-7}

Table C.14-Results of t-test Comparing Average dissolve copper Concentration at water with different treatment during conditioning phase (without phosphate addition and α=0.05).

For water with pH 7.2 and alkalinity 10mg/L($CaCO_3$)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.662	0.078	0.228	0.883	0.049	0.080
Free Cl2 -Lo		0.393	0.525	0.717	0.301	0.353
Free Cl2 -Hi			0.651	0.029	0.229	0.468
NH2Cl-Lo				0.0003	0.301	0.415
NH2Cl-Hi					0.018	0.023

For water with pH 7.2 and alkalinity 100mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.470	0.442	0.206	0.640	0.094	0.051
Free Cl2 -Lo		0.980	0.334	0.952	0.348	0.299
Free Cl2 -Hi			0.190	0.916	0.061	0.058
NH2Cl-Lo				0.0003	0.640	0.541
NH2Cl-Hi					0.216	0.452

For water with pH 8.5 and alkalinity 10mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.008	0.037	0.238	0.979	0.034	0.008
Free Cl2 -Lo		0.324	0.023	0.013	0.441	0.959
Free Cl2 -Hi			0.041	0.007	0.882	0.337
NH2Cl-Lo				0.072	0.093	0.022
NH2Cl-Hi					0.041	0.010

For water with pH 8.5 and alkalinity 100mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.037	0.140	0.016	0.258	0.012	0.035
Free Cl2 -Lo		0.231	0.781	0.555	0.959	0.537
Free Cl2 -Hi			0.169	0.884	0.302	0.341
NH2Cl-Lo				0.088	0.535	0.641
NH2Cl-Hi					0.442	0.628

Table C.15-Results of t-test Comparing Average dissolve copper Concentration at water with different treatment during conditioning phase (with phosphate addition and α=0.05).

For water with pH 7.2 and alkalinity 10mg/L($CaCO_3$)						
p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.797	0.002	0.175	0.324	0.0006	0.011
Free Cl2 -Lo		0.438	0.642	0.932	0.328	0.484
Free Cl2 -Hi			0.079	0.001	0.072	0.774
NH2Cl-Lo				0.0009	0.012	0.074
NH2Cl-Hi					0.001	0.005
For water with pH 7.2 and alkalinity 100mg/L(CaCO3)						
p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.009	0.055	0.118	0.327	0.0009	0.003
Free Cl2 -Lo		0.152	0.889	0.286	0.931	0.160
Free Cl2 -Hi			0.345	0.741	0.153	0.003
NH2Cl-Lo				0.004	0.935	0.552
NH2Cl-Hi					0.319	0.091
For water with pH 8.5 and alkalinity 10mg/L(CaCO3)						
p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.012	0.010	0.035	0.062	0.008	0.004
Free Cl2 -Lo		0.854	0.005	0.017	0.933	0.451
Free Cl2 -Hi			0.001	0.010	0.820	0.536
NH2Cl-Lo				0.148	0.009	0.003
NH2Cl-Hi					0.024	0.016
For water with pH 8.5 and alkalinity 100mg/L(CaCO3)						
p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.011	0.020	0.177	0.268	0.007	0.022
Free Cl2 -Lo		0.253	0.333	0.151	0.027	0.011
Free Cl2 -Hi			0.663	0.270	0.517	0.833
NH2Cl-Lo				0.284	0.956	0.871
NH2Cl-Hi					0.669	0.514

Table C.16-Results of t-test Comparing Average dissolve copper Concentration at water with different treatment during test phase (without phosphate addition and α=0.05).

For water with pH 7.2 and alkalinity 10mg/L(CaCO$_3$)

p-values	Free Cl2 -Lo	Free Cl2 –Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.016	0.023	0.008	0.133	0.039	0.618
Free Cl2 -Lo		0.927	0.291	$1.43*10^{-5}$	0.279	$1.30*10^{-6}$
Free Cl2 -Hi			0.289	$1.95*10^{-5}$	0.285	$2.30*10^{-6}$
NH2Cl-Lo				$4.71*10^{-8}$	0.569	0.0005
NH2Cl-Hi					0.0006	0.056

For water with pH 7.2 and alkalinity 100mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 –Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	$3.18*10^{-11}$	$6.58*10^{-11}$	$2.84*10^{-12}$	$2.66*10^{-11}$	$8.25*10^{-7}$	$4.97*10^{-10}$
Free Cl2 -Lo		0.0076	$3.34*10^{-11}$	$8.77*10^{-9}$	0.0278	$7.86*10^{-6}$
Free Cl2 -Hi			$5.67*10^{-11}$	$6.22*10^{-9}$	0.1319	0.0163
NH2Cl-Lo				$2.23*10^{-11}$	$7.07*10^{-9}$	$7.77*10^{-13}$
NH2Cl-Hi					$2.43*10^{-7}$	$7.49*10^{-11}$

For water with pH 8.5 and alkalinity 10mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 –Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	$1.95*10^{-6}$	$4.63*10^{-7}$	$2.45*10^{-7}$	$8.95*10^{-14}$	0.001	0.003
Free Cl2 -Lo		0.1259	$1.68*10^{-12}$	$2.80*10^{-16}$	0.003	0.0003
Free Cl2 -Hi			$2.34*10^{-13}$	$5.59*10^{-16}$	$8.43*10^{-5}$	$5.85*10^{-6}$
NH2Cl-Lo				$1.49*10^{-10}$	$2.27*10^{-11}$	$6.98*10^{-11}$
NH2Cl-Hi					$1.81*10^{-14}$	$3.37*10^{-14}$

For water with pH 8.5 and alkalinity 100mg/L(CaCO3)

p-values	Free Cl2 -Lo	Free Cl2 –Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.022	0.180	0.022	0.004	0.108	0.0004
Free Cl2 -Lo		0.0002	0.824	$8.30*10^{-6}$	0.002	$9.02*10^{-10}$
Free Cl2 -Hi			0.247	$2.59*10^{-5}$	0.015	$7.28*10^{-8}$
NH2Cl-Lo				$4.00*10^{-14}$	0.002	$1.09*10^{-5}$
NH2Cl-Hi					0.471	0.868

Table C.17-Results of t-test Comparing Average dissolve copper Concentration at water with different treatment during test phase (with phosphate addition and α=0.05).

For water with pH 7.2 and alkalinity 10mg/L($CaCO_3$)						
p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	$4.62*10^{-7}$	$2.42*10^{-8}$	0.112	0.0004	0.0004	0.001
Free Cl2 –Lo		0.0001	0.0006	$6.31*10^{-10}$	0.615	0.0003
Free Cl2 -Hi			$4.49*10^{-6}$	$2.94*10^{-11}$	0.044	$1.95*10^{-7}$
NH2Cl-Lo				$2.94*10^{-11}$	0.006	0.042
NH2Cl-Hi					$2.21*10^{-8}$	$4.57*10^{-9}$

For water with pH 7.2 and alkalinity 100mg/L(CaCO3)						
p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	$8.84*10^{-7}$	$1.86*10^{-6}$	$6.22*10^{-9}$	$3.66*10^{-7}$	0.0005	$1.87*10^{-5}$
Free Cl2 –Lo		0.559	$6.33*10^{-10}$	$1.29*10^{-5}$	0.606	0.029
Free Cl2 -Hi			$1.09*10^{-8}$	0.0001	0.495	0.011
NH2Cl-Lo				$2.13*10^{-10}$	$1.13*10^{-6}$	$1.15*10^{-11}$
NH2Cl-Hi					0.0003	$1.99*10^{-7}$

For water with pH 8.5 and alkalinity 10mg/L(CaCO3)						
p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	$3.04*10^{-5}$	$2.73*10^{-6}$	$3.59*10^{-6}$	$2.24*10^{-9}$	0.3752	0.805
Free Cl2 –Lo		0.001	$3.58*10^{-12}$	$2.32*10^{-14}$	$3.26*10^{-6}$	$1.03*10^{-7}$
Free Cl2 -Hi			$3.72*10^{-14}$	$3.15*10^{-15}$	$2.12*10^{-8}$	$1.46*10^{-9}$
NH2Cl-Lo				$4.29*10^{-7}$	$1.86*10^{-9}$	$6.09*10^{-10}$
NH2Cl-Hi					$8.56*10^{-12}$	$2.76*10^{-12}$

For water with pH 8.5 and alkalinity 100mg/L(CaCO3)						
p-values	Free Cl2 -Lo	Free Cl2 -Hi	NH2Cl-Lo	NH2Cl-Hi	ClO2-Lo	ClO2-Hi
CONTROL	0.001	0.0006	0.885	0.031	0.124	0.022
Free Cl2 –Lo		0.507	0.006	$3.06*10^{-5}$	0.0004	$2.41*10^{-7}$
Free Cl2 -Hi			0.0002	$2.07*10^{-7}$	$5.15*10^{-5}$	$2.65*10^{-10}$
NH2Cl-Lo				0.001	0.189	0.033
NH2Cl-Hi					0.480	0.597

Table C.18- Results of t-test Comparing Average dissolve copper Concentration at water with and without phosphate addition during the test phase (α=0.005).

	p-values	LALP	HALP	LAHP	HAHP
FOR Free Cl2 LOW	P-LALP	0.7469			
	P-HALP		0.8394		
	P-LAHP			0.1514	
	P-HAHP				0.0544
FOR Free Cl2 HIGH	P-LALP	0.0123			
	P-HALP		0.1776		
	P-LAHP			0.6275	
	P-HAHP				0.0980
FOR NH2Cl LOW	P-LALP	$2.35*10^{-10}$			
	P-HALP		$2.67*10^{-11}$		
	P-LAHP			$4.40*10^{-9}$	
	P-HAHP				$4.11*10^{-10}$
FOR NH2Cl HIGH	P-LALP	$1.53*10^{-5}$			
	P-HALP		$2.72*10^{-13}$		
	P-LAHP			$1.10*10^{-6}$	
	P-HAHP				0.0180
FOR ClO2-LOW	P-LALP	0.0893			
	P-HALP		0.0121		
	P-LAHP			$6.19*10^{-8}$	
	P-HAHP				0.0002
FOR ClO2-HIGH	P-LALP	0.0055			
	P-HALP		0.0160		
	P-LAHP			$3.95*10^{-5}$	
	P-HAHP				0.0408
FOR CONTROL	P-LALP	0.1898			
	P-HALP		$2.31*10^{-5}$		
	P-LAHP			0.2056	
	P-HAHP				0.0136