

THE EFFECT OF FREE CHLORINE AND CHLORAMINES
ON LEAD RELEASE IN A DISTRIBUTION SYSTEM

by

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ABSTRACT

Total lead release in drinking water in the presence of free chlorine and chloramine residuals was investigated in field, laboratory and fundamental investigations for finished waters produced from ground (GW), surface (SW), saline (RO) and blended (B) sources. Field investigations found more total lead was released in the presence of chloramines than in the presence of free chlorine for RO and blended finished waters; however, there were no statistical differences in total lead release to finished GW and SW. Laboratory measurements of finished waters oxidation-reduction potential (ORP) were equivalent by source and were not affected by the addition of more than 100 mg/L of sulfates or chlorides, but were significantly higher in the presence of free chlorine relative to chloramines. Development of Pourbaix diagrams revealed the PbO_2 was the controlling solid phase at the higher ORP in the presence of free chlorine and $\text{Pb}_3(\text{CO}_3)_2(\text{OH})_{2(s)}$ (hydrocerussite) was the controlling solid phase in the presence of chloramines at the lower ORP, which mechanistically accounted for the observed release of total lead as PbO_2 is much less soluble than hydrocerussite. The lack of differences in total lead release to finished GW and SW was attributed to differences in water quality and intermittent behavior of particulate release from controlling solid films.

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LIST OF ABBREVIATIONS

DPB	Disinfection by-product
redox	oxidation-reduction
<i>E</i>	potential
<i>E</i> ^o	Standard potential
pH	Potential hydrogen
pC	negative log of the molar concentration
°C	degrees Celsius
AL	Action level
WASA	Water and Sewer Authority
ORP	oxidation-reduction potential
GW	ground water
SW	surface water
RO	desalinated water
B	blended water
TBW	Tampa Bay Water
HPC	Heterotrophic plate count
PEPA	Potential of Exoproteolytic Activity
SM	Standard Methods
cfu	Coliform forming units
PDS	Pilot distribution system
HRT	Hydraulic retention time
DIPb	Dissolved lead
XPS	X-Ray Photoelectron spectroscopy

1 INTRODUCTION

The adverse health effects of human lead consumption have been and are presently an international concern (Fewtrell et al., 2004; Vinceti et al., 2001; Bellinger et al., 1991; and USEPA, 2004). Particulate and dissolved lead are known drinking water contaminants that primarily come from the release of lead in lead pipes, solders and plumbing fixtures in distribution and home plumbing systems (Lee et al, 1989; Gardels et al, 1989; and Leroy, 1993). Lead release in drinking water is not simplistic, and can be related to chemical oxidation, possibly biological oxidation and physical mechanisms (turbulence) of lead and lead solid phases (Schock, 1999; 1990; & 1989; and Leroy, 1993).

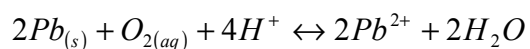
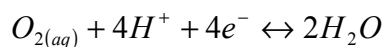
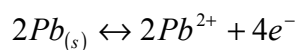
Chlorinated disinfection by-products (DBPs), like lead, are regulated in drinking water and can adversely affect human health. Many utilities have chosen to use chloramines for residual maintenance in drinking water distribution systems in order to comply with DBP regulations (Haas, 1999 and USEPA, 1998). However, concerns for lead release have recently increased due to recent reports of higher lead concentrations in a distribution system following the change from free chlorine to chloramines for residual maintenance (Cohn, 2004). This article presents a comparison of the thermodynamic potential of free chlorine and chloramines and theoretical controlling solid phases as measured in the laboratory and the lead release from field studies in the presence of free chlorine and chloramines for finished waters produced from ground, surface and saline sources.

2 LITERATURE REVIEW

Corrosion of metal pipes in drinking water distribution systems is a common problem in the water community. Corrosion can be described as a fundamental oxidation-reduction (redox) reaction and has been extensively studied by several researchers (Lytle et al., 2000 & 1993; Schock, 1990; 1989; 1983; 1981 & 1980; Boffardi, 1995; and Hem at al., 1973). Specific references to fundamental corrosion, thermodynamics and disinfection by-products (DBPs) are reported in this abbreviated literature review.

2.1 Fundamentals of Corrosion

All corrosion reactions require an electron donor, an electron acceptor, an electrical connection and return. A redox reaction demonstrating lead pipe corrosion by dissolved oxygen is shown in Equation 2.1.



Equation 2.1 Redox reaction of lead and water

Corrosion, as shown in Equation 2.1, occurs because all components of an electrochemical cell are present. Lead (the anode) transfers electrons to dissolved oxygen, which

is reduced to water (the cathode). Ions move between the cathode and anode because of an external connection, which could be water, and are returned through reactions with water or other chemical species. The standard potential (E°) value for the half reaction is determined by Gibb's free energy, as shown in Equation 2.2.

$$\Delta G^\circ = nFE^\circ$$

Equation 2.2 Gibb's free energy and potential

where: ΔG° = Gibb's free energy, kcal
 n = number of electrons involved in the half reaction, equivalent
 F = Faraday's constant, 23.06 kcal/(volt-equivalent)
 E° = standard potential, volt

The standard potential, E° , of the corrosion reaction in an actual solution is determined by the Nernst equation as shown in Equation 2.3, which determines the driving force and direction (oxidation, reduction or equilibrium) of the reaction (Snoeyink et al., 1980).

$$E = E^\circ - \frac{2.3RT}{nF} \log\left(\frac{red}{ox}\right)$$

Equation 2.3 Nernst equation

where: E = potential, volt
 E° = standard potential, volt
 R = ideal gas constant, 0.001987 Kcal/(deg-mole)
 T = degrees Kelvin, °K
 n = number of electrons involved in the half reaction, equivalent
 F = Faraday's constant, 23.06 kcal/(volt-equivalent)
 red = reduced species in a reaction written as a reduction reaction
 ox = oxidized species in a reaction written as a reduction reaction

2.2 Pourbaix Diagrams

The Nernst equation can be used to graphically represent controlling species during corrosion. An E -pH diagram, or Pourbaix diagram, portrays dominant soluble and insoluble species as a function of E , pH and other water quality parameters. Other species exist at these

conditions, but the Pourbaix diagram portrays the dominant species. Three dimensional Pourbaix diagrams are useful in that the effect of varying concentration can be shown as the negative log of the molar concentration of the oxidized species or pC. Pourbaix diagrams distinguish among dominant species and indicate corrosion, immunity, and passivation for given water quality conditions. Typically, solid films that are attributed to passivation could become an impervious barrier between the corroding metal and water, and "short-circuit" the corrosion reaction. Elimination of the electrical connection would stop corrosion. However, many solid films are not impervious and provide excellent conditions for continuing corrosion. Natural waters are complex; and if only stable and predominate species are considered, the dominant corrosion reactions can be observed (Stumm et al., 1981).

Pourbaix (1966) published Pourbaix diagrams for lead considering $\text{Pb}_{(s)}$, Pb^{2+} , $\text{PbO}_{(s)}$, $\text{PbO}_{2(s)}$, $\text{Pb}_3\text{O}_{4(s)}$, $\text{PbH}_2(\text{g})$, HPbO_2^- and $\text{PbCO}_3(\text{s})$ species that combined solid oxides and carbonates at equilibrium. These diagrams demonstrated inclusion of $\text{PbCO}_3(\text{s})$ (cerussite) extended the region of passivation into the stability region of water between pH 6 and 12. Cerussite formation increased passivation because of the extension of cerussite into the previous predominant, relatively soluble $\text{PbO}_{(s)}$, which reduced lead corrosion.

$\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2(\text{s})$ or hydrocerussite was incorporated into another Pourbaix diagram as an additional solid carbonate phase in 1985 (AWWARF). Similar results were shown in that immunity and passivation occurred when $\text{Pb}_{(s)}$ and $\text{PbO}_{2(s)}$ were dominant; however, basic lead carbonate, $\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2(\text{s})$ or hydrocerussite, displaced cerussite and passivated lead.

Varying carbonate concentrations affects lead species predominance (Schock, 1999). Schock demonstrated varying carbonate concentration dramatically changed hydrocerussite passivation from a large area at pH 8.5 to 11 for 2.4 mg C/L to a thin sliver near pH 11 for 24 mg

C/L in the stability region of water, and demonstrated that increasing carbonate alkalinity was not always beneficial for reducing lead corrosion. More recently, Schock's development and interpretation of lead release using thermodynamics was recognized as excellent because it clearly showed the increased potential of drinking water due to a free chlorine residual relative to a chloramine residual changed dominance of lead species from Pb^{+2} from a hydrocerussite controlling solid phase to the less soluble Pb^{+4} from a PbO_2 controlling solid phase. This provided a fundamental reason why total lead concentrations increased in the Washington D. C. drinking water following a conversion from free chlorine to chloramine residual maintenance (Renner, 2004).

2.3 Lead Corrosion and Disinfection

Chlorine and chloramines species are widely used for residual maintenance and the control of pathogenic microorganisms in drinking water distribution systems. Although both are used for disinfection, free chlorine ($HOCl$ and OCl^-) is a stronger oxidant and disinfectant than monochloramine (NH_2Cl), which is the primary form of chloramine residual in distribution systems (Singer et al., 1999). Either is predicted to chemically oxidize lead at equilibrium, which theoretically increases released lead in drinking water (Boffardi, 1988).

The difference in electrochemical potential between free chlorine ($HOCl$ and OCl^-) and chloramines (NH_2Cl) is depicted in Figure 2.1 at 10^{-4} M chlorine concentration and $25^\circ C$. As shown in Figure 2.1, the oxidation-reduction potential (ORP) of free chlorine is greater than the potential of chloramines, and both exist in a region where water is not stable. In the stable region of water, chlorides are the dominant species, which is why the presence of residual is desirable in drinking water as it move to equilibrium and deactivates pathogens in the process. The

subsequent reaction of either free chlorine or chloramines with metals in distribution systems will form different compounds that can affect corrosion (Schock, 1999).

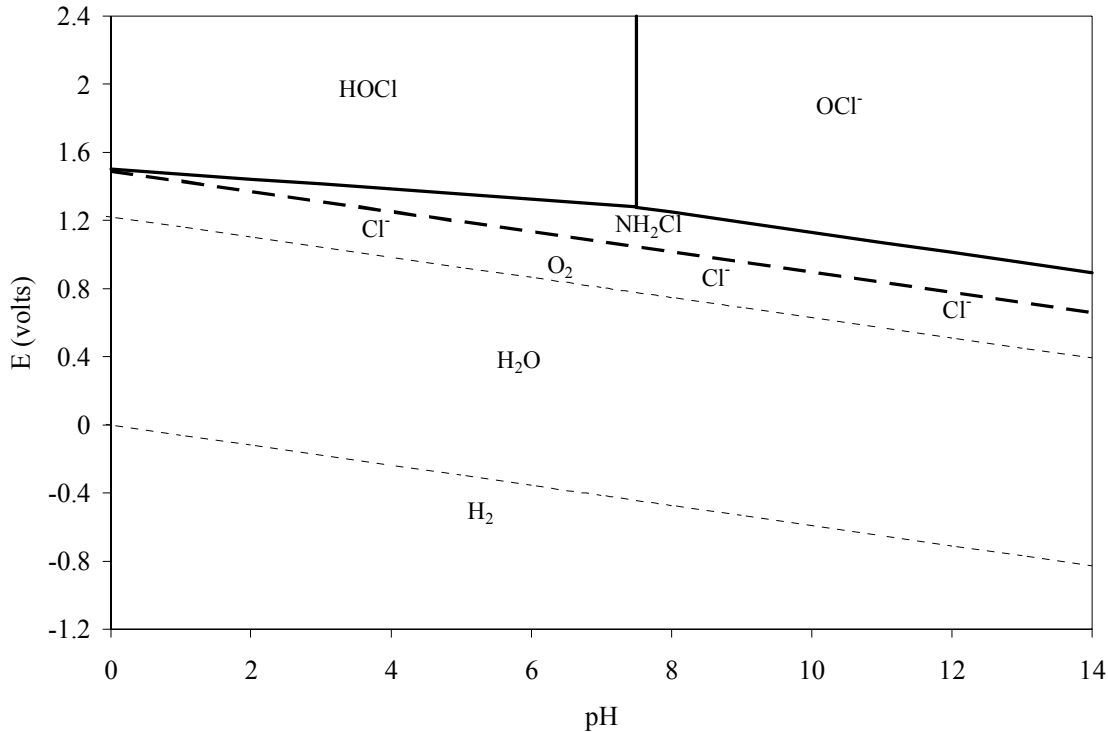


Figure 2.1 Electrochemical potential comparison of free chlorine and chloramines in water at 25 °C. Free chlorine concentration = 10^{-4} M, Chloramines concentration = 10^{-4} M and Ammonia concentration = 10^{-3} M.

Examination of actual lead corrosion by free chlorine and chloramines has been studied in practice. Lead corrosion in drinking water is defined by regulation to include dissolved and particulate lead. Physical effects such as turbulence, frequency of stagnation, and movement of valves can disrupt the solid films and increase lead release. Film disruption is also affected by water quality that prevents the adherence of precipitated solids to pipe surfaces or promotes the formation of porous layers (Leroy, 1993; Lytle, 1993 & 2000; and Schock, 1990 & 1989).

Treweek et al. (1985) investigated corrosion rates of different piping materials in the presence of free chlorine and chloramines in an aqueous environment. A fine powdery material

was barely visible on the surface of lead-tin solder coated copper inserts. A yellowish-brown film formed on the inner surface of lead pipe inserts and a green coating of powder formed on the copper coil tubing surfaces exposed to the free chlorine and chloramine residuals. The corrosion layers developed on the metals after three months and changed little throughout the study.

Corrosion and penetration rates are measured by weight loss of metal coupons due to scale removal following exposure to aqueous environments. Metal concentrations may or may not correlate to corrosion and penetration rates measured by weight loss. The corrosion and penetration rates of lead inserts were higher in a free chlorine environment than in a chloramine environment. Free chlorine and chloramines corrosion and penetration rates for the lead-tin solder coated copper inserts were not different. Corrosion of copper coil tubing with lead-tin solder was assessed by measuring dissolved lead and copper concentrations and showed higher lead concentrations in the presence of the free chlorine than in the presence of chloramines.

Lin et al. (1997) also studied the release of total lead from lead, copper/lead solder, and brass coupons in a static batch for varying disinfectant (free chlorine and chloramines) and pH. Total lead release from lead coupons (99% Pb) decreased as pH increased for both free chlorine and chloramines; however, total lead release was significantly higher in the presence of free chlorine than in the presence of chloramines at equivalent pHs. The release of total lead from the copper/lead solder coupons (50/50 Sn/Pb) was similar to the release of total lead from the lead coupons. Increasing pH decreased total lead release and was higher in the presence of free chlorine by a factor of two. For the brass coupons containing 3 % lead, increasing pH also decreased total lead release, but conversely in the presence of chloramines total lead release increased.

Cantor et al. (2003) investigated lead corrosion over time in raw, free chlorine and free chlorine plus corrosion treated ground waters. Corrosion treatment consisted of pH control using NaOH in a low alkalinity - low hardness ground water and orthophosphate addition in a high alkalinity - high hardness ground water. The lead action level (AL) was exceeded in all waters at all times during the study, but after one year lead release in the free chlorine with orthophosphate decreased to the AL. Lead concentrations in chlorinated waters were equal to or less than lead concentrations in untreated water, which indicated no adverse effects of free chlorine on lead release for these conditions. Although all waters exceeded the lead AL at some time, the results indicated that treatment was necessary to control lead release in these conditions, and was only accomplished by orthophosphate addition.

Edwards et al. (2004) investigated lead solubility and lead release from lead pipes and brass in waters without disinfectant, with ammonia, with free chlorine, and with chloramines at varying pHs. All waters were dosed with 5 mg/L of Pb using $PbCl_2$ in the solubility study. Dissolved and total lead release in solubility tests of waters without disinfectant or with chloramines were four to six times greater than in waters with free chlorine from pH 7.5 to 9. Lead release decreased slightly as pH increased from pH 7.5 to 9. However, the lead pipes studies found that total lead concentrations were not statistically different at 2 and 30 days. The soluble lead fraction was 66% of the total lead release in presence of chloramines as compared to 3-30 % in other waters.

Edwards found higher lead release from seven of eight different brass hose bibs that varied in Pb content (2 to 8%) over a 58 day study period in the presence of chloramines. Additional analysis on brass was done by adding 10 mg/L of NO_3-N to the waters after two months. With or without disinfectants, lead release increased after nitrate addition in waters in

contact with the seven of eight brass hose bibs. In a longer-term examination with the presence of nitrates, Edwards describes that chloramines leached less lead than free chlorine with the same type of water.

The effect of chloramines on total lead release in drinking water distribution systems has been reported by the Water and Sewer Authority (WASA) in Washington D.C. WASA switched from free chlorine to chloramine residual maintenance in 2000 for control of DBP formation (Leonig, 2000; and Nakamura, 2004). As early as mid 2001 through 2003, WASA exceeded the Pb AL 15 $\mu\text{g/L}$ (Nakamura, 2004; and Holder, 2004). Some of the lead concentrations significantly exceeded AL as highlighted by total lead concentrations of 48,000 and 24,000 $\mu\text{g/L}$ from two homes (Nakamura et al., 2004).

WASA uses a one-month free chlorine burn every spring to control bacterial growth in the distribution system and reported in 2004 the fraction of homes exceeding the Pb AL decreased from 54 to 26 % following the one-month free chlorine burn. In one home, the lead concentration fell tenfold (Cohn, 2004). Once chloramines was reintroduced to the distribution system, lead concentrations increased by a factor of 13.6 (Edwards et al., 2004).

The results from these investigations indicate that lead release from lead pipes increases when free chlorine is used for residual maintenance relative to chloramines (Trewick et al., 1985; Lin et al., 1997; and Edwards et al., 2004) and that released lead is greater or equal with free chlorine residual maintenance than with no disinfectant (Cantor et al., 2003 and Edwards et al., 2004). These observations are supported by the greater ORP of free chlorine relative to chloramines (Singer et al., 1999). But, when lead is coupled with another metal, such as in brass fixtures, soldered joints or in the distribution system where different pipe materials are connected, lead release is greater in the presence of chloramines relative to free chlorine as

shown by Treweek et al.(1985), Lin et al. (1997), and Edwards et al. (2004). Galvanic cells are one corrosion mechanism that is applicable to drinking water. Solder joints in brass fixtures connect dissimilar metals such as lead, zinc or copper in brass alloys or pipes to lead, tin, and silver in solder, which creates an galvanic cell resulting in lead release. Galvanic corrosion of the 23,000 lead and 107,000 copper pipes has been suggested as a mechanism for increased lead release in the WASA distribution and consumer home plumbing systems following a change from free chlorine to chloramine residual maintenance (Nakamura, 2004 and Nakamura et al., 2004).

Additionally, the dissipation of chloramines to free ammonia can facilitate ammonia oxidizing bacteria to nitrify and produce nitrates (NO_3^-). Edwards et al. (2004) demonstrated lead release caused by the addition of 10 mg/L- $\text{NO}_3\text{-N}$ to water in the presence of chloramines exceeded lead release in the presence of free chlorine. Other research has also shown high concentrations of nitrates increase lead release (Amin et al., 2004; Uchida et al., 1999; and Abd El Rehim et al., 1998). These studies demonstrated that in the presence of nitrates, dissolution of lead occurs and passive lead scales break down, which may add to the total lead concentration.

3 METHODS AND MATERIALS

3.1 Pourbaix Diagrams

The thermodynamic demonstration of the oxidation-reduction of lead consisted of constructing Pourbaix diagrams. The Pourbaix diagrams were created for the speciation of lead in water, accounting for the lead hydroxide, oxide and carbonate species. The reactions with lead and their associated Gibb's free energy were determined from literature, as well for the reactions of chlorine. Sources used for the construction of the Pourbaix diagrams for lead and chlorine are Schock (1999), AWWARF (1985), and Snoeyink et al. (1980).

3.2 ORP Titrations

Finished waters, prior to disinfection, were collected from the Tampa Bay Water (TBW) Regional Surface Water Treatment Plant in Brandon, FL; the TBW Desalination Water Treatment Plant in Tampa, FL; and the TBW Cypress Creek well field near the city of Land O'Lakes, FL. Blended water was made from 62% GW, 27% SW, and 11% RO finished waters.

Prior to the experiment, the initial chlorine residual of the waters were measured to verify no chlorine residual. The concentration of free chlorine or chloramines in the titrant was 20 and 1000 mg/L as Cl₂. ORP of the water was measured using an oxidation-reduction probe, a silver-silver chloride reference electrode with saturated potassium chloride and a platinum indicator electrode. The ORP measurement was conducted and then converted relative to the standard

hydrogen electrode. Titration continued until a 10 mg/L as Cl_2 was achieved. Chlorine concentrations were measured after titrations were complete. Free chlorine and chloramine titrations were done on (a) all source waters at 5, 15, 25 and 30 °C (b) RO finished water with 35.5, 71, and 106.5 mg/L of Cl^- addition at 25 °C and (c) SW finished water with 50, 100, and 150 mg/L of SO_4^{2-} at 25 °C.

3.3 Lead Field Study

The field study was conducted at a large pilot facility near the city of Land O'Lakes, FL at the Tampa Bay Water Cypress Creek well field. RO, surface, ground, and blended finished waters were distributed to eight identical pilot distribution systems (PDS) as shown in Figure 3.1. The first four PDSs received ground, surface, RO, and blended finished waters and used free chlorine for residual maintenance and the remaining four PDSs received identical finished waters and used chloramines for residual maintenance. The PDSs were identical and were made from actual distribution system pipes which discharged to a corrosion shed that housed copper coil tubing with lead coupon inserts as shown in Figure 3.2.



Figure 3.1 Influent treated water to pilot distribution system

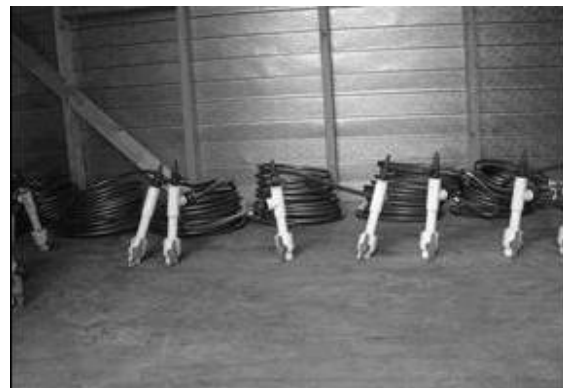


Figure 3.2 Copper coil tubing with lead coupons in corrosion shed

The field experiment was done as the final phase of a two year field study and lasted 3 months. Weekly samples were collected from the corrosion shed following flushing of two gallons and a 6 to 8 hour stagnation period. A one liter sample was collected for water quality measurement. The methods used to measure water quality are listed in Table 3.1.

Table 3.1 Water quality parameters and methods

Parameter	Method	Units
pH	SM 4500-H ⁺ B	pH units
Alkalinity	SM 2320 B	mg/L as CaCO ₃
Chlorides, Cl ⁻	SM 4110 B	mg/L
Sulfates, SO ₄ ⁻²	SM 4110 B	mg/L
Lead	SM 3113 B	µg/L
Nitrate, NO ₃ ⁻	Hach 8507	mg/L as N
Ammonia	SM 4500 NH ₃ D	mg/L as N
Free chlorine	SM 4500-Cl G	mg/L as Cl ₂
Total Chlorine	SM 4500-Cl G	mg/L as Cl ₂
Potential (ORP)	SM 2580 B	volts
HPC	SM 9215 C	cfu/mL
PEPA	Laurent et al. (1995)	cells/cm ²

* SM indicates techniques from *Standard Methods*, 19th edition (1995)

4 RESULTS AND DISCUSSION

4.1 Total lead release field study

The effects of free chlorine and chloramines residuals on total lead release in the pilot distribution systems were compared over a three month period by water source and water quality using identical water sources, PDSs and PDS operating conditions. The PDS hydraulic retention time (HRT) during this period was two days, which corresponded to a 10.8 mile equivalent pipe length in an actual distribution system flowing at 0.33 ft/sec. All statistical comparisons of free chlorine and chloramine distribution water quality were made using paired t-tests to determine statistically significant differences at a 95 % CL.

The actual and variation of total lead release is shown in Figure 4.1 for each source and the average of all sources in free chlorine and chloramine environments. As shown in Figure 4.1, the average release of total lead to GW, SW, RO and blended finished waters was 34.9 $\mu\text{g/L}$ in the presence of chloramines and 4.4 $\mu\text{g/L}$ in the presence of free chlorine. The magnitude of the greater average total release in the presence of chloramines is primarily due to the relatively high average lead release to the RO finished water in the presence of chloramines as shown in Table 4.1. As shown in Figure 4.1, there was significant variation in total lead release, especially in the RO finished water, which was attributed to particulate release and water quality. Total lead release was associated with high chloride concentrations, which may have adversely affected passivating lead films. Average total lead releases was higher in RO and B finished

water in the presence of chloramines, but there was no statistically significant difference in total lead release in the presence of either free chlorine or chloramines for GW or SW. These results are consistent with trends reported by other investigators (Treweek et al., 1985; Lin et al., 1997; and Edwards et al., 2004).

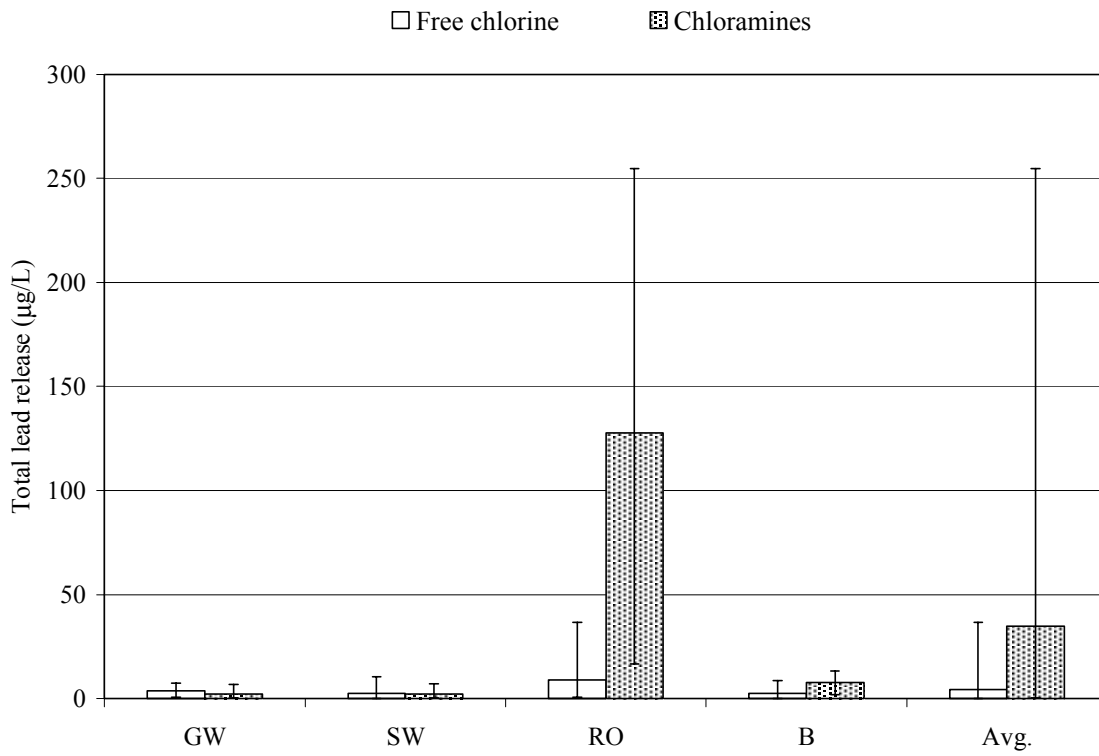
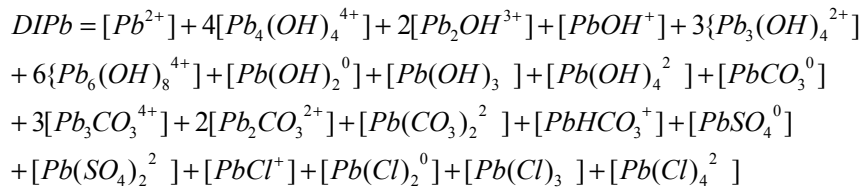


Figure 4.1 Average lead release by source and disinfectant

Table 4.1 Average field water quality data

Source	Disinfectant	Total Lead (mg/L)	pH	Alkalinity (mg/L CaCO ₃)	Temperature (°C)	Chlorine residual (mg/L - Cl ₂)	E (volts)	Chlorides (mg/L)	Sulfates (mg/L)	NO _x - N (mg/L - N)	Ammonia (mg/L - N)	log(HPC) (cfu/mL)	log(PEPA) (cells/cm ²)
GW	Free chlorine	3.7	8.0	197	28	0.8	0.8	20.0	19.5	0.02	0.01	3.5	9.2
SW	Free chlorine	2.7	8.2	66	28	1.2	0.8	26.0	222.7	0.17	0.01	3.0	9.1
RO	Free chlorine	8.9	8.3	77	28	2.6	0.9	75.3	3.9	0.02	0.01	3.3	8.8
B	Free chlorine	2.4	8.1	143	28	1.6	0.8	28.9	76.2	0.04	0.01	2.7	8.6
GW	Chloramines	2.2	7.8	196	28	0.3	0.6	23.8	24.4	0.25	0.47	4.1	9.6
SW	Chloramines	2.3	7.7	67	28	0.4	0.7	31.3	225.6	0.42	0.42	3.6	9.3
RO	Chloramines	127.6	8.0	72	28	0.6	0.6	82.0	4.4	0.14	0.57	3.6	8.9
B	Chloramines	7.7	7.9	160	28	0.8	0.6	32.0	55.1	0.13	0.56	3.4	9.6
# of observations		9	13	13	16	12	12	11	11	3	4	12	4

Tang (2005) developed empirical and fundamental equilibrium models based on speciation for total lead release during the investigation of water quality changes in distribution system water quality brought about by blending different waters (Tang, 2005 and Taylor et al., 2005). These models are shown in Equation 4.1 and Equation 4.2. The empirical model was developed in the presence of only a chloramine residual. A similar model was developed by Schock (1980; 1981 & 1983) based on the assumption that $Pb_3(OH)_2(CO_3)_2$ was the controlling solid phase for lead release. In his model, only carbonate and hydroxide complexes were considered. The complexes with chloride and sulfate were not included since their contributions are small compared to carbonate and hydroxide complexes. Schock's model successfully predicted soluble lead release when approximate equilibrium was achieved. Lead mass transfer is commonly limited by diffusion in home plumbing systems when lead solder is the source for lead release.



Equation 4.1 Tang equilibrium model for soluble lead release

$$[Pb]_{T\ 90} = 1.027^{(T-25)} \times Alkalinity^{0.677} \times pH^{-2.73} \times Chloride^{1.46} \times Sulfate^{-0.23}$$

Equation 4.2 Tang empirical model for lead release

Where: $[Pb]_{T\ 90}$ = total lead release corresponding to 90th percentile ($\mu\text{g/L}$)
 Alkalinity = mg/L as CaCO_3
 Chloride = mg/L
 Sulfate = mg/L
 T = Temperature, $^\circ\text{C}$

Ammonia complexes for lead have not been reported in the literature and do not impact lead release in drinking water. Hence, no lead-ammonia complexes were considered in either equilibrium, which indicates ammonia from chloramine degradation does not impact lead release in drinking water from the formation of lead complexes. The empirical model shown in Equation 4.2 was developed and verified using independent data over a year of operation during the blending effects study (Taylor et al., 2005). The data shown in Table 4.1 was not included in development or verification of the empirical total lead release model.

As predicted using Equation 4.1, the average soluble lead released during the comparison study is 165 $\mu\text{g/L}$, 95 % of which are in the form of a lead-carbonate complexes. The empirical model shown in Equation 4.2 predicts 28 $\mu\text{g/L}$ of total lead release for the average water quality conditions shown in Table 4.1. The actual average total lead release was 20 $\mu\text{g/L}$, which is relatively close to the empirically predicted total lead release. The equilibrium prediction was high because diffusion limited lead mass transfer limitations in the copper coils.

The data in Table 4.1 can be used to relate field water parameters to total lead release. There are no significant differences among source ORPs for a common disinfectant in the field. Chloramine ORP is always less than free chlorine ORP. As predicted in Equation 4.2, lead release tended to increase in the field with increasing chlorides and decrease with increasing sulfates. The highest lead release occurred in the RO finished water, which had the highest chlorides and the lowest sulfates. The lowest lead release occurred in the SW and GW finished waters, which had low chlorides and mixed sulfates. NO_x ($\text{NO}_2^- + \text{NO}_3^-$) is reported as an index for biological nitrification.

Chloramines were used for residual maintenance in the PDSs receiving free chlorine during the comparison investigation. Biological nitrification was practically insignificant in the presence of chloramines and was not observed in the presence of free chlorine. Average ΔNO_x ($\text{NO}_{x\text{-out}} - \text{NO}_{x\text{-in}}$) in the chloramine PDSs were 0.07 mg/L as N and 0.08 mg/L as N, respectively. Actual $\text{NO}_{x\text{-out}}$ varied from 0.42 to 0.02 mg/L as N because of nitrification in PDS storage tanks. Biological activity was significantly higher in the presence of chloramines. Average bulk water HPC was more than ten fold higher and average biofilm cell density was 2.6 fold higher in presence of chloramines relative to free chlorine. Finally, chloramine residual relative to free chlorine residual was lower in all finished waters. While this observation is surprising, lower chloramines residual were consistently observed during the comparison study. Chloramine residuals were accurately modeled and verified using independent data by Arevalo (2004) during the initial year of operation of the field study using data from eighteen PDSs as a function of water quality, pipe material, temperature and pipe geometry during the blending study (Arevalo et al., 2004; and Taylor et al., 2005). Arevalo demonstrated while bulk dissipation rate of chloramines was significantly less than the bulk dissipation rate of free chlorine, the wall reaction rate constants were much higher for chloramines than free chlorine, and more than compensated for the slower rate of chloramine bulk dissipation.

As increased total lead release in the presence of chloramines relative to free chlorine has been documented in literature (Treweek et al., 1985; Lin et al., 1997; and Edwards et al., 2004), source water quality and disinfectant in the field studies can be related to lead release. While there are some water quality differences that can be attributed to the water source, these differences do not account for the increased total lead

release in the presence of chloramines since source water qualities were practically identical with the exception of residual. There are no ammonia-lead complexes known in the literature, which practically eliminated ammonia as a cause of increased total lead release in the presence of chloramines. Investigators have reported total lead release increased as nitrates increased (Edwards et al., 2004; Amin et al., 2004; Uchida et al., 1999; and Abd El Rehim et al., 1998); however, the increased bulk nitrates in this work, are far below what has been observed to cause increases in total lead. Biological water quality as suggested (Schock, 1999) and field ORPs in the presence of both residuals are significantly different.

4.2 Effect of Cl₂ and NH₂Cl on Drinking Water Potential

ORP was determined for varying Cl₂ and NH₂Cl residuals for the four finished waters produced from ground, surface, saline and blending as shown in Figure 4.2, Figure 4.3, Figure 4.4 and Figure 4.5. The purpose was to determine ORP differences by disinfectant, temperature, and source (Figure 4.2 and Figure 4.3) and then to determine if major anions added during SW treatment (SO₄⁻²) or passing through RO filtration (Cl) would significantly increase ORP (Figure 4.4 and Figure 4.5). These ORPs would then be interpreted for their relative effects on lead release using the Pourbaix diagrams.

As shown in Figure 4.2, there is a significant difference in ORP between free Cl₂ and NH₂Cl residuals in stable RO finished water. ORP increases asymptotically to a maximum of approximately 0.9 V and 0.68 V for free Cl₂ and NH₂Cl, respectively, at 25 °C and is very close to these values at concentrations used for residual maintenance in drinking water distribution systems. The trends of all ORP versus residual titration

curves were similar in that ORP increased asymptotically to a maximum potential that was limited by disinfectant. Free Cl_2 ORPs always exceeded NH_2Cl ORPs.

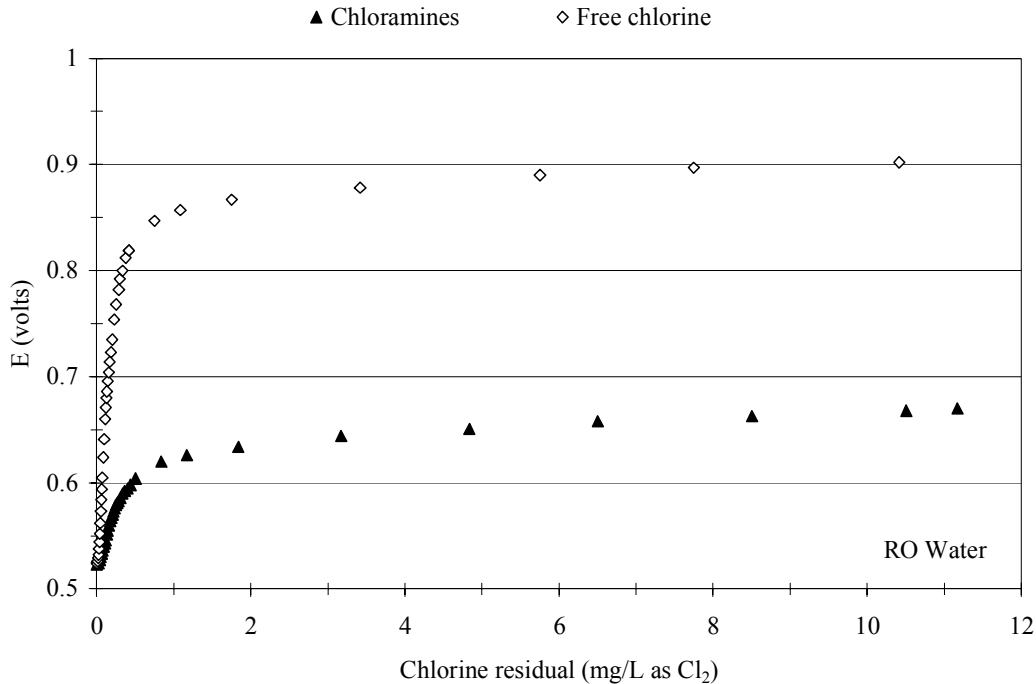


Figure 4.2 ORPs versus free Cl_2 and NH_2Cl for finished RO at 25 °C.

As shown in Figure 4.3, finished SW ORP decreased as temperature increased for both disinfectants. As shown in Figure 4.3 at 25 or 30 °C, the maximum finished RO ORP was approximately 0.9 V for free chlorine and 0.67 V for chloramines. However, at 5 or 15 °C, the ORP was approximately 0.97 V for chlorine and 0.72 V for chloramines. This is consistent with equilibrium using the Nernst Equation in positive ORP conditions common to drinking water distribution systems. This observation was the same for all waters, ORP decreased as temperature increased. Additionally, source water did not affect ORP titrations. Figure 4.2 and Figure 4.3 demonstrate the effect of disinfectant and temperature was consistent for the different waters. At 25 °C, the ORP for both RO and SW with free chlorine was about 0.9 V and with chloramines it was about 0.68 V.

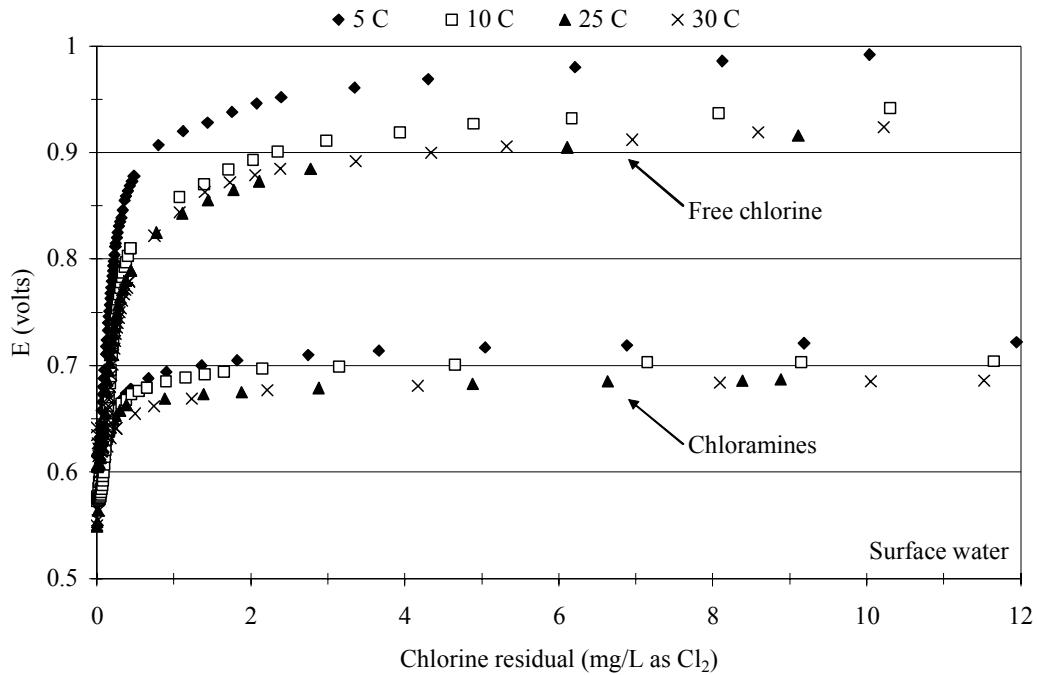


Figure 4.3 ORPs versus free Cl₂ and NH₂Cl for finished SW at different temperatures.

The titration presented in Figure 4.3 depicts equilibrium, which indicates equilibrium ORP decreases with increasing temperature. This is seemingly contrary to published literature that states lead corrosion rates increase with increasing temperature (Schock, 1999; AWWARF, 1985; and Boffardi, 1995 & 1988) and is consistent with the Arrhenius Equation that infers reaction rates double in increments of 10 °C. However, equilibrium constants often decrease with increasing temperature, which is consistent with the Nernst Equation for lead oxidation in common distribution system conditions.

Sulfates were added to finished surface water using NaSO₄ to determine the effect of sulfate addition from enhanced coagulation on ORP, and chlorides were added to finished RO water using NaCl to determine the effect of additional chlorides in RO finished waters. As shown in Figure 4.4, the addition of SO₄⁻² to finished SW did little to

affect ORP in the presence of free Cl_2 or NH_2Cl . The same observation was made of the of the data shown in Figure 4.5 as the addition of chlorides did little to effect finished RO water ORP. Although some slight increases are apparent, the eventual ORPs of either finished water differed little with or without anion addition. However, the free chlorine and chloramines ORP differences were observed again in Figure 4.4 and Figure 4.5. Lead corrosion has been positively correlated with increasing chlorides (Schock, 1999; AWWARF, 1985) and increasing sulfates (Schock, 1999; AWWARF, 1985; and Taylor et al., 2005). However, the data presented in Figure 4.4 and Figure 4.5 suggests that these effects are not due to associated ORP increases.

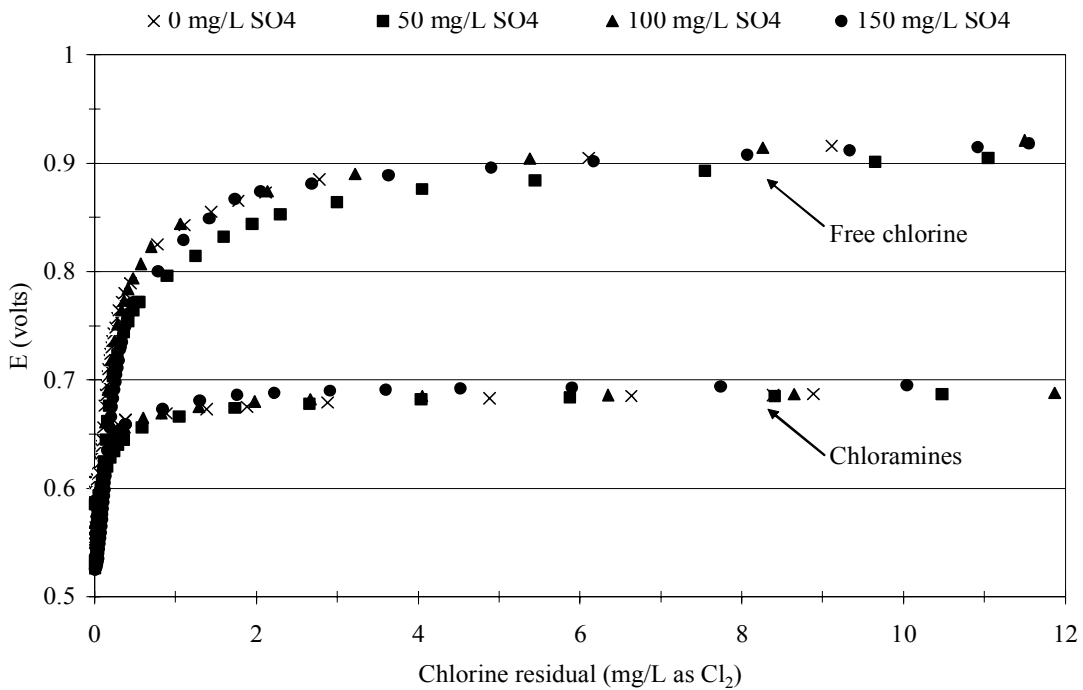


Figure 4.4 Effect of increasing sulfate addition on finished surface water ORP for varying free chlorine and chloramine residuals at 25 °C

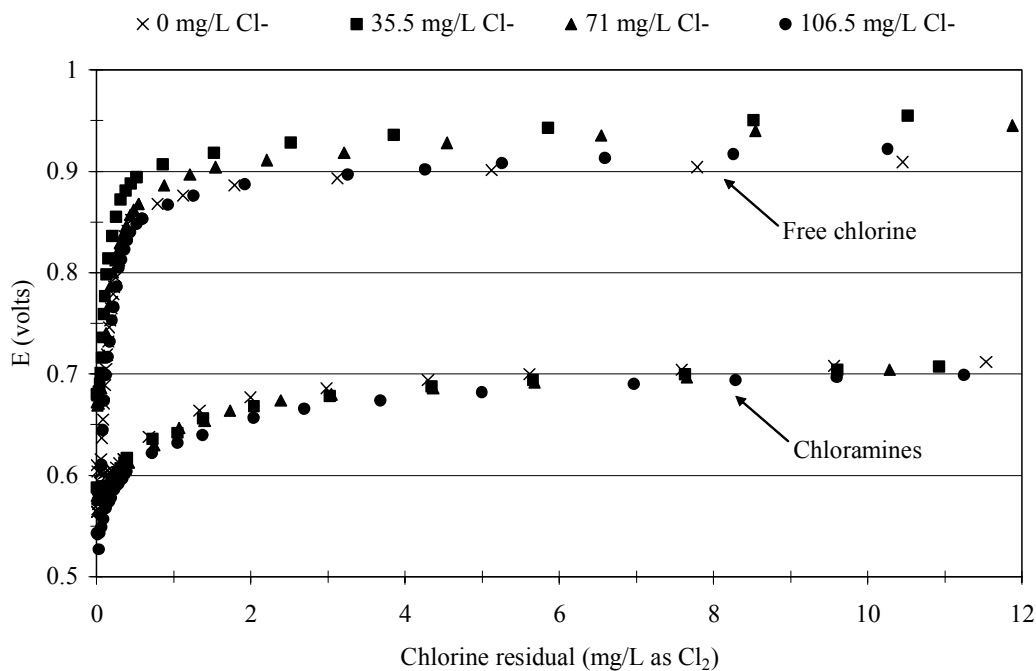


Figure 4.5 Effect of increasing chloride addition on finished RO water ORP for varying free chlorine and chloramine residuals at 25 °C.

4.3 Corrosion Thermodynamics

Pourbaix diagrams considered lead species $Pb_{(s)}$, Pb^{2+} , $PbO_{(s)}$, $PbO_{2(s)}$, $Pb(OH)^+$, $Pb(OH)_2^0$, $Pb(OH)_3^-$, $Pb(OH)_4^{-2}$, PbO_3^{-2} , $PbCO_{3(s)}$ (cerussite) and $Pb_3(CO_3)_2(OH)_2(s)$ (hydrocerussite) and were developed for dominant species as shown in Figure 4.6 and Figure 4.7 for low (50 mg/L as $CaCO_3$) and high (200 mg/L as $CaCO_3$) alkalinities, respectively. Similar diagrams have been developed and are continually used to demonstrate controlling species and phases in redox reactions (Schock, 1999; 1981; 1980; AWWARF, 1985; Hem, 1973; and Pourbaix, 1966). Figure 4.6 and Figure 4.7 show the predominance of solid phases controlling soluble lead release at equilibrium for water quality conditions common to drinking as indicated by the shaded areas in those

figures. As demonstrated by Schock, continually refinement and interpretation of these diagrams provides insight into metal release as controlled by solubility of controlling phases and even particle release as lead oxide solid phases are recognized as less soluble more durable than lead carbonates and less likely to break apart than lead carbonate solid phases (Renner, 2004).

Common distribution system water quality conditions in drinking water are shown in Figure 4.6 and Figure 4.7 as the shaded area defined by pH, E and pC_{Pb} . Although lead is immune to corrosion where $Pb_{(s)}$ is predominant, this only occurs in areas of unstable water and below pH 5, which do not exist in drinking water. Consequently, the controlling solid phases for lead at the potential generated by chloramine residual maintenance are lead carbonate ($PbCO_{3(s)}$ or cerussite) and basic lead carbonate ($Pb_3(CO_3)_2(OH)_2$ or hydrocerussite), and is PbO_2 for lead at the potential generated by free chlorine residual maintenance as shown in Figure 4.6 and Figure 4.7.

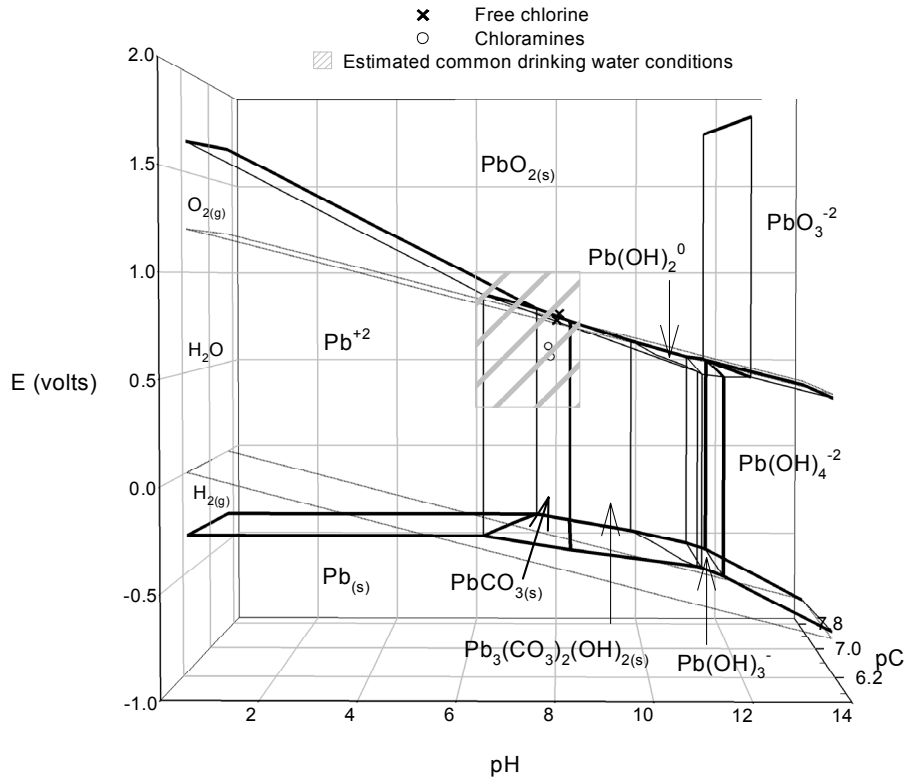


Figure 4.6 Lead potential versus pH and pC_{Pb} showing average total lead release and predominant lead species for groundwater and blended water quality conditions in field studies for free chlorine and chloramines. Alkalinity = 200 mg/L CaCO₃.

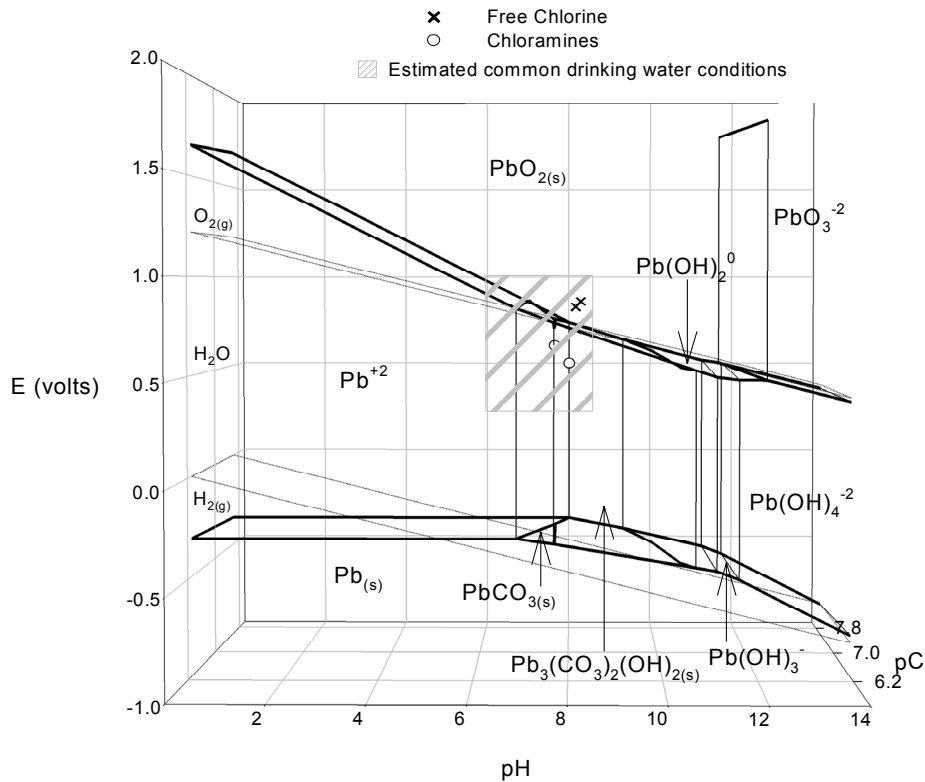


Figure 4.7 Lead potential versus pH and pC_{pb} showing average total lead release and predominant lead species for desalinated water and surface water quality in field studies for free chlorine and chloramines. Alkalinity = 50 mg/L $CaCO_3$.

Investigators have stated that either cerussite or hydrocerussite can control solid phases for lead release to drinking water (Schock, 1989 & 1990; Boffardi, 1995), and recently Shock has suggested that PbO_2 is the controlling solid phase for lead release in the presence of free chlorine (Renner, 2004). X-ray photoelectron spectroscopy (XPS) surface characterization of lead coupons in the blending study revealed PbO_2 , PbO , $PbCO_3$ and $Pb_3(CO_3)_2(OH)_2$ solid phases (Tang, 2003 & 2005); and associated $PbCO_3$ negatively and $Pb_3(CO_3)_2(OH)_2$ positively with total lead release in the presence of chloramines. No association of PbO_2 or PbO was found for the release of total lead in the presence of chloramines. Inclusion of the field data in the predominance diagrams clearly showed that hydrocerussite was the controlling solid phase because of the lower

potential caused by chloramine residual maintenance in the PDSs, which resulted in higher total lead release relative to free chlorine. Conversely, the diagram also clearly showed that PbO_2 was the controlling solid phase because of the higher potential caused by free chlorine residual maintenance in the PDSs, which resulted in lower total lead release relative to chloramines.

The significance of controlling solid films has been noted in the literature as these carbonate solid films may not adequately control lead release and may be disrupted and enhance soluble and particulate lead release due to changes in finished water quality (Leroy, 1993; Lytle, 1993 & 2000; and Schock, 1999; 1990; & 1989). Pb^{+4} release from PbO_2 dissolution at pH 8 and 25 °C is approximately 10^{-40} M at equilibrium, and Pb^{+2} release is approximately 10^{-10} M at equilibrium for cerussite or hydrocerussite at these same conditions for alkalinities of 50 to 200 mg/L CaCO_3 . Although equilibrium is seldom achieved in drinking water, the predicted release of soluble lead from these two solids illustrates the benefits of PbO_2 passivation. PbO_2 has been shown to be predominant to cerussite or hydrocerussite in these studies in the presence of free chlorine, which significantly reduced total lead release.

Figure 4.8 was developed by Tang (2003) to illustrate the soluble lead released at equilibrium (the light plane) and the limitation of mass transfer by diffusion (the dark plane) on lead released from hydrocerussite for varying pH and alkalinity. As Figure 4.8 clearly shows, soluble lead release increases with increasing alkalinity and decreasing pH. Actual data from the literature was included in Figure 4.8 that shows the actual release of dissolved lead was accurately predicted by the hydrocerussite model (Schock, 1990). Tang clearly shows the limitations of diffusion on lead release in the field study.

The lead surface area in the copper coils was simply not large enough to allow lead equilibrium to be achieved in the 6-8 holding periods prior to sample collections. The figure was modified to include total lead release in the presence of free chlorine (clear symbols) and chloramines (dark symbols) for the four different finished waters. As shown in Figure 4.8, the total lead release in the presence of chloramines is greater than the total lead release in the presence of chlorine. The variation in total lead release among sources was attributed to differences in source water quality and particulate release.

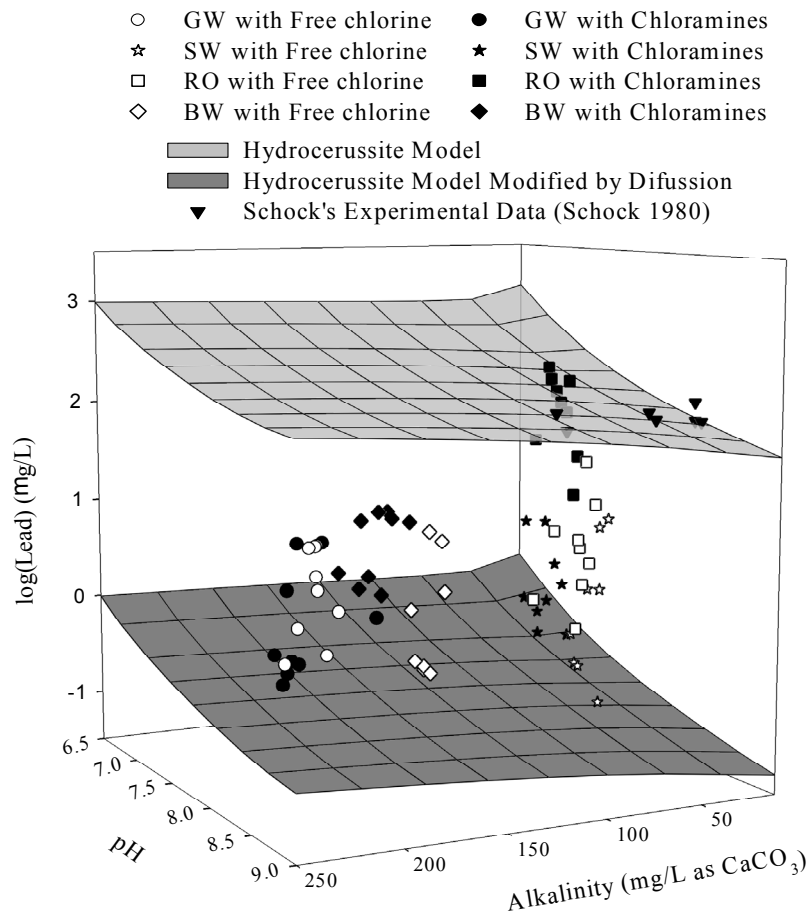


Figure 4.8 Log soluble lead species versus alkalinity and pH assuming cerussite and hydrocerussite controlling solid phases and actual data in the presence of free chlorine and chloramines and from Schock (1999)

5 CONCLUSIONS

- There were no ORP differences among sources in the presence of chloramines or free chlorine. The addition of 150 mg/L of SO_4^{2-} to finished SW or the addition of 106.5 mg/L of Cl⁻ to finished RO did not significantly change the ORP in the presence of chloramines or free chlorine.
- ORP decreased with increasing temperature, which was consistent with the magnitude of the Equilibrium constant as affected by temperature
- Source ORP was greater in the presence of free chlorine than in the presence of chloramines. HPCs and biofilm densities in the presence of chloramines were significantly greater than in the presence of free chlorine for the field study. Differences among water qualities of the four finished waters (alkalinity, sulfates, chlorides, and nitrates) used in the field study did not account for the observed differences in total lead release in the presence of chloramines or free chlorine.
- Chloramine residual produced a lower ORP and a hydrocerussite controlling solid phase, which released more average total lead relative to free chlorine. Conversely, free chlorine produced a higher ORP and a PbO_2 controlling solid phase, which released less average total lead relative to chloramines. The predicted release of soluble lead from hydrocerussite was approximately 10^{-10} M and the predicted release of soluble lead from PbO_2 was approximately 10^{-40} M, which supported the relative orders of total lead release in the presence of chloramines and free chlorine.
- The controlling solid phase as effected by ORP can fundamentally explain the higher lead release in the presence of chloramines relative to free chlorine, but does not eliminate the possibility of increased total lead release with increasing biological activity in the presence of chloramines relative to free chlorine.

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APPENDIX

Table A.1 Field pH

Date	PDS 1 GW	PDS 2 SW	PDS 3 RO	PDS 4 B	PDS 5 GW	PDS 6 SW	PDS 7 RO	PDS 8 B
4/17/03	8.00	8.10	8.34	8.08	7.87	7.92	8.20	7.95
4/24/03	7.93	8.13	8.28	8.04	7.82	7.78	8.25	7.88
5/01/03	8.04	8.25	8.34	8.15	7.92	8.02	8.18	7.95
5/8/2003	8.04	8.13	8.30	8.07	7.82	7.86	8.09	7.87
5/15/03	8.05	8.33	8.37	8.14	8.29	7.97	8.18	7.97
5/21/03	8.05	8.09	8.23	8.08	7.77	7.69	7.96	7.87
5/29/03	8.08	8.29	8.28	8.11	7.86	7.65	8.10	7.97
6/04/03	8.03	8.06	8.07	8.07	7.81	7.55	7.88	7.90
6/11/03	8.05	8.11	8.25	8.05	7.82	7.59	8.00	7.95
6/18/03	8.03	8.34	8.30	8.07	7.68	7.53	7.90	7.82
6/22/03	8.06	7.92	8.23	7.94	7.81	7.46	7.92	7.74
6/24/03	7.99	8.09	8.26	8.16	7.74	7.76	7.95	7.86
6/26/03	8.06	8.26	8.39	8.10	7.80	7.80	7.94	7.94
4/17/03	8.00	8.10	8.34	8.08	7.87	7.92	8.20	7.95

Table A.2 Field Lead Concentration

Date	PDS 1 GW	PDS 2 SW	PDS 3 RO	PDS 4 B	PDS 5 GW	PDS 6 SW	PDS 7 RO	PDS 8 B
04/25/03	3.48	0.70	0.90	0.40	0.40	1.11	40.41	2.34
05/02/03	2.83	2.05	2.50	0.41	0.57	0.61	105.66	11.27
05/09/03	1.31	0.33	6.72	1.60	2.46	2.75	127.58	3.44
05/16/03	1.76	2.13	4.10	2.34	1.80	1.84	16.72	10.25
05/23/03	0.70	0.08	1.80	0.45	0.45	0.49	201.02	1.93
05/30/03	7.58	0.16	5.45	0.53	0.33	0.78	201.23	13.48
06/06/03	0.61	0.33	7.05	0.04	0.61	-0.04	49.59	3.07
06/20/03	7.58	10.41	36.60	6.89	6.07	6.07	254.51	10.16
06/27/03	7.62	8.24	15.29	8.89	6.80	7.17	151.64	13.20

Table A.3 Field Alkalinity Concentration

Date	PDS 1 GW	PDS 2 SW	PDS 3 RO	PDS 4 B	PDS 5 GW	PDS 6 SW	PDS 7 RO	PDS 8 B
4/17/03	204	70	76	152	210	66	72	184
4/24/03	194	70	76	144	204	64	74	170
5/01/03	198	68	76	146	206	66	76	172
5/08/03	208	66	76	152	204	64	74	180
5/15/03	188	66	74	138	180	66	72	148
5/21/03	194	64	96	146	196	64	72	158
5/29/03	204	64	74	152	208	62	70	164
6/04/03	214	64	76	156	210	64	76	166
6/11/03	216	62	72	154	212	64	70	166
6/18/03	198	62	72	136	180	62	70	150
6/22/03	156	78	86	102	158	84	70	124
6/24/03	185	68	76	142	188	76	70	142
6/26/03	200	62	72	144	198	66	68	158
6/29/03	204	70	76	152	210	66	72	184

Table A.4 Field Temperature

Date	PDS 1 GW	PDS 2 SW	PDS 3 RO	PDS 4 B	PDS 5 GW	PDS 6 SW	PDS 7 RO	PDS 8 B
4/25/03	27.0	27.9	27.5	28.0	27.5	27.6	27.5	27.9
5/01/03	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0
5/05/03	30.8	30.8	30.8	30.8	30.8	30.8	30.0	30.0
5/08/03	30.2	30.2	30.2	30.2	30.2	30.2	29.8	29.8
5/12/03	30.6	30.6	30.6	30.6	30.6	30.6	30.2	30.2
5/15/03	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0
5/27/03	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
6/03/03	26.2	26.2	26.2	26.2	26.2	26.2	26.2	26.2
6/04/03	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0
6/13/03	30.1	30.1	30.1	30.1	30.1	30.1	30.1	30.1
6/17/03	28.6	28.6	28.6	28.6	28.6	28.6	28.6	28.3
6/18/03	25.5	25.5	25.5	25.5	25.5	25.5	25.4	25.4
6/19/03	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9
6/22/03	24.4	24.7	24.4	25.1	24.2	24.2	24.9	24.4
6/24/03	28.8	28.8	28.8	28.8	28.8	28.8	28.5	28.5
6/27/03	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.0

Table A.5 Field Sulfate Concentration

Date	PDS 1 GW	PDS 2 SW	PDS 3 RO	PDS 4 B	PDS 5 GW	PDS 6 SW	PDS 7 RO	PDS 8 B
04/18/03	29.0	216.9	3.8	79.5	35.0	215.0	4.7	48.7
04/25/03	4.8	208.8	4.0	61.7	21.9	206.8	4.8	47.6
05/02/03	18.0	213.1	6.7	70.9	22.4	224.2	6.3	45.0
05/09/03	22.8	224.5	4.1	74.9	22.9	225.2	4.6	47.4
05/16/03	5.5	227.1	3.4	62.9	2.6	224.7	4.1	45.2
05/23/03	21.1	217.7	3.6	74.5	25.3	212.2	3.6	55.3
05/30/03	28.1	227.1	4.1	81.8	28.0	221.6	3.9	58.9
06/06/03	25.3	227.0	3.7	80.3	25.8	230.4	3.4	66.1
06/13/03	26.0	231.3	3.1	83.7	26.5	225.2	3.2	60.5
06/20/03	6.3	228.2	3.0	82.0	28.6	262.4	3.8	62.9
06/27/03	28.0	227.8	3.4	85.7	29.6	234.1	5.9	68.3

Table A.6 Field PEPA

Date	Material	PDS 1 GW	PDS 2 SW	PDS 3 RO	PDS 4 B	PDS 5 GW	PDS 6 SW	PDS 7 RO	PDS 8 B
6/26/03	PVC	2.2E+08	1.5E+09	5.0E+08	2.2E+08	4.7E+09	1.2E+09	7.0E+08	4.3E+09
6/26/03	CICL	3.5E+09	5.5E+08	1.2E+09	9.2E+08	5.6E+09	4.5E+09	7.5E+08	2.8E+09
6/26/03	CI	9.7E+08	1.1E+09	1.7E+08	3.3E+08	4.5E+09	9.9E+08	7.9E+08	6.4E+09
6/26/03	G	1.2E+09	1.6E+09	5.6E+08	3.1E+08	1.4E+09	1.5E+09	7.1E+08	4.2E+09

Table A.7 Field Chloride Concentration

Date	PDS 1 GW	PDS 2 SW	PDS 3 RO	PDS 4 B	PDS 5 GW	PDS 6 SW	PDS 7 RO	PDS 8 B
04/18/03	22.9	23.5	80.9	29.5	24.0	26.2	85.9	30.5
04/25/03	17.4	23.5	85.6	27.9	22.6	29.6	91.6	31.1
05/02/03	17.5	24.6	51.4	23.6	20.4	29.3	56.9	24.7
05/09/03	18.1	26.5	76.3	28.0	21.7	29.1	82.9	28.4
05/16/03	18.9	25.4	71.6	27.2	21.4	32.1	79.8	31.3
05/23/03	19.1	25.8	72.7	27.3	23.2	30.7	78.7	31.0
05/30/03	23.1	26.6	79.2	31.9	25.6	31.9	87.2	34.2
06/06/03	23.1	28.9	79.2	32.5	27.3	34.9	87.4	36.1
06/13/03	19.2	25.9	78.6	28.8	26.1	35.1	86.7	35.5
06/20/03	19.5	27.2	76.3	31.2	26.4	33.7	82.7	35.5
06/27/03	21.0	28.1	76.8	29.8	23.3	31.5	82.4	33.9

Table A.8 Field Chlorine Residual Concentration

Date	PDS 1 GW	PDS 2 SW	PDS 3 RO	PDS 4 B	PDS 5 GW	PDS 6 SW	PDS 7 RO	PDS 8 B
4/24/03	1.29	1.81	3.32	1.82	0.44	1.05	0.59	2.46
5/01/03	0.87	1.02	2.50	1.65	0.74	0.49	0.91	1.41
5/08/03	0.25	1.29	2.42	1.11	0.26	0.31	0.39	0.54
5/15/03	0.66	0.92	2.08	1.35	0.27	0.83	0.56	0.76
5/21/03	0.61	1.08	3.06	1.05	0.22	0.10	0.56	0.70
5/29/03	0.76	1.20	2.08	1.38	0.25	0.20	0.71	0.52
6/04/03	0.58	1.26	1.62	1.40	0.15	0.44	0.62	0.54
6/11/03	0.56	1.18	1.85	1.11	0.19	0.23	0.54	0.66
6/18/03	1.12	1.59	3.18	2.17	0.19	0.13	0.61	0.47
6/22/03	1.15	0.66	2.60	1.96	0.28	0.36	0.57	0.67
6/24/03	1.18	1.30	3.18	2.44	0.28	0.24	0.47	0.70
6/26/03	1.05	1.21	3.20	1.62	0.44	1.05	0.59	2.46

Table A.9 Field NO_x-N Concentration

Date	PDS 1	PDS 2	PDS 3	PDS 4	PDS 5	PDS 6	PDS 7	PDS 8
	GW	SW	RO	B	GW	SW	RO	B
5/02/03	0.02	0.12	0.02	0.03	0.13	0.28	0.06	0.08
5/09/03	0.03	0.19	0.03	0.05	0.31	0.46	0.11	0.16
5/16/03	0.02	0.19	0.02	0.04	0.30	0.51	0.26	0.16

Table A.10 Field Ammonia Concentration

Date	PDS 1	PDS 2	PDS 3	PDS 4	PDS 5	PDS 6	PDS 7	PDS 8
	GW	SW	RO	B	GW	SW	RO	B
5/01/03	0.01	0.01	0.00	0.00	0.43	0.60	0.47	0.43
5/09/03	0.02	0.01	0.01	0.01	0.48	0.51	0.58	0.56
5/15/03	0.01	0.01	0.01	0.00	0.45	0.25	0.57	0.58
5/16/03	0.01	0.01	0.01	0.01	0.53	0.30	0.67	0.68

Table A.11 Field HPC

Date	PDS 1	PDS 2	PDS 3	PDS 4	PDS 5	PDS 6	PDS 7	PDS 8
	GW	SW	RO	B	GW	SW	RO	B
4/17/03	1.3E+04	2.2E+04	8.2E+02	3.7E+05	4.6E+05	8.3E+03	2.7E+04	1.3E+04
5/01/03	4.6E+05	7.0E+05	2.5E+05	4.3E+05	9.5E+02	2.5E+02	4.2E+05	9.1E+03
5/08/03	3.3E+03	1.0E+02	5.0E+02	3.5E+02	1.4E+04	9.9E+03	1.1E+04	2.3E+03
5/15/03	4.6E+04	5.0E+01	1.2E+06	3.0E+02	6.8E+03	6.0E+02	2.2E+03	1.6E+03
5/22/03	2.4E+04	1.5E+04	6.0E+05	1.8E+02	6.2E+03	6.9E+03	2.1E+03	1.2E+03
5/29/03	7.0E+02	2.5E+02	5.0E+01	5.0E+01	7.0E+03	1.3E+04	2.1E+03	1.1E+03
6/05/03	1.3E+03	2.0E+02	4.8E+04	1.0E+02	2.9E+05	9.5E+02	2.0E+03	7.5E+02
6/12/03	7.5E+02	2.5E+03	5.5E+02	5.0E+01	3.3E+03	3.6E+03	5.0E+02	1.3E+03
6/19/03	9.0E+02	5.5E+02	3.5E+02	1.0E+02	6.0E+03	5.4E+03	2.7E+03	3.3E+03
6/25/03	1.8E+02	2.7E+02	1.5E+01	1.1E+02	1.0E+04	1.1E+04	5.3E+03	3.1E+03
6/26/03	6.7E+02	4.4E+02	5.9E+02	2.7E+02	7.7E+03	8.0E+03	2.3E+03	3.0E+03
6/27/03	4.5E+02	3.2E+02	3.0E+01	3.9E+02	6.4E+03	2.7E+03	1.5E+03	1.4E+03

Table A. 12 ORP Titration of GW at 5C using Free Chlorine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
5.1	7.46	0.566	0.00
4.9	7.48	0.567	0.01
4.6	7.47	0.569	0.03
4.5	7.48	0.570	0.04
4.2	7.49	0.575	0.05
4.0	7.49	0.582	0.07
3.8	7.49	0.589	0.09
3.7	7.49	0.598	0.11
3.6	7.49	0.605	0.12
3.6	7.49	0.612	0.13
3.5	7.50	0.616	0.15
3.5	7.50	0.625	0.16
3.4	7.50	0.629	0.18
3.4	7.53	0.638	0.20
3.4	7.54	0.645	0.22
3.4	7.53	0.651	0.25
3.5	7.54	0.658	0.27
3.5	7.55	0.664	0.29
3.6	7.56	0.667	0.30
3.6	7.55	0.678	0.33
3.6	7.56	0.678	0.35
3.7	7.56	0.688	0.38
3.8	7.56	0.698	0.41
3.8	7.56	0.704	0.44
3.9	7.56	0.71	0.48
4.0	7.55	0.721	0.52
4.1	7.57	0.73	0.56
4.1	7.56	0.749	0.61
4.2	7.57	0.759	0.65
4.3	7.57	0.769	0.69
4.3	7.57	0.78	0.73
4.4	7.58	0.794	0.79
4.5	7.58	0.806	0.83
4.5	7.58	0.806	0.83
4.6	7.60	0.858	1.19
4.6	7.61	0.879	1.56
4.7	7.61	0.898	1.92
4.7	7.61	0.91	2.28
4.8	7.63	0.925	3.01
4.9	7.65	0.943	4.10
4.9	7.66	0.962	5.55
5.0	7.69	0.983	7.37
5.1	7.71	0.995	9.55
5.2	7.72	0.998	10.64

Table A.13 ORP Titration of GW at 10C using Free Chlorine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
10.9	7.60	0.707	0.00
10.6	7.62	0.704	0.01
10.3	7.62	0.699	0.03
10.0	7.62	0.699	0.04
9.8	7.63	0.696	0.06
9.5	7.63	0.696	0.08
9.2	7.63	0.696	0.11
9.0	7.63	0.697	0.13
8.8	7.64	0.697	0.16
8.7	7.64	0.697	0.19
8.6	7.65	0.698	0.21
8.5	7.66	0.698	0.23
8.3	7.67	0.698	0.26
8.3	7.68	0.699	0.30
8.3	7.67	0.702	0.34
8.4	7.65	0.703	0.37
8.4	7.66	0.705	0.40
8.4	7.67	0.705	0.43
8.5	7.67	0.708	0.47
8.6	7.68	0.710	0.52
8.7	7.70	0.710	0.55
8.8	7.69	0.713	0.59
9.1	7.71	0.713	0.63
9.2	7.70	0.714	0.68
9.2	7.70	0.720	0.71
9.2	7.71	0.722	0.75
9.2	7.71	0.735	0.80
9.1	7.72	0.739	0.83
9.0	7.72	0.742	0.86
8.9	7.72	0.753	0.90
8.8	7.72	0.757	0.93
8.7	7.72	0.761	0.95
8.7	7.73	0.766	0.98
8.7	7.73	0.771	1.01
8.8	7.74	0.776	1.04
8.9	7.74	0.792	1.11
9.1	7.71	0.807	1.16
9.2	7.73	0.814	1.21
9.4	7.72	0.819	1.27
9.5	7.71	0.819	1.27
9.6	7.73	0.860	1.93
10.0	7.73	0.885	2.27
10.1	7.74	0.905	2.60
10.0	7.75	0.915	2.93

ORP Titration of GW at 10 C using Free Chlorine (continued)

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
9.9	7.75	0.927	3.60
9.8	7.75	0.942	3.93
9.6	7.76	0.958	4.60
9.5	7.77	0.980	5.93
9.5	7.79	0.992	6.93
9.6	7.81	1.002	8.60
9.7	7.82	1.010	10.27
9.7	7.84	1.014	11.60
10.0	7.84	1.018	12.27

Table A.14 ORP Titration of GW at 25C using Free Chlorine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
21.8	7.64	0.614	0.00
21.9	7.64	0.612	0.01
22.7	7.54	0.611	0.03
22.8	7.56	0.612	0.05
22.9	7.54	0.613	0.07
22.9	7.55	0.615	0.08
23.0	7.55	0.617	0.09
23.0	7.56	0.620	0.11
23.0	7.56	0.623	0.12
23.1	7.58	0.627	0.13
23.1	7.58	0.630	0.15
23.1	7.58	0.633	0.16
23.1	7.60	0.636	0.17
23.1	7.60	0.640	0.19
23.1	7.61	0.643	0.20
23.1	7.62	0.646	0.21
23.1	7.62	0.649	0.23
23.1	7.62	0.654	0.25
23.1	7.63	0.658	0.27
23.1	7.63	0.661	0.29
23.1	7.64	0.664	0.31
23.1	7.65	0.668	0.33
23.1	7.66	0.674	0.36
23.1	7.66	0.677	0.38
23.0	7.67	0.679	0.40
23.0	7.68	0.683	0.43
23.0	7.68	0.686	0.45
23.0	7.68	0.687	0.48
23.0	7.70	0.691	0.51
22.9	7.71	0.695	0.54
22.9	7.72	0.697	0.57
22.9	7.72	0.697	0.57
22.9	7.74	0.794	0.90
22.9	7.75	0.834	1.22
22.9	7.76	0.861	1.54
22.9	7.77	0.879	1.86
22.9	7.79	0.902	2.50
22.8	7.80	0.927	3.79
22.8	7.83	0.954	6.36
22.9	7.85	0.975	8.29
22.9	7.88	0.987	10.87

Table A.15 ORP Titration of GW at 30C using Free Chlorine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
29.9	7.67	0.460	0.00
30.4	7.69	0.462	0.01
30.9	7.70	0.464	0.03
31.1	7.72	0.465	0.05
31.4	7.72	0.466	0.07
31.6	7.74	0.466	0.10
31.7	7.75	0.468	0.12
31.8	7.76	0.470	0.15
32.0	7.76	0.475	0.17
32.1	7.81	0.478	0.19
32.1	7.82	0.480	0.21
32.0	7.83	0.484	0.24
31.9	7.84	0.486	0.27
31.9	7.83	0.489	0.31
31.8	7.83	0.495	0.35
31.7	7.84	0.498	0.37
31.6	7.84	0.505	0.41
31.5	7.85	0.509	0.44
31.4	7.86	0.519	0.49
31.3	7.85	0.524	0.51
31.2	7.85	0.529	0.55
31.2	7.86	0.536	0.58
31.0	7.86	0.547	0.63
30.9	7.86	0.550	0.65
30.8	7.87	0.556	0.67
30.8	7.87	0.567	0.70
30.5	7.88	0.582	0.75
30.2	7.87	0.593	0.79
30.1	7.88	0.604	0.83
30.0	7.88	0.614	0.86
29.8	7.89	0.620	0.88
29.8	7.89	0.630	0.92
29.6	7.89	0.638	0.95
29.3	7.91	0.642	0.99
29.3	7.91	0.655	1.05
29.2	7.91	0.663	1.09
29.2	7.92	0.671	1.13
29.1	7.92	0.683	1.21
29.1	7.92	0.690	1.27
29.0	7.93	0.699	1.33
29.0	7.93	0.699	1.33
28.9	7.95	0.734	1.65
28.9	7.97	0.751	1.97
28.8	7.98	0.768	2.30

ORP Titration of GW at 30C using Free Chlorine (continued)

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
28.8	7.98	0.784	2.62
29.0	7.99	0.803	2.94
29.6	8.01	0.820	3.27
30.4	8.03	0.830	3.91
30.8	8.05	0.846	4.56
31.2	8.07	0.860	5.21
31.2	8.10	0.873	6.18
31.1	8.12	0.877	7.47
31.0	8.14	0.885	8.44
31.0	8.15	0.890	9.41
30.9	8.17	0.894	10.38
30.9	8.18	0.900	11.03
30.7	8.20	0.903	11.35
30.7	8.21	0.905	11.67
30.6	8.22	0.908	12.32

Table A.16 ORP Titration of GW at 5C using Chloramine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
6.6	8.03	0.611	0.00
6.5	8.03	0.610	0.01
6.4	8.03	0.609	0.01
6.4	8.03	0.609	0.03
6.3	8.03	0.610	0.04
6.2	8.02	0.617	0.07
5.8	8.02	0.621	0.08
5.7	8.03	0.628	0.10
5.4	8.03	0.633	0.12
5.2	8.03	0.641	0.16
4.9	8.03	0.649	0.20
4.7	8.03	0.653	0.23
4.5	8.03	0.656	0.27
4.5	8.03	0.661	0.32
4.3	8.03	0.661	0.32
4.1	8.04	0.674	0.55
3.9	8.04	0.688	1.24
3.9	8.04	0.695	2.39
3.8	8.04	0.697	3.77
3.8	8.04	0.301	5.15
3.8	8.04	0.700	6.99
3.8	8.03	0.224	7.91
3.8	8.03	0.701	9.29
3.8	8.03	0.701	10.67
3.8	8.03	0.701	11.59
3.8	8.03	0.701	12.51

Table A.17 ORP Titration of GW at 10C using Chloramine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
10.5	8.22	0.527	0.00
10.4	8.21	0.534	0.01
10.2	8.21	0.551	0.02
10.0	8.21	0.562	0.02
9.9	8.18	0.574	0.03
10.0	8.18	0.582	0.04
9.9	8.17	0.590	0.05
9.9	8.17	0.595	0.06
9.9	8.17	0.600	0.07
9.9	8.16	0.604	0.07
10.0	8.16	0.608	0.08
10.1	8.16	0.615	0.10
10.0	8.16	0.621	0.12
9.9	8.16	0.625	0.13
9.8	8.16	0.629	0.15
9.7	8.16	0.633	0.17
9.8	8.16	0.638	0.20
9.9	8.15	0.642	0.23
10.0	8.15	0.647	0.28
10.1	8.15	0.650	0.33
10.2	8.15	0.655	0.42
10.4	8.15	0.659	0.50
10.4	8.15	0.659	0.50
10.6	8.15	0.665	0.67
10.7	8.15	0.670	1.00
10.8	8.15	0.674	1.50
10.9	8.14	0.678	2.17
10.9	8.14	0.680	2.83
11.0	8.14	0.681	3.83
11.0	8.13	0.682	5.17
11.1	8.13	0.683	7.17
11.1	8.12	0.683	9.50
11.2	8.12	0.683	11.83

Table A.18 ORP Titration of GW at 25C using Chloramine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
24.7	8.07	0.517	0.00
26.1	8.06	0.542	0.02
25.5	8.06	0.557	0.03
25.4	8.06	0.566	0.03
25.4	8.07	0.574	0.04
25.4	8.08	0.580	0.05
25.5	8.09	0.590	0.07
25.6	8.09	0.599	0.08
25.6	8.10	0.608	0.11
25.7	8.10	0.616	0.14
25.7	8.11	0.623	0.18
25.6	8.11	0.627	0.21
25.5	8.12	0.631	0.24
25.5	8.12	0.636	0.29
25.4	8.13	0.642	0.38
25.4	8.13	0.645	0.46
25.4	8.14	0.645	0.46
25.2	8.14	0.65	0.62
25.1	8.14	0.652	0.79
25.1	8.14	0.655	0.96
25.1	8.14	0.658	1.29
25.2	8.15	0.661	1.96
25.2	8.14	0.664	2.96
25.2	8.14	0.665	4.29
25.3	8.13	0.665	5.96
25.3	8.13	0.665	7.96
25.3	8.12	0.665	10.29
25.3	8.11	0.665	12.96
25.4	8.10	0.665	13.63

Table A.19 ORP Titration of GW at 30C using Chloramine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
29.8	8.1	0.526	0.00
30.2	8.13	0.531	0.01
30.1	8.14	0.542	0.02
30.0	8.15	0.556	0.03
29.9	8.16	0.565	0.05
30.2	8.18	0.571	0.06
30.0	8.20	0.577	0.07
29.9	8.20	0.581	0.07
29.8	8.23	0.585	0.08
29.9	8.22	0.589	0.09
29.9	8.23	0.593	0.10
29.8	8.24	0.599	0.12
29.7	8.25	0.604	0.13
29.7	8.25	0.609	0.15
29.6	8.26	0.612	0.17
29.7	8.25	0.615	0.19
29.8	8.26	0.619	0.22
29.9	8.26	0.624	0.25
30.0	8.26	0.627	0.28
30.0	8.27	0.633	0.33
29.9	8.27	0.637	0.42
29.8	8.27	0.642	0.52
29.8	8.27	0.642	0.52
29.7	8.28	0.647	0.68
29.8	8.27	0.651	0.85
29.9	8.27	0.653	1.02
29.9	8.27	0.655	1.18
29.9	8.28	0.657	1.52
30.0	8.27	0.659	1.85
30.0	8.27	0.661	2.52
30.0	8.26	0.662	3.18
29.9	8.26	0.663	4.18
29.9	8.25	0.663	5.85
29.8	8.23	0.663	7.52
29.7	8.23	0.663	9.85
29.6	8.22	0.664	12.52

Table A.20 ORP Titration of SW at 5C using Free Chlorine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
5.3	7.99	0.615	0.00
5.2	7.99	0.617	0.01
5.2	7.99	0.622	0.03
5.1	7.99	0.626	0.03
5.1	7.99	0.630	0.04
5.1	7.99	0.633	0.05
5.1	7.99	0.639	0.05
5.0	7.98	0.646	0.06
5.0	7.98	0.658	0.07
4.9	7.98	0.666	0.07
4.9	7.98	0.673	0.08
4.8	7.98	0.680	0.08
4.8	7.97	0.688	0.09
4.8	7.97	0.696	0.10
4.8	7.97	0.711	0.12
4.8	7.97	0.718	0.12
4.8	7.97	0.724	0.13
4.9	7.96	0.733	0.14
4.9	7.96	0.74	0.15
4.9	7.97	0.746	0.16
4.9	7.97	0.751	0.16
5.0	7.96	0.757	0.17
5.0	7.96	0.763	0.18
5.1	7.96	0.768	0.18
5.2	7.96	0.773	0.19
5.3	7.96	0.779	0.20
5.2	7.96	0.784	0.20
5.0	7.96	0.789	0.21
4.9	7.96	0.794	0.22
4.8	7.96	0.798	0.22
4.7	7.96	0.804	0.23
4.9	7.95	0.812	0.24
5.0	7.96	0.815	0.25
5.0	7.96	0.820	0.26
5.1	7.96	0.825	0.27
5.1	7.96	0.831	0.29
5.2	7.96	0.835	0.30
5.1	7.96	0.839	0.32
5.1	7.95	0.846	0.34
4.9	7.95	0.855	0.36
4.8	7.95	0.859	0.38
4.7	7.95	0.864	0.41
4.7	7.96	0.869	0.43
4.8	7.96	0.873	0.46

ORP Titration of SW at 5C using Free Chlorine (continued)

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
4.9	7.95	0.878	0.48
4.9	7.95	0.878	0.48
4.7	7.97	0.907	0.80
4.7	7.99	0.920	1.12
4.8	8.02	0.928	1.44
4.8	8.02	0.938	1.76
4.9	8.04	0.946	2.08
5.0	8.04	0.952	2.39
5.2	8.06	0.961	3.35
5.3	8.09	0.969	4.30
5.5	8.14	0.980	6.21
5.6	8.18	0.986	8.12
5.7	8.20	0.992	10.03

Table A.21 ORP Titration of SW at 15C using Free Chlorine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
14.9	7.87	0.577	0.00
15.3	7.88	0.576	0.01
15.6	7.88	0.575	0.01
15.4	7.88	0.574	0.02
14.7	7.89	0.575	0.03
14.0	7.89	0.575	0.03
14.0	7.89	0.576	0.04
14.0	7.88	0.577	0.05
14.1	7.89	0.579	0.05
14.2	7.89	0.581	0.06
14.3	7.90	0.584	0.07
14.6	7.90	0.588	0.07
14.3	7.90	0.592	0.08
14.1	7.90	0.596	0.08
14.0	7.90	0.600	0.09
13.9	7.89	0.607	0.10
14.2	7.90	0.614	0.10
14.3	7.90	0.621	0.11
14.6	7.91	0.630	0.12
14.9	7.91	0.638	0.12
15.1	7.92	0.643	0.13
15.3	7.91	0.649	0.14
15.3	7.91	0.655	0.14
15.4	7.91	0.662	0.15
15.4	7.92	0.670	0.16
15.5	7.92	0.683	0.17
15.5	7.92	0.690	0.18
15.2	7.93	0.696	0.18
15.0	7.93	0.710	0.20
14.5	7.94	0.717	0.20
14.3	7.93	0.721	0.21
14.1	7.93	0.726	0.22
14.1	7.94	0.731	0.22
14.2	7.94	0.736	0.23
14.3	7.95	0.740	0.24
14.4	7.94	0.744	0.24
14.5	7.95	0.747	0.25
14.6	7.95	0.754	0.26
14.7	7.95	0.762	0.27
14.9	7.95	0.767	0.29
15.0	7.95	0.773	0.30
15.1	7.96	0.778	0.31
15.2	7.96	0.783	0.33
15.3	7.97	0.787	0.34

ORP Titration of SW at 15C using Free Chlorine (continued)

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
15.4	7.96	0.793	0.36
15.5	7.96	0.797	0.38
15.5	7.97	0.803	0.41
15.4	7.96	0.810	0.44
15.4	7.96	0.810	0.44
14.5	7.99	0.858	1.07
14.4	8.01	0.870	1.39
14.4	8.01	0.884	1.71
14.4	8.02	0.893	2.03
14.6	8.03	0.901	2.35
14.7	8.04	0.911	2.98
14.7	8.05	0.919	3.94
14.8	8.09	0.927	4.89
14.9	8.13	0.932	6.17
15.1	8.16	0.937	8.08
15.1	8.19	0.942	10.31

Table A.22 ORP Titration of SW at 25C using Free Chlorine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
22.6	7.56	0.606	0.00
22.6	7.58	0.605	0.01
22.6	7.59	0.606	0.02
22.6	7.59	0.608	0.04
22.6	7.60	0.613	0.05
22.6	7.60	0.614	0.05
22.6	7.61	0.624	0.07
22.6	7.62	0.632	0.08
22.6	7.63	0.636	0.09
22.6	7.64	0.639	0.09
22.7	7.64	0.644	0.10
22.7	7.65	0.656	0.11
22.7	7.66	0.676	0.13
22.7	7.67	0.686	0.14
22.7	7.68	0.695	0.15
22.7	7.68	0.703	0.16
22.8	7.69	0.710	0.18
22.8	7.70	0.718	0.19
22.8	7.70	0.724	0.20
22.9	7.71	0.73	0.21
22.9	7.71	0.736	0.22
22.9	7.71	0.743	0.24
22.9	7.71	0.748	0.26
23.0	7.72	0.757	0.28
23.0	7.72	0.764	0.30
23.0	7.71	0.772	0.34
23.1	7.71	0.780	0.37
23.1	7.72	0.789	0.44
23.1	7.72	0.789	0.44
23.2	7.72	0.825	0.78
23.2	7.74	0.843	1.11
23.3	7.75	0.855	1.44
23.4	7.77	0.865	1.78
23.4	7.79	0.873	2.11
23.4	7.82	0.885	2.78
23.5	7.88	0.905	6.11
23.5	7.94	0.916	9.11
23.5	7.99	0.923	12.11

Table A.23 ORP Titration of SW at 30C using Free Chlorine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
29.8	7.78	0.642	0.00
29.7	7.77	0.635	0.01
29.7	7.78	0.627	0.01
29.8	7.79	0.622	0.02
29.9	7.80	0.615	0.02
29.8	7.80	0.616	0.04
30.0	7.81	0.617	0.05
30.1	7.81	0.619	0.06
30.1	7.82	0.620	0.07
30.1	7.81	0.622	0.07
30.1	7.83	0.623	0.08
30.1	7.82	0.624	0.09
30.0	7.83	0.630	0.10
30.0	7.84	0.635	0.11
30.0	7.84	0.639	0.11
30.0	7.85	0.642	0.12
30.0	7.86	0.647	0.12
30.0	7.86	0.650	0.13
29.9	7.87	0.659	0.14
29.9	7.87	0.662	0.15
29.8	7.87	0.668	0.16
29.8	7.88	0.671	0.16
29.8	7.89	0.680	0.17
29.7	7.90	0.691	0.19
29.8	7.89	0.701	0.20
30.0	7.90	0.710	0.21
30.0	7.91	0.716	0.22
29.9	7.92	0.723	0.24
29.9	7.92	0.730	0.25
29.7	7.93	0.736	0.26
29.6	7.92	0.740	0.27
29.7	7.93	0.745	0.29
29.8	7.93	0.750	0.30
29.8	7.93	0.754	0.31
29.7	7.94	0.761	0.33
29.6	7.95	0.767	0.35
30.2	7.96	0.771	0.37
30.2	7.95	0.773	0.39
30.1	7.95	0.779	0.42
30.1	7.95	0.779	0.42
29.8	7.99	0.822	0.75
29.8	8.00	0.844	1.07
30.2	8.02	0.863	1.40
29.9	8.05	0.872	1.73

ORP Titration of SW at 30C using Free Chlorine (continued)

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
29.8	8.06	0.879	2.05
29.7	8.07	0.885	2.38
29.6	8.08	0.892	3.36
29.6	8.10	0.900	4.34
29.8	8.12	0.906	5.32
30.1	8.13	0.912	6.95
29.9	8.15	0.919	8.59

Table A.24 ORP Titration of SW at 5C using Chloramine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
5.5	7.95	0.570	0.00
5.5	7.95	0.571	0.01
5.5	7.95	0.575	0.01
5.5	7.95	0.582	0.02
5.4	7.95	0.592	0.03
5.4	7.94	0.596	0.04
5.4	7.94	0.602	0.04
5.4	7.94	0.606	0.05
5.4	7.94	0.611	0.06
5.4	7.94	0.615	0.06
5.4	7.94	0.618	0.07
5.3	7.94	0.621	0.08
5.3	7.94	0.627	0.09
5.2	7.94	0.631	0.10
5.1	7.93	0.636	0.11
5.1	7.94	0.640	0.13
5.0	7.93	0.643	0.14
5.0	7.93	0.647	0.15
5.0	7.93	0.651	0.18
5.0	7.93	0.654	0.20
5.0	7.93	0.659	0.24
5.0	7.93	0.664	0.28
5.1	7.93	0.669	0.33
5.2	7.92	0.674	0.38
5.3	7.93	0.678	0.44
5.3	7.93	0.678	0.44
5.4	7.93	0.688	0.67
5.5	7.93	0.694	0.90
5.6	7.93	0.700	1.36
5.6	7.93	0.705	1.82
5.7	7.93	0.71	2.74
5.7	7.93	0.714	3.66
5.7	7.92	0.717	5.04
5.7	7.92	0.719	6.88
5.7	7.91	0.721	9.18
5.7	7.91	0.722	11.94

Table A.25 ORP Titration of SW at 10C using Chloramine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
10.5	7.86	0.573	0.00
10.2	7.86	0.575	0.01
9.5	7.87	0.585	0.02
9.1	7.87	0.591	0.03
9.2	7.87	0.597	0.04
9.4	7.88	0.604	0.05
9.4	7.87	0.610	0.06
9.4	7.88	0.614	0.07
9.4	7.88	0.619	0.07
9.4	7.87	0.623	0.08
9.4	7.88	0.626	0.09
9.5	7.88	0.630	0.10
9.5	7.89	0.635	0.12
9.7	7.88	0.639	0.13
9.8	7.89	0.643	0.15
9.8	7.89	0.647	0.17
9.8	7.88	0.650	0.18
9.8	7.90	0.653	0.20
9.8	7.90	0.657	0.23
9.8	7.90	0.659	0.25
9.8	7.90	0.664	0.32
9.8	7.91	0.668	0.38
9.9	7.91	0.673	0.45
9.9	7.91	0.676	0.55
9.9	7.91	0.679	0.65
9.9	7.91	0.679	0.65
10.0	7.91	0.685	0.90
10.0	7.91	0.689	1.15
10.0	7.90	0.692	1.40
10.1	7.90	0.694	1.65
10.1	7.91	0.697	2.15
10.1	7.90	0.699	3.15
10.2	7.90	0.701	4.65
10.3	7.91	0.703	7.15
10.3	7.90	0.703	9.15
10.4	7.89	0.704	11.65

Table A.26 ORP Titration of SW at 25C using Chloramine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
25.3	7.67	0.549	0.00
25.4	7.67	0.553	0.01
25.5	7.69	0.564	0.02
25.6	7.71	0.575	0.03
25.6	7.76	0.582	0.04
25.6	7.83	0.593	0.05
25.5	7.85	0.600	0.06
25.5	7.87	0.606	0.07
25.4	7.86	0.610	0.08
25.4	7.86	0.613	0.08
25.3	7.86	0.619	0.09
25.3	7.86	0.622	0.10
25.2	7.86	0.626	0.11
25.2	7.87	0.629	0.12
25.1	7.87	0.631	0.13
25.1	7.87	0.633	0.13
25.1	7.88	0.635	0.14
25.0	7.88	0.638	0.15
25.0	7.89	0.639	0.16
25.0	7.88	0.642	0.18
24.9	7.89	0.645	0.19
24.9	7.89	0.649	0.22
24.8	7.90	0.653	0.25
24.8	7.89	0.658	0.30
24.7	7.90	0.663	0.38
24.7	7.90	0.663	0.38
24.6	7.91	0.669	0.88
24.5	7.92	0.673	1.38
24.5	7.92	0.675	1.88
24.4	7.92	0.679	2.88
24.4	7.91	0.683	4.88
24.4	7.91	0.685	6.63
24.3	7.91	0.686	8.38
24.3	7.9	0.687	8.88

Table A.27 ORP Titration of SW at 30C using Chloramine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
29.4	7.84	0.550	0.00
31.5	7.87	0.555	0.01
32.9	7.88	0.564	0.03
33.3	7.89	0.578	0.04
33.0	7.92	0.591	0.06
32.7	7.94	0.600	0.07
32.0	7.95	0.609	0.09
31.8	8.00	0.617	0.11
31.5	8.00	0.624	0.14
31.3	8.02	0.632	0.18
30.8	8.02	0.641	0.25
30.8	8.02	0.641	0.25
30.4	8.04	0.655	0.50
30.2	8.04	0.662	0.74
29.9	8.05	0.669	1.23
29.7	8.05	0.677	2.21
29.6	8.05	0.681	4.17
29.5	8.03	0.684	8.09
29.5	8.03	0.685	10.05
29.4	8.02	0.686	11.52
29.4	8.02	0.686	12.99

Table A.28 ORP Titration of SW at 25C using Free Chlorine with 50 mg/L SO₄⁻²

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
23.5	7.97	0.587	0.00
23.8	7.97	0.585	0.01
24.1	7.98	0.586	0.02
24.5	7.98	0.588	0.04
24.7	7.98	0.593	0.05
25.0	7.98	0.595	0.07
25.1	7.98	0.600	0.08
25.5	7.99	0.607	0.09
25.6	7.99	0.615	0.11
25.9	7.99	0.625	0.12
26.0	7.99	0.645	0.14
26.2	8.00	0.662	0.16
26.4	8.01	0.676	0.18
26.4	8.01	0.689	0.20
26.4	8.01	0.703	0.23
26.4	8.01	0.714	0.25
26.3	8.02	0.723	0.28
26.3	8.02	0.734	0.32
26.2	8.03	0.744	0.36
26.1	8.04	0.754	0.41
26.0	8.04	0.764	0.48
25.9	8.05	0.772	0.55
25.9	8.05	0.772	0.55
25.8	8.05	0.796	0.90
25.5	8.06	0.814	1.25
25.5	8.06	0.832	1.60
25.2	8.08	0.844	1.95
25.2	8.09	0.853	2.30
25.3	8.10	0.864	3.00
25.4	8.13	0.876	4.05
25.4	8.16	0.884	5.45
25.5	8.20	0.893	7.55
25.5	8.22	0.901	9.65
25.6	8.24	0.905	11.05
25.6	8.26	0.906	12.45

Table A.29 ORP Titration of SW at 25C using Free Chlorine with 100 mg/L SO₄⁻²

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
28.4	7.86	0.562	0.00
28.0	7.88	0.562	0.01
27.7	7.88	0.565	0.03
27.4	7.88	0.574	0.05
26.9	7.89	0.596	0.07
26.6	7.89	0.621	0.10
26.4	7.91	0.661	0.13
26.1	7.92	0.691	0.17
25.9	7.94	0.718	0.21
25.8	7.94	0.736	0.25
25.6	7.95	0.751	0.29
25.5	7.96	0.764	0.33
25.4	7.97	0.773	0.37
25.3	7.97	0.784	0.41
25.2	7.98	0.794	0.47
25.1	7.98	0.807	0.57
25.0	7.99	0.823	0.70
25.0	7.99	0.823	0.70
24.9	8.01	0.844	1.06
24.8	8.03	0.874	2.14
24.6	8.06	0.890	3.22
24.5	8.09	0.904	5.38
24.5	8.14	0.914	8.26
24.4	8.18	0.921	11.50

Table A.30 ORP Titration of SW at 25C using Free Chlorine with 150 mg/L SO₄⁻²

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
20.7	7.79	0.525	0.00
20.7	7.79	0.525	0.01
20.7	7.79	0.526	0.01
20.7	7.79	0.527	0.02
20.8	7.80	0.529	0.03
20.8	7.79	0.532	0.03
20.8	7.79	0.535	0.04
20.8	7.80	0.540	0.05
20.8	7.79	0.544	0.05
20.8	7.80	0.549	0.06
20.9	7.80	0.554	0.07
20.9	7.80	0.559	0.07
20.9	7.80	0.565	0.08
20.9	7.80	0.571	0.09
20.9	7.79	0.576	0.09
21.0	7.80	0.581	0.10
21.0	7.80	0.587	0.11
21.0	7.80	0.593	0.11
21.0	7.80	0.599	0.12
21.1	7.80	0.605	0.13
21.1	7.80	0.611	0.13
21.1	7.81	0.622	0.15
21.1	7.80	0.635	0.16
21.1	7.80	0.645	0.17
21.2	7.81	0.656	0.19
21.2	7.80	0.666	0.20
21.2	7.81	0.675	0.21
21.3	7.80	0.683	0.23
21.3	7.81	0.691	0.24
21.3	7.81	0.698	0.25
21.3	7.81	0.705	0.27
21.4	7.81	0.711	0.28
21.4	7.81	0.718	0.29
21.4	7.80	0.728	0.31
21.5	7.81	0.735	0.33
21.5	7.81	0.742	0.35
21.5	7.82	0.749	0.37
21.5	7.82	0.755	0.40
21.6	7.82	0.762	0.43
21.6	7.83	0.771	0.47
21.6	7.83	0.771	0.47
21.6	7.83	0.800	0.78
21.7	7.85	0.829	1.10
21.7	7.87	0.849	1.42
21.7	7.86	0.867	1.73
21.8	7.87	0.874	2.05

ORP Titration of SW at 25C using Free Chlorine with 150 mg/L SO_4^{-2} (continued)

Temperature °C	pH	Volts (SHE)	mg/L Cl_2 added
22.1	7.89	0.881	2.68
22.9	7.90	0.889	3.63
23.7	7.93	0.896	4.90
24.3	7.96	0.902	6.17
24.9	8.00	0.908	8.07
25.0	8.03	0.912	9.33
25.1	8.06	0.915	10.92
25.3	8.08	0.918	11.55

Table A.31 ORP Titration of SW at 25C using Chloramine with 50 mg/L SO₄⁻²

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
24.5	7.98	0.526	0.00
24.5	7.98	0.530	0.01
24.6	7.98	0.545	0.02
24.9	7.98	0.554	0.03
25.0	7.98	0.563	0.03
25.0	7.98	0.569	0.04
25.0	7.99	0.576	0.04
25.0	7.99	0.581	0.05
25.1	7.99	0.586	0.06
25.2	7.99	0.590	0.06
25.3	7.99	0.594	0.07
25.3	7.99	0.597	0.08
25.4	7.99	0.602	0.09
25.4	7.99	0.607	0.10
25.3	7.99	0.612	0.11
25.3	7.99	0.615	0.13
25.3	8.00	0.620	0.15
25.3	8.00	0.628	0.19
25.2	8.00	0.634	0.24
25.1	8.00	0.640	0.29
25.1	8.00	0.645	0.35
25.1	8.00	0.645	0.35
24.9	8.00	0.656	0.58
24.9	8.00	0.666	1.04
24.9	8.00	0.674	1.73
24.8	8.00	0.678	2.65
24.8	7.99	0.682	4.03
24.8	7.99	0.684	5.87
24.7	7.98	0.685	8.40
24.7	7.96	0.687	10.47
24.6	7.95	0.688	12.31

Table A.32 ORP Titration of SW at 25C using Chloramine with 100 mg/L SO₄⁻²

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
23.4	7.95	0.568	0.00
24.1	7.95	0.569	0.01
24.5	7.95	0.572	0.02
25.1	7.96	0.579	0.03
25.3	7.96	0.591	0.04
25.6	7.97	0.601	0.05
25.6	7.97	0.609	0.06
25.6	7.98	0.617	0.08
25.5	7.99	0.626	0.11
25.5	7.99	0.634	0.15
25.4	7.99	0.640	0.18
25.3	8.00	0.646	0.23
25.3	8.00	0.651	0.29
25.2	8.00	0.656	0.37
25.2	8.00	0.656	0.37
25.1	8.00	0.665	0.60
25.1	8.00	0.669	0.83
25.1	8.00	0.675	1.29
25.0	8.00	0.680	1.98
25.0	8.00	0.682	2.67
25.0	7.99	0.685	4.05
24.9	7.98	0.686	6.35
24.9	7.97	0.687	8.65
24.9	7.95	0.688	11.87
24.8	7.94	0.688	13.25

Table A.33 ORP Titration of SW at 25C using Chloramine with 150 mg/L SO₄⁻²

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
24.6	8.06	0.533	0.00
24.7	8.06	0.537	0.01
24.8	8.07	0.546	0.01
24.9	8.07	0.555	0.02
24.9	8.07	0.564	0.03
25.0	8.07	0.573	0.03
25.0	8.07	0.579	0.04
25.1	8.07	0.586	0.04
25.1	8.07	0.591	0.05
25.2	8.08	0.597	0.06
25.2	8.08	0.601	0.06
25.2	8.08	0.606	0.07
25.2	8.08	0.610	0.08
25.2	8.08	0.613	0.08
25.1	8.08	0.616	0.09
25.1	8.09	0.620	0.10
25.0	8.08	0.624	0.11
25.0	8.08	0.629	0.13
25.0	8.08	0.633	0.15
24.9	8.08	0.638	0.18
24.9	8.08	0.643	0.22
24.8	8.08	0.649	0.27
24.8	8.08	0.654	0.32
24.8	8.09	0.659	0.38
24.8	8.09	0.659	0.38
24.6	8.09	0.673	0.84
24.6	8.09	0.681	1.30
24.7	8.09	0.686	1.76
24.8	8.08	0.688	2.22
24.8	8.08	0.69	2.91
24.9	8.08	0.691	3.60
24.9	8.07	0.692	4.52
24.9	8.06	0.693	5.90
24.9	8.05	0.694	7.74
24.9	8.04	0.695	10.04
24.9	8.03	0.696	12.34
24.9	8.01	0.697	14.64

Table A.34 ORP Titration of RO at 5C using Free Chlorine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
5.5	7.67	0.722	0.00
5.5	7.67	0.720	0.01
5.4	7.67	0.716	0.01
5.2	7.66	0.710	0.01
5.1	7.65	0.708	0.03
5.1	7.65	0.705	0.03
5.0	7.65	0.699	0.05
4.9	7.63	0.694	0.06
4.8	7.61	0.695	0.09
4.8	7.60	0.695	0.11
4.7	7.60	0.699	0.13
4.7	7.59	0.703	0.14
4.7	7.58	0.711	0.15
4.6	7.57	0.717	0.16
4.5	7.55	0.722	0.17
4.4	7.55	0.734	0.18
4.4	7.55	0.74	0.19
4.4	7.54	0.748	0.19
4.4	7.55	0.754	0.20
4.5	7.54	0.758	0.21
4.6	7.54	0.762	0.21
4.7	7.54	0.767	0.22
4.7	7.55	0.769	0.23
4.7	7.55	0.777	0.24
4.7	7.55	0.781	0.25
4.7	7.55	0.785	0.26
4.7	7.56	0.789	0.26
4.7	7.57	0.794	0.28
4.8	7.56	0.799	0.28
4.9	7.58	0.802	0.29
4.9	7.57	0.806	0.30
4.9	7.57	0.809	0.30
5.0	7.68	0.813	0.32
5.0	7.57	0.819	0.33
5.1	7.56	0.828	0.35
5.1	7.57	0.833	0.36
5.1	7.57	0.838	0.37
4.9	7.57	0.845	0.39
4.9	7.57	0.849	0.40
5	7.58	0.853	0.41
4.9	7.58	0.858	0.42
4.7	7.58	0.86	0.44
4.7	7.58	0.864	0.45
4.8	7.58	0.871	0.48

ORP Titration of RO at 5C using Free Chlorine (continued)

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
5.0	7.58	0.879	0.51
5.2	7.58	0.887	0.57
5.2	7.58	0.887	0.57
5.2	7.64	0.917	2.50
5.2	7.66	0.935	3.14
5.2	7.71	0.945	4.10
5.3	7.74	0.954	4.75
5.3	7.77	0.961	6.03
5.4	7.81	0.967	7.64
5.5	7.84	0.970	8.93
5.5	7.86	0.974	10.22

Table A. 35 ORP Titration of RO at 15C using Free Chlorine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
14.5	7.44	0.631	0.00
14.6	7.44	0.634	0.01
14.5	7.44	0.636	0.01
14.4	7.46	0.641	0.02
14.6	7.47	0.646	0.02
14.8	7.47	0.652	0.03
15.0	7.47	0.666	0.04
15.2	7.45	0.683	0.05
15.2	7.44	0.701	0.06
15.2	7.45	0.720	0.06
14.7	7.46	0.737	0.07
14.5	7.46	0.758	0.07
14.6	7.46	0.770	0.08
14.7	7.46	0.780	0.09
14.8	7.50	0.791	0.09
14.9	7.52	0.801	0.11
15.0	7.52	0.814	0.11
15.1	7.51	0.826	0.12
15.2	7.49	0.835	0.12
15.3	7.48	0.842	0.13
15.3	7.49	0.850	0.14
15.3	7.48	0.856	0.14
15.3	7.49	0.861	0.16
15.3	7.50	0.864	0.16
15.4	7.50	0.871	0.17
15.4	7.50	0.878	0.18
15.1	7.50	0.885	0.19
14.7	7.50	0.893	0.20
14.6	7.51	0.898	0.22
14.5	7.52	0.902	0.23
14.5	7.51	0.906	0.25
14.5	7.51	0.910	0.27
14.6	7.52	0.914	0.30
14.6	7.52	0.914	0.30
14.7	7.55	0.935	0.62
14.8	7.57	0.943	0.95
14.9	7.59	0.950	1.28
15.0	7.61	0.955	1.60
15.1	7.69	0.963	3.56
15.2	7.74	0.972	5.52
15.4	7.80	0.976	7.48
15.5	7.86	0.980	10.10

Table A.36 ORP Titration of RO at 25C using Free Chlorine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
22.7	7.88	0.525	0.00
22.6	7.89	0.524	0.01
22.6	7.89	0.526	0.01
22.6	7.90	0.529	0.02
22.6	7.89	0.532	0.02
22.6	7.89	0.538	0.03
22.6	7.89	0.544	0.04
22.6	7.90	0.552	0.04
22.6	7.90	0.562	0.05
22.6	7.90	0.573	0.05
22.7	7.89	0.584	0.06
22.7	7.89	0.594	0.07
22.7	7.88	0.605	0.07
22.7	7.88	0.624	0.08
22.7	7.88	0.641	0.10
22.7	7.88	0.660	0.11
22.8	7.88	0.671	0.12
22.8	7.86	0.680	0.13
22.8	7.85	0.686	0.13
22.9	7.86	0.696	0.14
22.9	7.87	0.704	0.16
22.9	7.86	0.714	0.17
23.0	7.85	0.723	0.18
23.0	7.86	0.735	0.20
23.1	7.82	0.754	0.23
23.1	7.81	0.768	0.25
23.2	7.81	0.782	0.29
23.3	7.81	0.792	0.30
23.3	7.78	0.800	0.33
23.3	7.77	0.812	0.38
23.3	7.76	0.819	0.42
23.3	7.76	0.819	0.42
23.4	7.78	0.847	0.75
23.5	7.78	0.857	1.08
23.5	7.82	0.867	1.75
23.5	7.60	0.878	3.42
23.5	7.90	0.890	5.75
23.6	7.96	0.897	7.75
23.6	8.02	0.902	10.42

Table A.37 ORP Titration of RO at 30C using Free Chlorine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
31.0	7.78	0.533	0.00
30.7	7.52	0.537	0.01
30.6	7.53	0.545	0.01
30.5	7.53	0.553	0.02
30.4	7.52	0.563	0.02
30.3	7.53	0.571	0.03
30.2	7.53	0.580	0.04
30.2	7.53	0.587	0.04
30.1	7.53	0.595	0.05
30.0	7.54	0.603	0.05
29.9	7.54	0.612	0.06
29.9	7.54	0.621	0.07
29.8	7.54	0.630	0.07
29.8	7.55	0.640	0.08
29.7	7.56	0.650	0.08
29.7	7.55	0.660	0.09
29.6	7.56	0.669	0.10
29.6	7.56	0.678	0.10
29.5	7.56	0.685	0.11
29.4	7.56	0.691	0.11
29.7	7.55	0.697	0.12
29.6	7.55	0.705	0.13
29.7	7.55	0.712	0.14
29.6	7.55	0.718	0.14
29.6	7.56	0.725	0.15
29.6	7.55	0.728	0.16
29.8	7.55	0.733	0.16
29.7	7.56	0.736	0.17
29.7	7.56	0.74	0.17
29.7	7.56	0.746	0.18
29.7	7.56	0.752	0.18
29.7	7.56	0.757	0.19
29.6	7.55	0.763	0.20
29.5	7.55	0.769	0.21
29.7	7.54	0.774	0.21
29.9	7.54	0.777	0.22
29.8	7.54	0.787	0.23
29.7	7.53	0.804	0.27
29.6	7.53	0.811	0.28
29.5	7.54	0.814	0.29
29.6	7.53	0.819	0.30
29.6	7.54	0.824	0.32
29.5	7.54	0.829	0.33
29.6	7.54	0.832	0.34

ORP Titration of RO at 30C using Free Chlorine (continued)

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
29.7	7.55	0.835	0.35
29.7	7.55	0.837	0.36
29.7	7.55	0.837	0.36
29.6	7.59	0.852	0.69
29.6	7.61	0.862	1.02
29.5	7.64	0.868	1.34
29.7	7.64	0.872	1.67
29.9	7.71	0.883	3.63
29.8	7.80	0.891	5.59
29.7	7.83	0.896	7.88

Table A.38 ORP Titration of RO at 5C using Chloramine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
6.9	7.64	0.644	0.00
6.7	7.64	0.644	0.01
6.6	7.64	0.645	0.03
6.3	7.64	0.649	0.05
5.9	7.64	0.655	0.07
5.3	7.63	0.670	0.10
5.0	7.63	0.678	0.12
4.9	7.63	0.682	0.15
4.9	7.62	0.686	0.17
4.8	7.62	0.692	0.21
4.7	7.63	0.694	0.25
4.7	7.62	0.696	0.27
4.7	7.62	0.698	0.35
4.7	7.62	0.698	0.35
4.6	7.62	0.705	0.53
4.5	7.62	0.713	0.71
4.5	7.62	0.720	1.60
4.5	7.61	0.723	2.31
4.5	7.61	0.725	3.38
4.5	7.60	0.726	4.81
4.5	7.60	0.727	6.59
4.5	7.59	0.728	8.37
4.5	7.59	0.728	9.80
4.5	7.59	0.728	10.87

Table A.39 ORP Titration of RO at 10C using Chloramine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
11.6	7.29	0.421	0.00
11.4	7.3	0.427	0.01
11.0	7.29	0.442	0.03
9.2	7.31	0.463	0.04
8.9	7.32	0.480	0.06
8.5	7.33	0.502	0.08
8.5	7.31	0.524	0.12
8.6	7.32	0.547	0.16
9.0	7.34	0.566	0.20
9.5	7.36	0.576	0.25
9.8	7.37	0.582	0.30
9.7	7.38	0.595	0.43
9.6	7.39	0.614	0.63
9.6	7.39	0.614	0.63
9.4	7.41	0.621	0.94
9.5	7.42	0.631	1.57
9.6	7.42	0.644	2.19
9.7	7.43	0.661	7.21
9.9	7.44	0.672	12.85

Table A.40 ORP Titration of RO at 25C using Chloramine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
23.9	7.62	0.523	0.00
24.4	7.62	0.524	0.03
24.5	7.64	0.527	0.04
24.6	7.65	0.530	0.05
24.6	7.65	0.533	0.06
24.6	7.64	0.536	0.08
24.6	7.67	0.540	0.09
24.6	7.66	0.543	0.10
24.6	7.66	0.546	0.12
24.5	7.65	0.551	0.13
24.5	7.66	0.555	0.14
24.5	7.67	0.560	0.16
24.4	7.68	0.564	0.17
24.4	7.68	0.567	0.19
24.4	7.69	0.570	0.21
24.3	7.69	0.573	0.22
24.3	7.68	0.576	0.23
24.3	7.69	0.579	0.25
24.3	7.70	0.581	0.27
24.2	7.73	0.583	0.28
24.2	7.71	0.586	0.31
24.1	7.72	0.590	0.34
24.1	7.72	0.592	0.36
24.1	7.73	0.595	0.40
24.0	7.73	0.598	0.44
24.0	7.75	0.604	0.50
23.7	7.73	0.620	0.50
23.7	7.73	0.620	0.84
23.8	7.72	0.626	1.17
23.8	7.74	0.634	1.84
23.8	7.72	0.644	3.17
23.8	7.72	0.651	4.84
23.8	7.73	0.658	6.50
23.8	7.74	0.663	8.50
23.7	7.75	0.668	10.50
23.7	7.76	0.670	11.17

Table A.41 ORP Titration of RO at 30C using Chloramine

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
30.0	7.45	0.486	0.00
29.9	7.51	0.493	0.01
29.8	7.50	0.502	0.03
29.9	7.55	0.523	0.06
29.8	7.56	0.535	0.08
29.6	7.58	0.546	0.11
29.7	7.60	0.555	0.15
30.8	7.61	0.563	0.19
31.6	7.62	0.571	0.25
31.7	7.62	0.577	0.28
31.6	7.62	0.588	0.34
31.5	7.62	0.593	0.38
31.0	7.63	0.598	0.42
31.2	7.63	0.606	0.49
31.0	7.63	0.611	0.53
30.5	7.64	0.617	0.60
30.5	7.64	0.617	0.60
30.2	7.64	0.626	1.55
30.1	7.65	0.634	2.19
29.6	7.65	0.639	4.41
29.5	7.66	0.642	5.68
29.5	7.66	0.645	6.95
29.4	7.67	0.648	11.72

Table A.42 ORP Titration of RO at 25C using Free Chlorine with 35.5 mg/L Cl₂

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
19.9	7.50	0.680	0.00
20.0	7.53	0.679	0.01
20.0	7.55	0.683	0.03
20.0	7.56	0.690	0.04
20.1	7.56	0.701	0.05
20.1	7.59	0.716	0.07
20.2	7.61	0.736	0.08
20.3	7.62	0.759	0.09
20.3	7.63	0.777	0.11
20.4	7.65	0.798	0.13
20.5	7.66	0.814	0.15
20.6	7.68	0.836	0.20
20.6	7.69	0.855	0.25
20.7	7.70	0.872	0.31
20.7	7.71	0.881	0.37
20.8	7.72	0.888	0.44
20.8	7.72	0.894	0.52
20.8	7.72	0.894	0.52
20.8	7.74	0.907	0.85
20.9	7.77	0.918	1.52
20.9	7.81	0.928	2.52
20.9	7.83	0.936	3.85
20.9	7.88	0.943	5.85
21.0	7.91	0.950	8.52
21.0	7.94	0.955	10.52

Table A.43 ORP Titration of RO at 25C using Free Chlorine 71 mg/L Cl⁻

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
19.4	7.39	0.672	0.00
19.4	7.40	0.669	0.01
19.4	7.41	0.671	0.02
19.5	7.42	0.674	0.04
19.5	7.43	0.679	0.05
19.6	7.45	0.686	0.06
19.6	7.46	0.701	0.08
19.7	7.48	0.718	0.10
19.8	7.49	0.740	0.12
19.9	7.52	0.767	0.15
19.9	7.53	0.787	0.18
20.0	7.54	0.800	0.21
20.0	7.55	0.812	0.24
20.1	7.56	0.820	0.27
20.2	7.58	0.829	0.30
20.2	7.59	0.837	0.34
20.2	7.59	0.846	0.38
20.3	7.60	0.857	0.43
20.3	7.61	0.862	0.48
20.4	7.62	0.868	0.54
20.4	7.62	0.868	0.54
20.4	7.64	0.886	0.87
20.4	7.66	0.897	1.21
20.5	7.68	0.904	1.54
20.5	7.71	0.911	2.21
20.5	7.73	0.918	3.21
20.6	7.77	0.928	4.54
20.6	7.81	0.935	6.54
20.6	7.85	0.940	8.54
20.6	7.88	0.945	11.87
20.7	7.92	0.950	15.21
20.7	7.94	0.955	18.54

Table A.44 ORP Titration of RO at 25C using Free Chlorine 106.5 mg/L Cl⁻

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
20.0	7.48	0.491	0.00
20.1	7.52	0.527	0.02
20.1	7.53	0.562	0.04
20.1	7.54	0.589	0.05
20.1	7.54	0.611	0.06
20.2	7.55	0.645	0.08
20.2	7.56	0.674	0.10
20.2	7.56	0.699	0.12
20.3	7.57	0.717	0.14
20.3	7.58	0.732	0.17
20.3	7.58	0.753	0.20
20.4	7.59	0.766	0.22
20.4	7.60	0.786	0.26
20.4	7.61	0.805	0.29
20.5	7.63	0.813	0.32
20.6	7.64	0.823	0.36
20.6	7.64	0.832	0.40
20.6	7.65	0.840	0.43
20.6	7.66	0.848	0.52
20.7	7.67	0.853	0.59
20.7	7.67	0.853	0.59
20.7	7.69	0.867	0.92
20.7	7.71	0.876	1.25
20.7	7.74	0.887	1.92
20.7	7.77	0.897	3.25
20.7	7.80	0.902	4.25
20.8	7.82	0.908	5.25
20.8	7.85	0.913	6.59
20.8	7.87	0.917	8.25
20.8	7.89	0.922	10.25

Table A.45 ORP Titration of RO at 25C using Chloramine 35.5 mg/L Cl⁻

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
22.5	7.84	0.588	0.00
22.5	7.85	0.586	0.02
22.5	7.85	0.586	0.03
22.6	7.86	0.586	0.06
22.6	7.87	0.587	0.09
22.6	7.87	0.588	0.11
22.6	7.88	0.590	0.15
22.6	7.88	0.595	0.19
22.7	7.88	0.598	0.23
22.7	7.89	0.603	0.27
22.7	7.89	0.607	0.31
22.7	7.90	0.613	0.35
22.7	7.91	0.617	0.39
22.7	7.91	0.617	0.39
22.8	7.91	0.636	0.72
22.8	7.92	0.642	1.05
22.8	7.92	0.656	1.38
22.8	7.92	0.668	2.04
22.8	7.91	0.678	3.03
22.9	7.90	0.688	4.34
22.9	7.90	0.694	5.66
22.9	7.87	0.700	7.63
22.9	7.85	0.704	9.61
22.9	7.85	0.707	10.92
23.0	7.84	0.709	12.24

Table A.46 ORP Titration of RO at 25C using Chloramine 71 mg/L Cl

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
22.0	7.78	0.580	0.00
22.2	7.86	0.578	0.01
22.2	7.86	0.577	0.01
22.3	7.87	0.576	0.03
22.3	7.87	0.576	0.04
22.4	7.87	0.577	0.05
22.4	7.88	0.578	0.07
22.4	7.88	0.580	0.09
22.4	7.89	0.582	0.12
22.5	7.89	0.585	0.16
22.5	7.89	0.589	0.20
22.5	7.89	0.592	0.24
22.5	7.90	0.599	0.29
22.6	7.90	0.603	0.35
22.6	7.90	0.613	0.41
22.6	7.90	0.613	0.41
22.7	7.91	0.630	0.74
22.7	7.91	0.647	1.07
22.8	7.91	0.654	1.40
22.8	7.92	0.664	1.73
22.9	7.91	0.674	2.39
22.9	7.90	0.680	3.05
23.0	7.89	0.686	4.36
23.0	7.88	0.692	5.68
23.0	7.86	0.697	7.65
23.0	7.83	0.704	10.28
23.0	7.81	0.708	12.92
23.0	7.79	0.711	15.55

Table A.47 ORP Titration of RO at 25C using Chloramine 106.5 mg/L Cl⁻

Temperature °C	pH	Volts (SHE)	mg/L Cl ₂ added
21.8	7.78	0.543	0.00
21.9	7.79	0.542	0.01
22.0	7.81	0.543	0.03
22.0	7.81	0.549	0.06
22.1	7.84	0.557	0.08
22.2	7.84	0.568	0.12
22.2	7.85	0.574	0.16
22.3	7.85	0.578	0.19
22.3	7.86	0.586	0.23
22.4	7.87	0.592	0.28
22.4	7.87	0.597	0.33
22.5	7.87	0.604	0.39
22.6	7.87	0.604	0.39
22.6	7.88	0.622	0.72
22.7	7.88	0.632	1.04
22.7	7.88	0.640	1.37
22.8	7.88	0.657	2.03
22.8	7.88	0.666	2.69
22.8	7.87	0.674	3.68
22.9	7.86	0.682	4.99
22.9	7.84	0.690	6.97
22.9	7.83	0.694	8.28
23.0	7.82	0.697	9.60
23.0	7.81	0.699	11.24