AWT Lead and Copper Workshop Resource
Modeling Lead and Copper Corrosion and Solubility in Municipal Water Distribution Systems

Robert J Ferguson
French Creek Software, Inc.
1220 Valley Forge Road, Suite 21
Phoenixville, PA 19460
U.S.A.

ABSTRACT

Lead and copper in municipal water systems present a major health hazard in addition to the infrastructure loss associated with corrosion releasing them into the distribution system. Soluble lead and copper became a legal as well as economic concern with the implementation of the Lead and Copper rule in the United States in 1991 and its subsequent expansion. Similar regulations where implemented in Canada during the same time period. The regulations set action limits for the metals at 15 µg/L for Pb and 1.3 mg/L for Cu.

Mandated sampling, testing and remedial procedures covered in the Lead and Copper Rule and subsequent regulations and resource material, assume that Pb and Cu levels above the action limits are due to In-Situ corrosion. For example, sampling procedures target houses with pipes and transport lines built in the 1980's, which have been noted to have a higher incidence of corrosion. Remedial procedures address the hazardous metal levels above the Action Levels from a current corrosion basis only. In many cases the implementation of "anti-corrosive" treatments, or removal of piping considered prone to high corrosion will resolve the problem form a legal perspective. In other cases, the Pb and/or Cu source is the dissolution of existing corrosion product, which could be decades old, due to a change in water source or other chemistry changes. In these cases, "anti-corrosive" treatment might be considered the most appropriate legal step, but not the best approach technically.

Lead and copper in municipal systems can result from soluble lead in copper in the water source, corrosion releasing soluble ions into the water, and the dissolution of corrosion product and other lead and/or copper deposits. The dissolution process can be increased, or limited, by changes in water chemistry due to seasonal variations, changing water sources, or changes in treatment. In some cases, treatment directed towards minimizing corrosion as a source of lead and copper, can actually increase the solubility of the ions.

This paper describes a two fold approach to computer modeling of lead and copper corrosion, and the maximum solubility of lead and copper in the municipal water. The methods outlined can be used to:

- Model lead and copper corrosion in a distribution system.

- Model the maximum solubility of lead and copper as an indicator of the waters ability to dissolve deposits, and transport soluble Pb and Cu ions through the system.
- Predict the impact of changing water sources upon lead and copper levels in the system.
- Predict the impact of treatments, including pH adjustment upon lead and copper in the system.

Examples are provided based upon a recent, well publicized, water change that resulted in high lead levels in a municipal water system. The method outlined was used to evaluate a municipal water, and compare traditional indices, maximum lead and copper solubility, and predicted corrosion rates, to the river water that replaced it.

Key words: Lead Solubility, Lead Corrosion, Drinking Water Lead, Lead Action Limits

INTRODUCTION

Lead and copper in municipal water systems present a major health hazard in addition to the infrastructure loss associated with corrosion releasing them into the distribution system. Soluble lead and copper became a legal as well as economic concern with the implementation of the Lead and Copper rule in the United States in 1991and its subsequent expansion (1). Similar regulations where implemented in Canada during the same time period.

The regulations set action limits for the metals at 15 µg/L for Pb and 1.3 mg/L for Cu. Corrosion studies and control programs such as chemical treatment with phosphates and zinc are mandated when these levels are reached. In some cases, these treatments can increase lead and copper solubility, rather decreasing it, while addressing the problem. Langelier Saturation Index and Calcium Carbonate Precipitation Potential adjustment are another control approach mandated by some states. This is done despite the tenuous relationship between theses indices and lead and copper corrosion and transport.

This paper describes a two-fold approach to computer modeling of lead and copper corrosion, and the transport of the metals through the water distribution system. The soluble lead and copper transport through a distribution system is modeled based upon the maximum solubility of these metals over the temperature and pH range likely to be encountered from the water source, through the high end of the expected temperature range in hot water heaters and dishwashers. The impact of mixing water sources on solubility can also be modeled. An expanded version of methods developed by Dr. Shock of the US Environmental Protection Agency is used for the models for the solubility calculations (2). The ion association model calculations include the impact of phosphates and polyphosphate treatments on lead and copper solubility. Similar methods are used to determine the maximum soluble inhibitor concentrations in industrial and municipal systems. Corrosion rate models are developed and used for the prediction of lead, copper and mild steel corrosion rates. Generalized models are discussed as well as the development of models for a specific water source or blend based upon field and/or laboratory testing.

Many of these approaches to evaluating and optimizing control methods to minimize the lead and copper threat have been available since the early 1990s. This paper provides a framework for their application in evaluating existing and new water sources.

EXPERIMENTAL PROCEDURE

Two municipal water sources are compared using the modelling and prediction methods discussed in this paper. The water sources used for examples received national attention when the change from the city water to the alternate river water resulted in a drastic increase in soluble lead in the municipal water distribution system. The models are used to predict the parameters of interest over the temperature range encountered in a municipal water distribution system. pH is varied from 0.4 units below that of the water analysis used, to 0.4 units above the measured value to indicate the impact of variation due to seasonal variations and measurement error. Temperature profiles are evaluated over the range from reservoir temperature to that of a hot water heater, or dish washer.

The water analysis used for the evaluations are outlined in Table 1, for the original municipal water source, and in Table 3, for the river water which replaced it. Tables 2 and 4 profile the water chemistry versus temperature for the original municipal water and the river water. Profiles include simple indices, ion association model indices, lead and copper solubility, and predicted corrosion rates. It must be noted that a thorough evaluation would include at a minimum evaluation of monthly analysis at various distribution system sample points, an evaluation beyond the scope of this paper.

Parameters were modelled using commercially available software and included traditional simple indices, sophisticated ion association saturation ratios, calculated values for maximum Pb and Cu solubility, and predicted corrosion rates.

Traditional Approach

The Langelier Saturation Index (LSI) (3) and Calcium Carbonate Precipitation Potential (CCPP) (4) have been used since the l930's as a control index for minimizing corrosion to an acceptable level in potable water. These simple indices are even referenced in state lead and copper laws, despite the cautions by Dr. Langelier in his 1936 paper that introduced the index. The indices predict calcium carbonate scale formation, which has been inferred to form a film that inhibits corrosion.

A third simple index, the Larson-Skold Index (also called Larson's Ratio) has been used to compare the aggressiveness of the waters. The Larson-Skold Index for the Original City Water and River Water were calculated as 0.78 and 0.31 respectively. These ratios indicate that it would be easier for the River Water to form and maintain a protective film than the Original City Water.

Maximum Lead and Copper Solubility

Maximum solubility profiles are recommended for municipal water distribution system evaluation based upon the premise that soluble Lead and Copper will not be transported through the system to the user if the maximum solubility for the metal is below the Action Limit for the respective ion. The maximum solubility of the metals can be inferred as the maximum lead level expected in the water in stagnant areas of the distribution system.

Another major source of lead and copper in the water results from the dissolution of existing corrosion products. This can be of particular import when switching to a water with higher solubility for the target metal.

The maximum solubility is calculated by:

1) Determining the limiting factor for deposition from the water. For maximum soluble lead calculation hydrocerussite ($Pb_3\ (CO3)_2(OH)_2$) is typically used for municipal waters. Cerrusite (Pb (CO3)) has been suggested and demonstrated as a sound alternative for higher pH waters. (6)
2) Calculating the maximum lead concentration based upon other reactants for the scales formation present and saturating the water with the mineral scale.
3) Back calculating the associated lead species based upon the free Pb concentration required to saturate the water with hydrocerussite (or cerussite at higher pH).
4) Including the impact of corrosion control agents like polyphosphates on increasing, or decreasing lead solubility. (7,8,9)

5) Summing up the free Pb and associated species concentrations to calculate the theoretical maximum soluble lead concentration as in Equation 1.

$$[\mathrm{Pb}_{\mathrm{tot}}] = [\mathrm{Pb}_{\mathrm{free}}] + [\mathrm{Pb}_{\mathrm{hydroxides}}] + \{\mathrm{Pb}_{\mathrm{carbonates}}] + [\mathrm{Pb}_{\mathrm{phosphate}}] + [\mathrm{Pb}_{\mathrm{pyrophosphates}}] + \ldots$$

The lead phosphate and pyrophosphate species represent the impact of common corrosion inhibitors on lead solubility.

Steps 1 through 3 are placed inside of an iterative ion association model loop to improve the accuracy of the maximum soluble lead calculation. (10) The calculations and species involved are outlined in several references. (2,6,7,8,12,13,14)

Lead and Copper Corrosion

Corrosion of lead and copper in the distribution systems are considered a primary source for the ion in the water. Corrosion studies are run on the systems in an effort to minimize lead and copper into the water. Corrosion inhibitor studies are also mandated to minimize release of the metals into the water. Studies typically measure what might be expected with the water under the conditions studied, but with few exceptions do not provide a method for predicting the impact of changing parameters such as pH, temperature, and treatment.

Models have been developed for predicting relative corrosion rates in other water applications such as cooling water, and oil field production. (11) The models use standard statistical methods to correlate observed corrosion rates with parameters such as temperature, buffer capacity, pH, saturation ratios, individual ions and, in some cases, simple indices such as the Larson-Skold (5) index.

The correlation coefficients for a lead corrosion model, and significance levels for each parameter, are outline ion Table 5.

Table 5 Lead Corrosion Rate Model Correlation

		Max Sol Pb	Temp.	pH	LarsSkold	Buf.Cap.	T.D.S.
	Intercept	LOG(X)	1/RT	NONE	NONE	NONE	LOG(X)
Coef.	A 3.13	B 2.02	C -25097	D 5.64	E 0.20	F 3347	G -0.98
Std.Error	4.16	0.24	2703	0.47	0.02	857.97	0.17
Sig.Level	0.45	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

This correlation is expressed in Equation 2.

$$\mathrm{LOG(Rate)} = A + B * \mathrm{LOG(Max\ Pb)} + C/(RT) = D * \mathrm{pH} + E * \mathrm{LarsonSkold} + F * \mathrm{Buffer\ Capacity} + G * \mathrm{LOG(TDS)}$$

Where: **A,B,C,D,E,F**,and **G** are coeficients, **Max Pb** is the maximum soluble lead, **R** is the gas constant, **T** temperature, **TDS** the total dissolved solids, and **Larson Skold** is Larson's Ratio also known as the Larson-Skold Index, and **Rate** the predicted corrosion rate in mils per year.

Corrosion Control

Municipal drinking water corrosion inhibitors include polyphosphates, orthophosphates, zinc, and in some cases silicates. They typically are solubility limited inhibitors where the primary constraint for dosage is the solubility of the inhibitor. Zinc solubility, for example, can be limited by zinc phosphates, zinc hydroxides, zinc carbonates, or even zinc polyphosphates.

The impact of orthophosphate and polyphosphates upon Lead and Copper solubility add an additional constraint to the upper dosage, and in extreme cases, even selection of an inhibitor. The same solubility calculation methods can be used to calculate the maximum soluble zinc, orthophosphate, polyphosphate and zinc species and to show the impact of polyphosphate dosages upon lead and copper solubility.

Dosage and corrosion rate models can also be developed form data of observed corrosion rate, water chemistry, temperature, and inhibitor dosage, to further refine the problem and optimize the solution within the constraints of inhibitor solubility and inhibitor impact upon lead and copper solubility.

RESULTS

The Two Fold Approach was used to evaluate the current municipal water source and compare it to a replacement river water source. Profiles based upon the Traditional Approach, Lead and Copper Solubility, and predicted Lead and Copper Corrosion were calculated and compared.

Traditional Approach

Figures 1 and 2 profile these simple indices over the test pH and temperature for the comparison. The calcium carbonate scale potential predicted by the indices increases as the color coding goes from **BLUE** to **RED**;

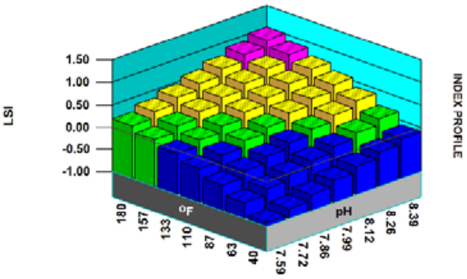

Figure 1: Original City Water Langelier Saturation Index

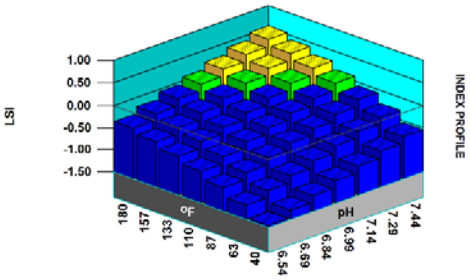

Figure 2: River Water Langelier Saturation Index

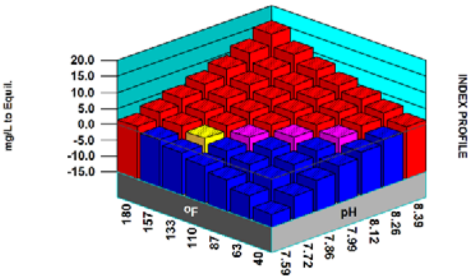

Figure 3: Original City Water C.C.P.P.

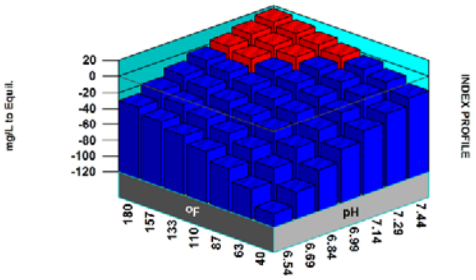

Figure 4: River Water C.C.P.P.

EPA recommendations for the two indices are a neutral or slightly positive Langelier Saturation Index, and 10 mg/L CCPP or above. It can be seen from the profiles that the Original City Water has a higher calcium carbonate scale potential as indicated by the Langelier Saturation Index and Calcium

Carbonate Precipitation Potential. Based on the old methods, the Original City Water would be expected to exhibit lower lead values, based upon the tenuous premise that a higher calcium carbonate scale potential results in decreased corrosion rates.

Maximum Lead and Copper Solubility

Figures 5 and 6 profile the maximum soluble lead expected over the test pH and temperature range employed for the evaluation. The action limit is indicated by a color coding transition to **MAGENTA**;

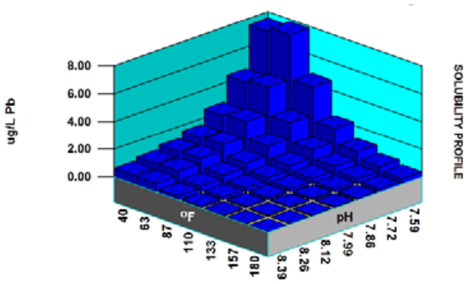

Figure 5: Original City Water Maximum Lead Solubility

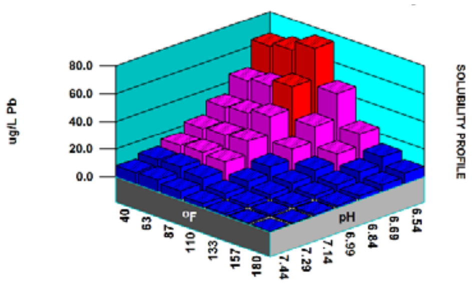

Figure 6: River Water Maximum Lead Solubility

It can be seen that the maximum soluble lead for the Original City Water is well below the 15 µg/L Pb EPA Action Limit over the evaluation range. Problems would be expected after a switch to the River Water due to the high predicted maximum Pb lead levels over twice the EPA Action Limit within a reasonable parameter range.

Similar calculations can be applied to maximum copper solubility. Copper levels are also regulated by the same legislation. Figures 7 and 8 compare the maximum soluble copper levels for the Original City Water and the River Water over the evaluation range.

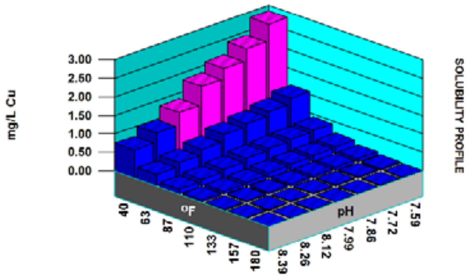

Figure 7: Original City Water Maximum Copper Solubility

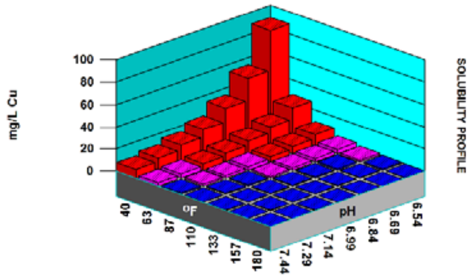

Figure 8: River Water Maximum Copper Solubility

A Copper solubility comparison predicts that the switch from the Original City Water to the River Water would also be hazardous with respect to copper levels in the municipal distribution system.

Lead and Copper Corrosion

Figures 9 and 10 compare projected mild steel corrosion rates for the Original City Water, and the River Water.

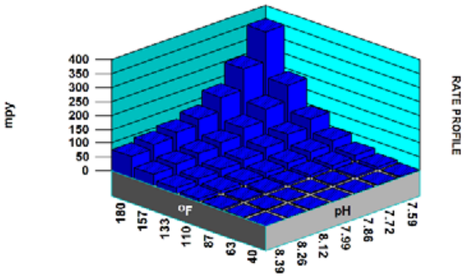

Figure 9: Original City Water
1010 Carbon Steel Corrosion Profile

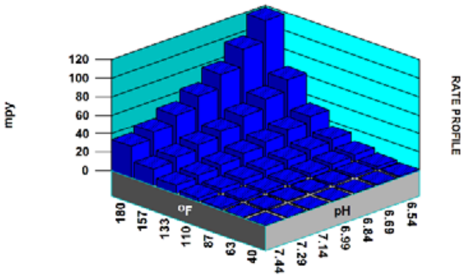

Figure 10: River Water
1010 Carbon Steel Corrosion Profile

The mild steel (C1010 Carbon Steel) models predict very high corrosion rates for the lower pH, higher temperature end of the evaluation range, with the Original City Water rates being higher than the River Water.

A similar model was developed for Lead corrosion rates. Data used was obtained from published corrosion studies in municipal water systems. (9) High significance parameters for the model included buffer capacity, pH, temperature, maximum soluble Pb, and the Larson-Skold index. Figures 11 and 12 compare the predicted lead corrosion rates.

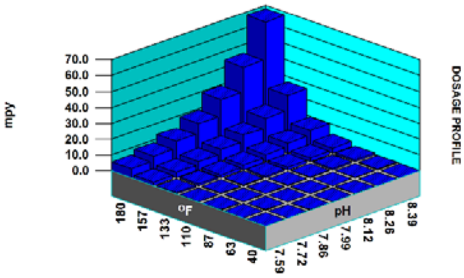

Figure 11: Original City Water
Lead (Pb) Corrosion Profile

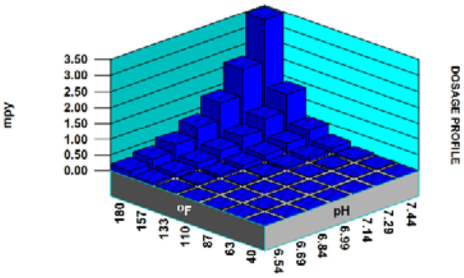

Figure 12: River Water
Lead (Pb) Corrosion Profile

The predicted untreated lead corrosion rates for Original City Water are significantly higher than those for the River Water at the high pH, high temperature end of the range. The Original City Water was treated to control this problem with a corrosion inhibitor blend.

CORROSION INHIBITOR TREATMENTS

Corrosion inhibitor treatments applied to potable water systems are solubility limited. Feeding above the maximum solubility for an inhibitor, or blend, may create a deposit and additional problems rather than providing improved inhibition over feeding at the maximum solubility. Figures 13, 14, 15 and 16 profile the maximum solubility for the primary inhibitors in the arsenal for municipal corrosion control, and a typical blend. It should also be noted that inhibitors such as polyphosphates can increase the maximum solubility for Pb and Cu. Modeling should include the impact of phosphate, polyphosphate and zinc inhibitors on solubilities.

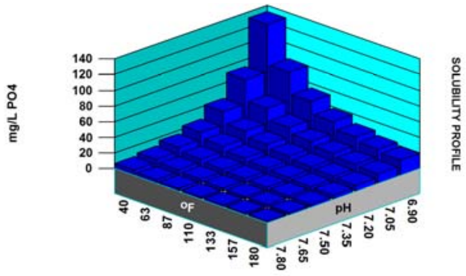

Figure 13
Maximum PO4 Solubility

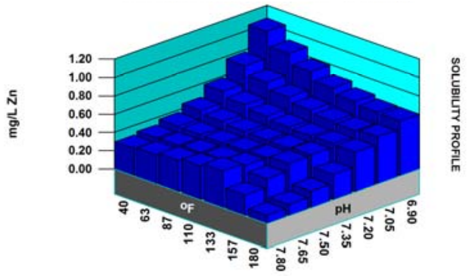

Figure 14
Maximum Zinc Solubility

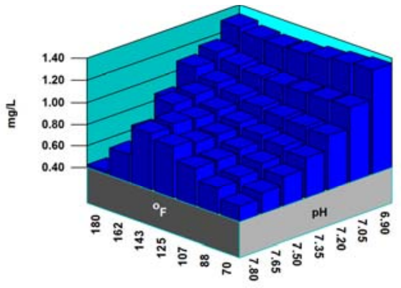

Figure 15
4:1Orthophosphate-Zinc Solubility Profile

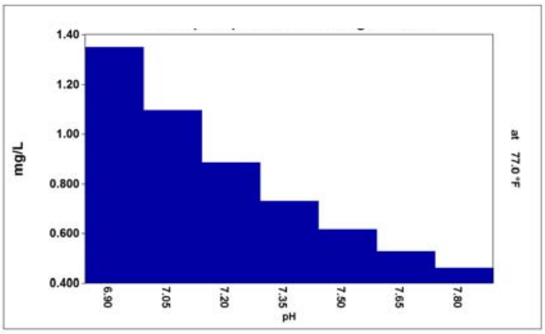

Figure 16
4:1 Orthophosphate-Zinc Recommended Dosage

WATER CONDITIONING

As outlined in figures 1 through 12, pH has a major impact upon the critical parameters of interest: Maximum Pb Solubility, Maximum Cu Solubility, and predicted corrosion rates. Figure 17 profiles projected Lime Addition requirements to increase the pH of Flint River water as an example of conditioning requirements.

Conditioning is normally not considered in evaluating remedial actions for systems above the action limits for Pb or Cu. It is recommended that conditioning options be evaluated, and costs versus distribution system replacement and corrosion inhibitor options considered.

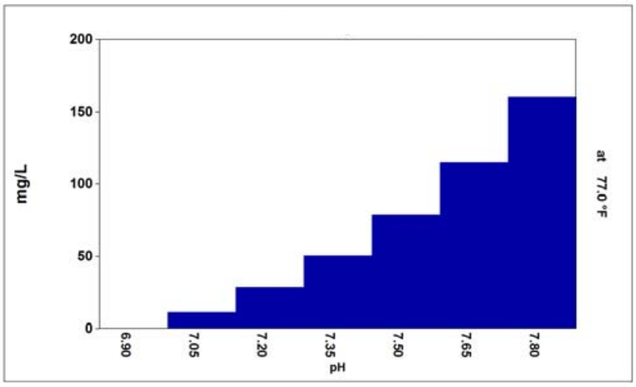

Figure 17
Lime Dosage Profile

CONCLUSIONS

Traditional indices such as the Langelier Saturation Index, Calcium Carbonate Precipitation Potential, and Larson-Skold index, do not adequately address the corrosion and solubility issues involved in identifying issues and implementing an effective lead and copper control program in a potable water distribution system.

Improved methods have been developed by the United States Environmental Protection Agency and private and university research centers. These methods for predicting and modelling solutions for lead and copper in potable water should be implemented.

Data from corrosion studies should be used to develop a model for a specific water system and used to optimize the approach to mitigating hazardous lead and copper levels in municipal drinking water systems.

Existing guidelines for selecting approaches to mitigating corrosion, Pb, and Cu levels (12) should be updated to incorporate computerized modelling. Computer algorithms for conditioning and anticorrosive optimization should also be included in evaluations of options. The risks associated with copper and lead in drinking water more than outweigh any additional costs over using simple flowcharts and manual calculations.

ACKNOWLEDGEMENTS

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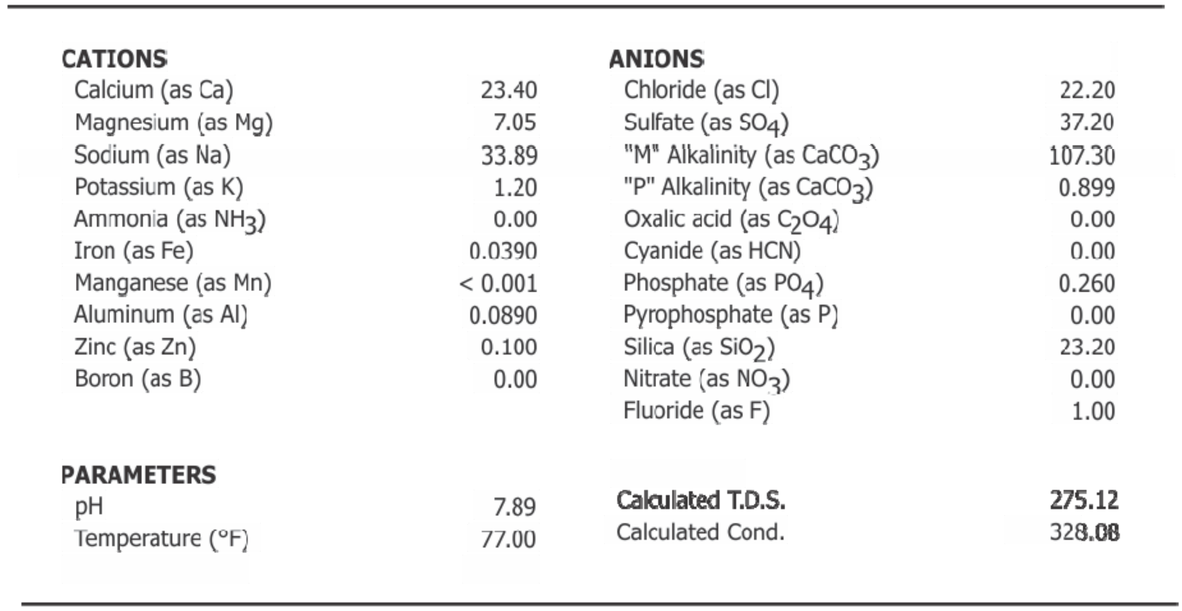
Table 1: Original City Water Analysis



CATIONS		**ANIONS**	
Calcium (as Ca)	23.40	Chloride (as Cl)	22.20
Magnesium (as Mg)	7.05	Sulfate (as SO_4)	37.20
Sodium (as Na)	33.89	"M" Alkalinity (as $CaCO_3$)	107.30
Potassium (as K)	1.20	"P" Alkalinity (as $CaCO_3$)	0.899
Ammonia (as NH_3)	0.00	Oxalic acid (as C_2O_4)	0.00
Iron (as Fe)	0.0390	Cyanide (as HCN)	0.00
Manganese (as Mn)	< 0.001	Phosphate (as PO_4)	0.260
Aluminum (as Al)	0.0890	Pyrophosphate (as P)	0.00
Zinc (as Zn)	0.100	Silica (as SiO_2)	23.20
Boron (as B)	0.00	Nitrate (as NO_3)	0.00
		Fluoride (as F)	1.00
PARAMETERS			
pH	7.89	**Calculated T.D.S.**	**275.12**
Temperature (°F)	77.00	Calculated Cond.	328.08

Table 2: Original City Water Temperature Profile

	Temperature (°F)						
SATURATION LEVEL	**40.00**	**63.33**	**86.67**	**110.00**	**133.33**	**156.67**	**180.00**
Calcite	0.0785	0.142	0.230	0.337	0.469	0.629	0.817
Aragonite	0.0704	0.125	0.199	0.287	0.393	0.521	0.668
Calcium oxalate	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Anhydrite	0.00266	0.00252	0.00273	0.00329	0.00434	0.00617	0.00934
Gypsum	0.00479	0.00443	0.00429	0.00457	0.00562	0.00674	0.00792
Calcium phosphate	< 0.001	< 0.001	0.00300	0.00893	0.0236	0.0560	0.121
Hydroxyapatite	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Ca pyrophosphate	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc phosphate	< 0.001	< 0.001	0.00121	0.00133	0.00123	< 0.001	< 0.001
Zinc pyrophosphate	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fluorite	0.00139	0.00120	0.00105	< 0.001	< 0.001	< 0.001	< 0.001
Silica	0.345	0.240	0.172	0.127	0.0954	0.0729	0.0564
Brucite	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.00131	0.00488
Magnesium silicate	< 0.001	< 0.001	0.00106	0.00398	0.0133	0.0396	0.106
Ferric hydroxide	9.37	19.06	36.54	65.51	107.04	155.84	195.25
Siderite	0.149	0.325	0.619	1.04	1.60	2.23	2.78
Strengite	0.0336	0.104	0.291	0.728	1.60	3.05	4.87
MOMENTARY EXCESS							
Calcite	-1.71	-1.26	-0.917	-0.653	-0.442	-0.265	-0.115
Aragonite	-1.92	-1.46	-1.10	-0.823	-0.599	-0.412	-0.253
Calcium oxalate	-0.651	-0.662	-0.676	-0.692	-0.711	-0.734	-0.761
Anhydrite	-1.1%E+	-1.1%E+	-1.1%E+	-965.35	-818.85	-664.57	-518.48
Gypsum	-929.86	-959.45	-963.30	-916.79	-806.84	-717.20	-643.35
Calcium phosphate	>-0.001	>-0.001	>-0.001	>-0.001	>-0.001	>-0.001	>-0.001
Hydroxyapatite	-313.67	-353.43	-394.42	-436.48	-479.47	-523.24	-567.74
Ca pyrophosphate	-0.0087	-0.0091	-0.0096	-0.0103	-0.0110	-0.0119	-0.0130
Zinc phosphate	>-0.001	>-0.001	>-0.001	>-0.001	>-0.001	>-0.001	>-0.001
Zinc pyrophosphate	-1.24	-1.27	-1.29	-1.32	-1.36	-1.40	-1.44
Fluorite	-37.92	-40.14	-42.32	-44.46	-46.56	-48.64	-50.69
Silica	-45.36	-75.29	-113.89	-162.42	-222.17	-294.33	-380.05
Brucite	-4.46	-4.63	-4.80	-4.96	-5.11	-5.22	-5.25
Magnesium silicate	-152.28	-174.58	-197.88	-222.07	-247.03	-272.66	-298.89
Ferric hydroxide	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Siderite	-0.166	-0.0875	-0.0320	0.00221	0.0217	0.0299	0.0296
Strengite	>-0.001	>-0.001	>-0.001	>-0.001	< 0.001	< 0.001	< 0.001
SIMPLE INDICES							
Langelier	-1.10	-0.833	-0.614	-0.436	-0.279	-0.134	0.00122
Ryznar	9.80	9.27	8.83	8.47	8.16	7.87	7.60
Puckorius	10.30	9.76	9.32	8.96	8.65	8.35	8.08
Larson-Skold	1.25	1.25	1.25	1.24	1.24	1.24	1.24
C.C.P.P.	-8.23	-6.04	-4.55	-3.46	-2.46	-1.42	-0.255
CHEMICAL PROPERTIES							
Pb Solubility(ug/L)	7.22	7.55	4.52	2.18	1.13	0.616	0.353
Cu Solubility(mg/L)	2.80	1.07	0.436	0.184	0.0825	0.0392	0.0195
Zn Solubility(mg/L)	1.19	1.10	1.04	1.03	0.516	0.184	0.0780
PPO4 Solubility(mg/L)	7.17	8.19	9.39	10.78	12.35	14.07	15.89
PO4 Solubility(mg/L)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
D.I.C.	14.39	14.20	14.10	14.04	14.00	13.97	13.93
CORROSION RATE (mpy)							
Lead (Pb)	0.00619	0.0249	0.0888	0.286	0.838	2.27	5.70
1010 Carbon Steel	**4.14**	**9.59**	**21.47**	**46.63**	**95.81**	**185.65**	**341.43**

Table 3: River Water Analysis

CATIONS		**ANIONS**	
Calcium (as $CaCO_3$)	84.14	Chloride (as Cl)	12.00
Magnesium (as $CaCO_3$)	9.86	Sulfate (as SO_4)	4.99
Sodium (as Na)	0.00	"M" Alkalinity (as $CaCO_3$)	86.77
Potassium (as K)	0.00	"P" Alkalinity (as $CaCO_3$)	0.0809
Ammonia (as NH_3)	0.00	Oxalic acid (as C_2O_4)	0.00
Iron (as Fe)	0.0300	Cyanide (as HCN)	0.00
Manganese (as Mn)	0.00	Phosphate (as PO_4)	3.57
Aluminum (as Al)	0.00	Pyrophosphate (as P)	0.00
Zinc (as Zn)	0.00	Silica (as SiO_2)	23.00
Boron (as B)	0.00	Nitrate (as NO_3)	0.00
		Fluoride (as F)	0.00
PARAMETERS			
pH	6.94	**Calculated T.D.S.**	**202.11**
Temperature (°F)	48.20	Calculated Cond.	190.58

Table 4: River Water Chemistry Temperature Profile

	Temperature (°F)						
SATURATION LEVEL	**40.00**	**63.33**	**86.67**	**110.00**	**133.33**	**156.67**	**180.00**
Calcite	0.0339	0.0614	0.0995	0.146	0.203	0.273	0.354
Aragonite	0.0303	0.0541	0.0861	0.124	0.171	0.226	0.290
Calcium oxalate	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Anhydrite	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.00132	0.00201
Gypsum	0.00101	< 0.001	< 0.001	< 0.001	0.00120	0.00144	0.00170
Calcium phosphate	0.00228	0.00997	0.0372	0.121	0.347	0.890	2.06
Hydroxyapatite	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.00401
Ca pyrophosphate	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc phosphate	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc pyrophosphate	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fluorite	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Silica	0.342	0.239	0.172	0.127	0.0960	0.0740	0.0581
Brucite	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Magnesium silicate	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.00199
Ferric hydroxide	0.403	0.815	1.57	2.86	4.87	7.64	10.85
Siderite	0.0376	0.0817	0.156	0.267	0.427	0.645	0.913
Strengite	0.232	0.751	2.20	5.86	13.98	29.88	56.20
MOMENTARY EXCESS							
Calcite	-1.15	-0.875	-0.678	-0.530	-0.417	-0.327	-0.255
Aragonite	-1.28	-1.00	-0.794	-0.638	-0.516	-0.420	-0.342
Calcium oxalate	-0.410	-0.416	-0.424	-0.434	-0.446	-0.461	-0.478
Anhydrite	-1.1%E+	-1.1%E+	-1.0%E+	-928.46	-787.25	-638.88	-498.75
Gypsum	-897.03	-924.75	-927.69	-882.29	-776.17	-689.66	-618.38
Calcium phosphate	>-0.001	>-0.001	>-0.001	>-0.001	>-0.001	>-0.001	< 0.001
Hydroxyapatite	-304.63	-343.11	-382.73	-423.31	-464.67	-506.66	-549.15
Ca pyrophosphate	-0.0030	-0.0032	-0.0033	-0.0035	-0.0037	-0.0040	-0.0044
Zinc phosphate	-0.0121	-0.0122	-0.0123	-0.0124	-0.0124	-0.0125	-0.0126
Zinc pyrophosphate	-1.23	-1.24	-1.25	-1.27	-1.28	-1.30	-1.31
Fluorite	-35.11	-37.17	-39.20	-41.20	-43.19	-45.18	-47.17
Silica	-45.54	-75.44	-113.98	-162.44	-222.04	-294.00	-379.41
Brucite	-5.84	-6.02	-6.19	-6.37	-6.54	-6.71	-6.87
Magnesium silicate	-150.07	-172.02	-194.93	-218.70	-243.19	-268.32	-293.97
Ferric hydroxide	>-0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Siderite	-0.219	-0.157	-0.109	-0.0718	-0.0427	-0.0201	-0.0037
Strengite	>-0.001	>-0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
SIMPLE INDICES							
Langelier	-1.47	-1.20	-0.985	-0.808	-0.651	-0.506	-0.372
Ryznar	9.88	9.35	8.91	8.56	8.24	7.95	7.68
Puckorius	9.56	9.03	8.60	8.24	7.93	7.64	7.37
Larson-Skold	0.311	0.311	0.311	0.311	0.310	0.310	0.310
C.C.P.P.	-32.07	-25.56	-21.16	-18.18	-15.66	-13.31	-11.08
CHEMICAL PROPERTIES							
Pb Solubility(ug/L)	25.70	26.84	28.99	14.00	7.24	3.95	2.26
Cu Solubility(mg/L)	25.75	9.05	3.61	1.53	0.686	0.328	0.165
Zn Solubility(mg/L)	0.696	0.584	0.504	0.447	0.411	0.395	0.404
PPO4 Solubility(mg/L)	2.98	3.16	3.37	3.63	3.94	4.28	4.66
PO4 Solubility(mg/L)	76.57	49.49	33.82	24.30	18.26	14.29	11.58
D.I.C.	21.55	20.85	20.42	20.19	20.02	19.86	19.73
CORROSION RATE (mpy)							
Lead (Pb)	< 0.001	0.00315	0.0112	0.0361	0.106	0.287	0.721
1010 Carbon Steel	1.81	4.08	8.92	19.02	38.55	74.20	136.71