

ACHIEVING OPTIMUM CORROSION CONTROL FOR LEAD IN CHARLESTON, S.C. A Case Study

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INTRODUCTION

Charleston, South Carolina, famous for its cobblestone streets, historic beauty, balmy weather, and friendly people, is considered by many to be the archetypal image of Southern grace and charm. But, this image was marred when it was discovered in 1992 that this city had in its drinking water the highest lead levels of any large water system in the nation. The purpose of this paper is to review the efforts taken by the Commissioners of Public Works of the City of Charleston to respond to the problem by developing and implementing a plan for achieving optimum corrosion control to reduce the risk from lead exposure.

BACKGROUND

The potable water for the Charleston Metropolitan area is provided by the Hanahan Water Treatment Plant. The raw water supply of the Hanahan plant is the Edisto River, which is the longest black water river in the United States (S.C. Water Resources Commission, 1993). As such, the water quality of this source is characteristically aggressive in that it is low in alkalinity and turbidity and high in color as a result of naturally occurring organics from the watershed. Typical raw water characteristics are shown in Table 1. Treatment consists of adding either ferric chloride or alum to remove color levels in the 100 to 300 PCU range. Effective color and TOC removal depends upon high coagulant doses and low coagulation pH (4.7 for FeCl₃ and 5.8 for alum). After coagulation, flocculation, sedimentation, and filtration, the water is chlorinated in the clearwell to meet the requirements of the Surface Water Treatment Rule. Finished water pH is adjusted using lime. Following the clearwells, ammonia is added to maintain a chloramine residual on the distribution system. Even with adjusting the pH with lime, there remains in the finished water very little carbonate alkalinity. Using alum, the dissolved inorganic carbonate (DIC) levels are approximately 5 mg C/L and using ferric chloride, DIC levels approach zero. Hence, without some form of corrosion control, the water is extremely aggressive.

PRELIMINARY EFFORTS

The Lead and Copper Rule (LCR) required all public water systems serving a population of over 50,000 people to complete the first round of a lead and copper monitoring program by June 30, 1992. During the monitoring period of January to June 1992, the Commissioners of Public

Works of the City of Charleston (CPW) sampled 115 Tier I, high-risk residences with the result that this first round of sampling yielded a 90th percentile for lead of 211 parts per billion (ppb). In addition to identifying these 115 homes as meeting the LCR high-risk criteria, these homes had been selected from a group of about 800 homes which had participated in an earlier study in which CPW had provided free lead sampling to interested customers. Therefore, the 115 homes selected represented homes which had initially tested as being among the highest of the 800 sampled during the earlier period. Because of this high 90th percentile in the first round of sampling, CPW entered into a Consent Agreement with the S.C. Department of Health and Environmental Control to greatly accelerate CPW's lead corrosion control program. Therefore, in October 1992, CPW began adding an orthophosphate inhibitor for lead corrosion control. The decision to add an orthophosphate, as opposed to taking another approach to corrosion control, was predicated upon an initial desk-top evaluation conducted in 1991 and preliminary pilot plant testing using lead weight-loss coupons prior to beginning the first round of Tier I sampling. The potential for high levels of lead corrosion was understood because of the nature of the raw water source, the treatment process, earlier lead sampling results, and the number of lead service lines in the historic district of the City.

In addition to conducting the lead sampling as required by the LCR, CPW began a monitoring program on three levels. First, the thirty-one (31) highest samples from the first round of Tier I monitoring were selected for monthly lead sampling so that the effectiveness of corrosion control program could be determined as currently as possible. This thirty-one customer sub-population proved to be an excellent indicator for what was happening on the entire water distribution system. Second, lead testing was provided at no cost to any customer concerned about the potential for high lead levels. And finally, CPW worked closely with its wholesale water customers and the S.C. Department of Health and Environmental Control by providing technical assistance and free analytical services.

DESK TOP EVALUATION

Even though an orthophosphate inhibitor was being fed, it had yet to be determined if this treatment was going to be effective in meeting the LCR requirements for optimum corrosion control. Hence, a more detailed desk-top evaluation was performed and the corrosion control methodologies evaluated included: 1) pH and alkalinity adjustment; 2) calcium carbonate precipitation; 3) adding sodium silicate; 4) adding a poly/orthophosphate blend; and 5) adding an orthophosphate (Cook, 1994).

There were two concerns associated with elevating the finished water pH to a level effective for corrosion control. Because of the high level of organics in the source water, there was a concern over increasing THM levels above the MCL as a result of raising the pH (Figure 1). There was also a concern over lowering the disinfection efficiency of chlorine because of the predominance of the less-efficient hypo-chlorite ion at pH levels above 8.0 (Figure 2). Because of the need for very high pH levels to achieve calcium carbonate precipitation (theoretically 9.8),

this alternative was rejected from further consideration. However, moderate pH adjustment to 8.0 was considered for pilot testing.

In addition, because of the concern over potential effects on wastewater discharges, zinc-based orthophosphate inhibitors were also eliminated from consideration. Treatment schemes which would require the DIC level of the finished water to be over 8.0 mg C/L were also not further considered. From studies by Schoch and Gerdels (1983) and Sheihan and Jackson (1981), optimum DIC levels for reducing lead solubility should be within a low range. The AWWA Research Foundation (1990) also indicated that a DIC concentration of 2 mg C/L was an approximate minimum value for sufficient pH buffering at the pipe surface to allow a protective passivating film to develop and a DIC concentration above 8 mg C/L was considered outside of the optimum range for reducing lead solubility. The criteria used to evaluate the specific water quality characteristics of the Hanahan WTP is outlined by the AWWA Research Foundation (1990) and the U.S. EPA (1992). This criteria is based upon theoretical model predictions for minimizing lead solubility as well as experimental field work and pilot studies.

The existing data indicated the following finished water quality characteristics:

pH - 7.8
alkalinity - 18 mg/L CaCO₃
total hardness - 46 mg/L CaCO₃
calcium hardness - 39 mg/L CaCO₃
specific conductance - 120 μ mhos/cm
combined chlorine residual - 2 mg/l
total dissolved solids - 100 mg/l

The dissolved inorganic carbonate (DIC) concentration in the water was estimated based upon approximate ionic strength, alkalinity, and pH of the finished water. Ionic strength was approximated using both the measured specific conductance and total dissolved solids in accordance with the following two formulas (AWWARF, 1990):

$$I = \text{specific conductance} \times 1.6 \times 10^{-5}; \text{ and}$$
$$I = \text{TDS} \times 2.5 \times 10^{-5}$$

These calculations yielded an ionic strength ranging between 0.0019 and 0.0035 which yielded a theoretical DIC concentration of 4 mg C/L for a finished water of pH 7.8 and an alkalinity of 18 mg/l (AWWARF, 1990, Figure 3). However, this assumes that adequate carbonate alkalinity is available in the raw water, which is not the case when using ferric chloride as the coagulant because of raw water alkalinity consumption at a low coagulation pH. Hence, this equation could be used only if alum were used as the coagulant or if carbonate alkalinity were supplied in treatment.

Evaluation of Inhibitor Addition

There were three basic approaches to inhibitor addition to be considered, namely, adding a silicate, polyphosphate blend, or orthophosphate corrosion inhibitor.

- a. Several pipe loop experiments performed by EPA in low alkalinity waters suggested a level of 20 mg SiO₂/L would be necessary to yield measurable results and that a very long application period could be necessary to form a protective coating (Schock and Wagner, 1985). However, little research had been done with silicate as a corrosion inhibitor, and predictions could not be considered reliable until further research was conducted.
- b. The addition of polyphosphate to control lead corrosion was completely uncertain given the absence of published information and the proprietary nature of these formations. Research reviewed by Schock and Wagner (1985), including studies by the Water Research Centre in Britain, showed that polyphosphates were not only ineffective in reducing lead levels but could actually increase levels by complexation and solubilization of potentially protective films. Any benefits perceived from actual useage may very well be the result of the reversion of polyphosphate to orthophosphate. A detailed discussion of this issue is contained in Appendix I of AWWARF, 1990, and a strong caution against their use is contained in Section 3.2.3.1. of U.S. EPA, 1992. Nonetheless, a polyphosphate was evaluated in the first round of the pilot testing.
- c. Orthophosphate had been well-documented even in low levels as being effective in reducing plumbosolvency. Under potable water conditons, the most likely phase to form is hydroxypyromorphite (Pb₅(PO₄)₃ OH) (AWWARF, 1990). Other metals such as zinc can form insoluble orthophosphate solids but the presence of trace metals is not necessary to achieve the formation of passivating films.

Based upon a DIC level of 4 mg C/L, a finished water pH of 7.5 to 8.0, and an orthophosphate concentration of 2.5 mg PO₄/L, a theoretical lead solubility concentration of 10 ppb could be obtained (Figure 4).

CORROSION CONTROL PILOT TESTING

Approach to Pilot Testing

There were several approaches that could have been taken in modelling corrosion rates, evaluating treatment scenarios, and in determining metal leaching. The approach decided upon was to use a continuous flow pilot system with a weight loss analysis of metal coupons for the first two rounds of testing. Metal coupon weight loss measures the average weight of coupon loss over a given period of time. The weight loss method can be used also to compare the effect

that various treatment schemes have on rates of corrosion. Further, weight loss techniques can give comparable results with corrosion rates in the distribution system if tests are run long enough to ensure that stable rates are achieved in both the pilot system and in the full-scale distribution system (AWWARF, 1990).

Rectangular coupons of 100% lead were used in the pilot system. The corrosion rate for these coupons were calculated using the following approach (U.S. EPA, 1992):

$$P = 1/\{1/H + 1/X + 1/Y\} \times (W_1 - W_2)/W_1D \times 1.825 \times 10^{-5} \text{ in which:}$$

- P = corrosion rate, in mils per year
- H = original coupon thickness, inches
- X = original coupon length, inches
- Y = original coupon width, inches
- W₁ = original weight of coupon, mg
- W₂ = final weight of coupon, mg
- D = exposure time, in days

Design of Pilot System

The pilot system was constructed with four distribution pipes coming off a central manifold water feed (Figure 5). The water feed supply was obtained from a location downstream of the filters and prior to pH adjustment and other chemical additions. Each of the four distribution pipes contained one rotameter followed by a chemical feed point, followed by an in-line static mixer, followed by a coupon. This arrangement was followed by a second feed point followed by an in-line static mixer and another coupon. In all, the pilot system contained eight (8) separate chemical feed points and eight (8) separate coupons, allowing eight treatment scenarios to be simulated during each phase.

The pilot system piping and fittings were of various-sized PVC Schedule 80. All rotameters were King Instrument 10.7 gpm. All static mixers were Koflo stainless steel. All metal coupons were of 100% lead and were provided by Metal Samples, Inc. The chemical feed equipment consisted of the following:

- six each 200 liter high density polyethylene tanks
- six each Dayton tank mixers with double three-blade propellers
- three each Prominent slurry metering pumps with backflush systems for feeding lime slurry
- three each Prominent Gamma 4-W metering pumps for feeding corrosion inhibitors
- two each Teal stainless steel pumps rated at 10 gpm @ 40 ft. head.

Results from Rounds One and Two of Pilot System

For the first round, the pilot system was placed into operation on February 6, 1992, and the coupons were removed on May 6, 1992. The Hanahan WTP operators operated the system and took samples in accordance with a prescribed data recording form. Weekly samples were collected in each loop for pH, temperature, alkalinity, hardness, THMs, and TDS. All analytical work was performed in accordance with Standard Methods (1989).

The following treatment schemes were evaluated during the first round:

1. Coupon 1
Control coupon, i.e., no pH adjustment or inhibitor added.
(This unadjusted pH represented the pH of coagulation which was in the range of 4.5 to 5.0 during the first round).
2. Coupon 2
Addition of lime to adjust pH to 7.2.
3. Coupon 3
Addition of 2 mg/l polyphosphate; no pH adjustment.
4. Coupon 4
Addition of 2 mg/l polyphosphate with lime addition to adjust pH to 7.2.
5. Coupon 5
Addition of 2 mg/l orthophosphate and no pH adjustment.
6. Coupon 6
Addition of 2 mg/l orthophosphate and addition of lime to adjust pH to 7.2.
7. Coupon 7
Addition of 2 mg/l sodium silicate with no pH adjustment.
8. Coupon 8
Addition of 2 mg/l sodium silicate with addition of lime to adjust pH to 7.2.

After weighing the coupons after a 90-day test, the following results were obtained:

<u>Coupon</u>	<u>Corrosion Rate (in mils/yr)</u>
1	17.40
2	0.28
3	8.78
4	0.36
5	1.44

6	0.14
7	11.84
8	0.58

Based upon the effectiveness of raising the pH in all scenarios, the second round of evaluation consisted of the following:

1. Coupon 1
Control coupon; no pH adjustment or inhibitor added.
2. Coupon 2
Addition of lime to adjust pH to 8.0.
3. Coupon 3
Addition of 2 mg/l orthophosphate with no pH adjustment.
4. Coupon 4
Addition of 2 mg/l orthophosphate with addition of lime to adjust pH to 8.0.
5. Coupon 5
Addition of 3 mg/l orthophosphate with no pH adjustment.
6. Coupon 6
Addition of 3 mg/l orthophosphate with addition of lime to adjust pH to 8.0.
7. Coupon 7
Addition of 2 mg/l orthophosphate with no pH adjustment.
8. Coupon 8
Addition of 2 mg/l orthophosphate with addition of lime to adjust pH to 8.0.

The second round of testing was begun on October 20, 1992, and the coupons were removed on January 20, 1993. After weighing the coupons from the second round, the following results were obtained:

<u>Coupon</u>	<u>Corrosion Rate (in mils/yr)</u>
1	Unavailable due to coupon condition
2	2.03
3	1.23
4	0.33
5	1.54
6	0.22
7	1.25
8	0.33

Evaluation of Results from Rounds One and Two

After the completion of two rounds of testing using the pilot system, several conclusions could be reached. First, pH adjustment had been found to be very helpful in lowering corrosion rates of the lead coupons in all cases. Secondly, orthophosphate addition had been found to be much superior to other inhibitors, namely silicates and polyphosphates, and it was also superior to pH adjustment alone. Third, pH adjustment along with orthophosphate addition of between 2 and 3 mg/l yielded the lowest coupon corrosion rates.

Therefore, based upon the results of the desk-top evaluation and the first two rounds of pilot testing, it was decided to continue with the addition of 2.5 mg/l orthophosphate and adjust the finished water pH to 8.0.

RESULTS OF FULL-SCALE TESTING

The first round of Tier I monitoring before the beginning of corrosion control in October 1992, yielded a 90th percentile of 211 ppb. The second round taken in December 1992, yielded a 90th percentile of 165 ppb; the third round, taken in June 1993, yielded a 90th percentile of 155 ppb; the fourth round, taken in December 1993, yielded a 90th percentile of 36 ppb; the sixth round, taken in December 1994, yielded a 90th percentile of 3 ppb; and the seventh round, taken in June 1995, yielded a 90th percentile of 4 ppb. (See Figure 6)

Currently, a maintenance concentration of 1.5 mg/l orthophosphate is being fed with excellent results.

SECONDARY IMPACTS

There have been no observable secondary impacts as a result of using the aforementioned approach to corrosion control. Nevertheless, it should be mentioned that there was a substantial increase in the number of "rusty water" complaints after switching in March 1992 from alum to ferric chloride. Evidence for this relationship was strengthened with an immediate decrease in rusty water complaints as a result of switching back to alum in July 1994.

By maintaining a relatively moderate finished water pH of 8.0, disinfectant efficiency using chlorine has been maintained. In addition, THM formation as a function of pH has been controlled.

There was some concern that the addition of an orthophosphate would supply a needed nutrient to precipitate biofilm regrowth. There has been no evidence of this occurring. Figure 7 indicates the number of positive total coliform samples for the period of October 1991 through December 1995. As can be seen, the frequency of coliform positive occurrence has been very stable since adding the corrosion inhibitor in October 1992.

SUMMARY

Without corrosion control treatment, the first round of monitoring for Tier I homes yielded a 90th percentile of 211 ppb, above the Lead and Copper Rule action level of 15 ppb. Based upon desk-top and pilot scale evaluations, it was determined that optimum treatment could be achieved with 2.5 mg/l orthophosphate and a pH of 8.0. Since treatment began in October 1992, lead levels were reduced to 3 mg/l by December 1994 and continue to remain well below the action level with a maintenance dose of 1.5 mg/l orthophosphate. In addition, there have been no observed secondary impacts from this treatment.

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TABLE 1
Hanahan Water Treatment Plant
RAW WATER QUALITY DATA
for 1994

<u>Parameter</u>	<u>Unit</u>	<u>Minimum</u>	<u>Maximum</u>	<u>Average</u>
Lab pH	SU	6.9	7.6	7.2
Alkalinity	mg/L	11	28	22
Turbidity	NTU	2.7	9.0	5.3
Color (apparent)	PCU	83	216	156
Fecal Coliform	No./100 ml	17	45	28
Temperature	C	16	24	21
Fluoride	mg/L	<0.10	0.12	0.10
Chloride	mg/L	8.3	12.9	10.6
Sodium	mg/L	4.9	9.1	6.7
Conductivity	umhos/cm	64	105	82
Total Solids	mg/L	63	103	86
Total Hardness	mg/L	23	42	33
Calcium Hardness	mg/L	15	33	26
Ammonia	mg/L	<0.10	0.32	0.12
Aluminum	mg/L	0.22	0.67	0.49
Iron	mg/L	0.38	1.03	0.82
Manganese	mg/L	<0.02	0.04	0.03
Lead	mg/L	0.002	0.014	0.006
Silica	mg/L	<1.0	7.9	5.0
Sulfate	mg/L	2.6	9.3	5.4
TOC	mg/L	4.6	15.5	9.8

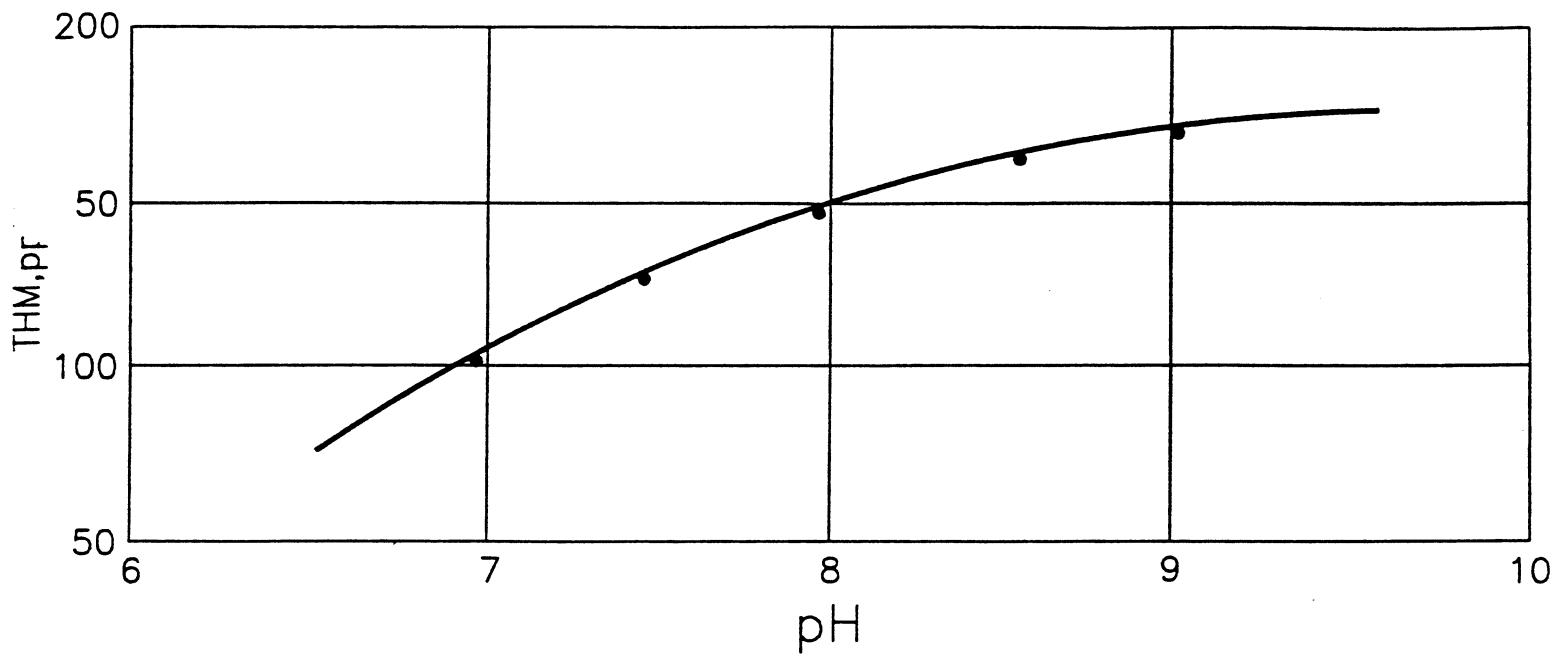


FIGURE 1. THM FORMATION AS A FUNCTION OF pH.(NOTE: TAKEN FROM JAMES MONTGOMERY,1985).

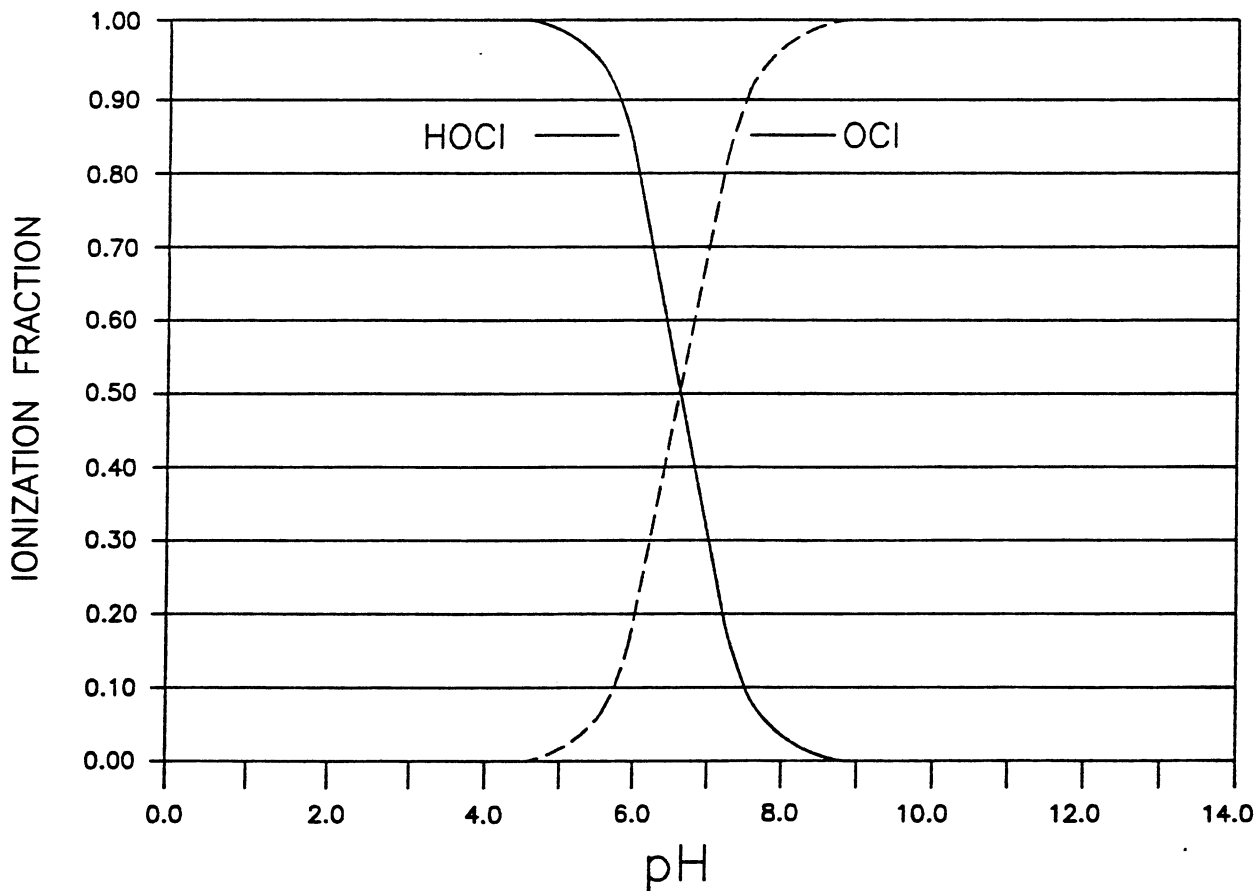


FIGURE 2. DISTRIBUTION DIAGRAM FOR HYPOCHLOROUS ACID. (NOTE: TAKEN FROM AWWARF, 1990)

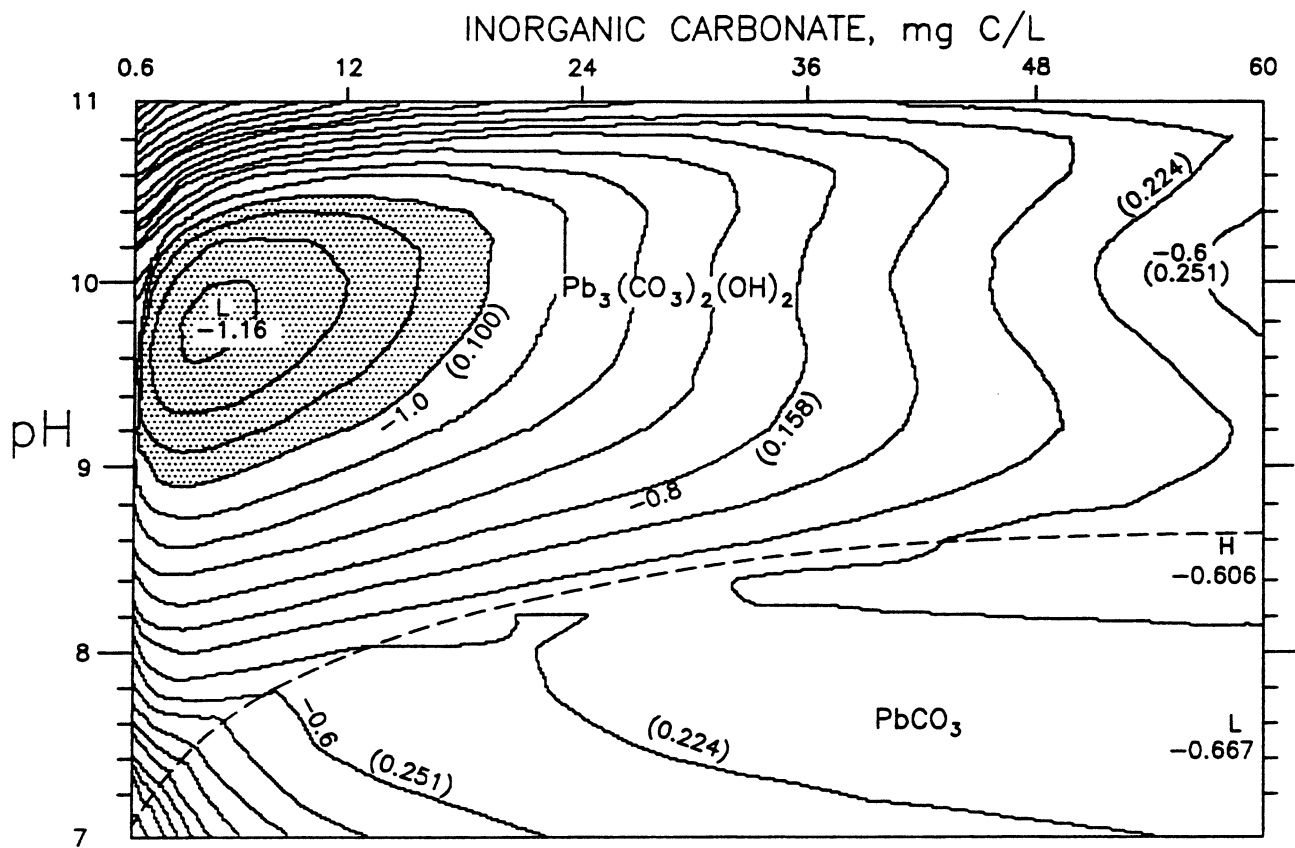


FIGURE 3.
DISSOLVED INORGANIC CARBONATE VERSUS pH:NO
PHOSPHATE, $I=0.01$, $T=25^\circ C$
(NOTE: TAKEN FROM AWWARF, 1990)

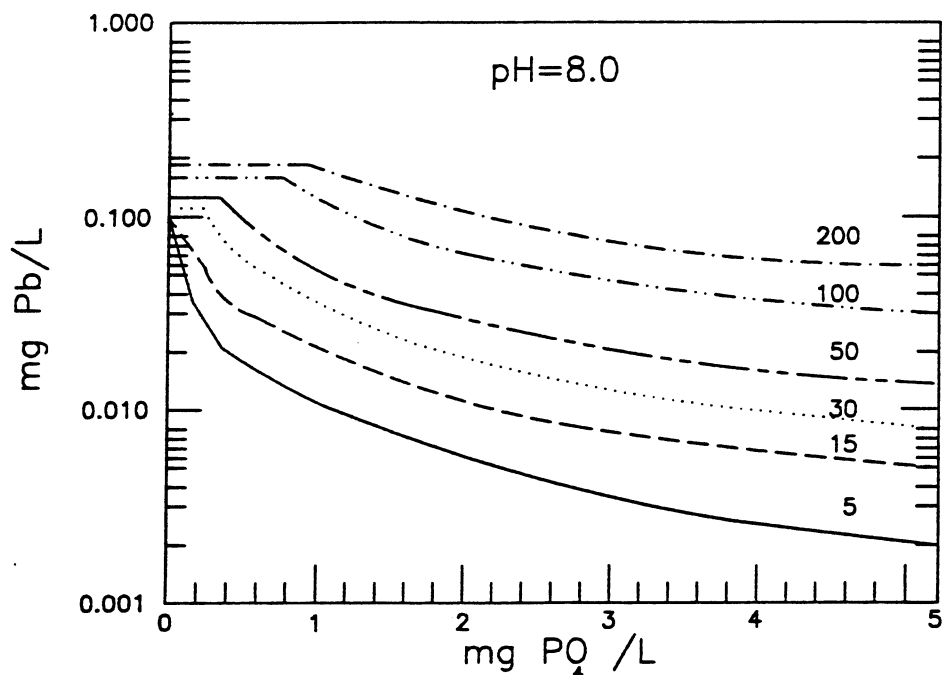
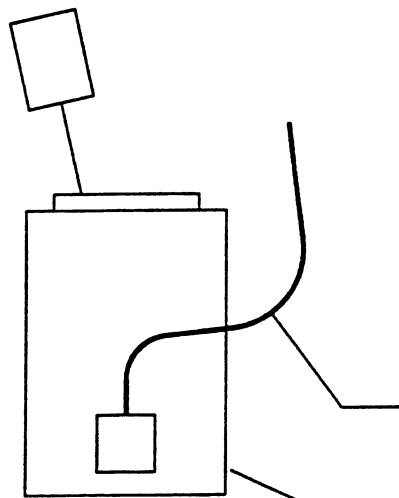
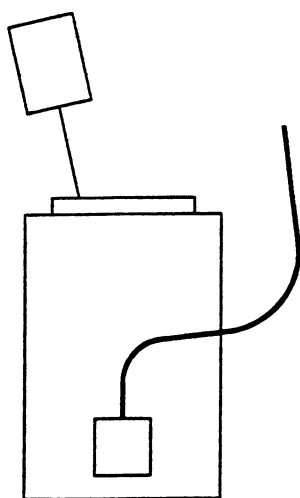
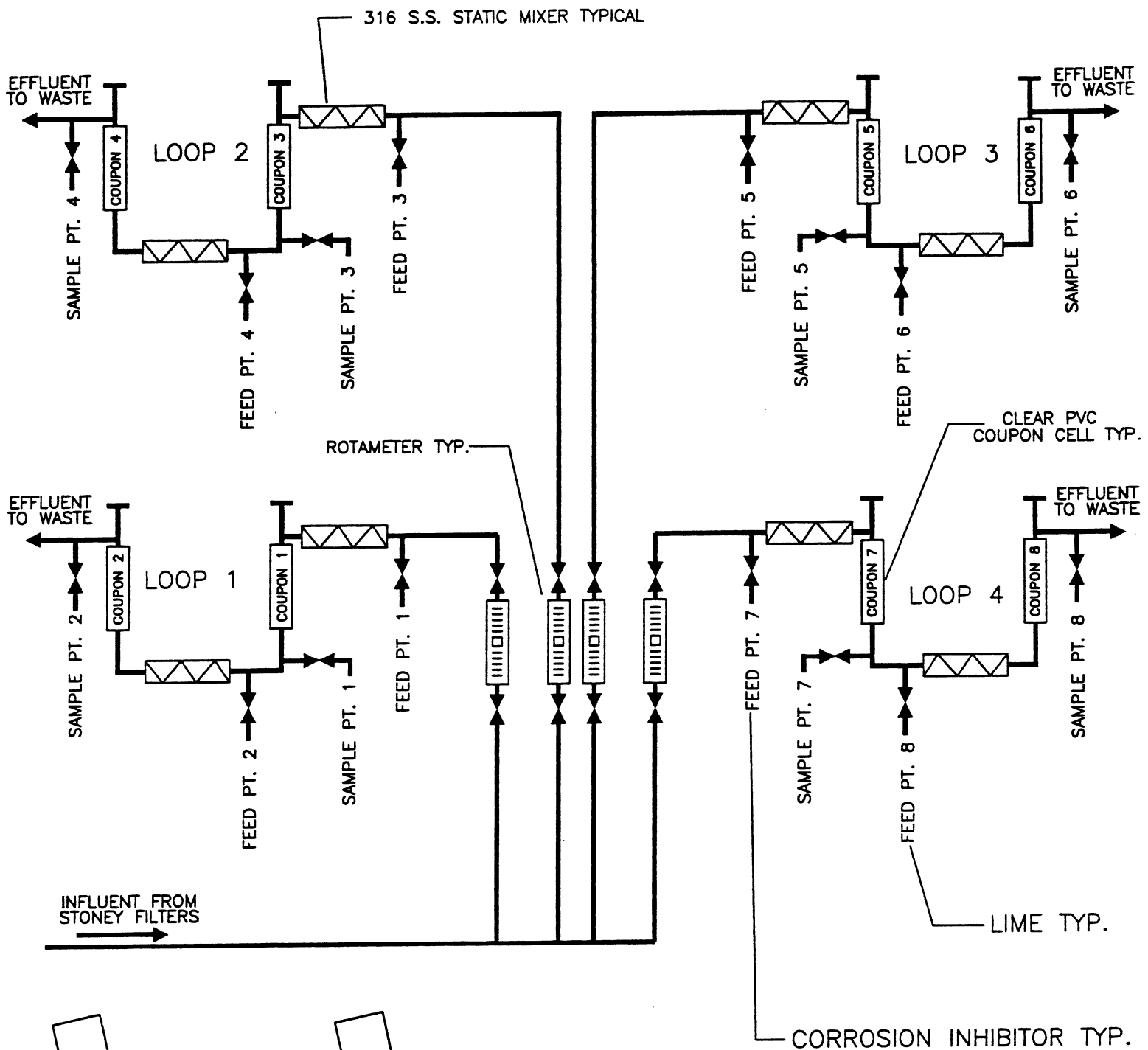


FIGURE 4.
LEAD SOLUBILITY VERSUS ORTHOPHOSPHATE AT
VARIOUS ALKALINITIES: pH=8.0, $I=0.005$, $T=25^\circ C$
(NOTE: TAKEN FROM AWWARF, 1990)



NOTES:

1. ALL MATERIALS ARE PVC UNLESS NOTED OTHERWISE.

POLYETHYLENE TUBING TO CHEMICAL FEED POINTS.

POLYETHYLENE CHEMICAL TANK AND CHEMICAL PUMP, 8 EA. REQ'D.

FIGURE 5. CORROSION CONTROL PILOT SYSTEM.

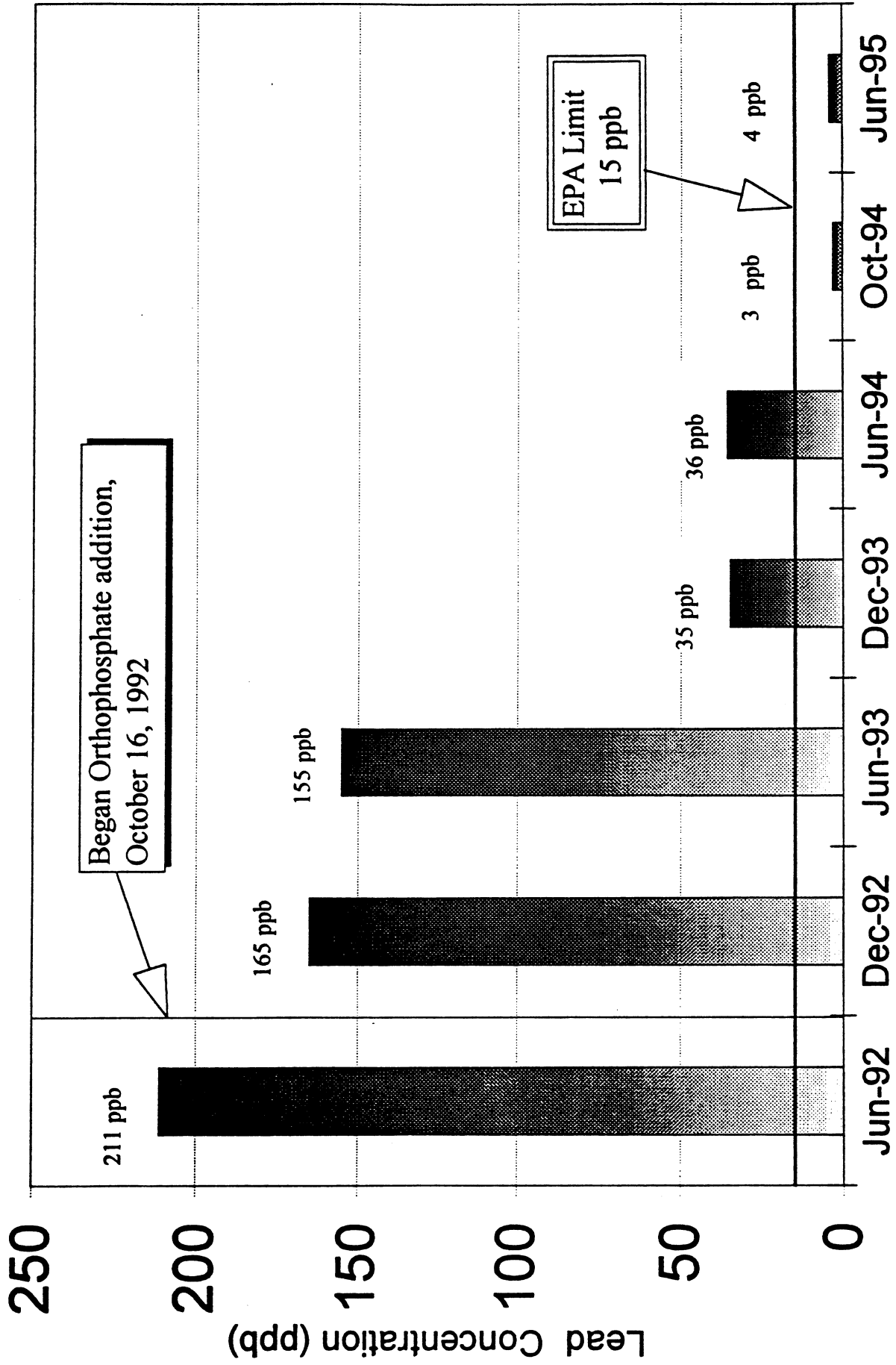


Figure 6: 95th percentile level for Tier I sampling

January 1991 through December 1995

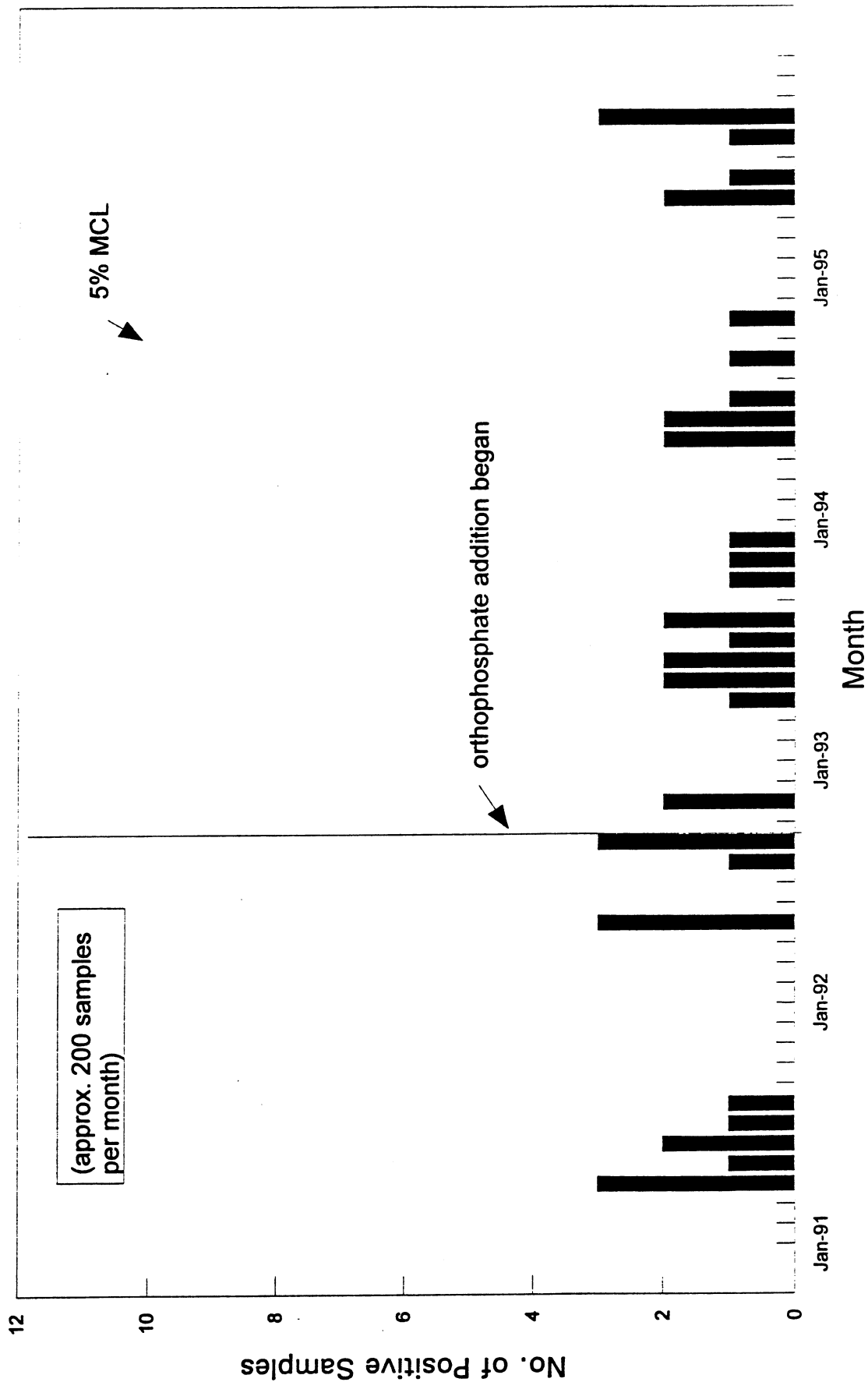


Figure 7. Incidence of Total Coliform Positive Samples

