



## Project Summary

# Corrosion in Water Distribution Systems of the Pacific Northwest

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Continuous linear polarization measurements (10-min increments) of corrosion rates on copper surfaces demonstrated an immediate response to changing water quality conditions found in Pacific Northwest distribution systems. Significant relationships were found between copper corrosion rates, pH, and free chlorine residual in these low-mineral waters. Regression analysis of copper corrosion rates versus four common chemical quality parameters was used to develop a statistical model of the relationship of copper corrosion to changing water quality conditions.

This study evaluated the impact of changing water quality conditions on copper surfaces coated with varying depths of oxide films. The presence of a well aged film (greater than 50  $\mu\text{m}$  depth) generally decreased the corrosion rate by more than 50 percent when compared with corrosion on surfaces coated with a relatively fresh film layer (less than 20  $\mu\text{m}$  depth).

The Seattle Water Department's program of corrosion control through lime and soda ash addition was evaluated during its 12-month implementation period. A gradual pH increase of approximately 2.0 units during this period decreased the corrosion rates of aged copper surfaces by approximately 9  $\mu\text{m}/\text{year}$ .

Selected chemical water quality parameters were measured in the distribution networks of Seattle, Tacoma, and Anacortes. Significant differences in quality variation were found as a function of distribution level. The higher the distribution level (i.e., the closer to the consumer tap), the

greater the degree of variation. More elaborate treatment processes (rapid sand filtration preceded by coagulation and flocculation) induced a greater degree of variation in the distribution system than systems that did not filter their water.

Particle counts and turbidity levels in the distribution system were only partially correlated. The strongest turbidity correlation was found for particles of less than 10- $\mu\text{m}$  diameter, which also constituted the great majority of particles in all the waters measured.

*This Project Summary was developed by EPA's Water Engineering Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).*

## Introduction

The Pacific Northwest has some exceptionally pristine surface water sources of unusually low mineral content and high clarity. These sources are extremely low in alkalinity, pH, and buffer intensity, and they are undersaturated with respect to  $\text{CaCO}_3$ . The potential for deposition of protective carbonate films is minimal, and excessive metal corrosion on plumbing appurtenances is a common problem.

The general objective of this study was to demonstrate the effectiveness and capabilities of the U.S. Environmental Protection Agency mobile water quality monitoring laboratory (MWQML) in

monitoring the variation of water quality parameters and the impact of chemical dosing on corrosion rates in water systems of the Pacific Northwest. Other activities included evaluation of the Seattle Water Department's corrosion control program, determination of how instantaneous copper corrosion rates are affected by short-term variation in selected water quality parameters, and an assessment of the relationship between distribution system water quality and distribution level, raw water source, and treatment level.

The communities of Seattle, Tacoma, and Anacortes participated in this study. Selection was based on raw water source (which for all cases was surface water originating on the western slopes of the Cascade Mountains), the type of treatment provided, and the history of corrosion-related problems within the system. Table 1 summarizes some basic information about the sampling program distribution systems

## Procedures

The MWQML is a self-contained, mobile, microprocessor-controlled laboratory capable of continuously sampling, analyzing, and recording 20 water quality and corrosion parameters. Specific capabilities of the MWQML are directed at the automated monitoring of common chemical quality parameters in the distribution system, including pH, temperature, conductivity, chlorine residual, turbidity, alkalinity, hardness, chloride, and others. Specialized instrumentation includes a three-channel Petrolite\* linear-polarization corrosion-rate monitor, an HIAC/Royko particle counter, and an Ionics digital titrator. Control and data acquisition functions are provided by an HP 9845B microprocessor. Data storage is on floppy disk.

Standard procedure was to locate the MWQML at selected sampling sites within the distribution systems for periods of 2 to 4 weeks. This time was necessary to develop a sufficient data base of diurnal chemical variations. Sampling sites included endline user taps, raw water sources, reservoir outlets, water blending points, and other points of interest within the systems. Data collected and stored by the MWQML were periodically uploaded by means of modem connection to the Cyber 1500

**Table 1.** Information Summary on Sampling Program Distribution Systems

Service Community	Raw Water Pop.	Source	Treatment
Seattle (North)	500,000+	So. Fork Tolt River	Screening and $Cl_2$ and F-corrosion control initiated 6/82
Tacoma	70,000+	Green River	$Cl_2$ only
Anacortes	20,000+	Skagit River	$Cl_2$ , coagulation, flocculation, and rapid sand filtration

system at the University of Washington Academic Computing Center. Basic statistical analysis and data reduction were performed using the 1984 edition of "Minitab" from Pennsylvania State University.

Corrosion rate measurements were made with a three-channel Petrolite model 1000 linear polarization instrument. Two different sets of copper electrodes were used to approximate copper plumbing with different degrees of oxide coating and age. The fresh electrode set was relatively clean and covered with a cuprous oxide layer of less than 20  $\mu m$  depth. The aged electrode set was coated with a heavy oxide layer exceeding 50  $\mu m$ .

## Results and Discussion

### The Seattle Corrosion Control Program

Seattle began its program of corrosion control in June 1982. The program called for the gradual increase of distribution water pH and alkalinity through the addition of lime and soda ash. Target dosages for the two chemicals were 2.0 and 9.0 mg/L, respectively, which resulted in an average overall alkalinity increase of 5.0 to 17.0 mg/L (as  $CaCO_3$ ). The adjustment period extended over 12 months. During this period, copper corrosion rates were measured on aged surfaces at selected sites throughout the northern Seattle distribution area. Figure 1 summarizes weekly median pH values and aged copper surface corrosion rates during the adjustment period. Overall, the pH was shifted from a median distribution level of 5.8 at the beginning of the program to a median level of 7.7 after 12 months of operation, producing a reciprocal decrease in corrosion rates from a weekly average of 20 to 12  $\mu m/y$

year, a decrease of approximately 40 percent.

Figure 2 presents a graph of weekly median rates for aged copper corrosion as a function of median pH. The inverse relationship between pH and the distribution copper corrosion rate is clear.

### Water Quality Variation and Copper Corrosion

Monitoring for short-term water quality variations and their impact on copper corrosion rates was conducted at several points in each of the sampled distribution systems. Figure 3 presents a 5-day summary of water quality and copper corrosion rate variations at one end-line tap in the northern Seattle distribution area. The strong positive correlation of both the aged and fresh electrode corrosion rates with the free chlorine residual is apparent. Also clear is a pronounced inverse relationship of the corrosion rates with the pH changes, including the larger pH spikes. Influence of temperature and conductivity are not readily apparent.

Multiple linear regression on lumped data sets was performed to evaluate the relative importance of the four water quality parameters on both the fresh and aged copper surfaces. A forward, stepwise regression was used with four independent parameters regressed in the following order: (1) pH, (2) free chlorine, (3) temperature, (4) conductivity. Table 2 presents the linear regression model developed for corrosion rates on the aged and fresh surfaces. Table 3 presents the analysis of variance (ANOVA) for the two regression models. From this table, it is apparent that the regression models account for 95 and 76 percent, respectively, of the overall corrosion rate variance on the two surfaces, and that in both cases, the free chlorine residual is the most significant predictor.

\*Mention of trade names or commercial products does not constitute endorsement or recommendation for use

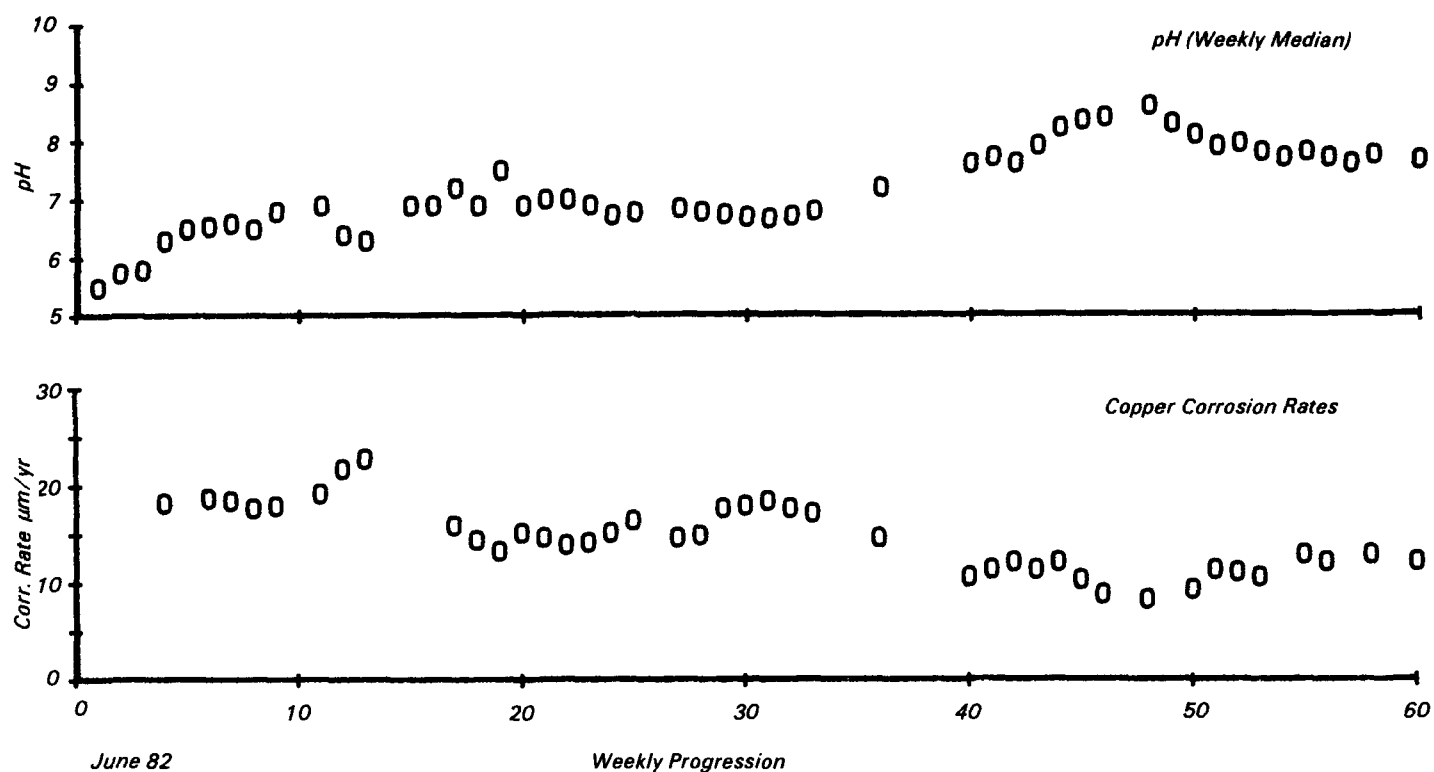


Figure 1. Average weekly pH and copper corrosion rates in the Tolt distribution area during the first year of the control program.

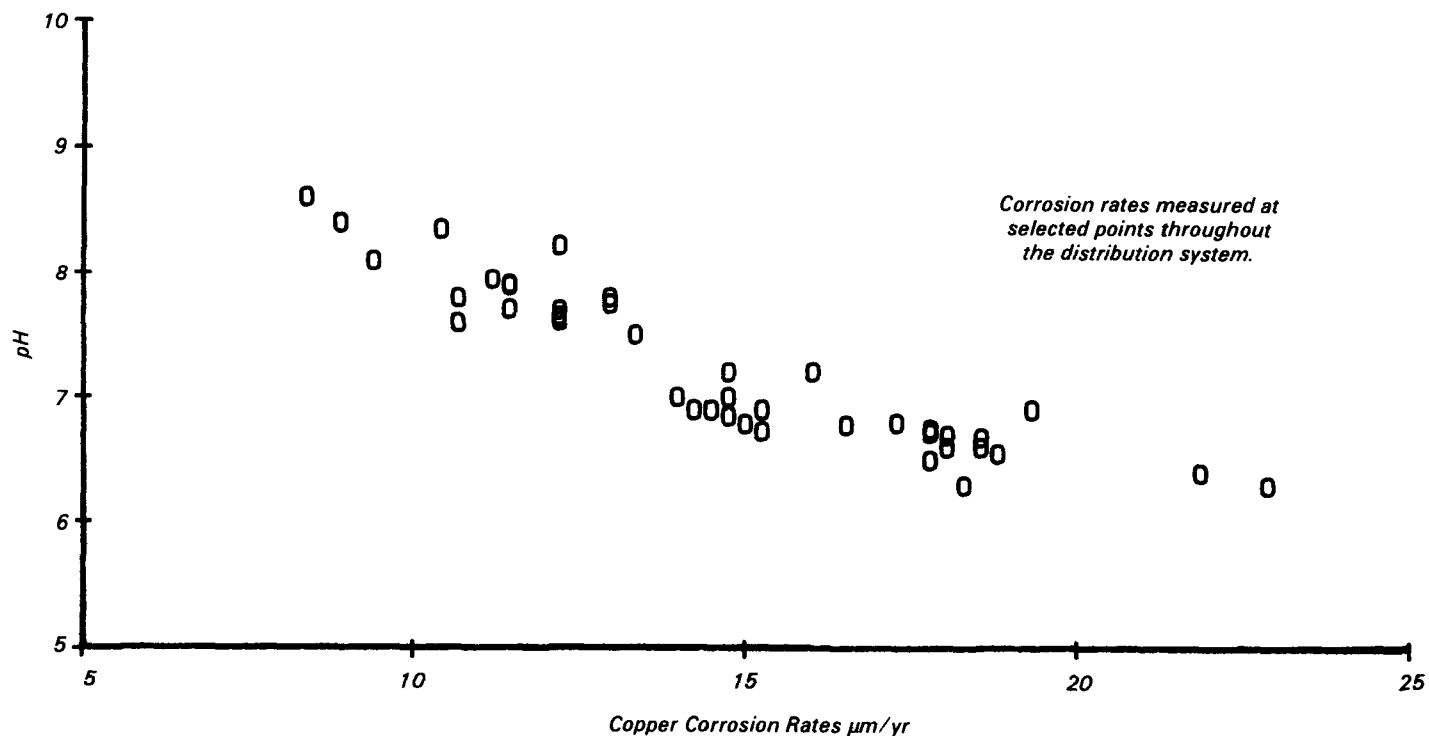
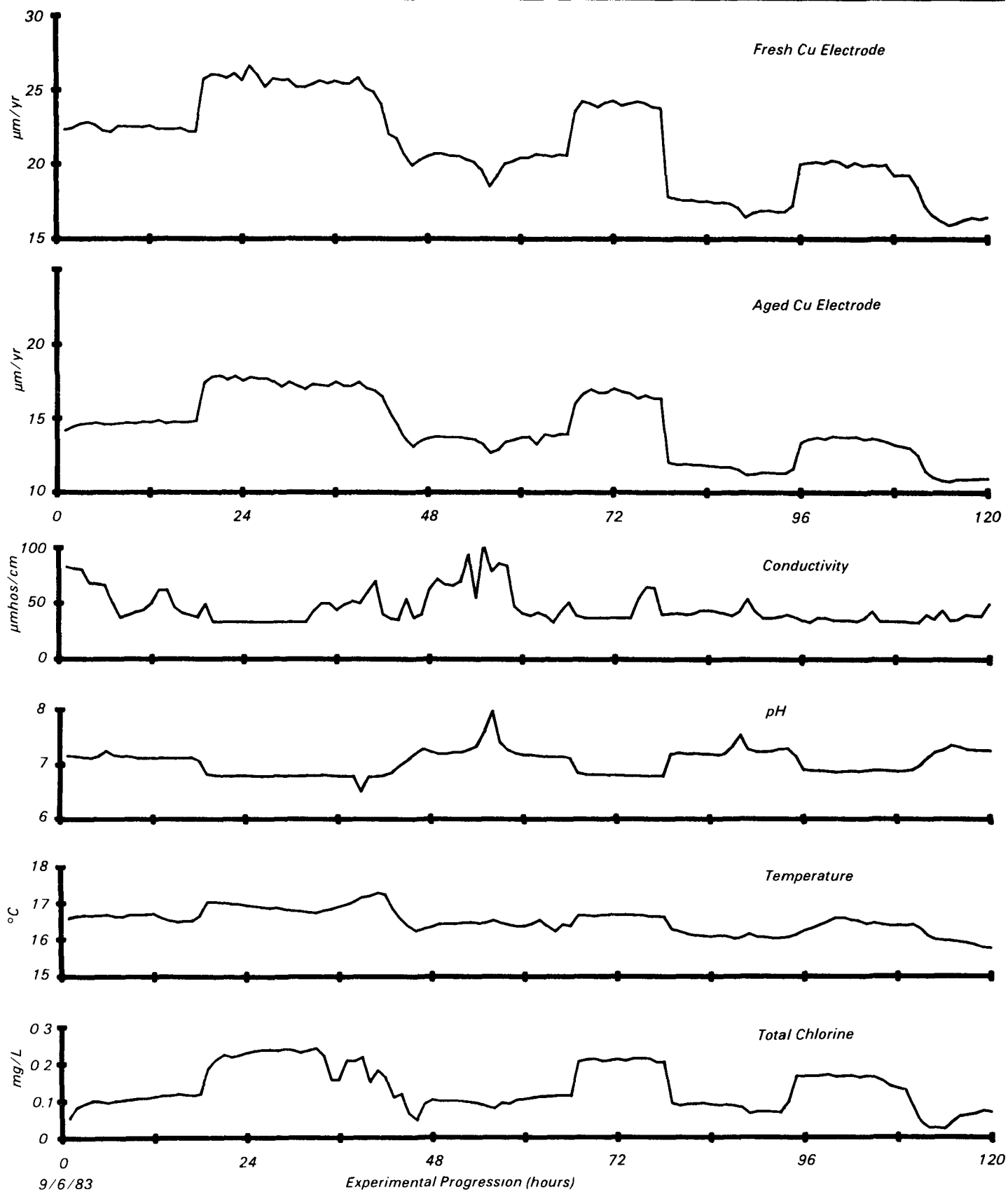


Figure 2. Copper corrosion rates in the Seattle System as a function of weekly median pH.



**Figure 3.** Variation of water quality and corrosion rate with time (data set S906).

**Table 2.** Linear Regression Models of Copper Corrosion on Aged and Fresh Surfaces

Parameter	Units	Coefficient	
		Aged Surface	Fresh Surface
Corrosion rate	$\mu\text{m}/\text{year}$		
Y intercept	—	0.553	1.820
pH	pH units	-0.078	-0.091
Free chlorine residual	mg/L	0.810	1.013
Temperature	$^{\circ}\text{C}$	0.026	0.013
Conductivity	$\mu\text{mhos}/\text{cm}$	0.005	0.0009

**Table 3.** Analysis of Variance for Aged and Fresh Copper Surface Corrosion Regression Models

Item	Degrees of Freedom	Sequential Sum of Squares		Coefficient of Determination $R^2$	
		Aged	Fresh	Aged	Fresh
Total	350	2.357	1.543		
Residual	346	0.118	0.373		
Regression	4	2.238	1.170	0.950	0.758
pH	1	0.354	0.001	0.15	0.001
Free Chlorine	1	1.491	1.055	0.632	0.684
Temperature	1	0.385	0.076	0.163	0.050
Conductivity	1	0.008	0.036	0.003	0.023

### Quality Variation in the Distribution Network

In each of the sampled communities, comparisons were made of specific chemical parameters at different levels of the distribution system to evaluate the impact of residence time and system contact on parameter variability. One example appears in Figure 4 where free chlorine residual at the point of discharge from the Anacortes treatment plant is compared with the residual found at an end-line tap at the extreme end of the distribution system. Water discharged from the plant carries a residual that varies erratically from 0.4 to 0.6 mg/L. The unevenness of the residual is apparently due to minor flow and dosage variations and incomplete mixing in the clear well. Chlorine residuals at the consumer tap are not erratic, but they show a smooth and pronounced diurnal variation. The highest concentration corresponds with the period of peak demand, indicating that retention time in the system affects residual levels. Presumably, longer contact times provide greater opportunity for chlorine depletion through reaction with plumbing materials and dissolved chlorine-consuming substances. Similar variation and periodicity were observed in other chemical and corrosion parameters in all of the distribution systems examined.

### Turbidity Versus Particle Concentration

For the northern Seattle distribution system, a comparison was made of turbidity values measured by a continuous-flow-ratio turbidimeter with particle concentrations measured by an HIAC/Royko counter. Figure 5 presents 4 days of concurrent turbidity and particle data, with the latter broken down into three different size ranges. A moderately strong correlation exists between the smallest particle size concentration and the turbidity data ( $R = .687$ ). However, the correlation diminishes dramatically for the larger particle concentrations. These and other results indicate that the smaller particle sizes (less than  $2\ \mu\text{m}$  diameter), which numerically make up the great majority of particles in all the distribution systems examined, also contribute the most to turbidity variation.

Regression analysis of turbidity data using the three particle-size-range concentrations as the independent predictors showed that the particle concentrations accounted for only 50 percent of the observed turbidity variation. Filtered particle samples were examined by scanning electron microscopy, which revealed that the bulk of the smaller particles consisted of siliceous diatom skeletons and mineral agglomerates. Evidence indicates that the mineral agglomerates may be cor-

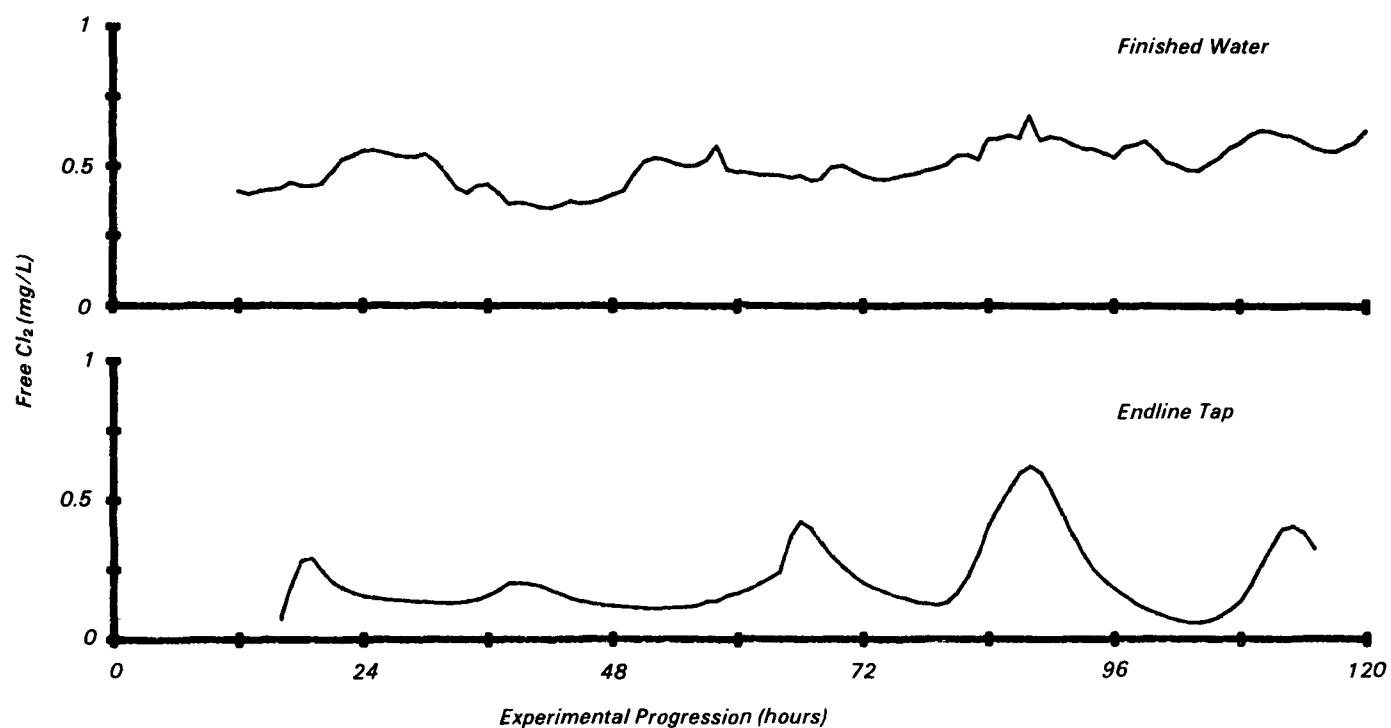
rosion products generated on exposed steel surfaces in the distribution system. Most of the observed diatom forms were common to clean surface water sources and may result from algae growth in impoundments and on open reservoir embankments.

### Conclusions

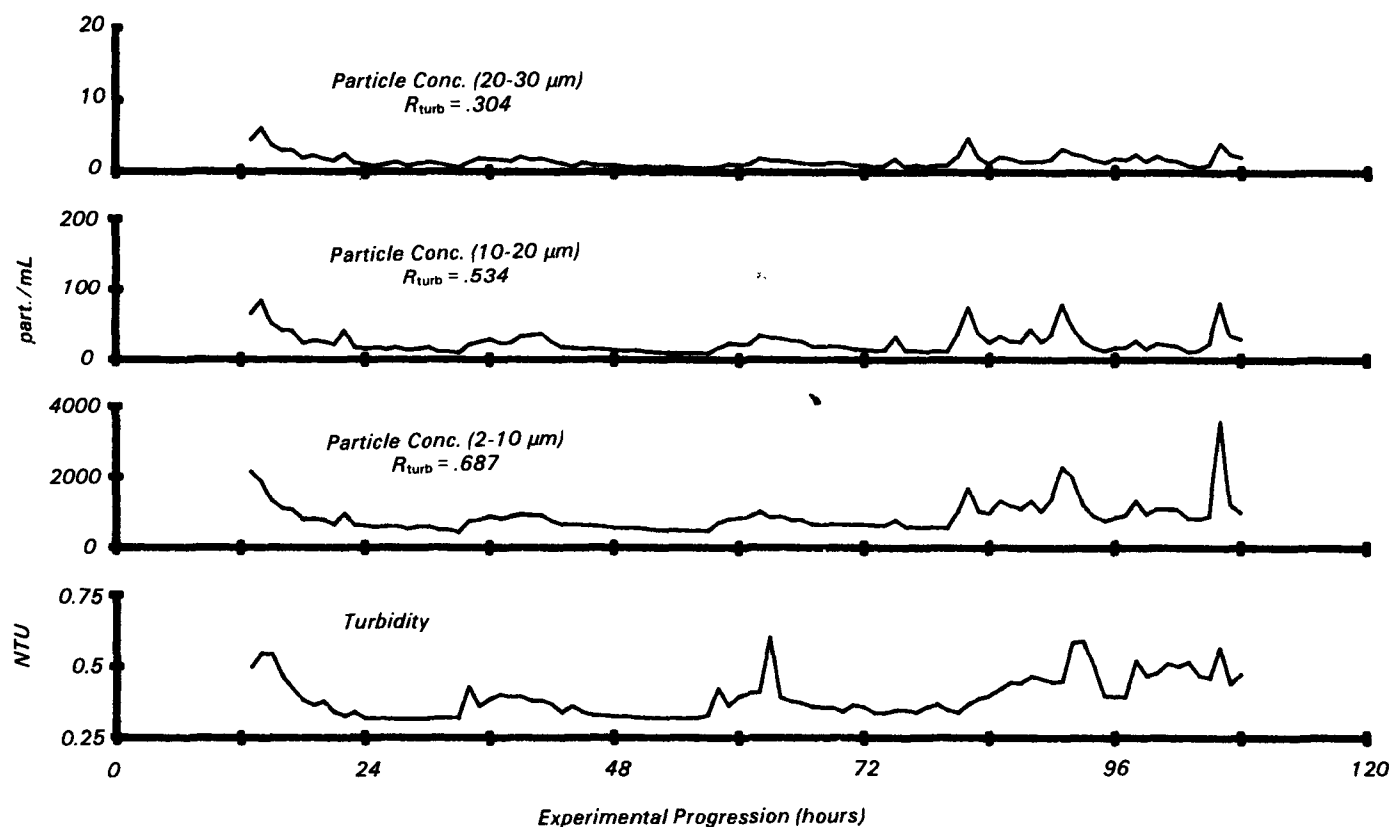
This study has explored the relationship between water quality variation distribution system location and copper corrosion rates. Some of the principal conclusions drawn from the study are as follows:

1. Seattle's program of corrosion control through moderate pH adjustment and alkalinity addition has effectively reduced corrosion of copper plumbing materials by approximately 40 percent.
2. Free chlorine residual is the most important of the common water quality parameters for predicting copper corrosion rates. In some cases over half of the variation in corrosion rate can be attributed to variation in the free chlorine residual.
3. Variable distribution system residence time as a result of demand cycling can induce substantial variation in pH, turbidity, and chlorine residual of the delivered water. Some treatment processes (filtration, coagulation/flocculation) induce further variation by chemically destabilizing the water, which is followed by reequilibration within the distribution system.
4. Turbidity is only partially useful as a predictor of particle concentration. Small particles of less than  $5\text{-}\mu\text{m}$  diameter correlate most closely with turbidity levels, however, the concentration variation of all size ranges studied accounted for only 60 percent of the overall variation in observed turbidity levels.

The full report was submitted in fulfillment of Cooperative Agreement No. 810508 by the Department of Civil Engineering, University of Washington, under the sponsorship of the U.S. Environmental Protection Agency.



**Figure 4.** Comparison of free chlorine residuals in finished and delivered water in the Anacortes System.



**Figure 5.** Comparison of turbidity and particle concentrations in the Seattle Water Distribution System (U. of Wa. Campus).

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**Marvin Gardels** is the EPA Project Officer (see below).

*The complete report entitled "Corrosion in Water Distribution Systems of the Pacific Northwest," (Order No. PB 87-197 521/AS; Cost: \$13.95, subject to change)*

*will be available only from:*

*National Technical Information Service*

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