Use of Aeration to Control Copper Corrosion in a Small Public Water System, in Florence, Montana

MBMG 400A

Prepared for the Drinking Water Assistance Program
Montanan State University
October 2000

Barbara J. Keller
Department of Chemistry
Lake Superior State University
Sault Ste. Marie, MI 49783

Ginette N. Abdo
Montana Bureau of Mines and Geology
Montana Tech of the University of Montana
Butte, MT 59701

Gretchen Rupp
Montana Water Center
Montana State University
Bozeman, MT 59717

Use of Aeration to Control Copper Corrosion in a Small Montana System

Abstract

Aeration of drinking water has been shown to directly impact the water's pH and dissolved inorganic carbon (DIC) content. Because of these impacts, aeration has been suggested as a useful technique to treat drinking water for copper corrosion provided the drinking water pH is less than 7 and DIC levels are *greater than 10 milligrams per liter*. In this study, aeration was applied to control copper corrosion in a small public water system, the Forest View Homeowners System, in Florence, Montana and was evaluated for 1) its ability to reduce copper concentrations; 2) its ease of installation and operation; and 3) its cost to a small system.

Introduction

Lead and Copper rule. In order to protect the public health, the US Environmental Protection Agency (EPA), in 1991, issued the National Primary Drinking Water Regulations (NPDWRs) for Lead and Copper, also known as the Lead and Copper Rule (EPA, 1991, 1991a, and 1992). The Lead and Copper Rule:

- requires all community and non-transient non-community water systems to monitor for lead and copper;
- establishes treatment technique requirements if the lead and copper levels exceed the "action levels" in ten percent of the tap water samples collected during any monitoring period.

The Rule sets the "action levels" for lead and copper at 0.015 mg/L and 1.3 mg/L, respectively. The treatment technique requirements include corrosion control treatment, source water treatment, lead service line replacement, and public education. Water systems that exceed the lead and/or copper "action level" are required to recommend a method of corrosion treatment or perform studies to determine the most effective method for corrosion treatment.

The financial impact of the Lead and Copper Rule is significant. According to EPA (1993), "the total capital costs are estimated to be between $2.9 and $7.6 billion; operation and maintenance costs, $240 million per year; and total annualized costs, between $500 and $790 million." Because larger water utilities have been practicing corrosion control for many years their treatment costs will probably not be significant (EPA, 1993). Unfortunately, acceptable treatment technology is often expensive and operationally burdensome for small public water systems. The EPA estimates that the costs incurred by smaller systems to 1) conduct corrosion control studies; and 2) operate and maintain corrosion control treatment will be up to $15,000 and $1500/year, respectively (EPA, 1993). Therefore, there is a need for treatment technologies that will provide an affordable and operationally practical means to meet the requirements of the Lead and Copper Rule in rural communities.

Copper corrosion. Drinking-water copper that exceeds the action level rarely arises from the source water. Its primary cause is the corrosion of plumbing materials (EPA, 1995). Corrosive water attacks the plumbing and releases copper into the water that is passing through the copper pipes on its way to drinking water taps.

The initial corrosion rate of the metal in new piping is relatively rapid, but over time, as precipitates deposit on the pipe and form a scale, the corrosion slows down or is passivated. The scale or deposits themselves are subject to secondary reactions of dissolution depending upon the chemical parameters and/or constituents present in the water passing through the piping. Some of these chemical parameters/constituents include the water pH, redox potential, dissolved inorganic carbon (DIC), and dissolved oxygen (DO).

Types of treatment. Several types of treatment technologies have been specified by the Lead and Copper Rule as technologies which might be appropriate for removal of lead and copper. Those technologies include:

- Ion exchange
- Reverse osmosis
- Limestone contactors
- Coagulation/filtration

Recent studies have also suggested that aeration might also be an appropriate technology for controlling lead and copper corrosion (EPA, 1995).

Several factors must be considered when choosing the appropriate technology for treating copper corrosion. The initial water quality of the system is of paramount importance when deciding upon a treatment strategy. At a minimum, factors such as water pH, hardness, alkalinity, DIC, and $CaCO_3$ are critical in choosing the appropriate technology (EPA, 1997; EPA, 1995). Additional factors such as iron and manganese concentrations are also consideredwhen evaluating the efficacy of the treatment techniques. Guidance manuals and flow charts (figure 1) are available to aid in the selection of the appropriate treatment technology (EPA, 1997).

Aeration chemistry

The degree with which aeration impacts corrosion is directly related to the raw ground-water quality and the efficiency with which the aeration process removes $CO_{2\,(aq)}$ from the ground water**.** Some of the ground-water parameters that directly impact the aeration process include pH, DIC, DO, and calcium (Lytle and others, 1998). Aeration works by reducing the amount of DIC in the water and raising the pH of the water. Copper corrosion rates are directly impacted by the resulting changes in the water chemistry (i.e., increased pH and decreased DIC) caused by aeration (AWWA, 1990; EPA, 1995; Edwards and others, 1993, 1996; Ferguson and others, 1996; Lytle and others, 1998; Rehring and others, 1994; Schock and others, 1994; Schock and others, 1995)**.**

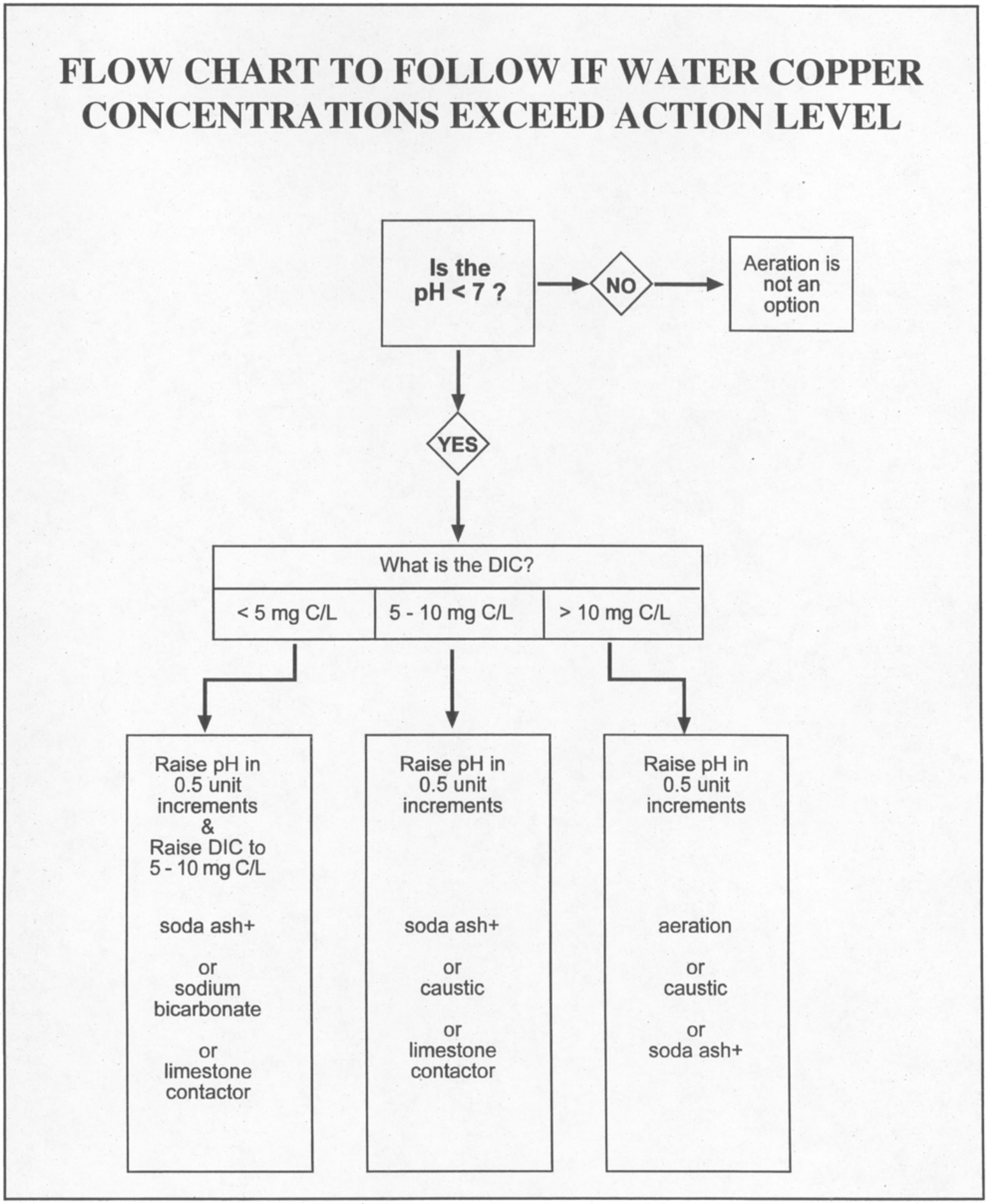

Figure 1. Flow Chart developed by *Black and Veatch*[6] to determine if aeration is the appropriate treatment technology for a corrosive ground water

In carbonate based ground-water systems the following reactions dominate the carbonate chemistry in the ground water (Stumm and Morgan, 1996):

Reaction	Reaction Equilibrium Constant
$(CO_2 \cdot aq) + H_2CO_3 = 2H_2CO_3^*$	K
$H_2CO_3^* = H^+ + HCO_3^-$	K_1
$H_2CO_3 = H^+ + HCO_3^-$	K_{H2CO3}
$HCO_3^- = H^+ + CO_3^{2-}$	K_2
$H_2O = H^+ + OH^-$	K_w

where DIC is comprised of H_2CO_3, HCO_3^-, and CO_3^{2-} plus any carbonate-containing metal ion pairs and complexes.

Below pH = pK_1, aqueous CO_2 is the dominant carbonate species. Aeration works to transfer CO_2 from the water phase into the air phase. The transfer of CO_2 between air and water will continue until an equilibrium between the two is reached (provided aeration is given adequate time). The removal of the aqueous carbon dioxide, $(CO_2 \cdot aq)$, into the air causes the system to seek to replace the $(CO_2 \cdot aq)$ component. In order to do this the chemical reactions shown above shift in the reverse direction (to the left). When this happens, the concentration of H^+ and H_2CO_3 are reduced and the water pH and DIC increase and decrease, respectively.

Lytle and others (1998) have shown that the pH change resulting from aeration can be closely approximated from:

$$pH_f = pH_i - \log[CO_{2f} / CO_{2i}] \qquad (1)$$

where pH_i is the initial pH, pH_f is the pH of the aerated water, CO_{2i} is the CO_2 concentration of the initial water, and CO_{2f} is the CO_2 concentration of the aerated water**.** Additionally, Lytle and others (1998) or is it have calculated the initial DIC and theoretical DIC at CO_2 equilibrium by using the pH and corresponding total alkalinity for either initial or theoretical conditions of equilibrium with atmospheric CO_2 from:

$$DIC = (1 + K_2/[H^+] + [H^+]/K_1) \left(\frac{\text{Alkalinity} - (K_w/[H^+] + [H^+]}{1 + (2K_2/[H^+])} \right) \qquad (2)$$

where [ ] represents molar concentrations and alkalinity is expressed as eq/L. The theoretical DIC removed during aeration is calculated as the difference between the initial DIC and the equilibrium DIC (Lytle and others, 1998).

The typical chemical profile for water collected at the Forest View Homeowners Association is listed below in the section on **Test site.**

Test site

The aeration testing was carried out a small public water system in Florence, Montana. Florence is located in the Bitterroot Valley in northwestern Montana. Since the mid-nineteen eighties, the valley has been experiencing significant population growth. Florence currently has a population of 2,000, and drinking water is primarily obtained through domestic wells and small public water supplies that draw on ground water. Due to the water's corrosive nature, lead and copper concentrations have exceeded action levels in taps in many of the small systems.

For this study, the aeration treatment technology was tested at the Forest View Homeowners Association, a water system in Florence that serves twenty-four homes. The water system relies on a primary well and a backup well (which provides water only during times of high water demand). The two wells are located approximately 1/4 mile apart. Both wells are relatively shallow, ranging in depth from 40 to 60 feet. The backup well is located at an elevation five feet higher than the primary well. The water from each well is stored in pressurized storage tanks (each well having its own tanks) prior to distribution to the homes. The water is pumped from the primary well at a rate of 60 gpm. Figure 2 is a schematic of the Forest View pumphouse for the primary well (prior to aeration). The typical chemical profile of the water collected from the homes at the Forest View Homeowners Association includes:

1) pH ranging from 6.4 to 7.1;
2) alkalinity ranging from 22 to 43 mg/L as $CaCO_3$;
3) lead concentrations ranging from non-detect to 0.02 mg/L ;
4) copper concentrations ranging from non-detect to 5.6 mg/L;
5) iron and manganese concentrations ranging from non-detect to 0.001 mg/L (for both).

Note that lead concentrations were not an issue at the Forest View Homeowners Association; only copper concentrations had historically exceeded the "action level" (1.3 mg/l). Using equation (2) the typical profile for DIC was calculated to be 11 mg/L to 23 mg/L. Because the pH was generally less than 7.0, and the DIC greater than 10 mg/l, the flow charts developed by Black and Veatch (EPA, 1997) (figure 1) indicated that aeration was one of the viable treatment options.

Aeration treatment system

Aerator system. The aeration system installed at Forest View has several components: 1) a 6-stage air diffusion tank (figure 3); 2) a 200 gallon clearwell storage tank; 3) a 215 cfm, 2.5 hp air blower; 4) a 5 hp centrifugal pump for re-pressurizing the water; and 5) a wall-mounted control panel (Lowry Aeration Systems, 1997).

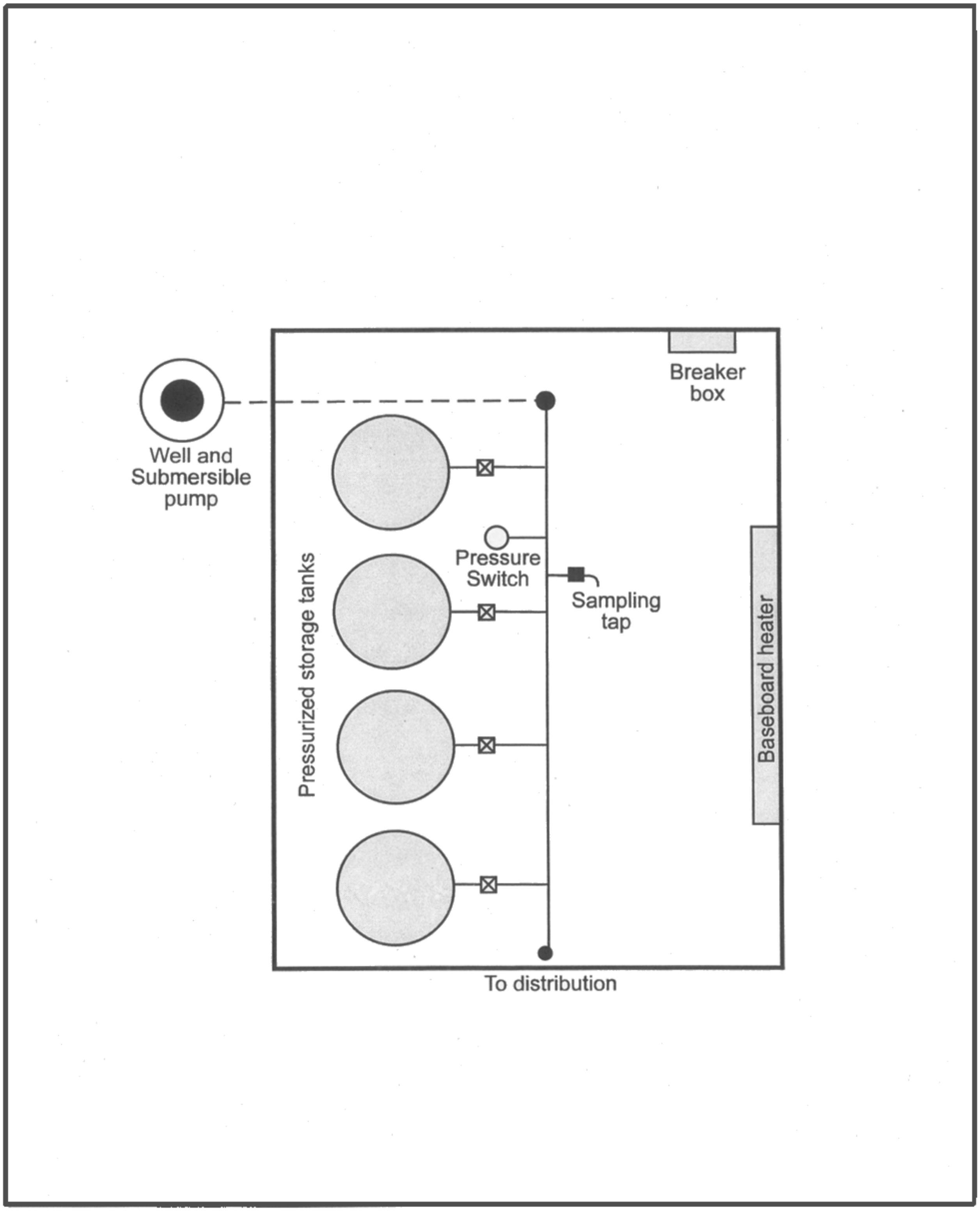

Figure 2. Schematic of the Forest View Homeowners Association pumphouse prior to expansion to accommodate the aeration system.

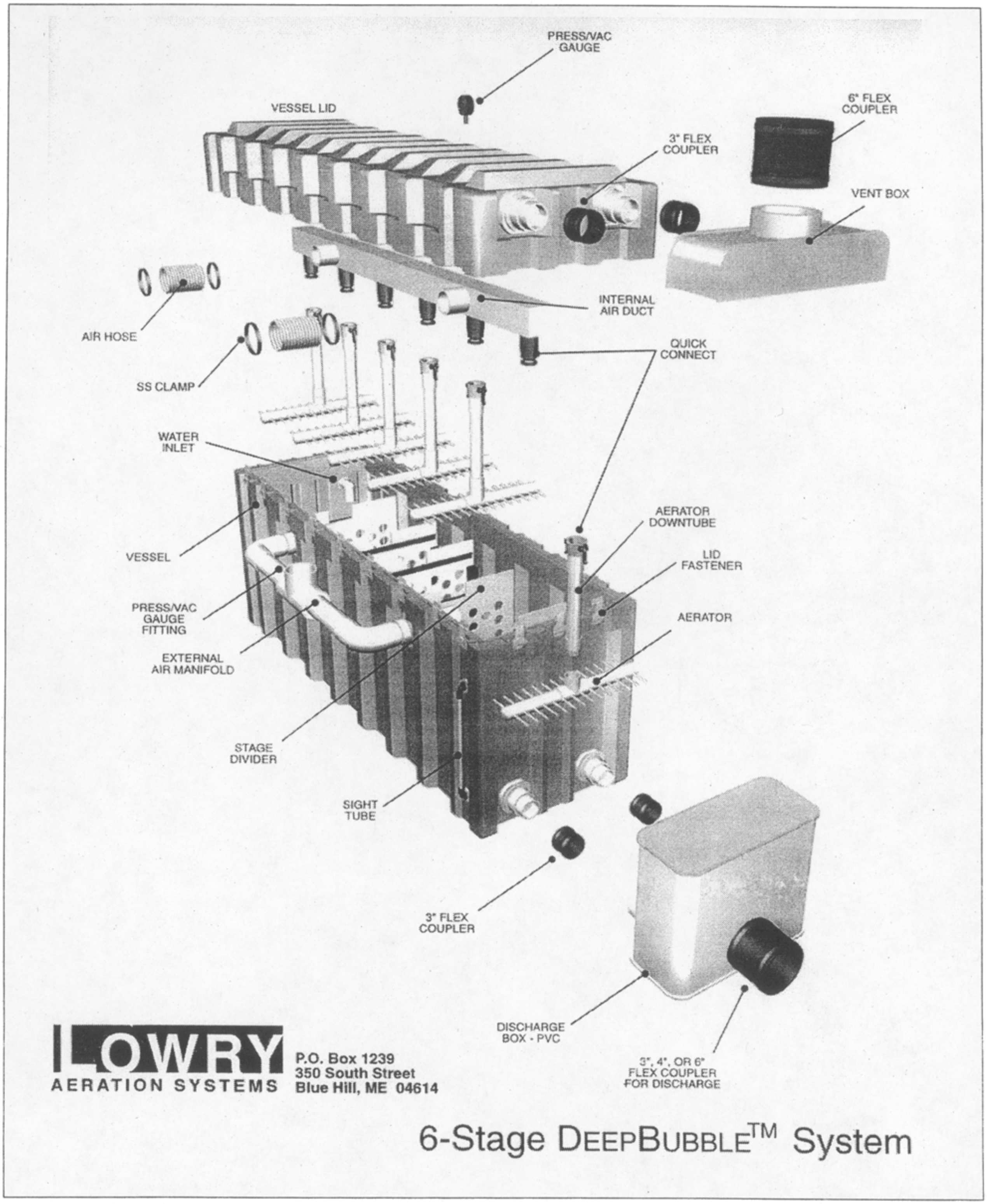

Figure 3. Schematic of Lowry's 6-Stage DeepBubble™System[17], the aerator component of the aeration system.

In the Forest View pumphouse the ground water is pumped at 60 gpm into the diffuser tank, where the water pressure is reduced to atmospheric pressure. Filtered outside air is forced by the blower through the six aerators in the bottom of the aeration tank. The aerated ground water then passes into the clearwell storage tank, while the air containing the removed carbon dioxide is vented to the atmosphere. From the clearwell the water is pumped into the pressure tanks and ultimately flows through an UV disinfection system to the distribution system. Controls for the system are dependent on the water demand. Four separate pressure and water-level sensors control system pressure from 40 to 60 psi.

Disinfection. Forest View water had never been disinfected before aerator installation. Because aeration involves vigorous mixing with ambient air disinfection was required by the Montana Department of Environmental Quality. The Forest View homeowners were adamant that no chemicals be added to their water, so ultraviolet disinfection downstream from the pressure tanks was specified.

Installation of the treatment system. The pumphouse was enlarged to twice its original size in December 1997; much of the labor was contributed by the homeowners. Figure 4 is a schematic of the pumphouse after the installation (compare to figure 2, which is a schematic prior to the installation). System installation was completed in February 1998 and treatment of the ground water began on February 16, 1998.

Maintenance for the aeration system. The maintenance of the aeration system is relatively easy to perform. Three components are checked weekly: the aerators, the inlet air filter, and the blower. The aerators are checked by monitoring the blower pressure gauge. The typical reading for the blower pressure initially ranged between 10 and 11 inch WC (water column). It was later determined that one of the six aerators was not hooked up correctly in the diffusion tank. After the problem was corrected, the pressure increased to 18 to 18.5 inch WC which is slightly below the recommended Lowry specification of 20 -25 inch WC. Thereafter, the aerators required very little maintenance during the 8 month period of the study. According to the manufacturer drinking water aerators can go years without maintenance (Lowry Aeration Systems, 1997).

The air filter is monitored by measuring the vacuum readings on the blower gauge. These range between 1 and 3 inch WC which is slightly higher than the Lowry specification of 1 inch WC (Lowry Aeration Systems, 1997). During the study the vacuum pressure remained very constant in this range, and the air filter did not require cleaning.

The blower should be maintenance free for several years. The blower bearings are rated for 17,000 hours of operation and should be replaced at that time. The Forest View system operates about 5 hours a day, so the bearings should last 8 to 9 years. During month 6 of the study, the blower malfunctioned. It was determined that it had been damaged during shipping. The manufacturer supplied a new blower, which has been operating trouble-free since that time.

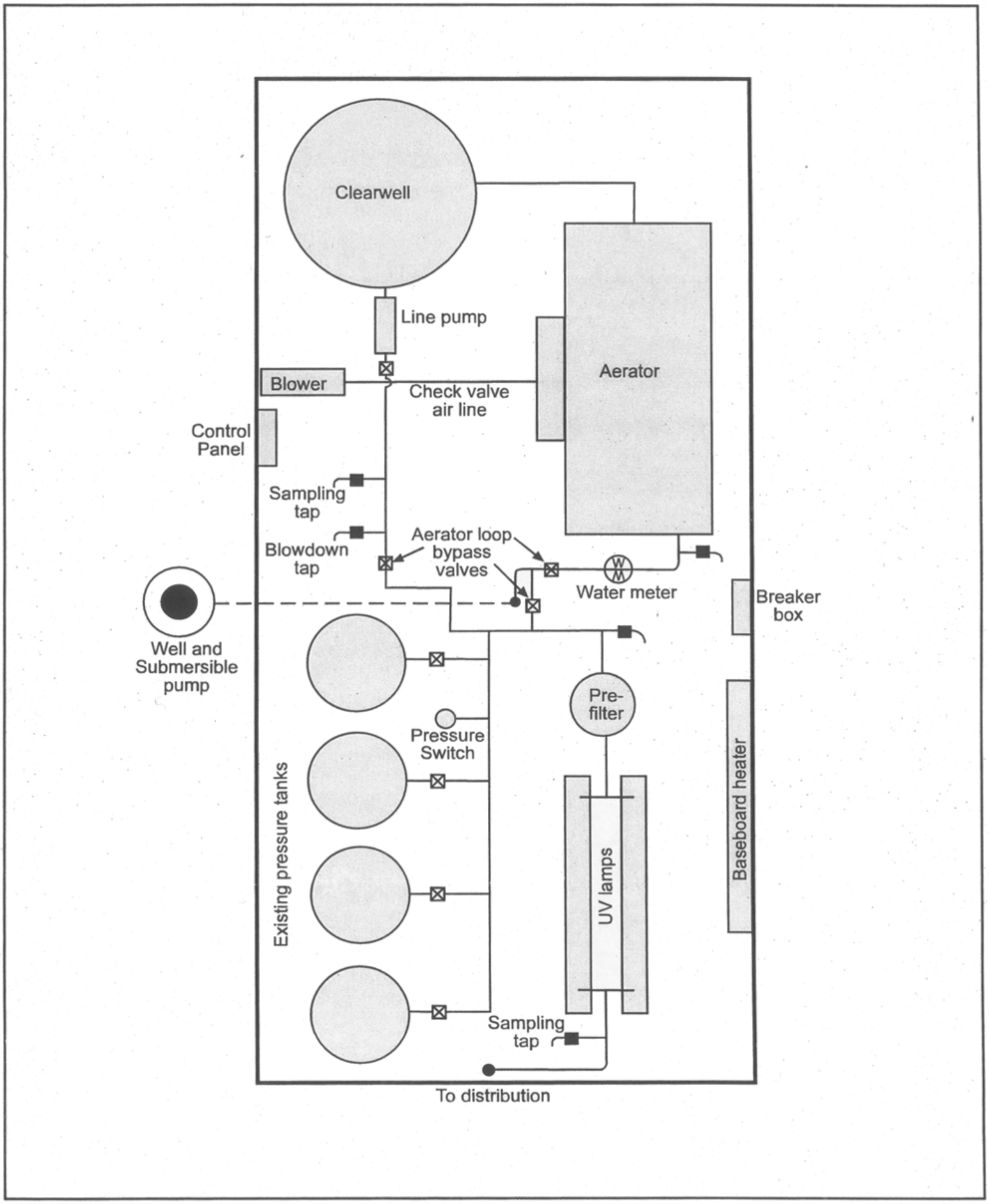

Figure 4. Schematic of the Forest View Homeowners Association pumphouse after the installation of the aeration system.

UV disinfection system. Two UV systems** were installed in parallel (figure 4). Each unit is designed to treat water at a rate of 60 gpm and a dosage of 10 milliwattsecond/centimeter^2 (mWsec/cm^2). The water is passed through a 5-micron prefilter prior to entering the UV disinfection chambers.

Maintenance of the UV disinfection system. Maintenance of the UV disinfection system consists of weekly monitoring of the UV lamps to determine if a lamp has burned out, and cleaning with the wiper to eliminate deposits on the quartz sleeve.

Prefilter system. In the Forest View pumphouse, the prefilter unit*** is installed just prior to the UV disinfection units (figure 4). It employs centrifugal separation to remove dense particles from the water and a five-micron filter to remove small diameter particles. The unit is designed to treat up to 100 gpm.

Maintenance of the prefilter system. Maintenance of the filter includes weekly monitoring of the two filter pressure gauges located upstream of the filter and at the filter. A pressure difference of 10 psi is indicative of a filter that needs to be cleaned or replaced. The filter was cleaned 2 times in 6 months during the study. The filter is easily cleaned by spraying it with water from a standard hose equipped with a pressure nozzle. A new filter was installed at the end of the study prior to the Homeowners Association's acquisition of the aeration system. Overall, routine maintenance of the new system requires a weekly visit by the operator lasting 30 to 60 minutes.

Problems experienced with the aeration process

The aeration process was interrupted several times during the 8-month study period. The first interruption occurred on 2/27/98, when power problems were experienced in two homes due to the operation of the aeration system. The homes had power fluctuations sufficient to shut off televisions and computers each time the aeration system started up. These homes and the pumphouse were served by the same power transformer. A new transformer was installed solely for the pumphouse, and aeration was resumed on 3/3/98.

The second interruption in aeration was discovered on 3/18/98. The Forest View backup well was supplying water to the homes and the primary well was not operating. Although there was nothing wrong with the aeration system, no aerated water was being supplied to the homes. It turned out that the back up well controls had overridden those of the primary well because it is at an elevation five feet higher than the primary well. The storage tank pressure/well pump relay gauges for both the primary system and the backup system were reset to ensure that the primary well pump would always supply water to the homes and the backup well would function only as a backup. The system was back in operation on 3/19/98.

On 3/31/98 the aeration system blew a fuse. The fuse was replaced and the aeration system was back in operation on 4/1/98. On 4/15/98 it was discovered that the backup well was

** Atlantic Ultraviolet, Sanitron Model S2400B, Haupauge, New York

*** Harmsco, Model HUR-90-HP, North Palm Beach, Florida supplying water to the homes again. The pressure relays were readjusted and the aeration system was working again the same day.

On 7/2/98 the homeowners noticed that the aeration-system fault light was on and that the aeration system had shut down. It was determined that another fuse had blown. Through discussions with the aeration system manufacturer it was discovered that this particular type of blower had been experiencing problems at other locations. The problem had been tracked down to damage, which can occur to the blower during shipping. The aeration system remained offline until a new blower was obtained. While the aeration system was down, on 8/5/98 the storage tank pressure gauge/well pump relay system malfunctioned probably due to the age of the system. The well pump turned on, but did not turn off after the pressure tanks were filled. The emergency release valves blew and flooded the pumphouse. The pressure tank bladders were ruined and had to be replaced and the UV disinfection system electronics were shorted out and had to be replaced. Repairs to the system were completed and a new blower was installed. The aeration system was back in operation on 8/11/98. The study was concluded and the system was turned over to the homeowners on 8/28/98. Since that time the aerator has been operating with no problems.

Results of the aeration study

Analytical sampling scheme. Prior to the initiation of the study, samples were taken from the well to characterize the ground water. After the aeration study began, analytical samples were taken in the pumphouse 1) before the aeration system (ground water from the well); 2) after the aeration system (directly after the clearwell storage tank); and 3) exiting the pumphouse (after storage in the pressurized tanks) on the way to the homes. Weekly samples were taken at the three pumphouse locations and analyzed for:

- temperature
- pH
- alkalinity
- specific conductance
- dissolved oxygen
- turbidity

Weekly first-draw samples were taken at the Schwartz and Dean residences, two Forest View residences that historically had high levels of copper in their drinking water. The residential samples were analyzed for:

- temperature
- pH
- alkalinity
- specific conductance
- lead
- copper

Based upon the method of Schock (Lytle and others, 1998) alkalinity and pH measurements were used to determine weekly DIC values at the three pumphouse locations and at both residences. Weekly sampling was initiated on February 16, 1998 and continued through August 26, 1998.

Monthly heterotrophic plate counts (HPC) samples were taken as the water exited the UV disinfection system on the way to the homes. High HPC results were used to determine when the UV quartz sleeves needed to be cleaned.

Analytical results. Results for the initial water quality characterization for the Forest View Homeowner's Association well are shown in table 1. DIC values were calculated using equation (2) above. The values for K_w, K_1, and K_2 were taken from standard tables (Hem, 1985) equilibrium constants for the $CaCO_3 + H_2O + CO_2$ system at temperatures of 10 °C and 20 °C (which most closely matched the water temperatures at the pumphouse and in the homes). The data (pH, DIC, and dissolved oxygen) collected at the pumphouse are graphically depicted in figures 5, 6, and 7, respectively. The pH, DIC, and copper data collected at the residences are depicted in figures 8, 9, and 10. Two of the lines on each graph trace residential water quality and one line, included for comparative purposes, shows the corresponding ground-water quality upstream of the aeration system**.** The shaded arrows correspond to times when the aeration system was not operating.

Table 1. Initial water quality results for the Forest View Homeowners Association's primary well.

Parameter	Measurement
pH	6.45
DIC	18.8 mg C/L
Hardness	35 mg $CaCO_3$/L
Manganese	0.001 mg/L
Iron	<0.005 mg/L
Copper	<2 ug/L

HPC results revealed that the quartz sleeve surrounding the UV lamp must be cleaned weekly to maintain HPC levels less than 200 cfu/ml.

Discussion of the analytical results. As shown in figure 7, aeration of the ground water resulted in an average increase in pH of around 0.5 units. The pH remained relatively unchanged during storage of the aerated water (figure 5, exiting sample) and as the water passed through the distribution system to the homes (figure 8). Conversely, aeration of the ground water resulted in a decrease in the ground-water DIC (figure 6) by an average 35%. This decrease in DIC was maintained throughout the storage and distribution of the aerated water (figure 6, exiting sample, and figure 9). These results are important in that they indicate that CO_2 is not reabsorbed into the water while it is in the clearwell in contact with atmospheric air.

Figure 10 depicts the copper levels that were observed in the two homes during this study. The shaded arrows show when the aeration system was not operating. Copper levels at the two test residences were initially substantially higher than 1.3 mg/L (data for 12/18/97). Upon the initiation of aeration, the copper levels dropped below 1.3 mg/L. The levels remained consistently below the action level while the aerator was in operation. Whenever aeration was suspended, the copper returned to the elevated levels. This provides good evidence that it was the aeration of the water that reduced the levels of copper in the two homes. The dissolved oxygen content of the ground water averaged around 3 mg/L coming from the aquifer (figure 7). During aeration, the dissolved oxygen content of the water increased to an average value of 8 mg/L. Although this is a significant increase in dissolved oxygen, it does not appear to have caused an increase in copper corrosion in the homes. This is probably due to the relatively high level of dissolved oxygen (3mg/L) found in the ground water. Copper solubility in waters containing higher levels of dissolved oxygen is likely due to dissolution of copper (II) solids rather than copper(I) solids (EPA, 1995). Increases in copper solvency due to increases in dissolved oxygen concentrations have been previously observed in waters with very low dissolved oxygen levels (0.4 mg/L or less) (Lytle and others, 1998) where dissolution of copper(I) solids is primarily responsible for the observed copper levels. In this type of system, increasing the concentration of dissolved oxygen results in the formation of copper(II) solids which are significantly more soluble than copper(I) solids (Lytle and others 1998). The copper levels observed in the Forest View homes prior to aeration were probably due to the dissolution of copper(II) solids. This would not be expected to increase significantly when the dissolved oxygen content is raised to 8 mg/L by aeration

Cost Analysis. Table 2 shows the initial costs that were incurred for the Forest View aerator installation. This and the following tables give total costs, plus an estimated value for those that would have been incurred, had it not been necessary to install a new disinfection system. At Forest View, a system serving 24 households, the total initial cost was $24,270.

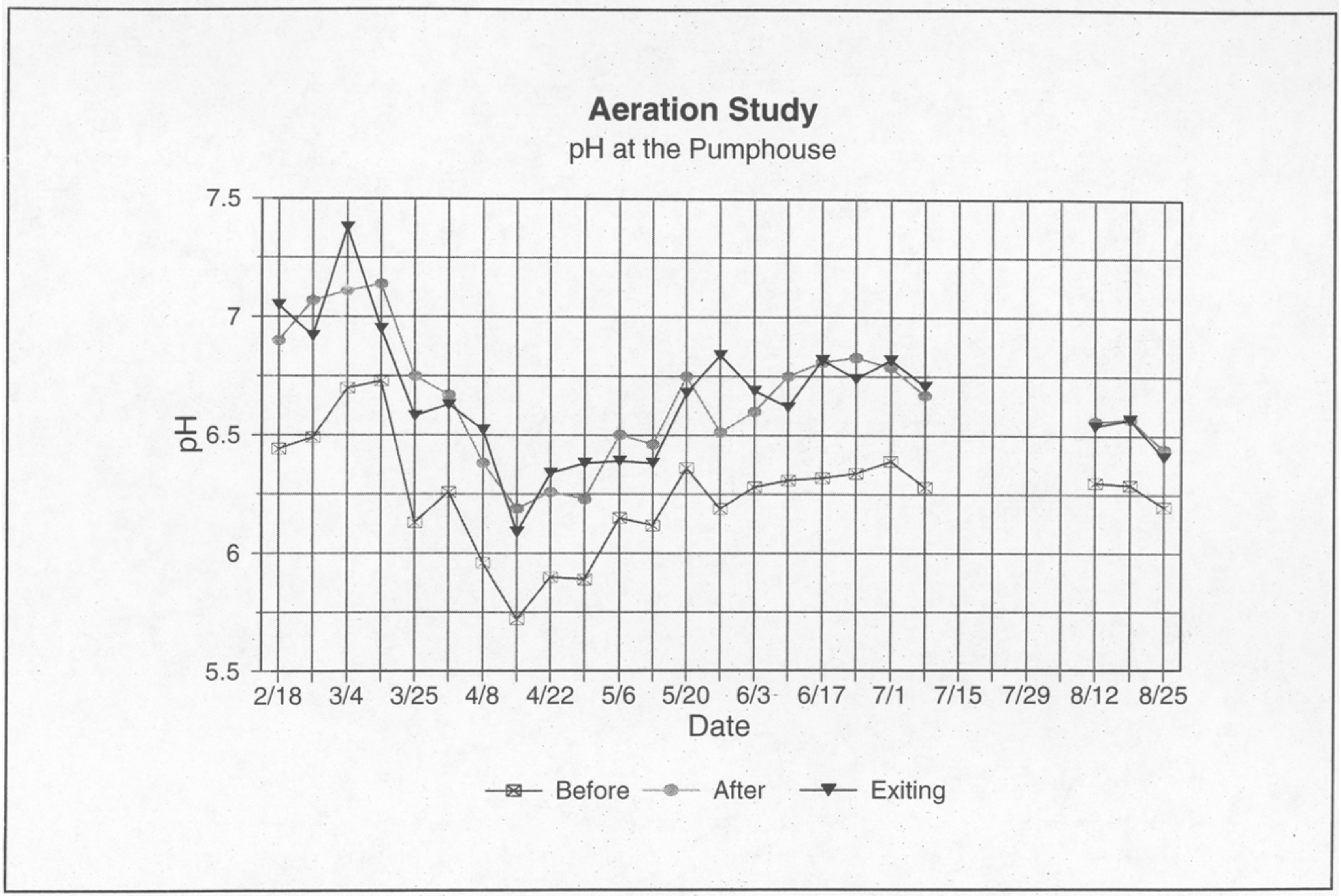

Figure 5. Graphic presentations of seven months of pH measurements taken form three sampling ports located: 1) before the aerator (ground water); 2) after the aerator; and 3) as the water exits the pumphouse on the way to homes (after storage in pressurized storage tanks).

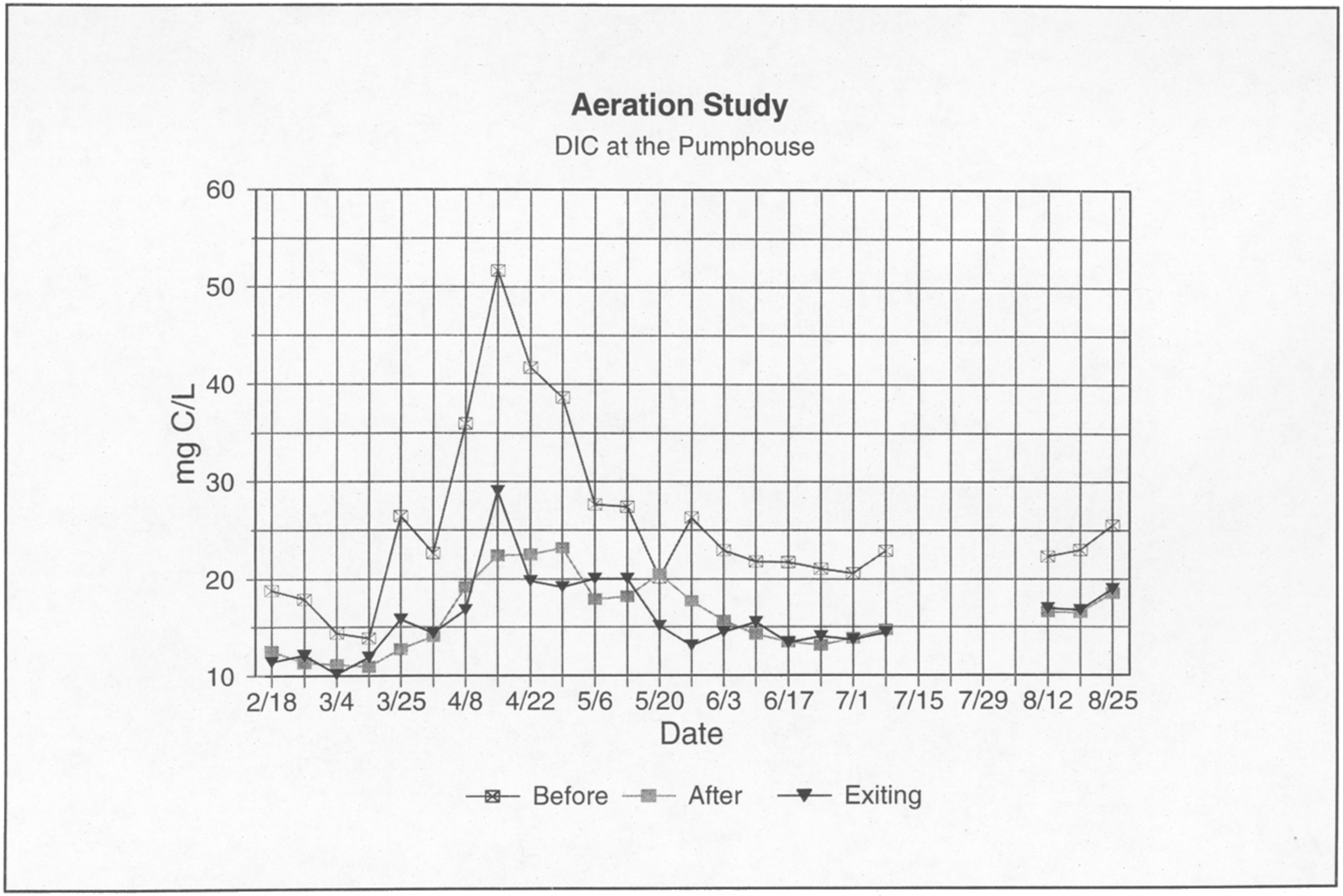

Figure 6. Graphic presentations of seven months of DIC values calculated using the method *of Shock et al.*[7] from measurements made at three sampling ports located: 1) before the aerator (ground water); 2) after the aerator; and 3) as the water exits the pumphouse on the way to homes (after storage in pressurized storage tanks).

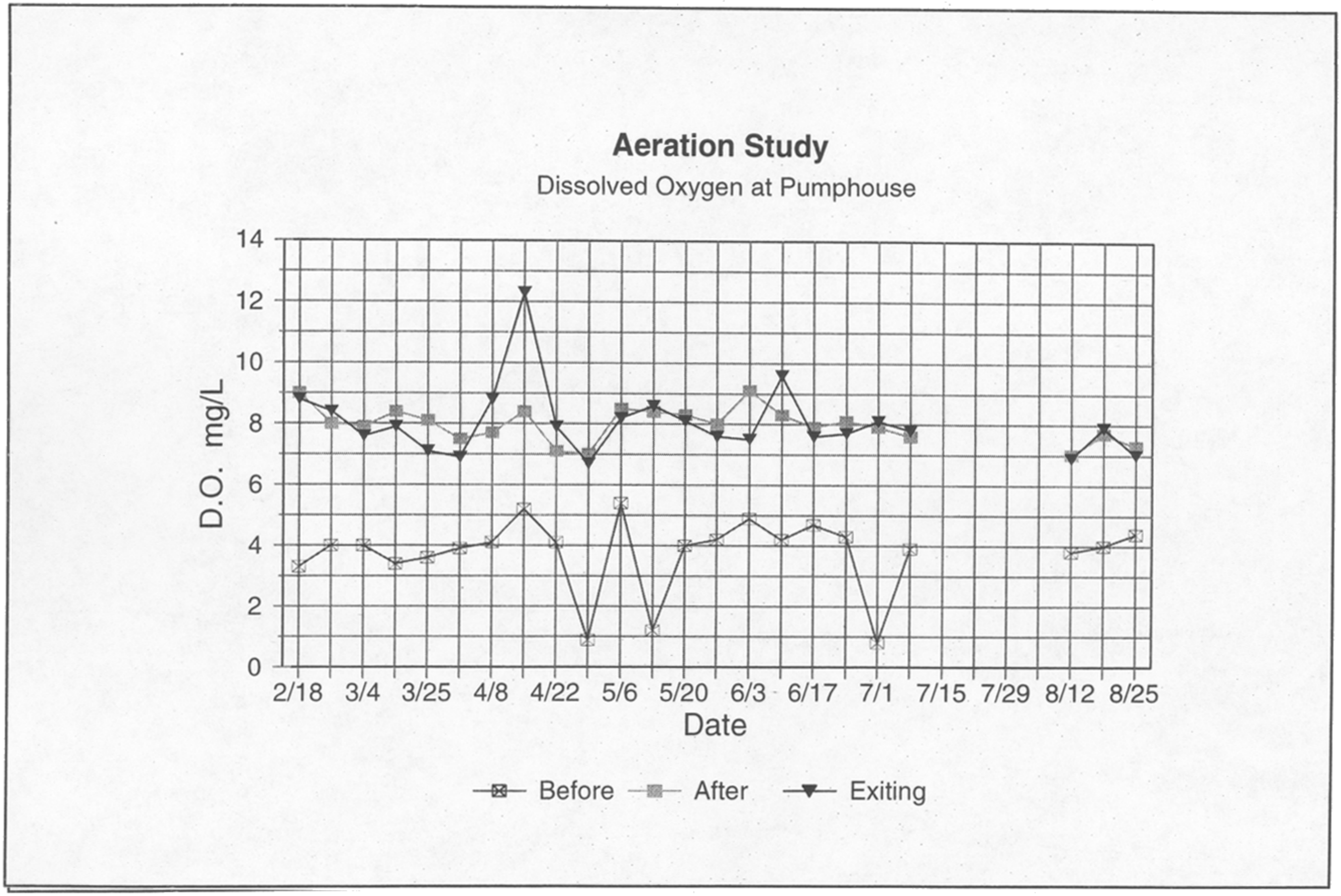

Figure 7. Graphic presentations of seven months of oxygen measurements taken from measurements made at three sampling ports located: 1) before the aerator (ground water); 2) after the aerator; and 3) as the water exits the pumphouse on the way to homes (after storage in pressurized storage tanks).

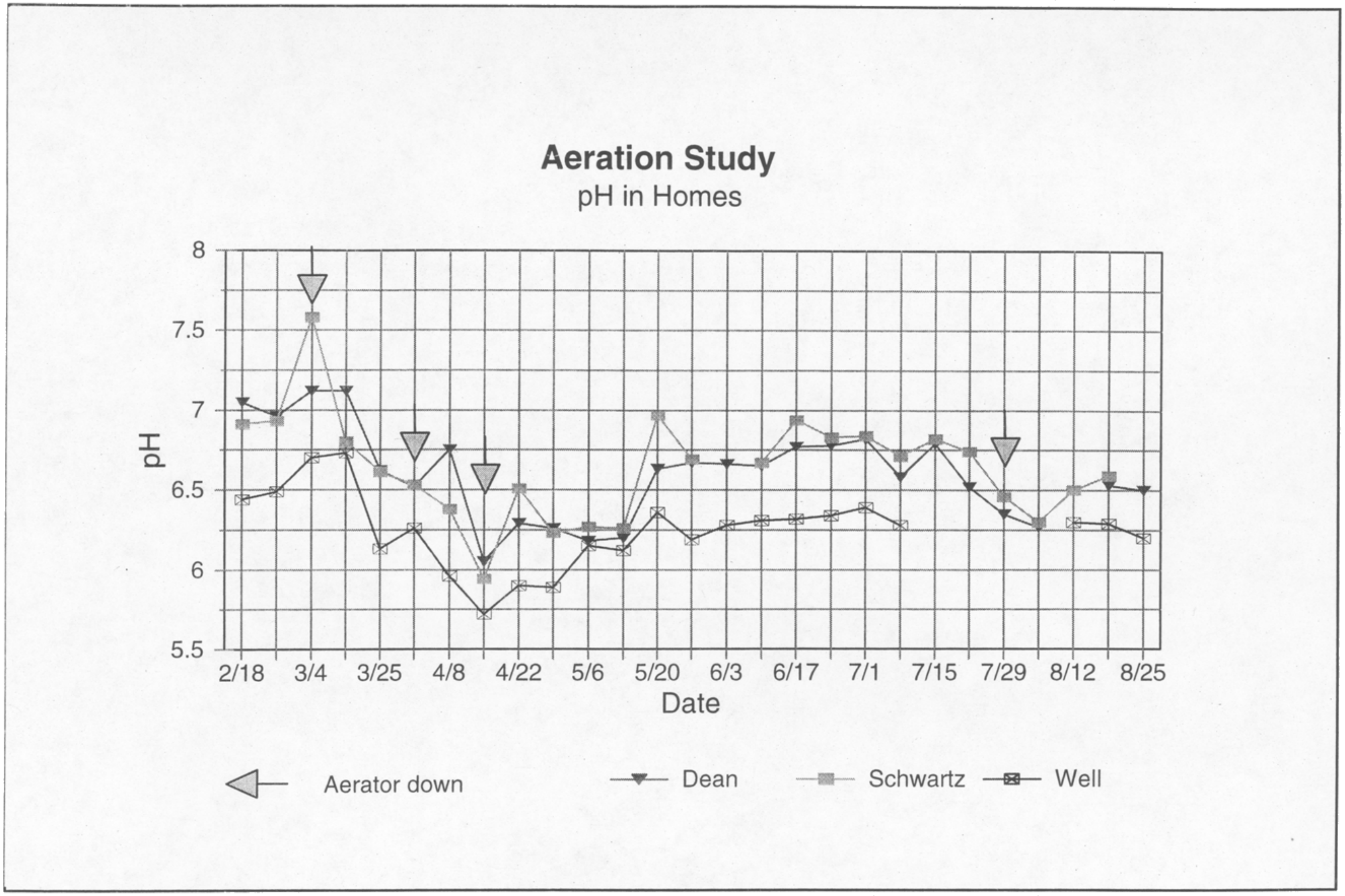

Figure 7. Graphic presentations of seven months of pH measurements made on first draw water samples taken at the Dean residence and the Swartz residence.

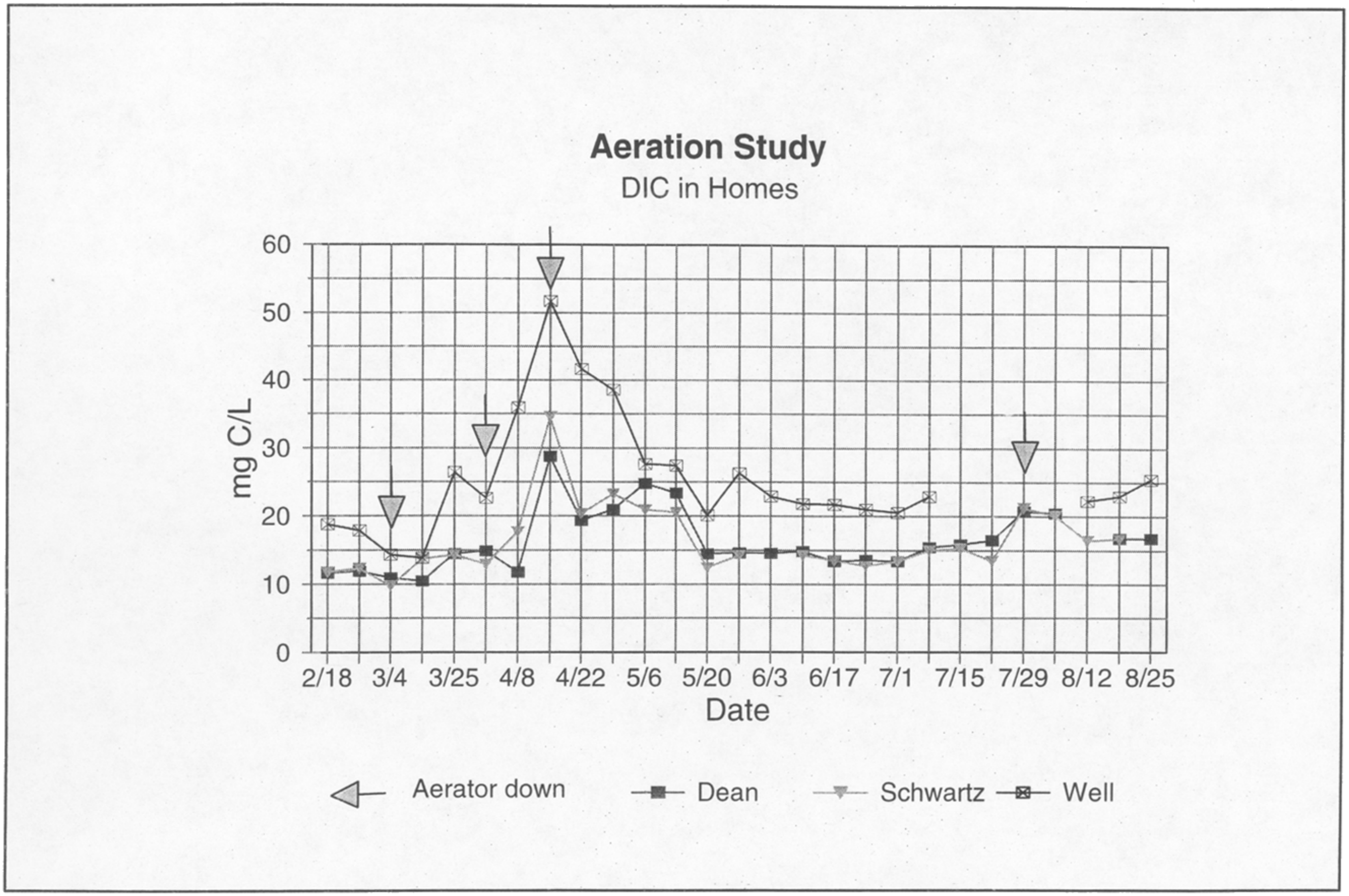

Figure 9. Graphic presentations of seven months of DIC values calculated using the method *of Shock et al*.[7] from measurements made on first draw water samples ate the Dean residence and the Swartz residence.

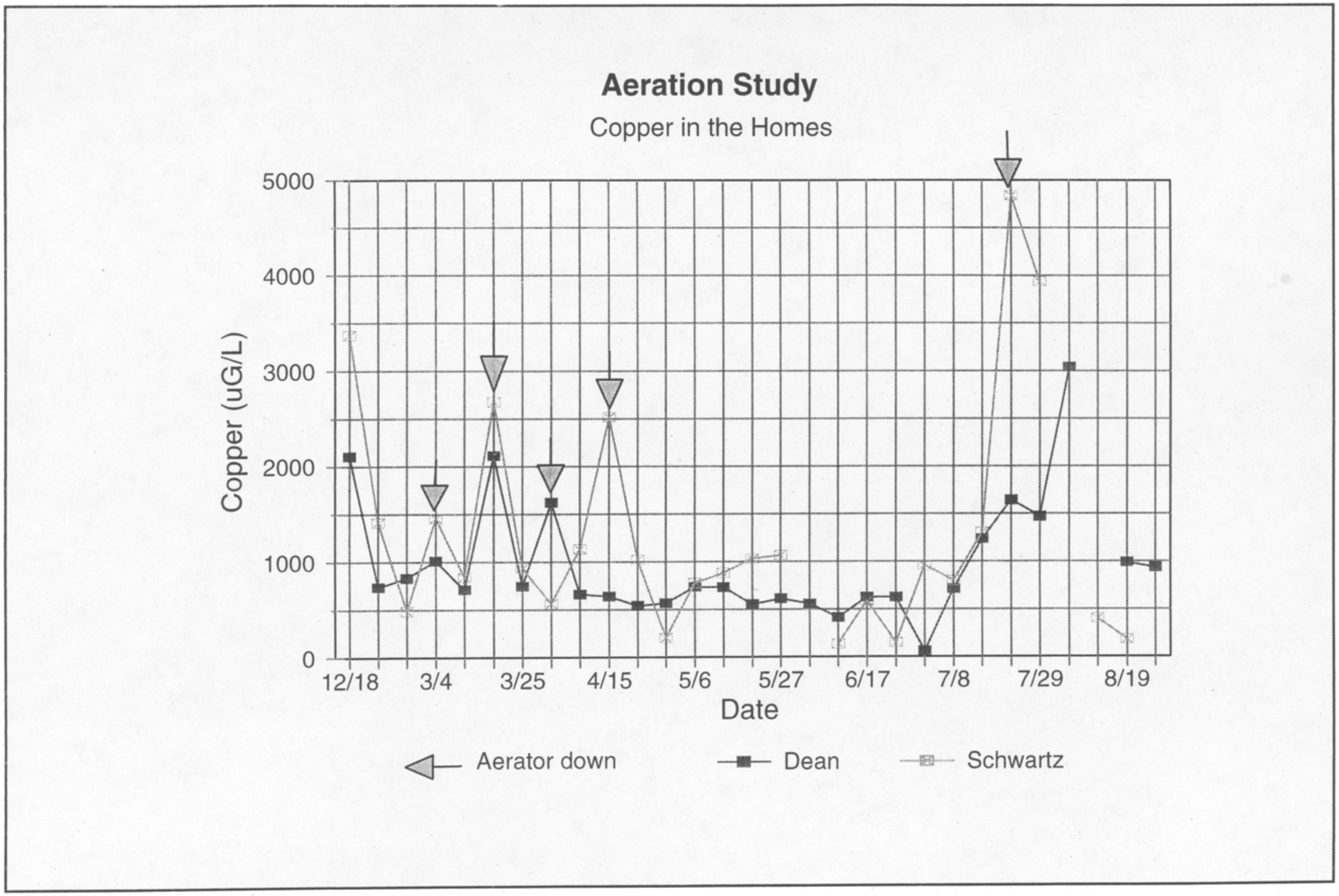

Figure 10. Graphic presentations of seven months of copper measurements made on first draw water samples taken at the Dean residence and the Swartz residence.

would have been $27,210. The Forest View system as now configured could serve 30 households without the need to increase equipment capacity or enlarge the pumphouse further.

Table 2. Initial Costs of the Aerator System

ITEM	TOTAL ($)	EXCLUDING DISINFECTION ($)
Site/building preparation[a]	$ 2,230	$ 2,230
Capital equipment	$17,040[b]	$12,200[c]
Installation labor	$ 5,000[b]	$ 4,000[c]
Engineering and review fees[d]	$ 2,940	$ 2,600
TOTAL	**$27,210**	**$21,030**

Notes:

a. The cost of adding 50 ft^2 to the pumphouse was largely underwritten by homeowner "sweat equity."

b. Includes aerator, clearwell tank, re-pressurization pump, blower, water meter, sampling taps and other air and water lines; prefilter and ultraviolet units and lamps.

c. As above, excluding prefilter and UV.

d. Estimated values; fees were waived for this project.

Table 3 summarizes the estimated long-term costs for operating this system. The aeration system components - blower and re-pressurization pump - are on about 5 hours a day. The two UV lamps operate continuously. The power used by these new devices was approximately one-seventh that used by the well pumps. At $0.0635/kWh, the power required to operate the aeration and disinfection devices was a minor cost component, estimated at $360 for a typical year.

Table 3. Long-Term Costs of the Aerator System

Annual Operating Costs	Total ($)	Excluding Disinfection($)
Power[a]	$ 360	$ 227
Operator labor	$ 1,200	$ 1,000

Equipment Replacement Costs	Total ($)
Aerator, clearwell, controls, UV ballasts, prefilter housing[b]	$0
Blower	replace bearing 3 times in 20 years @ $100
Re-pressurization pump	replace every 5 years @ $400
UV lamps	2 new lamps per year @ $235 ea.
Prefilter	replace annually@ $115

Notes:

a. Power cost is $0.0635 kWhr. Power requirement of well pumps not included.

b. These are all assumed to last 20 years or longer.

The operator spends a minimum of one 30-minute period a week checking the system, and charges the homeowner’s association $100 per month for his services. About one-sixth of his time is devoted to maintaining the disinfection equipment.

The aerator, the clearwell tank, the UV prefilter housing and the aerator system controls are very robust, and are not expected to require substantive maintenance over a 20-year lifetime. The other new components of the treatment train will need periodic maintenance or replacement on the schedule shown. The most expensive maintenance item is replacement of the two UV lamps every 12 or 13 months, at a cost of almost $500.Table 4 presents a simplified present worth analysis for the Forest view aerator installation. In these calculations, a 20-year lifetime and a 7% discount rate are used, and no salvage value is assumed for the pumps that will be replaced periodically. Overall, initial expenses, and power and equipment replacement costs are modest. The most costly element of the new system is the ongoing operator oversight.

The monthly cost of the new system amounts to about $56 per household. This is equivalent to 2.4 percent of the median 1995 household income in the county where Florence is located. Including the cost of power for the “old system” - the two well pumps that are still integral to the system - boosts this to $65 per household per month, or 2.7 percent of median income. Affordability guidelines of the State of Montana indicate that combined water and sewer rates that exceed 2.2% of a community’s median household income may qualify the community for grant or loan assistance. Households in communities with individual on-site wastewater

Table 4. Forestview Aeration System Present Value Analysis[a]

Cost Category	Present Value ($)	Excluding Disinfection ($)
Capital equipment; site preparation; installation; engineering and review fees	$27,210	$21,030
Power[b,c]	$ 3,814	$ 2,405
Operator Labor[b]	$127,100	$105,940
Phased equipment replacement	$ 12,915	$ 1,800
TOTAL Present Value	**$171,039**	**$131,145**
Annualized	$16,144/year	$12,379/year
Monthly[d]	$56/household	$43/household

Notes:
a. The analysis uses a 20-year planning period and a 7% discount rate. No salvage value is assumed for the equipment that is replaced.
b. Power costs and labor costs are assumed to rise at the rate of inflation.
c. Excludes power use by the well pumps, which is about seven times the value shown for “present value.”
d. When all power costs are included, monthly costs are $65 and $52 respectively.

disposal systems, like Forest View, could presumably be expected to pay that much solely for provision of safe drinking water. By this criterion, the upgraded Forest View system that includes aeration and disinfection is expensive, but not inordinately so. It should be noted that small systems which are not owned by towns or water districts can seldom access public funding for such infrastructure upgrades.

Conclusions

Based upon the observed results it appears that aeration is successfully treating the corrosive ground water of the Forest View Homeowner's Association, consistently reducing the levels of tap-water copper to below the action level. In August 1998, a report detailing the observed aeration results was submitted to the State of Montana Department of Environmental Quality (DEQ). In that report, it was requested that the Forest View Homeowner's Association be given long-term approval to use aeration as a method to control copper corrosion. The DEQ reviewed the results and concurred. In late August 1998, DEQ granted such approval. The Forest View Homeowner's Association purchased the aerator in September 1999 and it continues to operate there.

Given appropriate source-water characteristics, a basic aeration system effectively alters the properties of the water that induce corrosion. However, this is a much higher level of treatment than is common in small ground water-based systems. Consequently, the need for additional services and accouterments should be foreseen. At Forest View, it became apparent that:

- It is probably worth installing 3-phase power, if possible.
  A number of electrical devices may switch on simultaneously. If single-phase power is used, a dedicated transformer is essential.
- A period of adjustment should be expected for the system controls, especially if multiple well pumps are involved. A number of motors must switch on or off at the correct times, in the correct sequences, in response to various triggers. A malfunction ramifies through the system, and can be difficult to trace.
- Squeezing a new treatment train into an existing, small pumphouse in the interest of frugality may backfire. In this case, ultraviolet disinfection lamps were installed a few inches above the floor, in a convenient place between the pressure tanks and the service main. Within a few months of installation, they were flooded, necessitating replacement of the electronics.
- Old switches and valves may be overtaxed. At Forest View, replacing the existing switches as part of the upgrade would have prevented a costly malfunction.
- Aeration entails forcing ambient air through the water at atmospheric pressure. If it is not already practiced, disinfection will be needed. It was not explored here,

but the addition of chemical disinfection may affect the corrosivity of the water in unpredictable ways.

Adding an aeration system makes the operator's job more complicated. However, the technology - pumps, blowers, tanks - is not exotic, and it is very robust. There is no need for ongoing tweaking after the installation phase. The operator of the Forest View system has found that his only long-term challenge is to become accustomed to the filters, so that he knows when to check and clean them. He currently spends about 30 minutes a week at Forest View.

A large portion of the up-front cost of the new installation was underwritten as a demonstration project expense. If that were not so, the cost to each household would have exceeded $1000. Very small systems like Forest View cannot issue bonds, and it's difficult for them to borrow money or obtain grants. In an ordinary situation, an installation like this one would represent a hardship for many system customers. The longer-term costs are relatively high, but not out of line with what many people pay for water service. The estimated per-household cost over the life of this system is approximately $65 a month. For comparative purposes, it should be noted that few other areas of the United States are favored with such low power or labor costs. Equivalent facilities elsewhere would undoubtedly be more expensive.

Acknowledgements

The authors gratefully acknowledge the Montana Water Center's Drinking Water Assistance Program for Small Systems that provided funding for this study. They also gratefully acknowledge Mr. Jeff McCleary, Program of Shared Operation and Management, who first mentioned the Florence problem. Additionally, the authors would like to acknowledge Mr. Archie Thomas of Kinetico Quality Water Systems who installed and helped maintained the aeration system. Finally, they would like to express appreciation to the Forest View Homeowners Association for participating in this study.

References

AWWA, 1990, Water Quality and Treatment (3rd ed.): New York, New York, McGraw Hill, 654 pp.

Edwards, M., Meyer, T., Meyer, J.P., 1993, Effect of Various Anions on Copper Corrosion Rates, Proceedings: San Antonio, Texas, AWWA Annual Conference.

Edwards, M., Meyer, T.E., Schock, M.R., 1996, Alkalinity, pH, and Copper Corrosion By-Product Release, JAWWA, v. 88, no. 3, pp. 81 – 94.

EPA, 1991, Lead and Copper, Final Rule, Fed. Reg. 56:110:26460, June 7, 1991.

EPA, 1991a, Lead and Copper, Final Rule Correction, Fed. Reg. 56:135:32112, July 15, 1991.

EPA, 1992, Lead and Copper, Final Rule Correction, Fed. Reg. 57:125:28785, June 29, 1992.

EPA, Office of Research and Development, 1993, Control of Lead and Copper in Drinking Water, EPA/625/R-93/001, May 1993 and the references listed therein, Washington, D.C.: U.S. Government Printing Office.

EPA, Office of Research and Development, 1995, Effect of pH, DIC, Orthophosphate and Sulfate on Drinking Water Cuprosolvency", EPA/600/R-95/085, June 1995 and the reference listed therein, Washington, D.C.: U.S. Government Printing Office.

EPA, Office of Research and Development, 1997, Guidance Manual for Selecting Lead and Copper Control Strategies, USEPA Contract 68-C4-007, Black & Veatch under Subcontract to The Cadmus Group.

Ferguson, J.F., von Franque, O., Schock. M.R., 1996, Corrosion of Copper in Potable Water Systems, Internal Corrosion of Water Distribution Systems, (2nd ed.): Denver, Colorado, AWWA Research Foundation/DVGW Forschungsstelle.

Hem, J.D., 1985, Study and Interpretation of the Chemical Characteristics of Natural Water, U.S. Geological Survey Water-Supply Paper 2254, 3rd edition, Washington, D.C.: U.S. Government Printing Office, 263 pp.

Lowry Aeration Systems, Inc., 1997, Installation and Operation Manual - DeepBubble™ 6-Stage Aeration System, Dec. 1997.

Lytle, D.A., Schock, M.R., Clement, J.A. Spencer, C.M., 1998, The Use of Aeration for Corrosion Control, JAWWA, May 1998.

Schock, M.R., Lytle, D.A., Clement, J.A, 1994, Modeling Issues of Copper Solubility in Drinking Water, Proceedings, Boulder, Colorado: ASCE National Conference on Environmental Engineering.

Schock, M.R., Lytle, D.A., Clement, J.A. Effects of pH, Carbonate, Orthophosphate and Redox Potential on Cuprosolvency, NACE Corrosion/95, Orlando, Florida, 1995.

Stumm, W., Morgan, J.J., 1996, Aquatic Chemistry - Chemical Equilibria and Rates in Natural Waters (3rd ed.): A Wiley-Interscience Publication, New York, New York, John Wiley and Sons, Inc., 1022 pp.

Rehring, J.P., Edwards, M., 1994, The effects of NOM and Coagulation on Copper Corrosion, Proceedings, Boulder, Colorado: ASCE National Conference on Environmental Engineering.