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Electrochemical Flocculation and Chlorination for Domestic Water Supplies

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ELECTROCHEMICAL FLOCCULATION AND CHLORINATION FOR DOMESTIC WATER SUPPLIES

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ABSTRACT

Three electrochemical chlorinators were developed, tested and evaluated. The first used natural chlorides in the water to produce a chlorine residual; the second and third produced chlorine residuals by electrolysis of brine solution. Brine feed rate of the second chlorinator was controlled by a metering pump; this control in the third chlorinator was by the electro-osmotic flow through a cation exchange membrane.

Two electrochemical flocculators were developed, tested and evaluated. The first used a low current density, a long polarity reversal period and low purity aluminum alloy electrodes, so that the scale which formed on the plates was loosely attached. The second flocculator eliminated scaling of the plates by using a high current density, shorter polarity reversal period and higher purity aluminum alloy electrodes.

The low current density flocculator and the low-chloride chlorinator were field tested on surface pond water. The high current density flocculator, electro-osmotic chlorinator and incline tube settler were also field tested. The operating costs of the two systems for treating surface pond water were $1.13 per 1000 gal and 92.7¢ per 1000 gal, respectively. Both systems were capable of removing color and turbidity along with reducing other chemical elements such as iron, calcium and silica.

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LIST OF SYMBOLS AND ABBREVIATIONS

amp	ampere
°C	degrees Centigrade
cm	centimeter
coul	coulombs
CTD	coulomb treatment dosage
°F	degrees Fahrenheit
ft	feet
gal	gallon
gpm	gallons per minute
g	gram
hr	hour
in	inch
Kg	kilogram
Kw	kilowatt
l	liter
lb	pound
m	meter
ma	milliampere
mg	milligram
ml	milliliter
min	minute
ppm	parts per million
psig	pounds per square inch gauge
r	coefficient of correlation

LIST OF SYMBOLS AND ABBREVIATIONS (continued)

rpm	revolutions per minute
sec	second

INTRODUCTION

The "water problem" - how to have water in adequate quantity and quality available at a reasonable cost when and where needed is of world-wide importance. As population, irrigation and industrialization increase, the problem becomes increasingly serious.

In rural areas, ever-increasing quantities of pure water are being required. This has been caused by the recent increase in rural population and the increase in the amount of water used per person in rural areas.

Water from wells, springs and cisterns may be highly mineralized or contaminated with bacteria in many parts of Texas. Where water from these sources is unusable, or in short supply, many farmers are turning to ponds as a source of water. Farm pond water contains a large amount of suspended material, bacteria and organic matter. These contaminants must be removed by one of two processes: (1) filtration and chlorination, (2) coagulation, sedimentation, and chlorination. Both of these conventional methods require considerable amounts of labor and skill to keep them operating properly. The need for a small automated clarification and purification system is great.

Electrochemical water treatment systems may be the answer to this great rural need. Two different electrochemical flocculation units for removing colloidal material and three chlorination units for disinfecting the water were developed. The final system contains a high current density flocculation unit, an electro-osmotic chlorination unit, and the necessary controls for automation of the system.

CHAPTER I

CHLORINATION

Introduction

The most practical means for disinfecting rural water supplies is by chlorination. It is favored over other methods because the chlorine residual remains in the water after treatment providing continued protection, and this residual can be measured at any time to determine how much protection is present. The standard method of chlorination of small water supplies is by adding hypochlorite solution. These solutions lose their strength with time and must be renewed often.

Three different types of chlorination units were developed which generated chlorine gas continuously as needed by electrolysis of chlorides. Thus, hypochlorite solution need not be stored. The first unit (low-chloride chlorinator) releases chlorine by electrolysis of natural chlorides in the water. In the second unit (high-chloride chlorinator) a concentrated brine solution is metered into the electrolysis cell and chlorine is released. In the third chlorinator developed (electro-osmotic chlorinator), the brine solution flowed into the cell due to the electro-osmotic pressure across the membrane. This eliminated the need for a metering pump.

Review of Literature

Chlorination is the most widely used method of disinfecting water. The United States produces approximately 10 million tons of chlorine per year. Of this, 300 thousand tons are used for water disinfection according to Taylor (1962). The use of chlorine gas is limited to large scale applications because of the associated danger.

Most disinfection units for small water supplies use chlorine tablets, solutions containing chlorine, heat or ultraviolet light. The chlorine is available in the form of hypochlorites such as sodium hypochlorite and calcium hypochlorite. There are two basic methods for using chlorine solutions. In the first system, a tablet-type chlorinator, a small amount of water from the pump delivery line is circulated through a container of chlorine tablets. The tablets dissolve to form a chlorine solution which is returned to the delivery line. In the second system, a solution of chlorine is prepared and metered into the delivery line by a small diaphragm pump. The problem of these systems is that chlorine solution loses strength with time and must be changed monthly.

Disinfection by heating is accomplished by heating water to 161°F and maintaining this temperature for 15 seconds. This is accomplished by a unit called a pasteurizer which partially heats the incoming water by a heat exchanger. The remaining amount of heat is added by an electric heating element. Water is maintained at 161°F for 15 seconds, then is passed through a heat exchanger into storage. Water pasteurizer units are very expensive and must be operated for long periods of time in order to prevent excessive waste of energy.

The third method of disinfection used in a small water treatment unit is ultraviolet light. The unit consists of one or more ultraviolet lamps each encased in a quartz sleeve. A thin layer of water is passed around each sleeve exposing it to ultraviolet light. The disinfecting action is the same as sunlight in killing bacteria in a natural stream. The main mechanical problems of this method are keeping the lamp clean and the aging of the lamps. Neither the heat nor the ultraviolet disinfection methods protect the water from future contamination. In the chlorine disinfection method the water is protected from future contamination by the presence of a small free chlorine residual left in the treated water.

The presence of a guard against further contamination is essential in a small water supply; therefore, a chlorine method of disinfection should be used. Due to the maintenance problem associated with the loss of chlorine solution strength during storage, the ideal unit must be able to generate chlorine as it is used.

Electrolysis of brine in a diaphragm cell is the major commercial process used for chlorine production. It uses a concentrated brine solution from which chlorine is released during electrolysis from the sodium chloride present.

A diaphragm cell consists of three basic parts: anode, cathode, and diaphragm. The water enters the cell at the anode where chlorine is released by the following reaction:

$$2\,Cl^- \longrightarrow Cl_2 + 2e \quad \ldots\ldots\ldots\ldots \quad 1$$

At the same time some of the chlorine loss is due to the migration of hydroxide across the diaphragm. This hydroxide combines with the chlorine to form hypochlorous acid and hypochlorite ions which tend to further react to produce chlorate ions according to the following reactions:

$$Cl_2 + OH^- \longrightarrow Cl^- + HOCl \quad \ldots\ldots\ldots\ldots \quad 2$$

$$HOCl \longrightarrow H^+ + OCl^- \quad \ldots\ldots\ldots\ldots \quad 3$$

$$2HOCl + OCl^- \longrightarrow ClO_3^- + 2Cl^- + 2H^+ \quad \ldots\ldots\ldots \quad 4$$

The current efficiency of chlorine production is reduced by the formation of oxygen from hydroxide ions.

To reduce these energy and chlorine losses, the hydroxide ion must be restricted from migrating across the diaphragm. This is accomplished in a commercial chlorine cell by forcing the used brine solution to flow from the anode to the cathode compartment. The flow rate across the diaphragm must be accurately controlled for the proper operation of these cells, according to Kircher (1972). The flow resistance of the diaphragm is continually changing due to the plugging problem. Because of this fact, there would be a serious maintenance problem if this process were used in a small system.

There have been some attempts to use the diaphragm cell in small treatment units. An early unit of this type was manufactured by Wallace & Tiernan, Inc., according to Chase (1931). A similar chlorinator built by Paterson Engineering Co., Ltd., in London generated chlorine which was used to make sodium hypochlorite according to The Chemical Age (1952). The main disadvantage to all of these units which used a diaphragm separator was maintaining the delicate flow balances across the separator.

One type of chlorinator which may possibly be better adapted to a small rural water system is the electrochemical chlorinator. This type of chlorinator releases free chlorine by electrolysis from natural chlorides present in the water. Most surface waters likely have a natural content of chlorides in suitable concentration for self-chlorination in this manner.

The possibility of chlorinating water in this way was observed by Hiler and Lyle (1970). In an experiment with an electrophoretic-electrochemical water clarifying unit with stainless steel electrodes, they noticed that all coliform bacteria put into the influent were killed after passing through the unit. Upon making chlorine determinations it was found that the total residual chlorine was as high as 2.30 mg l^{-1} when current density was 1.4 mg cm^{-2}. The chloride concentration of the water being chlorinated was around 50 mg l^{-1}. This indicated that it may be feasible to use this process effectively in the chlorination of water.

There has been some research in the area of electrochemical chlorination of water. At Naples, Italy, an experimental installation for treating waste water effluent used iron and carbon electrodes in an electrochemical chlorination process according to White (1972). The efficiency of the process was increased by mixing one part sea water to three parts waste effluent. At the Mariner Fish Company, Gloucester, Massachusetts, described by Ziemba (1951), an electrochemical cell was used to produce chlorinated water used for washing fish and equipment in their processing procedure. The cell had graphite anodes and iron cathodes. Harbor water, after passing through the cell, had a chlorine residual of 120 mg l^{-1}. Another study by Simplex Manufacturing (1973) dealt with the application of the electrochemical process to the chlorination of swimming pools. In that research, to increase the efficiency of chlorine production, chlorides were added to the swimming pool water to bring the total chloride concentration to about 1000 mg l^{-1}.

Another possibility for disinfection of small water supplies when natural chlorides are low is to produce needed chlorine or hypochlorite solution from a membrane cell as described by Michalek and Leitz (1972). In this cell the anode and cathode compartments were separated by a cation exchange membrane. The brine solution was fed into the anode compartment where chlorine was released. The caustic stream (sodium hydroxide) from the cathode compartment was cooled and mixed with the chlorine to form sodium hypochlorite. The cation exchange membrane prevented the hydroxide from entering the anode compartment. Some sodium and water flowed through the membrane due to the electro-osmotic properties of the membrane. The main disadvantage in using a similar system on small water systems is the accurate metering equipment required to balance the chlorine and caustic production. The cost of this type of cell would be high if the chlorine was used directly from the cell for disinfection, due to the fact that the anode and cathode streams both require metering equipment. If a cell using the electro-osmotic flow was used to meter the brine solution in the anode compartment, the mechanical metering system could be eliminated.

Low-Chloride Chlorination Unit

Introduction

The use of natural chlorides for chlorination offers many advantages. The main one is that no chemical would have to be added to the water. To design a cell capable of using natural chloride for chlorination, a series of tests was conducted. The first series of tests using graphite and steel electrodes was unsuccessful (Peters, 1973). The final successful unit used a platinized-titanium anode and steel cathodes. A summary of the test results is presented in this section. A more detailed report on the development of the low-chloride chlorination unit is presented by Peters (1973).

Test Cell

The cell consisted of a platinized-titanium anode 15.2 cm long and 7.6 cm high with a total electrode area of 232 cm^2, both sides being active. It was sandwiched between two perforated steel cathodes. The spacing between the anode and the cathode was 0.64 cm. The cell was placed inside an open Plexiglas container. The untreated water entered at one end, passed between the plates and was removed at the other end by a vertical pipe. A more detailed description of this cell and other test equipment is presented by Peters (1973).

Procedure

Current density tests. Thirty-six tests were performed to determine the relationship between "coulomb treatment dosage" and chlorine residuals. The coulomb treatment dosage term is used to describe the amount of electrons that were used to treat a unit volume of water (coul ml^{-1}). Voltage, current and chlorine residuals were all measured during each test. College Station, Texas, tap water was used with a chloride concentration of 50 mg l^{-1} and a conductivity of 800 micromhos cm^{-1}.

Chloride concentration test. To determine the effect of chloride concentration on the electrolysis process, tests were conducted using six different chloride concentrations (50 mg l^{-1} to 300 mg l^{-1}) at three different current densities (26 ma cm^{-2}, 19 ma cm^{-2}, and 13 ma cm^{-2}).

Temperature test. The effect of water temperature on cell performance was determined. Tests were conducted at three current densities. The water temperature was varied and chlorine residuals were measured. Water with a chloride concentration of 50 mg l^{-1} at a constant flow rate of 6.67 ml sec^{-1} was used.

A more detailed description of the testing procedure is presented by Peters (1973).

Results and Conclusions

Current densities test. The results indicated that as the current density is increased for each coulomb treatment dosage the chloride residual increased (Figure 1-1). At the higher current densities the increase in chlorine residual with increasing current densities was less than at lower current densities. At current densities less than .5 ma cm^{-2} there was no chlorine residual present.

In Figure 1-2 the amount of work required to get a particular chlorine residual at a particular current density is shown. The optimum current density is the one at which the work required to obtain a desired residual is the least. For all the given residuals, a current density of 17 ma cm^{-2} was optimum. At a current density of 17 ma cm^{-2} it was determined that the electrical cost (at 2¢ per kwhr) to chlorinate 3785 l (1000 gal) of water to 2.5, 2.0, 1.5, and 1.0 mg l^{-1} total chlorine residuals was 28.7, 21.8, 16.0, and 11.8 cents, respectively.

Chloride concentration. The effect of the chloride concentration of the water is illustrated in Figure 1-3. The chlorine residual increased considerably with chloride concentration. The rate of increase of the chlorine residual with increasing chloride concentration is greater with the higher coulomb treatment dosages and current densities than with the lower ones.

Temperature test. In Figure 1-4 it is shown that as the temperature increased, the chlorine residual decreased. The chlorine residual was over twice as high for a water temperature of 7.7°C than for a water temperature of 32.2°C.

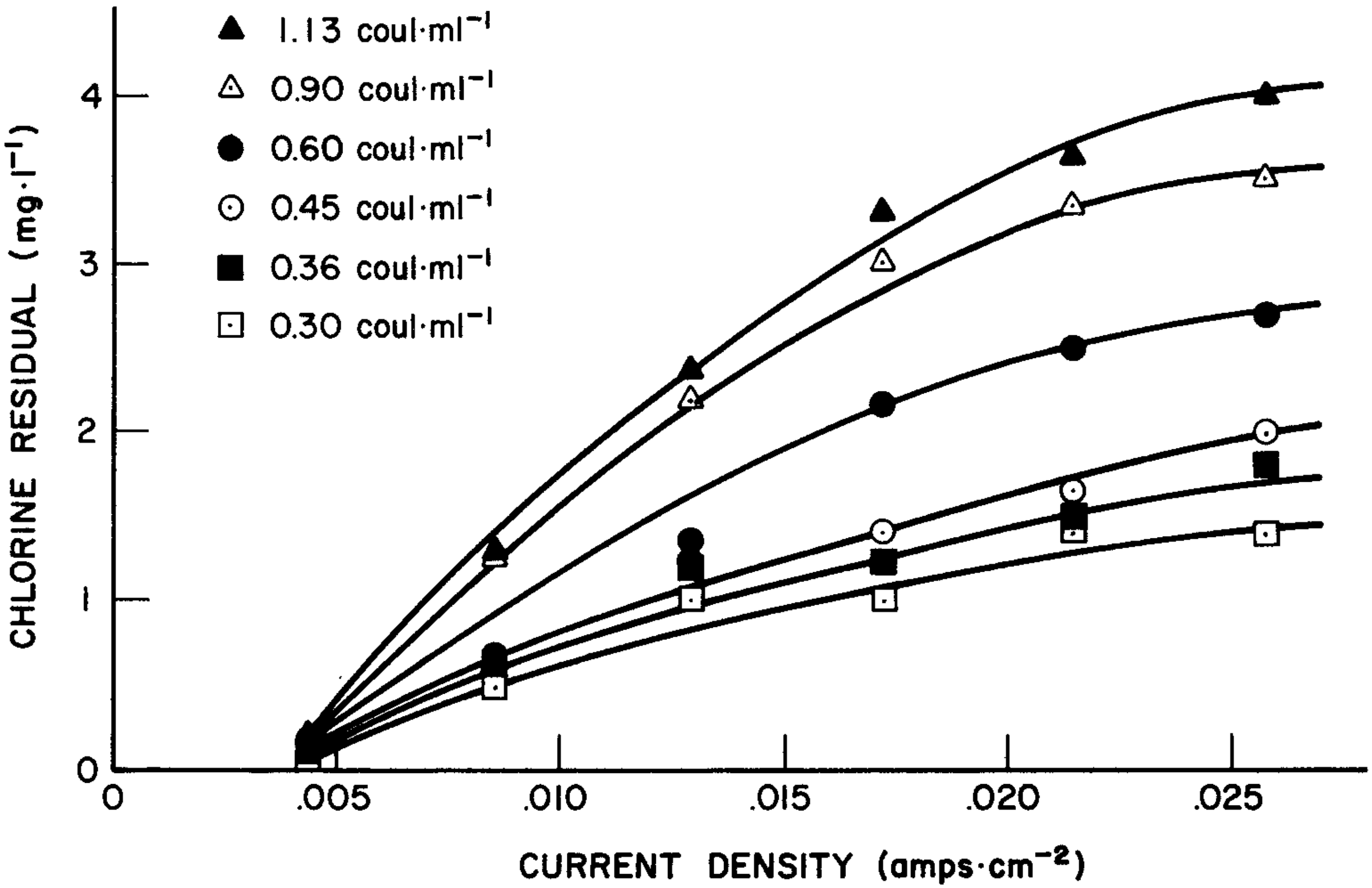

Fig. 1-1. Chlorine residual versus current density for different coulomb treatment dosages (Peters, 1973).

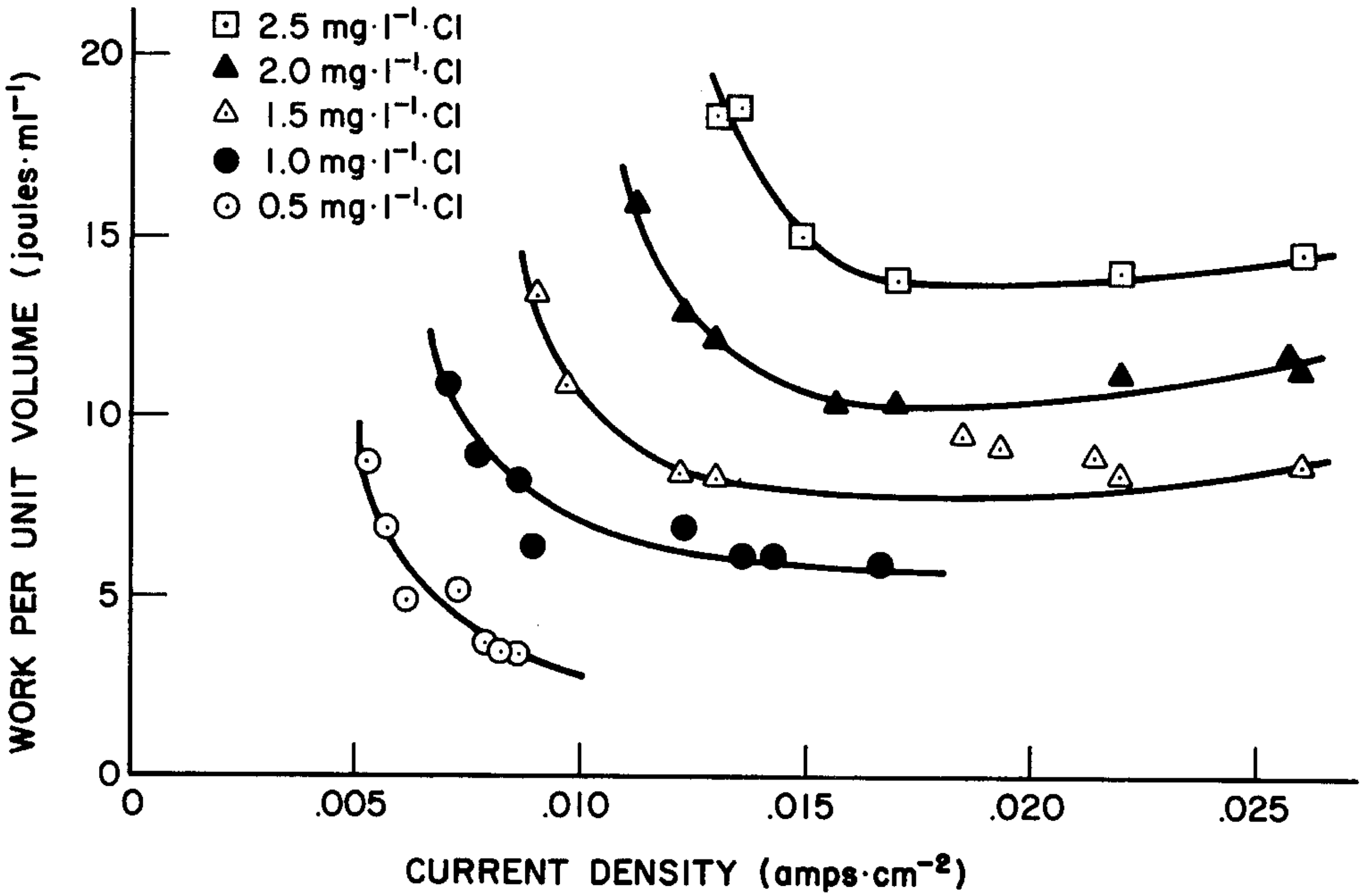

Fig. 1-2. Work per unit volume versus current density for various values of chlorine residual (Peters, 1973).

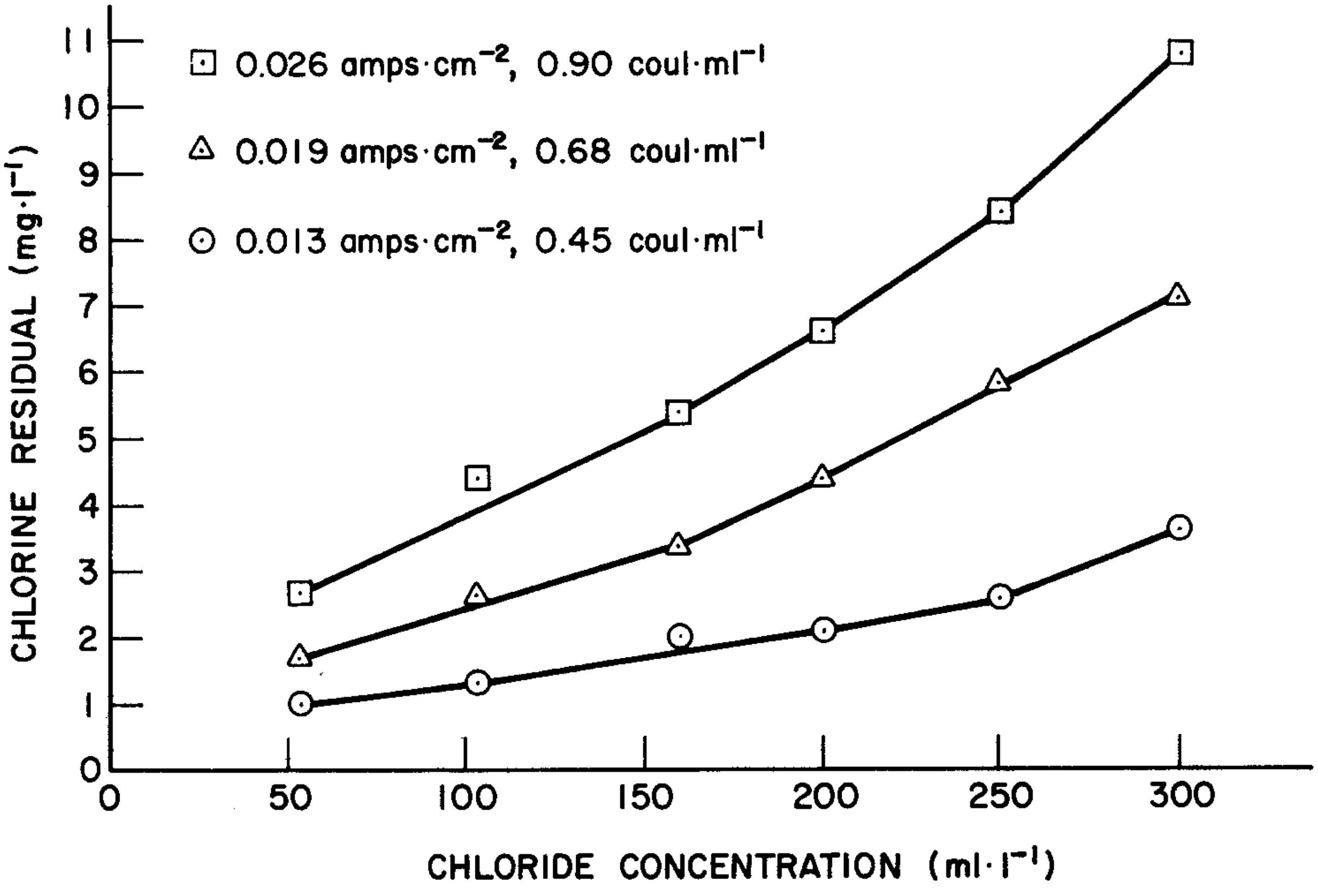

Fig. 1-3. Chlorine residual versus influent chloride concentration results at 6.67 ml sec^{-1} flow rate (Peters, 1973).

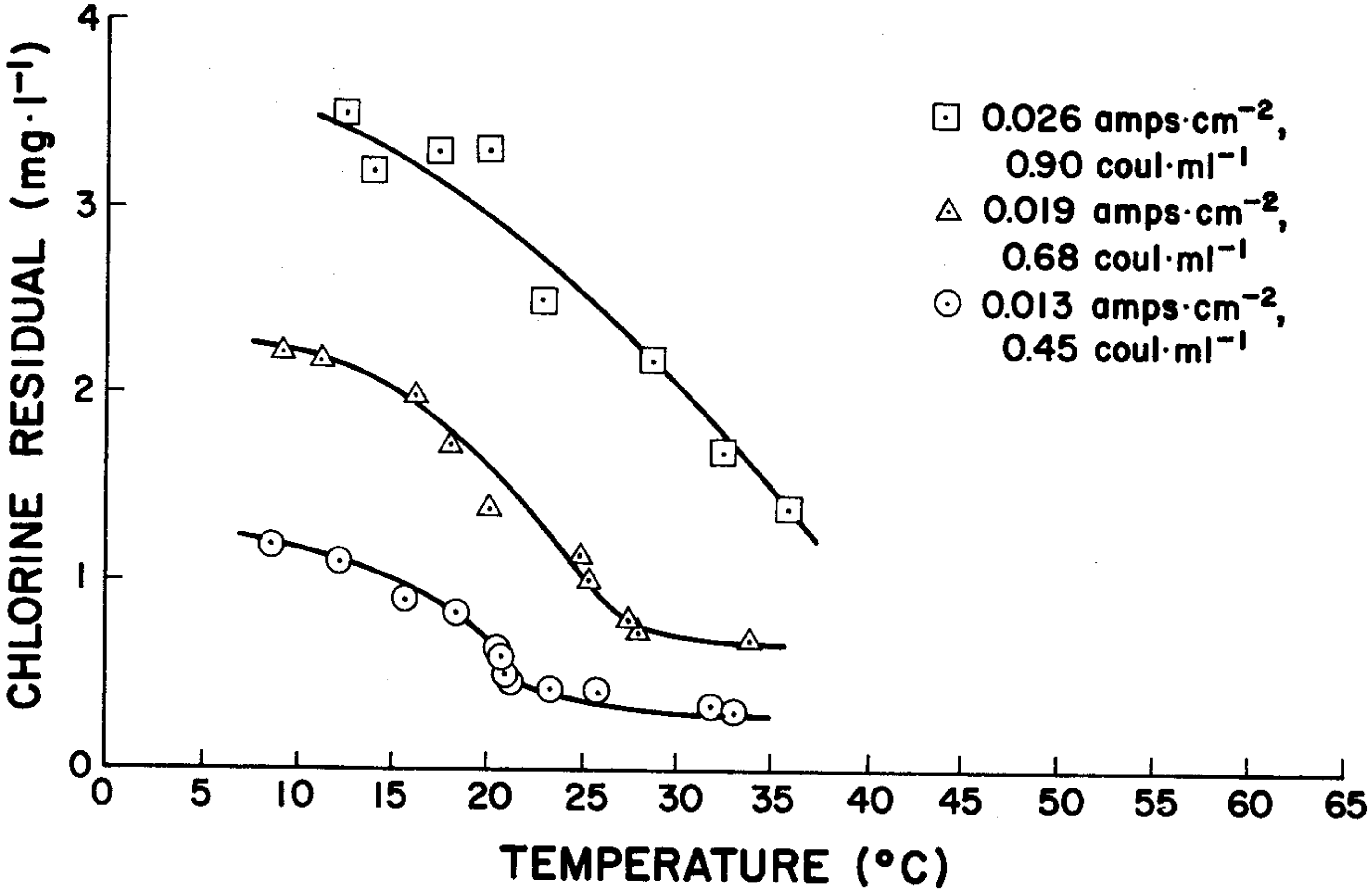

Fig. 1-4. Chlorine residual versus influent water temperature (Peters, 1973).

High-Chloride Chlorination Unit

Introduction

Some waters are very low in natural chlorides; therefore, another chlorination unit was developed to be used in this situation. It was decided to use the basic design of the previous low-chloride chlorinator, except that a brine solution instead of water was passed between the anode and cathode. The cell is similar to the one described by Simplex Manufacturing (1973). To determine if this cell would be practical for a small rural water system, several tests were conducted.

Equipment

Test cell. The cell (Figure 1-5) consisted of a platinized-titanium anode (1.27 cm x 5.08 cm) with a surface area of 6.45 cm^2 spaced .318 cm from a stainless steel (type 316) cathode. The electrodes with spacers on both sides of the center cell were clamped between two 1.27 cm thick Plexiglas holders. The electrical connections were made at a plate tab, then they were covered with tygon tubing and filled with silicon rubber. Attached directly above this cell was a polyethylene check valve which allowed chlorine gas and spent brine solution to escape into the cell container. A polyethylene hose was connected to the lower portion of the cell, and a Lab-Line Instrument, Inc., "Delta" micro-metering pump was used to supply the brine. The pump was capable of producing flow rates from 2.31 ml min^{-1} to 8 ml min^{-1}. A Sorenson Model DRC 300-25A cable of constant current control was used as a source of power.

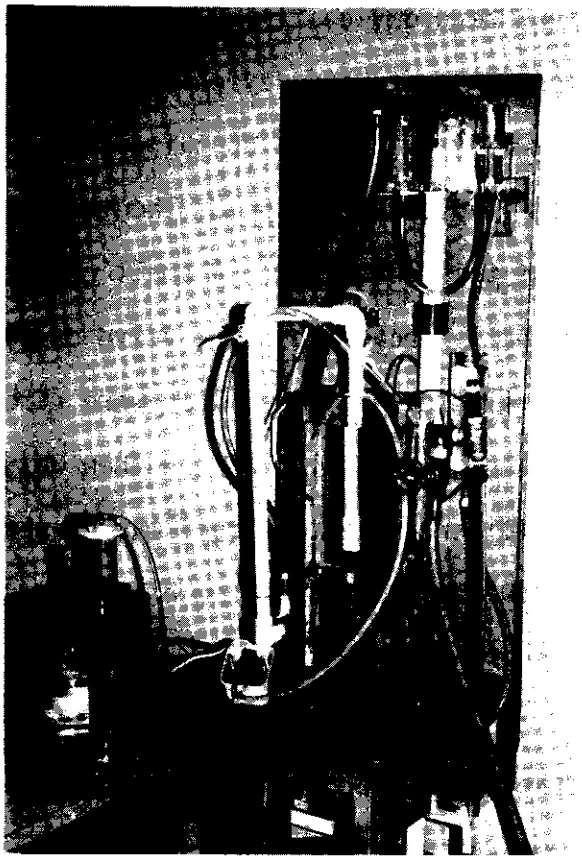

Fig. 1-5. High-chloride chlorinator during testing.

Piping and cell container. College Station tap water passed through an activated charcoal filter (which removed all of the city chlorine residual) into a 75 liter tank. A small centrifugal pump was used to keep a constant head device filled with influent. The water was metered by another constant head device into the bottom of the cell container (Figure 1-5). The cell container was 81.3 cm by 7.6 cm by 15.3 cm with a volume of 9.45 l. The testing cell was placed in the bottom of this container. A small centrifugal pump's intake was located directly above the check valve on the test cell. The chlorine that was released and some water were circulated by this pump insuring dissolution of the chlorine and then returned to the bottom of the cell container. The test cell was connected at the bottom to the micro-metering pump which fed brine solution from a 200 ml graduated cylinder.

Procedure

The 200 ml graduated cylinder was filled with brine solution, and the micro-metering pump was started. The current was set by adjusting the current-limiting circuit of the power supply. The influent water flow rate was set at approximately 1100 ml min^{-1}. The cell was allowed to operate for two hours at these conditions before measurements were taken.

A Hach Chemical Company spectrophotometer model DR/2 was used with DPD method, as described in Standard Methods for the Examination of Water and Wastewater (1971), to determine the free chlorine residual of the effluent water. The brine metering rate was determined by periodic readings of solution level in the graduated cylinder. The water temperature during testing ranged from 22°C to 25°C.

Results and Conclusions

The results for each test are presented in Table 1-1. The current efficiency was determined by dividing the measured free chlorine residual per unit current by the theoretical amount of chlorine which should be released per unit current. It is a measure of the fraction of total current used in electrolysis of NaCl to chlorine. The chloride use efficiency was determined by dividing the free chlorine residual by the amount of chloride required to produce it. It is a measurement of the fraction of chloride which was used to produce chlorine.

Figure 1-6 is a plot of the chloride use efficiency and current efficiency versus the coulomb treatment dosage for the test conducted with a strong brine solution (275.7 g l^{-1} NaCl). The current efficiency and chloride efficiency are both functions of the coulomb treatment dosage (CTD) and can be determined by the following emperical expressions:

$$\text{Chloride use efficiency} = 19.76\,(1 - e^{-CTD}) + 0.028$$

$$r^2 = 0.950 \quad \ldots\ldots\ldots\ldots 5$$

$$\text{Current efficiency} = 41.80\,(e^{-CTD}) + 17.31$$

$$r^2 = 0.938 \quad \ldots\ldots\ldots\ldots 6$$

The total cost, electrical cost and chloride cost of treating 3785 l (1000 gal) of water at a chlorine dosage rate of 2 mg l^{-1} are presented in Table 1-1. The largest percentage of the total cost for each set of conditions was the sodium chloride cost. The lower total treatment costs are at the higher current efficiencies. Therefore, the chloride use efficiency must be kept high in order to operate at the lowest treatment cost. The control of the treatment dosage would depend greatly on the accuracy of the metering pump. Accurate low capacity metering pumps are expensive.

The results of the tests with the weaker brine concentrations are presented in Figure 1-7 and Figure 1-8. The current efficiency (Figure 1-7) is a function of the coulomb treatment dosage and current density. As the coulomb treatment dosage is increased for a given current density the current efficiency decreases. The change is greater at low current densities than at high ones. The chloride use efficiency (Figure 1-8) is also a function of the treatment dosage and current density. However, at lower current densities the metering rate of brine solution into the cell becomes a variable. This type of behavior is similar to the result from the low-chloride cell (Peters, 1973). It would be very difficult to design a chlorine cell which uses weak brine solution.

The major disadvantage of using this type of chlorine cell in a rural water system is that the metering pumps with the required accuracy and low capacity are very expensive.

Table 1-1. High-chloride chlorination unit test results.

Brine Strength NaCl gr L^{-1}	Brine Feed Rate NaCl mg hr^{-1}	Current ma	Voltage volts	Effluent Free Chlorine mg hr^{-1}	Chlorine Use Efficiency	Current Efficiency	Coulomb Treatment Dosage coul mg^{-1}	Current Density ma cm^{-2}	Costs for a 2 mg l^{-1} Cl^0 Dosage ---- ¢/1000 gal		
									Electrical[1]	Chloride[2]	Total
275.7	3940.9	1700	4.00	627.5	16.0	27.9	1.553	263.6	0.164	1.05	1.214
275.7	3940.9	1000	3.70	459.5	11.6	34.7	0.913	155.0	0.122	1.43	1.550
275.7	3940.9	495	3.48	312.4	7.9	47.7	0.452	76.7	0.083	2.10	2.180
275.7	3940.9	300	3.34	199.4	5.1	50.2	0.274	46.5	0.076	3.30	3.380
275.7	2925.6	290	3.19	183.7	6.3	47.9	0.357	44.9	0.076	3.58	3.656
275.7	2975.6	680	3.43	339.3	11.6	37.7	0.837	105.4	0.104	1.94	2.044
275.7	2925.6	1000	3.55	423.5	14.5	32.6	1.230	155.0	0.127	1.55	1.677
275.7	2925.6	1500	3.72	405.1	14.1	20.4	1.845	232.6	0.286	1.62	1.910
275.7	1768.0	1700	4.15	376.4	21.3	16.7	3.462	263.6	0.284	1.75	2.030
275.7	1768.0	1000	3.70	300.9	17.0	22.8	2.036	155.0	0.186	2.18	2.370
275.7	1768.0	700	3.52	256.7	14.5	27.7	1.425	108.5	0.145	2.56	2.710
275.7	1768.0	280	3.18	134.5	7.6	36.3	0.570	43.4	0.100	4.88	4.920
275.7	1768.0	100	2.45	62.1	3.5	46.9	0.204	15.5	0.060	10.58	10.646
58.0	620.0	293	3.49	118.8	19.1	30.6	1.701	45.4			
58.0	620.0	678	3.91	331.6	33.8	37.0	3.936	105.1			
58.0	620.0	1000	4.20	370.2	40.0	28.0	5.806	155.0			
58.0	620.0	1680	4.73	397.8	40.3	17.9	9.755	260.5			
58.0	378.6	1680	5.68	182.7	29.5	8.2	15.973	260.5			
58.0	378.6	980	4.46	178.4	28.7	13.8	9.317	152.0			
58.0	378.6	700	4.11	167.2	27.0	18.1	6.655	108.5			
58.0	378.6	500	3.82	117.8	17.4	17.8	4.754	77.5			
58.0	378.6	283	3.43	79.5	12.8	21.2	2.691	43.9			
58.0	802.5	1700	4.93	467.3	36.7	20.7	7.626	263.6			
58.0	802.5	1000	4.23	369.6	27.4	27.9	4.486	155.0			
58.0	802.5	680	3.94	276.4	20.7	30.7	3.051	105.4			
58.0	802.5	297	3.45	160.3	12.4	40.8	1.358	46.0			

[1] The electrical costs were determined at an electrical rate of 2¢/Kw-hr.

[2] The chloride costs were determined at a sodium chloride cost of 10¢/lb.

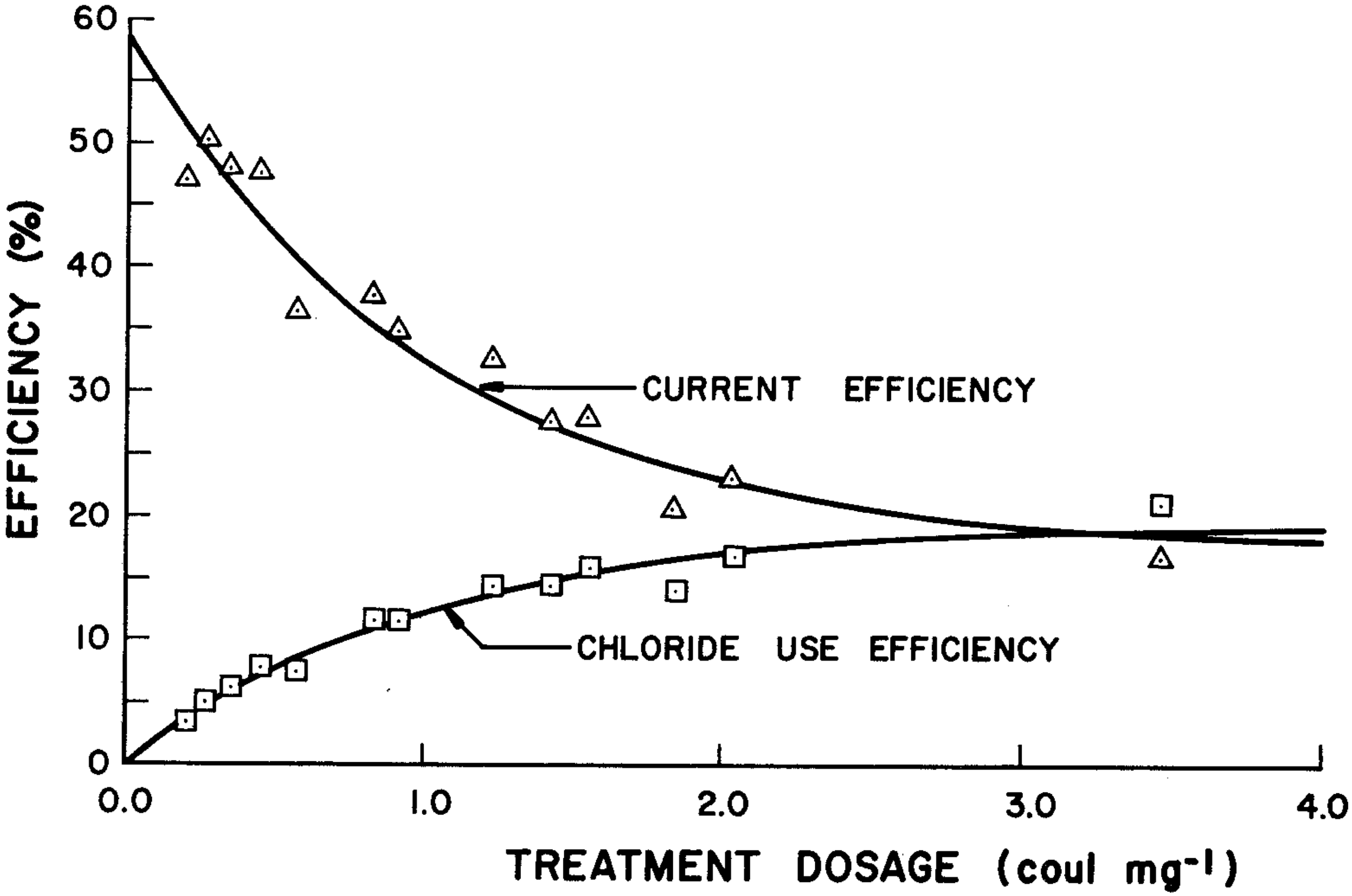

Fig. 1-6. Current efficiency and chloride use efficiency versus treatment dosage for strong brine solution.

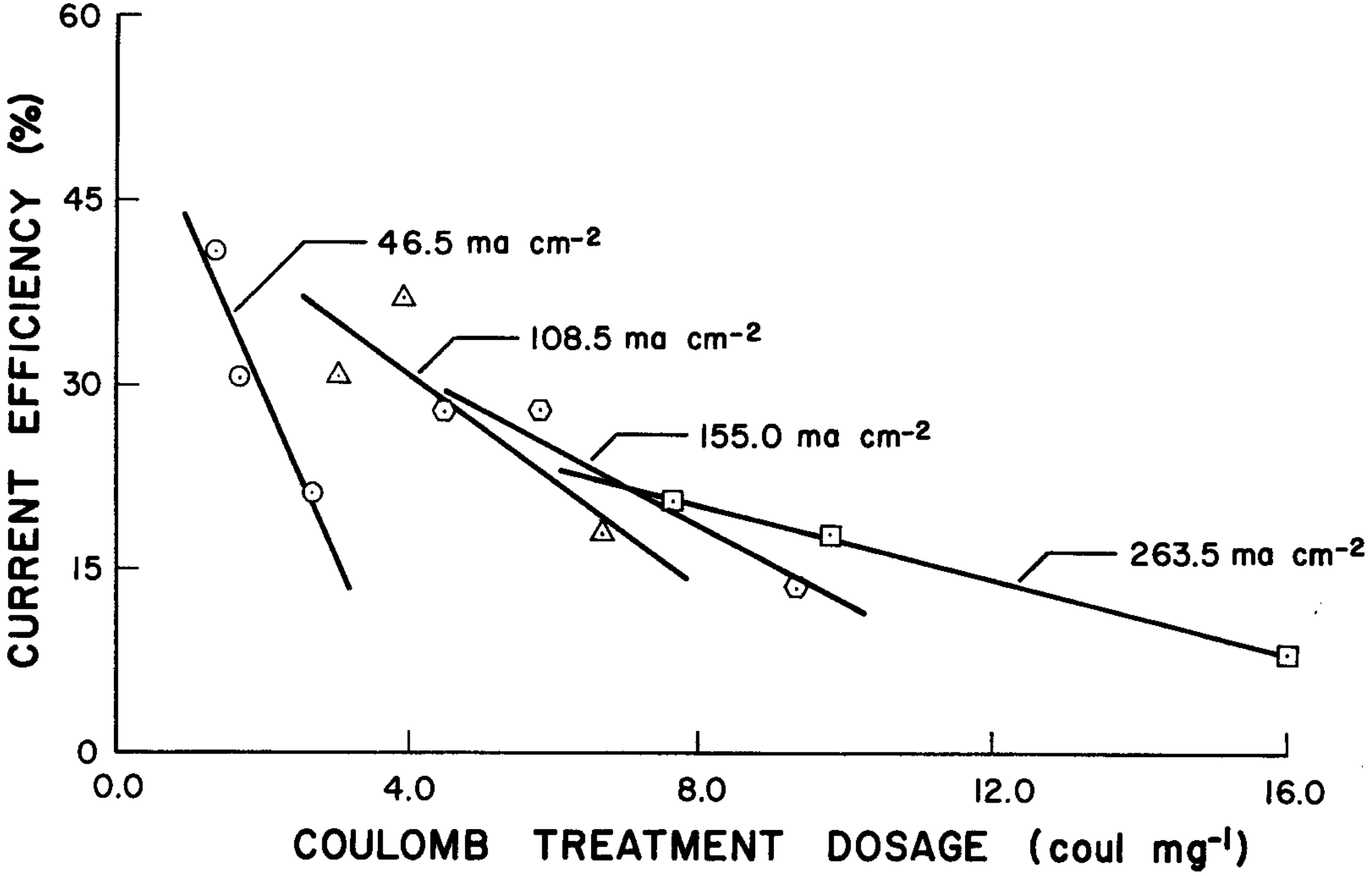

Fig. 1-7. Relationship for a weak brine solution between current efficiency and coulomb treatment dosages for various current densities.

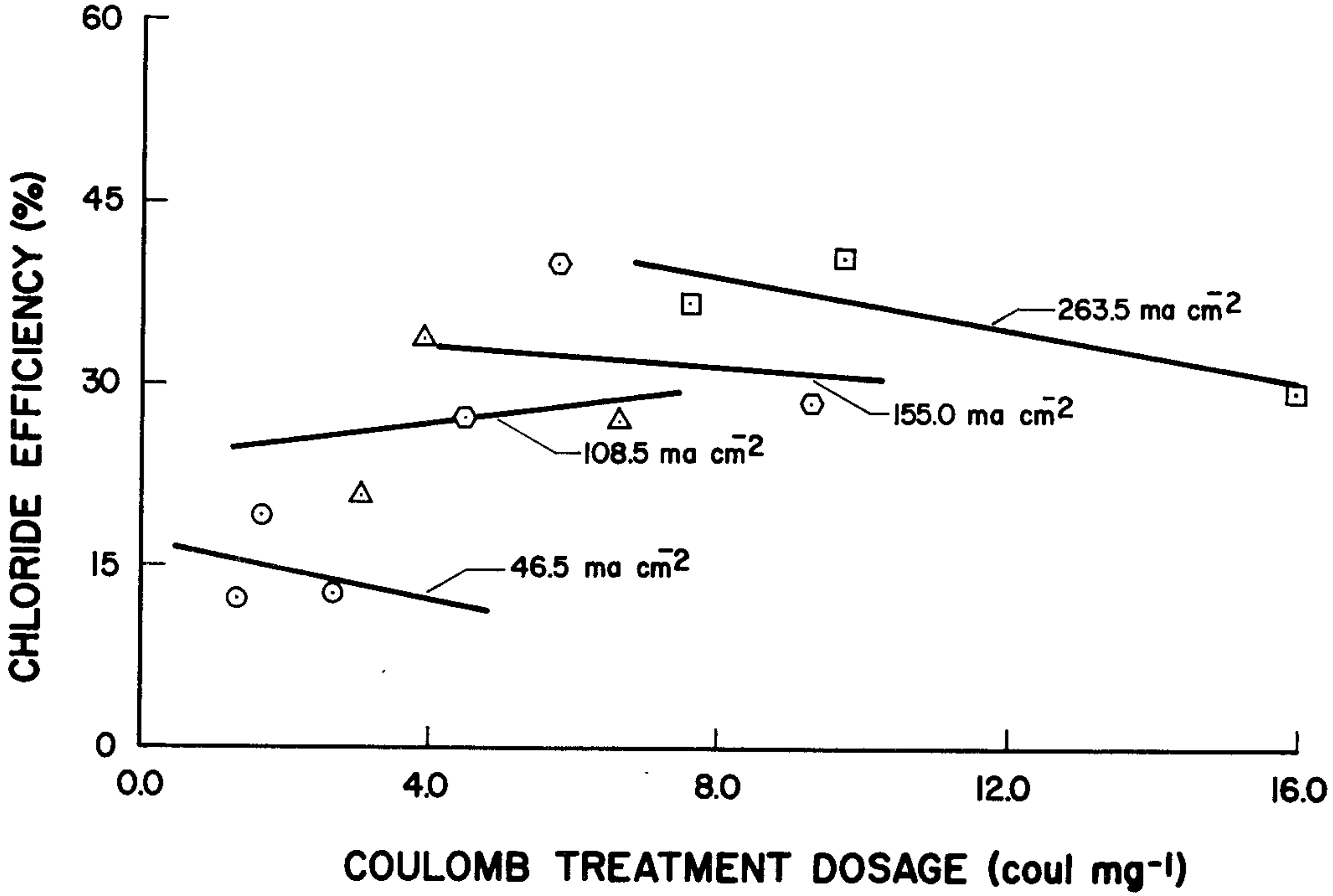

Fig. 1-8. Relationship for a weak brine solution between chloride use efficiencies and coulomb treatment dosage at various current densities.

Electro-Osmotic Chlorination Unit

Introduction

The high-chloride cell was not practical for a small water system because of the required accuracy and cost of the metering pump. One way to eliminate the metering pump was to use the electro-osmotic properties of a cation exchange membrane for metering the brine solution. The cation exchange membrane resists entrance of hydroxide ions into the anode compartment and provides the needed electro-osmotic flow of water from the anode compartment. It was realized after a few preliminary tests that the anode compartment would have to be drained periodically. This was because some hydroxides which migrated across the membrane formed chlorate causing the brine solution to become diluted. Several tests were conducted on the electro-osmotic chlorine cell to determine if it was applicable to a small water system.

Equipment

Electro-osmotic chlorine cell. The electro-osmotic chlorine cell consisted of two compartments connected through a Teflon solenoid valve (Figure 1-9 and Figure 1-10). The brine solution entered the cell at the rear and from below the anode compartment. It flowed upward through a sloped area into the anode compartment. The anode was platinized-titanium approximately 0.01 cm thick. The anode's exposed edges were covered by a 0.15 cm thick Plexiglas spacer to prevent the erosion of titanium along the edges. The anode was spaced 0.2 cm from the membrane. A tab attached to the anode was bent 90° back and extended out the Plexiglas anode holder. The tab was sealed by compressing Teflon packing around the tab. The upper portion anode compartment sloped back and a 1.27 cm diameter port extended down from the top to meet it. A polyethylene tube which carried the chlorine gas to the treatment cylinder was attached to this port. A 0.625 cm diameter port from the back of the compartment intersected the upper portion of the anode compartment just below the intersection of the 1.27 cm diameter port. A 0.625 cm polyethylene tube was attached here and was connected to the inlet side of the solenoid valve.

The cathode compartment was made similar to the anode compartment. The outlet side of the solenoid valve was connected by a 0.625 cm polyethylene tube to the upper sloping portion of the cathode compartment. The cathode was also platinized-titanium spaced 0.635 cm from the membrane. Platinized-titanium was used instead of a metal with a better cathode potential because when the unit was not in operation no trickle protecting current would need to be provided. A 1.27 cm diameter PVC stand pipe was located above the compartment allowing hydrogen gas to escape during operation. The cathode solution was drained away through a 0.625 cm diameter polyethylene tube connected to the lower sloping portion of the compartment. A constant head overflow device was connected to the other end of the tube.

The chlorine gas traveled up through a check valve and then back down through the polyethylene tube into the lower portion of the 10.2 cm treatment cylinder. The chlorine gas then bubbled up through a 16 cm bed of 1 cm diameter glass beads which kept the chlorine bubbles in the water long enough to insure dissolution.

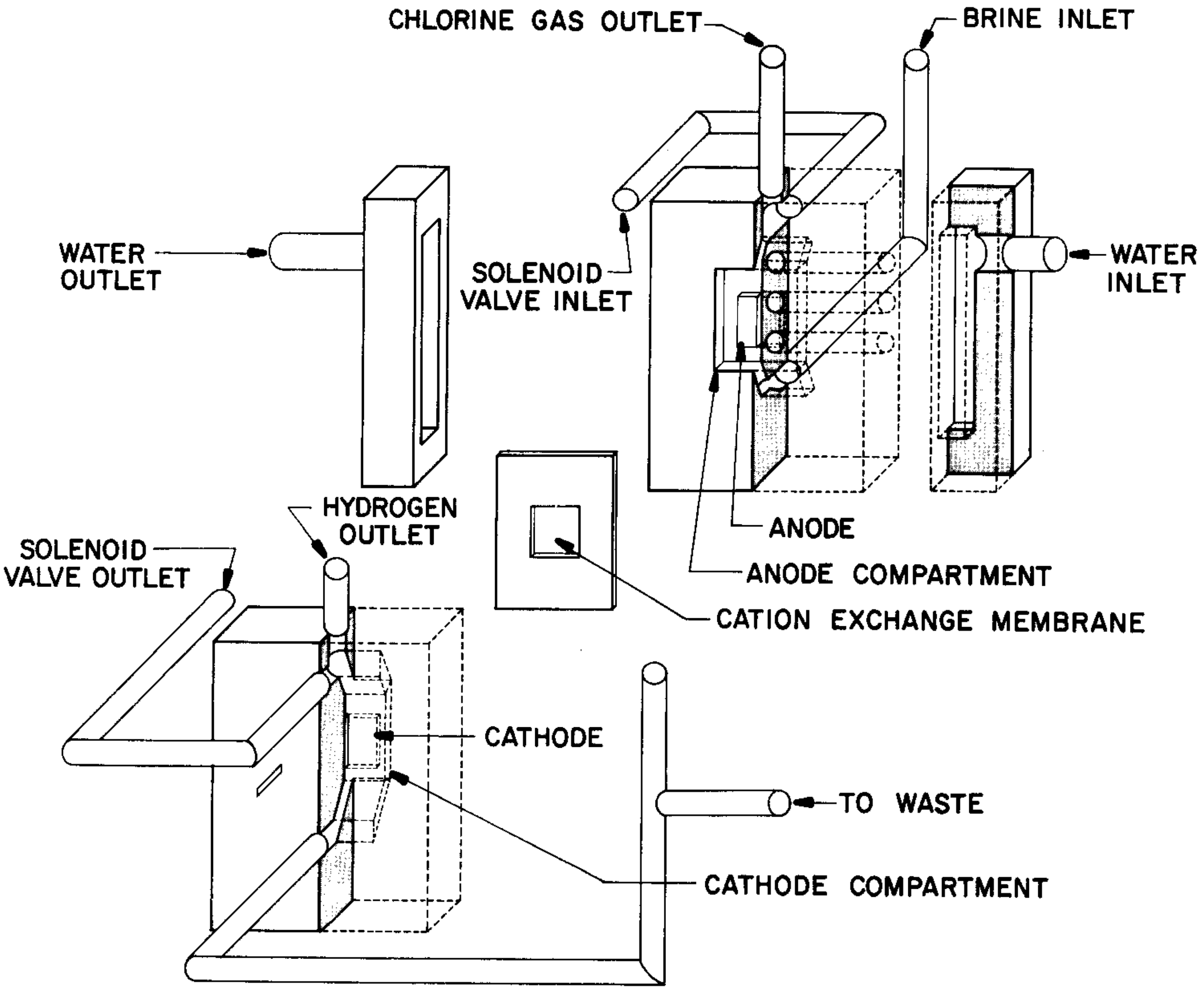

Fig. 1-9. Electro-osmotic chlorine cell.

The unchlorinated water entered a manifold on one side of the anode compartment and passed behind the anode through three channels into another manifold thus cooling the anode compartment. The water then entered the lower portion of the treatment cylinder below the glass beads. It then flowed up through the glass beads where it reacted with the chlorine and was disinfected. The disinfected water then exited through an overflow opening.

Membranes. The DuPont Nafion 1200 E. W. Membrane was boiled for 30 min, then immediately transferred to stretching frame shown in Figure 1-11. The membrane was stretched 0.635 cm in both directions of the membrane's Teflon cloth weaving. It was then allowed to dry for 24 hrs at room temperature. Small holes were punched around the outside perimeter through the Teflon cloth weaving. Two 0.159 cm thick PVC sheets with outside dimensions of 10.64 cm by 10.64 cm with a 2.54 cm by 2.54 cm area removed from the center were glued on each side of the membrane. Industrial Polychemical Service Company Type 705 glue was allowed to dry overnight before removing the membrane holder from the stretching frame. The excess membrane was trimmed away and the edges were sealed.

Zitex membranes are a non-woven, porous, hydrophilic Teflon membrane supplied by Chemplast, Inc. In Table 1-2 the properties of the Zitex membranes which were used as membranes or as separators are shown. The Gelman Instrument Company Aeropor AN800 membrane is copolymer of acrylontrile and polyvinyl chloride on nylon supporting material.

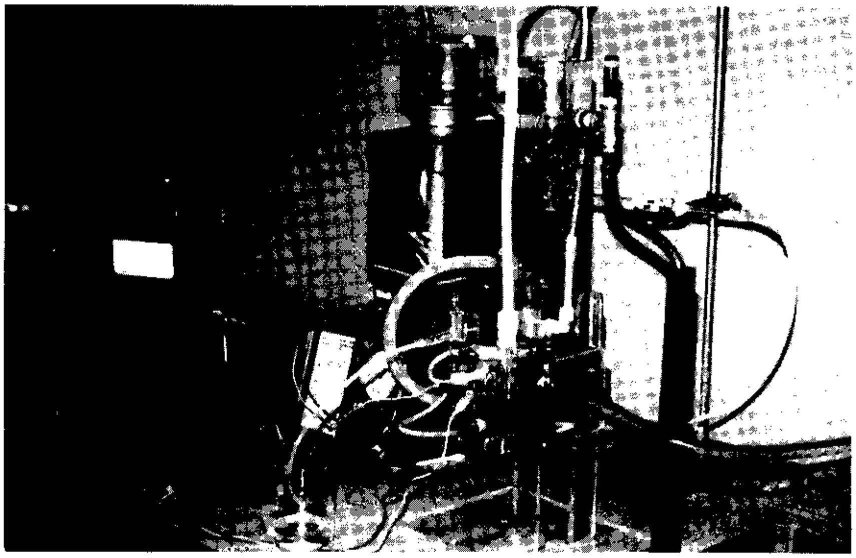

Fig. 1-10. Electro-osmotic chlorination unit during testing.

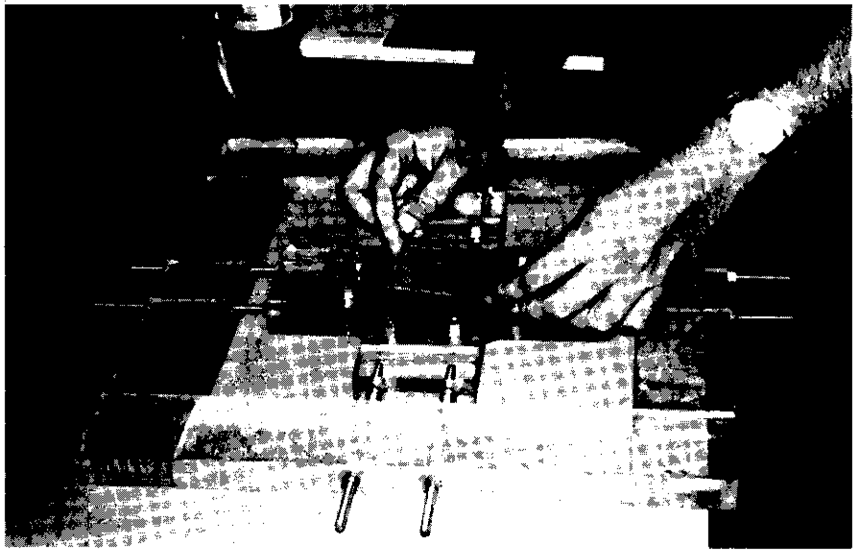

Fig. 1-11. Stretching frame used in mounting Dupont Nafion membranes.

TABLE 1-2. Typical properties of standard Zitex membrane which were used as separator or membrane (1).

	Maximum Functional Pore Size (Microns)	Thick-ness Mils ± 15%	Flow Rates		Initiation Pressure for Water PSI (4)	Ethanol Bubble Point PSI	Tensile Strength PSI	(Approx.) Weight Lbs/Ft^2
			(2) Water	Air (3) Sec.				
HV100-122 (5,6)	30-60	4.0	50-80	.20-.50	.30-.70	.13-.26	80-160	.02
E249-122 (5,6)	10-20	4.0	15-30	1.50-2.50	.90-1.80	.35-.70	130-260	.02
E606-223 (5)	2-5	6.5	.5-3	20.00-90.00	1.80-3.60	.70-1.40	200-400	.03
E606-223/5 (5)	1-2	5.0	.05-.30	150-500	3.00-6.00	1.00-2.00	225-450	.03

Data shown are representative and not to be used as material specification.
Pore volumes of all membranes shown fall within the 65% to 85% range.

(1) Chemplast, Inc., Product Bulletin on Zitex membranes.
(2) G.P.M. Ft^{-2} Δ P 13.5 P.S.I.
(3) Time required for 100 cc air to pass through 1 square inch @ Δ P 0.176 P.S.I. (Gurley Test)
(4) Pressure differential necessary to overcome hydrophobic and internal resistance.
(5) Used as separator between anode compartment and treated water.
(6) Used as membrane between cathode and anode compartments.

Procedure for Electro-Osmotic Cell Testing

A cylinder located on a balance was filled with brine solution at a concentration of 280 g l^{-1} NaCl. The brine passed through a small twist valve (which was closed when weight of NaCl was determined) into the electro-osmotic test cell. The flow of the brine through the cell was described earlier (Figure 1-10).

The cell was run for 24 hours before measurements were made. After draining 200 ml of liquid from the cell by opening the solenoid valve, the brine container was refilled and testing started.

The free chlorine of the effluent water residual was determined by the DPD method described earlier. The flow rate of the brine solution into the cell was determined from the weight change of the solution with time. The voltage and amperage were measured at the cell with a Simpson Model 260 volt-ohm-milliampmeter.

Discussion of Results

Zitex and Gelman membranes. Preliminary testing was conducted using several Zitex membranes (HV-100-122, E 606-122, and E 606-122-L) and a Gelman Acropor AN-800 membrane. The Zitex types HU-100-122 and E 606-122-L were unsuccessful because of their hyperbolic properties. The membranes acted as insulators between the anode and cathode compartment and ruptured when pressure was applied to start the brine flowing. The Zitex E 606-122-L wet-table membrane lasted for approximately 70 hrs before rupturing. The cell using a Gelman Acropor AN-800 membrane acted as a diaphragm chlorine cell instead of a membrane cell. After 125 hrs of testing the Acropor material was removed and examined. The examination revealed that the nylon support material had deteriorated causing the membrane to rupture. Portions of the membrane coating were severely attacked by the chlorine and eroded away. The chloride use efficiency ranged from 48% to 38% and the current efficiency ranged from 90% to 69% during testing before rupturing.

Initially, several porous Teflon Zitex membranes (Table 1-2) were tried as separators between the anode compartment and the treated water. The chlorine gas passed through these membranes but water flow was blocked due to its hyprobolic characteristics. These materials were not good separators because the chlorine that passed through it left behind a brine film on the separator which restricted the flow of the gas. The resulting buildup of gas forced the brine from the anode compartment. This method of introducing the chlorine to the water was abandoned for the polyethylene tube method described earlier.

Nafion membranes. Preliminary testing of the chlorine cell revealed that periodically at least 200 ml of brine solution must be drained before the anode and cathode compartments were filled with fresh brine solution.

The cell was tested at four current settings (1250 ma, 1000 ma, 750 ma, and 490 ma). The results of these tests are presented in Figure 1-12 and Table 1-3. The chlorine produced declines with testing time at all current settings. At the two higher current settings the chlorine production declined very rapidly at first, then became relatively constant. At the two lower current settings the chlorine product slowly declined at about the same rate throughout the test.

In Table 1-3 the chloride use efficiencies and current efficiencies for each current setting are presented. They were determined from the total amount of brine solution used (electro-osmotic flow volume plus drain volume). The chloride use efficiency declines as the current setting is lowered. This was due to the large percentage of brine that was not completely used before draining.

Current efficiencies were equal for the 1250 ma and 750 ma current test (49.6%). The 1000 ma current test had the lowest efficiency (44.1%); and the 495 ma current test was the highest current efficiency (68.1%).

The cost for treating 3785 liters (1000 gal) of water with a chlorine dosage of 2 mg l^{-1} is presented in Table 1-3. Only the electrical cost at 2¢ per kwhr and chloride cost of 10¢ per pound of sodium chloride are included in the total cost. The 1250 ma current test had the lowest cost (1.078¢), and the 750 ma current test had the highest cost (1.434¢).

Summary

Of the three chlorinator units developed, the electro-osmotic chlorinator is the most applicable to a small rural treatment system.

The main advantage of the low-chloride chlorinator is that it uses the natural chloride in the water. The operating costs are extremely high for this chlorinator, and the chlorine residual is a function of water temperature and chloride concentration.

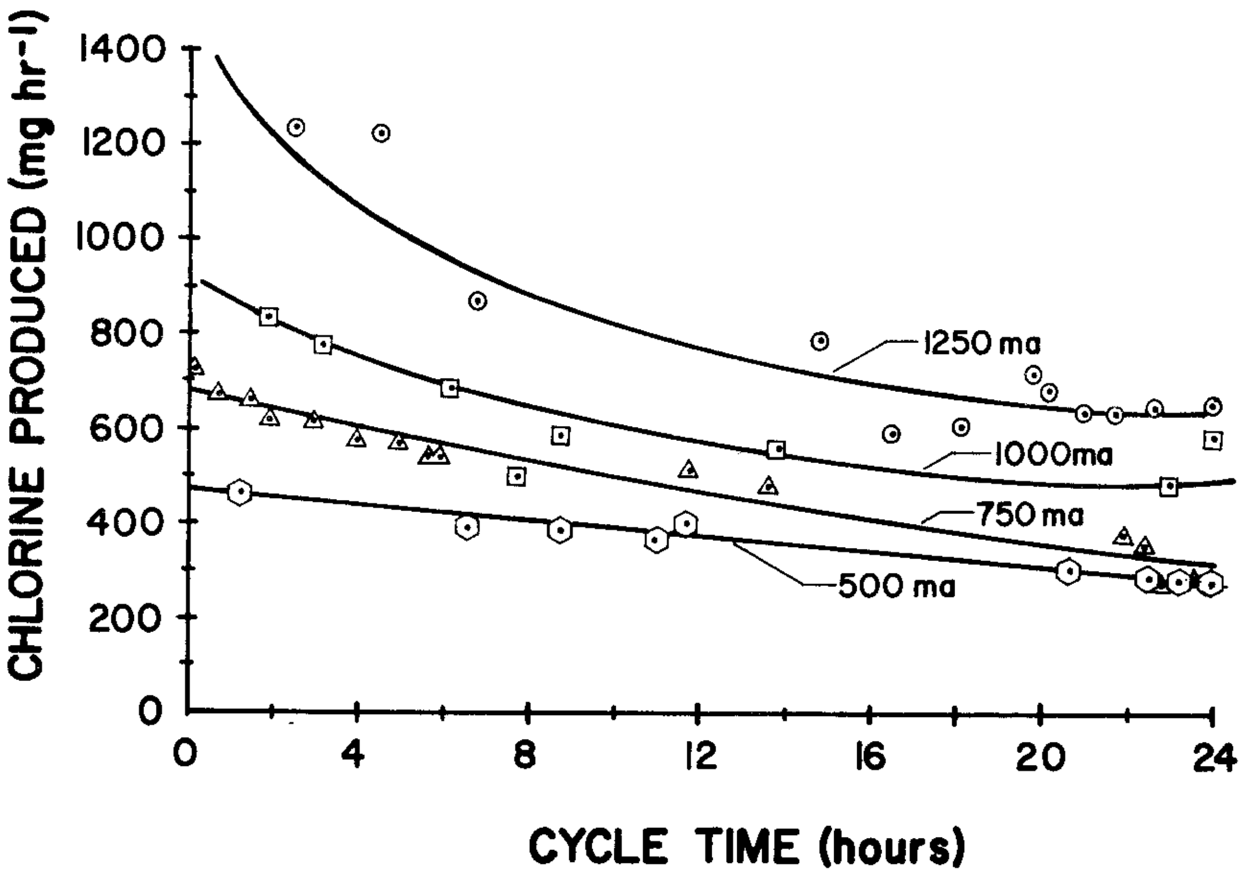

Fig. 1-12. Electro-osmotic chlorination unit chlorine production versus cycle time.

TABLE 1-3. Summary of test performed on the electro-osmotic chlorination unit.

								Cost 2 ppm Dosage ¢/3785 1		
Current ma	Average Voltage Volts	Electro-osmotic-Chloride Used mg day^{-1}	Drained Chlorides Used mg day^{-1}	Total Chlorides Used mg day^{-1}	Chlorine Released mg day^{-1}	Chloride[3] Use Efficiency %	Current Efficiency %	Electricity[1] (D.C.) ¢	Chloride[2] ¢	Total ¢
1250	5.07	26,580	37,370	63,950	19,700	30.8	49.6	.233	.845	1.078
1000	4.76	22,490	37,370	59,860	14,000	23.4	44.1	.232	1.040	1.272
750	4.40	18,950	37,370	56,320	11,800	21.0	49.6	.203	1.231	1.434
495	4.00	10,260	37,370	47,630	10,240	21.5	68.1	.141	1.187	1.328

[1] Electrical cost determinations are based on an electrical rate of 2¢/kwhr.

[2] Chloride cost determinations are based on a rate of 10¢/lb of NaCl.

[3] Determined from total chloride used during a complete cycle.

Operating costs for the high-chloride chlorinator ranged from 1.21 to 10.65¢ per 1000 gal. For use in rural water systems this unit is unfeasible due to the cost of an accurate low flow metering pump. The possibility of mechanical problems is increased when a metering pump is used in a chlorination system.

The need for a metering pump was eliminated by using the electro-osmotic flow of water across a membrane to meter the brine into the cell. The operational cost ranged from 1.08 to 1.43¢ per 1000 gal and was the lowest of all three chlorinators tested. Though chlorine residual of the water was a function of the drain cycle time, this variation can be overcome by the averaging effect of a storage tank and proper scheduling of the drain time.

CHAPTER II

LOW-CURRENT DENSITY ELECTROCHEMICAL FLOCCULATION

Introduction

Most surface waters contain suspended materials which must be removed before the water is safe for human consumption. The suspended material can be removed by one of two methods: (1) filtration or (2) flocculation and sedimentation. The flocculation and sedimentation method also removes color and bacteria. In the flocculation process a positively charged ion is added to the water which helps form large fast-settling flocs.

In this research two electrochemical methods for adding positively charged aluminum ions to the water were evaluated. In the low-current density method the scale which formed on the aluminum electrodes was removed at the same rate as it formed. The high current density method prevented the scale from forming on the electrodes. Each method for releasing aluminum ions was evaluated and field tested.

Review of Literature

When two active metal electrodes are immersed in an electrolyte and a potential is applied, the anode is oxidized and goes into solution. The metal ions in the electrolyte are reduced and deposited on the cathode. This process has been used to purify metals and to electroplate one metal over another.

The aluminum ion is the most commonly used and most effective ion for coagulation. In most installations this ion is added to the water in the form of filter alum (aluminum sulfate, $Al_2(SO_4)_3$). The removal of suspended material and color is accomplished by coagulation.

The coagulation of colloidal material is one of the basic treatment processes used on water. The settling velocities of finely divided and colloidal clays are so small that removing them in a settling tank is impossible; therefore, these very small particles must be formed into large fast-settling flocs by coagulation. Coagulation proceeds in three steps according to Steel (1960). As the coagulant dissolves, the aluminum or ferric ions form positively charged hydroxide complexes which are available to neutralize the negative charges on the particles of colloidal clay and colored particles. This is the first stage of coagulation which is improved by rapid mixing. In the second stage the small neutralized particles collide with each other and form larger fast-settling flocs. The possibility of collision of the neutralized particles is increased during this stage by slow stirring. During the third stage, surface absorption of particles, such as bacteria, takes place on the large surface area.

Aluminum sulfate requires the presence of alkalinity. If water is naturally low in alkalinity, lime must be added. The basic reaction in water containing natural alkalinity is as follows:

$$Al_2(SO_4)_3 - 18\ H_2O + 3\ Ca(HCO_3)_2 \longrightarrow$$

$$2\ Al(OH)_3 + 3\ CaSO_4 + 18\ H_2O + 6\ CO_2\ .\ .\ .\ .\ .\ 7$$

When the water is low in alkalinity, lime is added so the following reaction will occur:

$Al_2(SO_4)_3 + 18\ H_2O + 3\ Ca(OH)_2 \longrightarrow 2\ Al(OH)_3 + 3\ CaSO_4 + 18\ H_2O$ . . 8

Alkalinity must be present in both cases for alum to form aluminum hydroxide. The water in many ponds contains alkalinity that is insufficient in quantity for alum to be used. Therefore, both alum and lime would have to be fed into the water making the treatment system more complex and harder to automate.

When aluminum ions are added to the water by oxidation of the anode, there is also electrolysis of water taking place according to the following reaction:

Reduction at cathode

$4\ HOH + 4\ e \longrightarrow 4\ OH^- + 2\ H_2 \uparrow$ 9

Oxidation at anode

$4\ OH^- - 4\ e \longrightarrow 2\ H_2O + O_2 \uparrow$ 10

The hydroxide released at the cathode combines with the aluminum ion to form aluminum hydroxide. Thus, the reaction can take place in water that is low in natural alkalinity and, obviously, without the addition of lime.

The aluminum hydroxide ($AlOH_3$) is not stable and crystallizes in the course of time to give a monohydrate ($\gamma\ Al_2O_3 \cdot H_2O$) or bohmite. The bohmite crystallizes into trihydrate ($Al_2O_3 \cdot 3\ H_2O$) or bayerite according to Deltombe et al (1966). This process is known as aging. The various hydrates formed during the aging are characterized by an increased stability and decreased solubility.

Stuart (1946) developed a unit called a "flash coagulator" which used electrical current to release aluminum ions by oxidation of an aluminum anode into water to coagulate colloidal materials. A small experimental unit consisting of 96 aluminum plates spaced 0.32 cm apart with an electrode area of 71,120 cm^2 was used to treat eleven different waters. The unit was effective in removing color and reducing the alkalinity of eleven waters tested. The unit was able to reduce the color of North Carolina swamp water with a pH of 5.0 from 400 ppm to 10 ppm in 30 seconds. The color of water from a Florida swamp with a 7.5 pH was reduced from 120 ppm to 20 ppm. The lengths of the tests were all very short (less than 30 minutes). This prevented the plate surfaces from becoming covered with scale during the test. The cost of using this process for treating water was estimated at 1.8¢ per 1000 gallons. However, this included only the electrical cost. Bonilla (1947) did some additional work using the "flash coagulator" in which he estimated the total cost (including aluminum consumed electrically) to be 1.8 to 3¢ per 1000 gallons. Bonilla also indicated that the electrodes may become fouled. Additional research was needed to prevent fouling and to determine the best operating conditions.

Stuart (1947) presented three different designs for a "flash coagulator." The first one, similar to the experimental unit, contained four stationary plate units that were connected so the water could flow through each unit before leaving the flocculator. The second design consisted of four plate units, each being suspended from the ends of two levers. Simultaneously, the levers rocked up and down dipping one of the units into the water with each downward motion. The third flocculator design consisted of four plate units in which two sets of units rotated in separated tanks. The polarity of the electrodes was reversed periodically so the plates were consumed evenly.

Boyd (1963) reported using electrochemical coagulation along with electrophoresis to successfully clean up heavy water at the Hansford Plutonium Recycle Test Reactor. Numerous other methods that were tried had failed. Using electrochemical coagulation and electrophoresis coupled with standard filtration and ion exchange processes, complete removal of the following contaminants was achieved:

(a) oil in colloidal suspension,
(b) oil in emulsion,
(c) finely divided particles of dust and rust in suspension, and
(d) metallic ions.

The unit consisted of twelve parallel aluminum plates spaced 0.63 cm apart providing 39,150 cm^2 of plate surface area. The total current was 10 amps that gave a current density of .256 ma cm^{-2}. The plate lasted for a period of 100 hours after which they failed to provide the necessary Al^{+++} ions to sustain the current flow. If it is assumed that aluminum was released at a current efficiency of 100%, only one percent of the aluminum was consumed. Therefore, it can be assumed that the unit stopped releasing aluminum ions because the plate became covered with a deposit of bayerite or scale.

Lyle and Hiler (1970) did several experiments using stainless steel and aluminum grid electrodes. The effective surface area of the grid was 900 cm^2. In all of the tests aluminum proved superior to stainless steel in the removal of turbidity. The operating cost of aluminum electrodes ranged from 7.5 to 10¢ per 1000 gal (3785 l), while the stainless steel electrode had an operating cost that ranged from 11 to 17.5¢ per 1000 gal. The unit was operated at current densities ranging from 1.4 to 5.5 ma cm^{-2}. The minimum current which would maintain flocculation at a flow rate of 5.2 gal/hr was 3 amps. This gave a current density of 0.83 ma cm^{-2}. The authors did not mention any scaling problem during the experiment. This was possibly due to the short length of the tests which did not allow scale to build up on the electrodes. Also, thin aluminum strips were used to make the grid. This provided the aluminum to be consumed before a scale coating could seal the electrodes. The voltage rise during the experiment indicated that a scale was developing on the electrodes.

The experiments performed by Stuart (1946) and Hiler and Lyle (1970) were all done for short periods of time. Plate scaling did not occur due to these short time periods. In Boyle's unit the plate became sealed with scale after 100 hours, thus no aluminum entered the water.

Sealing of the electrode could have been prevented if scale was loosely attached to the electrode and was removed at the same rate it was formed. To achieve this, the effects of the following on scale formation were evaluated:

(1) length of the polarity reversing cycle,
(2) type of aluminum alloy,
(3) current density,
(4) ultrasonic energy, and
(5) mechanical vibration.

Several different test models were used to evaluate these.

Equipment

Piping System

The influent test suspensions were mixed in a 150 gallon polyethylene tank from which they were pumped by a small centrifugal pump into a constant head device located 3.66 m above. A regulated bypass from the pump back into the holding tank agitated the suspension.

The flow rate to the unit being tested was controlled by raising or lowering a second constant head device which was connected by a hose to the first constant head device.

Electrical System

Direct current to the electrodes was supplied by two identical power supplies (300 volt, 3 amp) connected in parallel for a maximum of 6.0 amps. These power supplies were capable of controlling the DC power at a constant voltage or constant current. The polarity reversal was achieved by using a two-pole double-throw relay and a cycle timer. An 8.0 amp, 24 volt DC power supply was used when more than 6.0 amps was required. The current of this power supply was controlled manually by a variable transformer.

Instrumentation

A manually operated Hellige Model 801D nephelometic type turbidimeter was used for determining the influent and effluent clay concentrations. The electrical potential to the electrodes was measured accurately with a Keithley Model 610B electrometer. The current was obtained from ampmeters located on the power supplies after calibrating them. The electrical conductivity of the influent suspensions was measured with a YSI Model 31 conductivity bridge.

Vertical Flow Mixing Tank

The tank was constructed of 16 gauge sheet metal and coated with epoxy paint. The inside was 30 cm wide, 30 cm long, and 122 cm high. The bottom section was sloped toward a drain valve located in the center. The drain valve was opened periodically to remove accumulated scale and sludge. The treated water entered the tank at the bottom, passed through a suspended floc bed, and was removed at the top. The total volume of water held was 111 l. The average upward flow velocity was 1.08 cm/min at a flow rate of 1.0 l/min.

Vertical Flow Settling Tank

The tank was constructed of 16 gauge sheet metal and coated with epoxy paint. The inside dimensions were 91 cm by 91 cm and the tank was 122 cm high. The bottom sloped toward two drain outlets. The interior was divided into 10.2 cm^2 compartments extending from 10 cm above the bottom to above the water level. The water entered the tank at the bottom and was distributed by a manifold into each compartment. The water moved upward inside the compartments and was removed by another manifold located 4 cm under the water level. The total volume of water held in the tank was 1968 l.

At a flow rate of 1.31 l/min (500 gal/day), the average upward flow velocity was 0.009 cm/min. According to Stoke's Law the unit at 100% efficiency should remove particle sizes less than 15 microns in diameter.

Materials

Water

Water for the test suspensions was from the College Station water supply. A chemical analysis done by Orlando Laboratories, Inc., is presented in Table 2-1.

Clay

The clay suspensions used for evaluating the removal of charged particulate matter by the various test models were prepared with colloidal Kaolinite clay obtained from the Georgia Kaolin Company. Lyle and Hiler (1971) presented a detailed description of the chemical analysis and electrophoretic mobility properties of the clay used in these experiments.

Aluminum Alloys

The aluminum used in the low current density test models was obtained from Joseph T. Ryerson & Son, Inc. The limits and ranges of the chemical impurities for the 1100 aluminum and 6061 aluminum alloys are listed in Table 2-2.

Tests of Models

Two Plate Vertical Flow Test Unit

A drawing of this model is presented in Figure 2-1. The outside of the electrolysis compartment was constructed of three pieces of 1/2 in Plexiglas. There was a transition zone at the top and bottom where the water entered and left the unit. The plate spacing was adjusted from the outside by four screws. The spacing could be varied

TABLE 2-1. Chemical analysis[1] of College Station, Texas, tap water. July 26, 1972.

Total Dissolved Solids, @ 105°C	490	mg l^{-1}
Phenolphthalein Alkalinity, as $CaCO_3$	0	mg l^{-1}
Total Alkalinity, as $CaCO_3$	366	mg l^{-1}
Carbonate Alkalinity, as $CaCO_3$	0	mg l^{-1}
Bicarbonate Alkalinity, as $CaCO_3$	366	mg l^{-1}
Carbonates, as CO_3	0	mg l^{-1}
Bicarbonates, as HCO_3	447	mg l^{-1}
Hydroxides, as OH	0	mg l^{-1}
Carbon Dioxide, as CO_2	5	mg l^{-1}
Chloride, as Cl	57	mg l^{-1}
Sulfate, as SO_4	11	mg l^{-1}
Fluoride, as F	0.51	mg l^{-1}
Phosphate, as PO_4	3.9	mg l^{-1}
Total Hardness, as $CaCO_3$	30	mg l^{-1}
Calcium Hardness, as $CaCO_3$	6	mg l^{-1}
Magnesium Hardness, as $CaCO_3$	24	mg l^{-1}
Calcium, as Ca	2.4	mg l^{-1}
Magnesium, as Mg	5.8	mg l^{-1}
Sodium, as Na	240	mg l^{-1}
Iron, as Fe	0.0	mg l^{-1}
Manganese, as Mn	0	mg l^{-1}
Copper, as Cu	0	mg l^{-1}
Silica, as SiO_2	23	mg l^{-1}
pH (Laboratory)	8.2	
pHs	8.3	
Stability Index	8.4	
Saturation Index	-0.1	
Color, Standard Platinum Cobalt Scale	0	
Odor Threshold	0	
Turbidity, Jackson Units	3	

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[1] Test performed by Orlando Laboratories, Inc., Orlando, Florida, according to Standard Methods for the Examination of Water and Wastewater, APHA, New York, New York.

TABLE 2-2. Chemical composition limits of 1100 and 6061 aluminum alloys.[1]

	1100 Aluminum Alloy[2] (Percent)	6061 Aluminum Alloy[3] (Percent)
Silicon	1.0 (Fe+Si)	.4-.8
Iron	-	.7
Copper	.05-.20	.15-.40
Magnesium	-	.8-1.2
Manganese	.05	.15
Chromium	-	.15-.35
Zinc	.10	.25
Titanium	-	.15
Others	.15	-

[1] Maximum or range given unless otherwise noted; impurities limited to .05 percent maximum each and .15 percent maximum total.

[2] Parker (1967).

[3] Reynolds Aluminum Mill Products Catalog (1972).

from 0.28 cm to 1.25 cm. The plates were 0.28 cm thick with a vertical dimension of 19 cm and a horizontal dimension of 51 cm. It had a total area of 968 cm^2. The electrical connection was made at the back of the plates. The plate area was decreased in Test B and Test C by placing two vertical spacers between the plates.

Test D was performed at a high flow velocity with a large plate area by dividing the unit into four compartments. The water flowed through each compartment before leaving the unit. This was accomplished by replacing both entrance transition zones with manifolds which channeled the water from one compartment to the next. The gas which formed during the electrolysis of water was exhausted through a stand pipe at the top of the unit.

Test A Procedure. Aluminum alloy 6061 was used for the electrodes which had a total area of 968 cm^2. It was spaced 0.33 cm apart. The influent turbidity was 50 mg l^{-1} of kaolinite clay. The test was started at a flow rate of 100 ml min^{-1}. After 22 hours of testing it was increased to 1000 ml min^{-1}. The water entered at the top of the plates and left at the bottom. The total current was 3.0 amps (current density of 3.15 ma cm^{-2}) at the start of the test and was increased to 6.0 amps (current density of 6.3 ma cm^{-2}) after 22 hrs. The polarity of the plates was reversed every 30 secs.

Test B Procedure. This test was run under the same conditions as in Test A, except for the following: The plate area was reduced to 484 cm^2 and the flow rate was increased to 1000 ml min^{-1}. This caused

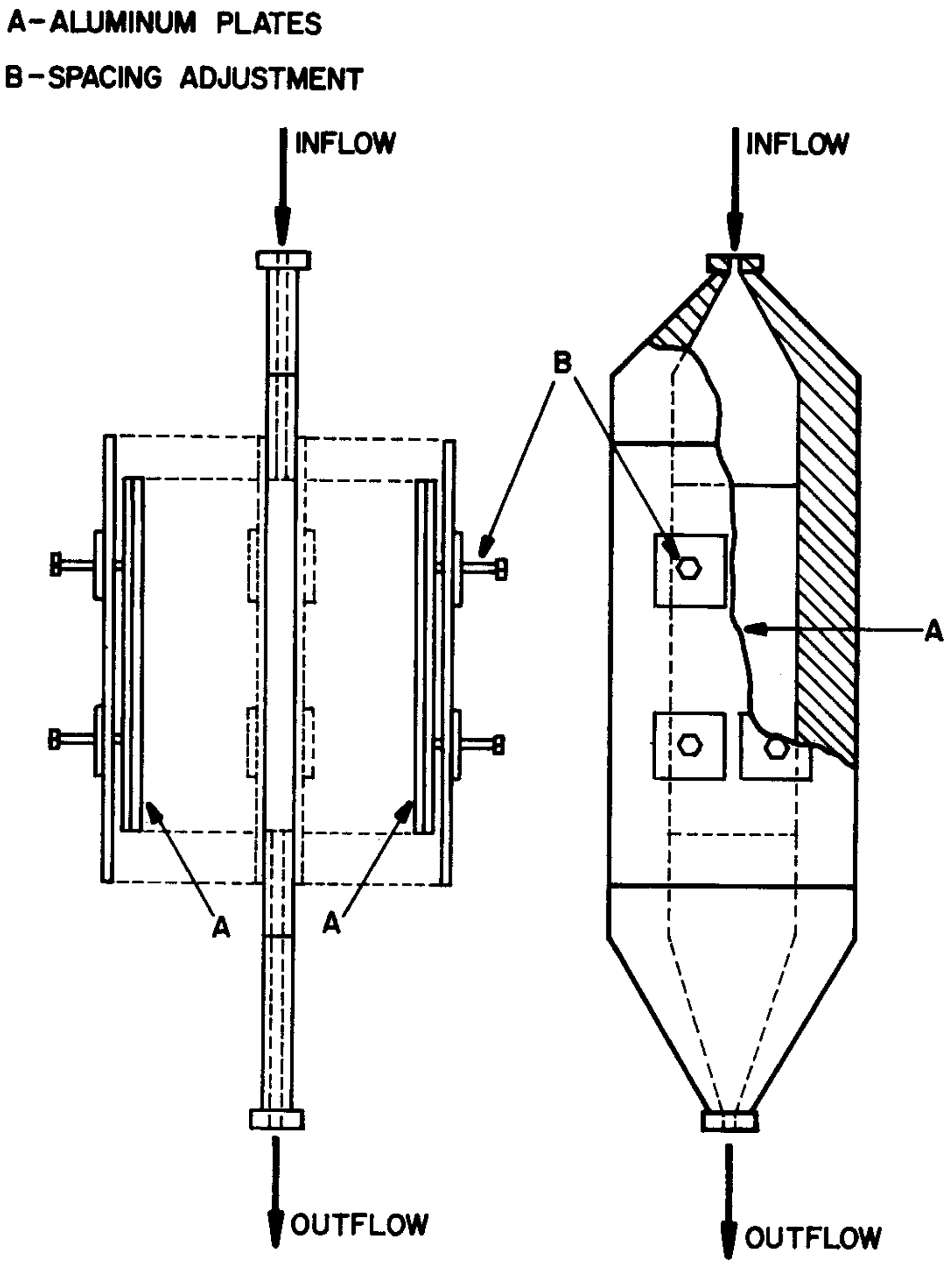

Fig. 2-1. Two plate vertical flow test unit.

the water velocity between the plates to be 5.44 cm sec^{-1}. The spacing between the plates was 0.65 cm. The current density was 12.4 ma cm^{-2} at a constant current of 6 amps.

Test C Procedure. This test was run under the same conditions as in Test B, except the flow direction was changed to an upward flow.

Test D Procedure. The voltage was held constant at 5.0 volts, and the amperage was allowed to decrease as scale resistance increased. Two runs were made of this test. Run 1 was terminated at about 75 hrs and run 2 was continued until hour 200 (Figure 2-4). All other conditions were the same as in Test C.

The apparent unit area resistance was used to compare the various units tested. It indicated the amount of scale formation on the plates by the approximate amount of resistance to current flow caused by this scale. Apparent unit area resistance was determined by the following equations:

$$\text{Apparent unit area resistance} = (Rt - Rw) \times A \quad \ldots\ldots\ldots \quad 11$$

$$Rt = V / I \quad \ldots\ldots\ldots\ldots\ldots \quad 12$$

$$Rw = \frac{R \times S}{A} \quad \ldots\ldots\ldots\ldots\ldots \quad 13$$

where

Rt = total resistance of the plates and water,
Rw = resistance due to the water,
S = spacing between the plates,
A = area of the plates
R = resistivity of the water,
V = voltage across the plates, and
I = current.

Discussion of Results. Scale developed in all four tests which eventually caused the unit to become clogged and water flow to cease.

The outside layer of scale was loose and it flaked off during the test (Figure 2-2). The scale which was under this layer was very dense and was tightly attached to the surface of the plates. In Figure 2-3 the apparent unit area resistance for Tests A, B and C increased at the same rate. Good coagulation occurred at the beginning of each test; however, toward the end of the tests coagulation stopped. This indicated that the plates had become sealed by the layer of scale next to the electrode surface and no aluminum was dissolving in the water.

At the beginning of Test D (Figure 2-4) the apparent unit area resistance increased at a slower rate than in previous tests. However, toward the end of the test the rate at which the apparent unit area resistance was increasing was approximately equal to the first three tests.

It was concluded that at a polarity reversal period of 30 sec the scale formation and the resulting sealing of the plate could not be prevented from occurring on 6061 aluminum alloy. The scale formation could be slowed by running the unit at a low constant voltage which resulted in low densities. The voltage fell off immediately when the polarity was switched and then slowly started to increase. This is similar to what occurs when a capacitor is charged and discharged. Therefore, at short polarity reversal periods much electrical energy is wasted by charging and discharging the plates.

Fig. 2-2. Aluminum plates removed from vertical flow test model.

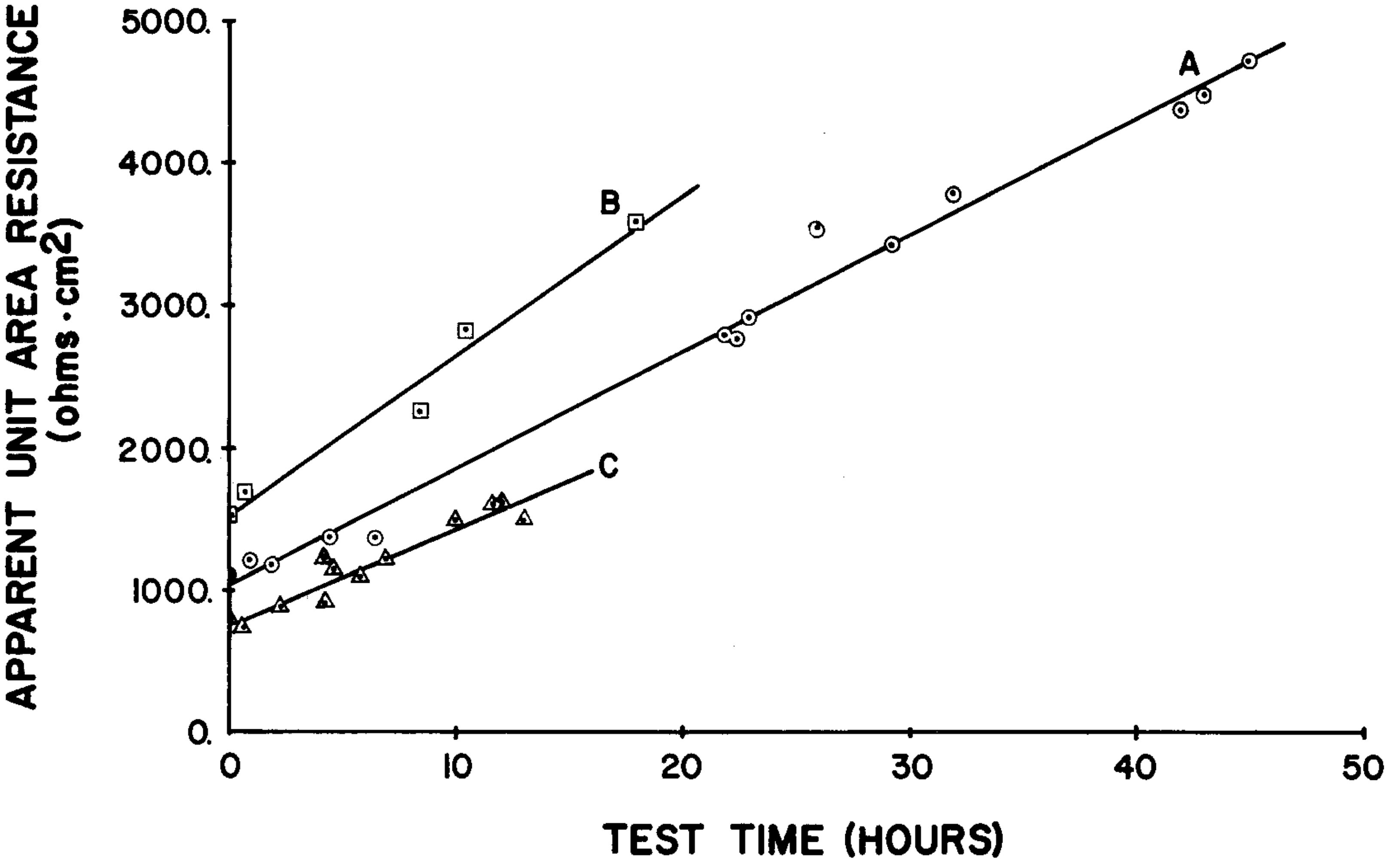

Fig. 2-3. Apparent unit area resistance versus test time for the vertical flow flocculator.

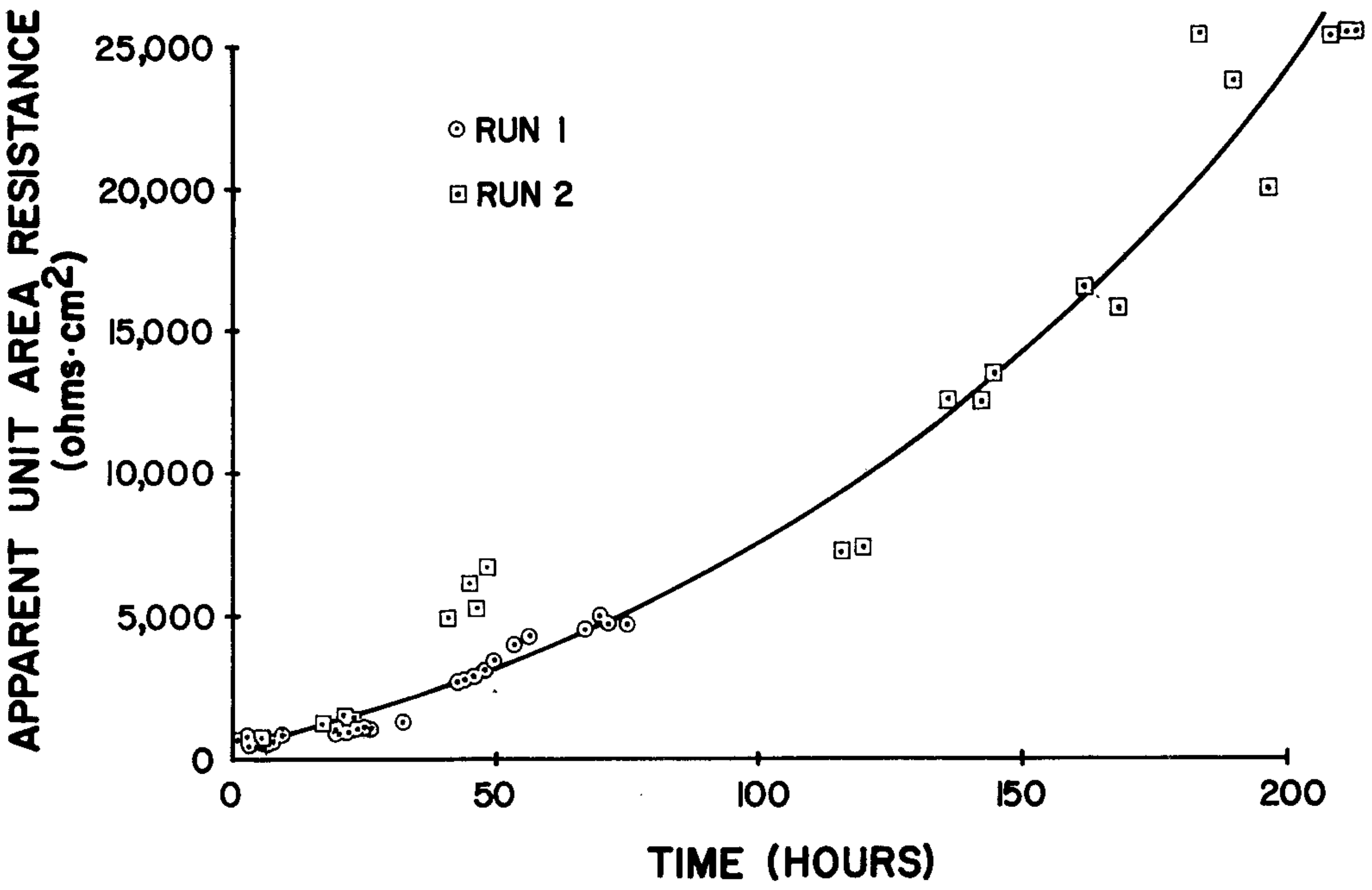

Fig. 2-4. Apparent unit area resistance versus test time for the two plate vertical flow unit at a constant voltage.

Horizontal Test Unit

The unit (Figure 2-5) was constructed of 1.27 cm Plexiglas side walls and 0.64 cm dividers with these dimensions: 15.2 cm wide, 76.2 cm long, and 17.2 cm high. The unit was designed for water to enter, pass between the plates, and exit over a weir into a drain. The plates were held in place by two slotted Plexiglas supports at each end. The bottom of the unit under the plates was sloped toward the drain located at one end. The drain valve could periodically be opened to remove scale which had fallen to the bottom of the unit.

Each plate was 9.5 cm tall and 50.8 cm long with an area of 484.1 cm^2. A tab was welded onto one end of each plate. When the unit was in operation, this tab was above the water level, as shown in Figure 2-5, the electrical connections were made at the top of these tabs. The total electrode area of the ten plates was 4,355 cm^2. The plates were made from 6061 aluminum alloy spaced 0.95 cm apart.

Procedure

College Station tap water and kaolinite clay were mixed to achieve an influent turbidity concentration of 50 mg l^{-1}. The flow rate was 950 ml min^{-1}. A constant current of 6.0 amps was applied which resulted in a 1.38 ma cm^{-2} current density. The polarity of the plates was reversed every 15 min. A mechanical vibrator was added to the unit after the 100th test hr.

Discussion of Results

The effluent was allowed to settle until clear. During the first portion of the test (without vibration) the effluent was clear after

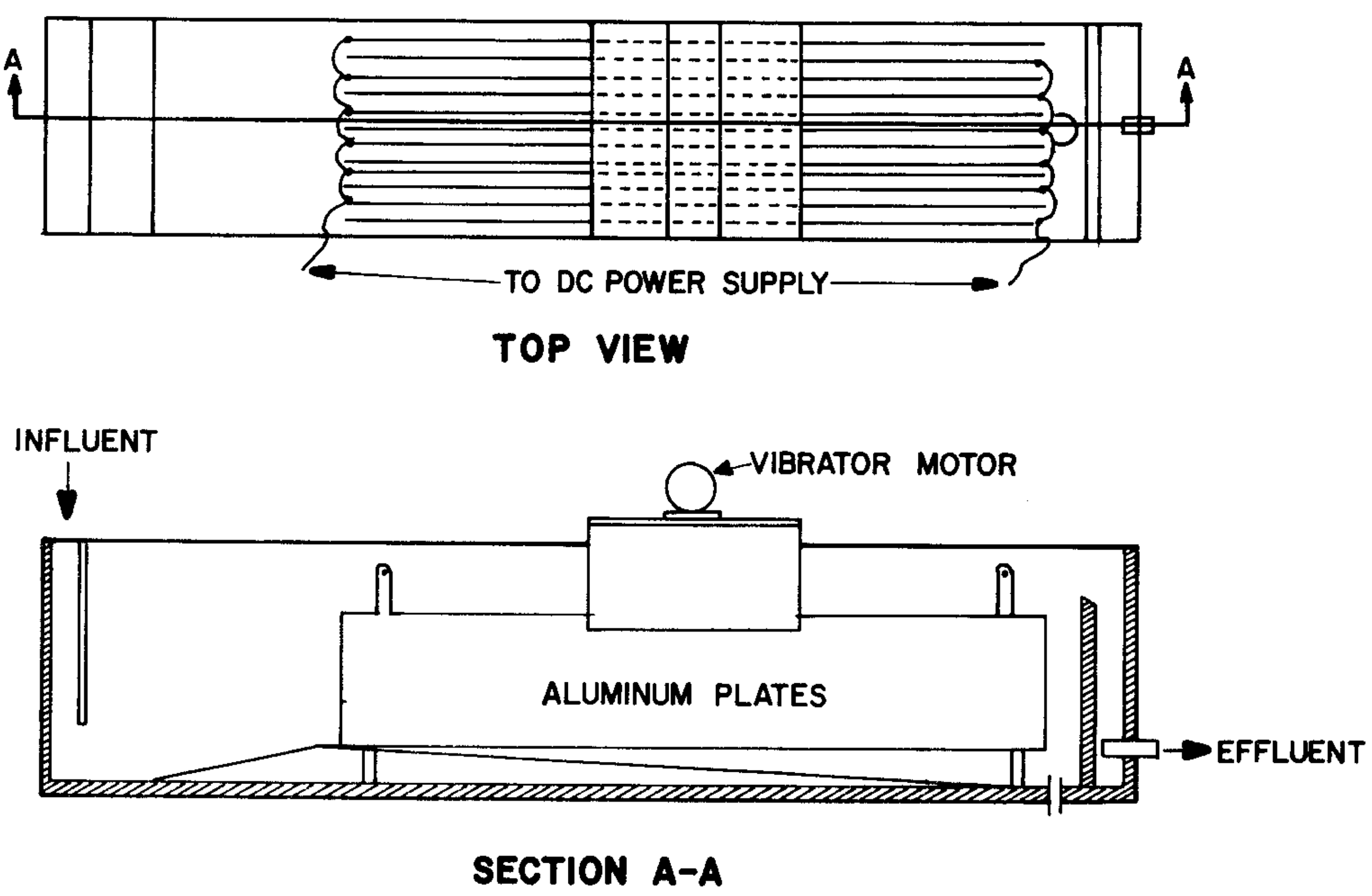

Fig. 2-5. Low current density horizontal test unit.

6 hrs. However, after 24 hrs of test time the effluent required greater than 24 hours of settling to become clear. After the vibrator was added the effluent cleared within 16 to 24 hrs for the next 50 test hrs. After the 200th hr of the test, however, no flocs formed in the effluent. This indicated that a scale coating had not sealed the electrode as fast with the vibrator. This vibration caused the scale to come off in sheets.

The apparent unit area resistance increased during the entire test (Figure 2-6). When the vibrator was added, the apparent unit area resistance decreased immediately due to the sheets of scale coming off the plates. After scale had again covered the plates, the voltage would vary during the reversal cycle. The voltage, after polarity reversal, dropped to approximately 1/3 of the maximum voltage, then increased to its maximum which occurred 10 min after switching. The plates' electrical capacitance was discharged immediately after switching and slowly charged for the next 10 min.

Ultrasonic Flocculation Test Model

Introduction

Ultrasonic cleaners have been used for a variety of cleaning applications. The cleaning action is produced by ultrasonic sound waves in a cleaning medium (usually water) which causes cavities to form and collapse between the medium molecules.

Aluminum wire can be soldered by using an ultrasonic soldering iron. Ultrasonic energy is used to remove the oxide coating on the surface of the aluminum while the solder is applied.

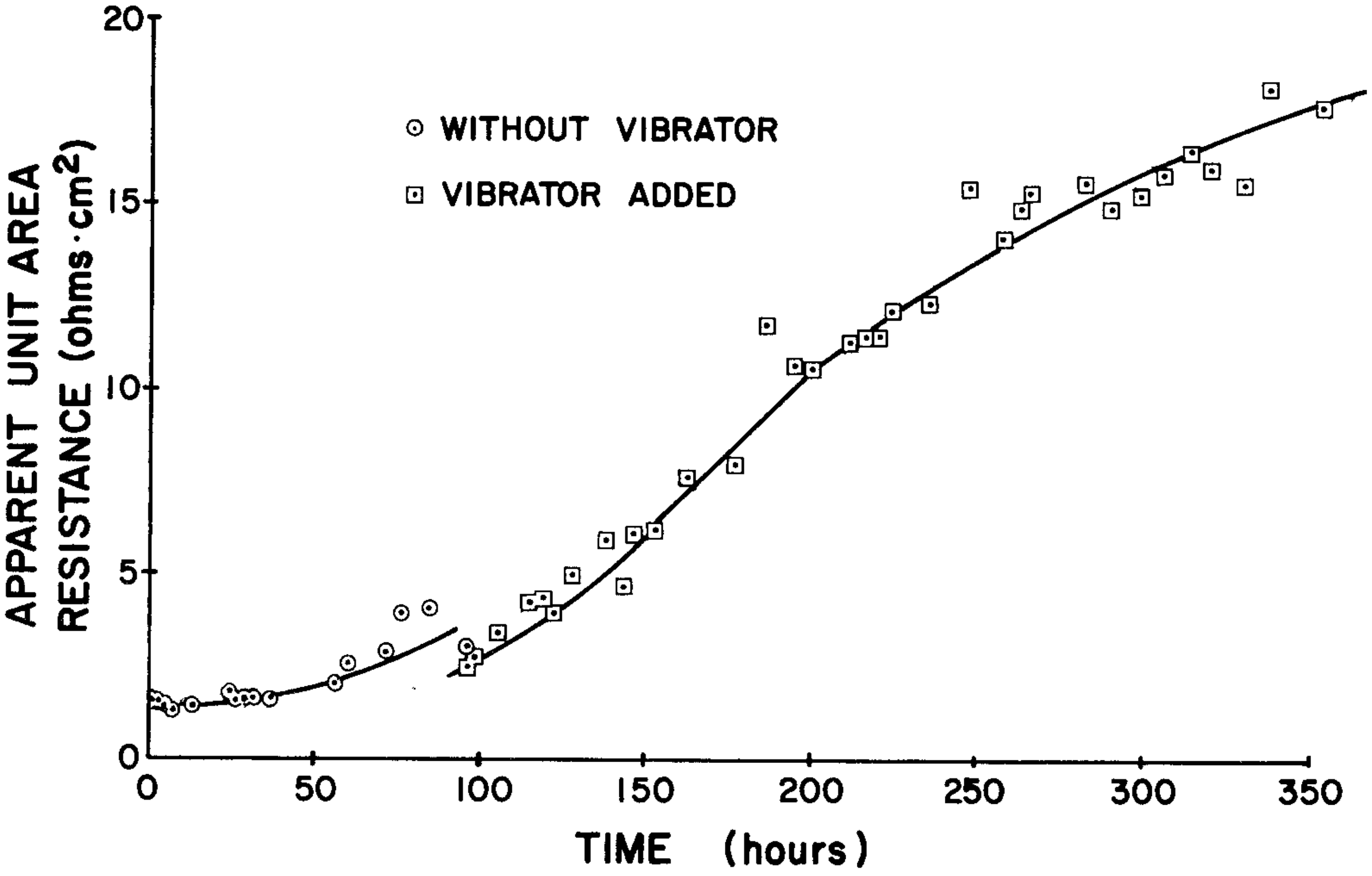

Fig. 2-6. Apparent unit area resistance versus testing time for horizontal test unit.

The ultrasonic test model was designed to test the possible uses of ultrasonic energy to remove the plates' oxide coating. The coating could be removed at the same rate as it forms on the plates.

Equipment

The test unit was constructed of 1/2 in Plexiglas containing several aluminum electrodes and a submergible ultrasonic transducer (Figures 2-7 and 2-8). The plates were placed perpendicular to the surface of the transducer. The unit measured 20.3 cm wide, 27.9 cm long, and 40.6 cm deep. The bottom of the unit was funneled toward the center where scale could settle out. The volume of water in front of the transducer was 20.2 l with an ultrasonic energy density of 12.38 watts l^{-1}.

The plates, made from aluminum alloy 1100, were .318 cm thick. Each of the plates had an area of 541.9 cm^2 (17.8 cm wide and 30.5 cm long). The plates were held in place at the bottom by slotted Plexiglas supports. The electrical connection was made above the water level to the plate tabs. Alternate plates were connected together and to the power supply.

The water entered the unit at the top. The treated water and scale were removed at the bottom. A portion of the treated water and floating flocs were removed at the top of the plates.

Procedure

Three different tests were made with the unit. The first one ran with the ultrasonic unit. Twenty plates, with a spacing of 0.64 cm and a total surface area of 10,297 cm^2, were used. College Station tap

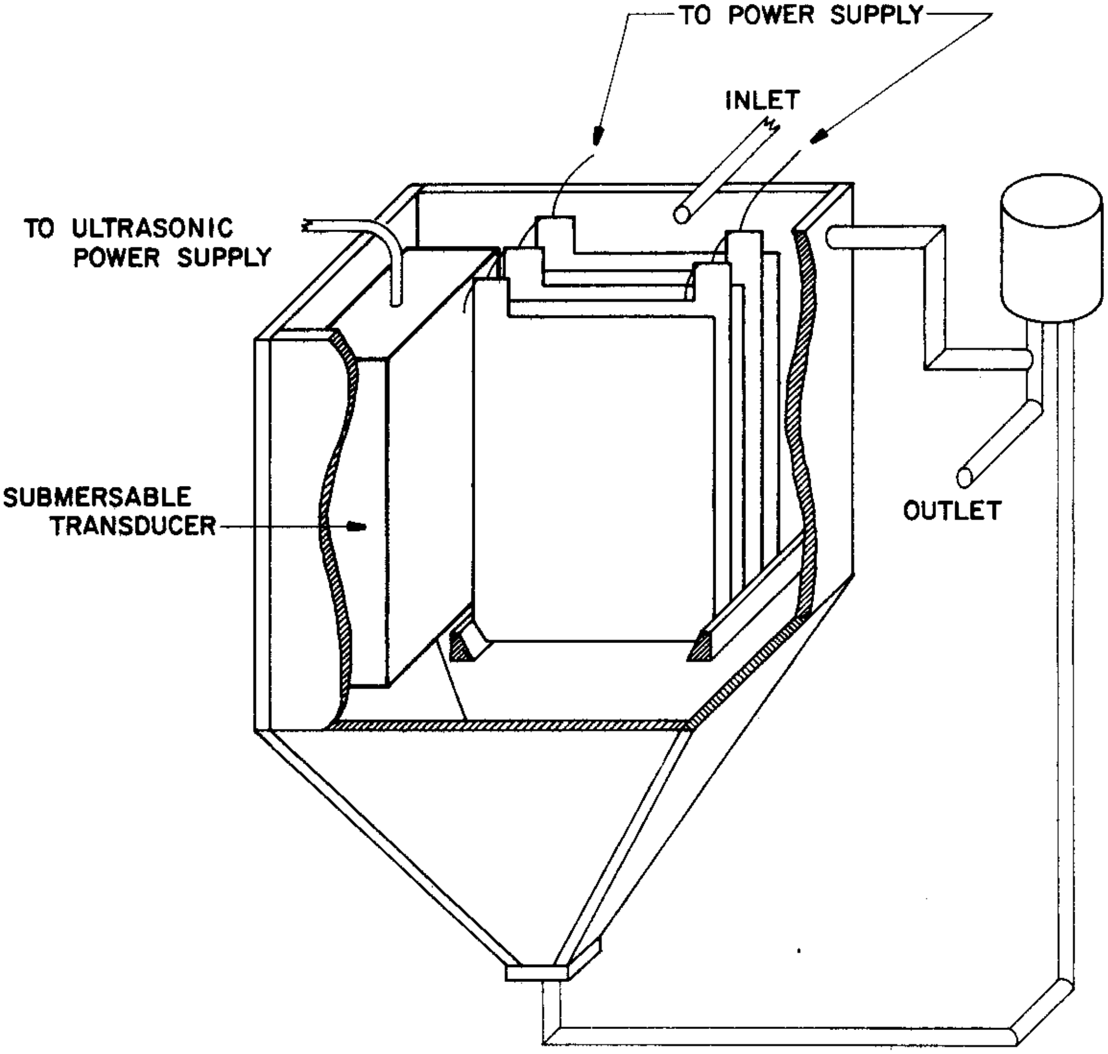

Fig. 2-7. Ultrasonic electrochemical flocculation test model.

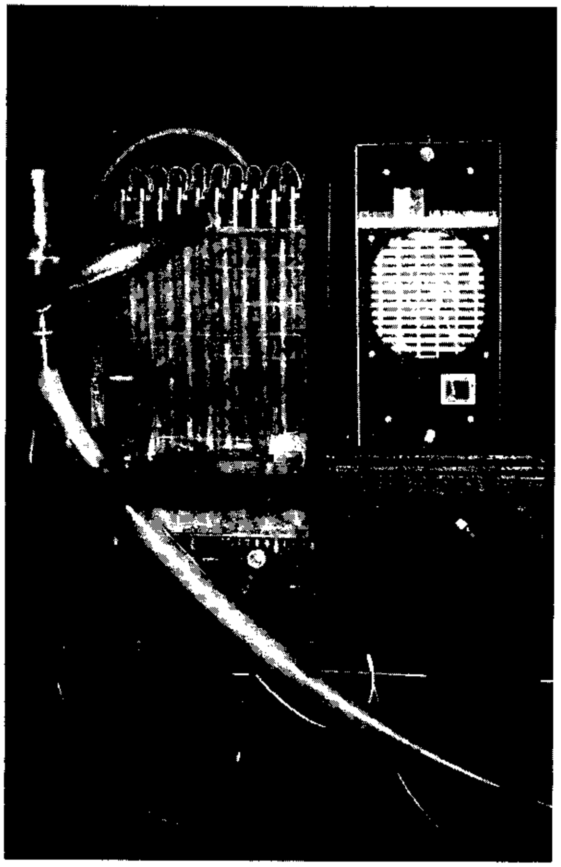

Fig. 2-8. Ultrasonic flocculator during testing.

water and kaolinite clay were mixed so that the influent water had a turbidity of 50 mg l^{-1}. The flow rate was 1250 ml min^{-1}. The test was run at a constant current of 8 amps which resulted in a current density of 0.777 ma cm^{-2}. The polarity of the plates was reversed every 12 hrs. The aluminum concentration was determined with a Hellige Aqua Tester comparator. The treated water left the test unit, passed through a vertical flow mixing tank and settled in the vertical flow settling tank. The water turbidity was determined after leaving the settling tank with a Hellige Turbidimeter.

The second test was run under the same conditions as the first except the total plate area was reduced to 3794 cm^2 with a resulting current density of 2.11 ma cm^{-2}.

The third test was run under the same conditions as the first two except the total plate area increased to 4877 cm^2, and the resulting current density was 1.64 ma cm^{-2}. The ultrasonic cleaner was not used in this test.

Discussion of Results

The ultrasonic cleaner was not effective in removing the scale from the plates except for the edge immediately next to the transducer. Approximately 1.0 cm of the plate along this edge was kept clean. When the plates were removed, variations in ultrasonic energy over the transducer's surface were noticed because the plates were consumed in localized areas along the edges.

The scale which developed in the first test was trapped between the plates due to the small spacing. However, the apparent unit area resistance became constant after 130 hrs of testing (Figure 2-9). This was apparently due to the lower current density rather than the ultrasonic energy.

At a high current density (second and third tests), the apparent resistance was increasing during the entire testing period (Figure 2-9). The rate of increase of the apparent resistance of the high current density test with ultrasonic cleaning was less at the beginning of testing than the high current density test without ultrasonic cleaning. Therefore, the ultrasonic cleaning was effective only in delaying scale formation.

The aluminum concentration averaged 20 mg l^{-1} for the entire testing period for both the 0.777 ma cm^{-2} current density test and the 2.11 ma cm^{-2} current density test. In the test without ultrasonic cleaning the aluminum concentration decreased to 15 mg l^{-1} after 24 hrs of testing.

Combined Mixing and Flocculation Unit

Introduction

In the testing of the ultrasonic flocculation model, it was apparent that the current density should be less than 0.78 ma cm^{-2} so that the oxide coating would flake off at the same rate it is being formed. Therefore, this model was designed for a current density of 0.396 ma cm^{-2}. A mechanical vibrator was connected to the plates to help in removing the oxide coating.

The scale which did flake off during the previous test periodically caused plugging problems at the drain outlet at the bottom of the unit. To eliminate this problem the vertical flow mixing unit and

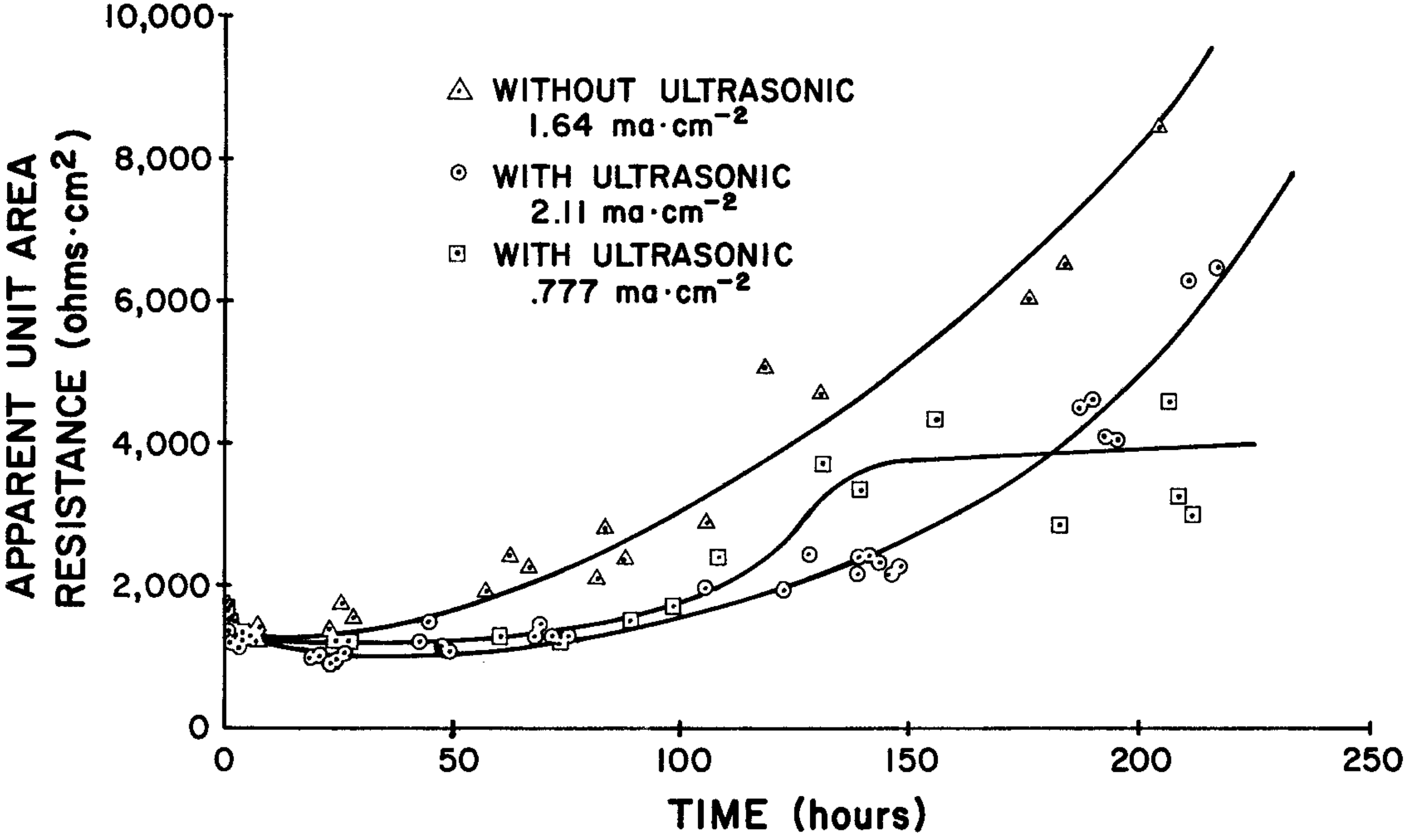

Fig. 2-9. Apparent unit area resistance versus testing time for ultrasonic test model.

the flocculator unit were combined. The scale settled out at the bottom of the combined unit before the water entered the settling tank.

Test Unit

The test unit consisted of four compartments: plate compartment, mechanical mixing compartment, and two vertical flow mixing compartments (Figure 2-10). The plates were constructed from 1100 aluminum alloy measuring 29.2 cm wide and 10.5 cm long with an area of 1197.9 cm^2. Eighteen plates (0.315 cm thick) were spaced 1.6 cm apart and had a total electrode area of 20,177 cm^2. Alternate plates were electrically connected together and to the power supply. This electrical connection was made on the plate tabs above the water level.

This plate compartment was constructed from Plexiglas with inside dimensions of 35.6 cm wide, 33.0 cm long and 47.0 cm deep. A mechanical mixing compartment was situated immediately below the plates. The bottom half of the unit funneled down toward the drain at the bottom. Two vertical flow mixing compartments were located on each side of the plate compartment. The total volume of the unit was 155 l. A 4 rpm shaded pole motor was used to drive a mixing blade that was located under the plates in the mechanical mixing compartment.

The water entered the unit above the plates and passed between the plates into the mixing compartment. It was then funneled toward the center of the unit and approached the bottom. The water then flowed upward through the vertical flow mixing compartments located along each side of the unit, passed through the suspended floc bed in each of these compartments and overflowed at the top. The scale, after breaking from the plate, fell down into the lower portion of the unit and was removed periodically by draining the unit.

Procedure

The unit was tested for a period of 1100 hours. College Station tap water and kaolinite clay were mixed to get a 50 mg l^{-1} turbidity. Flow rate was 1250 ml min^{-1}. The polarity was reversed every 12 hrs and the amperage was controlled at 8.0 amps with a current density of 3.96×10^{-1} ma cm^{-2}. Voltage and current were monitored during the entire test.

Water flowed through the combined mixing unit and flocculator unit and then through the vertical flow settling tank (previously described). The aluminum concentration of water leaving the test model was determined with the Hellige Aqua Tester and the appropriate reagents. Turbidity of the water was determined at the inlet of the test model and at the outlet of the vertical flow settling tank with a Hellige Turbidimeter.

Discussion of Results

The voltage increased during the entire test; thus, the apparent unit area resistance increased during the entire test (Figure 2-11). The rate of increase of the apparent unit area resistance was relatively constant until the 800th hour of testing when it began to increase exponentially with testing time. The apparent unit area resistance was larger immediately after switching than it was toward the end of the reversal cycle. The variation between the apparent

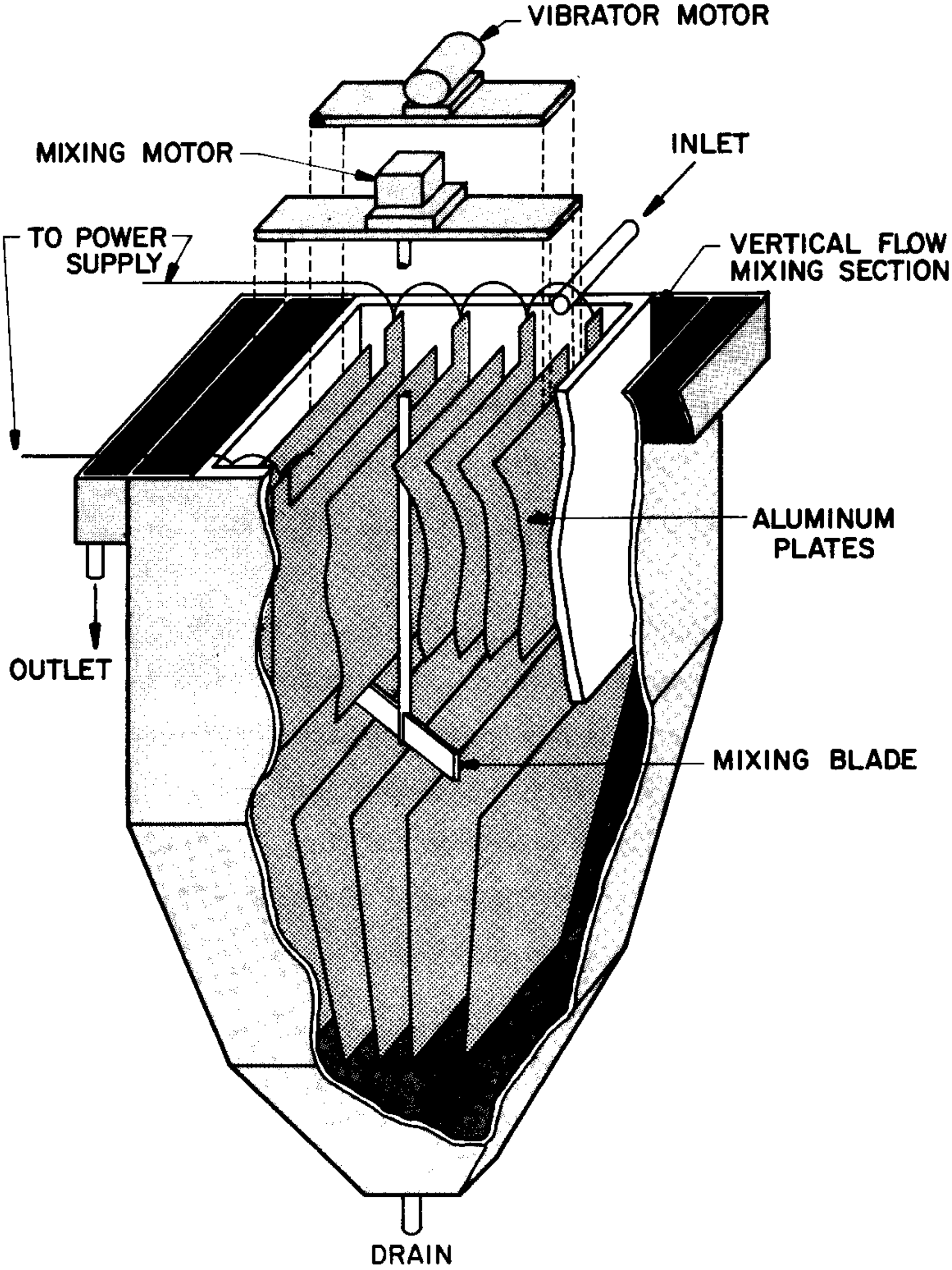

Fig. 2-10. Combined flocculation and mixing test model.

unit area resistance determined early in the reversal cycle and that determined later in the cycle increased as the test progressed. This indicated that the scale was never completely removed during the polarity reversal period. A portion of the scale came off the plates and fell to the bottom of the unit; however, a large portion of the scale remained attached to the plates. Thus, the thickness of the oxide coating increased throughout the test.

Another problem was the difficulty of keeping the floc bed formed in the vertical flow mixing section. This was because it was difficult to divide the flow equally between the vertical mixing compartments.

Low Current Density Flocculator Final Model

Introduction

In the combined mixing and flocculator unit the flocs, after forming, remained between the plates. A large portion of the scale formed was due to the flocs remaining in contact with the plate surfaces. In this model a majority of the flocs were removed before or just after they formed, thus preventing the flocs from contact with the plates. The performance of 6061 and 1100 aluminum alloys at the lowest current density possible was compared.

Equipment

The test unit contained thirty-two aluminum alloy plates, mixing section, and scale breakup section (Figure 2-12). Plexiglas was used to construct the unit's outside shell. The inside dimensions of the plate compartment were 61.0 cm wide, 61.0 cm long and 40.6 cm deep.

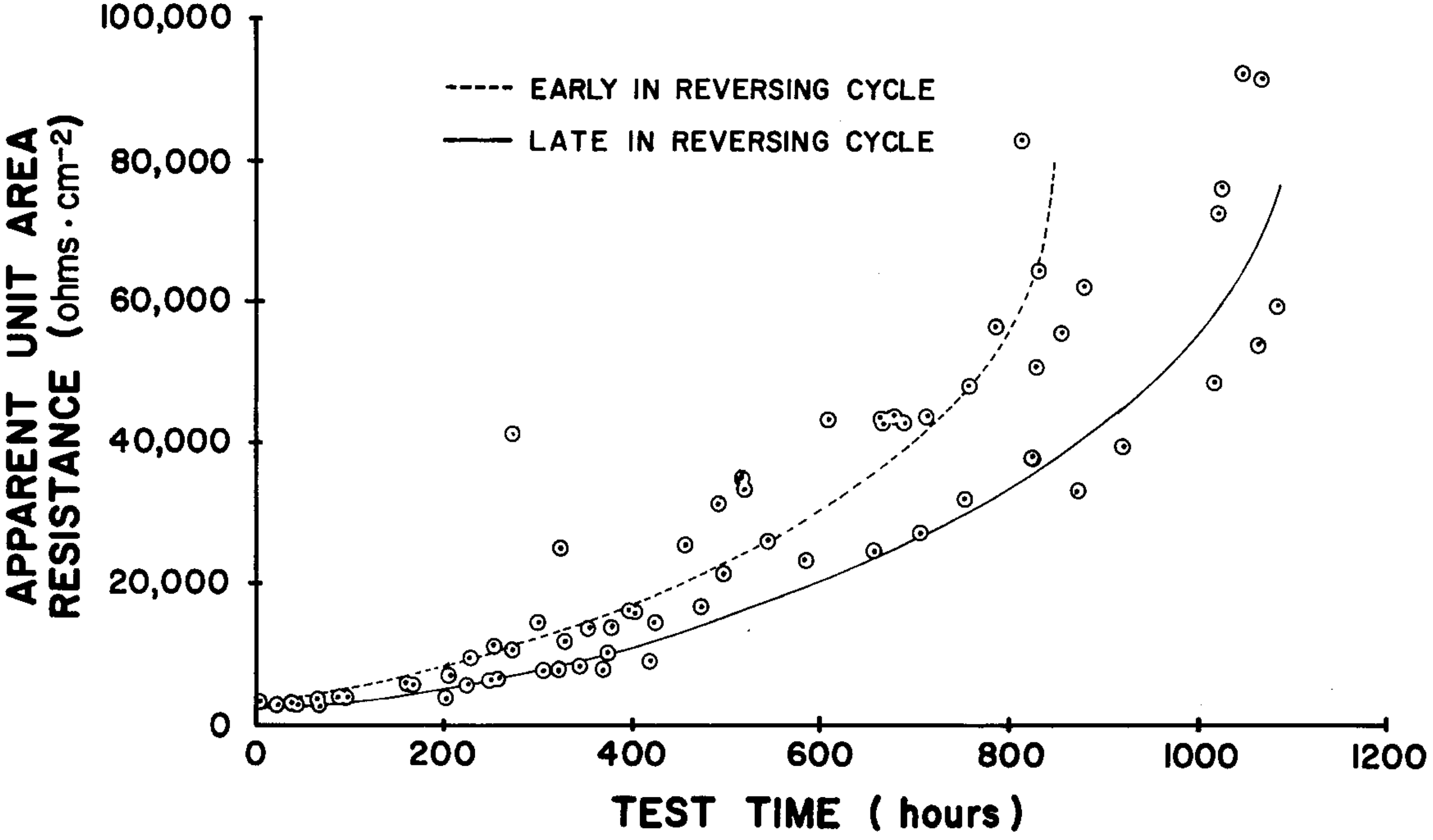

Fig. 2-11. Apparent unit area resistance for combined flocculation and mixing tank.

A funnel-shaped section with sides sloped 45° inward was located below the plate compartment. These two sections were separated by a perforated screen. The total volume of the test unit was 201 l. The slotted Plexiglas support at the bottom held thirty-two 0.325 cm thick aluminum plates 1.6 cm apart. Each plate was 22.9 cm wide and 61.0 cm long with a total surface area of 1894 cm^2 with a tab placed at one end. Alternate plates were electrically connected at the plate tabs which were above the water level. Each of these sets of plates was connected to the power supply. A vibrator motor was mounted on a slotted piece of Plexiglas which fit on top of the plates.

A 4 rpm shaded pole gear motor was located above the plates and powered a 0.635 cm diameter shaft covered with tygon tubing extended down between the middle plates. Attached to the lower end of the shaft was a Plexiglas scraper which was run on top of the perforated aluminum sheet. Scale which fell onto this sheet was broken up and entered the drain at the bottom.

The untreated water was distributed on top of the plates, mixing with the water already in the unit. A portion of the flow and any flocs which floated to the top were skimmed out by a weir along one side of the unit. The majority of the water was removed at the bottom of the unit along with scale which had fallen through the perforated screen. The weir was removed during field testing of the unit.

The water and scale flowed up through a tube which was attached to the bottom of the unit and then into a constant head control device. During laboratory testing the scale was separated from the flocs and water by allowing it to settle in a Plexiglas cylinder. The inside diameter of the outlet at the bottom of the unit was 1.25 cm.

Procedure

A test was conducted using twenty-six 1100 aluminum alloy plates and six 6061 aluminum alloy plates. The total electrode area of the plates was 58,700 cm^2 (1100 alloy - 43,200 cm^2; 6061 alloy - 15,500 cm^2). Only the area of the 1100 alloy plates was used in the results because scaling of the 6061 alloy occurred very early in the test thus rendering it ineffective.

College Station tap water and kaolinite clay were mixed to a turbidity of 50 mg l^{-1}. The flow rate of 1250 ml min^{-1} was divided so that 10% was taken from the top of the unit, 90% from the bottom. After leaving the flocculator the water and scale entered the vertical flow mixing tank at the bottom. The scale settled out and was periodically drained out the bottom. The water left the mixing tank, entered the vertical flow settling tank at the bottom and was then taken off at the top.

The aluminum concentration in the flocculator was determined periodically by the Hellige Aqua Tester. Voltage and current readings were taken during the entire test. The turbidity of the effluent from the vertical flow settling tank was determined by a Hellige Turbidimeter. Scale was collected in a 14.7 cm diameter cylinder trap and drained periodically.

A constant current of 8 amps was applied to the plates resulting in current density of 0.185 ma cm^{-2} determined by excluding the 6061 alloy plate area. The polarity of the plates was reversed every 12 hrs.

Discussion of Results

The test was run for a total of 2160 hrs. After about 500 hrs, the voltage was constant at approximately 3.2 volts (measured 4 hrs after reversing the polarity). Therefore, the apparent unit area resistance was also constant (Figure 2-13). Scale flaked from the plates at the same rate as it was formed.

The apparent unit area resistance dropped immediately after the polarity was reversed, then increased rapidly to a maximum in 15 min (Figure 2-14). This indicated the charge on the plates was due to their electrical capacitance. After reaching a maximum, the voltage decreased slowly for the next 2 hrs. This denoted that the scale which had formed on the plates during the previous cycle was slowly eroding away. This scale was resisting the flow of current mostly in one direction (similar to a semiconductor, such as a diode). There was no apparent increase in voltage toward the end of the reversing cycle.

The apparent unit area resistance increased slowly during the first 500 hrs before reaching a constant value (Figure 2-13). Scale was forming faster than it was breaking off during this initial period. The high value shown in Figure 2-15 occurred during the first four hrs of the reversing cycle.

The aluminum concentration varied throughout the reversal cycle (Figure 2-16). The average aluminum concentration was 15 mg l^{-1}; therefore, the average aluminum dissolution rate was 0.027 mg cm^{-2} hr^{-1}. The maximum aluminum concentration occurred 10 hrs after polarity reversal while the minimum occurred 2.5 hrs after switching (Figure

2-16). Due to the volume of water in the unit (201 l), the measured concentration of aluminum lagged behind the actual amount which was dissolving from the plates. The lag period was approximately 2.7 hrs, determined from the unit volume and flow rate. Therefore, the maximum rate of aluminum dissolution occurred 7.2 hrs after polarity reversal; the minimum occurred at the time of reversal. The aluminum dissolution rate began decreasing slowly after reaching its maximum. From this it was concluded that the polarity reversal time of 12 hrs was effective in preventing scale from sealing the plates.

Scale flaked off the 1100 alloy plates in small pieces approximately 0.4 cm in diameter. This scale was granular and grayish in color. The 6061 aluminum alloy plates were completely covered with a soft layer of aluminum hydroxide. Under this layer was a very tight layer of scale (Figure 2-17). After 500 hrs the 6061 plates were completely sealed with layers of scale, but the 1100 plates went through a scaling-flaking cycle which kept them effective.

The 1100 aluminum alloy plates were 70% consumed (determined from weight loss) during the test. The average aluminum concentration was determined to be 15.8 mg l^{-1} for the entire test period. At a flow rate of 1250 ml min^{-1}, the total amount of aluminum dissolved in the water was 2.474 Kg. The total amount of weight loss of the 1100 plates was 21.540 Kg. Therefore, 11.4% of the aluminum actually dissolved into the water. At a cost of $1.43 per Kg of aluminum, replacement of the plates would cost $32.16. The aluminum cost per liter treated was

0.019¢ (71.9¢ per 1000 gal). Total cost, including electrical cost (2¢ per Kw), was 72.9¢ per 1000 gal.

The turbidity of the settling tank effluent ranged from 2.1 mg 1^{-1} to 9.5 mg 1^{-1}, an average of 5.0 mg 1^{-1}.

Summary

All models which used 6061 aluminum alloy were unsuccessful in preventing scale from sealing the plates. Even at low current density used in the final model (0.185 ma cm^{-2}), the 6061 alloy became scaled after 500 hrs of operation.

The use of ultrasonic sound waves for removing scale as it formed was unsuccessful. Only a small area immediately adjacent to the transducer surface remained clean during testing, indicating that only at very high energy densities would the plates be cleaned. This would not be feasible because of the high power requirement and the large investment cost of an ultrasonic unit.

The combined mixing and flocculator unit was unsuccessful in preventing scaling of the plates because flocs, after forming in this unit, remained in contact with the plates. The plates formed scale faster than it flaked off; therefore, the flocs must be removed soon after they form to prevent scaling of the plates.

The final test model was successful in preventing scaling of the plates by using 1100 aluminum alloy as electrode material and operating at a current density of 0.185 ma cm^{-2}. The vibration of the plates helped remove scale coating which was loosely attached to the plates.

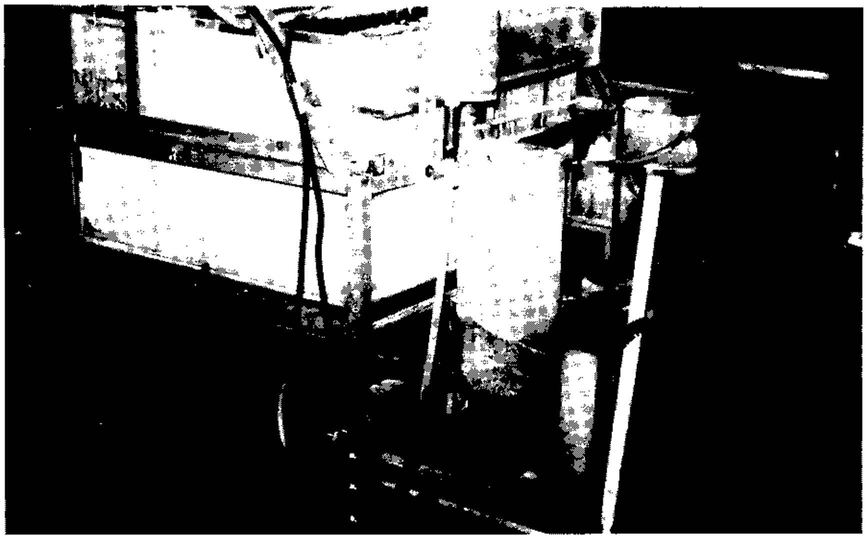

Fig. 2-12. Low current density flocculator during testing.

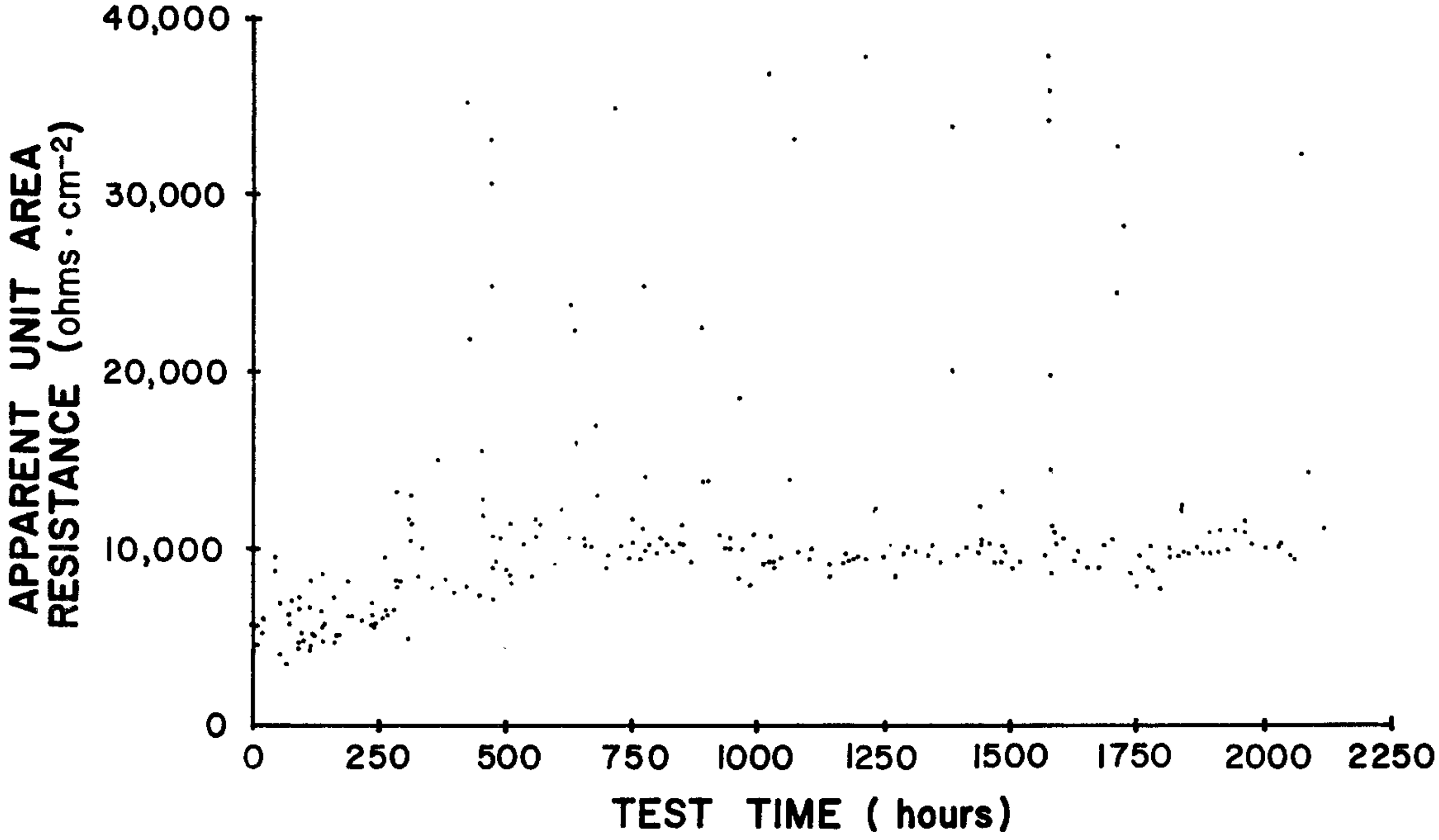

Fig. 2-13. Apparent unit area resistance versus test time for final low current density model.

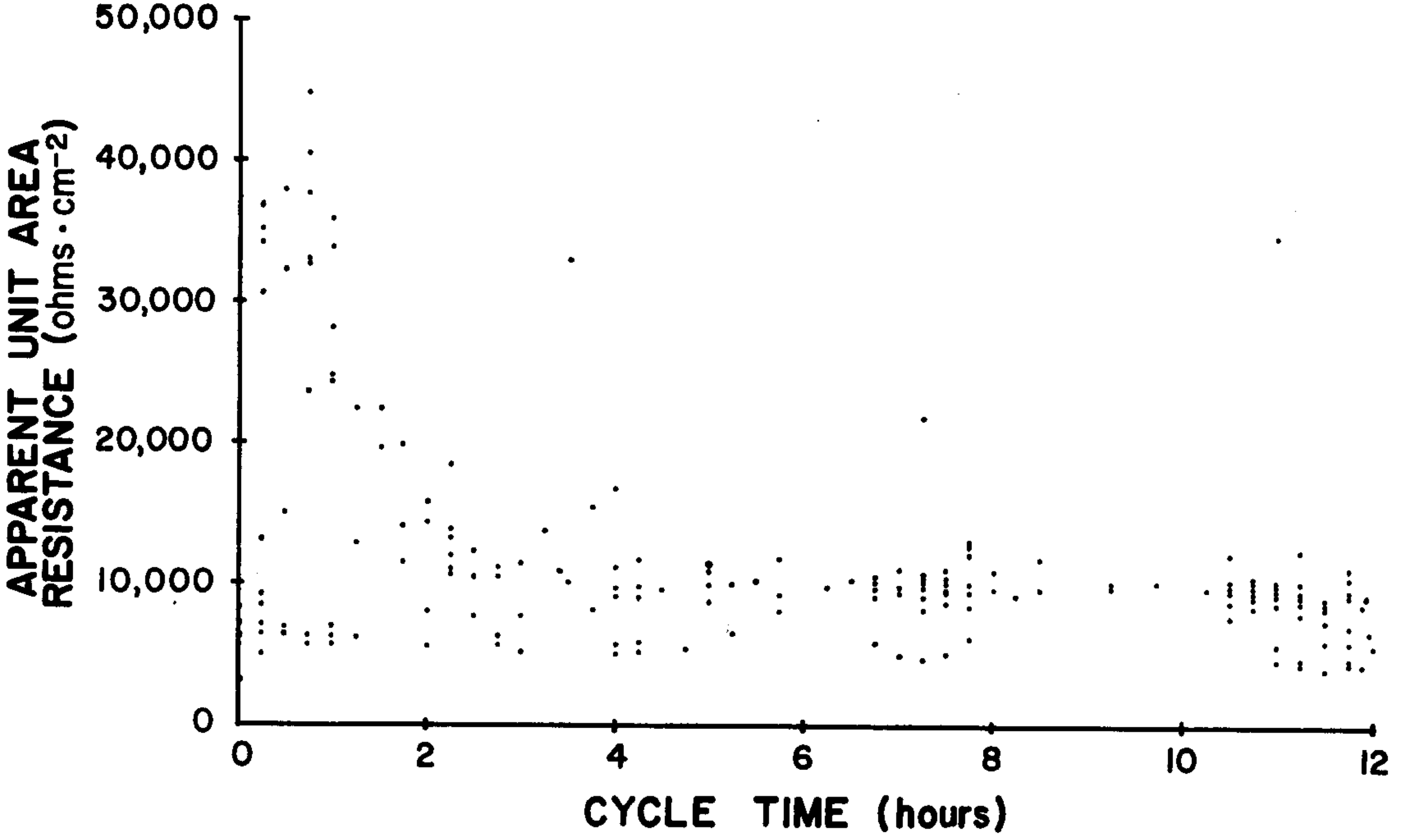

Fig. 2-14. Apparent unit area resistance versus reversal cycle time for low current density model.

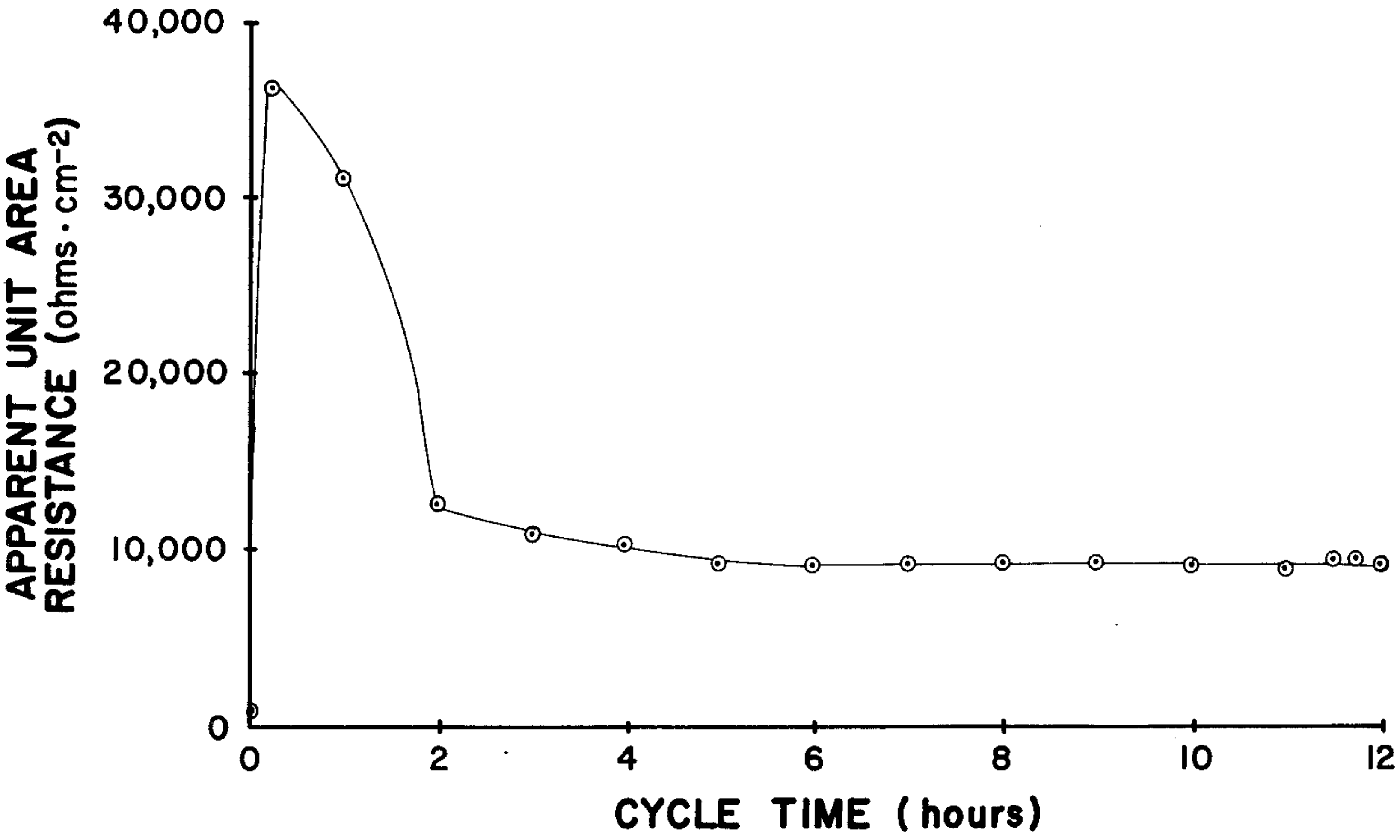

Fig. 2-15. Apparent unit area resistance versus reversal cycle time for the final low current density model during the 1122-1134 test hours.

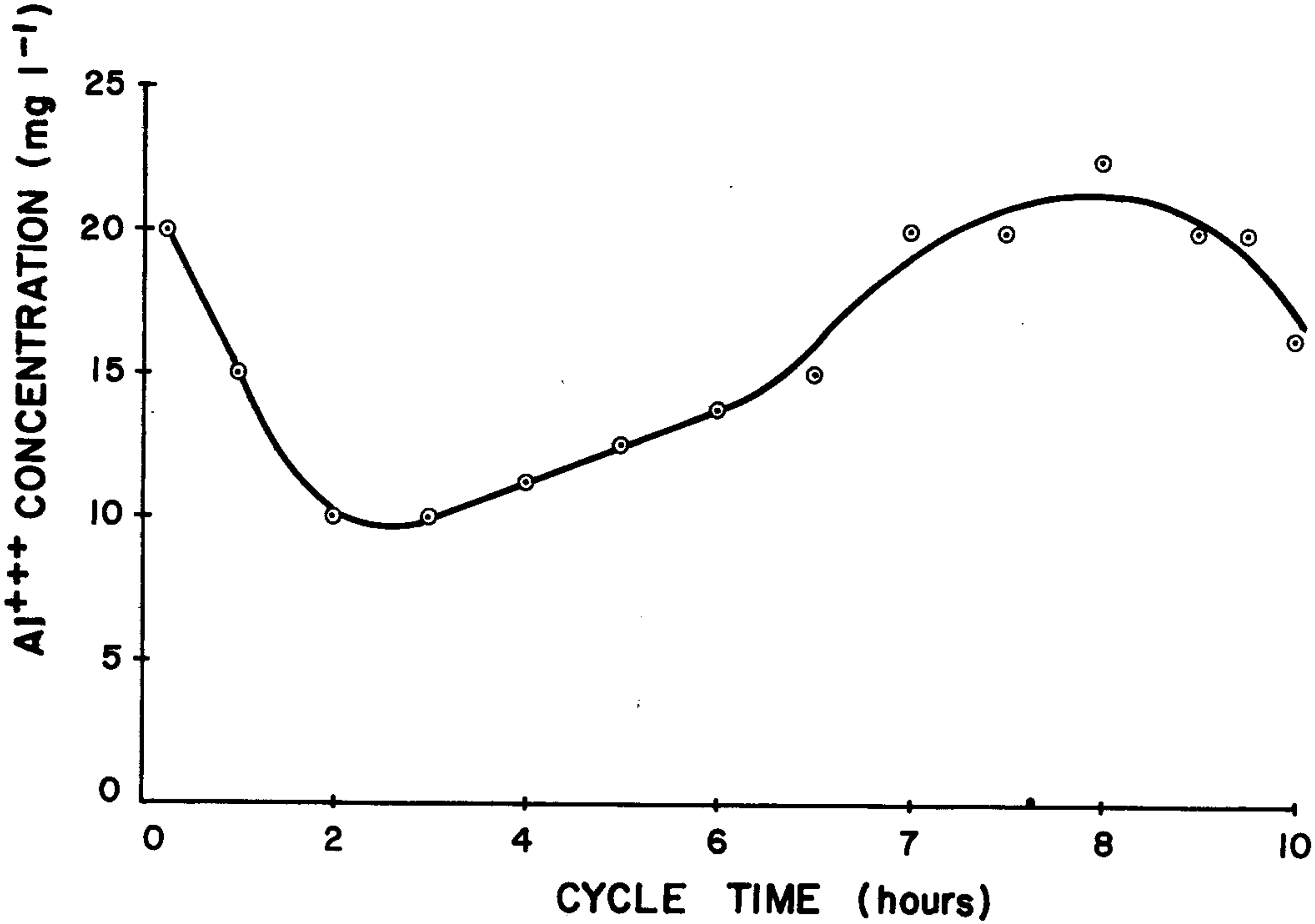

Fig. 2-16. Aluminum concentration versus reversal cycle time for final low current density model during 1122-1134 test hours.

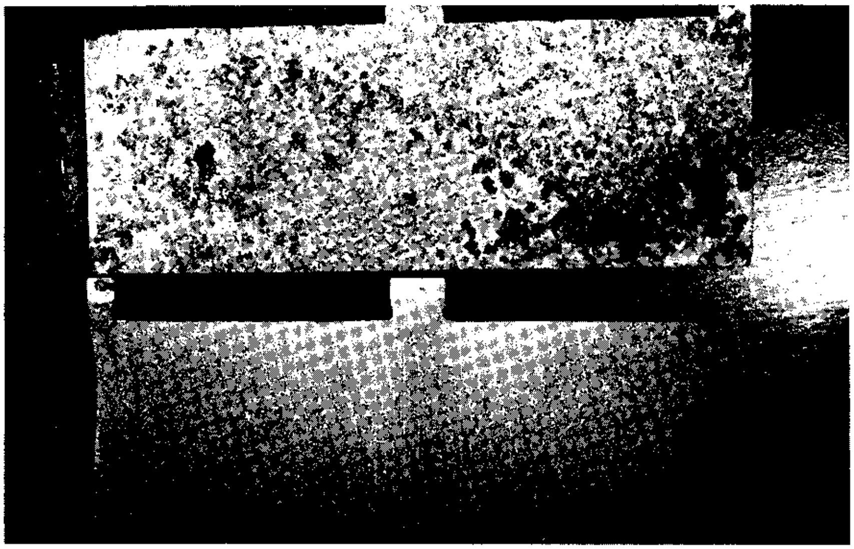

Fig. 2-17. Plates removed from low current density flocculator. (Top plate - 6061 and bottom plate - 1100.)

The mixing and scraper motor provided slow mixing which aided in floc formation and broke scale into small pieces which prevented plugging of the outlet. A polarity reversal period of 12 hrs was used successfully because it caused the scale to be loosely attached to the plates and was long enough so the aluminum dissolution rate did not decrease appreciably after reaching its maximum.

An aluminum concentration of 15.8 mg l^{-1} was effective in removing the colloid turbidity in College Station tap water. Only 11.4% of the available aluminum was detected in the water; the majority (88.6%) was wasted in the formation of insoluble scale. The operating cost of this unit was estimated at 72.9¢ per 1000 gals (only electrical and aluminum costs were included).

As a result of the exhaustive testing of the various models, the following conclusions are drawn:

1. Turbid water can successfully be clarified by electrochemical dissolution of aluminum plates. Unlike the electrophoretic process which was unsuccessful in high conductivity water (Hiler and Lyle, 1970), the electrochemical process was successful in removing turbidity.
2. Aluminum alloy 1100 was successful as an electrode material at low densities.
3. To prevent scaling of the plates, current density should be less than 0.185 ma cm^{-2}.
4. A polarity reversal cycle of 12 hrs should be used so that the scale which forms is loosely attached and can be removed by

mechanical vibration of the plates. Also, at this reversal cycle period, the aluminum dissolution rate does not decrease significantly during the cycle before it is reversed.

5. Flocs must be removed from the plate area soon after they are formed.

CHAPTER III

FIELD TESTING OF ELECTROCHEMICAL LOW CURRENT DENSITY FLOCCULATION SYSTEMS

Introduction

Two electrochemical low density flocculation systems and an electrochemical natural chloride chlorinator were constructed and evaluated. The first system contained an electrochemical low density flocculator, vertical flow mixing tank, electrochemical chlorinator, and vertical flow settling tank. The second system contained a single unit which had a vertical flow mixing section, tube settler sections, and electrochemical chlorinator.

The first system was tested previously on College Station tap water with added turbidity. This water was soft and had a relatively small amount of impurities. Also, the first system and modified systems were tested on a typical pond located near Bryan, Texas. This water was low in dissolved impurities but high in apparent color and turbidity.

Evaluation of each system considered turbidity removal, impurity removal, operating cost, maintenance problems, and operating procedure. Neither system was completely automated; draining of sludge and scale was done manually by opening a drain valve.

Equipment

Low Current Density Flocculator

The final low current density model (described in Chapter II) was modified by removing the weir along the top edge and used in the low current density system. Treated water was removed at the bottom of the unit along with scale which had been broken up on the perforated screen. Treated water entered the bottom of the mixing tank through a 3.8 cm diameter pipe.

All thirty-two plates used were constructed from 1100 aluminum alloy. Each plate was 22.9 cm wide, 61.0 cm long, and 0.32 cm thick, each with a total surface area of 1894 cm^2. The total electrode area of the unit was 58,700 cm^2. Electrical connections were made at a tab located at one end of the plate above the water level. A vibrator motor was mounted on a slotted Plexiglas strip which fit on top of the plates.

A 4 rpm shaded pole gear motor was located above the water level and connected through a shaft to the mixer and scraper below the plates. A more detailed description is presented in a previous section.

Vertical Flow Mixing Unit

The mixing tank was used to separate scale and to mix the treated water as it flowed upward through a suspended floc bed. Treated water and scale entered 30 cm above the bottom. The outlet was located 10 cm below the top where the water and flocs left and entered the top of the chlorinator. A drain valve was located at the bottom for the periodic removal of scale and settled flocs. Details of the mixing unit are given in a previous section.

Chlorinator

The low chloride chlorinator (Figure 3-1) was designed according to the recommendations of Peters (1973). It was designed to give a chlorine dosage rate of 2.0 mg l^{-1} at a flow rate of 1.31 l/min (500 gal/day). Two platinized-titanium anodes were sandwiched between pairs of stainless steel cathodes, each anode having a total area of 265 cm^2 (both sides). Each electrode measured 17.8 cm long and 7.6 cm deep. The shorter dimension was parallel to the downward water flow. The electrodes were held 0.32 cm apart by grooves cut into the Plexiglas end plates. The two sets of electrodes were connected in series to the power supplies. The optimum current density of .017 amp cm^{-2} was used giving a total current of 4.5 amps. The flow was divided so that half passed between each set of electrodes. These conditions give a chlorine dosage rate of 2 mg l^{-1} when the chloride concentration of the water is 50 mg l^{-1}.

Two sets of electrodes were enclosed in a Plexiglas unit, the total volume being 8 l. Water was distributed by a tube above the electrodes flowing downward between the electrodes. After passing through the electrodes, it was removed at the bottom of the unit.

Vertical Flow Settling Tank

Water entered at the bottom and dispersed through a manifold in the bottom of the settling tank (Figure 3-2). The water moved upward through the internal compartment, leaving the flocs behind, and clear water left through the manifold at the top. Sludge was drained periodically through the drain valve at the bottom of the unit. The total volume of water held was 1068 l. The unit was designed to remove particle sizes less than 15 microns in diameter. A detailed description of the settling tank is presented in Chapter II.

Tube Settler Unit (Robert's Pond)

Tube settlers are a variation of the shallow basin settling tanks presented by Hazen (1904) and Camp (1946). In a shallow settling basin the detention time is reduced because the particle has to travel only a short distance before reaching the bottom of the basin being removed. Two major problems with these basins were: (1) the unstable hydraulic problem and (2) the mechanical sludge removal problem. According to Culp, et al (1968) and Hansen and Culp (1967), the tube settler solves both problems. The unstable hydraulic problem is solved by using tubes in which laminar flow is easily achieved. The sludge removal problem is solved by inclining the tubes so that sludge slides into the bottom compartment. It is recommended that the tube be inclined 60° from horizontal.

The tube settler used in the Pond water evaluation test of the modified low current density flocculation system is shown in Figure 3-3. This unit combined the following components at a 60° incline: vertical flow mixing section, two stages of a tube settler, and electrochemical natural chloride chlorinator. The unit was constructed from 0.48 cm (3/16 in) fiberglass sheet. Seams were braced by aluminum covered with fiberglass.

The vertical flow mixing section was 30.5 cm wide, 7.6 cm deep, and 109.7 cm long with a total volume of 35.4 l. As water passed through this section the aluminum was mixed with the water and scale was removed. A scale collection area was located at the bottom of this section. A transfer section separated the vertical flow mixing

Fig. 3-1. Low-chloride chlorinator tested with low current density flocculator.

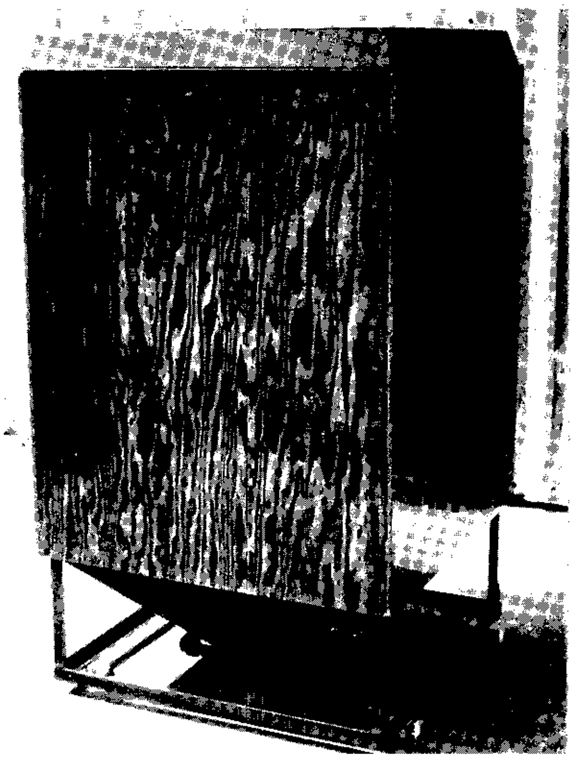

Fig. 3-2. Vertical flow settling tank tested with low current density flocculator system.

section from the first stage tube settler section. This section removed water from the top of the mixing section and channeled it to the bottom of the first stage tube settler section. The transfer section was 6.4 cm deep, 30.5 cm wide, and 109.7 cm long.

The first stage tube settler was 30.5 cm wide, 15.2 cm deep, and 114.3 cm long; it held 78.7 l water. Tubes were constructed of corrugated fiberglass roofing material with a 6.35 cm pitch and 1.27 cm depth. The roofing was cut into 30.5 cm-wide panels. The panels were riveted together so the ridges of one panel were connected to the ridges of the next. An elliptically shaped tube 91.4 cm in length was thus formed. The area at the bottom of each compartment was sloped toward a drain used to remove sludge. A control system was to be used to open a solenoid valve to automatically drain the tube settler when it became filled with sludge. The breaking of a light beam triggered the solenoid drain valve. However, any reflective surface placed under this floc bed soon became covered with sludge causing the sensing unit to malfunction. The unit was drained manually during the majority of the field testing.

After leaving the first stage tube settler, the water entered the chlorinator which consisted of two sets of anodes and cathodes. Each set had one anode of platinized-titanium sandwiched between two stainless steel cathodes. The anodes were 17.8 cm wide and 7.6 cm long; total anode area was 542 cm^2. Electrical power was obtained from a Silicon Control Rectifier power supply capable of 5 amps at 20 volts.

Water left the chlorinator at the bottom through a channeling compartment entering the second stage tube settler which is 30.5 cm wide, 30.5 cm deep, and 109.7 cm long, with a total volume of 140.0 l. Settler tubes (constructed as described earlier) were located 6.0 cm below the water surface. A skimmer at the top removed water from the unit.

Testing Equipment

Influent and effluent turbidity was monitored by Hach Models 1889 and 1861 surface scatter turbidity meters connected to a Texas Instrument Servo/Riter II dual channel recorder. The meters were calibrated with a Hellige 801D nephelmoetic type turbidimeter.

Apparent color, free chlorine residual, and aluminum concentrations were determined by a Hellige Aqua Tester Color Comparator and associated chemicals, described previously.

Two Sorenson Nobutron Models DCR 300-2.5A power supplies connected in series were used to provide a constant current to the chlorinator of the first system. Two Silicon Control Rectifier power supplies were used with the second system's chlorinator. A 10.0 amp DC power supply with a variable transformer was used to control the current to the flocculation unit.

A mobile laboratory was constructed to house the test system and associated equipment. The laboratory contained a sink, cabinets, desk, and electrical outlets and measured 6.6 m by 17.5 m with 115.5 m^2 of floor space (Figure 3-4).

Procedure

The first system consisting of the low current density flocculator, vertical flow mixing tank, low chloride chlorinator and vertical flow settling tank was tested on two different waters (College Station tap water and Robert's Pond water). The chlorinator unit of this system was tested with College Station tap water only because of the absence of chlorides in the Pond water.

The second system was made by modifying the first system, replacing the mixing tank, chlorinator and settling tank with the combined mixing tank, verticle tube settlers and chlorinator. This system was tested only at Robert's Pond. The chlorinator of this system was tested by metering a chloride solution into the flocculator with a diaphragm pump. The chloride content was kept constant at 50 ppm during testing.

Influent and effluent turbidity was monitored continuously by Hach Models 1889 and 1891 surface scatter turbidimeters. The output signal from the turbidimeters was supplied to a Texas Instruments Servo/Riter II dual channel recorder which continuously recorded the effluent and influent turbidity. A manually operated Hellige Model 8010 nephelometric type turbidimeter was used to calibrate the recorder.

Aluminum concentration was monitored at the flocculator, mixing tank outlet, chlorinator outlet and settling tank outlet. Concentration was determined by the eriochrome cyanine R method according to the Standard Methods for the Examination of Water and Wastewater (1970). A Hellige Aqua Tester Color Comparator was used to compare the color of the sample with a standard disk to determine the aluminum concentration.

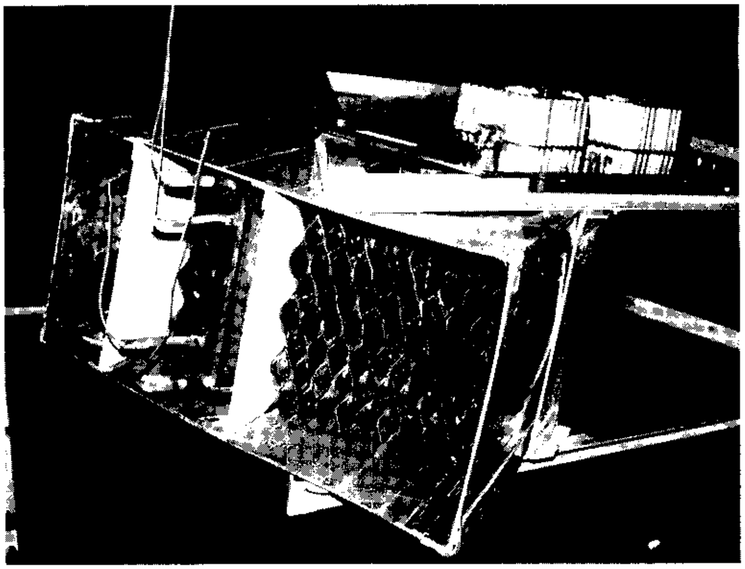

Fig. 3-3. Incline tube settler unit tested at Robert's pond.

Fig. 3-4. Mobile laboratory at Robert's pond site.

Free chlorine residual was measured at the chlorinator outlet and the settling tank outlet. Residual was determined by the orthotolidine-arsenite method using a Hellige Aqua Tester Color Comparator. Apparent color of the water was determined at the Pond site by the Hellige Water Color Comparator. Odor of the influent and effluent Robert's Pond water was also monitored. Complete chemical analysis of the influent and effluent water was done periodically by Orlando Laboratories, Inc., Orlando, Florida.

Flow rate of the systems was controlled by a double constant head flow regulator system. Flow rate of all tests was held constant at 1385 ml min^{-1} (500 gal day^{-1}).

The vertical flow mixing tank was partially drained manually every 24 hrs. Approximately 15 l of sludge along with scale was removed by a drain valve at the bottom of the unit. The first stage of the tube settler and mixing section was drained every 24 hrs during testing at Robert's Pond.

Discussion of Results

First Electrochemical Water Treatment System

College Station tap water test. The 1100 alloy plates were broken in by running the system for 500 hrs before testing was begun. Aluminum concentration was high when the plates were new and clean. It slowly decreased until reaching a constant dissolution rate. Testing lasted for a period of 1125 hrs (46.9 days).

Apparent unit area resistance varied during the reversal cycle. Current was constant at 8.0 amps and voltage changed proportionally to the apparent unit resistance. Average electrical conductivity was 800 micromhos cm^{-1}. Unit area resistance during the entire test is shown in Figure 3-5. Apparently the plates were not completely broken in until 250 hrs into the test. Apparent unit area resistance averaged 8500 ohms cm^2 during the last of the test. Fluctuation of the apparent unit area resistance during the reversal cycle is shown in Figure 3-6. Apparent area resistance increased to its maximum immediately when polarity was reversed, then slowly decreased to its minimum after 3.5 hrs. Apparently the scale coating developed during the reversal cycle was dissolved during this period. Apparent unit area resistance increased slowly after 3.5 hrs until polarity was reversed. This corresponds to a buildup of scale on the electrodes. The electrodes acted as diodes after switching because the apparent unit resistance increased after switching.

Aluminum concentration of the flocculation unit fluctuated during the reversal cycle (Figure 3-7). It was highest immediately after switching, then slowly decreasing for 3.5 hrs. The aluminum hydroxide coating on the outside of the plate quickly went into solution after switching. Aluminum concentration slowly increased from 3.5 hrs to 10 hrs during the reversal cycle. After 11 hrs the concentration slowly decreased. Therefore, the reversal cycle could not be longer than 12 hrs because of the decrease in aluminum concentration. The average aluminum concentration was 16.7 mg l^{-1} which gives an average dissolution rate of 0.020 mg hr^{-1} cm^{-2}. The aluminum concentration of the water leaving the settling tank was 8.5 mg l^{-1}. Fourteen

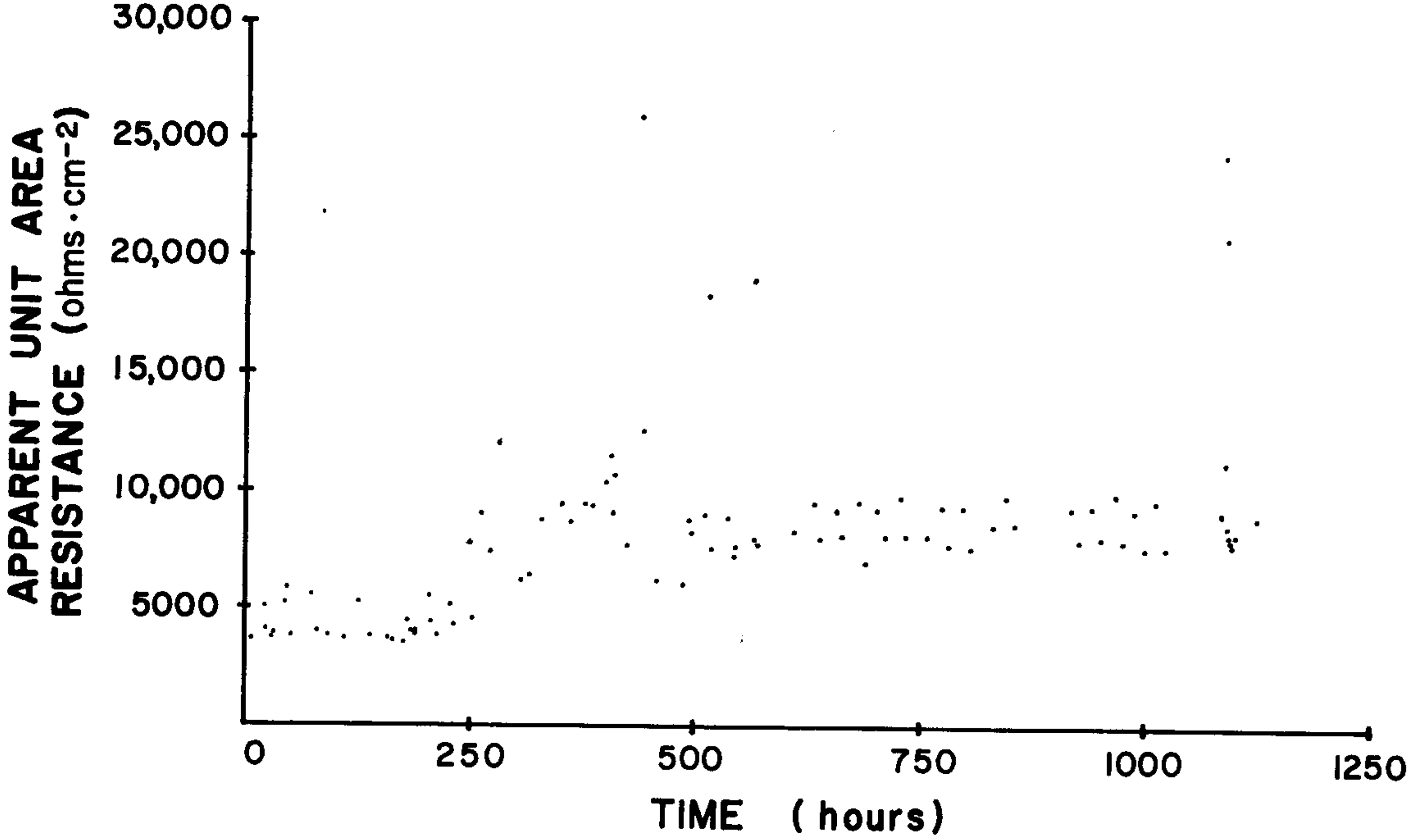

Fig. 3-5. Unit area resistance versus test time for low current density unit tested on College Station tap water.

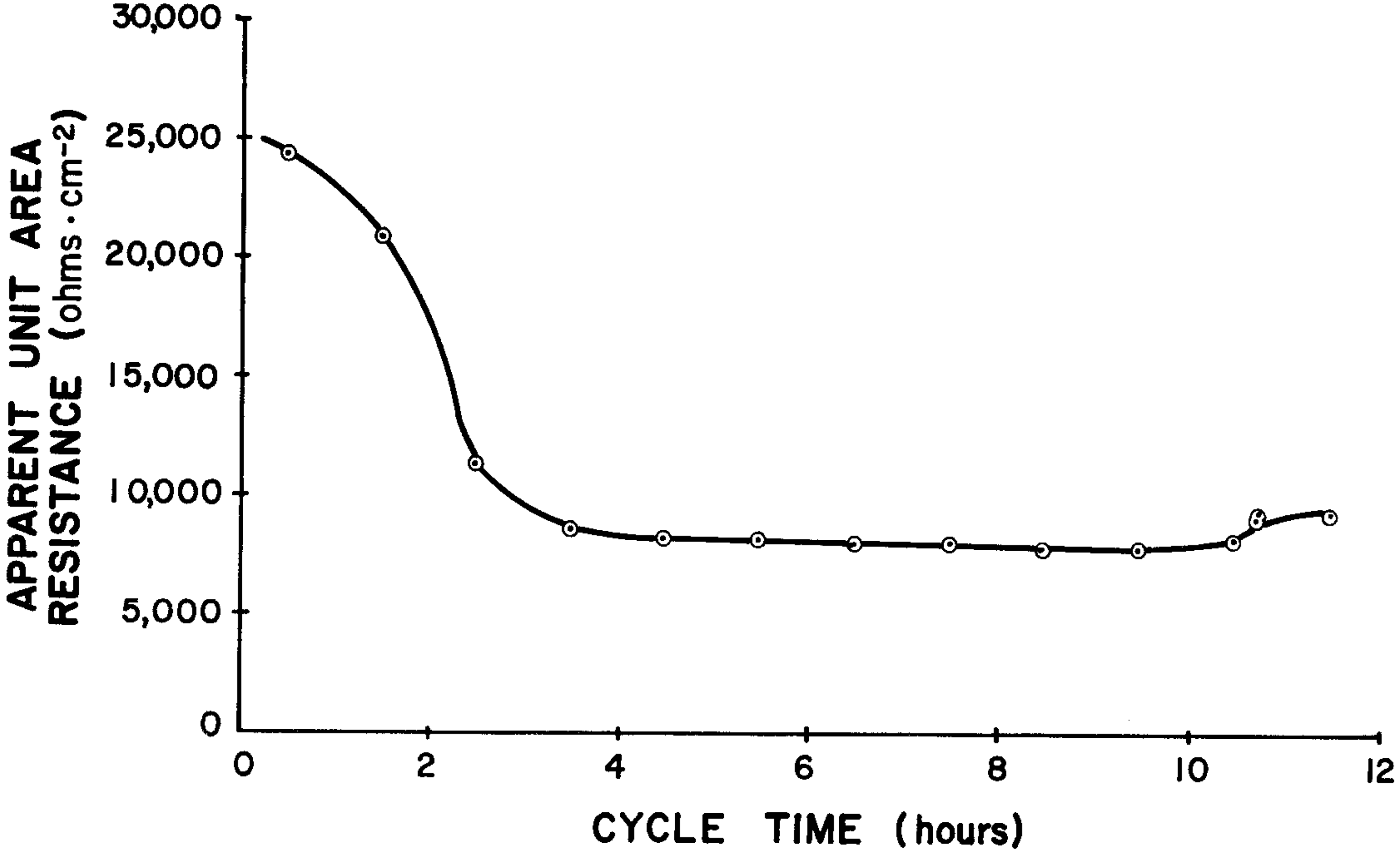

Fig. 3-6. Unit area resistance during a polarity reversal cycle.

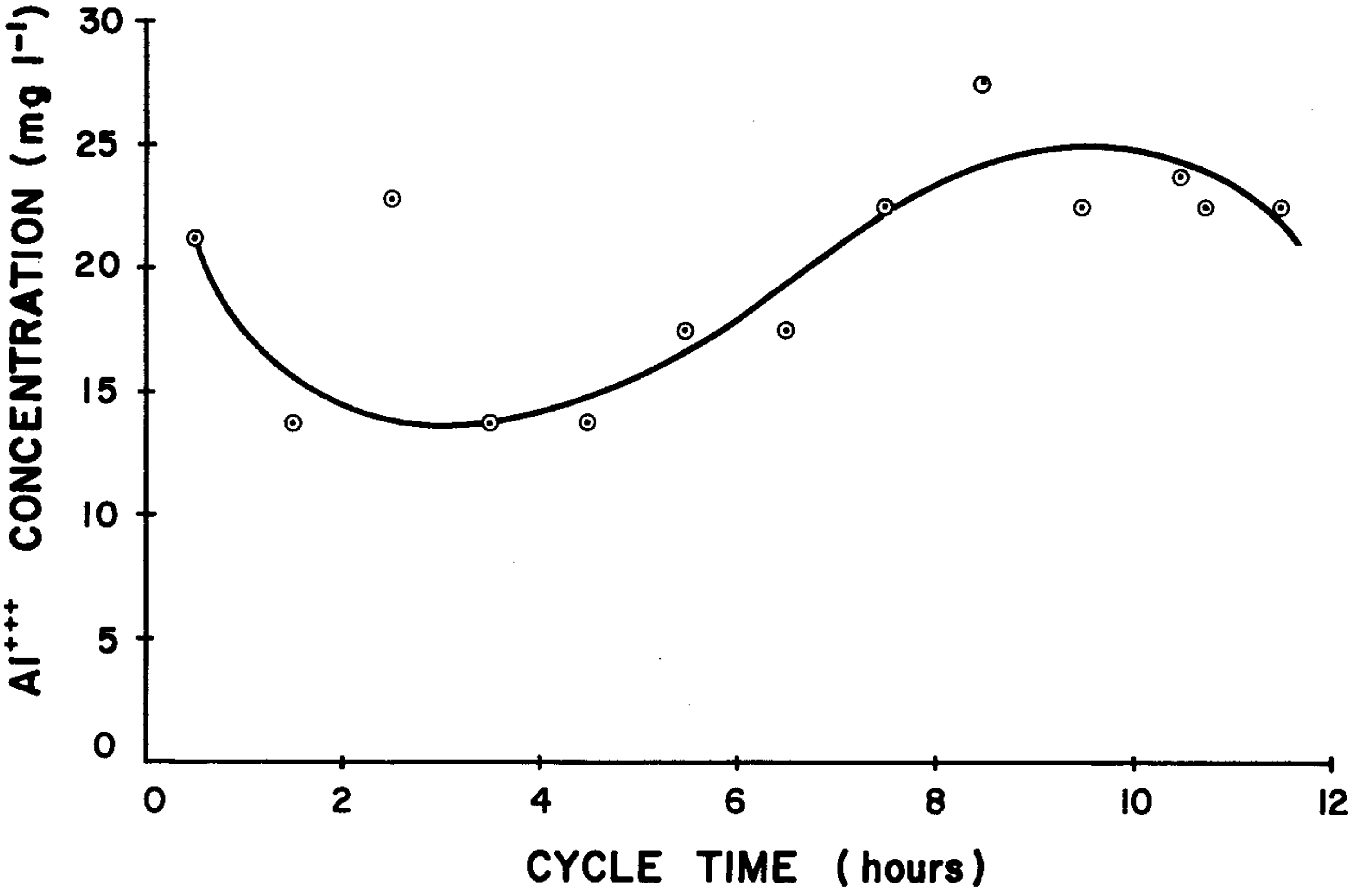

Fig. 3-7. Aluminum concentration of the low current density system during a polarity reversal cycle.

percent of the aluminum used actually dissolved in the water. The remaining 86% of the aluminum was wasted by forming scale. During testing the aluminum was used at an average rate of 7.11 g hr^{-1}. A total of 8000 g of aluminum was consumed during the test.

Average effluent turbidity was 5.0 mg l^{-1} which was a 90% reduction of turbidity. Twice during the test the settling tank became filled with sludge and was drained. There were several plugging problems in the outlet at the top of the settling tank. The problem was caused by an accumulation of settlement and air locks in the connecting pipes.

The chlorinator was designed to operate at 4.5 amps; however, the unit was operated at 5.0 amps to get a more clarifying action. The voltage during the test started at 20 volts and increased to 40 volts after 400 hrs of operation. The reason for this increase was that a coating formed on the plates. Flocs which passed between the electrodes slowly coated them. Reversing the polarity of the electrodes did not remove the coating. The average free chlorine residual leaving the chlorinator was 1.96 mg l^{-1}. The average free chlorine residual leaving the settling tank was 1.36 mg l^{-1}. Actual chlorine measured was lower than that computed by Peters (1973) due to the chlorine demand of the water.

Chemical analysis of the system influent and effluent is presented in Table 3-1. Total dissolved solids decreased slightly after passing through the system. Bicarbonates were decreased and carbonates increased by about the same proportion. Carbon dioxide, phosphates, total hardness, magnesium hardness, magnesium, silica and turbidity were reduced by the system.

TABLE 3-1. Chemical analysis of water at College Station.

Determination	Untreated ppm	Treated ppm	Amount Increased or Reduced	% Change	
				% Reduced	% Increase
Total Dissolved Solids @ 105°C	490	480	10	2	-
Phenolphthalein Alkalinity, as $CaCO_3$	0	21	21	-	-
Total Alkalinity, as $CaCO_3$	366	336	30	8	-
Carbonate Alkalinity, as $CaCO_3$	0	42	42	-	-
Bicarbonate Alkalinity, as $CaCO_3$	366	294	72	20	-
Carbonates, as $CaCO_3$	0	26	26	-	-
Bicarbonates, as $CaCO_3$	447	359	88	20	-
Hydroxides, as OH	0	0	0	-	-
Carbon Dioxide, as CO_2	5	1	4	80	-
Chlorine, as Cl	57	54	3	5	-
Sulfate, as SO_4	11	10	1	9	-
Fluorides, as F	.51	.26	.25	49	-
Phosphate, as PO_4	3.9	.1	3.8	97	-
pH (Laboratory)	8.2	8.8	.6	-	7
Total Hardness, as $CaCO_3$	30	18	12	40	-
Calcium Hardness, as $CaCO_3$	6	6	0	-	-
Magnesium Hardness, as $CaCO_3$	24	12	12	50	-
Calcium, as Ca	2.4	2.4	0	-	-
Magnesium, as Mg	5.8	2.9	2.9	50	-
Iron, as Fe	0	0	0	-	-
Manganese, as Mn	0	0	0	-	-
Copper, as Cu	0	0	0	-	-
Silica, as SiO_2	23	2	21	91	-
Turbidity, Jackson Units	3	0	3	100	-

Pond water test. The system was tested at Robert's Pond for 172.5 hrs. During testing the chlorinator was not operated because of a coating problem, and there were no chlorides present at the test site.

Apparent unit area resistance of the flocculator averaged 35,000 ohm cm^2 which was higher than the College Station test (Figure 3-5). This resulted from the low conductivity of the water and a thin coating of organic material which formed on the plates during testing. Apparent unit area resistance fluctuated during the reversal cycle (similar to the previous test). The highest apparent unit area resistance occurred 0.5 hrs after plate polarity reversal and averaged 44,000 ohm cm^2. Average conductivity of the Pond water was 200 micromhos cm^{-1}, and the flocculator voltage averaged 7.8 volts during testing.

Aluminum concentration varied during the reversal cycle (similar to previous tests). Average concentration was 14.6 mg l^{-1}. When concentration decreased below 8 mg l^{-1}, effluent turbidity increased.

Influent turbidity varied throughout the test while effluent turbidity remained relatively constant, averaging 1.0 mg l^{-1} (Figure 3-8). Influent apparent color ranged from 70 to 150 and averaged 110 units on the Standard Platinum Cobalt Scale. Color was due to high organic material and algae in the water. Effluent apparent color ranged from 0.0 to 2.0 and averaged 0.5 of the Standard Platinum Cobalt Scale. Influent water had a slight odor; no odor was detectable in the effluent. Sludge drained from the mixing and settling tanks was very odorous.

The system completely removed the iron, silica, color and turbidity in the sample taken for chemical analysis (Table 3-2).

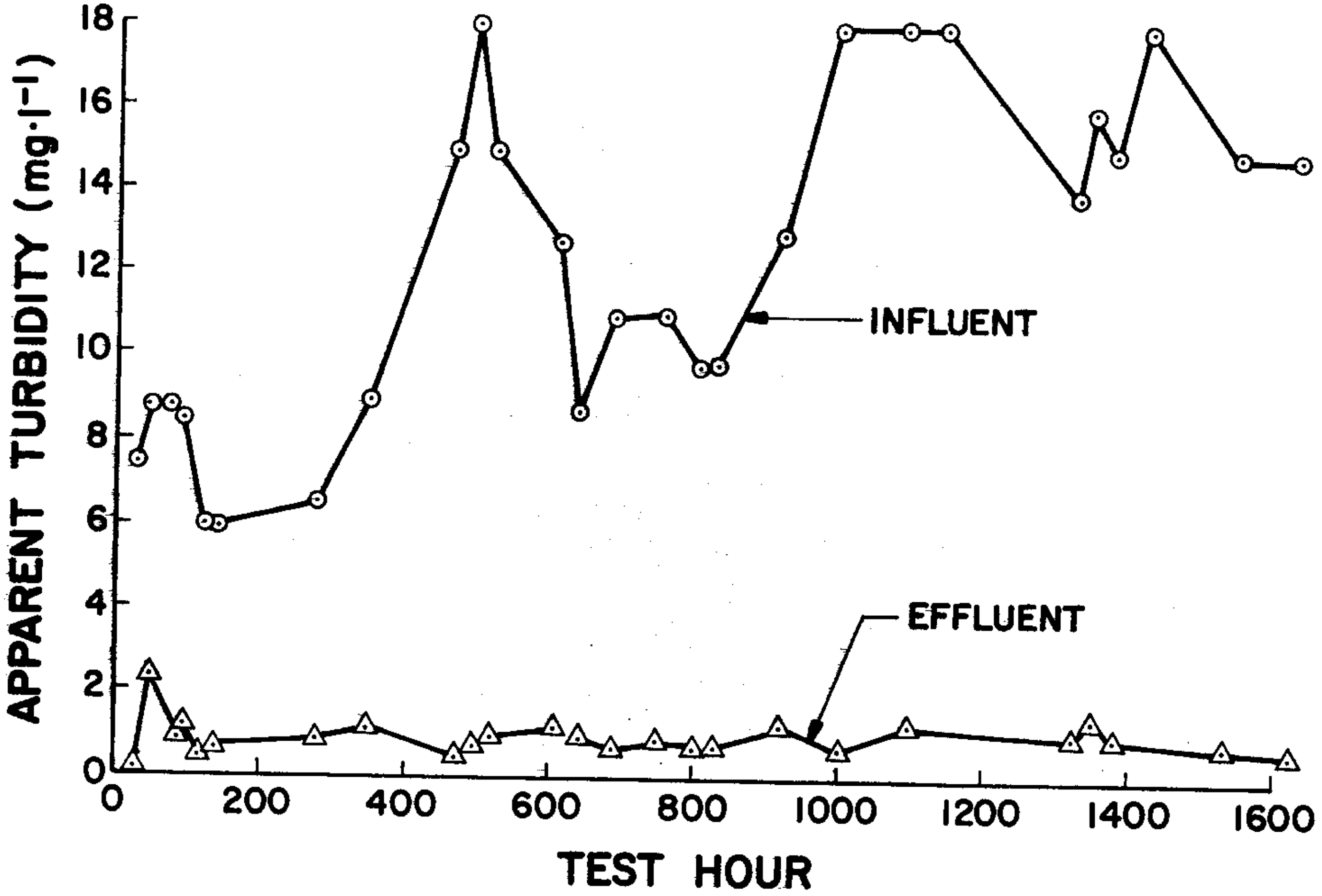

Fig. 3-8. Influent and effluent apparent turbidity during test of low current density unit at Robert's pond.

Carbon dioxide, total hardness, magnesium hardness, and magnesium were reduced significantly during the process. There was also a reduction in alkalinity, bicarbonates, and sodium. Reduction of impurities experienced in the treatment of Pond water was similar to reductions in the College Station tap water. There was greater reduction of total hardness, total alkalinity and silica in the Pond water than the tap water. Phosphates decreased during treatment of the College Station water and increased during the treatment of Pond water.

Modified low current density flocculator with tube settler. The system was tested for a total of 44 days. The optical drain control, designed to drain the first stage tube settler, did not operate properly. The optical lens which detected the floc bed in the tube settler would operate for a maximum of two days before it became coated. The controller was therefore removed, and the first stage tube settler was drained manually every 24 hrs. This method worked satisfactorily; however, a small amount of floc did pass through the chlorinator.

Effluent turbidity averaged 1.5 mg l^{-1} when the drain control was working properly. Influent turbidity averaged 34 mg l^{-1}. Color of the effluent, when the unit was operating properly, was less than 1 unit on the Standard Platinum Cobalt Scale.

The chlorinator was operated at 6.6 volts, 2.0 amps. This resulted in a current density of 0.0178 amp cm^{-2} and coulomb treatment dosage of 0.183 coul ml^{-1}. Average influent chloride concentration was 50 mg l^{-1} which was added to the flocculator as NaCl solution by a metering pump. The average free chlorine residual of the effluent

TABLE 3-2. Chemical analysis of influent and effluent water of the low current density unit at Robert's Pond.

Determination	Untreated ppm	Treated ppm	Amount Increased or Reduced ppm	% Change	
				% Reduced	% Increase
Total Dissolved Solids @ 105°C	82	70	12.0	14.63	-
Phenolphthalein Alkalinity, as $CaCO_3$	0	0	-	-	-
Total Alkalinity, as $CaCO_3$	54	48	6.0	11.11	-
Carbonate Alkalinity, as $CaCO_3$	0	0	-	-	-
Bicarbonate Alkalinity, as $CaCO_3$	54	48	6.0	11.11	-
Carbonates, as CO_3	0	0	-	-	-
Bicarbonates, as HCO_3	66	59	7.0	10.6	-
Hydroxides, as OH	0	0	-	-	-
Carbon Dioxide, as CO_2	11	2	7.0	81.8	-
Chloride, as Cl	0	0	-	-	-
Sulfate, as SO_4	0	0	-	-	-
Fluoride, as F	1.1	1.0	.1	9.09	-
Phosphate, as PO_4	3.9	4.4	.5	-	12.82
pH (Laboratory)	7.0	7.7	.7	-	10.00
Total Hardness, as $CaCO_3$	54	36	18.0	33.33	-
Calcium Hardness, as $CaCO_3$	36	30	6.0	16.66	-
Magnesium Hardness, as $CaCO_3$	18	6	12.0	66.66	-
Calcium, as Ca	15	12	3.0	20	-
Magnesium, as Mg	4.3	1.5	2.8	65.11	-
Sodium, as Na	5.9	5.6	.3	5.08	-
Iron, as Fe	.6	0	.6	100	-
Manganese, as Mn	0	0	-	-	-
Copper, as Cu	0	0	-	-	-
Silica, as SiO_2	3	0	3.0	100	-
Color, Standard Platinum Cobalt Scale	45	0	45.0	100	-
Odor, Threshold	0	0	-	-	-
Turbidity, Jackson Units	10	0	10.0	100	-

averaged 0.4 mg l^{-1}. The predicted chlorine residual from Peters (1973) for the current density and coulomb treatment dosage used in this test was 0.5 mg l^{-1}. The lower actual chlorine residual was due to the chlorine demand of the water. The plates became coated because the first stage was not drained frequently enough to prevent flocs from entering the unit. Flocs must be prevented from entering the chlorinator by draining the first tube settler section every 16 to 20 hrs or enlarging the section.

The silicon control rectifier DC power supplies used for the chlorinator were limited on the maximum amperage due to the capacitance of the plates.

The tube settlers operated effectively during testing; the first stage removed 95 to 99% of the flocs. In the first stage a bed of flocs would form at the bottom after draining and slowly rise, in time filling the unit. Water above the floc bed was completely clear.

Cost analysis. Operational cost of the systems was determined for the treatment of College Station tap water and Robert's Pond water. The cost of each system was estimated to be $1200; the life expectancy would be 20 yrs, resulting in a depreciation rate of $60 yr^{-1}. Maintenance cost for repairs of the pump and power supply was estimated to be $40 yr^{-1}. Cost of operation contributed to depreciation and maintenance is 0.01445 l^{-1} (54.7¢ per 1000 gal) assuming that the system treated 690.760 l yr^{-1} (182,500 gal yr^{-1}).

Electrical cost of treating College Station tap water and Robert's Pond water was based on 3.15 volt DC and 7.8 volt DC, respectively. Power supply conversion efficiency of 0.80, current of 8.0 amps, treatment rate of 1261.7 l day^{-1} (500 gal day^{-1}), and a power cost of 2¢ per kwhr were used to determine power consumption and costs. Power cost required to treat College Station tap water was 0.000798¢ per l (3.02¢ per 1000 gal). Power cost to treat water at Robert's Pond was 0.0019¢ per l (7.49¢ per 1000 gal).

Aluminum cost for treating College Station tap water and Pond water was based on an aluminum consumption rate of 90.20 mg l^{-1} (7.113 g hr^{-1} at a flow of 78.85 l hr^{-1}). The cost of the aluminum was based on \$1.43 Kg^{-1} (65¢ lb^{-1}). It was assumed that plates would be replaced after they were 85% consumed. Aluminum for treatment cost 0.0106¢ l^{-1} (40.2¢ per 1000 gal).

Chlorination costs were 0.00342¢ l^{-1} (13.0¢ per 1000 gal) and 0.00292¢ l^{-1} (11.1¢ per 1000 gal) for tap water and Pond water, respectively. A potential of 30 volts, current of 4.5 amps and power cost of 2¢ per kwhr were used to determine the cost for the College Station test. Power cost of chlorinating Pond water was determined using an average of 6.6 volts and 2.0 amps for each set of plates. The NaCl added to the Pond water cost 0.00172¢ l^{-1} (6.5¢ per 1000 gal). This was added to the cost.

Free chlorine residual was below State drinking water recommendations. Therefore, the cost of treating Pond water would have been greater than the cost for tap water if the dosage rates were equal.

Total cost of treating College Station tap water was 0.0293¢ l^{-1} (\$1.11 per 1000 gal). Total cost for treating Pond water was

0.0315¢ 1^{-1} (\$1.13 per 1000 gal). In both systems the depreciation-plus-maintenance cost was approximately 50% of the total operating cost.

Summary

Both systems tested contained a low current density flocculator unit, mixing unit, chlorinator unit and settling unit. The modified system combined the mixing, chlorinator and settling (tube settlers) unit into one unit.

The first system tested on College Station tap water and Pond water reduced influent turbidity by 90% (to 5 mg 1^{-1} and 1.0 mg 1^{-1}, respectively). Effluent color of Pond water averaged 0.5 on the Standard Platinum Cobalt Scale, resulting in a 99.6% reduction. Also, there was significant reduction of carbon dioxide, total hardness, silica and iron at both test locations. The electrochemical chlorinator in this system used natural chlorides to produce free chlorine. Free chlorine residual of the chlorinator was 1.96 mg 1^{-1} for the first system at the Pond. The plates became coated during testing due to flocs passing between them.

By using a tube settler in the modified system, the settling tank size was reduced by 75%. At the Pond location turbidity and color averaged 1.5 mg 1^{-1} and 1 unit, respectively. Chlorine residual averaged 0.4 mg 1^{-1} which was slightly less than predicted. The plates in the chlorinator were coated because the first stage of the tube settler was not drained frequently enough to prevent flocs from entering. Approximately 90 to 99% of the flocs were removed by the first stage tube settler.

Cost of treating College Station tap water was 0.0293¢ l^{-1} ($1.11 per 1000 gal) and 0.0315¢ l^{-1} ($1.13 per 1000 gal) for treating Pond water. Maintenance and depreciation costs were responsible for approximately 50% of these operating costs.

Based on these tests the following conclusions are made:

1. Low current density flocculation can be used to remove turbidity and other impurities of drinking water.
2. Tube settlers are very effective in removing flocs and are very compact, thus decreasing the size of the system.
3. Flocs must be prevented from entering the plate area of the electrochemical low chloride chlorinator in order to prevent the plates from being coated.
4. The chlorinator, when operating properly, will produce enough chlorine for proper disinfection although cost of operation is high.
5. Cost of operating the system is acceptable but could be reduced by using a different type of chlorination unit.

CHAPTER IV

HIGH CURRENT DENSITY FLOCCULATION

Introduction

High current density and high purity aluminum have been used experimentally in Japan to successfully prevent scale formation. There are several advantages of this process over low current density flocculation. One is that no scale is formed; therefore, additional equipment for disposal is not needed. Aluminum dissolution rate per unit area for this process is considerably higher than for low current density flocculation. Thus, the plate area of this type of flocculation unit would be less, resulting in a smaller unit.

Aluminum use efficiency is greater for high current density flocculation than for low current density flocculation. This results in lower operating costs.

Review of Literature

For several years in Japan, high purity aluminum dissolved at high current densities has been proven effective experimentally in preventing electrode scaling during electrochemical flocculation.

Okamoto (1956) used hydroxides of aluminum, zinc, and iron prepared electrolytically for removing silica, clarifying, and decoloring industrial waters. Aluminum hydroxide proved to have the most favorable coagulation power. However, after a few hours of electrolysis the electrodes became covered with scale formation. It was determined that the scale coating was a trihydrate of aluminum called bayerite and was covered with calcium carbonate. The mechanism which caused this bayerite to form was explained as follows: When electrolysis is continued, the solution in contact with the cathode becomes alkaline, favoring the formation of bayerite.

Akagami (1964) proved that by reversing the polarity of the plates scaling could be prevented on commercially pure aluminum. Dissolution efficiency was improved by polarity reversal. Akagami (1966) determined the optimum reversal period to be 15 min for all combinations of electrolysis. Scale tended to form on the anode when reversal time was too short and on the cathode when it was too long.

Twenty-one different aluminum alloys ranging in purity from 99.99 to 99.12% were tested as possible electrode materials by Akagami and Kaga (1971). It was determined that minimum current density is necessary to prevent scaling. Minimum current density to prevent scale increased as water temperature increased for all alloys. Dissolution rate at a given current density also increased as water temperature increased. The high purity alloys' (99.99 to 99.93% Al) minimum scale prevention current density increased linearly with increasing water temperatures above 10°C. Aluminum dissolution rates of these alloys were largely influenced by small variations in impurities. Alloys with copper contents greater than 0.01% had minimum scale prevention current density which increased exponentially with water temperature. Dissolution rates of these alloys increased faster with water temperature than did alloys with less than 0.01% copper. Minimum scale prevention of current densities for alloys with less than 0.01%

copper increased proportionally with increasing water temperature. The recommended alloy purity ranged from 99.70 to 99.85% with copper contents less than 0.01%. Current efficiency was from 240 to 280%.

Two processes are involved in formation of scale on the electrode. These processes are cathode corrosion and anodization. To select an alloy which will prevent scale from forming during polarity reversing electrochemical coagulation, a basic understanding of the effect of impurities on cathode corrosion and anodization is needed.

Impurities are found in aluminum in various forms. They can be located at the grain boundary or as precipitates in the grain structure. When they occur in localized areas, such as along grain boundaries, the structure becomes a series of anodic and cathodic regions depending on the electrode potential of the impurities. Table 4-1, presented by Binger, Hollingsworth and Sprowls (1967), shows various electrode potentials of aluminum impurities. Impurities with electrode potentials higher than aluminum are anode areas with respect to aluminum; impurities with lower electrode potentials are cathode areas.

Impurities with electrode potentials higher than aluminum will be corroded while those with lower potential will corrode the surrounding aluminum. Hydrogen erosion plays an important role in preventing scale. The amount of hydrogen erosion occurring will be low in anodic area surrounding the impurities with lower electrode potential. Therefore, scale is more likely to occur when the electrode contains those impurities. Desirable impurities include magnesium, zinc, and

TABLE 4-1. Electrode potentials of aluminum solid solutions and constituents. Binger, Hollingsworth and Sprowls (1968).

Solid Solution or Constituent	Potential, v(a)
Mg Al_3	- 1.24
Al + 4 $MgZn_2$(b)	- 1.07
Al + 4 Zn(b)	- 1.05
$MgZn_2$	- 1.05
$CuMgAl_2$	- 1.00
Al + 1 Zn(b)	- 0.96
Al + 7 Mg(b)	- 0.89
Al + 5 Mg(b)	- 0.88
Al + 3 Mg(b)	- 0.87
$MnAl_6$	- 0.85
99.95 Al	- 0.85
Al + 1 Mg_2Si(b)	- 0.83
Al + 1 Si(b)	- 0.81
Al + 2 Cu(b)	- 0.75
$CuAl_2$	- 0.73
Al + 4 Cu(b)	- 0.69
$FeAl_3$	- 0.56
$NiAl_3$	- 0.52
Si	- 0.26

(a) 0.1 N-calomel scale, measured in an aqueous solution of 53 g per liter NaCl + 3 g per liter H_2O_2 at 25 C.

(b) Solid solution.

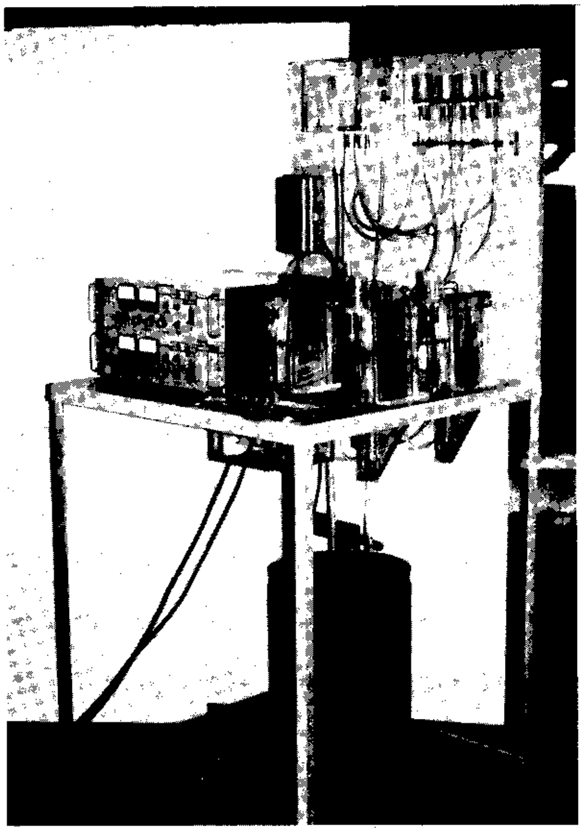

Fig. 4-1. Unit used to test various aluminum alloys at high current densities.

and manganese; undesirable impurities are copper, iron, nickel, and silicon due to their electrode potentials.

Impurities also affect the oxide coating forming on the anode during anodization. In high purity alloys, the copper found is in the $AlCu_2$ form. According to Van Lancker (1967), during commercial anodization it forms heavy intergranular corrosion. Therefore, it would be an undesirable impurity because of the difficulty in cleaning these alloys by hydrogen erosion.

In commercial electrolytic surface brightening, the aluminum is exposed to high current densities to smooth the surface and remove surface films. Aluminum content of alloys used ranges from 99.9 to 99.5%. With low purity aluminums, recommended additives are magnesium and zinc, according to Van Lancker (1967). It is recommended that silicon, iron, copper, and chromium be avoided when using lower purity alloys. This process is similar to that occurring at the anode during high current density coagulation.

All three processes discussed indicate that copper, iron, silicon, and chromium should be low in the alloy selected as electrode material. The selected alloy should contain magnesium, zinc, and manganese as major impurities.

Equipment

High Current Density Aluminum Alloy Testing Unit

The testing unit, shown in Figure 4-1, was used to determine the performance of various aluminum alloys under high current density conditions. A schematic of the testing unit is shown in Figure 4-2.

College Station tap water entered the constant temperature bath through a float valve which controlled the bath's water level. A Blue M Electric Company Magic Whirl Model MR-3240-C constant temperature bath was used to control water temperature within ± 1°C. A small pump removed water from the constant temperature bath and pumped it into the constant head device. Excess water flowed back into the constant temperature bath. Four flow-metering devices consisted of four constant water level cups connected to the constant head device and were moved up and down to control water flow. An individual test cell (Figure 4-3) was connected to each of the metering devices. The test cells contained a pair of aluminum plates held in a Plexiglas holder. The holders could be removed to charge the plates after a completed test. Water entered the cell at the top, passed between the plates and was removed at the bottom. The water then entered another set of constant head cups which maintained water level in the cell at about 6 cm above the plate. Water left the cups and was wasted to a drain.

The plates' dimensions were 10.2 cm by 10.2 cm. In one corner of each plate, approximately 2 cm from the side and 1.5 cm from the top, a 0.32 cm in diameter hole was drilled. Two slots, 0.32 cm wide, were cut down from the top on each side of the hole. A wire was attached to an electrical connecting terminal fastened to the plate at the hole by a pop-rivet. Short tygon tubing slid over the connection and was filled with silicon rubber. The plates slid inside the holder so that the wire connections were on opposite sides.

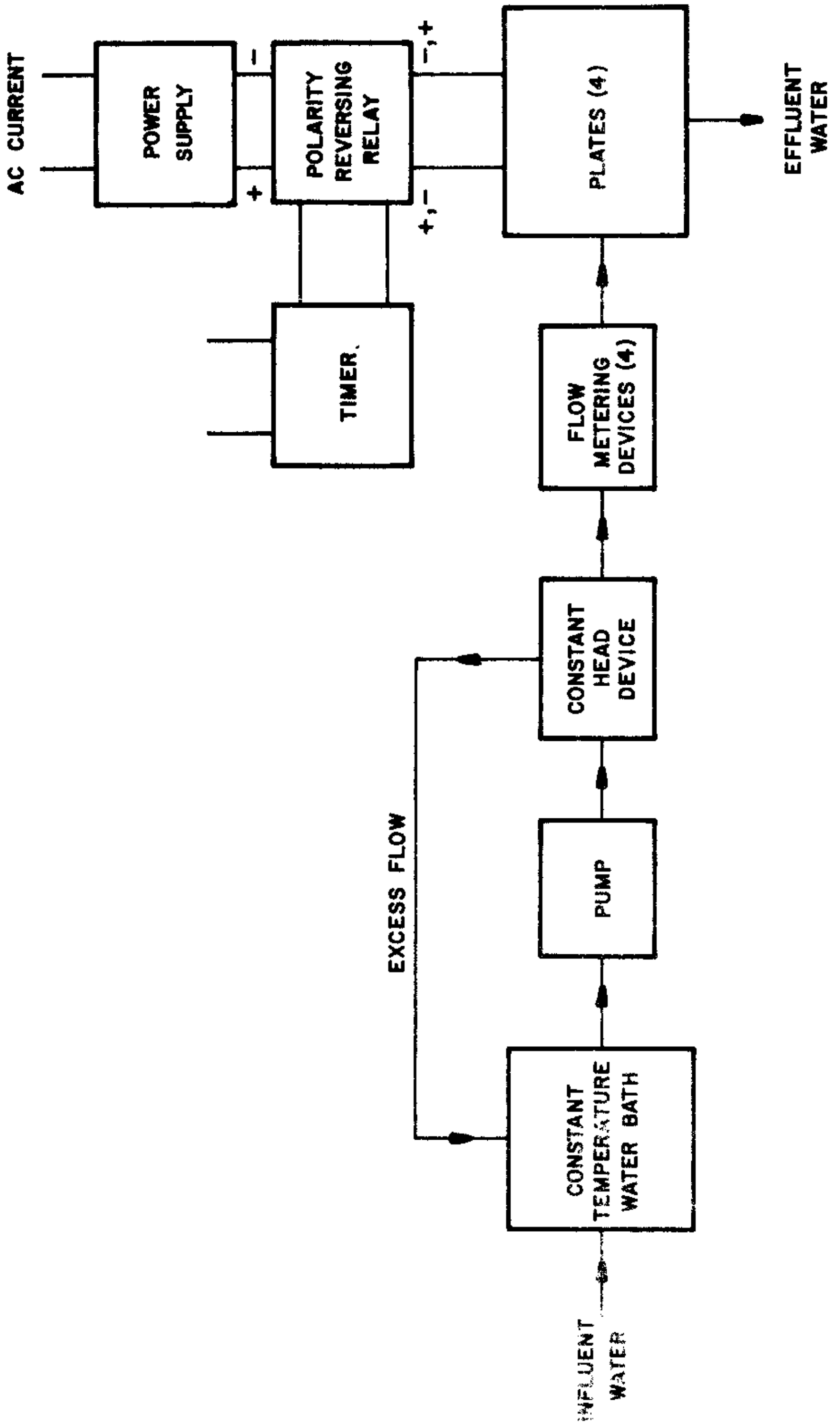

Fig. 4-2. Schematic of the high current density testing unit.

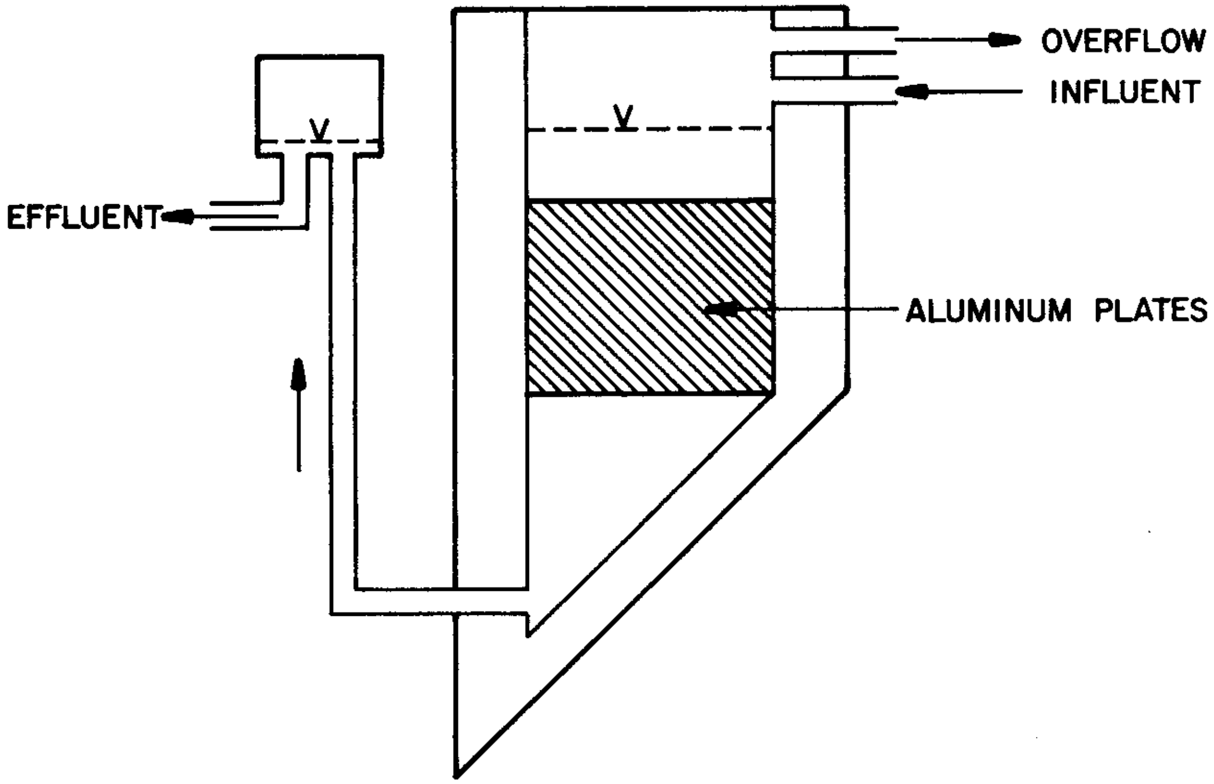

Fig. 4-3. High current density testing cell.

Two DC power supplies were used to supply constant current to the two polarity reversing relays. A thirty-minute cycle timer connected to the relays' coils reversed polarity on the plates every 15 min. One or more sets of plates could be connected to each power supply by connecting the different sets in series.

Upward flow testing was done with the same test cell by connecting the flow metering device to the bottom of the cell.

High Current Density Mixing Unit

The testing unit (Figure 4-4) was used to evaluate the effect of mixing on high current density flocculation. The unit consisted of a Plexiglas container. Inside the container were located four plate holders (Figure 4-5) separated by Plexiglas dividers. Each holder contained two sets of plates separated by a Plexiglas divider. The plates were located 8.9 cm below water surface. A total of 16 plates could be used at once. A mixing section was located 7.62 cm below the plates. The mixing blade was turned by a shaded pole gear reduction motor located above the water level.

Water entered the unit above the plate and passed through a channel formed by the Plexiglas dividers (1.9 cm wide, 28.8 cm long, and 8.9 cm deep). It then passed between the plates into another channel under the plate (1.9 cm wide, 28.8 cm long, and 7.62 cm deep) and into the mixing section. This section had a bottom sloped toward a drain located at one end, was 31.8 cm long, 22.9 cm wide, and had an average depth of 10.2 cm. Total volume was 7.4 l.

During the testing of this unit only two sets of plates (one holder) were used at one time. The remainder of the area above the mixing section was sealed off.

The unit used the same temperature control, flow control, and electrical system used in the high current density aluminum alloy test unit. One of the flow control devices was connected to the mixing unit.

Materials

Aluminum

Samples of aluminum were donated by Reynolds Metals Company, Richmond, California, and Aluminum Company of America, Pittsburgh, Pennsylvania. Chemical analysis of these alloys is presented in Table 4-2.

Water

College Station tap water was used in all laboratory testing. Chemical analysis is presented later in this chapter.

Procedure

Aluminum Alloy Tests

One hundred and three tests were conducted with different alloys. The majority of the tests were conducted using the high purity alloy (Sample 1) and 3002 alloy (Sample 2). Four tests were performed using 1100 aluminum alloy (same alloy used in low current density unit); three tests were performed with 3003 alloy; and one test was performed with 5005 alloy.

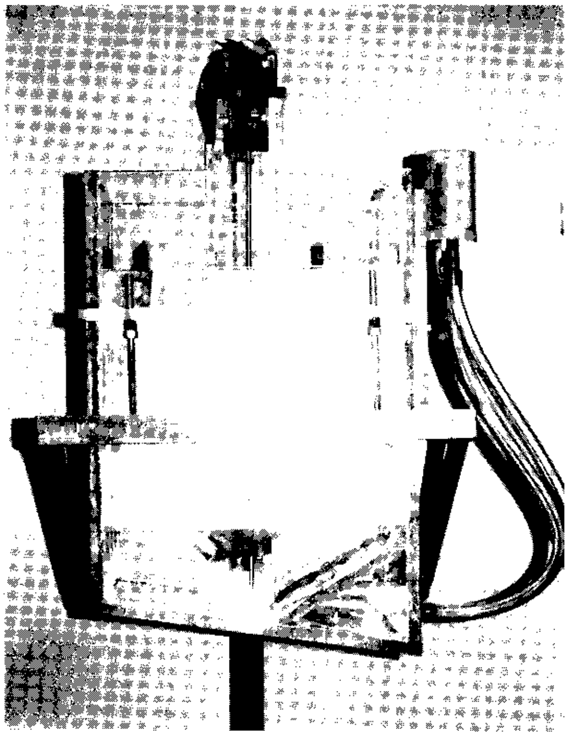

Fig. 4-4. High current density mixing test unit.

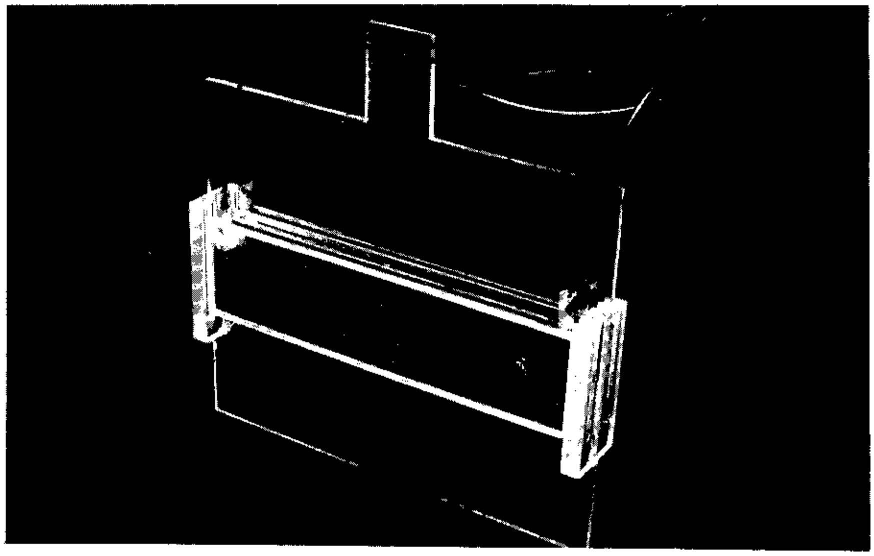

Fig. 4-5. Plate holder used with high current density mixing test unit.

TABLE 4-2. Chemical analysis of different alloys tested.

Element	Sample 1	Sample 2 S-28547	Sample 3 Alcoa 5005	Sample 4 Alcoa 3003
Silicon	.002	.04	.09	.26
Iron	.004	.08	.18	.48
Copper	.004	.06	.015	.11
Manganese	<.000	.17	.02	1.12
Magnesium	<.000	.16	2.67	.001
Chromium	<.000	<.01	<.17	<.003
Zinc	<.000	.01	.020	.020
Nickel	<.000	<.01	.002	.004
Ti		.02		

Approximate area of the plate was determined from plate dimensions minus estimated area covered by electrical connections. Temperature of the water bath and flow rate were set before placing the plates in the test cell. Current control which would give the desired current density was then set. The test was run for an initial break-in period of approximately 24 hrs before testing began. Plates were removed, dried, weighed, and re-installed in the test cell. A minimum of four sets of data was taken during each test . Each data set consisted of voltage, amperage, aluminum concentration, flow rate, and temperature. Voltage was measured across the electrodes during the last 5 min of the polarity reversal period. Amperage was measured by switching a volt-ohm-milliampmeter in series with the plates. Flow rate was determined by measuring water leaving each test cell for 1 min. Temperature was determined by a thermometer in the top of each test cell. A sample from each test cell was collected for 30 min (two reversals of polarity) and vigorously mixed. From this sample the aluminum concentration was determined by the method described in Standard Methods for the Examination of Water and Wastewater (1971).

After the test was completed, the plates were removed and examined for scale. If scale was present, area and location were recorded. The plates were then dried and weight loss determined. The area was again determined, and the average of the before-and-after testing areas was used in all calculations.

Other Tests

Several tests were performed to determine the effect of flow velocity and mixing on scale formation. The same testing cells used previously were used to test the 19.05 cm long plates for effects of flow velocity. The test of the 40.51 cm long plate was performed with a special test cell similar in design, but of greater length, than the previous ones. Plates were spaced 0.32 cm apart during all tests. Flow direction was changed by placing the inlet at the top or bottom of the test cell. Plates were removed after each test, and the area covered by scale was measured.

Five tests were run on the mixing test unit. Each test was run for a period of 90 hrs after which the plates were removed and examined for scale. Two tests were conducted with plates spaced 0.32 cm and 0.64 cm apart. One test was run with a flow straightener section between the plates and mixing compartment, one with a narrow channel between the plates and mixing compartment. The last test was conducted with the mixing motor turned off.

Discussion of Results

Minimum Scale Prevention Current Density

Table 4-3 contains data for different alloys tested. Minimum scale prevention (MSP) current density is slightly lower than actual current density at which scaling occurs because current density at which no scaling occurred was chosen as MSP current density. The difference between these current densities was usually less than 0.15 ma cm^{-2}.

MSP current densities were less for Sample 1 (high purity alloy) than for Sample 2 (3002 alloy) for all temperatures (Figure 4-6). Both alloys' MSP current densities decreased as water temperature decreased. MSP current densities for alloys at different temperatures can be predicted by the following empirical relationships:

Sample 1:

MSP current density = $1.297 - 0.0674T + 0.0048T^2$

Multiple correlation coefficient squared = 0.9932

Sample 2:

MSP current density = $2.528 - 0.1497T + 0.0064T^2$

Multiple correlation coefficient squared = 0.9995

where T is the water temperature in degrees centigrade.

The relationship for Sample 2 alloy is almost identical to a type B alloy characteristic curve described by Akagami (1971). (Values for current densities presented by Akagami were 0.85 times the actual testing current density.) Sample 2 had six times (0.06%) the amount of copper allowed by Akagami as the maximum amount for B type characteristic alloy (0.01%). Therefore, other impurities present in this alloy decreased the effect of copper on MSP current density. This was caused by the presence of a large percentage of magnesium and manganese in respect to other impurities and low amount of iron present. Copper was probably in the $CuMgAl_2$ form which is anodic to aluminum. This form of copper did not develop localized cathodic area during the period the electrode was a cathode.

TABLE 4-3. Results of high current density tests on aluminum alloy Sample 1 and Sample 2.

Sample	Test Hours hr.	Avg. Voltage volts	Avg. Amps Ma	Water Temp. °F	Al+++ Conc. mg l^{-1}	Plate Area cm^2	Current Density ma cm^{-2} (MSP)	Flow Rate ml min^{-1}	Weight Loss g	Total Al+++ Wt. Loss Rate mg hr^{-1} cm^{-2}	Al+++ Dis. Rate mg hr^{-1} cm^{-2}	Al Use Efficiency %	Actual Current Efficiency	Total Current Efficiency
1	77	2.1125	140	60.38	2.67	97.298	1.43	123.8	6.71	0.896	0.204	22.7	42.2	185.6
2	72.25	2.46	178.60	60.075	2.887	100.0	1.79	123.7	10.22	1.415	0.214	15.1	35.7	236.2
1	49.75	3.123	299.714	60.333	3.366	98.43	3.05	127.7	8.97	1.832	0.262	14.3	25.7	179.4
2	49.75	2.90	299.71	60.333	3.40	100.0	3.00	126.2	11.45	2.302	0.257	11.2	25.6	229.0
1	87.42	3.653	412.37	60.0	4.228	99.02	4.17	124.6	20.40	2.356	0.319	13.5	22.8	168.8
2	87.42	4.57	412.37	60.0	3.48	92.716	4.45	129.6	25.77	3.180	0.292	9.2	19.6	213.2
1	55.33	4.807	500.0	60.50	5.44	97.298	5.14	121.1	15.59	2.896	0.406	14.0	23.6	168.0
2	55.33	6.704	500.0	60.50	5.31	92.716	5.39	128.3	19.38	3.778	0.440	11.7	24.4	208.9
1	51.0	5.777	597.125	60.45	5.385	100.0	5.91	128.8	20.12	3.945	0.416	10.5	21.0	179.0
2	51.0	5.848	591.25	60.5	5.54	100.0	5.91	123.8	20.23	3.967	0.412	10.4	20.8	200.0
1	55.08	6.63	699.63	60.50	5.8	99.02	7.07	126.6	20.55	3.768	0.445	11.8	18.8	159.0
2	55.08	7.76	699.5	60.50	5.74	98.6	7.09	123.3	24.96	4.596	0.431	9.4	18.1	193.1
1	93.55	2.71	205.86	70.36	3.44	98.43	2.09	213.4	13.27	1.440	0.440	31.0	64.1	206.0
2	78.62	3.02	228.0	71.125	4.65	101.43	2.25	226.3	14.95	1.875	0.620	33.2	82.5	248.6
1	46.83	3.545	300.0	68.833	3.708	97.298	3.08	191.7	9.73	2.133	0.440	20.6	42.6	206.5
2	46.83	3.54	300.0	68.833	3.72	92.687	3.33	205.0	10.92	7.516	0.492	15.1	34.0	225.0
1	46.83	4.31	397.714	68.83	4.183	99.02	4.01	196.2	11.94	2.575	0.497	19.3	36.9	225.0
2	73.0	5.06	402.66	69.06	4.17	98.6	4.08	203.5	23.39	3.250	0.515	15.9	37.6	237.3
1	73.0	4.9	494.625	69.06	4.456	99.02	5.00	199.2	22.83	3.158	0.538	17.0	32.1	188.5
2	73.0	4.425	495.0	69.05	4.36	96.468	5.13	206.3	27.93	3.966	0.559	14.1	32.5	230.5
1	28.0	7.465	599.6	69.5	5.25	100.0	6.00	207.3	10.80	3.857	0.652	16.9	32.5	191.8
2	28.0	6.385	599.6	69.5	5.35	100.0	6.00	156.0	12.53	4.475	0.501	11.2	24.9	222.5
1	29.58	6.75	696.86	69.9	6.13	100.0	6.97	155.5	13.09	4.425	0.572	12.9	24.5	189.4
2	29.58	7.69	696.86	69.7	5.9	100.0	6.97	206.5	14.12	4.773	0.729	15.3	31.3	204.3
2	120.95	2.725	227.86	70.75	4.66	101.43	2.25	251.2	21.97	1.791	0.690	38.7	91.9	237.6

TABLE 4-3. Results of high current density tests on aluminum alloy Sample 1 and Sample 2. (continued)

Sample	Test Hours hr.	Avg. Voltage volts	Avg. Amps Ma	Water Temp. °F	Al+++ Conc. mg l^{-1}	Plate Area cm^2	Current Density ma cm^{-2} (MSP)	Flow Rate ml min^{-1}	Weight Loss g	Total Al+++ Wt. Loss Rate mg hr^{-1} cm^{-2}	Al+++ Dis. Rate mg hr^{-1} cm^{-2}	Al Use Efficiency %	Actual Current Efficiency	Total Current Efficiency
1	71.17	3.26	279.85	79.57	3.466	97.298	2.88	218.9	12.72	1.84	0.467	25.4	48.5	190.5
2	71.17	3.33	304.25	79.31	3.51	96.468	3.15	204.1	17.29	2.52	0.446	17.7	42.2	238.3
1	71.17	3.49	304.25	79.31	3.67	99.02	3.07	192.3	14.34	2.04	0.428	21.0	41.5	197.5
2	71.17	3.36	279.857	79.21	3.721	92.687	3.02	203.7	15.45	2.34	0.491	21.0	48.5	231.5
1	32.55	4.38	297.0	81.0	4.14	74.885	3.97	157.0	7.42	3.04	0.521	17.1	39.7	228.9
2	32.55	3.94	297.66	81.0	3.783	73.853	4.03	197.7	8.64	3.59	0.608	16.9	44.9	265.9
1	71.75	6.3	373.5	80.50	4.60	74.885	4.99	160.4	16.55	3.08	0.591	19.2	35.3	184.1
2	71.75	4.79	372.0	80.50	4.46	73.853	5.04	217.8	19.83	3.74	0.789	21.1	46.7	221.5
1	40.0	6.35	590.0	80.2	6.425	95.48	6.18	219.5	17.08	4.47	0.886	19.8	42.9	215.8
2	40.0	5.29	590.0	80.2	7.20	98.71	5.98	168.3	19.92	5.05	0.736	14.6	36.7	251.7
1	29.5	6.41	699.0	80.66	6.243	100.0	6.99	220.8	14.23	4.82	0.827	17.1	35.2	205.8
2	29.5	5.41	699.0	80.74	6.85	100.0	6.99	166.0	17.09	5.79	0.682	11.8	29.1	247.2
1	73.75	3.37	393.33	87.58	2.80	98.465	4.00	364.2	27.68	3.81	0.621	16.3	46.4	284.5
2	73.75	4.31	376.5	87.6	2.52	98.0	3.84	365.0	21.42	2.96	0.561	18.9	43.5	230.0
1	143.0	2.87	270.22	88.1	3.09	98.43	2.75	386.3	28.46	2.02	0.727	36.0	79.0	219.5
2	164.15	2.93	300.77	86.18	6.13	100.99	2.98	288.8	45.31	2.73	1.052	38.5	105.7	273.5
1	73.75	4.31	376.5	87.6	2.52	98.0	3.84	365.0	21.42	2.96	0.561	18.9	43.5	230.0
2	73.75	3.37	393.33	87.58	2.80	98.465	4.00	364.2	27.68	3.81	0.621	16.3	46.4	284.5
1	121.5	4.19	501.0	87.0	3.244	97.84	5.12	297.1	43.42	3.65	0.591	16.2	34.4	212.7
2	121.5	4.57	501.0	87.0	3.577	98.14	5.10	286.7	52.78	4.43	0.627	14.2	36.6	258.5
1	42.25	6.5	600.0	87.33	3.15	96.45	6.22	337.5	15.75	3.87	0.661	17.1	31.7	185.3
2	42.25	6.1	600.0	87.33	3.55	98.465	6.09	305.0	18.58	4.47	0.660	14.8	32.3	218.5
1	41.25	5.3	700.0	87.29	3.65	97.84	7.16	301.0	21.02	5.21	0.674	12.9	28.0	217.0
2	40.75	6.38	700.0	87.30	3.925	100.99	6.93	764.3	17.36	4.22	0.616	14.6	26.5	181.5

Actual Aluminum Dissolution Rates

Actual aluminum dissolution rates expressed the actual amount of soluble aluminum compounds and aluminum ions released into water per unit area and unit time. Figure 4-7 and Figure 4-8 present relationships between actual aluminum dissolution rate and temperature at various applied current densities for Sample 1 and Sample 2, respectively.

Actual aluminum dissolution rate decreased with temperature for both Samples 1 and 2 at all current densities. This was caused by the change in the solubility of aluminum hydroxide. At high temperature (30°C), the aluminum dissolution rates for Sample 1 were almost equal at all current densities.

At lower current densities (4.0 ma cm^{-2} to 5.0 ma cm^{-2}) actual dissolution rate relationships for both samples were similar. Dissolution rates at these current densities for both samples increased with temperature until approximately 27°C, then remained constant. At higher current densities (6.0 ma cm^{-2} to 7.0 ma cm^{-2}) there was a considerable amount of variation between the dissolution rates and water temperature. This was probably due to experimental error since the tests at the two high current densities and the two high temperatures were shortened because of aluminum alloy shortage. Second order polynomial regression curves and squared multiple correlation coefficients for the curves presented in Figures 4-7 and 4-8 are given in Table 4-4.

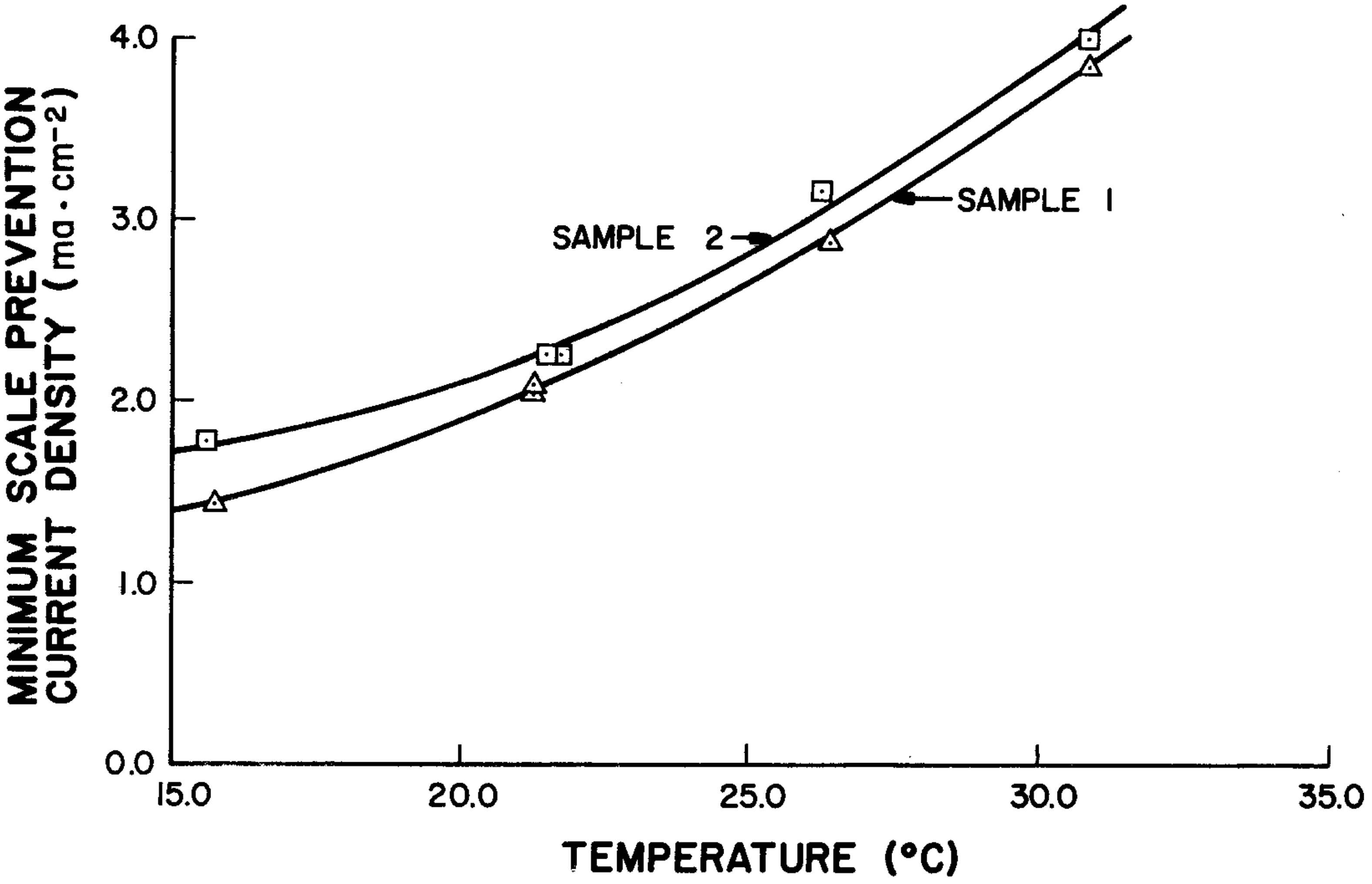

Fig. 4-6. Relationship between minimum scale prevention current density and water temperature.

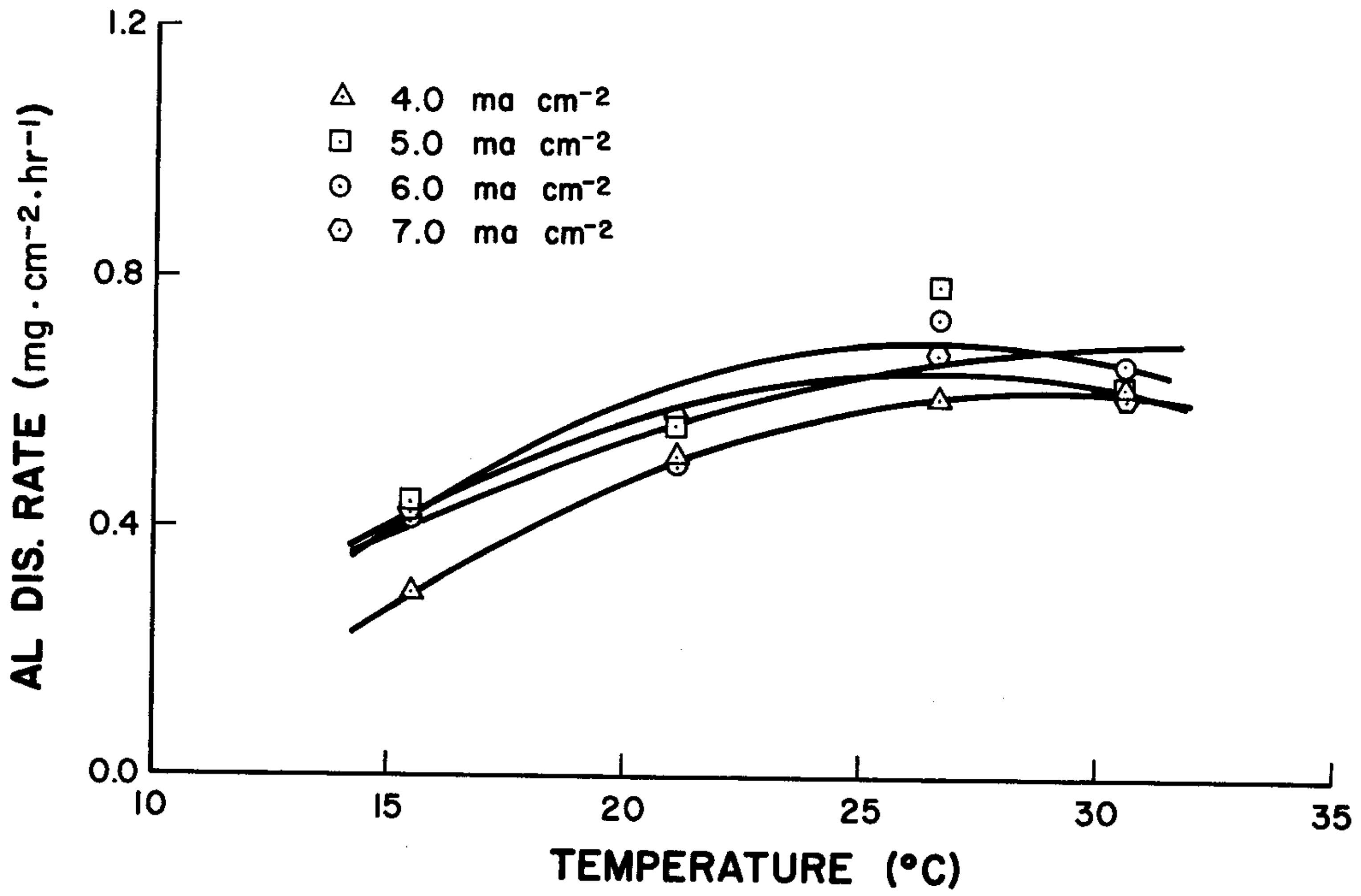

Fig. 4-7. Relationship between actual aluminum dissolution rates and water temperature for sample 1.

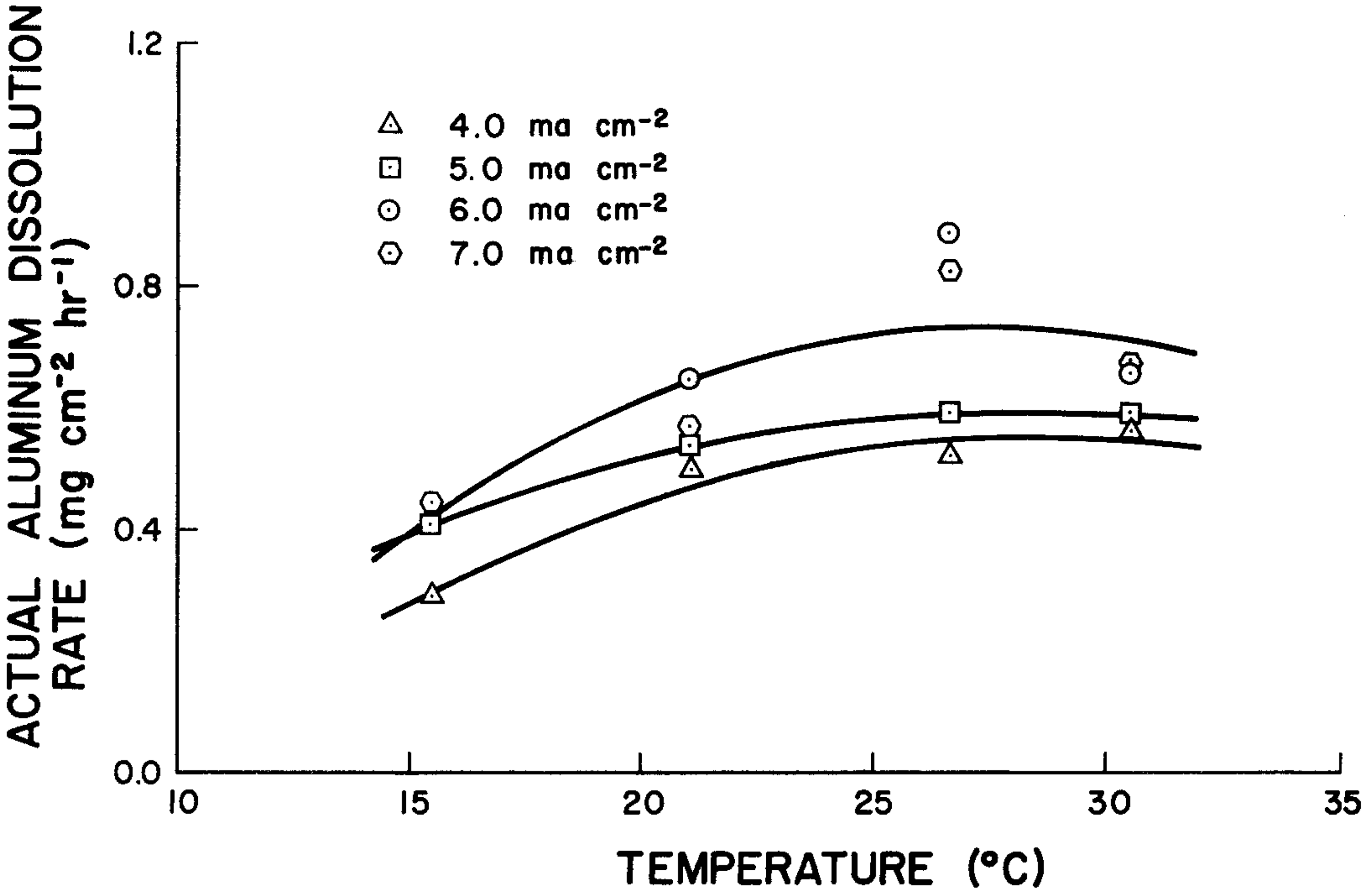

Fig. 4-8. Relationship between actual aluminum dissolution rates and water temperature for sample 2 (3002 Alloy).

TABLE 4-4. Equations for actual aluminum dissolution rate versus water temperature.

Sample 1:		
4.0 ma cm^{-2}	Actual Al. Dis. Rate	$= -.901 + .1052\ T - .0018\ T^2$
	r^2	$= .9991$
5.0 ma cm^{-2}	Actual Al. Dis. Rate	$= -.920 + .1218\ T - .0023\ T^2$
	r^2	$= .7635$
6.0 ma cm^{-2}	Actual Al. Dis. Rate	$= -.427 + .0697\ T - .0011\ T^2$
	r^2	$= .837$
7.0 ma cm^{-2}	Actual Al. Dis. Rate	$= -.6408 + .0966\ T - .0018\ T^2$
	r^2	$= .9544$
Sample 2:		
4.0 ma cm^{-2}	Actual Al. Dis. Rate	$= -.686 + .087\ T - .0015\ T^2$
	r^2	$= .9613$
5.0 ma cm^{-2}	Actual Al. Dis. Rate	$= -.3296 + .0654\ T - .00116\ T^2$
	r^2	$= .9997$
6.0 ma cm^{-2}	Actual Al. Dis. Rate	$= -.636 + .560\ T - .0108\ T^2$
	r^2	$= 1.0$
7.0 ma cm^{-2}	Actual Al. Dis. Rate	$= -.931 + .1215\ T - .0022\ T^2$
	r^2	$= .791$

T = Water temperature °C.

Total Aluminum Dissolution Rates

Total aluminum dissolution rate was based on weight loss of plates during testing. In Figure 4-9 (Sample 1) and Figure 4-10 (Sample 2), the relationship between total aluminum dissolution rate and water temperature is presented for various current densities. The possible cause of variation in data at high current densities has been previously discussed.

Total dissolution rate increased with temperature for both samples at all current densities. Sample 2 (3002 alloy, Figure 4-10) had higher dissolution rates than Sample 1 (high purity, Figure 4-9) under all test conditions. These relationships are very similar to characteristics of type B aluminum alloy described by Akagami (1971). Total dissolution rate of both samples varied considerably less with temperature. Sample 2 (3002 aluminum alloy) was a better alloy than type B alloy because total aluminum dissolution rate varied less with water temperature. Dissolution rates for Sample 1 were lower than for Sample 2 at lower current densities. Dissolution rates were approximately equal at higher current densities. Dissolution rate of Sample 2 also varied less with changes in current densities than did Sample 1 and Akagami's type B alloys.

The empirical equation for the relationships presented in Figures 4-9 and 4-10 are given in Table 4-5.

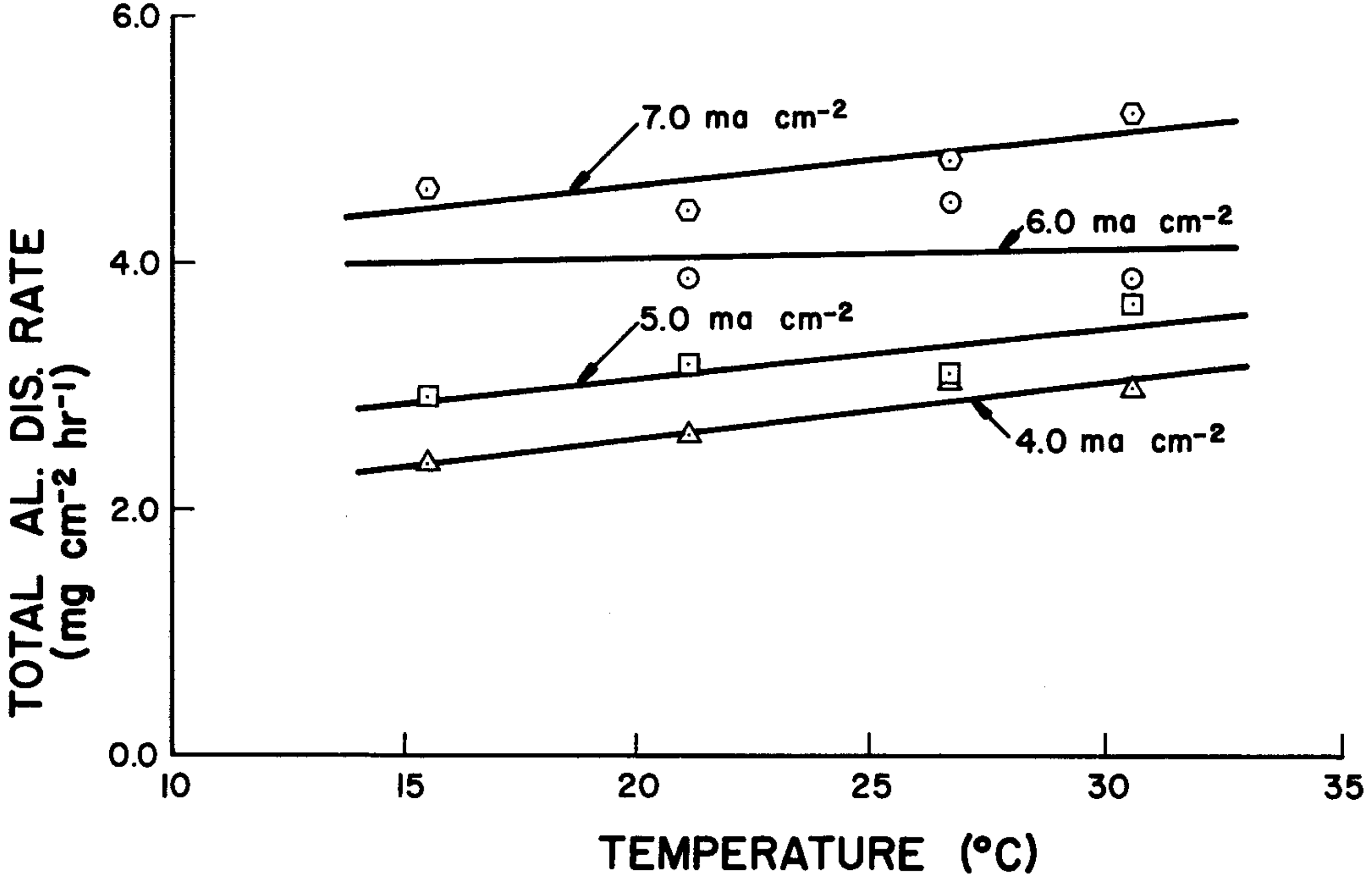

Fig. 4-9. Relationship between total aluminum dissolution rate and water temperature for various current densities for aluminum alloy sample 1.

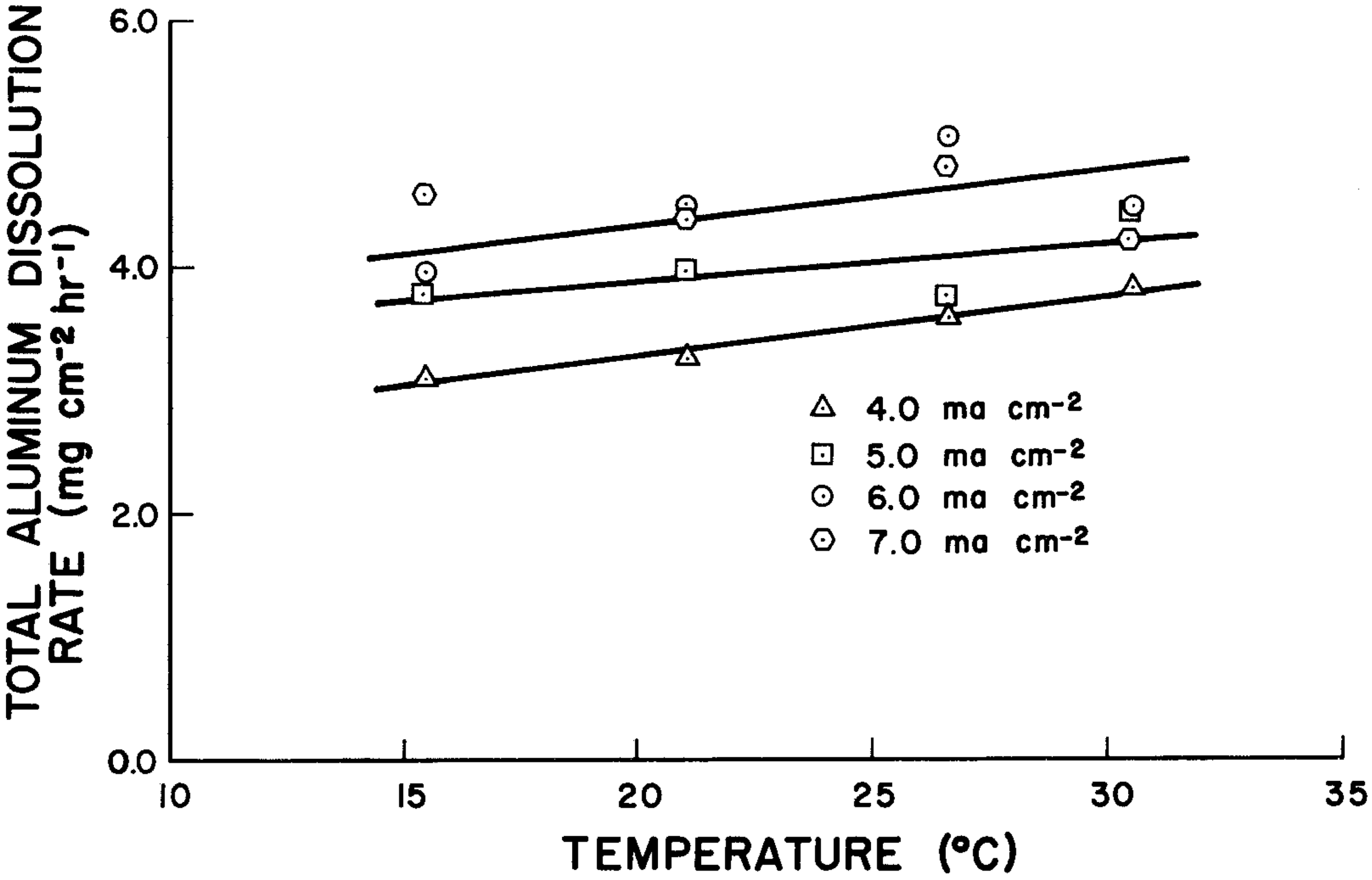

Fig. 4-10. Relationship between total aluminum dissolution rate and water temperature at various current densities for aluminum alloy sample 2 (3002).

TABLE 4-5. Relationship of total aluminum dissolution rate and water temperature.

Sample 1:		
4.0 ma cm^{-2}	Total Aluminum Dissolution Rate	= 1.646 + 0.046 T
	r^2	= 0.879
5.0 ma cm^{-2}	Total Aluminum Dissolution Rate	= 2.23 + 0.0413 T
	r^2	= 0.704
6.0 ma cm^{-2}	Total Aluminum Dissolution Rate	= 3.86 + 0.008 T
	r^2	= 0.01
7.0 ma cm^{-2}	Total Aluminum Dissolution Rate	= 3.77
	r^2	= 0.67
Sample 2:		
4.0 ma cm^{-2}	Total Aluminum Dissolution Rate	= 2.44 + 0.044 T
	r^2	= 0.966
5.0 ma cm^{-2}	Total Aluminum Dissolution Rate	= 3.246 + 0.031 T
	r^2	= 0.425
6.0 ma cm^{-2}	Total Aluminum Dissolution Rate	= 3.40 + 0.046 T
	r^2	= 0.456
7.0 ma cm^{-2}	Total Aluminum Dissolution Rate	= 4.79 - 0.012 T
	r^2	= 0.094

T = Temperature °C.

Testing of Sample 3 (5005) and Sample 4 (3003) Aluminum Alloys

Sample 3 (5005) aluminum alloy, very high in magnesium, was completely covered with scale within 45 hrs at current density of 4.9 ma cm^{-2} and temperature of 21.1°C. Voltage increased from 2.5 to 42.0 volts during the test period.

Sample 4 (3003) aluminum alloy (tested under the same conditions as Sample 3) had scale covering approximately 60% of the area. Voltage increased from 2.5 to 5.0 volts during this test.

High magnesium alloy, Sample 3 (5005), was ineffective in preventing scaling. High manganese alloy, Sample 4 (3003), also was ineffective in preventing scaling; however, scaling occurred at a slower rate than with high magnesium alloy.

Effect of Mixing, Flow Direction, and Flow Velocity in High Current Density Flocculator

Scale which formed in all tests conducted on the mixing unit was caused by flocs formed and remaining between the plates. Flow straighteners and narrow channel sections below the plates were designed to prevent flocs from reentering the plate section after forming. Both modifications were unsuccessful in preventing flocs from entering the plate section because the slow flow velocities did not prevent the flocs with entrapped gas bubbles from rising. Also, mixing currents forced the flocs up between the plates.

Eleven tests were conducted to determine flow direction and velocity required to prevent scaling. Results are presented in Table 4-6. The only successful tests were with downward flow direction and flow velocities greater than 1.7 cm sec^{-1}. Tests with upward flows were unsuccessful. Small amounts of scale formed along the edges flaked off and became lodged at the bottom of the unit between the plates. In the downward flow test these small pieces of scale from the edge were flushed out before they became lodged. Scaling occurred in downward flow tests with slow velocities because flocs with entrapped gas bubbles remain suspended between the plates.

It was decided from these results that the final high current density flocculator should have downward flow with flow velocity greater than 2.0 cm sec^{-1}.

Current Efficiency and Aluminum Use Efficiency

Current efficiencies represent the amount of electrical current used to dissolve aluminum from the plates. These were determined from both plate weight loss (total current efficiency) and measured aluminum concentration in the treated water (actual current efficiency). Actual current efficiencies for various test temperatures and current densities are presented in Figure 4-11 (Sample 1) and Figure 4-12 (Sample 2). At all temperatures both samples' current efficiencies increased as current density decreased. At approximately minimum scale prevention current density, current efficiency increased more rapidly with further decreases in current density. At the test temperature with both samples, the current efficiency was approximately 45%. Sample 1 approached 100% actual current efficiency at current density less than minimum scale prevention current density. Current efficiency of

TABLE 4-6. Effect of flow velocity and flow direction on scale prevention.

Test Number	Plate Dimensions Length cm	Plate Dimensions Width cm	Flow Direction	Flow Velocity cm sec^{-1}	Testing Time, hr.	Current Density ma cm^{-2}	Area Covered by Scale, %
1	19.05	Top 8.25 Bottom 10.16	Upward	2.43	116.5	4.0	28
2	19.05	Top 8.25 Bottom 10.16	Upward	3.96	91.5	4.0	28
3	19.05	9.55	Upward	7.53	144.0	4.0	28
4	19.05	9.53	Upward	3.01	92.0	4.0	29
5	19.05	6.35	Upward	5.64	157.0	4.0	66
6	19.05	6.35	Upward	6.61	157.0	4.0	66
7	19.05	6.35	Downward	1.71	142.5	4.0	6.6
8	19.05	6.35	Downward	7.18	142.5	4.0	3.2
9	40.57	7.62	Downward	1.1	69.0	4.0	50
10	40.54	7.62	Downward	2.2	48.5	4.0	1.5
11	40.54	7.62	Downward	1.1	77.0	4.0	25

Sample 2 exceeded 100% at low current densities because a portion of the aluminum in solution eroded from the cathode during the evolution of hydrogen.

Total current efficiencies for Samples 1 and 2 exceeded 200% at most current densities. In all cases total current efficiency was never equal to actual current efficiency, indicating that a majority of aluminum eroded by hydrogen was not dissolving in the water. This was also confirmed by the presence of small granular pieces of aluminum present in the lower portion of the test cells.

Actual aluminum use efficiency was determined by comparing measured aluminum in the water to weight loss of the plates. Aluminum use efficiency increased as water temperature increased; it decreased as the current density increased. Aluminum use efficiency was 2 to 3% higher in most cases for Sample 1 than for Sample 2. Aluminum use efficiency of Sample 1 averaged 12.5%, 16.5%, 18.3%, and 16.3% for 15.56°C, 21.11°C, 26.67°C, and 30.56°C, respectively (average of 4.0, 5.0, 6.0, and 7.0 ma cm^{-2}). For Sample 2, aluminum use efficiency averaged 10.2%, 14.1%, 16.1%, and 14.8% for test temperatures of 15.56°C, 21.11°C, 26.67°C, and 30.56°C, respectively (average of 4.0, 5.0, 6.0, and 7.0 ma cm^{-2}).

At current densities less than minimum scale prevention current density, aluminum use efficiencies for both alloys increased to approximately 40 to 55%. This corresponded to high current efficiencies at these current densities. If the plates were allowed to operate at

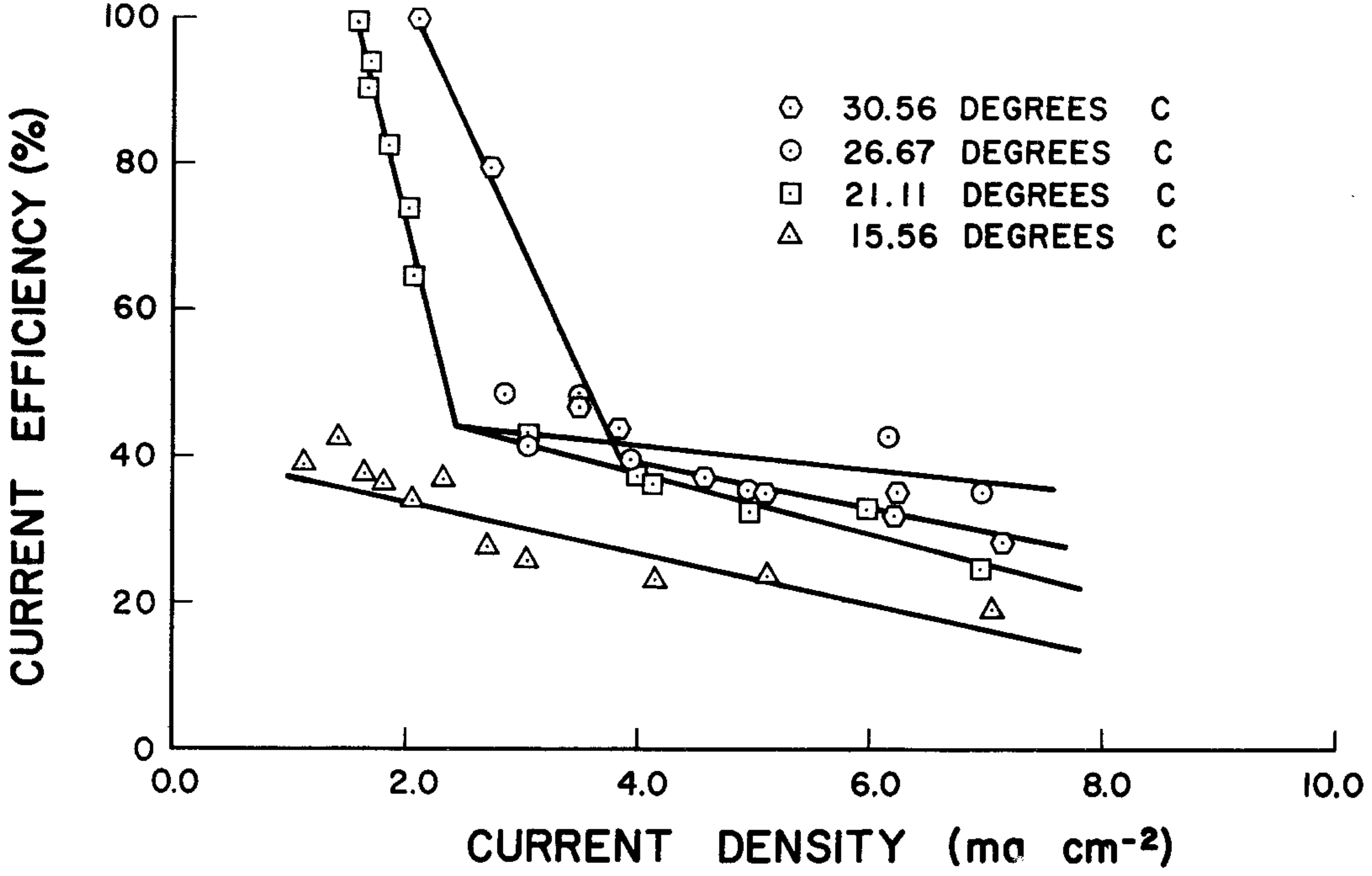

Fig. 4-11. Actual current efficiencies versus current densities at different water temperatures for sample 1.

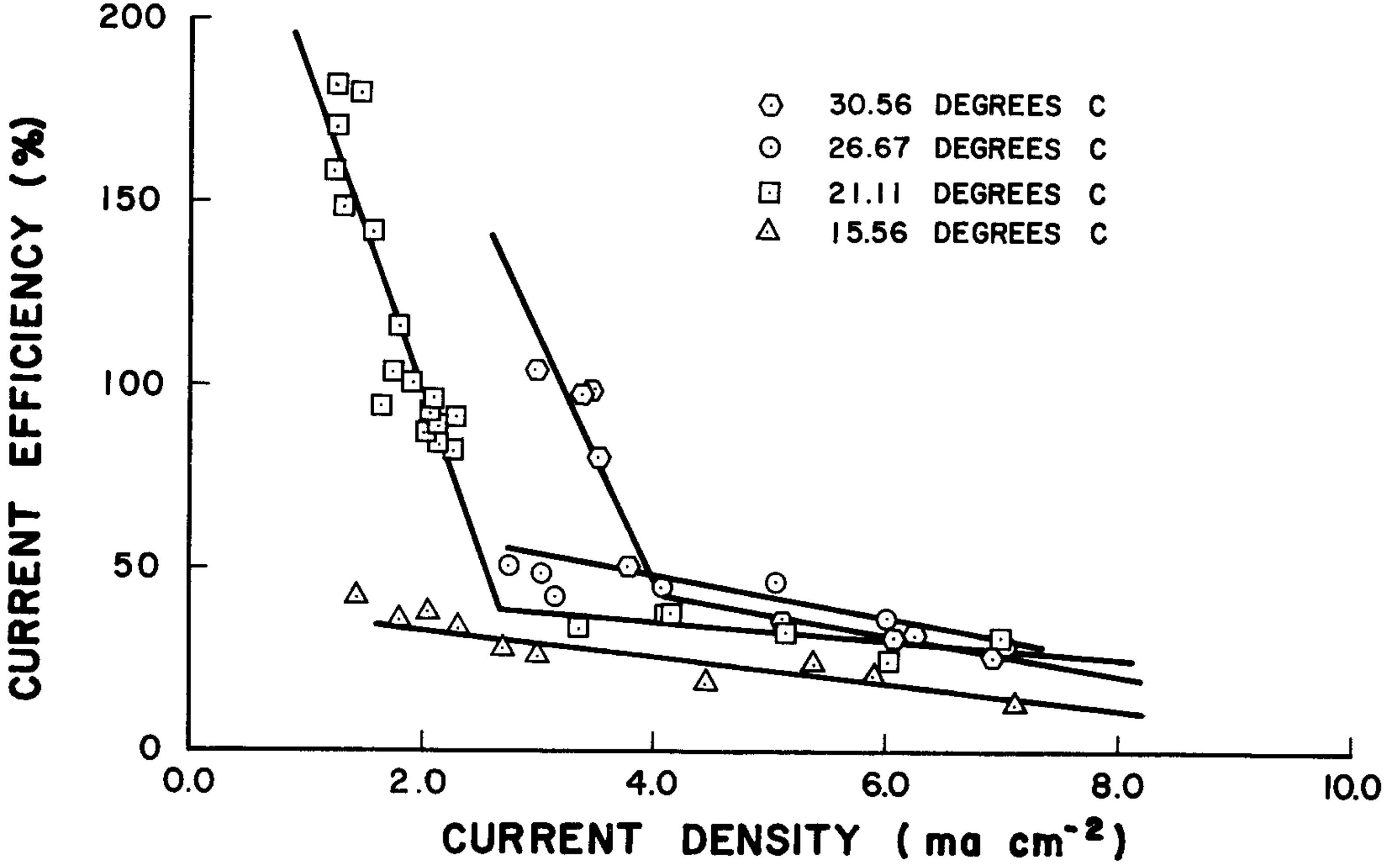

Fig. 4-12. Actual current efficiencies versus current densities at various water temperatures for sample 2.

these low current densities, aluminum use efficiency and current efficiency would have decreased because of the formation of scale on the plates.

Summary

Minimum scale prevention (MSP) current density for Sample 2 (3002 alloy) was higher than for Sample 1 (high purity alloy) at all temperatures. Copper content of Sample 2 was 6 times the maximum amount allowable for B type characteristic described by Akagami (1971). This was because of low iron and higher percentage of magnesium and manganese.

Actual aluminum dissolution rate of both samples decreased with temperatures less than 27°C and were approximately equal for both samples. At temperatures greater than 27°C, dissolution rate remained constant.

Total aluminum dissolution rate (based on weight loss of the plates) of both alloys tested decreased linearly with temperature. At the two lower current densities, Sample 1 had a lower dissolution rate than Sample 2. At the two high current densities, dissolution rate relationships were approximately equal at all temperatures.

Actual current efficiency for Samples 1 and 2 increased with decreasing current densities, ranging from 20 to 40% at current densities below MSP current density. At current densities less than MSP current density, actual current efficiency ranged from 40 to 175%. Total current efficiency exceeded 200% due to hydrogen erosion of the plates.

Aluminum use efficiency ranged from 10.2 to 18.3% at temperatures less than MSP current densities with Sample 1 averaging 2% greater than Sample 2. At current densities less than MSP current density, aluminum use efficiency ranged from 40 to 55%.

Neither 3003 nor 5005 alloy tested was effective in preventing scale formation. Scale formed at a slower rate on 3003 alloy than on 5005 alloy, indicating that manganese was more effective in scale prevention than magnesium.

All plates tested with the mixing unit during high current density flocculation formed scale. Therefore, flocs must be removed from the plate area immediately after forming. This is the same conclusion reached with low current density flocculation testing. Only downward flow direction with velocity greater than 2 cm sec^{-1} was effective in preventing scaling. Flow direction and velocity more effectively removed flocs which formed in the plate area.

After exhaustive high current density flocculation testing the following conclusions are drawn:

1. It is possible to prevent scale formation on aluminum plates by using high current densities along with high purity alloys.
2. Aluminum alloy must be low in silicon, iron, and copper content relative to their magnesium and manganese content. Alloys with copper content of 0.06% can be used.
3. MSP current density increases as water temperature increases.

4. Both actual and total aluminum dissolution rates increase with water temperature.
5. Flocs must be removed immediately after forming by using downward flow velocity greater than 2 cm sec^{-1}.
6. Current and aluminum use efficiencies were both higher at current densities less than MSP current density. If the plates could be operated at these low current densities and scaling prevented, cost of operation would be decreased considerably.

CHAPTER V

FIELD TESTING OF HIGH CURRENT DENSITY FLOCCULATION SYSTEM WITH ELECTRO-OSMOTIC CHLORINATOR

Introduction

A system containing a high current density flocculator, tube settler unit, electro-osmotic chlorinator, and automatic controls was built and tested at the Robert's Pond site. Only preliminary testing of the unit was completed. Evaluation of the system includes turbidity removal, impurity removal, operating procedure, maintenance problems, and operating cost.

Equipment

Intake Pump

A progressing cavity Robin and Myers, Inc. Model BA100 Moyno pump was driven by a 1/4 horsepower totally enclosed induction motor. Pump speed was 500 rpm which produced a discharge rate of 1.31 l min^{-1} (0.35 gal min^{-1}) at 5 psig. The inlet hose to the pump was 30 cm below water level at the center of the Pond. The outlet was connected to a flow divider unit at the top of the flocculator unit. A schematic of the system is shown in Figure 5-1.

High Current Density Flocculator

Design of the flocculator unit was based on testing results of 3002 aluminum alloy discussed in Chapter IV. It was assumed that the water would require an 8 mg l^{-1} aluminum dosage rate and maximum expected water temperature would be 30°C. Minimum current density for 30°C is

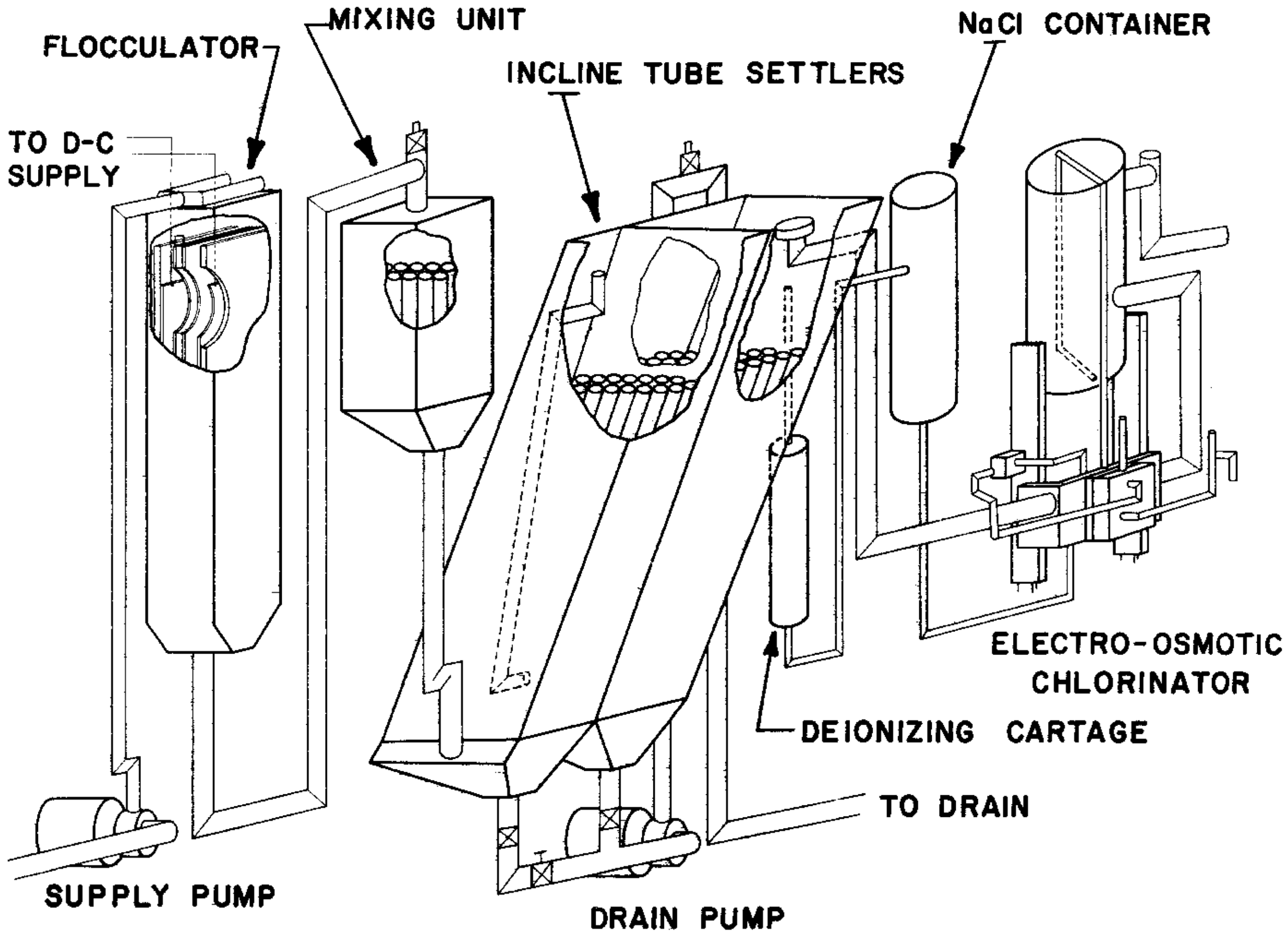

Fig. 5-1. Schematic of high current density water treatment system.

3.6 ma cm^{-2} (Figure 4-6). The unit was designed to operate at 4.0 ma cm^{-2}, which included a 10% safety factor. At 4.0 ma cm^{-2}, actual aluminum dissolution rate was 0.45 mg cm^{-2} hr^{-1}, for 17°C water temperature (Figure 4-8). The area of the plates required for a flow rate of 78.85 l hr^{-1} (500 gal day^{-1}) was 1402 cm^2. The 3002 alloy plates needed to be 61 cm long and 11.5 cm wide if two sets of two plates connected in series would be used. Actually the final plate was slightly wider (11.75 cm). Actual total plate area was 1433 cm^2, resulting in applied current of 2.87 amp with current density of 4 ma cm^{-2}.

The flocculation container, 100 cm tall, 17.0 cm wide and 4.7 cm thick, was constructed from 1.27 cm and 1.91 cm Plexiglas (Figures 5-2 and 5-3). The sides were grooved and three 0.64 cm Plexiglas plate holders slid into them. One plate was glued to each plate holder 17.8 cm from the top of the unit. Two plates were glued to the middle holder, one on each side. Plate spacing was 0.32 cm. All electrical connections were made at the top and side of each plate in the manner described in Chapter IV.

At the beginning of testing, the inlet was a perforated tube which distributed the water directly over the middle plate holder. This was replaced by a weir box at the top of the unit which provided a more accurate division of flow between the two sets of plates.

The area above and below the plate was filled with a Plexiglas spacer so that the 0.32 cm opening between the plates extended from above the plate to the outlet at the bottom. These spacers were installed after a short period of testing.

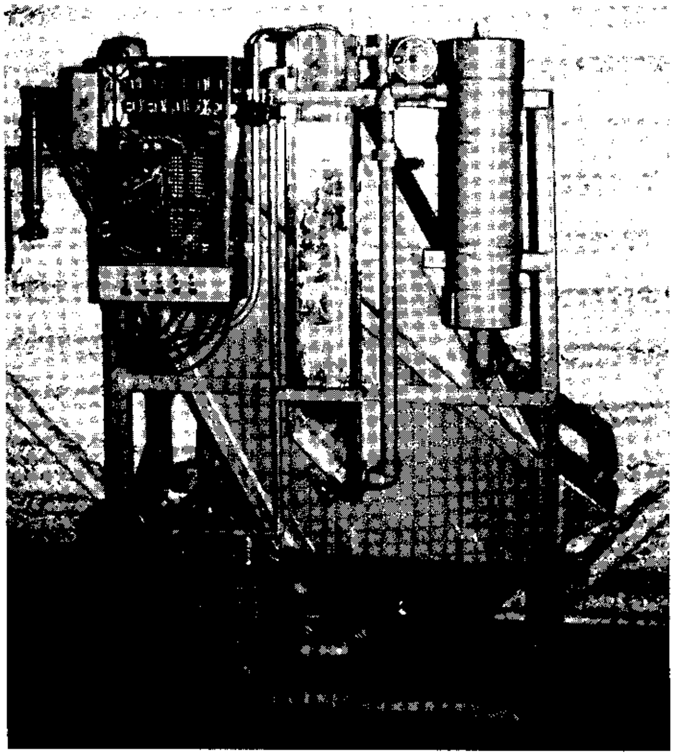

Fig. 5-2. High current density flocculation system. (Electro-osmotic chlorinator not shown).

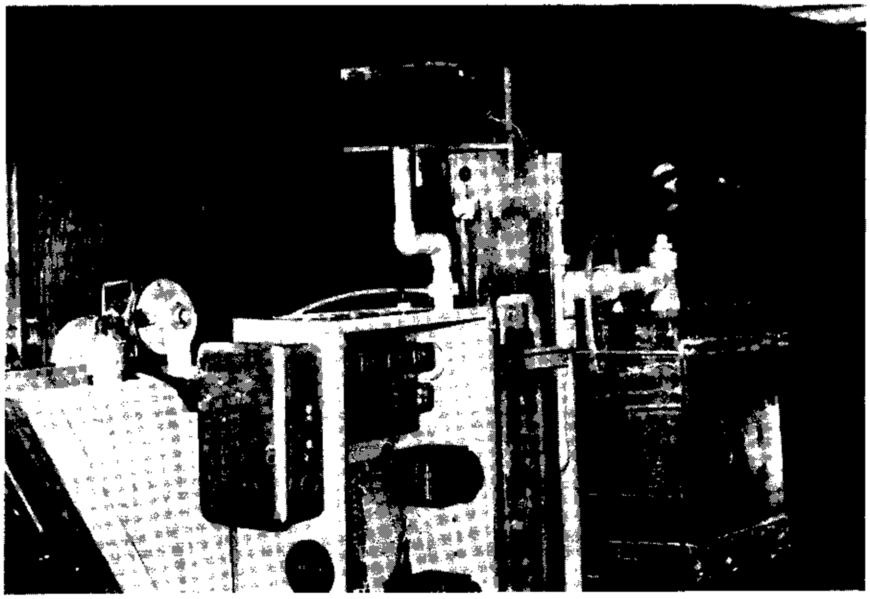

Fig. 5-3. High current density flocculation system with flow divider and modified mixing unit.

Mixing and Floating Floc Separator Unit

The purpose of this unit was to: (1) release the gas bubble attached to floc formed in the flocculator unit, (2) mix the aluminum hydroxide with treated water, and (3) trap all flocs which floated, preventing them from entering the tube settler unit.

Water entered at the top of the unit and dropped onto the floating floc bed. An air check valve at the top of the unit released any gas. Water flowed downward leaving behind any floc which floated to the surface. Water exited at the bottom through a 2.54 cm pipe connected to the tube settler.

The first unit used was a cylinder 15.2 cm in diameter and 45.7 cm long (Figure 5-2). This unit was removed and replaced by a unit 20.3 cm wide, 30.5 cm long, and 35.6 cm deep (Figure 5-3). Inside area under the water level was filled with a vertical tube section constructed from corrugated roofing. The tubes were designed to prevent short circuiting the water flow inside the unit. The bottom was sloped 45° from all sides toward the center to which a 2.54 cm pipe was attached.

Incline Tube Settler Unit

The incline tube settler, containing two stages, was constructed with 0.476 cm (3/16 in) fiberglass with seams braced by aluminum angles (Figures 5-2 and 5-3). Tubes which filled each section were constructed from corrugated fiberglass roofing described in Chapter III. All tubes were inclined 60° from horizontal.

The first stage of the unit was 30.5 cm wide, 29.2 cm deep, and

114.3 cm long, with a total volume of 114 l (30.3 gal). Water from the mixing and floating floc separator unit entered the first stage of the settler below the incline tubes. The first outlet used at the top of this section skimmed water from the water surface. The second outlet removed water from 4 cm below the water surface because of the small amount of floating flocs.

The first and second stages of the tube settler were connected by a 3.8 cm pipe mounted on the outside of the unit. Water removed from the top of the first section entered below the tube in the second stage of the settler. The second stage was 30.5 cm wide, 36.8 cm deep, 114.3 cm long and held 140 l (37 gal) of water. Water was removed at the top by a 7.6 cm diameter circular weir located in the center of the section.

Electro-osmotic Chlorinator

The electro-osmotic chlorinator described in Chapter I was connected to the outlet of the second stage tube settler. The sodium chloride solution was placed on a balance and connected to the bottom of the anode compartment. Used brine solution from the cathode compartment was caught. Between the anode and cathode compartments was a Teflon solenoid valve opening allowing 250 ml used brine solution to drain every 24 hrs during the drain cycle. See Chapter I for complete description.

Power Supplies

Two independently operated Sorenson power supplies (previously described) were used as DC power sources for the flocculator and the chlorinator.

Control System

The electrical control system (Figure 5-4 and Table 5-1) had four functions: starting cycle, draining cycle, shutdown cycle, and safety control. When the system started, the supply pump, flocculation unit, and chlorinator power supply were energized. The chlorinator unit started automatically when the second stage tube settler filled with water.

The drain cycle occurred every 24 hrs or whenever the system was stopped. The drain pump was connected through a check valve to the first tube settler and to the second stage tube settler through a flow control valve and check valve. The first stage tube settler was completely drained; the second stage tube settler was partially drained. The flocculation and mixing section was completely drained when the first tube settler drained. Anode liquid was drained into the cathode compartment of the chlorine cell during the drain cycle.

The shutdown cycle turned off the flocculation unit and chlorination unit and allowed the drain cycle to be completed before de-energizing the system. The safety control turned off the system if the water supply stopped or if the pump failed. Also, the chlorination unit did not operate unless there was flow through it, thus preventing superchlorination of the water.

Water Level Sensors and Pressure Sensors

A water level sensor was located in both stages of the tube settler. Two Dwyer Instruments, Inc. Model 1823 low differential pressure switches with an operating pressure range from 1.27 cm to

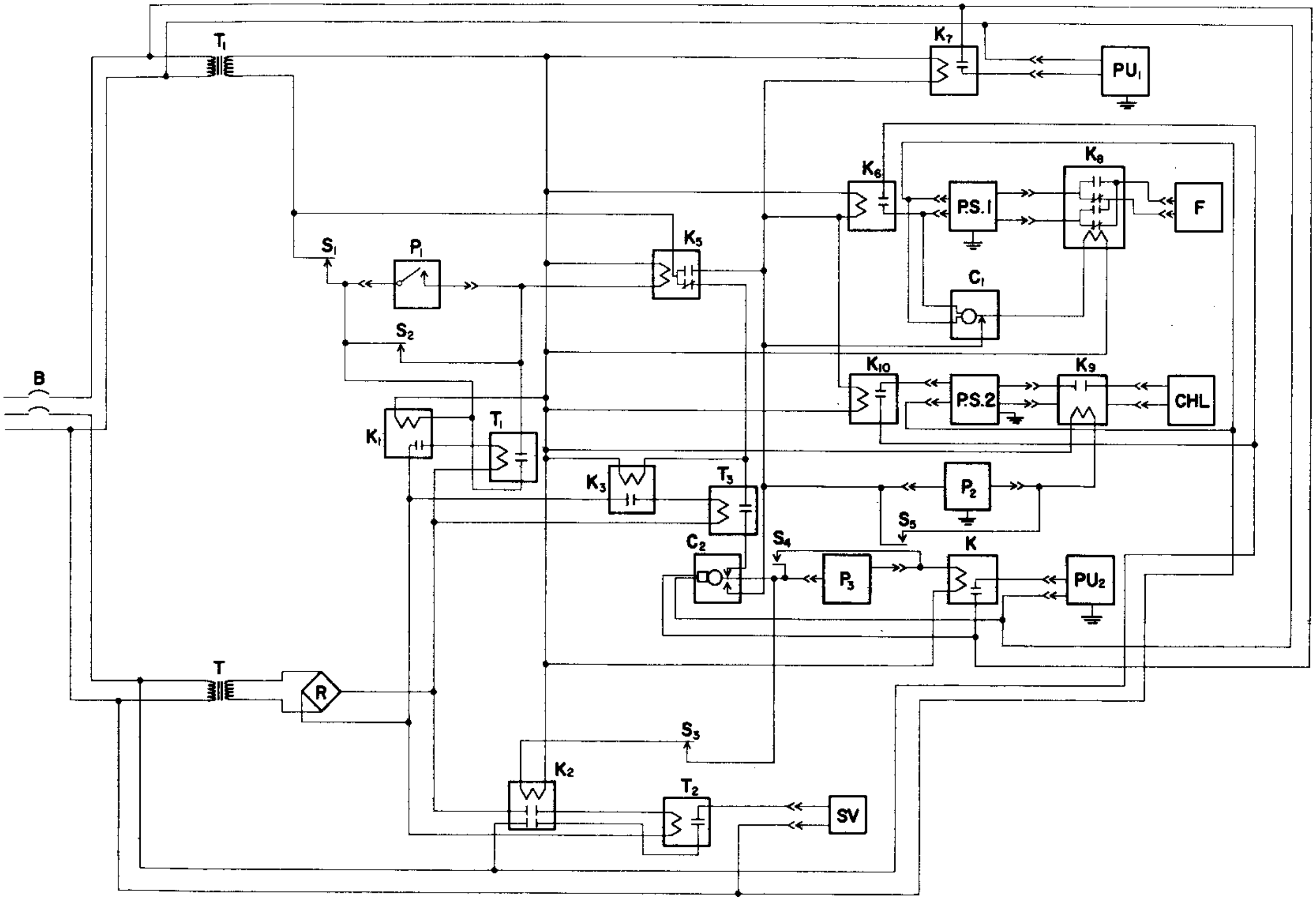

Fig. 5-4. Electrical control circuit of the test system. (See Table 5-1 for meaning of symbols.)

TABLE 5-1. Control circuit components.

B - - - Circuit breaker 15 amp

T_1 - - - Transformer (110AC-24 AC, 8 amps)

T_2 - - - Transformer (110 AC-24 AC, 4 amps)

R - - - Full wave rectifier (5 amps 50 volt)

S_1 - - - System control switch

S_2 - - - Bypass switch (pressure switch)

S_3 - - - Chlorinator solenoid valve bypassswitch

S_4 - - - First settling stage level control bypass switch

S_5 - - - Second settling stage level control bypass switch

K_1 - - - Relay for pressure switch time delay relay (24 volt, 10 amps, SPST, N.O.)

K_2 - - - Relay for chlorinator's time delay relay solenoid valve (24 volt, 10 amps, SPST, N.O.)

K_3 - - - Relay for system off cycle time delay relay (24 volt, 10 amps, SPST, N.O.)

K_5 - - - Relay for system off and on cycle (24 volt, 10 amps, SPDT)

K_6 - - - Flocculator power supply relay (24 volt, 10 amps, SPST, N.O.)

K_7 - - - Supply pump relay (24 volt, 10 amps, SPST, N.O.)

K_8 - - - Flocculator power supply relay (24 volt, 10 amps, DPDT)

K_9 - - - Chlorinator control relay (24 volt, 10 amps, SPST, N.O.)

K_{10} - - - Chlorinator power supply relay (24 volt, SPST, N.O.)

K_{11} - - - Drain pump control relay (24 volt, SPST, N.O.)

T_1 - - - Pressure switch time delay relay

T_2 - - - Chlorinator solenoid valve time delay relay

T_3 - - - System off cycle time delay relay

P_1 - - - System water supply pressure switch

P_2 - - - Second settling stage level control switch

P_{s1} - - - Flocculator power supply

P_{s2} - - - Chlorinator power supply

PU1 - - - Supply pump (1/3 hp 110 v drip proof)

PU2 - - - Drain pump (1/4 hp 110 v drip proof)

F - - - Flocculator plates

CHL - - - Chlorinator electrodes

SV - - - Solenoid valve (110 volt N.C.)

C1 - - - Cycle timer (30 min cycle)

C2 - - - Cycle timer (24 hr cycle)

5.1 cm (water) were used by connecting a dip tube to the high pressure port. The dip tube in the first stage tube settler extended down to the bottom of the compartment; the one in the second compartment extended to 5.0 cm below the water surface. The normally open electrical terminals were connected to the controls. When the water level of the second stage tube settler dropped, the control system disconnected the chlorinator from the power supply. The drain pump was stopped when the first stage of the tube settler was completely drained by the level control in this section.

A Dwyer Instruments, Inc. Model 1823-80 differential pressure switch with an operating range from 22.86 cm to 215.9 cm (water) was used as a pressure sensitive switch located on the outlet side of the pump. The normally open electrical terminals were connected to the electrical controls. If pressure on the outlet side of the supply pump ever decreased below a set pressure level, the system would be stopped.

Drainage System

Two drains at the bottom of the tube settler stages were connected to the drain pump. Sludge and water left the first stage, passed through a check valve, and went into the intake of a centrifugal pump driven by a 1/4 horsepower motor. Pump capacity was 64.4 l min^{-1} (17 gpm) at 1.83 m (6 ft) of head. The check valve presented the water from the second stage tube settler from draining into the first stage. Water and sludge from the second stage passed through a check valve and a gate valve into the intake line of the drain pump. The gate valve controlled the amount the second stage was drained, and the check valve prevented water from entering the first stage settler.

Water and sludge from the drain pump were carried by a 3.18 cm (1.25 in) diameter pipe to a point 10 cm above the water level in the first stage tube settler. An air check valve was located above the water level on the drain line to prevent siphoning after the drain cycle was completed.

Procedure

Only preliminary testing of the system was accomplished during the 30-day test period. The system was installed in the mobile laboratory described in Chapter III located at Robert's Pond near Bryan, Texas.

The system was tested initially at a flow rate of 1314 ml min^{-1} and current density of 4.0 ma cm^{-2}. The plates were removed every 24 or 48 hrs and examined for scale formation. The tube settlers were examined immediately before draining every 24 hrs for floating flocs and for clarity.

Plate area was decreased and current density increased until the plate remained clean for 24 hrs. Flow rate was increased by increasing pump rpm until the second stage tube settler became turbid and colored. The system then was run for a 10-day period at a flow rate just lower than that where turbidity developed in the second stage tube settler.

The chlorinator was connected to the system after the second stage tube settler. The chlorinator was run for only a short period of time because an air lock problem developed. A water sample of effluent water was taken during the 20-day test immediately before the system was drained. Complete chemical analysis of influent and effluent water was determined.

Discussion of Results

Plates with a total area of 1433 cm^2 were used. These were glued to the plate holders with silicone rubber glue. The glue held the plate for three days of operation before the plate loosened. Epoxy glue proved to be reliable and was used for the remaining test. At a flow rate of 1314 ml min^{-1} flocs which floated to the top of the plates remained there. After 48 hrs a coating of organic material formed on the upper 5 cm of the plates. The plates became loose, and one set blocked flow through them. Once the flow was blocked, the plates immediately formed scale. The next set of plates was glued using epoxy glue; however, the spacing was decreased to 0.2 cm. Spacers were placed above and below the plates forming a channel 0.318 cm wide. These spacers were intended to keep flocs from being trapped above the plates. After only 48 hrs of testing, flow through both sets of plates had stopped because coating at the top of each set had blocked the passages.

In the next test the plates were spaced 0.318 cm apart and a weir type flow divider was placed above them. During the previous tests, once a pair of plates became slightly plugged, scale immediately formed because all water went through the other pair of plates which was open. By forcing half the flow down each set of plates, flocs which tended to become wedged between the plates would be forced out the bottom. After 48 hrs of testing, flocs which had floated to the top of the plates formed a coating along the top 5 cm of the plates and caused flow between the plates to cease.

The next set of plates was 53.8 cm long and 11.8 cm wide having a total area of 1265 cm^2 (632.4 cm^2 per set). The upper 5 cm of the plate was spaced at 0.62 cm; the spacing between the lower portion of the plates was 0.32 cm. This was accomplished by milling 0.32 cm from the upper 5 cm of the plates. The shoulder between the mill portion and lower plate was sloped. Current density of 4.65 ma cm^{-2}, resulting in total current of 2.94 amps, was applied to the two sets of plates connected in series. Flow rate averaged 1600 ml min^{-1} (609 gal day^{-1}); influent water temperature averaged 9°C (48°F). The system was tested for a total of 10 days during which the flow rate was increased to 2200 ml min^{-1}. Above 1700 ml min^{-1} the second stage of the tube settler became turbid. Voltage during this test averaged 66 volts and ranged from 50 to 78 volts. After 10 days the plates were removed and examined. A total of 10 cm on each plate set had formed scale. The majority of scaled area was around the wire connection; the remainder was along the edges.

Chemical analysis of influent and effluent water is shown in Table 5-2. Color, copper, and turbidity of effluent water were completely removed. Carbon dioxide, iron, silica, and nitrate concentrations were reduced significantly. Some reduction occurred in calcium hardness, magnesium hardness, total hardness, and bicarbonates. There was a small increase in total alkalinity, bicarbonate alkalinity,

TABLE 5-2. Chemical analysis of influent and effluent water of the high current density unit at Robert's Pond.

Determination	Untreated ppm	Treated ppm	Amount Increased or Reduced ppm	% Change	
				% Reduced	% Increase
Total Dissolved Solids, @ 105°C	61	60	1	2	-
Phenolphthalein Alkalinity, as $CaCO_3$	0	0	0	-	-
Total Alkalinity, as $CaCO_3$	36	42	6	-	17
Carbonate Alkalinity, as $CaCO_3$	0	0	0	-	-
Bicarbonate Alkalinity, as $CaCO_3$	36	42	6	-	17
Carbonate, as CO_3	0	0	0	-	-
Bicarbonate, as HCO_3	44	51	7	16	-
Hydroxide, as OH	0	0	0	-	-
Carbon Dioxide, as CO_2	6	2	4	67	-
Chloride, as Cl	0	0	0	-	-
Sulfate, as SO_4	0	2	2	-	-
Fluoride, as F	.1	.1	0	-	-
Phosphate, as PO_4	2.1	1.8	.3	-	14
pH (Laboratory)	7.1	7.6	.5	-	7
Total Hardness, as $CaCO_3$	36	30	6	16.7	-
Calcium Hardness, as $CaCO_3$	30	24	6	20	-
Magnesium Hardness, as $CaCO_3$	6	6	0	-	-
Calcium, as Ca	12	9.6	2.4	20	-
Magnesium, as Mg	1.5	1.5	0	-	-
Sodium, as Na	3.5	3.6	.1	-	2.9
Iron, as Fe	4.4	.1	4.3	97.8	-
Manganese, as Mn	0	0	0	-	-
Copper, as Cu	.2	0	.2	100	-
Silica, as SiO_2	8	1	7	87.5	-
Color, Standard Platinum Cobalt Scale	80	0	80	100	-
Turbidity, Jackson Units	60	0	60	100	-
Nitrates, as NO_3	1.77	.44	1.33	75.1	-

phosphates, and pH. Both the low current density floccuation system and the high current density system completely removed iron, color, and turbidity. Silica, carbon dioxide, copper, magnesium hardness, and total hardness were reduced by both systems. The low current density unit was more effective in removal of most of the water's impurities. The pH and phosphate levels of the effluent were increased by both systems at the Pond site.

The electro-osmotic chlorinator was installed after the second stage tube settler and was tested for 120 hrs. Voltage averaged 4.9 volts, ranging from 4.5 to 5.0 volts at a current of 750 ma. Due to air locks which developed, free chlorine concentration was not determined. According to previous testing of the chlorinator, it would be expected that the chlorine rate would be 5.12 mg l^{-1} at a flow rate of 1600 ml min^{-1} (609 gal per day). Air locks in the chlorinator were due to restriction of the small passageways behind the anode compartment. The passageways must be enlarged to prevent the air locks from occurring.

During the entire testing period the flocculator developed foam which flowed over the top of the unit. It is recommended that the top be placed on the flocculator and an outlet in the top be connected to the drainage system of the unit. The foam, as it is formed, then will be forced into the drainage system and will be flushed away every 24 hrs.

Cost Analysis

Cost of the system was estimated to be \$1200 with a 20-year expected life, resulting in a \$60 yr^{-1} depreciation cost. Maintenance cost would be \$40 yr^{-1} for pump and power supply repair. Maintenance and depreciation cost is 0.0119¢ l^{-1} (42.48¢ per 1000 gal) assuming that the system is run at a flow rate of 1600 ml min^{-1} (609 gal day^{-1}) and treats 890,960 l yr^{-1}.

Total power cost required to treat the water was 0.00518¢ l^{-1} (19.61¢ per 1000 gal). Power cost for the flocculator was determined from a potential of 66 volts, current of 2.92 amps, conversion efficiency of 0.8, and power cost of 2¢ per kwhr. Power cost for the flocculator was 0.00501¢ l^{-1} (19.25¢ per 1000 gal). Power cost for the chlorinator was 0.000096¢ l^{-1} (0.36¢ per 1000 gal).

Aluminum cost for treating the Pond water was 0.0072¢ l^{-1} (2.92¢ per 1000 gal). Cost was based on total aluminum dissolution rate of 3.8 mg cm^{-2} hr^{-1}, aluminum cost of \$1.54 Kg^{-1} (70¢ lb^{-1}), and flow rate of 1.600 l min^{-1} (609 gal day^{-1}).

Cost of chloride used in chlorination was 0.000325¢ l^{-1} (1.23¢ per 1000 gal). This was based on chloride consumption of 56.3 gal day^{-1} at a cost of 22.03 Kg^{-1} (NaCl).

Total cost of operation of the system was 0.0245¢ l^{-1} (92.74¢ per 1000 gal). Operating cost, without depreciation, was 0.0132¢ l^{-1} (50.04¢ per 1000 gal). This system was 0.00536¢ l^{-1} (20.3¢ per 1000 gal) less expensive to operate than the low current density system.

Summary

During preliminary testing, the system operated for 10 days with no scale formation on the plates. The automatic control operated the system without failure. The first stage of the tube settler was effective in removing 90 to 95% of flocs; the second stage removed the remainder. There was a small problem in removing floating flocs. Foaming of organic matter in the flocculator caused some problems which easily can be corrected.

The electro-osmotic chlorinator formed air locks in the cooling channels behind the anode which limited the testing of the unit. Aluminum electrodes with greater spacing at the top and current density of 4.65 ma cm^{-2} were successful in preventing scale formation. The unit was able to treat 1600 ml min^{-1} (609 gal day^{-1}) effectively in removing, or significantly reducing, turbidity, color, iron, copper, silica, and nitrates.

Operating cost of the system was 0.0245¢ l^{-1} (92.7¢ per 1000 gal); this was less than for the low current density system. Depreciation cost was 46.1% of operating cost.

The following conclusions can be drawn after testing:

1. Current density must be increased as organic matter increases in order to prevent scaling.
2. The plate should be spaced farther apart at the top of the plates along with narrow channels above and below the plates. Flow must be divided between the sets to prevent one set from plugging and scaling.

3. The high current density flocculation system is easily automated; this is a requirement of small water systems because no scale removal equipment is needed.
4. The system is effective in removing turbidity and color which is a major requirement of a surface treatment system.
5. Iron, nitrate, and copper can be reduced or removed completely by the system. This leads to the possibility of using the system on groundwater problems.
6. Electro-osmotic chlorination should be effective as a disinfection unit.
7. Operating cost of the system is acceptable where no other source of drinking water is available.

SUMMARY

Three electrochemical chlorinators were developed and tested. The main advantage of the low chloride chlorinator was that no additional chemicals were added to the water. However, this system had the highest operating cost and was influenced by water temperature and chloride concentration of the water. The high chloride chlorinator was low in operating cost but required an accurate metering pump for successful operation. The electro-osmotic chlorinator eliminated the need for a meter pump by using electro-osmotic flow through the cation exchange membrane to control brine flow. Operating cost was low, and little maintenance would be needed.

Two electrochemical flocculation units were developed and laboratory and field tested. The first used 1100 aluminum alloy, had current density of 0.185 ma cm^{-2} and polarity reversal period of 12 hrs. Scale formed on the plates flaked off with vibration of the plates. The second flocculation unit used a purer alloy (3002), higher current densities (4.0 to 7.0 ma cm^{-2}), and shorter polarity reversal periods (15 min). This unit prevented scale from forming on the plates because of the cleaning action of hydrogen erosion.

Field testing of the two systems was conducted on College Station tap water and surface pond water. The first system used for final testing consisted of low current density flocculator, low chloride chlorinator, vertical flow mixing tank, and vertical settling tank, later replaced with an incline tube settling unit. The system was

able to remove the majority of suspended materials and also reduce and remove many chemical elements in the water. Chlorine provided an adequate residual in the tap water; however, no residual was present at the pond location because of the absence of chlorides. Scale was the cause of the majority of mechanical problems. Operating cost of the system on College Station tap water and surface pond water was 0.0293¢ l^{-1} (\$1.11 per 1000 gal) and 0.0315¢ l^{-1} (\$1.13 per 1000 gal), respectively.

The final system contained a high current density flocculator, electro-osmotic chlorinator, and incline tube settler. Testing conducted on pond water showed that the system could remove all suspended material and reduce or remove such elements as iron, silica, and copper. The system was completely automated. Operating cost for treating pond water was 0.0245¢ l^{-1} (92.7¢ per 1000 gal). This system, because of its reduced size, lower operating cost, elimination of scale, and ease of automation, would be more applicable for a rural water supply than the first system.

SUGGESTIONS FOR FUTURE RESEARCH

It is suggested that future research should be done on electrochemical chlorination and high current density flocculation in the following areas:

1. *The final system should be evaluated for the removal efficiency of iron, nitrates, and nitrites in water.* The concentration of the influent pond water could be varied by injection of concentrated solutions containing the impurities.
2. *Depending on the result from the impurity removal tests, another site for testing should be selected which is high in these impurities.* The system should be tested at this location for a reasonable period of time in order to properly evaluate it.
3. *The electro-osmotic chlorinator should be placed inside the second stage tube settler.* The surrounding water will properly cool the anode compartment, and all the hazardous external piping handling chlorine gas can be eliminated.
4. *A modified high current density polarity reversal cycle should be tested.* From the results of high current density testing the aluminum use efficiency increases rapidly when the current density is less than that at which scale is prevented. This may be used to increase aluminum use efficiency by using current density less than minimum scale

prevention current density for a majority of the time during the reversal cycle, then increase it to a current density 2 or 3 times the minimum scale prevention current for a short period of time. The higher current density should be applied during the last and the first portions of the polarity reversal cycle. This may increase aluminum use efficiency without scaling the plates. Effects of temperature and current densities should be determined so that a system could be designed using this method of scale prevention. It is expected that the method will result in saving of power and aluminum cost.

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