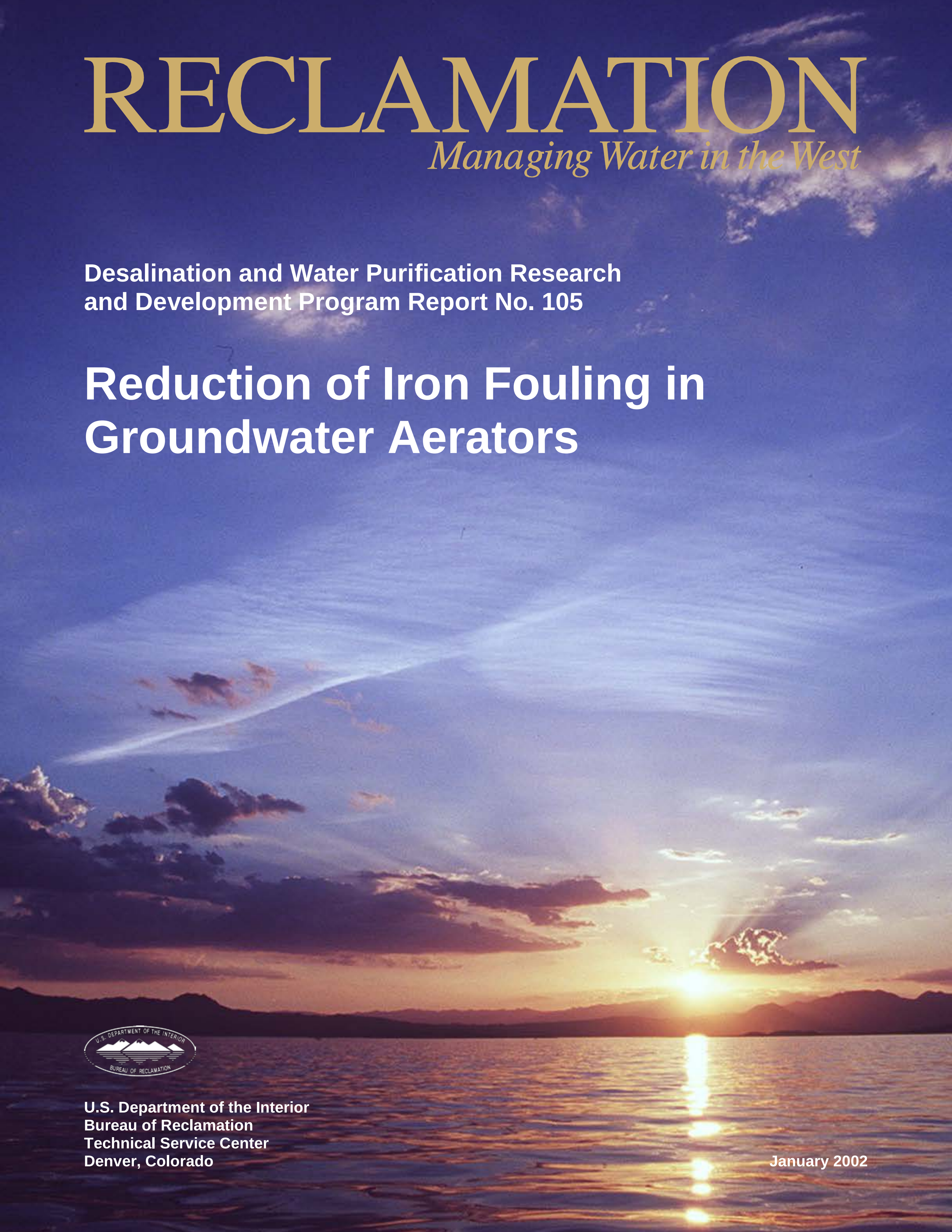

RECLAMATION

Managing Water in the West

Desalination and Water Purification Research
and Development Program Report No. 105

Reduction of Iron Fouling in Groundwater Aerators

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

January 2002

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14. ABSTRACT
In order to reduce the severity of iron buildup within the aerator of a working treatment plant that supplies water from a ground water source, a pilot aerator including a number of parallel cells was set up to test several operating conditions. Iron in the water can precipitate through oxidation during aeration. The pilot aerator consisted of cells that were operated under nine different aeration conditions, with cells containing various packings. Chemical additions included sodium silicate and shock chlorination. During operation of the pilot aerator, measurements were made of water temperature, air temperature, influent flow rate, pH, alkalinity, CO_2, ferric iron, total iron, and dissolved oxygen. Packing was periodically removed to measure buildup of scale. All test cells provided similar CO_2 removal. The greatest reduction of iron buildup on the packing was achieved through the shock chlorination process, closely followed by the sodium silicate addition process. The most severe iron buildup occurred in cells operated under conditions similar to current plant practices. Lime dosage rates practiced by the plant were compared to the theoretical amount required for softening. This evaluation was studied to determine if increased CO_2 removal through aeration would result in the desired economic benefit of reduced lime usage. Plant operations respond to changes in required lime doses, so it is beneficial to increase CO_2 removal in the aeration process.

15. SUBJECT TERMS
Aeration, Iron Fouling, CO_2 Reduction

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Desalination and Water Purification Research and Development Program Report No. 105

Reduction of Iron Fouling in Groundwater Aerators

Prepared for the Bureau of Reclamation under Agreement No. 1425-97-FC-81-30006

by

Eric DeGruson
University of Missouri
Columbia, Missouri

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

January 2002

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ACRONYMS AND ABBREVIATIONS

CWTP	Columbia Water Treatment Plant, Columbia, MO
DI	deionized
DO	dissolved oxygen
ft	foot
ft^3	cubic foot
gal	gallon
gpm	gallons per minute
in or ”	inch
in^3	cubic inch
lbs	pounds
MGD	million gallons per day
min	minute
PVC	polyvinyl chloride
psi	pounds per square inch

METRIC CONVERSIONS

The metric equivalents for non-metric units used in the text are as follows:

Unit	Metric equivalent
1 cubic foot	28.3 liters
1 foot	0.3048 meters
1 gallon	3.785 liters
1 gallon per minute	3.785 liters per minute
1 inch	2.54 centimeters
1 million gallons per day	3,785 cubic meters per day
1 pound	0.454 kilograms
1 pound per square inch	6.895 kilopascals
1 square foot	0.093 square meters
1 ton	907 kilograms

EXECUTIVE SUMMARY

The Columbia Water Treatment Plant (CWTP) supplies water from a ground-water source. The first step in its treatment process is aeration. As is the case with many ground-water sources, iron in the water is precipitated out through oxidation during aeration. This precipitated iron poses a problem in the aeration chambers when it builds up and clogs the packing within these units.

In order to reduce the severity of iron buildup within the aerator, a pilot aerator was set up to test several operating conditions. The pilot aerator consisted of eight cells, which were operated under nine different aeration conditions. Cell 1 operated with 2” Tonka packing (twice the diameter of the existing packing), which provided less surface area per unit volume. Cell 2 was initially left empty and run without packing to evaluate the effectiveness of packing for increased CO_2 removal. This cell was also operated with new 1” Tonka packing to compare the effectiveness of new packing to reused packing. Cell 3 was run with a solid (low efficiency) packing. This cell was operated see if the CO_2 removal was enhanced by the Tonka packing with a greater surface area. Cell 4 was operated with 1” reused Tonka packing and a sodium silicate addition. The sodium silicate was added to inhibit the iron oxidation/precipitation process. Cells 5 and 6 were set up to model the existing CWTP aeration conditions. These cells were used to evaluate how well the pilot replicated the full-scale aerator and also served as a check on one another to see if results between cells were reproducible. In the latter part of the experiment, Cell 6 packing was replaced with triangular packing. This packing was used simply to evaluate how effective it was at CO_2 removal and the rate at which iron built up on it. Cell 7 consisted of 1” reused Tonka packing and was operated at half the standard flow rate. The lower flow rate was used to decrease the amount of iron available to precipitate out within the cell. Finally, Cell 8 was operated with 1” reused Tonka packing and daily shock chlorination. The shock chlorination was used to kill bacteria on the packing that served to enhance oxidation and iron buildup.

Throughout the operation of the pilot aerator, measurements were made of water temperature, air temperature, influent flow rate, pH, alkalinity, CO_2, Fe II, total Fe, and dissolved oxygen. Additionally, packing was periodically removed to calculate the scale buildup. The data collected showed that all cells performed at similar CO_2 removal levels. Iron buildup on the packing was reduced the most by the shock chlorination process, closely followed by the sodium silicate addition process. The greatest iron buildup occurred in Cells 5 and 6, which were operated under current CWTP aeration practices.

Finally, the lime dosage rates in use by the CWTP were compared to the theoretical amount required for softening, to determine if increased CO_2 removal through aeration would result in the desired economic benefit of reduced lime usage. Results indicated that CWTP operations do indeed respond to changes in required lime doses and therefore it is worthwhile to attempt to improve on CO_2 removal in the aeration process.

Section 1. Introduction

The following report presents and evaluates the operation of a pilot aerator test at the Columbia, Missouri, Water Treatment Plant (CWTP). The goal of the aeration analysis is to find the optimal operating conditions for CWTP aeration process, considering CO_2 removal and iron fouling problems. Ideally, the aerator will perform at a high CO_2 removal efficiency and a low iron removal condition. These criteria will allow the CWTP to perform aeration in a manner that reduces the cost of lime addition and reduces aerator maintenance.

The report begins with information concerning past CWTP aeration performance to provide a background to compare pilot data against. Following this section the pilot aerator setup is described briefly. A third section outlines the tests used to gather data from the pilot aerator. Following sections report pilot test data with evaluation and discussion of the results. These sections include influent conditions and individual cell performance. A final section then reviews the results and presents recommendations.

Section 2. Present Columbia Water Treatment Plant Aeration

Currently, the CWTP performs aeration as the first step in the water treatment process. Aeration is achieved through the use of two large chambers filled with polypropylene 1” Tonka packing (from Tonka Water, Plymouth, MN). Water is distributed through these chambers by spray nozzles. The use of 1” Tonka packing in these chambers was established in 1995. Past research determined these units are capable of performing at a 75 percent CO_2 removal average under CWTP operating conditions (Konavec, 1998). However, due to iron fouling in these units (causing portions of the aerator packing to become clogged with iron) a CO_2 removal average of 50 to 60 percent is a more common operating status.

Figure 1 shows a plot of the CO_2 removal for the CWTP aerators between the dates of January 1, 1997, and October 31, 1999. Based on the data presented there, an average of 52.5 percent CO_2 removal with a standard deviation of 9.4 was attained over the operation period presented in the graph. Inlet water had an average pH of 7.12. As seen in Figure 1, even this substandard removal efficiency is gradually decreasing with time. This decrease, as previously stated, can be largely attributed to iron fouling of the units.

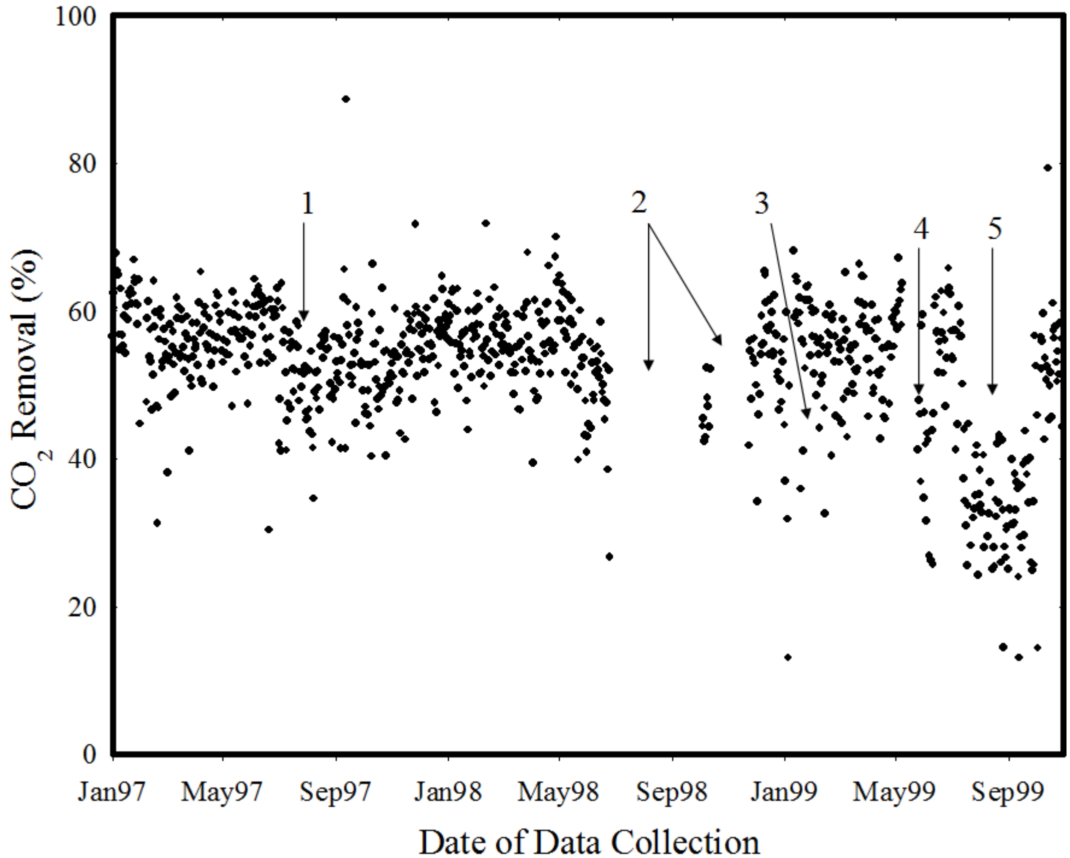

Figure 1. Historical CO_2 removal for CWTP aerators.
Source: Data collected from CWTP daily log records.

Similarly, the total iron removal within the aerator has decreased with increasing time. The reason for this decrease in total iron removal is also due to the buildup of iron on the packing. In other words, space was not available for water and air to properly flow throughout the aerator; therefore the amount of air contacting the influent water decreased. In turn, the amount of iron precipitated within the aeration unit also decreased, increasing effluent iron concentrations. Additionally, the adhesion of the iron scale to the packing can only be maintained up to a certain capacity. Once this capacity has been exceeded, the iron scale will fall off the packing and a portion of this will be available to leave with the effluent. The portion leaving with the effluent increases the effluent total iron concentration, and the removal is decreased. Figure 2 illustrates this decreasing iron removal trend. The average influent total iron concentration, for the time period presented in Figure 2, is 5.86 mg/L. The average total iron removal over the time period plotted was 14.5 percent with a standard deviation of 7.7 percent.

No data exists for the 3-month period from July to September of 1998 because the plant aerators were not in operation during this period. The aerators were shut down for cleaning. Iron fouling had developed to the degree that the operation was significantly impaired, and therefore they were shut down to remove the packing and clean the iron from it. There were a few other short periods during which the aerators were valved out or partially valved out for various reasons during the span of time presented. Table 1 presents a timeline of the operation of the aerators with a brief description of the reason they were valved out for the corresponding time period. The number in parentheses ahead of each date corresponds to the numbers in Figure 1.

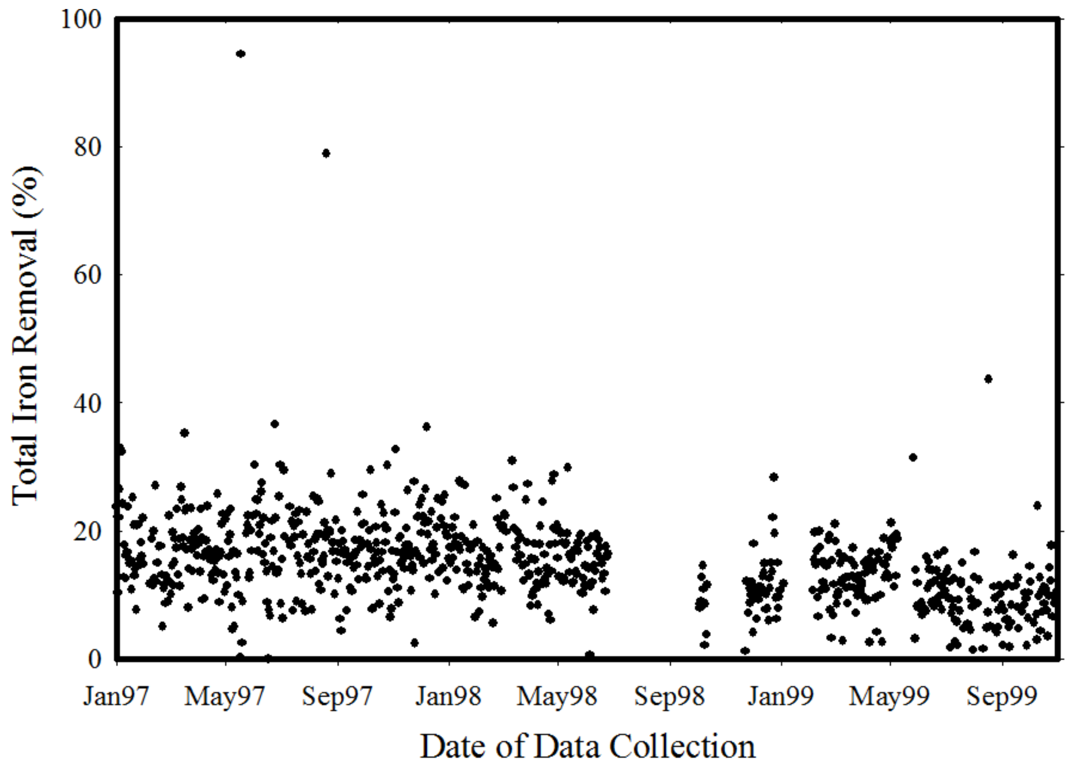

Figure 2. Historical iron removal for aerators.
Source: Data collected from CWTP daily log records.

Table 1. CWTP Aerators Operation History

Time Period Valved Out	Reason for Change in CO_2 Removal Data
(1) June 25 – August 9, 1997	Aerators valved out or partially valved out due to high influent flow rates.
(2) June 24–October 1 1998 & October 12–November 23, 1998	Aerators valved out and packing removed for cleaning due to iron fouling.
(3) January 6–February 7, 1999	Aerators valved out or partially valved out due to high influent flow rates.
(4) May 10–26,1999	Aerators valved out or partially valved out due to high influent flow rates.
(5) Summer 1999 (@ 1 July to 30 September)	Increase of average influent flow rate from 12.5 MGD to 16 MGD

The decreasing CO_2 and iron removal trends can be seen a little more clearly in Figure 3, which plots the average monthly removals for CO_2 and iron for the same time period as the two previously presented historical CWTP data graphs (Figures 1 and 2).

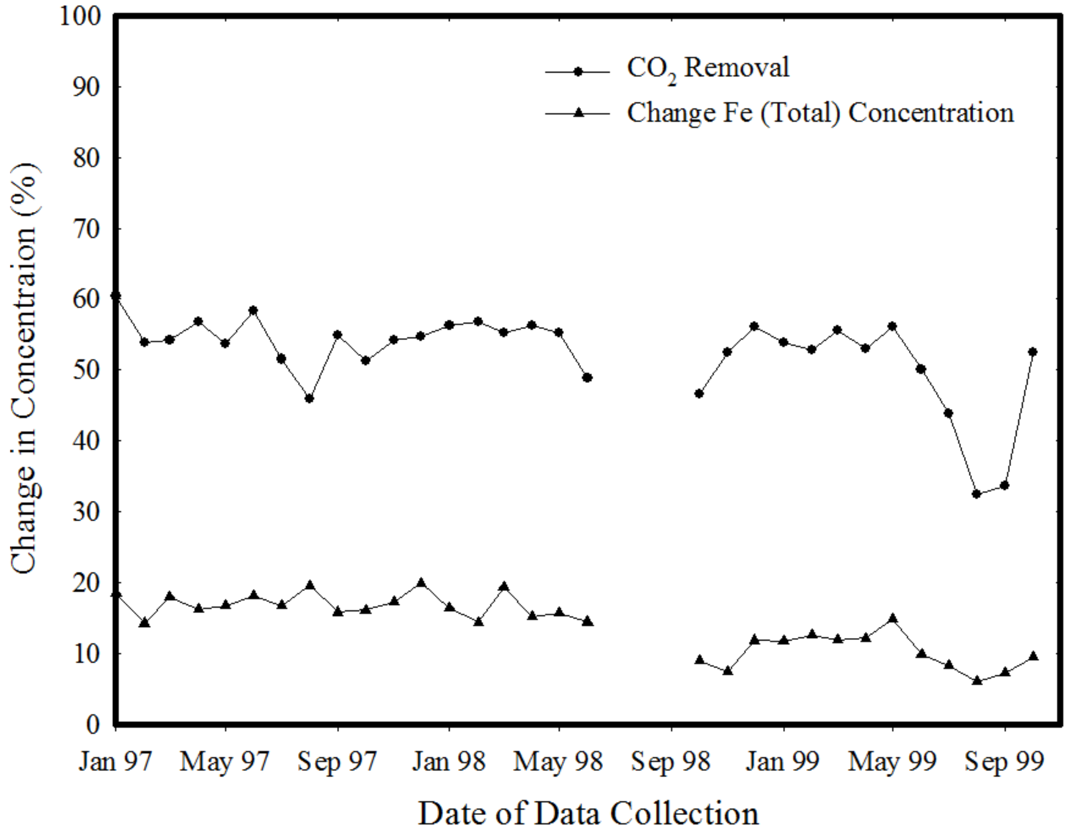

Figure 3. Historical average monthly CO_2 and iron removal for CWTP aerators.
Source: Data collected from CWTP daily log records.

SECTION 3. THE PILOT AERATOR

3.1 Pilot Aerator Setup

Figure 4 provides a simple diagram of the pilot aerator used is this study. Additional descriptive information follows. A more detailed analysis of the development of the pilot aerator setup can be found in Hanke (1999).

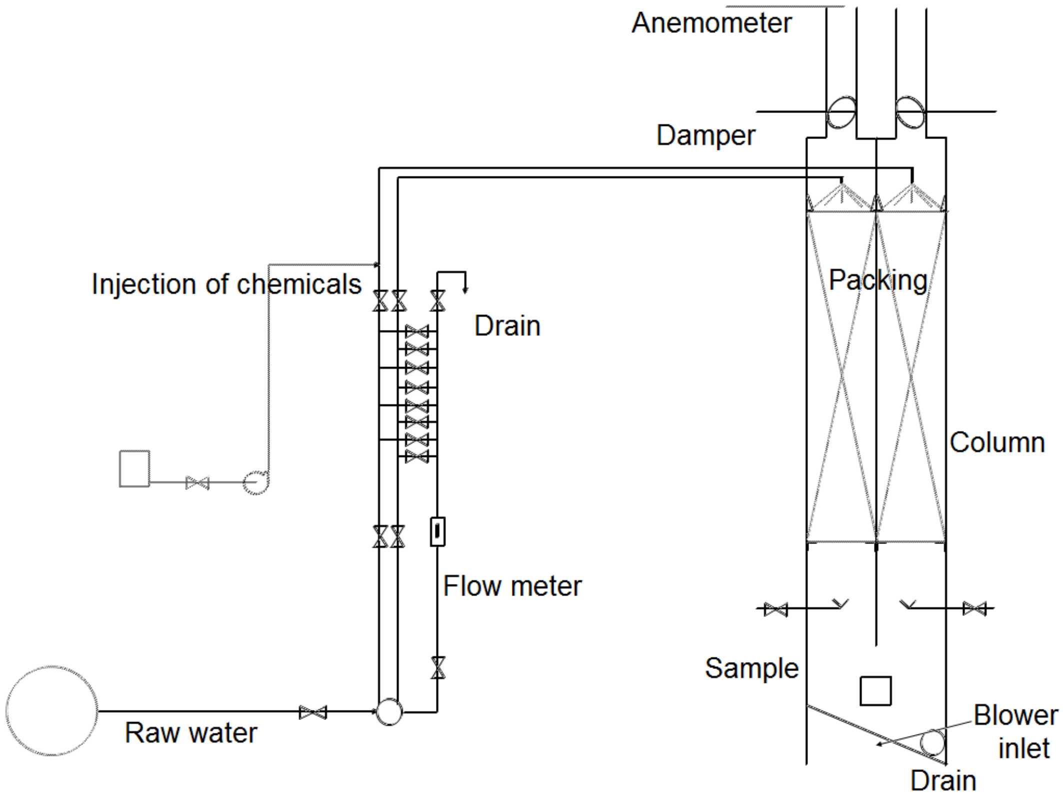

Figure 4. Pilot aerator setup.

3.1.1 Inlet Connection

The raw water main was connected to the system through a 4” polyvinyl chloride (PVC) line. A gate valve was installed directly beyond the main tap to allow for pressure changes, which were monitored downstream with a pressure gauge. The supply line fed a header near the pilot aerator where eight 1½” lines split the flow to each test cell. Contained within the 1½” PVC pipelines were removable sections in which a flowmeter could be inserted for flow measurement during the course of the aerator operation. These removable sections were valved above and below, and connected with unions. A gate valve was placed directly above the top ball valve of the removable section to allow for regulation of the flow to each cell.

3.1.2 Outlet Setup

The base of the pilot aerator was made of plywood and coated to help protect the wood against the extreme moisture conditions during its operation. Within the plywood base were three drains to collect the aerated water. These 4” PVC drains fed into 4“ PVC pipes that extended to just above the ground. The downspouts were then connected to a 6” PVC line that directed the aerated water into the lime flocculation basin.

Additional drain channels (made from halved 6” PVC pipe sections) were placed just below the sampling taps to collect excess water. These drain channels fed directly into the pipe that emptied into the lime flocculation basin.

3.1.3 Blower Installation

The blower was installed on a shelf approximately 1 foot above the pilot aerator unit and connected to the pilot aerator base with flexible ductwork. Exhaust vents with dampers were installed in the top of the pilot aerator to allow for airflow adjustment. Airflow adjustment was accomplished by reorienting the dampers while monitoring the exit velocity with an anemometer.

3.1.4 Calibration of Chemical Feed Pumps

The pumps’ flow rates were calibrated by timing the fill of a specific volume. The pumps were adjusted until the desired volume was achieved in 1 minute of fill time. The flow rates achieved were 130 mL/min for the chlorine addition and 1.3 mL/min for the sodium silicate addition.

3.2 Test Cell Conditions

Table 2 provides a brief overview of the conditions for each of the eight pilot aerator cells along with the dates of their operation.

Table 2. Aerator Cell Condition and Operational Time Line

Cell	Start Date	End Date	Duration (Days)	Packing Type	Operating Condition
1	16 July	17 Nov.	119	2” Tonka Packing	New, standard flow rate
2	2 July	14 July	13	Empty	Standard flow rate
	16 July	17 Nov.	119	1” Tonka Packing	New, standard flow rate
3	29 June	17 Nov.	136	1” Solid Packing	New, standard flow rate
4	29 June	17 Nov.	136	1” Tonka Packing	Reused, standard flow rate, sodium silicate added
5	14 July	17 Nov.	121	1” Tonka Packing	Reused, standard flow rate
6	29 June	7 Oct.	101	1’ Tonka Packing	Reused, standard flow rate
	7 Oct.	17 Nov.	36	Triangular Packing	New, standard flow rate
7	30 June	17 Nov.	135	1” Tonka Packing	Reused, low flow rate
8	29 June	17 Nov.	136	1” Tonka Packing	Reused, standard flow rate, shock chlorination

Figure 5, a plan view of the pilot aerator setup, is provided below to allow for a perspective of each cell’s position relative to the other cells and CWPT equipment.

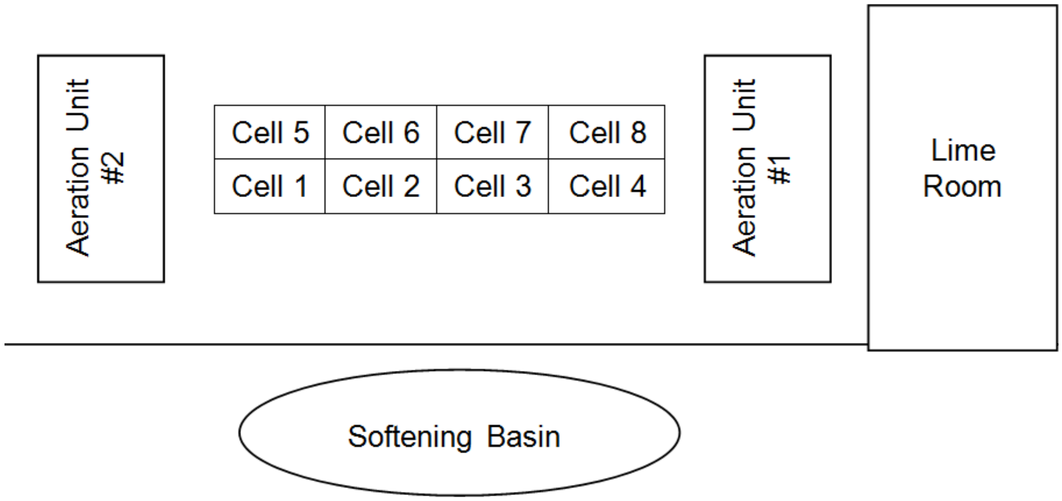

Figure 5. Plan view of pilot aerator setup.

SECTION 4. MATERIALS AND METHODS

4.0 Overview

Over the span of pilot aerator operation the following types of data were gathered under raw, influent and aerated effluent conditions: pH, alkalinity, CO_2 concentrations, Fe II concentrations, total Fe concentrations, dissolved oxygen content, and water temperature. Additionally, air temperature, air/water flow rate, and pressure were measured. The previously listed water qualities were usually measured three times weekly. The buildup of iron on the packing, in terms of mass of buildup per unit length of column (grams per minute), was also measured four times over the life of the project.

4.1 Analytical Techniques

Table 3 provides an overview of the testing techniques used in the gathering of data for the pilot aerator. The next section gives more detailed descriptions of these methods.

4.2 Testing Procedures

4.2.1 Influent Flow Rate

The flow rate was periodically measured by inserting a flow meter section in the 1½" PVC influent pipe run. This was accomplished by valving out the pilot aerator, removing the detachable section of influent piping and inserting the flow meter (previously discussed in the set-up section of this report), returning the flow to the aerator, and reading the flow meter measurement.

Table 3. Testing Techniques

Property	Method of Determination
Water Temperature	Orion Model 23A pH meter with Triode electrode
Air Temperature	Thermo-anemometer model 407112
Air Flow Rate	Thermo-anemometer model 407112
Influent Water Flow Rate	Great Plains Ind. Flow Meter Model A108GMA100NA1
Influent Pressure	Ashcroft 0–15 psi, Model 10681-01P
pH	Orion Model 23A pH meter with triode electrode
Alkalinity	Standard Methods 2320, APHA 1994
CO_2	Calculation based on pH, alkalinity, water temp., & TDS
Fe II	Hach DR13000 spectrophotometer, program 93
Total Fe	Hach DR13000 spectrophotometer, program 26
DO	YSI Model 58 dissolved oxygen meter

4.2.2 Influent Pressure

Influent pressure was measured with a pressure gauge, which was a part of the inflow piping network. The location of this pressure gauge is discussed in the setup section of this report (section 3.1.1). The inlet pressure was adjusted by monitoring the pressure gauge while adjusting the preceding gate valve.

4.2.3 pH

An Orion Model 23A pH meter with a triode electrode was used to measure pH values. Prior to each run of tests, the meter was calibrated with a 2-point calibration using pH 7 and pH 10 buffer solutions from Fisher Scientific. The typical slope was 99.7. The pH was measured in automatic temperature compensation mode.

The pH of each sample was measured outside at the aerator. This was accomplished by allowing the sample cup to overflow with sample water and then placing the electrode into the sample cup while the water remained running.

4.2.4 Alkalinity

Alkalinity was measured using the CWTP's standard operating technique (Standard Methods 2320, APHA 1994). First, three or four drops of bromcresol green-methyl red indicator solution (Hach Company, Loveland, CO) were added to 50 ml of water sample. The indicator solution turned the water to a greenish-blue color. The sample was then stirred and simultaneously titrated with 0.01*M* H_2SO_4 to an endpoint of pH 4.5. This was achieved by adding the acid slowly until a dark pink color appeared. The alkalinity in units of mg-$CaCO_3$/L was calculated by multiplying the milliliters of acid used for titration by a factor of 20.

4.2.5 CO_2

CO_2 concentrations for the influent and effluent were calculated based the measured alkalinity, pH, and temperature. A total dissolved solids value of 589 mg/L was assumed. This value is based on past raw water data. Additionally, a temperature of 14.7 °C was assumed for the influent water. An example of the spreadsheet used in these calculations can be found in the appendix of this report. The spreadsheet was developed by Katja Konavec (Konavec 1998).

4.2.6 Iron

A Hach DR1300 spectrophotometer was used to measure total and ferrous iron after reaction with Hach reagents. Samples were first diluted (1:4) with deionized (DI) water because the method cannot accurately measure concentrations above 3 mg/L.

To measure ferrous iron the Hach ferrous iron AccuVac ampules were used. First, a container was filled with 200 mL of DI water, and taken outside to the pilot aerator. Next, a sample cup was allowed to overflow with sample water. At that time, a syringe was placed into the cup and 50 mL was drawn up. Immediately, the 50 mL was added to the DI water, and the tip of the ampule was broken off against the wall of the container. The vacuum inside the ampule allowed it to fill with the sample water. The AccuVac ampule was inverted several times and wiped clean of any water and fingerprints. A reaction time of 3 minutes was needed.

A stored program, 93, was used, which selected a wavelength of 510 nm. Then the buttons CLEAR, ZERO, CONC were pressed to zero the machine. After the 3 reaction minutes, the ampule was placed into the spectrophotometer. The concentration reported was multiplied by a factor of 5 to correct for the dilution ratio of 1:4.

The reagent used for the measurement of total iron was the FerroVer Iron Reagent. First, the stored program 26 was entered into the spectrophotometer. Then, it was zeroed in the same manner as described above in the Fe II measurement procedure. Next, 5 mL of the sample water was measured out and placed into a 25-mL vial. DI water was then added to the 25-mL mark on the vial. One scoop of the reagent was added to the DI water. The vial was then inverted several times and let stand for a reaction time of 3 minutes. After the 3-minute period, the vial was placed into the spectrophotometer. Again, the displayed concentration was multiplied by the factor of 5 for the 1:4 dilution factor.

4.2.7 Dissolved Oxygen (DO)

The dissolved oxygen of each cell effluent was measured using a YSI Model 58 dissolved oxygen meter. It was calibrated by saturating deionized water with oxygen via shaking. The temperature was measured and the corresponding saturation concentration was determined. Then, the meter and probe were taken outside. The sample cup was allowed to overflow and the DO probe was placed in the sample cup. The stable DO was measured and recorded.

4.2.8 Iron Scale Accumulation

Periodically, over the running phase for the pilot aerator, water to the system was shut off and three pieces of packing were taken out from the top, middle, and bottom sections of each of the cells. (Only one piece of packing was taken from each of these levels in the 2" packing cell due to the lower quantity of packing in the cell). The packing was collected in disposable aluminum pans that, prior to the collection, were weighed on an analytical scale. The packing was allowed to air dry for at least a week and a half, then was placed in a 105 °C oven for about 30 minutes. After they were taken out of the oven, the pans were weighed again. Finally, the scale was removed from the packing into the pan using a bottlebrush. The scale was collected into a beaker that had been previously weighed. The beaker with the scale was weighed. The weight of the scale was found by subtracting the weight of the beaker and scale from the weight of the beaker.

4.2.9 Water Temperature

The pH meter described above was used to measure the temperature of the water during measurement of pH from the water samples. The sampling probe was equipped with a temperature sensor.

4.2.10 Air Temperature & Air Flow Rate

The air temperature and airflow rate were measured using a thermo-anemometer. The thermo-anemometer was placed under one of the vents of the aerator. The temperature was read off of the screen of the instrument and recorded.

SECTION 5. INFLUENT OPERATING CONDITION

The following section provides information concerning the properties of the raw water entering the water plant and moving directly into the aeration units during the pilot aerator operation period. Graphs of the influent CO_2 concentration, pH, and iron content are presented.

As seen in Figure 6, the water being pumped into the aerator developed an increasing CO_2 trend over the course of the pilot aeration operation. Over the same period the pH of the entering water remained fairly constant, with an average of 7.11 and standard deviation of 0.125. The average influent CO_2 value was 50.7 mg CO_2/L with a standard deviation of 13.9. Influent Fe II concentration shown in Figure 7 began at a relatively low level of 3.13 mg/L but quickly increased to a level of approximately 6.5 mg/L, where it remained reasonably constant for the remainder of the pilot aerator study. The first two points of data collection for influent Fe II were thought to be erroneous and therefore were excluded from these averages.

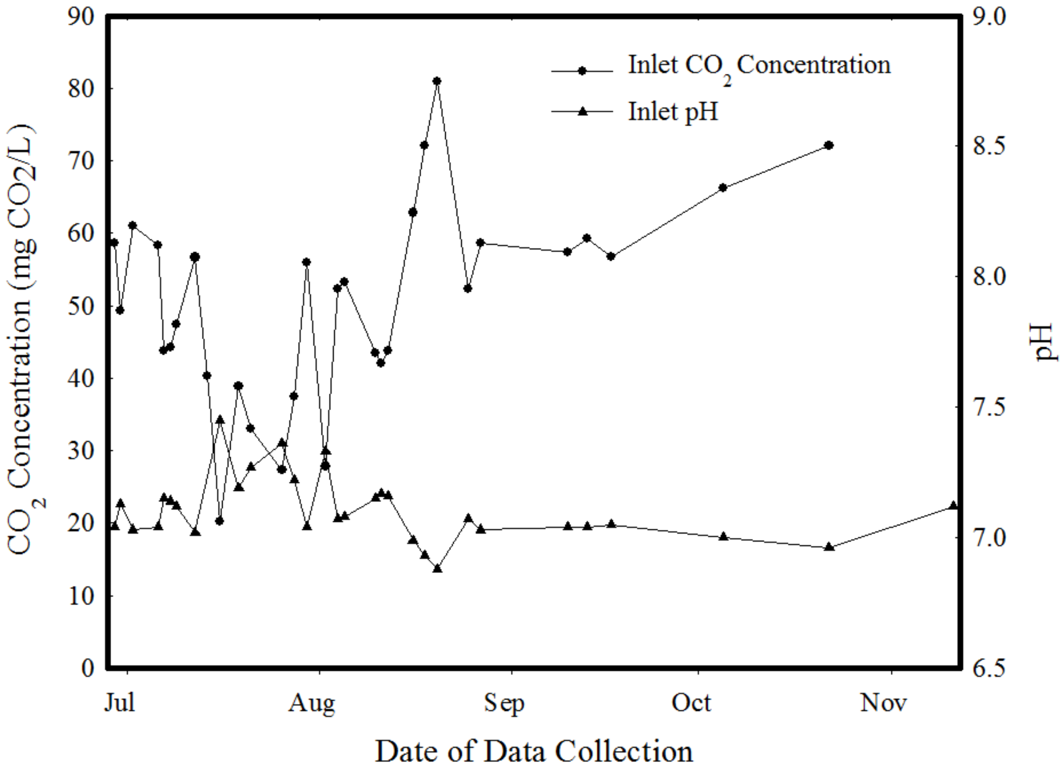

Figure 6. Influent pH and CO_2 concentrations.

Total iron levels were more erratic, starting at level of 6.37 mg/L, dropping slightly below 6 mg/L, then rising back close to the original concentration and leveling off. These results show that most of the iron entering the aerators is ferrous iron.

Initial water pressure and flow rates are provided in Figure 8. Flow rates were maintained consistent with the plant operating conditions, scaled down for the pilot aeration unit. Cell 7 was operated at half the flow rate of the other cells. Similarly, pressure fluctuated with the variation of the influent flow rates and pressure to the CWTP.

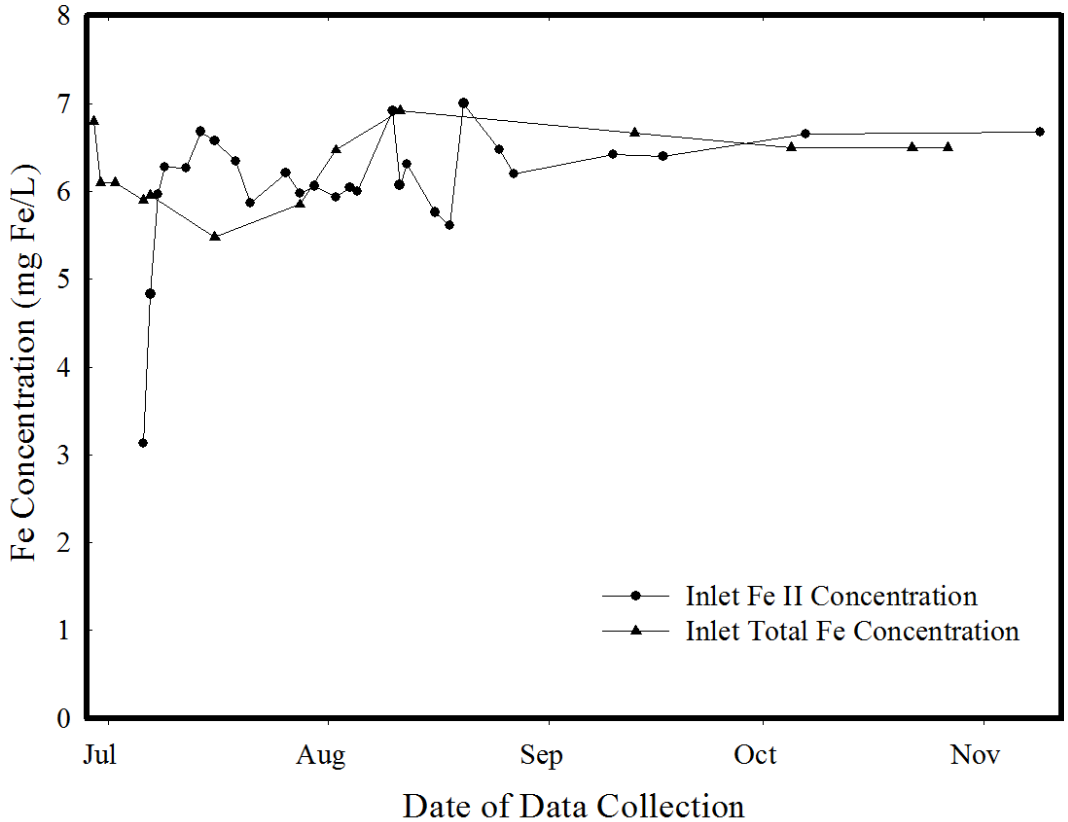

Figure 7. Influent Fe II and Fe (total) concentrations.

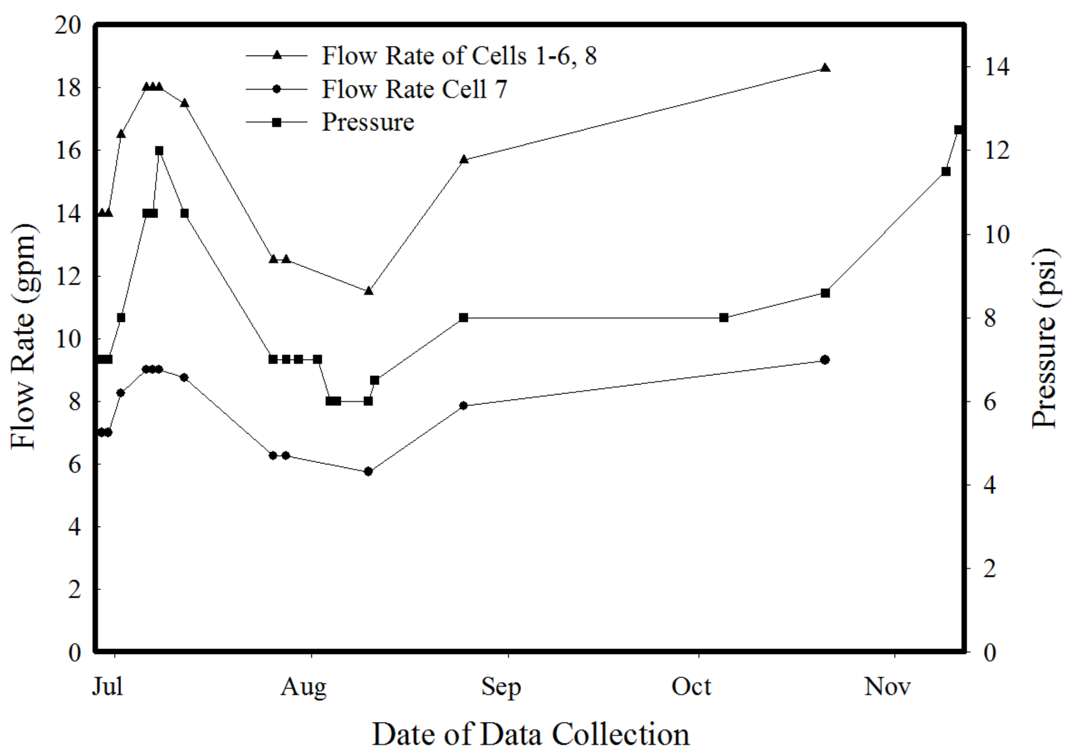

Figure 8. Influent flow rate and pressure conditions.

SECTION 6. RESULTS AND DISCUSSION

6.1 Cell 2 No Packing (Empty)

Before Cell 2 was filled with Tonka packing, the unit was operated with this cell empty. The results of the empty Cell 2 operation, shown in Figure 9, serve as a basis of comparison for the effectiveness of the use of packing to enhance the aeration process. The empty cell was run at the standard flow rate.

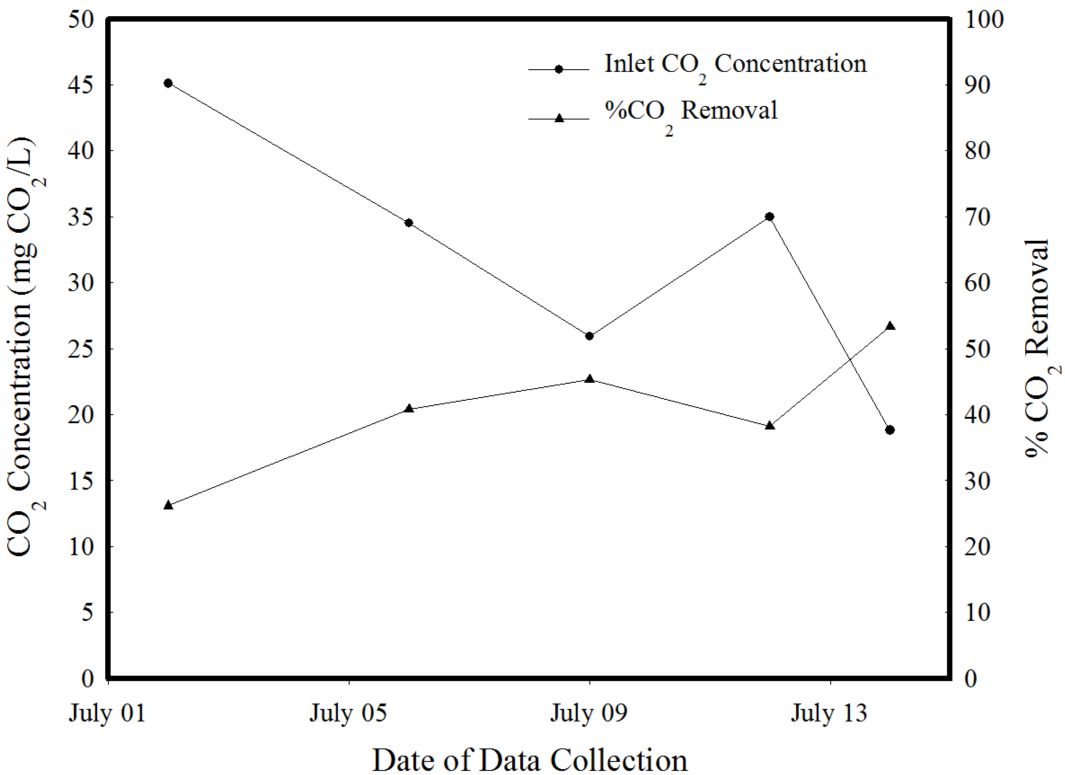

Figure 9. Cell 2 (empty) CO_2 removal. (See Appendix table C for data.)

CO_2 removal in the empty cell generally increases over the observed period, while the effluent CO_2 concentration decreases. The data for this aeration setup was gathered over a short period of time. Therefore, the long-term implications of aerating without packing cannot be deduced from this pilot aerator test. However, past operation of the aerator nozzles without trays or packing exhibited a CO_2 removal of approximately 60 percent (Konavec, 1998). The data collected for this project produced an average CO_2 removal of 41 percent, with removal ranging from 26 to 53 percent.

Changes in iron concentrations recorded for the operation of an empty aeration cell do not appear to follow any obvious trend (Figure 10). A longer testing term would be needed before a relationship for changes in iron concentration over time could be determined. The average of the few data points collected was a change in concentration of 20.8 percent for Fe II and 5.2 percent for total iron removal. These results seem reasonable. Without packing present, there is little surface area on which iron could be deposited; therefore, there is little change in total iron concentration. The change in Fe II concentrations can be attributed to the oxidation of Fe II to Fe III.

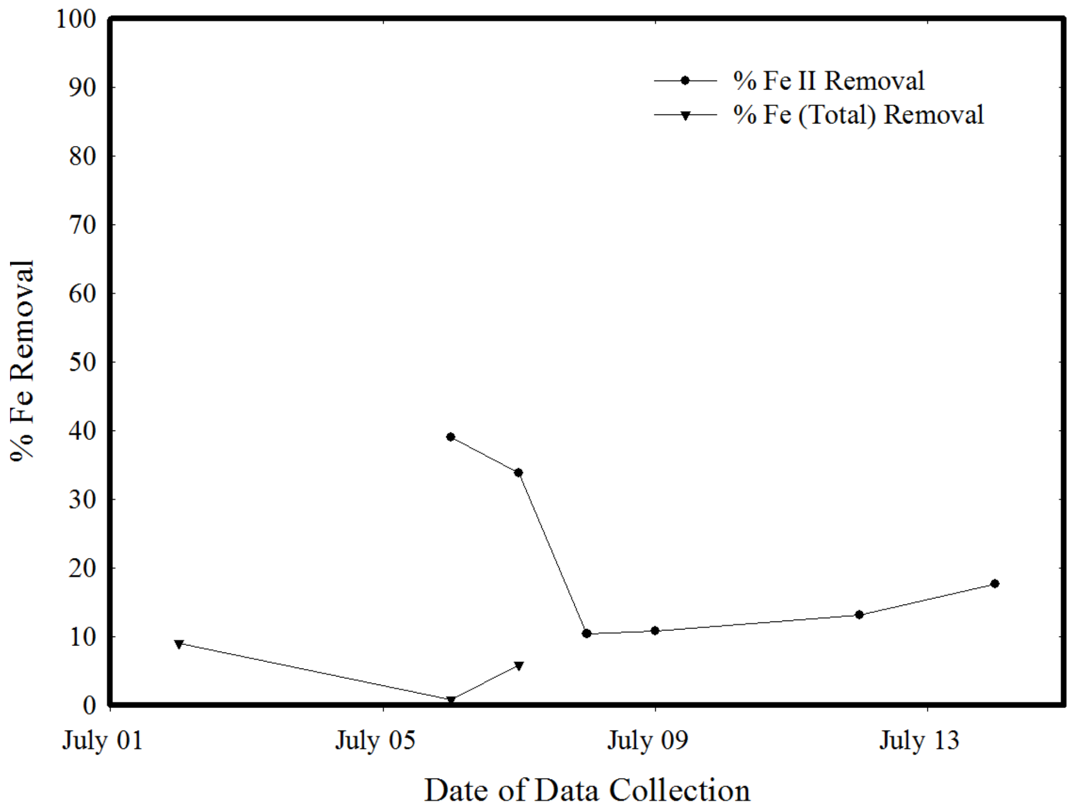

Figure 10. Cell 2 (empty) iron concentration. (See Appendix table D for data.)

6.2 Cell 5 – 1” Reused Tonka Packing, Standard Flow Rate

Cell 5 was used to simulate the continued use of the existing packing in the aerators after cleaning. Operating conditions for the cell included reused 1” Tonka packing placed at a standard spacing that allows for a density of approximately 79 tube-ft/ft^3, and a standard influent water flow rate was maintained. Data from this cell are shown in Figure 11.

An average CO_2 removal of 70 percent was recorded for the cell. This removal value is within the expected value range of 60–75 percent, which had been achieved during the early stages of operation of the full-scale aerator with new packing (Konavec, 1998). As seen in Figure 11, ignoring the first two data points, which are likely to be erroneous, operation of Cell 5 produced fairly stable results. The effluent CO_2 concentration proved to have a slightly increasing inclination, but again fairly stable results, with an average concentration of 13.7 mg CO_2/L. This value is significantly lower than the concentration of 22.6 mg CO_2/L recorded for the full-scale aerator operation. The difference in these values may be caused by the decreasing efficiency of the full-scale aerator. A variance in the influent CO_2 concentration was not the source of the difference in values. Historical data presented for the time period of January 1997 to October 1999 averaged an influent CO_2 concentration of 46.3 mg CO_2/L, while CO_2 influent concentrations during the test period averaged 50.7 CO_2/L.

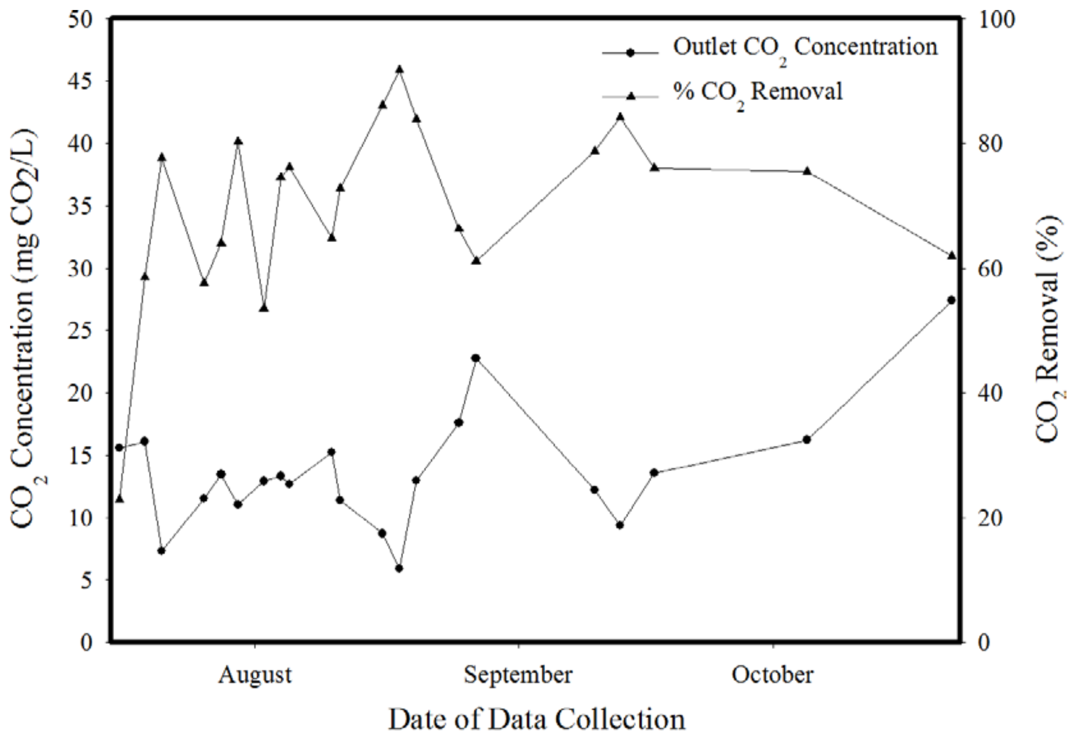

Figure 11. Cell 5 CO_2 removal. (See Appendix table K for data.)

The degree of iron removal (for both Fe II and total Fe) in Cell 5, shown in Figure 12, appears to have a relatively consistent trend. However, there appears to be a slight increase followed by a decrease. These mild beginning upward and ending downward trends are not a result of fluctuations in the influent concentration, which remained fairly constant. The initial increase may be the result of the time lag needed for bacterial growth; the later decrease may result from attaining the maximum amount of iron that can be accumulated on the packing. Initially, bacteria were not established well enough to perform at the same level that they accomplished as time progressed; this could be the cause of the initial upward trend. The final downward slope may commence once the packing has reached its maximum accumulation, after which the exopolymers from the bacteria are not strong enough to hold it all together. The average change in Fe II concentration was found to be 29.0 percent, while an average of 15.2 percent was recorded for total iron removal. This latter average is very close to the value of 14.5 percent achieved historically for the full-scale aerator.

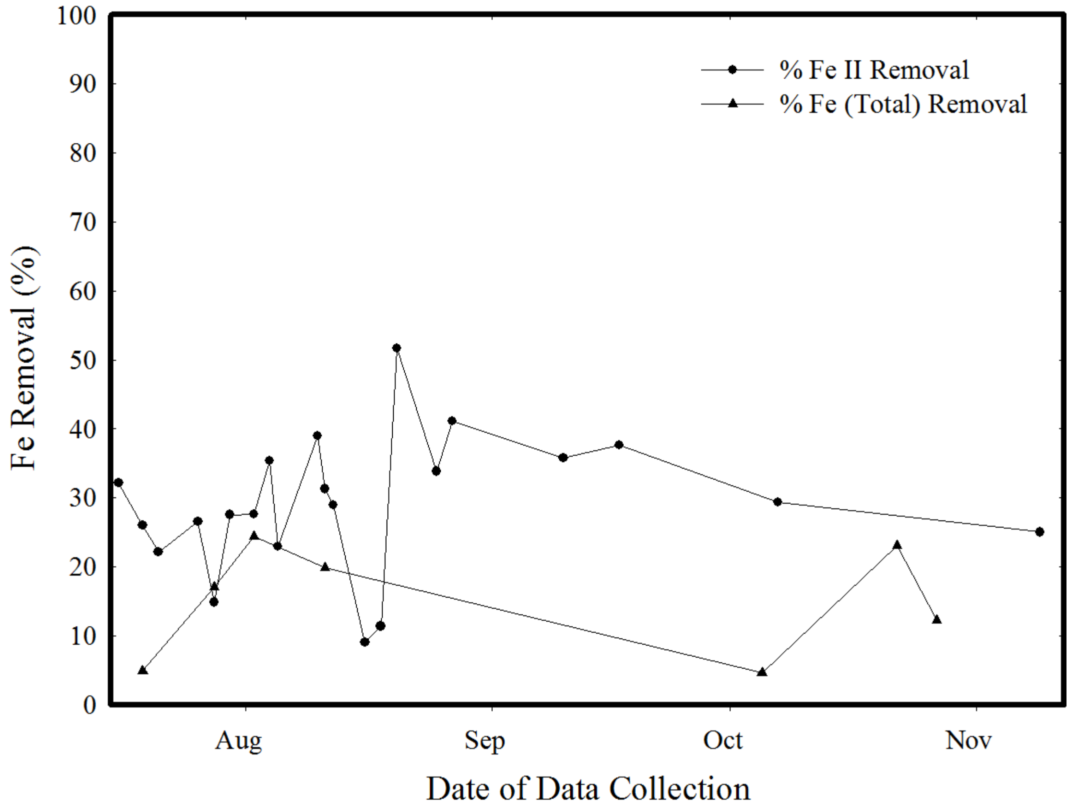

Figure 12. Cell 5 iron concentration. (See Appendix table L for data.)

Measurements of scale buildup on the packing were also taken. After 77 days of operation, a buildup of 539 g/m had occurred. Scale data from the CWTP aerator is not available for comparison.

When the fouled packing was removed from Cell 5 of the pilot unit, a heavy iron scale buildup, orange in color, was observed. Spraying one of the tubes with a hose under normal pressure removed a majority of the scale easily with only a thin layer remaining.

Based on the similar average CO_2 and total iron removal values, it appears Cell 5 performs in a manner that effectively simulates the full-scale aerator.

6.3 Cell 6 – 1" Reused Tonka Packing, Standard Flow Rate

Cells 5 and 6 operated as a crosscheck on the ability of the pilot aerator to simulate the full-scale aeration. The two identical cells also served as a check on one another, to test the reproducibility of results within the pilot aerator unit. Like

Cell 5, Cell 6 was operated with packing at regular spacing and standard influent flow rates. Data from Cell 6 are shown in Figure 13.

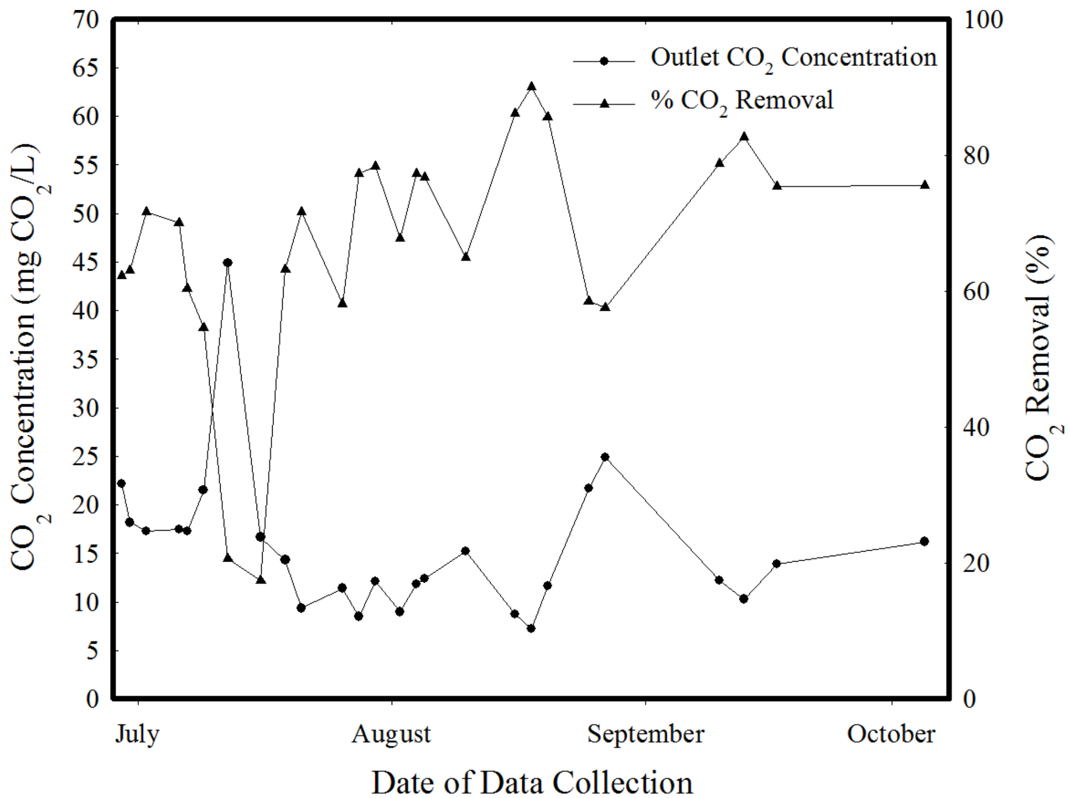

Figure 13. Cell 6 CO_2 removal. (See Appendix table M for data.)

Similar to the 60- to 75-percent CO_2 removals achieved under conditions of minimal iron buildup in the full-scale aerator and in Cell 5, Cell 6 produced a CO_2 removal average of 67 percent. Exit CO_2 concentrations were also very close to values produced by Cell 5, with an average effluent CO_2 concentration of 16 mg/L. Again, these values are lower than what was seen in the full-scale aerator. Possible reasons for these lower values are explained in the Cell 5 discussion.

It is also worth noting that Figure 13 shows a slight upward trend for the CO_2 removal, while the outlet concentration seemed to remain relatively steady, with a slight downward tendency. This downward trend of effluent CO_2 concentration is opposite of what was found in Cell 5 (where a slight upward trend was observed), but very similar to the trend exhibited by the CWTP full-scale aerator.

The Cell 6 changes in iron concentration data, shown in Figure 14, do not appear to have any clear trend. An average of 24.3 percent removal was found for the change in Fe II concentration. This value, like the CO_2 removal and effluent concentrations, was very close to that achieved in Cell 5. However, a total Fe removal average, excluding negative values, of 10.7 percent produced in this cell was lower than what was seen in Cell 5 and in the full-scale aerator. Reasons to account for this minor difference have not been determined, and it may be attributed to experimental error.

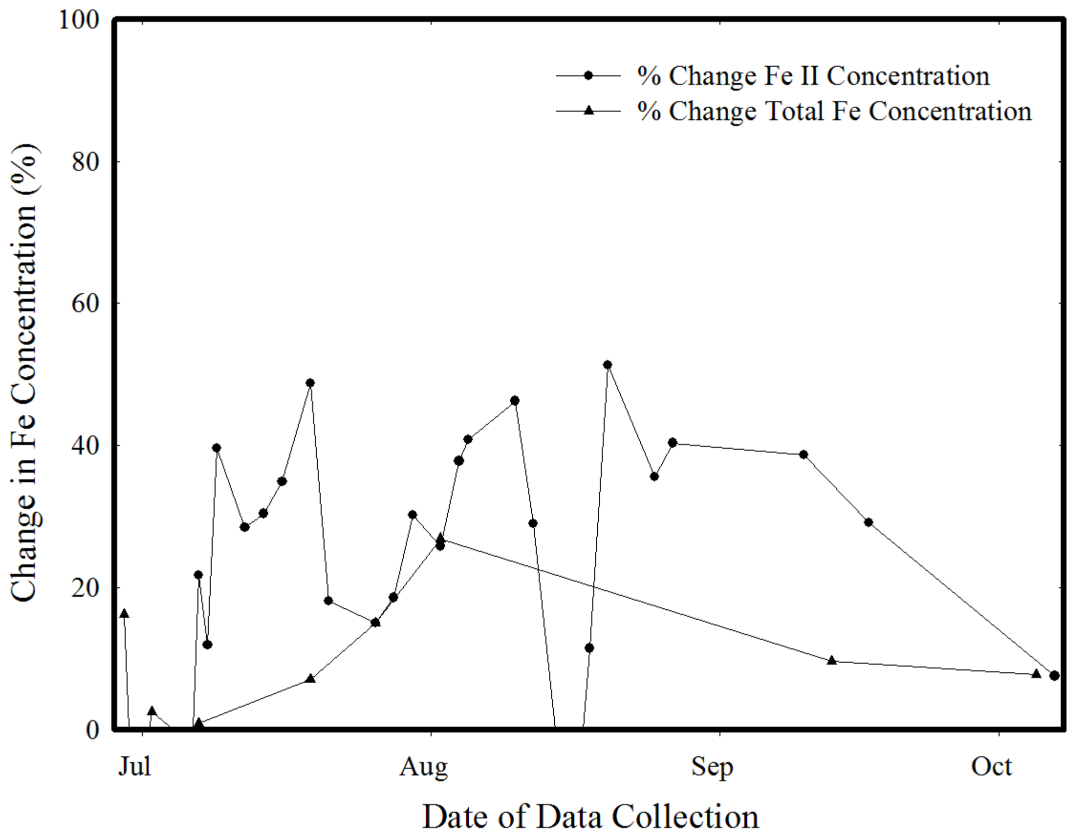

Figure 14. Cell 6 iron concentration. (See Appendix table N for data)

Iron-scale buildup on the packing for Cell 6 was measured to be 260 g/m after 49 days of service. This value is very close to what was measured in Cell 5. Observations made when removing the fouled packing were also to what was observed in Cell 5.

6.4 Cell 7 – 1" Reused Tonka Packing, Low Flow Rate

Cell 7 included 1" reused Tonka packing spaced at a standard interval, as noted in Cells 5 and 6. The varied component for this cell was in the low flow rate. A flow rate approximately half that of all other cells and the CWTP operating condition was used. For further information on the Cell 7 flow rates refer to Section 5, "Influent Conditions."

Cell 7 CO_2 removals, shown in Figure 15, display a slight trend upwards as time progresses. The average CO_2 removal was 65 percent, which is slightly higher than the current aerator operation average, and approximately equal to the removal achieved by Cells 5 and 6 (used, 1" Tonka packing). The outlet CO_2 concentration shows a fairly stable progression with an average outlet concentration of 15.7 mg CO_2/L. This value, like the removal percentage, is approximately equal to what was found in Cells 5 and 6, and is slightly lower than the value of 22.5 mg/L attained by the full-scale aerator. This result is not surprising since the low flow rate should provide for twice the detention time in the aerator unit, thus allowing for additional release of CO_2.

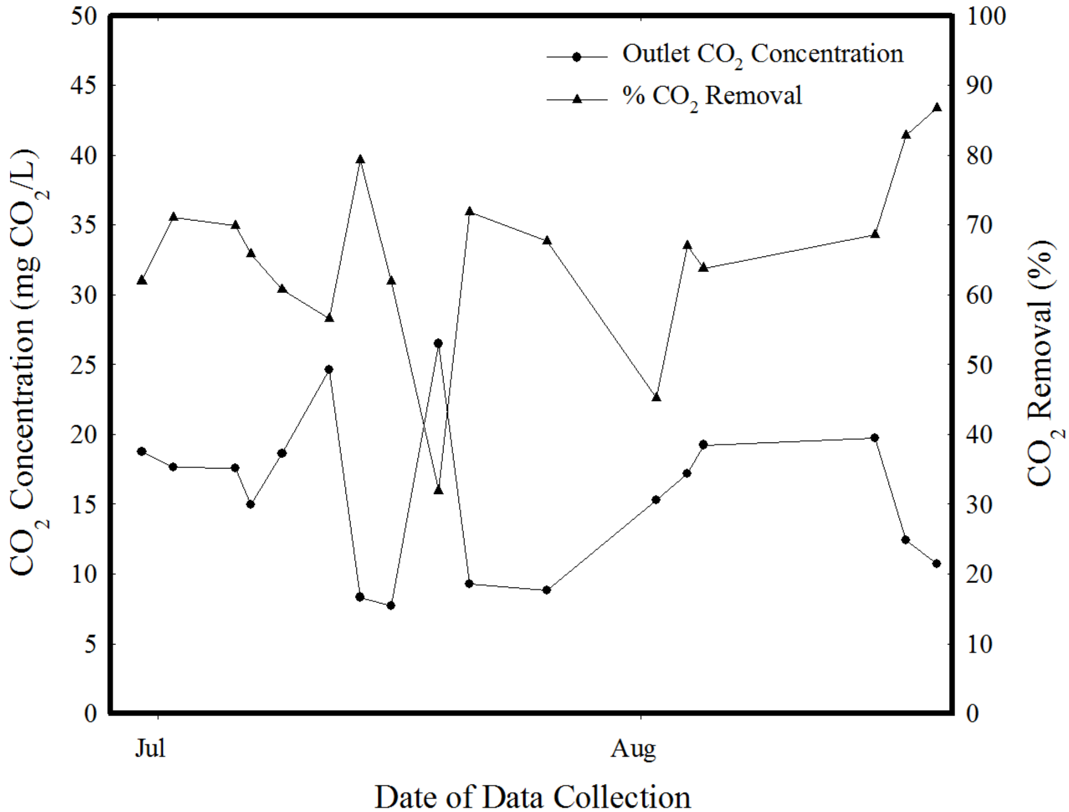

Figure 15. Cell 7 CO_2 removal. (See Appendix table Q for data.)

Cell 7 iron data, shown in Figure 16, proved to have an upward trend in both Fe II and total iron percent change in concentration. This trend was much more pronounced in the Fe II data. The average change in concentrations for Fe II and total Fe removal, excluding negative data values, were 34.6 and 12.6 percent respectively. The total iron removal is close to the value of 14.5 percent recorded for the average removal at the CWTP. Fe II removal is also similar to the value of 29.0 percent achieved in Cell 5. Like the CO_2 removal, iron removal was expected to increase slightly due to the lengthened detention time, which promoted the oxidation process.

Overall, the Cell 7 setup performed nearly equal to the existing system cells (5 and 6) and the historical data. However, the graphical analysis of the data does not take into account the number of days data was not recorded in the latter portion of the pilot aerator operation. The reason for the missing data is that water would not come out of the sampling tap. The tap was cleaned and flushed on several occasions. It is very likely that clogging in the system was not an issue. The true problem probably stemmed from the low flow rate not properly distributing the water throughout the cell. Therefore, water did not build up in the sampling cup and disabled the sampling process.

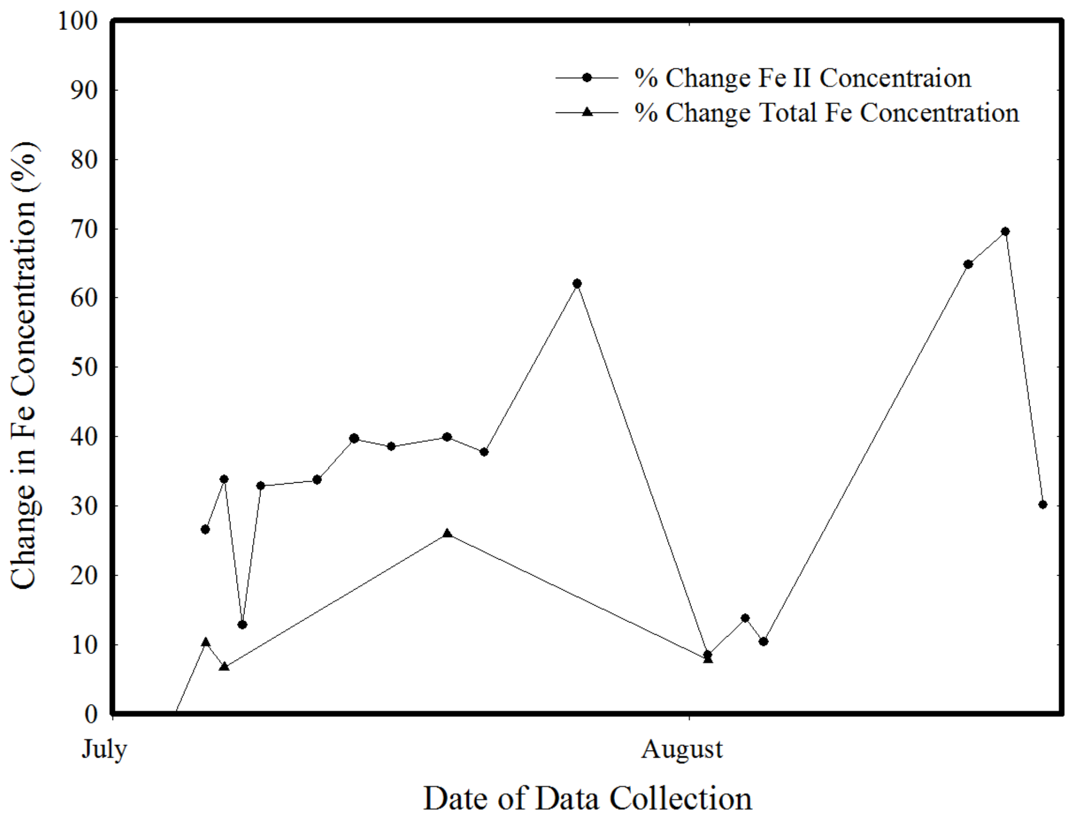

Figure 16. Cell 7 iron concentration. (See Appendix table S for data.)

When the packing was removed from Cell 7, observers noted an orange scale buildup of moderate proportion with light buildup on the back end of the packing. The back portion of the packing was discolored black. Spraying the freshly removed packing resulted in a majority of the scale being removed with a thin layer remaining, as was seen in Cells 5 and 6.

Cell 7 gained an average scale buildup of 255 g/m after 92 days of service. This value is nearly half of what was found in Cells 5 and 6. The reduction of nearly half can be accounted for in the fact that the flow entering this cell was approximately half of that entering Cells 5 and 6.

6.5 Cell 4 – 1" Reused Tonka Packing, Standard Flow Rate, Sodium Silicate Addition

Cell 4 packing consisted of 1" reused Tonka packing. The unit was operated at a standard flow rate with a sodium silicate addition to the influent. The sodium silicate was pumped into the system at a rate that would theoretically produce a concentration of 15 to 20 mg/L in the influent water. Additional information regarding the addition rate of the sodium silicate can be found in the appendix.

Sodium silicate has traditionally been used by water treatment facilities to solve aesthetic problems of color and taste caused by iron. The reasoning behind the use of sodium silicate as an additive in the aeration process is based largely on the same reason for its historical use. The sequestering agent addition to the influent water was expected to complex Fe III, preventing it from precipitating and subsequently adhering to the packing.

As shown in Figure 17, CO_2 concentrations and CO_2 removals appear to have a slight upward trend. An average CO_2 removal of 63.7 percent was recorded, which is approximately equal to results seen in Cells 5 and 6 (cells which modeled existing aeration practice). The effluent CO_2 concentration average of 17.2 mg CO_2/L was also similar to the results measured in Cells 5 and 6. These results are what would be expected, because the sodium silicate should not affect the CO_2 removal process.

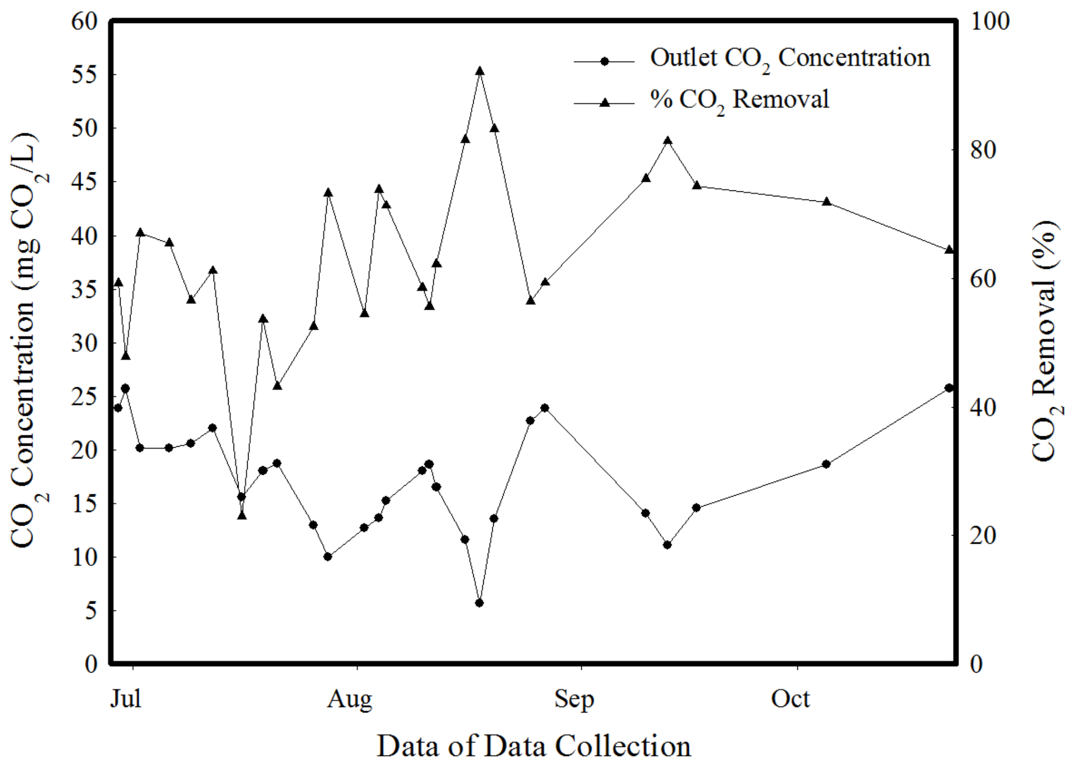

Figure 17. Cell 4 CO_2 removal. See Appendix table I for data.)

The change in iron concentration in Cell 4, for both Fe II and total Fe, exhibits an upward trend (Figure 18). An average value of 35.4 percent was recorded for the change in Fe II concentration, while the average total iron removal, excluding negative values, was calculated to be 11.4 percent. These values differ slightly from the values found for iron removal in Cells 5 and 6.

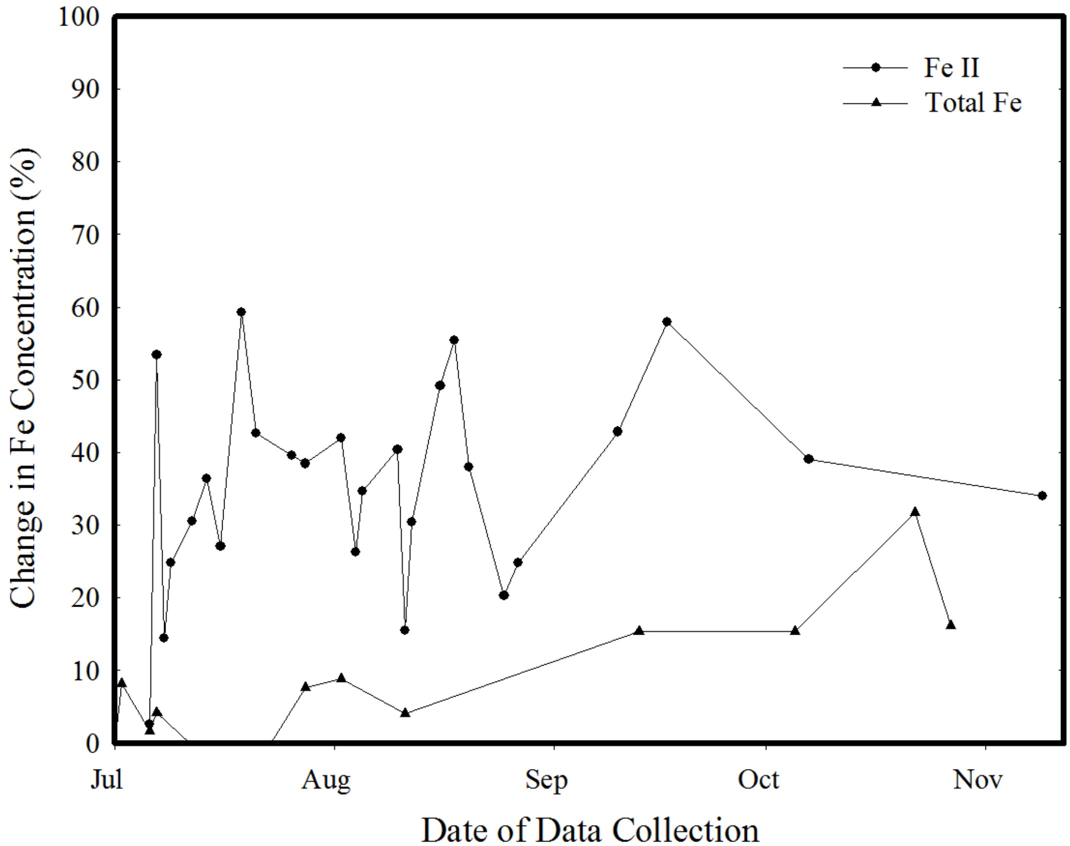

Figure 18. Cell 4 iron concentration. See Appendix table J for data.)

Based on the data in Figure 18, it appears the sodium silicate addition is performing as expected. Relative to Cell 5, Figure 18 shows an increase by approximately 5 percent in the change in Fe II concentration and a decrease of approximately 5 percent in total iron removal. It appears that the sodium silicate either enhances oxidation or interferes with Fe II measurements. Additionally, iron buildup on the packing after 93 days of operation in Cell 4 was recorded as 175 g/m, while after the same operating period Cell 6 was found to have 517 g/m build up. Cell 5 was recorded as accumulating 539 g/m after only 77 days of operation. Clearly, the sodium silicate addition is significantly inhibiting the amount of iron available for precipitation and subsequent buildup on the packing.

Observations during removal of the packing after fouling showed a moderate buildup of scale that was black in color and “crumbly.” Spraying the packing with a hose completely removed the iron fouling in areas the spray hit directly, while other areas remained covered. However, it should also be noted that the scale fell off fairly easily when the packing was agitated.

6.6 Cell 8 – 1” Reused Tonka Packing, Standard Flow Rate, Shock Chlorination

Cell 8 was operated under shock chlorination conditions. The packing installed was reused 1” Tonka placed at standard spacing. Flow rates were maintained at standard quantities. Chlorine was added to the influent water at a rate of 130 mL/min. The concentration of the chlorine added to the system was 52.5 g/L, which resulted in a concentration of 100 mg/L in the influent water. Calculations for these values can be found in the appendix of this report.

The chlorine addition to the system was expected to improve the performance by inactivating the bacteria on the packing. The bacteria perform two functions that promote iron buildup in the aeration unit. First, they promote the oxidation of the iron, which causes the iron to be precipitate. Second, the bacteria excrete exopolymers, which provide a fastening substance to promote additional iron buildup on the packing. The reactions describing the interaction between the iron and the bacteria can be found in the appendix.

CO_2 removal in pilot aerator Cell 8 appears to have a slight upward trend (Figure 19). Effluent CO_2 concentrations also show the upward trend, but it is not as distinct. An average value of 67.2 percent was calculated for CO_2 removal. Average effluent CO_2 concentrations were determined to be 16.1 mg/L. As expected, these values were similar to those recorded in Cells 5 and 6.

Changes in Cell 8 Fe II concentrations, as expected, were significantly lower than all other cell results despite increased potential for Fe II oxidation. An average change in concentration of Fe II of 17.1 percent was achieved. The only other cell with results close to this value was the empty Cell 2, which yielded a 20.8-percent change in Fe II concentration. Additionally, Cell 8 had minimal buildup on the packing. A buildup of 115 g/m over a 93-day period was observed. In comparison, Cell 6 (operated under conditions similar to current aeration practice) showed a buildup of 517 g/m over the same time period, nearly 5 times the amount recorded in Cell 4. It is apparent that the chlorine addition is effective in inhibiting the buildup of iron on the packing.

Additionally, it should be noted that Figure 20 displays a slight upward trend for the total iron removal, which had an average value, excluding negative data values, of 9.6 percent (the lowest of all the full cells). This upward trend may be due to a slow accumulation of the bacteria, which, if true, could be resolved by periodic higher dosages of chlorine. Another possible reason for this upward trend is that an initial buildup of iron scale on the packing provides protection for underlying bacteria from the chlorine.

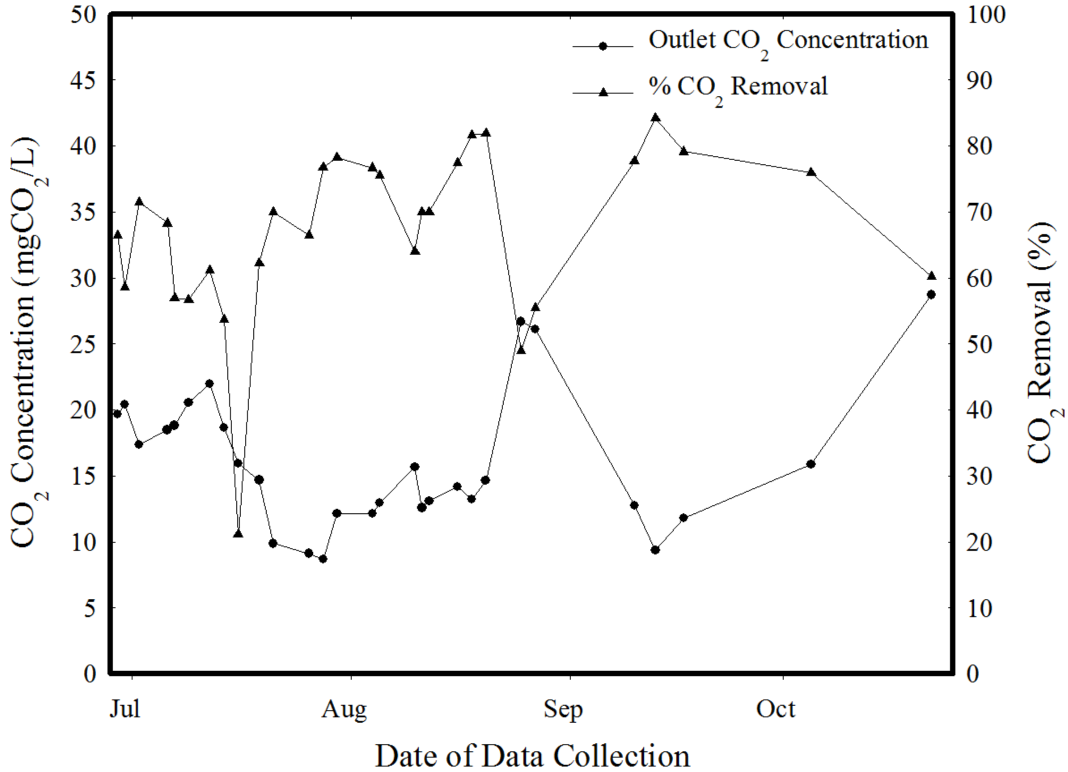

Figure 19. Cell 8 CO_2 removal. (See Appendix table S for data.)

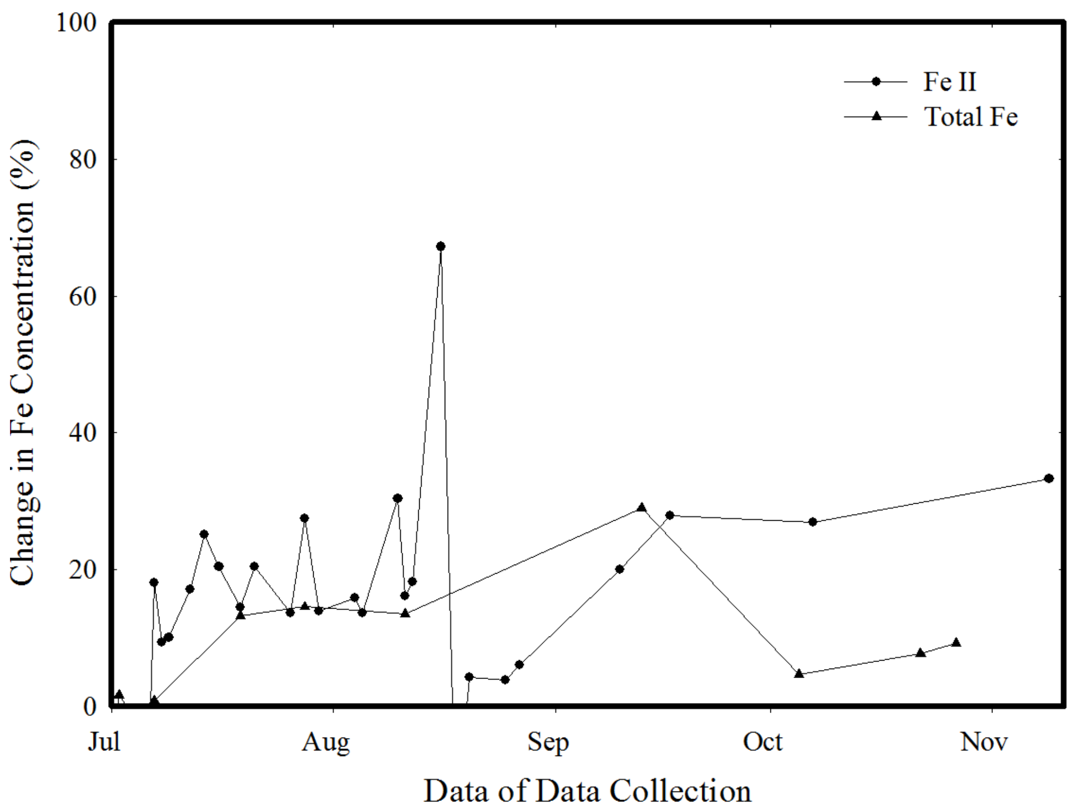

Figure 20. Cell 8 iron concentration. (See Appendix table T for data.)

Despite the reason for additional total iron removal as time progresses, the shock chlorination process appears to be an effective solution for inhibiting iron buildup on the packing. A study over a longer period would be needed to further evaluate the increase in total iron removal and the long-term effectiveness of this process.

Observations concerning the iron buildup, when the packing was removed, were that the minor buildup that occurred was solid, black in color, and had a flaky texture. The buildup appeared to dry quickly. Spraying the freshly removed packing with a hose resulted in minimal scale removal.

6.7 Cell 2 – 1" New Tonka Packing, Standard Flow Rate

Cell 2 was initially left empty to evaluate the effectiveness of the aeration process without the addition of packing. After approximately 2 weeks of operation, new 1" packing was installed within this cell at standard spacing. Throughout both runs water was added at a standard flow rate.

As seen in Figure 21, both percent CO_2 removal and effluent CO_2 concentrations remained fairly steady with a slight increase in the effluent concentration and a subsequent decrease in the percent CO_2 removal in the ending weeks. Average values for both data series were similar to those seen in previously evaluated cells, with an average CO_2 removal of 69.5 percent and average effluent concentration of 17.5 mg CO_2/L.

The change in Fe II concentrations (Figure 22) shows a tendency to increase with time of operation. Total iron removal remains fairly constant throughout the process. Average values for this data were 30.0 percent for the change in Fe II concentration and 14.7 percent total iron removal. Both average values were similar to those seen in Cells 5 and 6 (reused 1" Tonka packing and standard spacing and flow rate). Iron buildup in Cell 2 was slightly lower than that seen in Cells 5 and 6, with a buildup of 284 g/m after 75 days of operation. There are several possible explanations for this lower buildup. First of all, the reason may be found in the fact that the new packing is "slicker" than the reused packing, which is installed with some iron residue present. Additionally, the time needed for the establishment of bacteria on the packing may contribute to the initial lower iron buildup rates. As previously discussed in the Cell 8 section, the presence of bacteria acts as a catalyst for the oxidation of Fe II to Fe III, which builds up on the packing. The bacteria also provide an exopolymer that aids in the adhesion of the converted Fe III and Fe III naturally present in the water to the packing. All of these reasons probably combined to result in the low iron buildup in the early stages of Cell 2 operation.

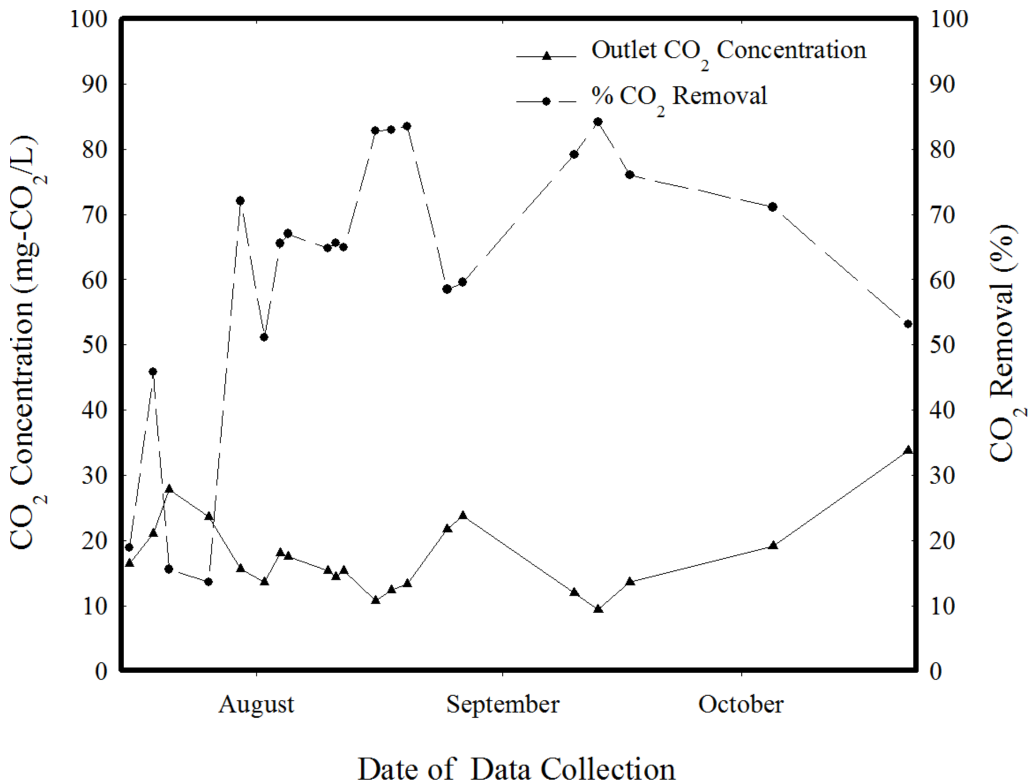

Figure 21. Cell 2 CO_2 removal. (See Appendix table E for data.)

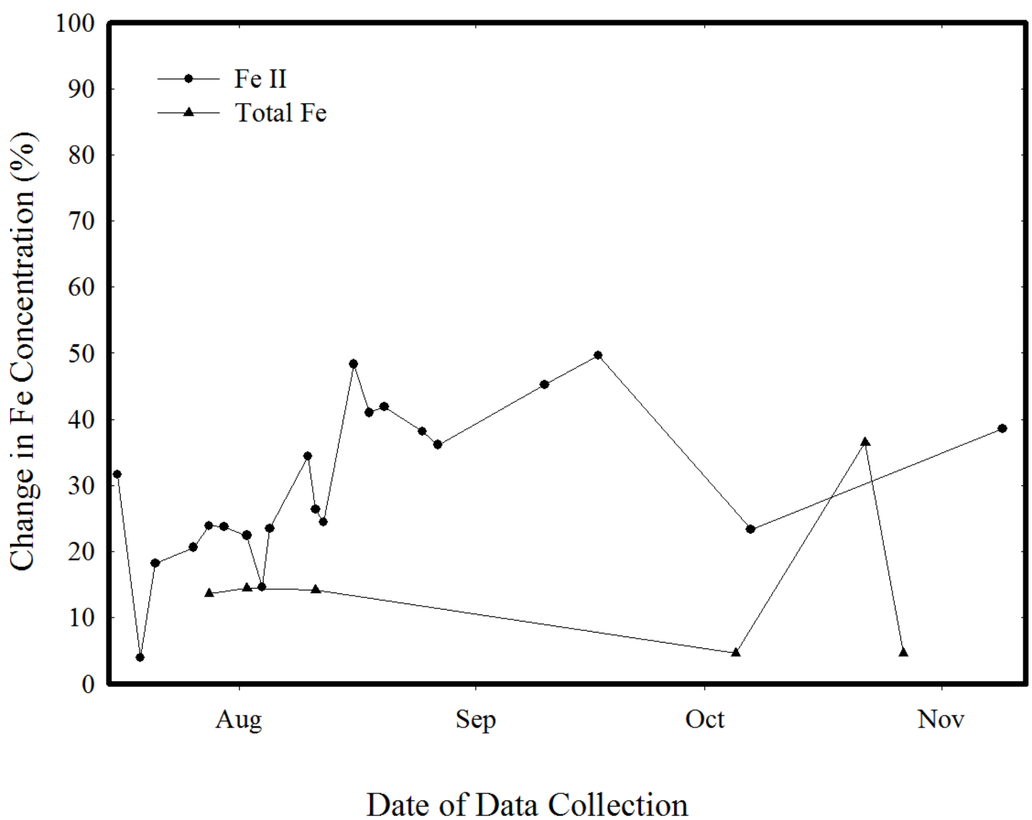

Figure 22. Cell 2 iron concentrations. (See Appendix table F for data.)

When the fouled packing was removed from Cell 2, heavy iron fouling occurred with an orange coloration was observed. Spraying the freshly removed packing with a hose resulted in a majority of the scale being removed. A thin layer was left intact, as reported for Cells 5 and 6. However, the remaining layer in this case appeared to be slightly thinner that that observed for Cells 5 and 6.

6.8 Cell 1 – 2” New Tonka Packing, Standard Flow Rate

Cell 1 contained 2” new Tonka packing installed at a spacing that allowed for a density of approximately half the standard density of 79 tube-ft/ft^3. The increase in space between packing units was necessary due to the larger diameter of the packing. Influent flow for the cell was operated at a standard rate.

Figure 23 shows the measured inlet and outlet CO_2 concentrations.

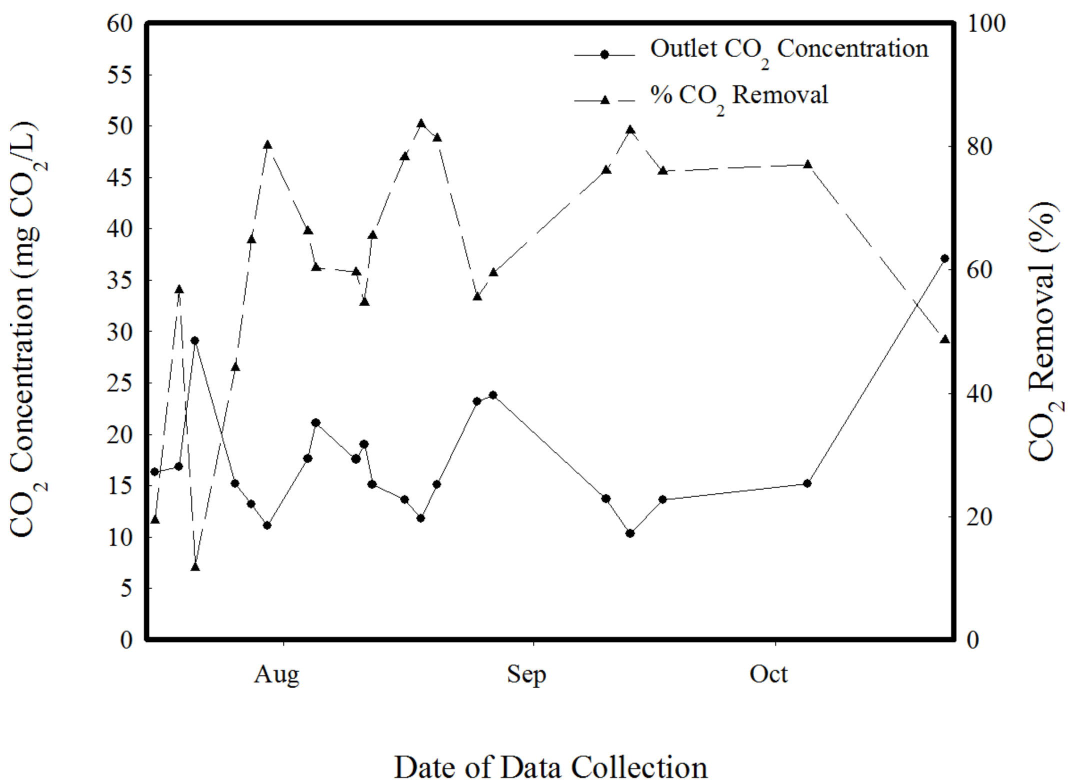

Figure 23. Cell 1 CO_2 removal. (See Appendix table A for data.)

An average CO_2 removal of 62.0 percent was produced in this pilot aeration cell, with an average effluent CO_2 concentration of 17.6 mg/L. This removal percentage is slightly lower than what was found with new 1” packing. The reason for this difference may be a result of the variation in diameter and spacing of the two packings. More specifically, the increased size of the packing provided less surface area per unit volume. In turn, there was less resistance for water movement, which inhibited CO_2 removal.

Changes in the iron concentration between influent and effluent conditions appear to have an upward trend for both Fe II and total Fe measurements (Figure 24). An average change in Fe II removal was calculated to be 24.6 percent. Total iron removal, on average excluding negative values, was 15.6 percent over the time period observed. These average results are comparable to those for Cells 5 and 6, which were operated under conditions similar to the current aeration process. Changes in both Fe II concentration and total iron removal were essentially the same as observed in Cells 5, 6, and in historical aerator operation data. Additionally, scale buildup, on a basis of grams per meter over a set time period was significantly greater on Cell 1 when compared to all other cells. The increase in iron scale buildup can be accounted for when viewed with respect to the surface area. Twice the surface area per unit length was available for iron scale buildup on the 2” packing (compared to the 1” packing). Therefore, it would be expected that twice the iron buildup would occur. Although twice the buildup was not the case, the amount of iron scale on the 2” packing was significantly greater than that on the 1” packing. The 2” packing also had twice the surface area available for bacteria colonization, thus adding another factor that would tend to increase iron attachment to the packing.

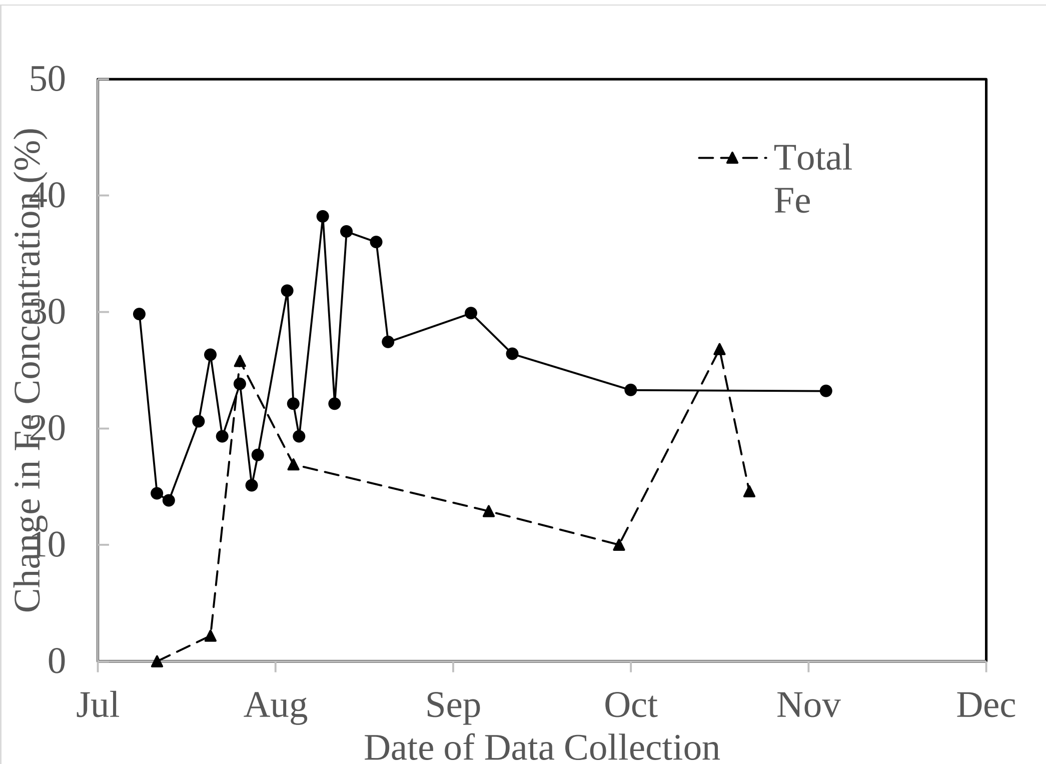

Figure 24. Cell 1 iron concentration. (See Appendix table B for data.)

During the removal of Cell 1 packing after iron fouling, a heavy, orange iron scale buildup was observed. When the freshly removed packing was sprayed with a hose a large portion of the scale was removed, but a significant amount remained.

6.9 Cell 3 – 1” Solid Packing, Standard Flow Rate

Cell 3 was filled with 1” solid (low-efficiency) packing at a standard spacing and flow rate. The 1” solid packing was simply 1” PVC pipe cut to appropriate length and installed in the pilot aerator.

Cell 3 CO_2 removals show a slight upward trend (Figure 25), while the effluent CO_2 concentrations mirror these values with a slight downward trend. The average CO_2 removal was calculated to be 64.3 percent, which is very close to the value found in Cells 5 and 6 (operated at conditions similar to the current CWTP aeration process). The effluent CO_2 concentration for this cell was also close to that observed in Cells 5 and 6, with an average value of 18.3 percent. These results are surprising, in that it seems the mesh provided by the Tonka packing provides little advantage, if any, for the release of CO_2 in the aeration process.

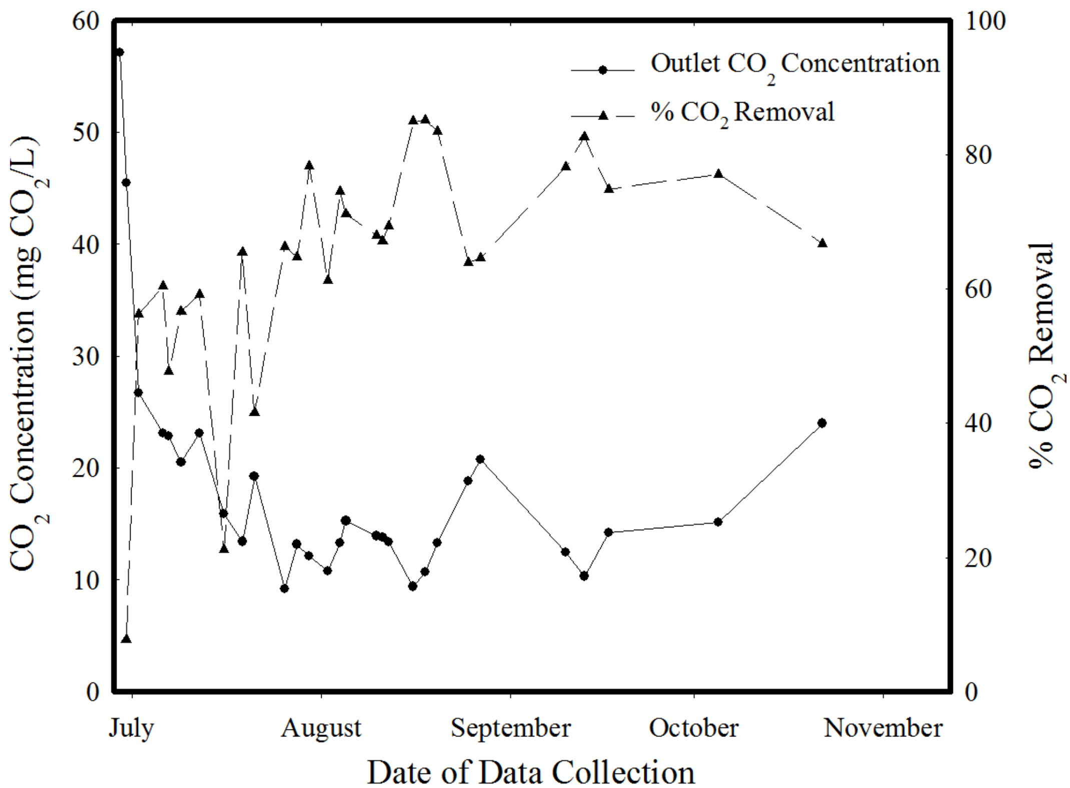

Figure 25. Cell 3 CO_2 removal. (See Appendix table G for data.)

The changes in iron concentrations follow a relatively constant trend (Figure 26). Average concentrations were similar to the Cell 5 and 6 operating values. The average reduction of Fe II in Cell 3 was 32.7 percent, which is slightly greater, but not significantly higher than the value found in Cells 5 and 6. The average total iron removal was 13.4 percent (excluding negative data values), which is close to the values recorded for Cell 5 (15.2 percent) and Cell 6 (10.7 percent). The Cell 5 value is closer to the average value of the full-scale aerator and therefore will be used for the following comparison. The reason for this lower value may be accounted for in the fact that the solid packing did not provide for full airflow throughout the aeration unit, which in turn slightly impeded the formation of Fe III and the precipitation of iron within the aeration cell. Additionally, the solid packing provided a lower surface area for water resistance, which also could have contributed to the lower total iron removal values reported.

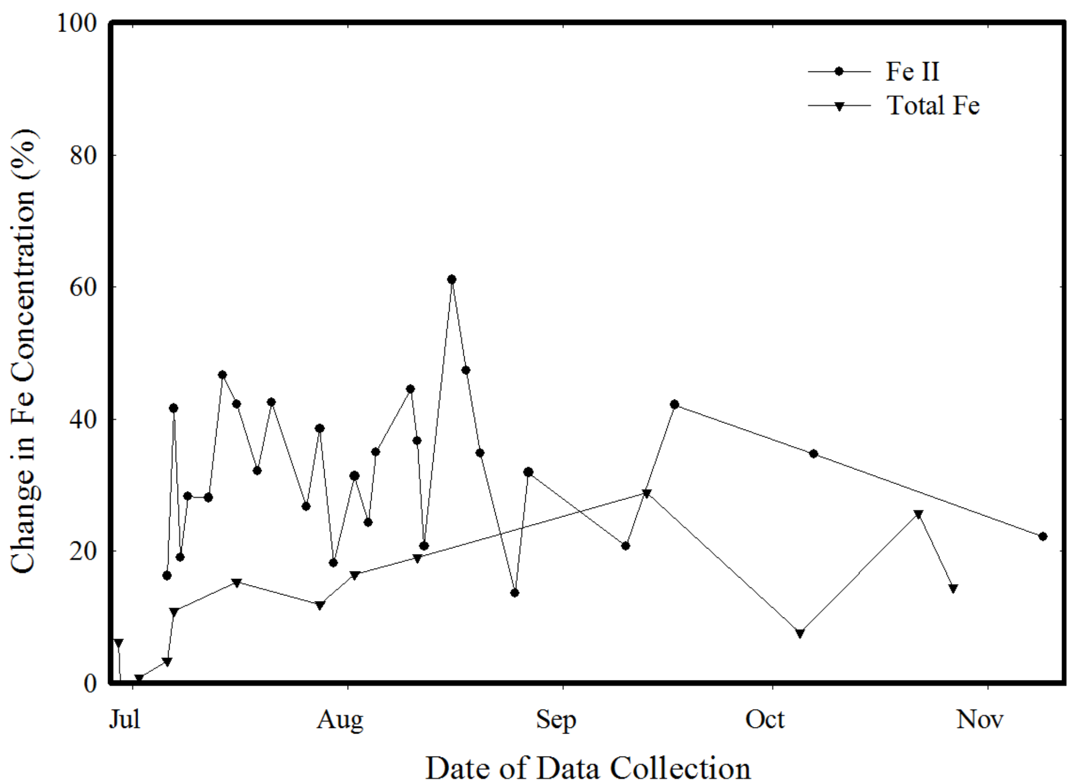

Figure 26. Cell 3 iron concentration. (See Appendix table H for data.)

When the fouled packing was removed from Cell 3, a moderate to heavy orange-colored buildup was observed. Spraying the freshly removed packing with a hose removed a majority of the scale, leaving only a thin layer.

6.10 Cell 6 – Triangular Packing, Standard Flow Rate

During the period of the pilot scale operation from October 7 to November 17, Cell 6's reused Tonka packing was replaced with triangular packing supplied by Fluid Equipment Company, Inc. (Lake Ozark, MO, office), a representative for

General Filter, and the cell then resumed operation at a standard flow rate. The triangular packing consisted of equilateral right triangles approximately 2” wide at the base and 1” in height. Each was positioned so that the peak of the right angle pointed upwards. The wall thickness of the packing varied from roughly 1/16” to 1/8”.

Limited data was obtained for the packing (Table 4). CO_2 removal data and total Fe removal was collected only once. A reasonable value for Fe II removal was never recorded. The one value for this property was negative.

Table 4. Cell 6 (Triangular Packing) Data

Cell #	Avg. % CO_2 Removal	Avg. Effluent CO_2 Conc.	Avg. % Fe II Removal	Avg. % Total Iron Removal
6	65.2	25.1	---	1.5

6.11 Overview of Pilot Test Results

Table 5, below, provides a review of the test results for the individual cells of the pilot aerator.

Table 5. Summary of Pilot Test Results

Cell #	Avg. CO_2 Rem. (%)	Avg. Effluent CO_2 Conc.	Avg. Fe II Rem. (%)	Avg. Total Iron Rem. (%)	Avg. Eff. DO* Saturation (%)
CWTP	52.5	22.6	--	14.5	--
Cell 2 (Empty)	40.8	31.9	20.8	5.2	--
Cell 5	70.0	13.7	29.0	15.2	90.0
Cell 6	67.1	16.0	24.3	10.7	88.7
Cell 7	65.5	15.7	34.6	12.6	87.6
Cell 4	63.7	17.2	35.4	11.4	86.9
Cell 8	67.2	16.1	17.1	9.6	87.6
Cell 2	69.5	17.5	30.0	14.7	108.4
Cell 1	62.0	17.6	24.6	15.6	87.0
Cell 3	64.3	18.3	32.7	11.1	88.8
Cell 6 **	65.2	25.1	--	1.5	95.3

* Values based on table from Davis (1991).
** Triangular packing, results of only one data collection.

6.12 Iron Buildup on Packing

As noted in earlier sections of this report, packing from the cells was removed approximately once a month for iron scale buildup measurements. The results of these measurements are presented in Table 6.

Table 6. Iron Scale Buildup

Cell #	Packing Location	Service Time (days)	Scale Buildup (g/m)	Service Time (days)	Scale Buildup (g/m)	Service Time (days)	Scale Buildup (g/m)	Service Time (days)	Scale Buildup (g/m)
Cell 1 (2" Tonka New)	Top			31	254	75	482	125	304
	Middle			31	392	75	740	125	321
	Bottom			31	299	75	710	125	342
	Average			**31**	**315**	**75**	**644**	**125**	**322**
Cell 2 (1" Tonka New)	Top			31	110	75	264	125	162
	Middle			31	98	75	333	125	166
	Bottom			31	98	75	256	125	182
	Average			**31**	**102**	**75**	**284**	**125**	**170**
Cell 3 (1" solid)	Top	18	75	49	241	93	303	143	90
	Middle	18	75	49	208	93	304	143	119
	Bottom	18	34	49	149	93	240	143	98
	Average	**18**	**62**	**49**	**199**	**93**	**283**	**143**	**102**
Cell 4 (1" Tonka Sodium Silicate)	Top	18	41	49	106	93	120	143	154
	Middle	18	43	49	55	93	206	143	151
	Bottom	18	37	49	44	93	199	143	163
	Average	**18**	**40**	**49**	**68**	**93**	**175**	**143**	**156**
Cell 5 (1" Tonka Reused)	Top			33	205	77	457	127	194
	Middle			33	337	77	671	127	231
	Bottom			33	303	77	490	127	254
	Average			**33**	**282**	**77**	**539**	**127**	**227**
Cell 6 (1" Tonka Reused)	Top	18	61	49	188	93	365		
	Middle	18	113	49	322	93	655		
	Bottom	18	55	49	270	93	530		
	Average	**18**	**76**	**49**	**260**	**93**	**517**		
Cell 6 (Trian-gular)	Top							42	40
	Middle							42	34
	Bottom							42	38
	Average							**42**	**37**
Cell 7 (1" Tonka Low Flow)	Top	17	41	48	148	92	299	142	168
	Middle	17	66	48	147	92	299	142	168
	Bottom	17	51	48	79	92	167	142	101
	Average	**17**	**53**	**48**	**124**	**92**	**255**	**142**	**146**
Cell 8 (1" Tonka Chlorine)	Top	18	38	49	31	93	92	143	106
	Middle	18	31	49	29	93	137	143	91
	Bottom	18	29	49	32	93	117	143	121
	Average	**18**	**33**	**49**	**31**	**93**	**115**	**143**	**106**

Figure 27 is provided to allow for a better comparison of the iron scale buildup on individual cells. All cells are presented except Cell 6, which was omitted to prevent additional cluttering of the graph. Cell 6 results, as noted throughout the report, were very similar to what was observed in Cell 5. Also, there were not enough results from the triangular packing, which was housed in Cell 6 for a short period, to present on the graph.

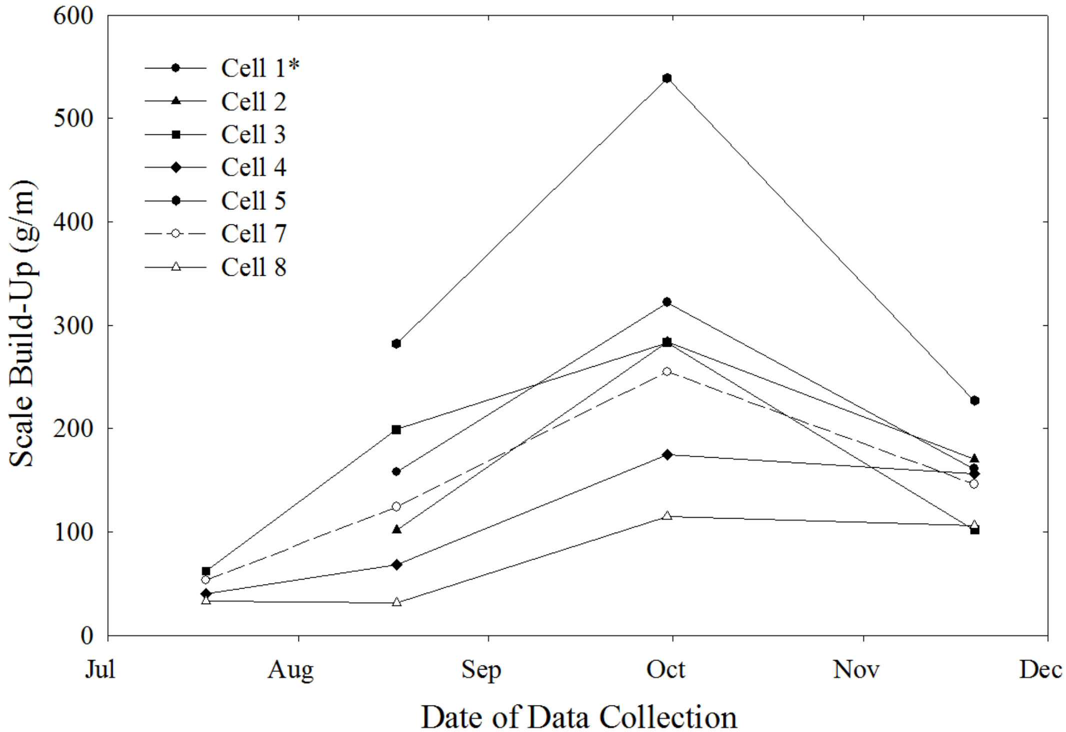

Figure 27. Iron scale buildup.
* The iron scale buildup data for Cell 1 was divided by two for comparison (the 2" packing in Cell 2 had twice the surface area of the other 1" packing).

Figure 27 shows an upward trend with a distinct dropoff at the end of all cell data plots. Although it is expected that the accumulation of scale would level off over time, a drastic drop at the end does not seem logical. Reviewing the influent flow rate for the period between the third and fourth data points did not indicate an increase in flow, which could have removed a portion of the iron buildup. More than likely, the reason for the dropoff in the end is experimental error in either the third or fourth data collection. A possible source of the experimental error may be the removal of previously removed packing. Although each packing section removed in previous buildup calculations was marked, the additional iron buildup made it difficult to distinguish between the marked and unmarked packing.

Cell 5, which modeled the current CWTP operating conditions exhibited the highest iron scale buildup. This result comes about because the majority of the other cells were treated to reduce iron buildup through shock chlorination, low flow rate, etc. The shock chlorination of Cell 8 proved to be the most effective method of reducing iron buildup. This low buildup is largely attributed to the ability of the chlorine to kill bacteria present on the packing. Further discussion concerning iron buildup for each cell can be found in its respective section.

SECTION 7. CWTP LIME ADDITION

Determining the optimal aeration conditions based largely on maximizing CO_2 removal is useless if CWTP operators do not respond to changes in lime addition requirements. This section of the report has been added to evaluate whether changes in lime addition requirements regularly result in an appropriate response of reducing or increasing lime addition. Figure 28 provides an overview of CWTP's water qualities that directly affect the required lime addition.

In order to evaluate the reaction of CWTP operators to the change in lime addition requirements, the theoretical and actual lime addition amounts were plotted on the same graph (Figure 29). The process for calculation of the theoretical lime addition requirements and the actual lime amounts added can be found in the appendix. As shown in Figure 29, the CWTP does respond to changes in lime addition requirements. Therefore, basing the composition of the aeration process on attaining high CO_2 removal should result in savings for CWTP.

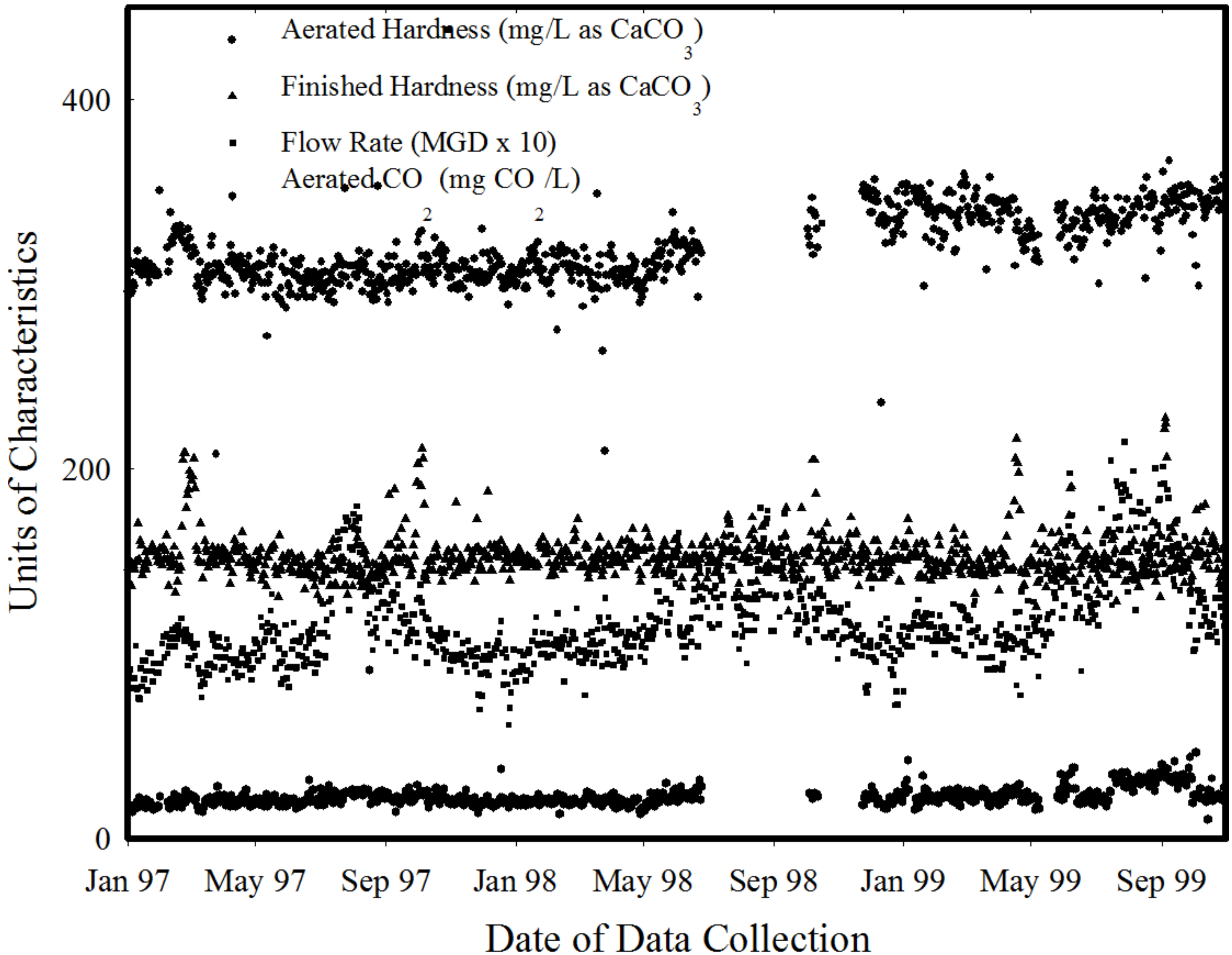

Figure 28. CWTP historical water quality parameters related to lime softening requirements.

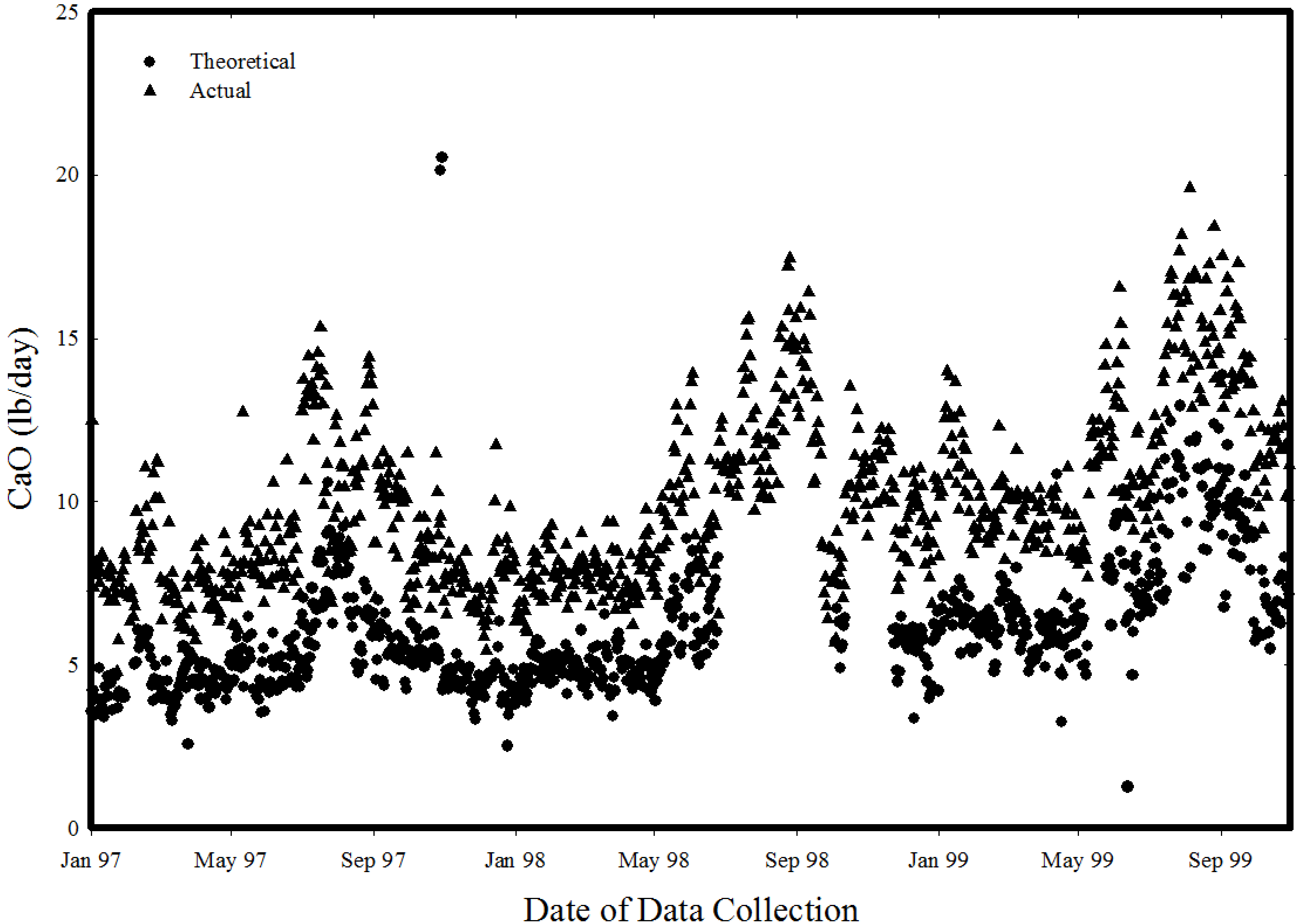

Figure 29. Theoretical and actual lime addition.

SECTION 8. CONCLUSION

Based on the data presented in this report, which was collected from the pilot aerator, all cells operated fairly similarly in regard to CO_2 removal. However, some did perform better in reducing the rate at which iron scale built up on the packing. Determining what composition will provide a maximum economical efficiency for the aerator process would require additional cost information.

If the process were to be chosen solely on the data presented, ignoring cost of chemical addition, it would seem logical to choose the Cell 8 composition. Cell 8 contained 1" Tonka packing with shock chlorination. Test results proved this cell to perform equally, in terms of CO_2 removal, to the other cells. Additionally, Cell 8 produced significantly lower total iron removal and scale buildup results. However, it was noted that the scale formed from this process was somewhat difficult to remove from the packing.

Due to the difficulty of scale buildup removal, the sodium silicate addition process used in Cell 4 should be considered for future use. Cell 4 also achieved comparable CO_2 removal and relatively low iron removal and scale buildup. Unlike the shock chlorination scale buildup, the iron buildup on the Cell 4 packing was noted as being fairly easy to remove.

The fact that Cell 3, which included simply 1" PVC, seemed to remove CO_2 about as well as the 1" Tonka packing suggests that the PVC pacing may also be used to enhance the efficiency of the aeration process. The use of 1" PVC pipe may make it more economical to periodically replace the packing rather than cleaning and reusing the 1" Tonka packing.

Any process chosen will need to be adjusted over time to attain maximum performance of the aeration process. Therefore, it might be a worthwhile endeavor to try a combination of chlorine and sodium silicate on the full-scale aerator and evaluate how this combination performs. Running other processes discussed in combination with shock chlorination and/or sodium silicate addition should also be considered in future operation of the aerators.

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APPENDIX

Chlorine Addition Calculation

Theoretical Chlorine Addition

The chlorine was added as 5.25-percent NaOCl.

$C_1V_1 = C_2V_2$
C_1 = Concentration of chlorine solution to be added
C_2 = Concentration of chlorine to be achieved in influent water
V_1 = Volume of chlorine solution to add
V_2 = Volume of water the chlorine solution will be added to (including added chlorine volume)

Initial conditions:
V_1 =?
C_1 = 5.25 g/100 mL = 52,500 mg/L

Final conditions:
V_2 = 68.2 L/min
C_2 = 100 mg/L

(52,500 mg/L) V_1 = (100 mg/L)(68.2 L/min)

(52,500 mg/L) V_1 = 6,820 mg/min
V_1 = 0.1299 L/min = 130 mL/min

The chlorine was to be added during a 15-minute period.

Actual Chlorine Addition

No records were kept to determine the total amount of chlorine used. However, approximately 1 gallon (3.785 L) of 5.25-percent Cl_2 was added daily.

Assuming the chlorine was added in a 15-minute period, the following calculation gives a rough idea of the actual chlorine addition.

$$\frac{52{,}500\ \mathrm{mg/L}}{(15\ \mathrm{min}) \times (15.5\ \mathrm{g/min})} = 226\ \mathrm{mg/L}$$

Therefore, the actual dose rate of approximately 226 mg/L is slightly higher than the predetermined rate of 130 mg/L.

Sodium Silicate Addition Calculation

Theoretical Sodium Silicate Addition

Based on a literature review and stoichiometry, a goal of 15 to 20 mg/L of SiO_2 was set as the concentration goal.

An average flow rate for the nozzle on the full-scale aerator was previously calculated to be 18 gpm (68.2 L/min). However, over the course of the pilot aerator operation an average flow rate of 15.5 gpm (56.8 L/min.) was determined.

(56.8 L/min) × (15 mg/L) = 852 mg/min

The pilot aerator sodium silicate cell operated for 143 days (=205,920 min).
The sodium silicate was added at a purity of 41.5 percent.
Therefore, the theoretical amount of sodium silicate needed was:

$$\frac{(852\ \text{mg/min}) \times (205{,}920\ \text{min})}{0.415} = 4.2 \times 10^{8}\ \text{mg} = 932\ \text{lbs}$$

Actual Sodium Silicate Addition

In order to determine if the actual sodium silicate addition could have been close to the intended 15 to 20 mg/L condition, the following calculation was performed.

The amount of sodium silicate used over the course of the pilot aerator operation was measured based on the amount of sodium silicate remaining in the 55-gallon barrel after the pilot aerator was shut down.

V_i = 55 gal
W_i = 650 lbs
V_f = 6.5” × 3.14 × (23”/2)^2 = 2,699 in^3 = 11.7 gal
W_f = 138 lbs
Volume of sodium silicate used = 43.3 gal
Weight of sodium silicate used = 512 lbs. (2.3×10^5 g)

Therefore, either the pumping rate was less than 15 mg/L or the pump was periodically out of service. If the pump was run continuously, the following calculation provides the actual pumping rate.

$$\frac{(2.3 \times 10^{5}\ \text{g}) \times 0.415}{205{,}920\ \text{min}} = 464\ \text{mg/min}$$

Then, $\dfrac{464\ \text{mg/min}}{56.8\ \text{L/min}} = 8.2\ \text{mg/L}$

However, it is more likely that the actual cause for the use of only 512 lbs SiO_2, is that the pump was out of service for a period of time. The primary reason it may have been put out of service would be because it had lost its prime.

Iron/Bacteria Reaction

(1) $4Fe^{2+} + O_2 + 4H^+ \rightarrow$ (iron bacteria) $4Fe^{3+} + 2H_2O$
(2) $Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+$ + precipitate

Water Flow Rate Calculation

Aeration Unit Rating = 8 MGD
Number of spray heads for one aerator = 300

8,000,000 gal/day
300 spray heads
= (26,666.7 gal/day/spray head) × (1 day/24 hr)
= (1111.1 gal/hr) × (1 hr/60 min)
= 18.5 gpm/spray head

$$\frac{8{,}000{,}000 \text{ gal/day}}{300 \text{ spray heads}} = 26{,}666.7 \text{ gal/day/spray head}$$

$$\frac{26{,}666.7 \text{ gal/day/spray head}}{1{,}440 \text{ min/day}} = 18.5 \text{ gpm/spray head}$$

Calibration of Flow Meter

The flow meter was calibrated for 9 gpm. This was done by marking off a large cylindrical tank in 2-L increments. Then, the piping of the pilot aerator was routed into the tank by removing the detachable section and adding a pipe. The flow meter was connected. Then, the tank was allowed to fill with water. The time it took the tank to fill a certain amount was timed, and the flow was adjusted accordingly via a gate valve.

Lime Addition Calculations

Theoretical Lime Addition Calculation

Theoretical lime addition calculations were based on a stoichiometric approach. The following reactions were evaluated.

(1) $CaO + H_2O = Ca(OH)_2$
(2) $H_2CO_3 + Ca(OH)_2 = CaCO_3(s) + 2H_2O$
(3) $Ca^{+2} + 2HCO_3^- + Ca(OH)_2 = 2CaCO_3(s) + 2H_2O$

Based on the above equations, and assuming the hardness due to magnesium is not removed, the following stoichiometry is known.

(a) 1 mole of CaO is required to neutralize 1 mole of CO_2.
(b) 1 mole of CaO is required to remove 1 mole of hardness (as $CaCO_3$).

A sample calculation is provided below.

Given (from 22 January 1997 CWTP data):

Aerated hardness = 311 mg/L as $CaCO_3$
Final hardness = 155 mg/L as $CaCO_3$
Aerated CO_2 concentration = 18.7 mg CO_2/L
Flow rate = 10.07 MGD

Calculations:

Calculate change in hardness between aerated and final hardness:

(311 – 155) mg/L as $CaCO_3$ = 156 mg/L as $CaCO_3$

Calculate m*M* of CaO needed:

$$\mathrm{m}M\ \mathrm{CO_2}\text{ to be neutralized} = 18.7\ \mathrm{mg\ CO_2/L} \times \frac{1\ \mathrm{m}M/\mathrm{L}}{44\ \mathrm{mg/L}} = 0.42\ \mathrm{m}M/\mathrm{L}$$

$$\mathrm{m}M\ \text{hardness as } \mathrm{CaCO_3} \text{ to be removed} = 156\ \mathrm{mg/L}\text{ as }\mathrm{CaCO_3} = 1.56\ \mathrm{m}M/\mathrm{L}$$

Sum of m*M* CO_2 and m*M* $CaCO_3$ = m*M* of CaO needed = 1.98 m*M* CaO

$$1.98\ \mathrm{m}M\,\mathrm{CaO} \times \left(\frac{56\ \mathrm{mg/L}}{1\ \mathrm{m}M\,\mathrm{CaO}}\right) = 111.1\ \mathrm{mg/L\ CaO}$$

Converting mg/L CaO to lb/gal.

$$111.1\ \mathrm{mg/L\ CaO} = \left(\frac{1\ \mathrm{g}}{1{,}000\ \mathrm{mg}}\right) \times \left(\frac{2.205 \times 10^{-8}\ \mathrm{lb}}{1\ \mathrm{g}}\right) \times \left(\frac{3.785\ \mathrm{L}}{1\ \mathrm{gal}}\right) = 0.000928\ \mathrm{lb/gal}$$

$$0.000928\ \mathrm{lb/gal} = 927.5\ \mathrm{lb/million\ gallon}$$

Calculate lb/day of lime theoretically needed

$$10.07\ \mathrm{MGD} \times (927.5\ \mathrm{lbs/million\ gallon}) = 9340.2\ \mathrm{lbs/day}$$
$$9340.2\ \mathrm{lb/day} \times \left(\frac{1\ \mathrm{ton}}{2{,}000\ \mathrm{lb}}\right) = 4.67\ \mathrm{ton/day}$$

Actual Lime Addition

Given (from 22 January 1997 CWTP data):

Lime addition rate = 600 lbs/hr

Calculate lbs/day of lime actually added

lbs/day = (600 lbs/hr) × (24 hr) = 14,400 lbs/day = 7.2 ton/day

Sample CO_2 Calculation Spreadsheet

INPUT VALUES

Alkalinity	296 mg $CaCO_3$/L = 5.92 meq/L
pH	7.71
Temperature	14.2 °C = 287.2 K
TDS	589 mg/L

OUTPUT VALUES

$[H_2CO_3^*]$ =	2.403×10^{-4} *M* = 10.6 mg/L as CO_2		
$[HCO_3^-]$ =	5.886×10^{-3} *M* = 359.0 mg/L		
$[CO_3^{-2}]$ =	1.691×10^{-5} *M* = 1.0 mg/L		
m =	0.014225 *M*		
$^cK_1$ =	4.776×10^{-7} *M*	K_1 =	3.737×10^{-7} *M*
$^cK_2$ =	5.603×10^{-11} *M*	K_2 =	3.430×10^{-11} *M*
^cK_w =	4.885×10^{-15} *M*	K_w =	3.822×10^{-15} *M*
$[H^+]$ =	1.950×10^{-8} *M*		
$[OH^-]$ =	2.505×10^{-7} *M*		
α_0 =	3.912×10^{-2}		
α_1 =	9.581×10^{-1}		
α_2 =	2.753×10^{-3}		
C_T =	6.143×10^{-3} *M* = 73.7 mg/L as inorganic C		
$\gamma_{H}{}^{+}$ =	0.885		
$\gamma_{OH}{}^{-}$ =	0.885		
γ_{H2CO3*} =	1.000		
$\gamma_{HCO3}{}^{-}$ =	0.885		
$\gamma_{CO3}{}^{-2}$ =	0.612		

Data Record

Table A. Cell 1 — 2" New Tonka Packing Data – Used to construct figure 23

Date of Data Collection	Water Temp. (°C)	Air Temp. (°C)	Flow Rate (gpm)	Pressure (psi)	pH		Alk. (mg/L)		CO_2 (mg/L)		% CO_2 Removal
					Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	
16-Jul-99	14.7	22.0			7.45	7.54	310	310	20.2	16.3	19.3*
19-Jul-99	14.8	22.5			7.19	7.55	328	328	38.9	16.8	56.8
21-Jul-99	14.8	22.7			7.27	7.32	334	334	33.0	29.1	11.7*
26-Jul-99	14.7	16.5	12.5	7.0	7.36	7.61	340	340	27.3	15.2	44.2
28-Jul-99	14.7		12.5	7.0	7.22	7.67	338	338	37.4	13.2	64.8
30-Jul-99	14.7	22.0		7.0	7.04	7.74	334	334	56.0	11.1	80.2
02-Aug-99	14.5	17.3		7.0	7.33	7.73					
04-Aug-99	14.5	25.6		6.0	7.07	7.54	334	334	52.2	17.6	66.3
05-Aug-99	14.5	24.0		6.0	7.08	7.48	348	348	53.2	21.1	60.3
10-Aug-99	14.7		11.5	6.0	7.15	7.54	334	334	43.5	17.6	59.6
11-Aug-99	14.8	27.8		6.5	7.17	7.51	338	338	42.0	19.0	54.7
12-Aug-99	14.6				7.16	7.62	344	344	43.7	15.1	65.5
16-Aug-99	14.7				6.99	7.65	334	334	62.8	13.6	78.3
18-Aug-99	14.9	26.0			6.93	7.71	334	334	72.1	11.8	83.6
20-Aug-99	14.3	24.2			6.88	7.61	334	334	80.9	15.1	81.4
25-Aug-99	14.6	27.0	15.7	8.0	7.07	7.42	334	334	52.2	23.2	55.6
27-Aug-99	14.6	29.0		6.0	7.03	7.42	342	342	58.7	23.8	59.5
10-Sep-99	14.5	26.6		6.0	7.04	7.66	342	342	57.3	13.7	76.1
13-Sep-99	14.2			4.6	7.04	7.80	354	354	59.3	10.3	82.6
17-Sep-99	14.3	23.0		7.0	7.05	7.67	346	346	56.7	13.6	76.0
05-Oct-99	14.2	18.8		8.0	7.00	7.64	360	360	66.2	15.2	77.1
07-Oct-99											
21-Oct-99			18.6	8.6							
22-Oct-99	14.2	15.3			6.96	7.25	358	358	72.1	37.1	48.6
27-Oct-99											
09-Nov-99		20.0		11.5							
11-Nov-99	14.2	19.0		12.5	7.12	7.43					
Average	14.6	22.6	14.2	7.3	7.11	7.57	324	324	49.4	16.8	66.9

* Value was not included in calculation of the average.

Table B. Cell 1 — 2" Tonka Packing Data – Used to construct figure 24

Date of Data Collection	Fe (II) (mg/L)		Change in Fe II Conc. (%)	Total Fe (mg/L)		Total Fe Rem. (%)	DO (mg/L)		Effluent DO % Saturated
	Inf.	Eff.		Inf.	Eff.		Inf.	Eff.	
16-Jul-99	6.57	4.61	29.8						
19-Jul-99	6.34	5.43	14.4	5.48	5.61	–2.4	1.31	7.17	70.3
21-Jul-99	5.87	5.06	13.8				1.52	6.63	65.0
26-Jul-99	6.21	4.93	20.6				3.30	10.10	98.8
28-Jul-99	5.98	4.41	26.3	5.85	5.72	2.2	2.40	7.82	76.5
30-Jul-99	6.06	4.89	19.3				2.40	10.00	97.8
02-Aug-99	5.93	4.52	23.8	6.47	4.80	25.8	4.40	10.50	102.3
04-Aug-99	6.04	5.13	15.1				2.80	9.90	96.5
05-Aug-99	6.00	4.94	17.7						
10-Aug-99	6.92	4.72	31.8				1.70	9.00	88.1
11-Aug-99	6.07	4.73	22.1	6.92	5.75	16.9	0.50	8.90	87.3
12-Aug-99	6.31	5.09	19.3				0.80	8.80	85.9
16-Aug-99	5.76	3.56	38.2				1.82	8.56	83.8
18-Aug-99	5.61	4.37	22.1				3.06	8.32	81.8
20-Aug-99	7.00	4.42	36.9				1.24	8.30	80.6
25-Aug-99	6.47	4.14	36.0				0.80	9.40	91.8
27-Aug-99	6.20	4.50	27.4						
10-Sep-99	6.42	4.50	29.9						
13-Sep-99				6.66	5.80	12.9	0.70	9.80	94.9
17-Sep-99	6.40	4.71	26.4						
05-Oct-99				6.50	5.85	10.0			
07-Oct-99	6.65	5.10	23.3				0.60	9.50	
21-Oct-99							0.70	9.20	
22-Oct-99				6.50	4.76	26.8			
27-Oct-99				6.50	5.55	14.6	1.40	9.50	
09-Nov-99	6.67	5.12	23.2						
11-Nov-99							0.80	9.40	91.0
Average	6.26	4.71	24.6	6.36	5.48	13.4	1.70	8.99	87.0

Table C. Cell 2 — No Packing (Empty) – Used to construct figure 9

Date of Data Collection	Water Temp. (°C)	Air Temp. (°C)	Flow Rate (gpm)	Pressure (psi)	pH		Alk. (mg/L)		CO_2 (mg/L)		% CO_2 Removal
					Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	
02-Jul-99	17.0	29.6	16.5	8.0	7.03	7.14	356	356	61.1	45.1	26.2
06-Jul-99	16.8	30.0	18.0	10.5	7.04	7.24	348	342	58.3	34.5	40.8
07-Jul-99	15.0	30.0	18.0	10.5							
08-Jul-99		40.7	18.0	12.0							
09-Jul-99	14.5	30.5			7.12	7.38	340	340	47.4	25.9	45.3
12-Jul-99	14.2	17.5	17.5	10.5	7.02	7.25	338	338	56.7	35.0	38.2
14-Jul-99	14.4			9.0	7.17	7.50	324	324	40.3	18.8	53.3
Average	15.3	29.7	17.6	10.1	7.08	7.30	341	340	52.7	31.9	40.8

Table D. Cell 2 — No Packing (Empty) – Used to construct figure 10

Date of Data Collection	Fe (II) (mg/L)		Change in Fe II Conc. (%)	Total Fe (mg/L)		Total Fe Rem. (%)	DO (mg/L)		Effluent DO % Saturated
	Inf.	Eff.		Inf.	Eff.		Inf.	Eff.	
02-Jul-99		3.00*		6.10	5.55	9.0			
06-Jul-99	3.13*	1.91*	39.0*	5.90	5.85	0.8			
07-Jul-99	4.83*	3.2*	33.7*	5.95	5.60	5.9			
08-Jul-99	5.96	5.34	10.4						
09-Jul-99	6.28	5.60	10.8						
12-Jul-99	6.26	5.44	13.1						
14-Jul-99	6.68	5.50	17.7						
Average	6.30	5.47	13.0	5.98	5.67	5.2			

* Value was not included in calculation of the average.

Table E. Cell 2 — 1" New Tonka Packing – Used to construct figure 21

Date of Data Collection	Water Temp. (°C)	Air Temp. (°C)	Flow Rate (gpm)	Pressure (psi)	pH		Alk. (mg/L)		CO_2 (mg/L)		% CO_2 Removal
					Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	
16-Jul-99	14.4	22.0			7.45	7.54	310	310	20.2*	16.4*	18.9*
19-Jul-99	15.0	22.0			7.19	7.45	328	328	38.9	21.1	45.8
21-Jul-99	14.7	22.7			7.27	7.34	334	334	33.0*	27.8*	15.5*
26-Jul-99	14.7	16.5	12.5	7.0	7.36	7.42	340	340	27.3*	23.6*	13.6*
28-Jul-99			12.5	7.0	7.22	7.89	338	338	37.4		
30-Jul-99	14.7	22.0		7.0	7.04	7.59	334	334	56.0	15.7	72.0
02-Aug-99	14.4	17.3		7.0	7.33	7.64	324	324	27.9	13.6	51.1
04-Aug-99	14.6	25.6		6.0	7.07	7.53	334	334	52.2	18.0	65.5
05-Aug-99	14.5	24.0		6.0	7.08	7.56	348	348	53.2	17.5	67.0
10-Aug-99	14.7		11.5	6.0	7.15	7.60	334	334	43.5	15.3	64.8
11-Aug-99	14.7	27.8		6.5	7.17	7.63	338	338	42.0	14.5	65.6
12-Aug-99	14.9				7.16	7.61	344	344	43.7	15.3	64.9
16-Aug-99	14.8				6.99	7.75	334	334	62.8	10.8	82.8
18-Aug-99	15.2	26.0			6.93	7.69	334	334	72.1	12.3	82.9
20-Aug-99	14.7	24.2			6.88	7.66	334	334	80.9	13.3	83.5
25-Aug-99	14.5	27.0	15.7	8.0	7.07	7.45	334	334	52.2	21.7	58.5
27-Aug-99	14.7				7.03	7.42	342	342	58.7	23.7	59.6
10-Sep-99	14.5				7.04	7.72	342	342	57.3	11.9	79.2
13-Sep-99	14.3				7.04	7.84	354	354	59.3	9.4	84.2
17-Sep-99	14.3				7.05	7.67	346	346	56.7	13.6	76.0
05-Oct-99	14.2	18.8		8.0	7.00	7.54	360	360	66.2	19.1	71.1
07-Oct-99											
21-Oct-99			18.6	8.6							
22-Oct-99	14.2	15.3			6.96	7.29	358	358	72.1	33.8	53.1
27-Oct-99											
09-Nov-99		20.0		11.5							
11-Nov-99	14.1	19.0		12.5	7.12	7.73					
Average	14.6	21.9	14.2	7.8	7.11	7.59	338	338	54.4	16.7	68.0

* Value was not included in calculation of the average.

Table F. Cell 2 — 1" New Tonka Packing – Used to construct figure 22

Date of Data Collection	Fe (II) (mg/L)		Change in Fe II Conc. (%)	Total Fe (mg/L)		Total Fe Rem. (%)	DO (mg/L)		Effluent DO % Saturated
	Inf.	Eff.		Inf.	Eff.		Inf.	Eff.	
16-Jul-99	6.57	4.49	31.7						
19-Jul-99	6.34*	6.09*	3.9*				1.31		
21-Jul-99	5.87	4.80	18.2				1.52		
26-Jul-99	6.21	4.93	20.6				3.30	10.20	100.2
28-Jul-99	5.98	4.55	23.9	5.85	5.05	13.7	2.40	8.18	
30-Jul-99	6.06	4.62	23.8				2.40	10.20	100.2
02-Aug-99	5.93	4.60	22.4	5.93	5.07	14.5	4.40	10.90	94.3
04-Aug-99	6.04	5.16	14.6				2.80	9.90	103.4
05-Aug-99	6.00	4.59	23.5						
10-Aug-99	6.92	4.54	34.4				1.70	9.10	112.3
11-Aug-99	6.07	4.47	26.4	6.92	5.94	14.2	0.50	9.00	113.6
12-Aug-99	6.31	4.77	24.4				0.80	8.90	114.3
16-Aug-99	5.76	2.98	48.3				1.82	8.95	113.9
18-Aug-99	5.61	3.31	41.0				3.06	8.55	118.2
20-Aug-99	7.00	4.07	41.9				1.24	8.67	117.9
25-Aug-99	6.47	4.00	38.2				0.80	9.70	105.8
27-Aug-99	6.20	3.96	36.1						
10-Sep-99	6.42	3.52	45.2						
13-Sep-99					5.55			9.80	105.1
17-Sep-99	6.40	3.22	49.7						
05-Oct-99				6.50	6.20	4.6			
07-Oct-99	6.65	5.10	23.3				0.60	9.70	
21-Oct-99							0.70	9.50	
22-Oct-99				6.50	4.13	36.5			
27-Oct-99				6.50	6.20	4.6	1.40	9.40	
09-Nov-99	6.67	4.10	38.5						
11-Nov-99							0.80	9.40	110.1
Average	6.26	4.29	31.3	6.37	5.45	14.7	1.75	9.41	108.4

* Value was not included in calculation of the average.

Table G. Cell 3 — 1" Solid Packing – Used to construct figure 25

Date of Data Collection	Water Temp. (°C)	Air Temp. (°C)	Flow Rate (gpm)	Pressure (psi)	pH		Alk. (mg/L)		CO_2 (mg/L)		% CO_2 Removal
					Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	
29-Jun-99	15.7	24.1	14.0	7.0	7.04	7.04	350	350	58.7	57.1	
30-Jun-99	16.9	23.0	14.0	7.0	7.13	7.17	362	384	49.3*	45.5*	7.8*
02-Jul-99	17.0	29.6	16.5	8.0	7.03	7.36	356	350	61.1	26.7	56.3
06-Jul-99	17.0	30.0	18.0	10.5	7.04	7.40	348	332	58.3	23.1	60.4
07-Jul-99	14.5	30.0	18.0	10.5	7.15	7.43	336	336	43.7	22.9	47.7
08-Jul-99		40.7	18.0	12.0	7.14		332	332	44.2		
09-Jul-99	14.7	30.5			7.12	7.48	340	340	47.4	20.5	56.7
12-Jul-99	14.3	17.5	17.5	10.5	7.02	7.43	338	338	56.7	23.1	59.3
14-Jul-99	14.4						324	324	40.3		
16-Jul-99	14.7	22.0			7.45	7.55	310	310	20.2	15.9	21.2
19-Jul-99	14.6	22.5			7.19	7.65	328	328	38.9	13.4	65.5
21-Jul-99	14.7	22.7			7.27	7.50	334	334	33.0	19.3	41.6
26-Jul-99	14.7	16.5	12.5	7.0	7.36	7.83	340	340	27.3	9.2	66.4
28-Jul-99	14.7		12.5	7.0	7.22	7.67	338	338	37.4	13.2	64.8
30-Jul-99	14.7	22.0		7.0	7.04	7.70	334	334	56.0	12.2	78.3
02-Aug-99	14.5	17.3		7.0	7.33	7.74	324	324	27.9	10.8	61.3
04-Aug-99	14.7	25.6		6.0	7.07	7.66	334	334	52.2	13.3	74.5
05-Aug-99	14.5	24.0		6.0	7.08	7.62	348	348	53.2	15.3	71.3
10-Aug-99	14.8		11.5	6.0	7.15	7.64	334	334	43.5	13.9	67.9
11-Aug-99	14.7	27.8		6.5	7.17	7.65	338	338	42.0	13.8	67.1
12-Aug-99	14.7				7.16	7.67	344	344	43.7	13.4	69.3
16-Aug-99	14.8				6.99	7.81	334	334	62.8	9.4	85.0
18-Aug-99	15.2	26.0			6.93	7.75	334	334	72.1	10.7	85.1
20-Aug-99	14.7	24.2			6.88	7.66	334	334	80.9	13.3	83.5
25-Aug-99	14.6	27.0	15.7	8.0	7.07	7.51	334	334	52.2	18.9	63.9
27-Aug-99	14.5				7.03	7.48	342	342	58.7	20.7	64.7
10-Sep-99	14.5				7.04	7.70	342	342	57.3	12.5	78.2
13-Sep-99	14.2				7.04	7.80	354	354	59.3	10.3	82.6
17-Sep-99	14.3				7.05	7.65	346	346	56.7	14.2	74.9
05-Oct-99	14.3	18.8		8.0	7.00	7.64	360	360	66.2	15.2	77.1
07-Oct-99											
21-Oct-99			18.6	8.6							
22-Oct-99	14.1	15.3			6.96	7.44	358	358	72.1	24.0	66.8
27-Oct-99											
09-Nov-99		20.0		11.5							
11-Nov-99	14.1	19.0		12.5	7.12	7.49					
Average	14.8	24.0	15.6	8.3	7.11	7.57	340	340	50.8	17.4	66.3

* Value was not included in calculation of the average.

Table H. Cell 3 — 1" Solid Packing – Used to construct figure 26

Date of Data Collection	Fe (II) (mg/L)		Change in Fe II Conc. (%)	Total Fe (mg/L)		Total Fe Rem. (%)	DO (mg/L)		Effluent DO % Saturated
	Inf.	Eff.		Inf.	Eff.		Inf.	Eff.	
29-Jun-99				6.80	6.37	6.3			
30-Jun-99				6.10	7.15	-17.2			
02-Jul-99		2.12		6.10	6.05	0.8			
06-Jul-99	3.13*	2.62*	16.3*	5.90	5.70	3.4			
07-Jul-99	4.83	2.82	41.6	5.95	5.30	10.9			
08-Jul-99	5.96	4.82	19.1						
09-Jul-99	6.28	4.50	28.3						
12-Jul-99	6.26	4.50	28.1						
14-Jul-99	6.68	3.56	46.7						
16-Jul-99	6.57	3.79	42.3	5.48	4.64	15.3			
19-Jul-99	6.34	4.30	32.2				1.3	6.9	67.4
21-Jul-99	5.87	3.37	42.6				1.5	6.6	64.6
26-Jul-99	6.21	4.55	26.7				3.3	10.6	103.7
28-Jul-99	5.98	3.67	38.6	5.85	5.15	12.0	2.4	8.8	86.1
30-Jul-99	6.06	4.96	18.2				2.4	10.6	103.7
02-Aug-99	5.93	4.07	31.4	6.47	5.40	16.5	4.4	10.7	104.3
04-Aug-99	6.04	4.57	24.3				2.8	9.9	96.9
05-Aug-99	6.00	3.90	35.0						
10-Aug-99	6.92	3.84	44.5				1.7	9.1	89.3
11-Aug-99	6.07	3.84	36.7	6.92	5.60	19.1	0.5	8.7	85.1
12-Aug-99	6.31	5.00	20.8				0.8	8.9	87.1
16-Aug-99	5.76	2.24	61.1				1.8	8.8	86.4
18-Aug-99	5.61	2.95	47.4				3.1	8.4	83.1
20-Aug-99	7.00	4.56	34.9				1.2	8.5	83.2
25-Aug-99	6.47	5.59	13.6				0.8	9.7	94.7
27-Aug-99	6.20	4.22	31.9						
10-Sep-99	6.42	5.09	20.7						
13-Sep-99				6.66	4.74	28.8		9.8	94.9
17-Sep-99	6.40	3.70	42.2						
05-Oct-99				6.50	6.00	7.7			
07-Oct-99	6.65	4.34	34.7				0.6	9.6	
21-Oct-99							0.7	9.5	
22-Oct-99				6.50	4.83	25.7			
27-Oct-99				6.50	5.56	14.5	1.4	9.6	
09-Nov-99	6.67	5.19	22.2						
11-Nov-99							0.8	9.4	90.8
Average	6.21	4.08	33.3	6.29	5.58	11.1	1.8	9.2	88.8

* Value was not included in calculation of the average.

Table I. Cell 4 — 1" Reused Tonka Packing, Sodium Silicate Addition – Used to construct figure 13

Date of Data Collection	Water Temp. (°C)	Air Temp. (°C)	Flow Rate (gpm)	Pressure (psi)	pH		Alk. (mg/L)		CO_2 (mg/L)		% CO_2 Removal
					Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	
29-Jun-99	15.5	24.1	14.0	7.0	7.04	7.44	350	366	58.7	23.9	59.3
30-Jun-99	16.9	23.0	14.0	7.0	7.13	7.38	362	352	49.3	25.7	47.9
02-Jul-99	16.6	29.6	16.5	8.0	7.03	7.49	356	354	61.1	20.2	67.0
06-Jul-99	16.7	30.0	18.0	10.5	7.04	7.44	348	316	58.3	20.2	65.4
07-Jul-99	14.7	30.0	18.0	10.5	7.15		336	336	43.7		
08-Jul-99		40.7	18.0	12.0	7.14		332	332	44.2		
09-Jul-99	14.6	30.5			7.12	7.48	340	340	47.4	20.6	56.6
12-Jul-99	14.4	17.5	17.5	10.5	7.02	7.45	338	338	56.7	22.0	61.2
14-Jul-99	14.5						324	324	40.3		
16-Jul-99	14.7	22.0			7.45	7.56	310	310	20.2	15.6	23.0
19-Jul-99	16.0	22.5			7.19	7.51	328	328	38.9	18.0	53.7
21-Jul-99	16.2	22.7			7.27	7.50	334	334	33.0	18.7	43.2
26-Jul-99	14.7	16.5		7.0	7.36	7.68	340	340	27.3	13.0	52.5
28-Jul-99	14.7		12.5	7.0	7.22	7.79	338	338	37.4	10.0	73.3
30-Jul-99		22.0	12.5	7.0							
02-Aug-99	14.5	17.3		7.0	7.33	7.67	324	324	27.9	12.7	54.5
04-Aug-99	14.6	25.6		6.0	7.07	7.65	334	334	52.2	13.7	73.9
05-Aug-99	14.6	24.0		6.0	7.08	7.62	348	348	53.2	15.3	71.3
10-Aug-99	14.6		11.5	6.0	7.15	7.53	334	334	43.5	18.0	58.6
11-Aug-99	14.6	27.8		6.5	7.17	7.52	338	338	42.0	18.7	55.6
12-Aug-99	14.6				7.16	7.58	344	344	43.7	16.5	62.2
16-Aug-99	14.7				6.99	7.72	334	334	62.8	11.6	81.5
18-Aug-99	15.0	26.0			6.93	8.03	334	334	72.1	5.7	92.2
20-Aug-99	14.9	24.2			6.88	7.65	334	334	80.9	13.6	83.2
25-Aug-99	14.5	27.0	15.7	8.0	7.07	7.43	334	334	52.2	22.7	56.5
27-Aug-99	14.4				7.03	7.42	342	342	58.7	23.9	59.3
10-Sep-99	14.4				7.04	7.65	342	342	57.3	14.0	75.5
13-Sep-99	14.2				7.04	7.77	354	354	59.3	11.1	81.3
17-Sep-99	14.3				7.05	7.64	346	346	56.7	14.6	74.3
05-Oct-99	14.3	18.8		8.0	7.00	7.55	360	360	66.2	18.6	71.8
07-Oct-99											
21-Oct-99			18.6	8.6							
22-Oct-99	14.0	15.3			6.96	7.41	358	358	72.1	25.7	64.3
27-Oct-99											
09-Nov-99		20.0		11.5							
11-Nov-99	14.2	19.0		12.5	7.12	7.48					
Average	14.9	24.0	15.6	8.3	7.11	7.57	340	339	50.6	17.2	63.7

Table J. Cell 4 — 1" Reused Tonka Packing, Sodium Silicate Addition – Used to construct figure 18

Date of Data Collection	Fe (II) (mg/L) Inf.	Fe (II) (mg/L) Eff.	Change in Fe II Conc. (%)	Total Fe (mg/L) Inf.	Total Fe (mg/L) Eff.	Total Fe Rem. (%)	DO (mg/L) Inf.	DO (mg/L) Eff.	Effluent DO % Saturated
29-Jun-99				6.80	6.00	11.8			
30-Jun-99				6.10	6.73	-10.3			
02-Jul-99				6.10	5.60	8.2			
06-Jul-99	3.13*	3.05*	2.6*	5.90	5.80	1.7			
07-Jul-99	4.83	2.25	53.4	5.95	5.70	4.2			
08-Jul-99	5.96	5.10	14.4						
09-Jul-99	6.28	4.72	24.8						
12-Jul-99	6.26	4.35	30.5						
14-Jul-99	6.68	4.25	36.4						
16-Jul-99	6.57	4.79	27.1						
19-Jul-99	6.34	2.58	59.3	5.48	5.83	-6.4	1.3	8.5	85.4
21-Jul-99	5.87	3.37	42.6				1.5	6.4	64.6
26-Jul-99	6.21	3.75	39.6				3.3	10.1	98.8
28-Jul-99	5.98	3.68	38.5	5.85	5.40	7.7	2.4	7.8	76.3
30-Jul-99									
02-Aug-99	5.93	3.44	42.0	6.47	5.90	8.8	4.4	10.8	105.3
04-Aug-99	6.04	4.45	26.3				2.8	9.9	96.7
05-Aug-99	6.00	3.92	34.7						
10-Aug-99	6.92	4.13	40.3				1.7	8.8	85.9
11-Aug-99	6.07	5.13	15.5	6.92	6.64	4.1	0.5	8.8	85.9
12-Aug-99	6.31	4.39	30.4				0.8	8.8	85.9
16-Aug-99	5.76	2.93	49.1				1.8	8.0	78.3
18-Aug-99	5.61	2.50	55.4				3.1	8.4	82.8
20-Aug-99	7.00	4.34	38.0				1.2	8.3	81.6
25-Aug-99	6.47	5.16	20.3				0.8	9.4	91.6
27-Aug-99	6.20	4.66	24.8						
10-Sep-99	6.42	3.67	42.8						
13-Sep-99				6.66	5.64	15.3		9.4	91.0
17-Sep-99	6.40	2.69	58.0						
05-Oct-99				6.50	5.50	15.4			
07-Oct-99	6.65	4.05	39.1				0.6	9.6	
21-Oct-99							0.7	9.3	
22-Oct-99				6.50	4.44	31.7			
27-Oct-99				6.50	5.45	16.2	1.4	9.6	
09-Nov-99	6.67	4.40	34.0						
11-Nov-99							0.8	9.7	93.9
Average	6.22	3.95	36.7	6.29	5.74	8.3	1.7	9.0	86.9

* Value was not included in calculation of the average.

Table K. Cell 5 — 1" Reused Tonka Packing – Used to construct figure 11

Date of Data Collection	Water Temp. (°C)	Air Temp. (°C)	Flow Rate (gpm)	Pressure (psi)	pH		Alk. (mg/L)		CO_2 (mg/L)		% CO_2 Removal
					Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	
14-Jul-99											
16-Jul-99	14.7	22.0			7.45	7.56	310	310	20.2*	15.6*	23.0*
19-Jul-99	14.7	22.5			7.19	7.57	328	328	38.9	16.1	58.6
21-Jul-99	14.6	22.7			7.27	7.92	334	334	33.0	7.3	77.7
26-Jul-99	14.7	16.5	12.5	7.0	7.36	7.73	340	340	27.3	11.5	57.7
28-Jul-99	14.8		12.5	7.0	7.22	7.66	338	338	37.4	13.5	64.0
30-Jul-99	14.8	22.0		7.0	7.04	7.74	334	334	56.0	11.1	80.2
02-Aug-99	14.7	17.3		7.0	7.33	7.66	324	324	27.9	12.9	53.6
04-Aug-99	14.7	25.6		6.0	7.07	7.66	334	334	52.2	13.3	74.5
05-Aug-99	14.6	24.0		6.0	7.08	7.70	348	348	53.2	12.7	76.1
10-Aug-99	14.8		11.5	6.0	7.15	7.60	334	334	43.5	15.3	64.9
11-Aug-99	15.0	27.8		6.5	7.15	7.73	338	338	42.0	11.4	72.8
12-Aug-99					7.16	7.61	344	344	43.7		
16-Aug-99	15.2				6.99	7.84	334	334	62.8	8.7	86.1
18-Aug-99	16.3	26.0			6.93	8.00	334	334	72.1	5.9	91.8
20-Aug-99	14.9	24.2			6.88	7.67	334	334	80.9	13.0	84.0
25-Aug-99	14.6	27.0	15.7	8.0	7.07	7.54	334	334	52.2	17.6	66.3
27-Aug-99	14.4				7.03	7.44	342	342	58.7	22.8	61.2
10-Sep-99	14.5				7.04	7.71	342	342	57.3	12.2	78.7
13-Sep-99	14.4				7.04	7.84	354	354	59.3	9.4	84.2
17-Sep-99	14.3				7.05	7.67	346	346	56.7	13.6	76.0
05-Oct-99	14.3	18.8		8.0	7.00	7.61	360	360	66.2	16.2	75.5
07-Oct-99											
21-Oct-99			18.6	8.6							
22-Oct-99	14.3	15.3			6.96	7.38	358	358	72.1	27.4	62.0
27-Oct-99											
09-Nov-99		20.0		11.5							
11-Nov-99	14.4	19.0		12.5	7.12	7.44					
Average	14.7	21.9	14.2	7.8	7.11	7.66	338	338	52.1	13.6	72.3

* Value was not included in calculation of the average.

Table L. Cell 5 — 1" Reused Tonka Packing – Used to construct figure 12

Date of Data Collection	Fe (II) (mg/L)		Change in Fe II Conc. (%)	Total Fe (mg/L)		Total Fe Rem. (%)	DO (mg/L)		Effluent DO % Saturated
	Inf.	Eff.		Inf.	Eff.		Inf.	Eff.	
14-Jul-99	6.68	3.56	46.7						
16-Jul-99	6.57	4.46	32.1						
19-Jul-99	6.34	4.69	26.0	5.48	5.21	4.9	1.3	8.6	84.1
21-Jul-99	5.87	4.57	22.2				1.5	6.6	64.5
26-Jul-99	6.21	4.56	26.6				3.3	10.6	103.7
28-Jul-99	5.98	5.09	14.9	5.85	4.85	17.1	2.4	8.8	86.4
30-Jul-99	6.06	4.39	27.6				2.4	10.6	104.0
02-Aug-99	5.93	4.29	27.7	6.47	4.89	24.4	4.4	11.1	108.6
04-Aug-99	6.04	3.90	35.4				2.8	10.0	97.8
05-Aug-99	6.00	4.62	23.0						
10-Aug-99	6.92	4.22	39.0				1.7	9.0	88.3
11-Aug-99	6.07	4.17	31.3	6.92	5.54	19.9	0.5	8.5	83.7
12-Aug-99	6.31	4.48	29.0				0.8	8.5	
16-Aug-99	5.76	5.24	9.0				1.8	8.5	84.1
18-Aug-99	5.61	4.97	11.4				3.1	8.3	83.9
20-Aug-99	7.00	3.38	51.7				1.2	8.1	79.6
25-Aug-99	6.47	4.28	33.9				0.8	9.5	92.8
27-Aug-99	6.20	3.65	41.1						
10-Sep-99	6.42	4.12	35.8						
13-Sep-99					5.43			9.6	93.4
17-Sep-99	6.40	3.99	37.7						
05-Oct-99				6.50	6.20	4.6			
07-Oct-99	6.65	4.70	29.3				0.6	9.6	
21-Oct-99							0.7	9.4	
22-Oct-99				6.50	5.00	23.1			
27-Oct-99				6.50	5.70	12.3	1.4	9.8	
09-Nov-99	6.67	5.00	25.0						
11-Nov-99							0.8	9.7	94.4
Average	6.28	4.38	29.8	6.32	5.35	15.2	1.8	9.2	90.0

Table N. Cell 6 — 1" Reused Tonka Packing – Used to construct figure 14.

Date of Data Collection	Water Temp. (°C)	Air Temp. (°C)	Flow Rate (gpm)	Pressure (psi)	pH		Alk. (mg/L)		CO_2 (mg/L)		% CO_2 Removal
					Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	
29-Jun-99	15.5	24.1		7.0	7.04	7.46	350	352	58.7	22.2	62.2
30-Jun-99	16.9	23.0		7.0	7.14	7.53	362	352	49.3	18.2	63.1
02-Jul-99	16.8	29.6		8.0	7.03	7.55	356	350	61.1	17.3	71.7
06-Jul-99	17.3	30.0		10.5	7.04	7.50	348	318	58.3	17.5	70.0
07-Jul-99	14.6	30.0		10.5	7.15	7.55	336	336	43.7	17.3	60.4
08-Jul-99		40.7		12.0	7.14		332	332	44.2		
09-Jul-99	14.6	30.5			7.12	7.46	340	340	47.4	21.5	54.6
12-Jul-99	14.4	17.5		10.5	7.04	7.14	338	338	56.7	44.9	20.7
14-Jul-99	14.5				7.17		324	324	40.3		
16-Jul-99	14.7	22.0			7.45	7.53	310	310	20.2	16.7	17.5
19-Jul-99	14.8	22.5			7.19	7.62	328	328	38.9	14.3	63.2
21-Jul-99	15.1	22.7			7.27	7.81	334	334	33.0	9.4	71.6
26-Jul-99	15.3	16.5		7.0	7.36	7.73	340	340	27.3	11.4	58.2
28-Jul-99	14.7			7.0	7.22	7.86	338	338	37.4	8.5	77.3
30-Jul-99	14.8	22.0		7.0	7.04	7.70	334	334	56.0	12.1	78.3
02-Aug-99	14.4	17.3		7.0	7.33	7.82	324	324	27.9	9.0	67.7
04-Aug-99	14.7	25.6		6.0	7.07	7.71	334	334	52.2	11.9	77.3
05-Aug-99	14.6	24.0		6.0	7.08	7.71	348	348	53.2	12.4	76.7
10-Aug-99	15.0		11.5	6.0	7.15	7.60	334	334	43.5	15.2	65.0
11-Aug-99	15.0	27.8		6.5							
12-Aug-99					7.16	7.61	344	344	43.7		
16-Aug-99	15.2				6.99	7.84	334	334	62.8	8.7	86.1
18-Aug-99	15.4	26.0			6.93	7.92	334	334	72.1	7.2	90.0
20-Aug-99	14.6	24.2			6.88	7.72	334	334	80.9	11.6	85.6
25-Aug-99	14.5	27.0	15.7	8.0	7.07	7.45	334	334	52.2	21.7	58.5
27-Aug-99	14.6				7.03	7.40	342	342	58.7	24.9	57.6
10-Sep-99	14.5				7.04	7.71	342	342	57.3	12.2	78.7
13-Sep-99	14.4				7.04	7.80	354	354	59.3	10.3	82.7
17-Sep-99	14.3				7.05	7.66	346	346	56.7	13.9	75.5
05-Oct-99	14.4	18.8		8.0	7.00	7.61	360	360	66.2	16.2	75.5
07-Oct-99											
Average	15.0	24.8	13.6	7.9	7.11	7.63	339	338	50.3	15.6	67.1

Table O. Cell 6 — 1" Reused Tonka Packing

Date of Data Collection	Fe (II) (mg/L) Inf.	Fe (II) (mg/L) Eff.	Change in Fe II Conc. (%)	Total Fe (mg/L) Inf.	Total Fe (mg/L) Eff.	Total Fe Rem. (%)	DO (mg/L) Inf.	DO (mg/L) Eff.	Effluent DO % Saturated
29-Jun-99				6.80	5.70	16.2			
30-Jun-99				6.10	7.00	-14.8			
02-Jul-99				6.10	5.95	2.5			
06-Jul-99	3.13*	3.58*	-14.4*	5.90	6.00	-1.7			
07-Jul-99	4.83	3.78	21.7	5.95	5.90	0.8			
08-Jul-99	5.96	5.25	11.9						
09-Jul-99	6.98	4.22	39.5						
12-Jul-99	6.26	4.48	28.4						
14-Jul-99	6.68	4.65	30.4						
16-Jul-99	6.57	4.28	34.9						
19-Jul-99	6.34	3.25	48.7	5.48	5.09	7.1	1.31	8.81	86.5
21-Jul-99	5.87	4.81	18.1				1.52	6.23	61.5
26-Jul-99	6.21	5.28	15.0	6.21	5.28	15.0	3.30	10.70	106.0
28-Jul-99	5.98	4.87	18.6	5.85			2.40	8.80	86.1
30-Jul-99	6.06	4.23	30.2				2.40	11.00	107.9
02-Aug-99	5.93	4.40	25.8	6.47	4.73	26.9	4.40	11.20	108.9
04-Aug-99	6.04	3.76	37.8				2.80	10.10	98.8
05-Aug-99	6.00	3.55	40.8						
10-Aug-99	6.92	3.72	46.2				1.70	8.90	87.7
11-Aug-99									
12-Aug-99	6.31	4.48	29.0				0.80	8.50	
16-Aug-99	5.76	6.92	-20.1				1.82	8.43	83.4
18-Aug-99	5.61	4.97	11.4				3.06	7.73	76.8
20-Aug-99	7.00	3.41	51.3				1.24	8.42	82.2
25-Aug-99	6.47	4.17	35.6				0.80	9.40	91.6
27-Aug-99	6.20	3.70	40.3						
10-Sep-99	6.42	3.94	38.6						
13-Sep-99				6.66	6.02	9.6		7.80	75.9
17-Sep-99	6.40	4.54	29.1						
05-Oct-99				6.50	6.00	7.7			
07-Oct-99	6.65	6.15	7.5				0.60	9.10	
Average	6.23	4.45	27.9	6.18	5.77	6.9	2.01	9.01	88.7

* Value was not included in calculation of the average.

Table P. Cell 6 — Triangular Packing

Date of Data Collection	Water Temp. (°C)	Air Temp. (°C)	Flow Rate (gpm)	Pressure (psi)	pH		Alk. (mg/L)		CO_2 (mg/L)		% CO_2 Removal
					Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	
21-Oct-99			18.61	8.6							
22-Oct-99	14.1	15.3			6.96	7.42	358	358	71.6	25.1	65.2
27-Oct-99											
09-Nov-99		20		11.5							
11-Nov-99	14.4	19		12.5	7.12	7.31					
Average	14.3	18.1	18.61	10.9	7.04	7.37	358	358	71.6	25.1	65.2

Table Q. Cell 6 — Triangular Packing – Used to construct figure 15.

Date of Data Collection	Fe (II) (mg/l)		Change in Fe II Conc. (%)	Total Fe (mg/L)		Total Fe Rem. (%)	DO (mg/L)		Effluent DO % Saturated
	Inf.	Eff.		Inf.	Eff.		Inf.	Eff.	
21-Oct-99				6.5	6.3	3.1	0.7	8.9	
22-Oct-99				6.5	6.5	0.0			
27-Oct-99							1.4	9.6	
09-Nov-99	6.67	8.28	-24.1*						
11-Nov-99							0.8	9.8	95.3
Average	6.67	8.28	-	6.5	6.4	1.5	1.0	9.4	95.3

* Value was not included in calculation of the average.

Table R. Cell 7 — 1" Reused Tonka Packing, Low Flow Rate – Used to construct figure 16.

Date of Data Collection	Water Temp. (°C)	Air Temp. (°C)	Flow Rate (gpm)	Pressure (psi)	pH		Alk. (mg/L)		CO_2 (mg/L)		% CO_2 Removal
					Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	
30-Jun-99	16.5	23.0			7.13	7.52	362	352	49.3	18.7	62.0
02-Jul-99	17.0	29.6		7.0	7.03	7.55	356	358	61.1	17.6	71.1
06-Jul-99	17.3	30.0		8.0	7.04	7.50	348	320	58.3	17.6	69.8
07-Jul-99	15.0	30.0		10.5	7.15	7.61	336	336	43.7	15.0	65.8
08-Jul-99		40.7		10.5	7.14		332	332	44.2		
09-Jul-99	15.0	30.5		12.0	7.12	7.52	340	340	47.4	18.6	60.7
12-Jul-99	14.5	17.5			7.04	7.40	338	338	56.7	24.6	56.5
14-Jul-99	14.8			10.5	7.17	7.85	324	324	40.3	8.3	79.3
16-Jul-99	15.5	22.0			7.45	7.86	310	310	20.2	7.7	62.0
19-Jul-99	16.4	22.5			7.19	7.34	328	328	38.9	26.5	32.0
21-Jul-99	15.6	22.7			7.27	7.81	334	334	33.0	9.3	71.9
26-Jul-99	15.6	16.5		7.0	7.36	7.84	340	340	27.3	8.8	67.7
28-Jul-99	CLOGGED			7.0							
30-Jul-99	CLOGGED			7.0							
02-Aug-99	14.4	17.3		7.0	7.33	7.59	324	324	27.9	15.3	45.2
04-Aug-99	14.6	25.6		6.0	7.07	7.55	334	334	52.2	17.2	67.1
05-Aug-99	14.5	24.0		6.0	7.08	7.52	348	348	53.2	19.2	63.8
10-Aug-99	CLOGGED		11.5	6.0							
11-Aug-99	CLOGGED			6.5							
12-Aug-99	CLOGGED										
16-Aug-99	14.6				6.99	7.49	334	334	62.8	19.8	68.6
18-Aug-99	14.8	26.0			6.93	7.69	334	334	72.1	12.4	82.8
20-Aug-99	15.2	24.2			6.88	7.75	334	334	80.9	10.7	86.7
25-Aug-99		27.0	15.7	8.0							
27-Aug-99	CLOGGED										
10-Sep-99	CLOGGED										
13-Sep-99	CLOGGED										
17-Sep-99	CLOGGED										
05-Oct-99	CLOGGED										
07-Oct-99	CLOGGED										
21-Oct-99	CLOGGED										
22-Oct-99	CLOGGED										
27-Oct-99	CLOGGED										
09-Nov-99	CLOGGED										
11-Nov-99	CLOGGED										
Average	15.4	25.2	13.6	7.9	7.13	7.61	336	334	48.3	15.7	65.5

Table S. Cell 7 — 1" Reused Tonka Packing, Low Flow Rate – Used to construct figure 19.

Date of Data Collection	Fe (II) (mg/L)		Change in Fe II Conc. (%)	Total Fe (mg/L)		Total Fe Rem. (%)	DO (mg/L)		Effluent DO % Saturated
	Inf.	Eff.		Inf.	Eff.		Inf.	Eff.	
30-Jun-99				6.10	6.96	-14.1			
02-Jul-99		0.63*		6.10	6.96	-14.1			
06-Jul-99	3.13	2.30	26.5	5.90	5.30	10.2			
07-Jul-99	4.83	3.20	33.8	5.95	5.55	6.7			
08-Jul-99	5.96	5.20	12.8						
09-Jul-99	6.28	4.22	32.8						
12-Jul-99	6.26	4.15	33.7						
14-Jul-99	6.68	4.03	39.7						
16-Jul-99	6.57	4.04	38.5						
19-Jul-99	6.34	3.81	39.9	5.48	4.06	25.9	1.30	8.70	88.1
21-Jul-99	5.87	3.66	37.7				1.50	6.50	64.8
26-Jul-99	6.21	2.36	62.0				3.30	10.20	101.7
28-Jul-99	CLOGGED								
30-Jul-99	CLOGGED								
02-Aug-99	5.93	5.43	8.4	6.47	5.97	7.7	4.40	11.30	109.9
04-Aug-99	6.04	5.21	13.7				2.80	10.10	98.6
05-Aug-99	6.00	5.38	10.3						
10-Aug-99	CLOGGED								
11-Aug-99	CLOGGED								
12-Aug-99	CLOGGED								
16-Aug-99	5.76	2.03	64.8				1.80	8.20	80.1
18-Aug-99	5.61	1.71	69.5				3.10	8.10	79.5
20-Aug-99	7.00	4.89	30.1				1.20	7.90	78.1
25-Aug-99									
27-Aug-99	CLOGGED								
10-Sep-99	CLOGGED								
13-Sep-99	CLOGGED								
17-Sep-99	CLOGGED								
05-Oct-99	CLOGGED								
07-Oct-99	CLOGGED								
21-Oct-99	CLOGGED								
22-Oct-99	CLOGGED								
27-Oct-99	CLOGGED								
09-Nov-99	CLOGGED								
11-Nov-99	CLOGGED								
Average	5.90	3.85	34.6	6.00	5.80	3.7	2.43	8.88	87.6

* Value was not included in calculation of the average.

Table T. Cell 8. — 1" Reused Tonka Packing, Shock Chlorination Used to construct figure 20.

Date of Data Collection	Water Temp. (°C)	Air Temp. (°C)	Flow Rate (gpm)	Pressure (psi)	pH		Alk. (mg/L)		CO_2 (mg/L)		% CO_2 Removal
					Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	
29-Jun-99	15.8	24.1		7.0	7.04	7.51	350	356	58.7	19.7	66.5
30-Jun-99	16.9	23.0		7.0	7.13	7.48	362	352	49.3	20.4	58.6
02-Jul-99	16.8	29.6		8.0	7.03	7.56	356	360	61.1	17.4	71.5
06-Jul-99	17.1	30.0		10.5	7.04	7.48	348	320	58.3	18.5	68.3
07-Jul-99	15.0	30.0		10.5	7.15	7.51	336	336	43.7	18.8	56.9
08-Jul-99		40.7		12.0	7.14		332	332	44.2		
09-Jul-99	14.7	30.5			7.12	7.48	340	340	47.4	20.5	56.7
12-Jul-99	14.4	17.5		10.5	7.04	7.45	338	338	56.7	22.0	61.2
14-Jul-99	14.8				7.17	7.50	324	324	40.3	18.7	53.7
16-Jul-99	14.7	22.0			7.45	7.55	310	310	20.2	15.9	21.2
19-Jul-99	14.7	22.5			7.19	7.61	328	328	38.9	14.7	62.3
21-Jul-99	14.7	22.7			7.27	7.79	334	334	33.0	9.9	70.0
26-Jul-99	14.9	16.5		7.0	7.36	7.83	340	340	27.3	9.1	66.5
28-Jul-99	14.7			7.0	7.22	7.85	338	338	37.4	8.7	76.7
30-Jul-99	14.7			7.0	7.04	7.70	334	334	56.0	12.2	78.3
02-Aug-99	CLOGGED			7.0							
04-Aug-99	14.6	25.6		6.0	7.07	7.70	334	334	52.2	12.2	76.7
05-Aug-99	14.6	24.0		6.0	7.08	7.69	348	348	53.2	13.0	75.6
10-Aug-99	14.7		11.50	6.0	7.15	7.59	334	334	43.5	15.7	64.0
11-Aug-99	14.7	27.8		6.5	7.17	7.69	338	338	42.0	12.6	70.0
12-Aug-99	14.7				7.16	7.68	344	344	43.7	13.1	70.0
16-Aug-99	15.0				6.99	7.63	334	334	62.8	14.2	77.4
18-Aug-99	15.1	26.0			6.93	7.66	334	334	72.1	13.2	81.7
20-Aug-99	14.6	24.2			6.88	7.62	334	334	80.9	14.6	81.9
25-Aug-99	14.5	27.0	15.70	8.0	7.07	7.36	334	334	52.2	26.7	48.9
27-Aug-99	14.5				7.03	7.38	342	342	58.7	26.1	55.5
10-Sep-99	14.6				7.04	7.69	342	342	57.3	12.8	77.7
13-Sep-99	14.4				7.04	7.84	354	354	59.3	9.4	84.2
17-Sep-99	14.4				7.05	7.73	346	346	56.7	11.8	79.1
05-Oct-99	14.3	18.8		8.0	7.00	7.62	360	360	66.2	15.9	76.0
07-Oct-99											
21-Oct-99			18.61	8.6							
22-Oct-99	14.3	15.3			6.96	7.36	358	358	72.1	28.7	60.2
27-Oct-99											
09-Nov-99		20.0		11.5							
11-Nov-99	14.4	19.0		12.5	7.12	7.38					
Average	14.9	24.4	15.27	8.3	7.10	7.60	340	339	51.5	16.1	67.2

Table U. Cell 8. — 1" Reused Tonka Packing, Shock Chlorination Used with data from subsequent tables to construct figure 27.

Date of Data Collection	Fe (II) (mg/L) Inf.	Fe (II) (mg/L) Eff.	Change in Fe II Conc. (%)	Total Fe (mg/L) Inf.	Total Fe (mg/L) Eff.	Total Fe Rem. (%)	DO (mg/L) Inf.	DO (mg/L) Eff.	Effluent DO % Saturated
29-Jun-99				6.80	6.70	1.5			
30-Jun-99				6.10	6.85	-12.3			
02-Jul-99		1.72*		6.10	6.00	1.6			
06-Jul-99	3.13*	3.57*	-14.1*	5.95	6.20	-4.2			
07-Jul-99	4.83	3.96	18.0	5.95	5.90	0.8			
08-Jul-99	5.96	5.40	9.4						
09-Jul-99	6.28	5.65	10.0						
12-Jul-99	6.26	5.19	17.1						
14-Jul-99	6.68	5.00	25.1						
16-Jul-99	6.57	5.23	20.4						
19-Jul-99	6.34	5.42	14.5	6.34	5.50	13.2	1.3	8.5	83.2
21-Jul-99	5.87	4.67	20.4				1.5	6.4	62.6
26-Jul-99	6.21	5.36	13.7				3.3	10.6	104.2
28-Jul-99	5.98	4.34	27.4	5.85	5.00	14.5	2.4	8.5	83.2
30-Jul-99	6.06	5.22	13.9				2.4	10.6	103.7
02-Aug-99	CLOGGED								
04-Aug-99	6.04	5.08	15.9				2.8	10.1	98.6
05-Aug-99	6.00	5.18	13.7						
10-Aug-99	6.92	4.82	30.3				1.7	9.0	88.1
11-Aug-99	6.07	5.09	16.1	6.94	6.00	13.5	0.5	9.3	91.0
12-Aug-99	6.31	5.16	18.2				0.8	8.3	81.2
16-Aug-99	5.76	1.89	67.2				1.8	8.2	80.8
18-Aug-99	5.61	6.41	-14.3				3.1	8.1	80.0
20-Aug-99	7.00	6.70	4.3				1.2	8.3	81.1
25-Aug-99	6.47	6.22	3.9				0.8	9.1	88.7
27-Aug-99	6.20	5.83	6.0						
10-Sep-99	6.42	5.14	19.9						
13-Sep-99				6.66	4.73	29.0		9.7	94.4
17-Sep-99	6.40	4.62	27.8						
05-Oct-99				6.50	6.20	4.6			
07-Oct-99	6.65	4.86	26.9				0.6	9.6	
21-Oct-99							0.7	9.2	
22-Oct-99				6.50	6.00	7.7			
27-Oct-99				6.50	5.90	9.2	1.4	9.4	
09-Nov-99	6.67	4.45	33.3						
11-Nov-99							0.8	9.6	93.4
Average	6.22	5.08	18.4	6.35	5.92	6.6	1.6	9.0	87.6

* Value was not included in calculation of the average.

Scale Buildup Data

Table V. Scale Buildup (28 June to 15 July)

Cell No.	Packing Position	Length of Packing (m)	Mass of Scale (g)	Scale Buildup (g/m)
Cell 3 (1" Solid, New)	Top	27.9	20.9	74.7
	Middle	27.9	21.0	75.2
	Bottom	27.9	9.4	33.6
	Average	**27.9**	**17.1**	**61.1**
Cell 4 (1" Tonka, SiO_2)	Top	27.9	11.5	41.1
	Middle	27.9	11.9	42.7
	Bottom	27.9	10.4	37.3
	Average	**27.9**	**11.3**	**40.4**
Cell 6 (1" Tonka, Reused)	Top	27.9	17.1	61.3
	Middle	27.9	31.7	113.3
	Bottom	27.9	15.2	54.5
	Average	**27.9**	**21.3**	**76.4**
Cell 7 (1" Tonka, Low Flow)	Top	27.9	11.5	41.0
	Middle	27.9	18.3	65.6
	Bottom	27.9	14.3	51.3
	Average	**27.9**	**14.7**	**52.6**
Cell 8 (1" Tonka, Cl_2)	Top	27.9	10.6	37.9
	Middle	27.9	8.6	30.9
	Bottom	27.9	8.2	29.3
	Average	**27.9**	**9.1**	**32.7**

Table W. Scale Buildup (15 July to 15 August)

Cell No.	Packing Position	Length of Packing (cm)	Mass of Scale (g)	Scale Buildup (g/m)
Cell 1 (2" Tonka, New)	Top	27.9	71.1	254.5
	Middle	27.9	109.5	392.0
	Bottom	27.9	83.4	298.6
	Average	**27.9**	**88.0**	**315.0**
Cell 2 (1" Tonka, New)	Top	27.9	30.8	110.2
	Middle	27.9	27.3	97.6
	Bottom	27.9	27.3	97.7
	Average	**27.9**	**28.5**	**101.9**
Cell 3 (1" Solid, New)	Top	27.9	67.3	241.0
	Middle	27.9	58.1	208.0
	Bottom	27.9	41.7	149.1
	Average	**27.9**	**55.7**	**199.3**
Cell 4 (1" Tonka, SiO_2)	Top	27.9	29.7	106.3
	Middle	27.9	15.2	54.5
	Bottom	27.9	12.3	43.9
	Average	**27.9**	**19.1**	**68.3**
Cell 5 (1" Tonka, Reused)	Top	27.9	57.4	205.4
	Middle	27.9	94.2	337.2
	Bottom	27.9	84.7	303.2
	Average	**27.9**	**78.8**	**281.9**
Cell 6 (1" Tonka, Reused)	Top	27.9	52.5	187.9
	Middle	27.9	90.0	322.2
	Bottom	27.9	75.6	270.5
	Average	**27.9**	**72.7**	**260.2**
Cell 7 (1" Tonka, Low Flow)	Top	27.9	41.2	147.6
	Middle	27.9	40.9	146.5
	Bottom	27.9	22.0	78.7
	Average	**27.9**	**34.7**	**124.3**
Cell 8 (1" Tonka, Cl_2)	Top	27.9	8.6	30.9
	Middle	27.9	8.2	29.4
	Bottom	27.9	9.1	32.4
	Average	**27.9**	**8.6**	**30.9**

Table X. Scale Buildup (15 August to 28 September)

Cell No.	Packing Position	Length of Packing (cm)	Mass of Scale (g)	Scale Buildup (g/m)
Cell 1 (2" Tonka, New)	Top	27.9	134.6	482.3
	Middle	27.9	206.8	741.0
	Bottom	27.9	198.3	710.7
	Average	**27.9**	**179.9**	**644.7**
Cell 2 (1" Tonka, New)	Top	27.9	73.8	264.6
	Middle	27.9	93.1	333.6
	Bottom	27.9	71.4	255.9
	Average	**27.9**	**79.4**	**284.7**
Cell 3 (1" Solid, New)	Top	27.9	84.7	303.7
	Middle	27.9	84.9	304.3
	Bottom	27.9	67.2	240.8
	Average	**27.9**	**78.9**	**282.9**
Cell 4 (1" Tonka, SiO_2)	Top	27.9	33.5	120.1
	Middle	27.9	57.5	206.0
	Bottom	27.9	55.7	199.6
	Average	**27.9**	**48.9**	**175.2**
Cell 5 (1" Tonka, Reused)	Top	27.9	127.6	457.3
	Middle	27.9	187.6	672.3
	Bottom	27.9	137.0	491.0
	Average	**27.9**	**150.7**	**540.2**
Cell 6 (1" Tonka, Reused)	Top	27.9	102.1	365.8
	Middle	27.9	183.1	656.2
	Bottom	27.9	148.0	530.6
	Average	**27.9**	**144.4**	**517.5**
Cell 7 (1" Tonka, Low Flow)	Top	27.9	83.6	299.7
	Middle	27.9	83.6	299.7
	Bottom	27.9	46.7	167.4
	Average	**27.9**	**71.3**	**255.6**
Cell 8 (1" Tonka, Cl_2)	Top	27.9	25.7	92.0
	Middle	27.9	38.3	137.1
	Bottom	27.9	32.6	116.8
	Average	**27.9**	**32.2**	**115.3**

Table Y. Scale Buildup (28 September to 17 November)

Cell No.	Packing Position	Length of Packing (cm)	Mass of Scale (g)	Scale Buildup (g/m)
Cell 1 (2" Tonka, New)	Top	88.7	269.7	304.1
	Middle	87.8	281.5	320.6
	Bottom	84.7	289.6	341.9
	Average	**87.1**	**280.3**	**322.2**
Cell 2 (1" Tonka, New)	Top	79.8	128.9	161.6
	Middle	77.6	128.8	166.0
	Bottom	78.9	143.8	182.3
	Average	**78.8**	**133.9**	**170.0**
Cell 3 (1" Solid, New)	Top	84.3	75.6	89.7
	Middle	85.4	101.9	119.3
	Bottom	84.2	82.7	98.3
	Average	**84.6**	**86.7**	**102.4**
Cell 4 (1" Tonka, SiO_2)	Top	84.6	130.1	153.7
	Middle	84.6	127.8	151.0
	Bottom	84.2	137.6	163.5
	Average	**84.5**	**131.8**	**156.1**
Cell 5 (1" Tonka, Reused)	Top	85.2	165.7	194.5
	Middle	84.5	195.2	231.0
	Bottom	85.4	217.1	254.3
	Average	**85.0**	**192.7**	**226.6**
Cell 6 (Triangular)	Top	91.8	36.6	39.8
	Middle	92	31.1	33.8
	Bottom	92	35.2	38.3
	Average	**91.9**	**34.3**	**37.3**
Cell 7 (1" Tonka, Low Flow)	Top	84.2	141.6	168.1
	Middle	84.3	141.7	168.0
	Bottom	84.2	84.8	100.7
	Average	**84.2**	**122.7**	**145.6**
Cell 8 (1" Tonka, Cl_2)	Top	84.5	89.3	105.7
	Middle	84.6	76.9	90.9
	Bottom	84.3	102.2	121.3
	Average	**84.5**	**89.5**	**106.0**