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Report to

International Environmental, Inc.
Salt Lake City, Utah

Submitted by

Utah Water Research Laboratory
Utah State University
Logan, Utah 84322

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ABSTRACT

Sulfur dioxide has been shown to be an effective wastewater disinfectant. The aqueous sulfur dioxide creates an oxygen demand in the effluent which must be removed prior to discharge. Oxidation to sulfate is one means of accomplishing this task.

Experiments were carried out to determine the effectiveness of transition metals and activated carbon as catalysts for the oxidation of S+IV species in wastewater. Both the metals and carbon are known catalysts, but what inhibitory effect the wastewater might have was unknown. Effectiveness was defined as a combination of catalyst life, effluent quality, and cost.

Transition metals were eliminated as potential catalysts due to the high metal concentrations found in the effluent. The acidic nature of 500 mg/l SO_2 dissolved in wastewater (pH 2.5) would dissolve the metals or cause them to desorb from a carbon base.

Using downflow contactors, activated carbon was shown to catalyze the reaction as long as sufficient oxygen was available. At a loading rate of 5.5 g carbon/l and a hydraulic loading of 38 $M^3/M^2 \cdot$day, 24 hour runs were accomplished without SO_2 breakthrough (less than 4 mg/l). Longer runs resulted in gradual breakthrough (40 mg SO_2/l after 96 hours). The cause of the failure was assumed to be the self-poisoning of the catalyst by sulfuric acid (the product of SO_2 oxidation) and/or the reduced solubility of oxygen in the sulfuric acid solution. Carbon regeneration, as a catalyst, was accomplished by backwashing the column with tap water. The cost of sulfur dioxide disinfection ranged from \$0.23-\$0.73/1000 gallons treated. In general, this process was much more costly than other disinfection systems.

INTRODUCTION

The use of chlorine as a wastewater disinfectant is receiving worldwide attention with respect to its potential adverse health effects. This is partially due to the formation of chlorinated organics which may be carcinogenic. Sulfur dioxide has been shown to be an effective disinfectant (Reynolds and Adams 1979). Sulfur dioxide is a strong reducing agent and when dissolved in water forms sulfite, bisulfite, or sulfurous acid, depending on the pH of the solution. The majority of the sulfur species remains essentially unchanged during and following the disinfection process. Sulfite and bisulfite ions are quite reactive and create an oxygen demand. This oxygen demand must be removed if wastewater discharge requirements are to be met. Oxidation of the sulfite and bisulfite ions to sulfate, catalyzed by transition metals or activated carbon, is one means of removing the oxygen demand.

There are other means of controlling sulfite. Watkins (1977) in his summary of methods for controlling sulfur compounds lists biological, chemical precipitation, electrodialysis, ion exchange, and reverse osmosis. Hesketh and Potokar (1977) found (by bubbling 1100 ppm SO_2 gas through fly ash or carbon slurries) that fly ash from coal burning operations had a sorptive capacity three times greater than activated carbon. Neither the type of carbon nor its catalytic oxidative capacity was compared, however.

Strong oxidants have also been investigated. Penkett et al. (1979) studied the effects of ozone and hydrogen peroxide on the oxidation of aqueous sulfur dioxide to sulfate.

Most of these latter means of controlling sulfite are considered too costly for large scale operations such as sewage treatment facilities using sulfur dioxide for disinfection. Therefore, the focus of this research shall be the catalytic oxidation of aqueous sulfur dioxide by transition metals and/or activated carbon.

OBJECTIVES

The main objective of this research is the development of an efficient means of removing the oxygen demand created in wastewater following disinfection by sulfur dioxide. Specific objectives include:

1. Determination of an efficient catalyst for the oxidation of sulfite or bisulfite in wastewater.
2. Development of design parameters for use of the catalyst as a means of removing sulfite from wastewater.
3. Development of costs associated with use of the catalyst in sulfur dioxide-wastewater disinfection systems.

LITERATURE REVIEW

The oxidation of aqueous sulfur dioxide has been the subject of a great deal of research. This reaction does not occur at a measurable rate at low pH (0-3) without a catalyst present (EPA 1981). Thus most of this research has dealt with obtaining kinetic data in the presence of various catalysts.

Metal Catalysts

Fuller and Crist (1941) studied the effects of copper and pH on the rate of oxidation of sulfite in distilled water using pure oxygen. They found that copper ion concentrations greater than 10^{-9} M greatly increased the rate of oxidation. Lowering the pH from 8.2 to 3.2 decreased the rate of oxidation. Fuller and Crist accounted for this pH phenomenon by assuming the rate of oxidation is dependent on the sulfite ion concentration and the square root of the hydrogen ion concentration.

Other metals such as cobalt and manganese also catalyze the oxidation of aqueous sulfur dioxide. Coughanowr and Krause (1965) used manganous sulfate ($0-6.6 \times 10^{-4}$ M Mn^{2+}) as a catalyst and determined a reaction rate proportional to the square of the catalyst concentration. Their SO_2 concentration was approximately 1.7×10^{-3} M in distilled water saturated with oxygen. Cobaltous sulfate (10^{-7}-3×10^{-6} M Co^{2+}) as a catalyst was shown by Chen and Barron (1972) and Bengtsson and Bjeiles (1975) to affect the reaction rate (of 9.4×10^{-3} M SO_2 in distilled water) by the square root of the catalyst concentration.

The previous results were obtained under solution pH greater than 6.0. At low pH (0-3) the EPA (1981) found cobalt (2.5×10^{-5} M) to be an ineffective catalyst; the catalyzed reaction was second order in manganese (2×10^{-5}-2.5×10^{-4} M).

Tiwari et al. (1979), in studying the oxidation of ferrous sulfate under acidic conditions found that SO_2 would catalyze the reaction. This indicates that iron is another metal capable of increasing the rate of oxidation of sulfur dioxide. The EPA (1981) reported that iron (2.0×10^{-5} M Fe^{3+}) did catalyze the reaction under acidic conditions and that the reaction was first order in iron.

Brimblecombe and Spedding (1974) found in their work that the reaction order of the oxidation of sulfite was dependent on the pH of the solution. A 0.1 M ammonium sulfate solution containing 10^{-5} M of S+IV in the presence of 10^{-6} M Fe(III) was used to simulate aqueous atmospheric aerosols. They were able to show, using steady-state principles, that at low sulfite ion concentrations (low pH conditions) the reaction is first order with respect to sulfite ion concentrations. At higher sulfite ion concentrations (higher pH conditions) the reaction appears to be second order. Thus it can be concluded from this work that the rate of oxidation of sulfite in the presence of a metal catalyst is pH dependent.

Activated Carbon

The oxidation of S+IV species is catalyzed by activated carbon. Air pollution research has provided a great deal of information in this area.

Siedlewski (1965) and Novakov and Chang (1975) determined that sulfur dioxide in air would chemisorb to the surface of the activated carbon at points where free carbon radicals exist. The quantity of sulfur dioxide oxidized is a function of the number of these active sites on the carbon, and not the quantity of sulfur dioxide or oxygen present.

The adsorptive capacity and catalytic activity of activated carbon appear to be a function of the number of free radical sites on the carbon. Seaburn and Engel (1973) bubbled SO_2 gas through slurries of activated carbon (using several different commercial brands of activated carbon) and determined that the number of these free radical sites was dependent on the source material for the carbon.

Komiyama and Smith (1975) found that the rate of oxidation of sulfur dioxide in slurries of activated carbon was first order with respect to oxygen concentration and zero order with respect to sulfur dioxide. They concluded that the controlling step of the oxidation mechanism is the adsorption of oxygen on the active sites of the carbon.

It is fairly well established that surface carbon-oxygen complexes are responsible for activated carbon's catalytic ability.

The reaction mechanism between sulfite and activated carbon is more than a simple reaction with surface adsorbed oxygen, however (Eatough et al. 1979). Free radical carbon sites are probably involved in the complexation of sulfite and carbon, resulting in the formation of sulfate. Eatough et al. concluded that oxidative regeneration of these active sites is the rate limiting step in the oxidation of sulfite on activated carbon.

The rate of the oxidation reaction has been found to be independent of the pH at values less than 7.6. Above a pH of 7.6 the rate of reaction drops to zero thus, indicating a poisoning of the carbon (Chang et al. 1976-77; Brodzinsky et al. 1980). Eatough et al. (1979) proposed that bisulfite was the reacting species. However, Brodzinsky et al. concluded that it is the carbon's active site, affected by pH, that causes the change in rate of oxidation.

Although some confusion exists as to the mechanism, it is generally agreed that activated carbon is an effective catalyst in the oxidation of sulfur dioxide.

EXPERIMENTAL APPARATUS AND PROCEDURES

A review of the pertinent literature concerning catalytic oxidation of sulfur dioxide showed that the primary experimental procedure used involved jar tests to obtain kinetic data (Komiyama and Smith 1975; Chang et al. 1976-77; Brodzinsky et al. 1980). To obtain data necessary to meet the objectives of this study, upflow and downward contactors, in addition to jar tests, were utilized.

Catalysts

Filtrasorb 400, manufactured by Calgon Corporation, was the activated carbon used in the jar tests. Filtrasorb 300 was used in all column experiments. Specifications given by the manufacturer have been included in Appendix A.

The wide range of particle sizes provided in the Filtrasorb 300 was found to be unacceptable for use in the column experiments because the finer particles would quickly flush out of the column and thus be unavailable as a catalyst. It was determined that the carbon retained on a 24 mesh sieve would function the best in the column experiments. The carbon was placed in the 24 mesh sieve and washed with chlorine free tap water to remove the fines. If used in conjunction with a metal catalyst, the carbon was then dried for 24 hours at 103°C. If used alone, the carbon was air dried overnight for use the following day.

Metal catalysts were used in conjunction with the activated carbon by adsorbing the desired metal onto the carbon. A metallic ion solution ($FeCl_3$ or $MnCl_2$, for example) was made based on adsorbing

2 or 6 mg metal ion per g carbon. The carbon was added to the solution and shaken for one hour. The liquid was separated from the carbon and tested for metal ion content to determine the actual amount of metal ion adsorbed. The carbon was rinsed with tap water to remove excess metal ion solution and then considered ready for use in the column.

Also, metal catalysts alone were used in the downflow contactors. They took the form of 3.2 mm inert pellets covered with metal oxides. Catalysts used were manganese oxide (19 percent) on alumina, ferric oxide (20 percent) on alumina, nickel-cobalt-iron oxide (3 percent each) on alumina, and vanadium oxide (10 percent) on alumina-silica (all manufactured by Alfa Products). The catalysts were rinsed with tap water prior to being placed in the column to remove excess powder created during shipping.

Plain, 3/8-inch iron nuts were used as a catalyst in jar tests. The nuts were soaked in 6N HCl for several hours then rinsed with tap water prior to immediate use.

Sulfur Dioxide and Sewage Source

The source of sulfur dioxide for all experiments was reagent grade sulfurous acid produced by J. T. Baker Chemical Co. or Fisher Scientific Co. Sufficient sulfurous acid was added to the sewage to maintain a concentration of 500 mg/l as SO_2. This is referred to as the "feed solution."

Sewage used for all experiments was secondary clarifier effluent obtained from the City of Hyrum's oxidation ditch wastewater treatment plant. Typical characteristics are shown in Table 1.

Table 1. City of Hyrum secondary clarifier effluent characteristics.

Parameter	Value
BOD_5	15-20 mg/l
DO	5.5-6.0
pH	7.5-8.0
Alkalinity	270 mg/l as $CaCO_3$

Analytical Procedures

Sulfite concentrations were measured using the oxidation-reduction titration procedure described on pp. 451-452 of Standard Methods (APHA 1980). Sulfate concentrations were measured using the turbidimetric methods described on pp. 439-440 of Standard Methods (APHA 1980). A Bausch-Lomb Spec 70 set at 420 nm with a 5 cm light path was used to measure light absorbance.

Dissolved oxygen was measured using a YSI meter #54A and a YSI probe #5740. As effects of long term (i.e., hours) exposure to S=IV are unknown, the electrode membrane was changed daily (Reynolds and Adams 1979). The meter was calibrated by aerating tap water for 30 minutes to achieve saturation; a chart was used to calculate the saturation of oxygen based on temperature and altitude. The pH was measured using a Beckman Zeromatic II meter and a combination electrode.

Metal analysis was by atomic absorption using a Varian Model AA-6. Cobalt, iron, manganese, and nickel concentrations were determined using the direct aspiration method and vanadium was determined by the graphite furnace technique (EPA 1979; APHA 1980).

Experimental Procedures

Jar tests

Initial experimentation involved the determination of the ability of granular activated carbon to either adsorb or oxidize sulfite in wastewater. Carbon adsorption isotherms were developed for this purpose. Carbon amounts from 0 to 15 g were added to six 500 ml Erlenmeyer flasks; 250 ml secondary sewage from the Hyrum treatment plant containing 500 mg/l sulfur dioxide (SO_2) was then added to each flask. The flasks were stoppered with aluminum foil covered rubber stoppers and mixed for 2 hours at 150 rpm (see Figure 1). The samples were then filtered using a Millipore filter and analyzed for sulfite ($SO_3^=$), sulfate ($SO_4^=$), pH, and dissolved oxygen (DO). Isotherms were also developed to determine the effect of various metals adsorbed to the carbon. Metals used were iron and manganese. Adsorption of the metal to the carbon was discussed earlier.

Jar tests involving raw iron were conducted by placing iron nuts in the bottom of a 4000 ml beaker containing the sewage and SO_2. The solution was aerated at 500 ℓ/hr to assure that dissolved oxygen was not limiting. Iron, SO_2, dissolved oxygen, and pH were measured at one minute intervals.

Upflow contactor

The upflow contactor apparatus consisted of a 5 gallon feed tank, a variable speed centrifugal pump (Micropump, Inc.), a flowmeter (Laboratory Supplies, Inc.) calibrated for 0.6-5 gph (38-315 ml/min), and a 5 cm diameter glass column. The apparatus is shown schematically in Figure 2.

Figure 1. Jar test apparatus.

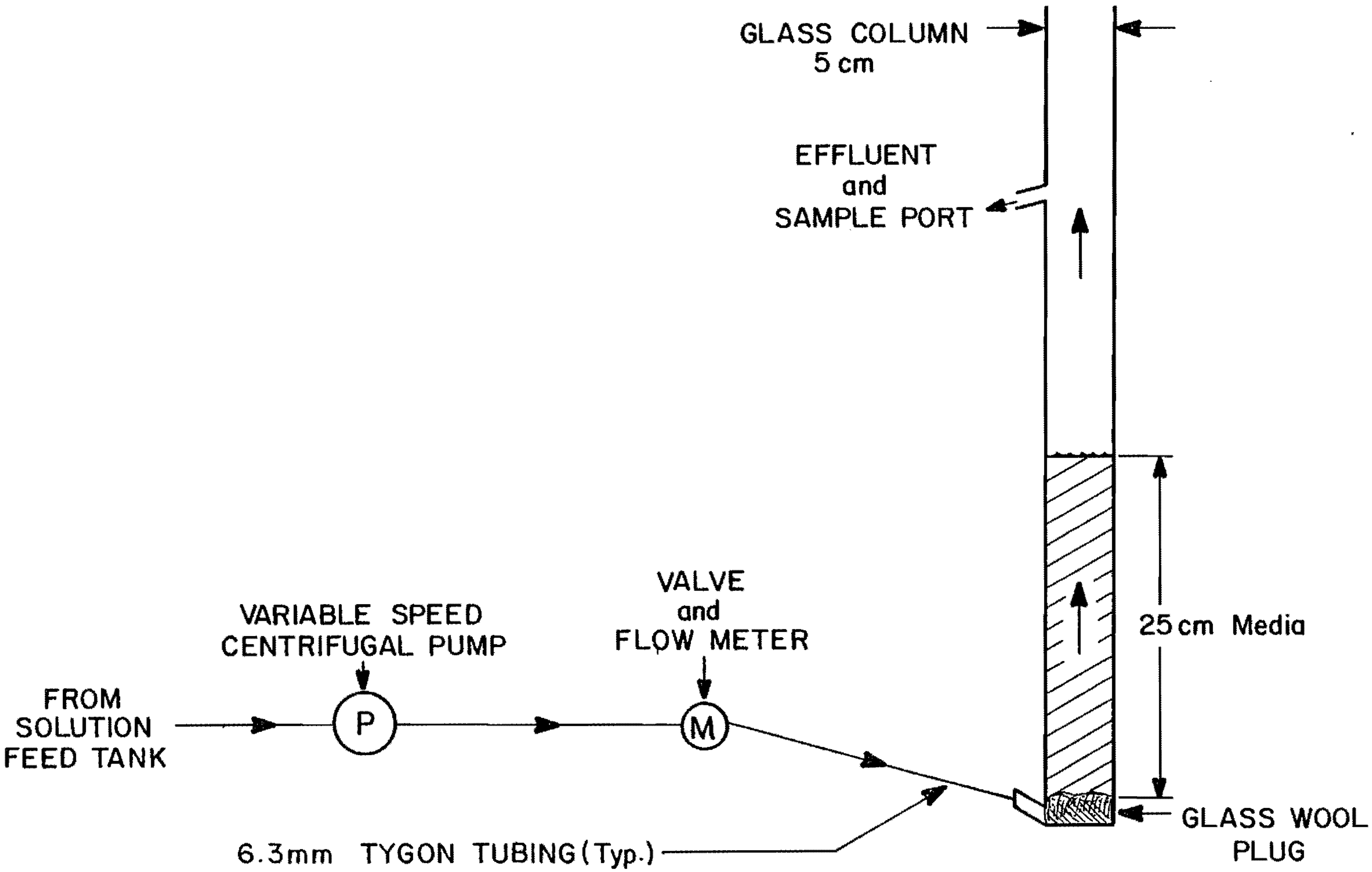


Figure 2. Bench scale upflow contactor.

Three upflow columns were run, each with a different media: activated carbon with either iron, cobalt, or manganese adsorbed to it. Columns were operated at 100 ml/min for one hour. Samples were collected at five minute intervals and analyzed for DO, pH, $SO_3^=$, $SO_4^=$, and the particular metal adsorbed to the carbon.

Downflow contactor

Initial downflow contactor runs utilized the same equipment as the upflow contactor. The only exception was insertion of a glass fritted gas dispersion tube in the side of the column to allow for aeration (see Figures 3, 4, and 5). Equipment changes made during the course of these experiments include replacement of the Micropump with a variable speed peristaltic pump (Masterflex Model 7016) and replacement of the flowmeter (Gilmont Compact Flowmeter #13, 2-300 ml/min). These changes were made to improve equipment performance.

Column runs using the metal oxides as the medium lasted 3 hours. A liquid flow rate of 50 ml/min and an air flow rate of 500 ℓ/hr were used. Medium depth was 25 cm.

Column runs using activated carbon or activated carbon plus metals initially lasted 6 hours, but were later extended to 24 hours. Liquid flow for all runs was 50 ml/min; air flow varied, 0 or 500 ℓ/hr. Medium depth was 25 cm.

Evidence of short circuiting along the glass wall of the column prompted replacement of the 5 cm column with an 8.5 cm diameter column (see Figure 6). The interior surface of the column was coated with activated carbon to further eliminate short circuiting. The adhesive used was silicon (GE SCS1000).

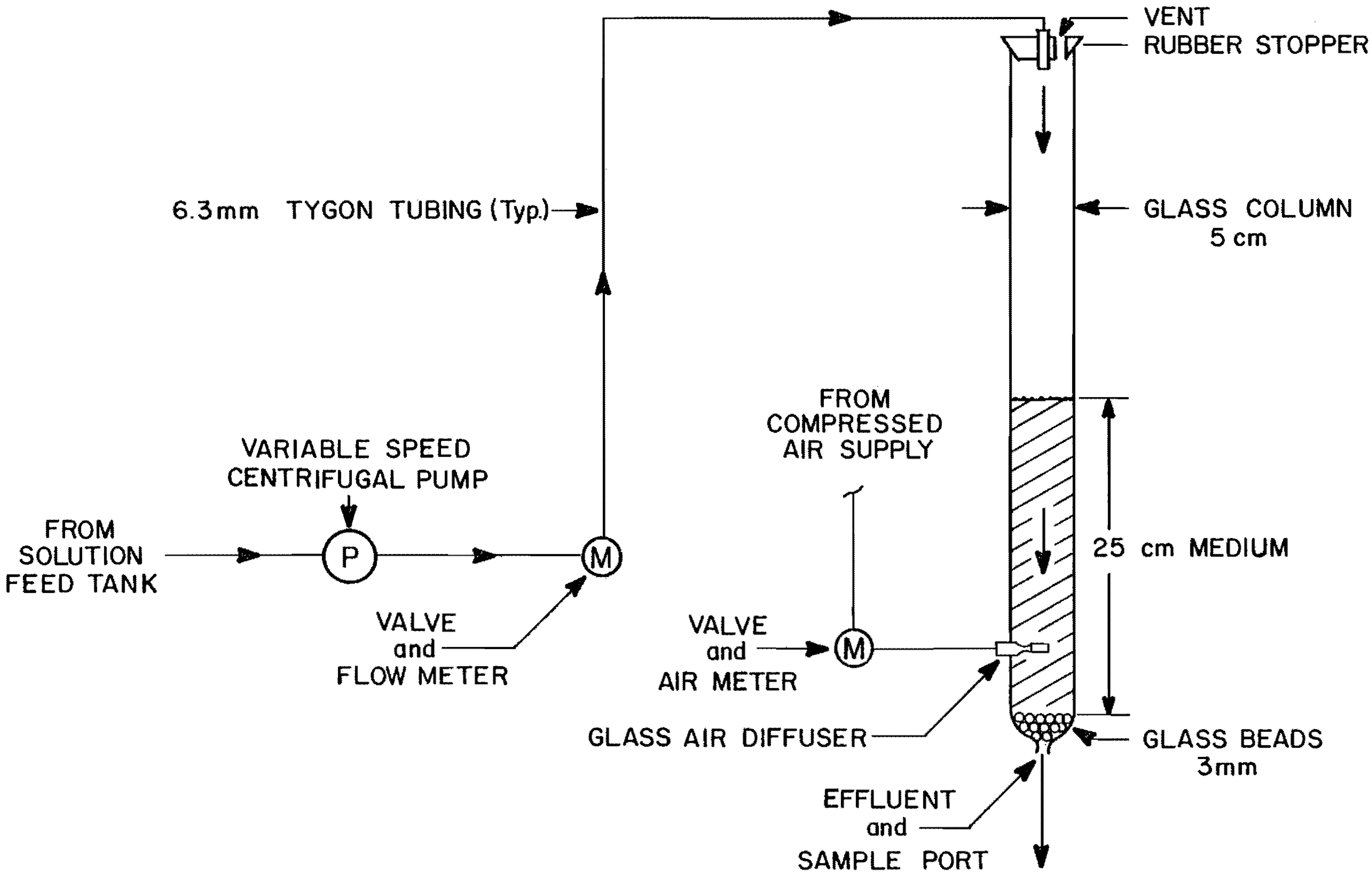


Figure 3. Bench scale downflow contactor.

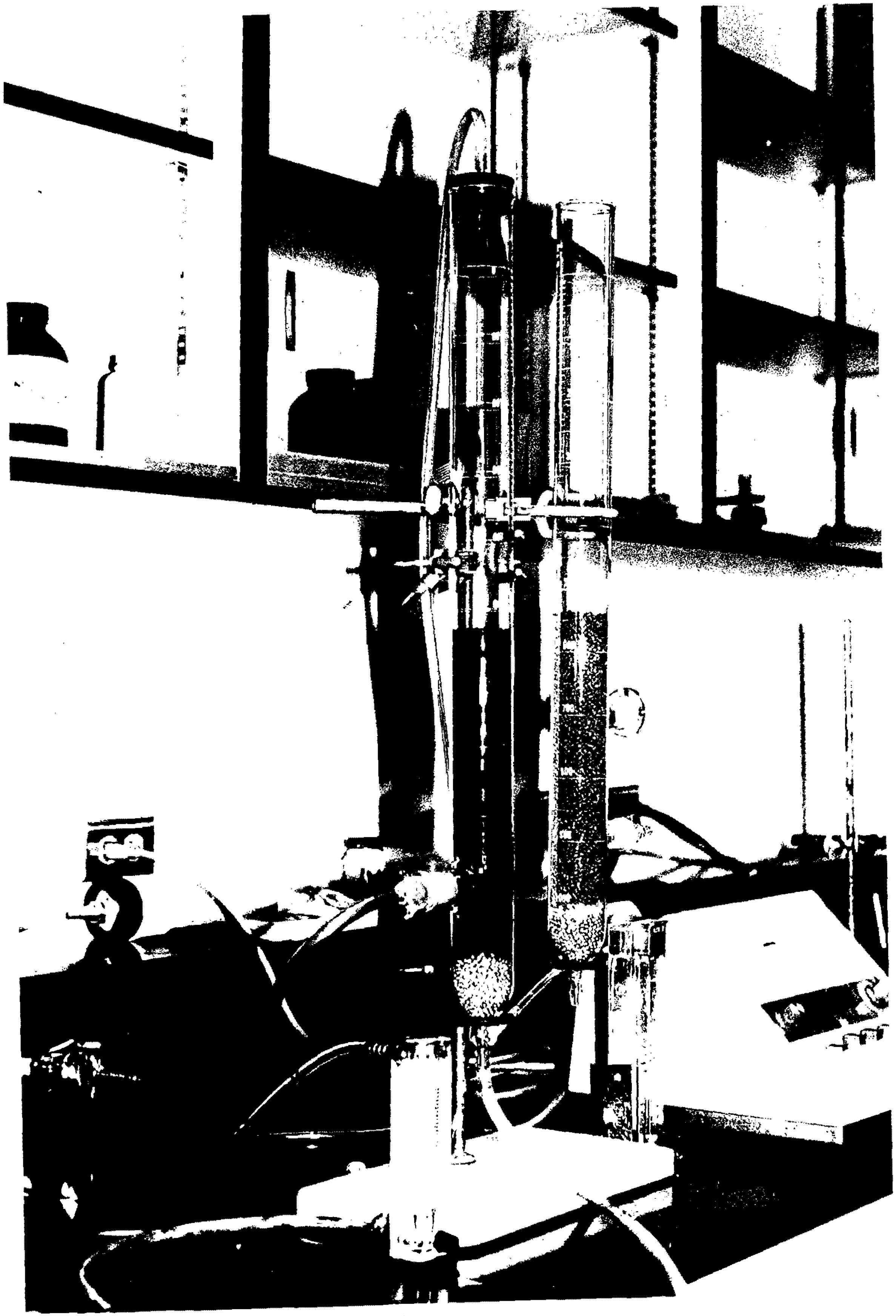


Figure 4. 5 cm downflow contactor.

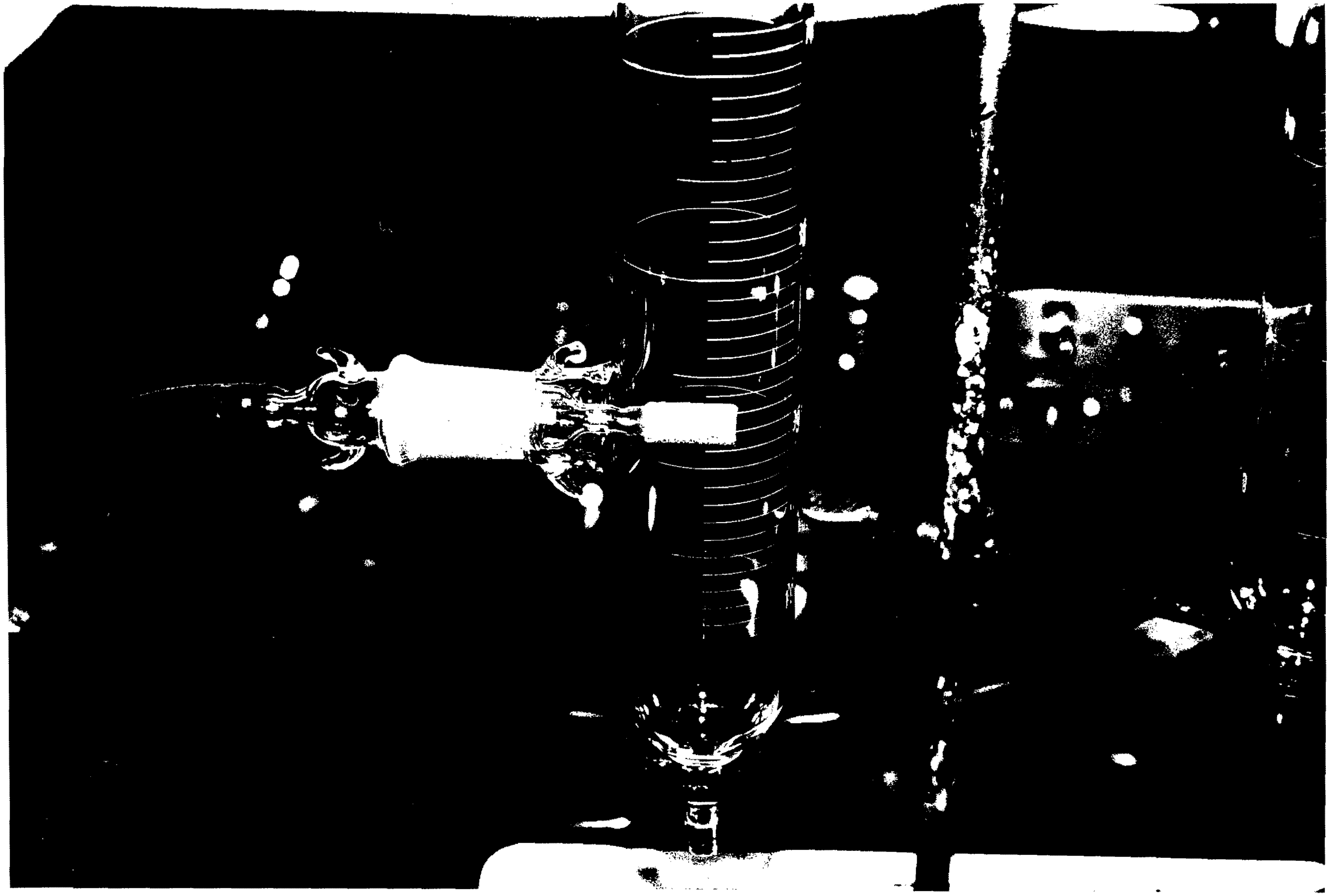


Figure 5. Air diffuser arrangement in 5 cm column.

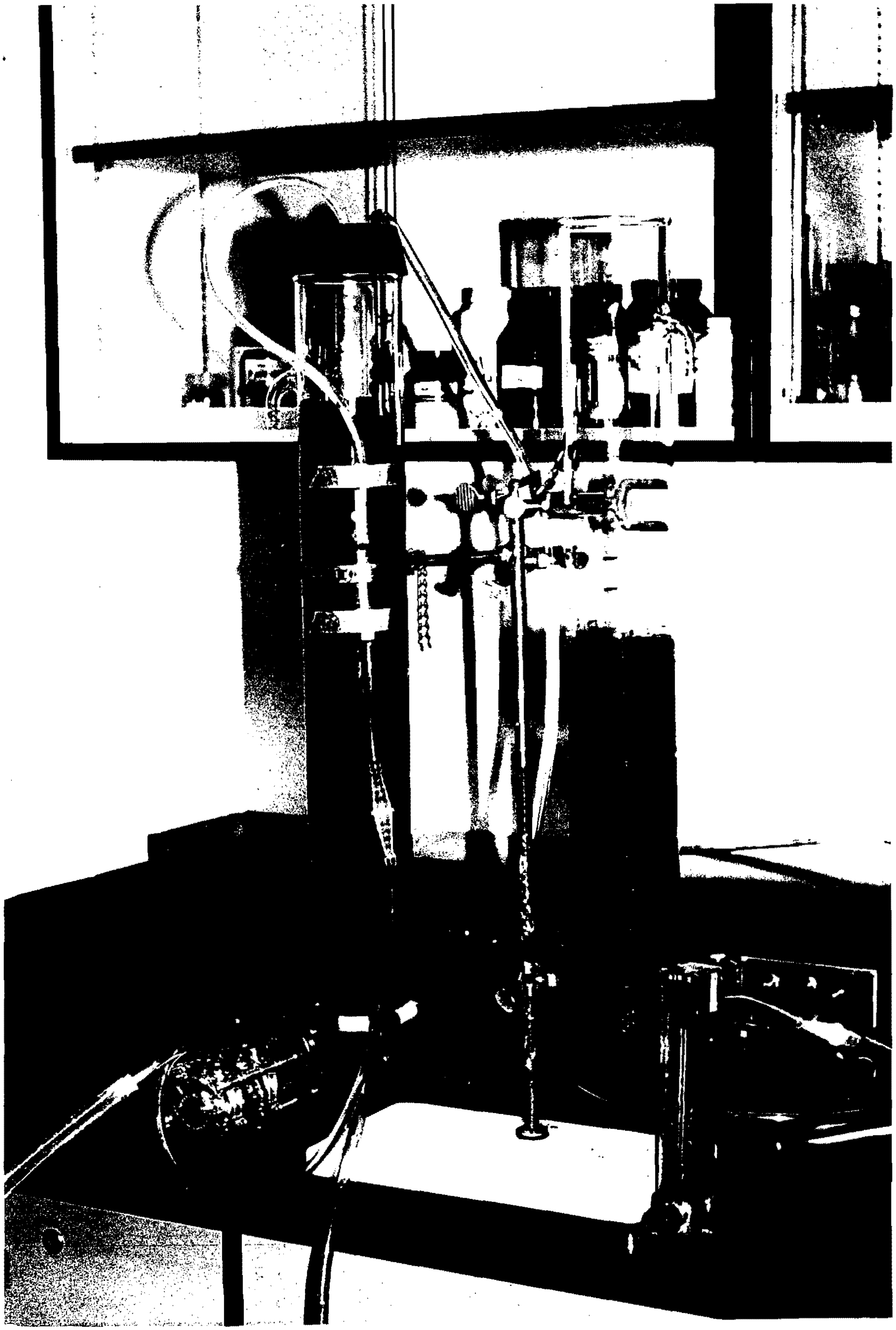


Figure 6. 8.5 cm downflow contactor.

All column runs using the larger column utilized activated carbon as a catalyst. Other column parameters varied as shown in Table 2. Prior to all column runs, chlorine free tap water was poured down the column to saturate the carbon.

Table 2. Variation of experimental design parameters.

Parameter	Range	Units
Air Supply	0, 70, 140, 210	ℓ/hr
Liquid Flow Rate	50, 75, 100, 150, 175	ml/min
Medium Depth	25, 35, 50	cm

RESULTS AND DISCUSSION

Sulfur dioxide has been shown to be an effective wastewater disinfectant (Reynolds and Adams 1979). Disinfection was found to be a function of three parameters, SO_2 concentration, time, and pH value. It was shown that 160 mg/1 SO_2 and a pH of 2.5 is the optimal combination of these two parameters at a 30 minute detention time. Using these values, the total coliform count can be reduced to less than 200 organisms/100 ml and fecal coliform counts to less than 20 organisms/100 ml. To obtain a pH value of 2.5 in high alkalinity wastewater (250-300 mg/1 as $CaCO_3$) a mineral acid must be added in addition to the 160 mg/1 SO_2, or 500 mg/1 SO_2 must be added to the wastewater. This research has been based on the latter case.

Sulfur dioxide dissolved in water will form either sulfite ($SO_3^=$), bisulfite (HSO_3^-) or sulfurous acid (H_2SO_3) depending on the pH of the solution. This is depicted graphically in Figure 7 (EPA 1979). It should be noted that Figure 7 is not quantitative in that all activity coefficients are assumed to be unity. It does show a qualitative relationship between aqueous SO_2 species.

As noted, with a SO_2 concentration of 500 mg/1, the pH of the secondary sewage used in these experiments is approximately 2.6 (depending on the alkalinity of the sewage). Thus the dominant species in solution will be HSO_3^-. Oxidation of HSO_3^- leads to the formation of sulfate plus a proton:

$$HSO_3^- + 1/2\ O_2 \rightarrow H^+ + SO_4^= \qquad (1)$$

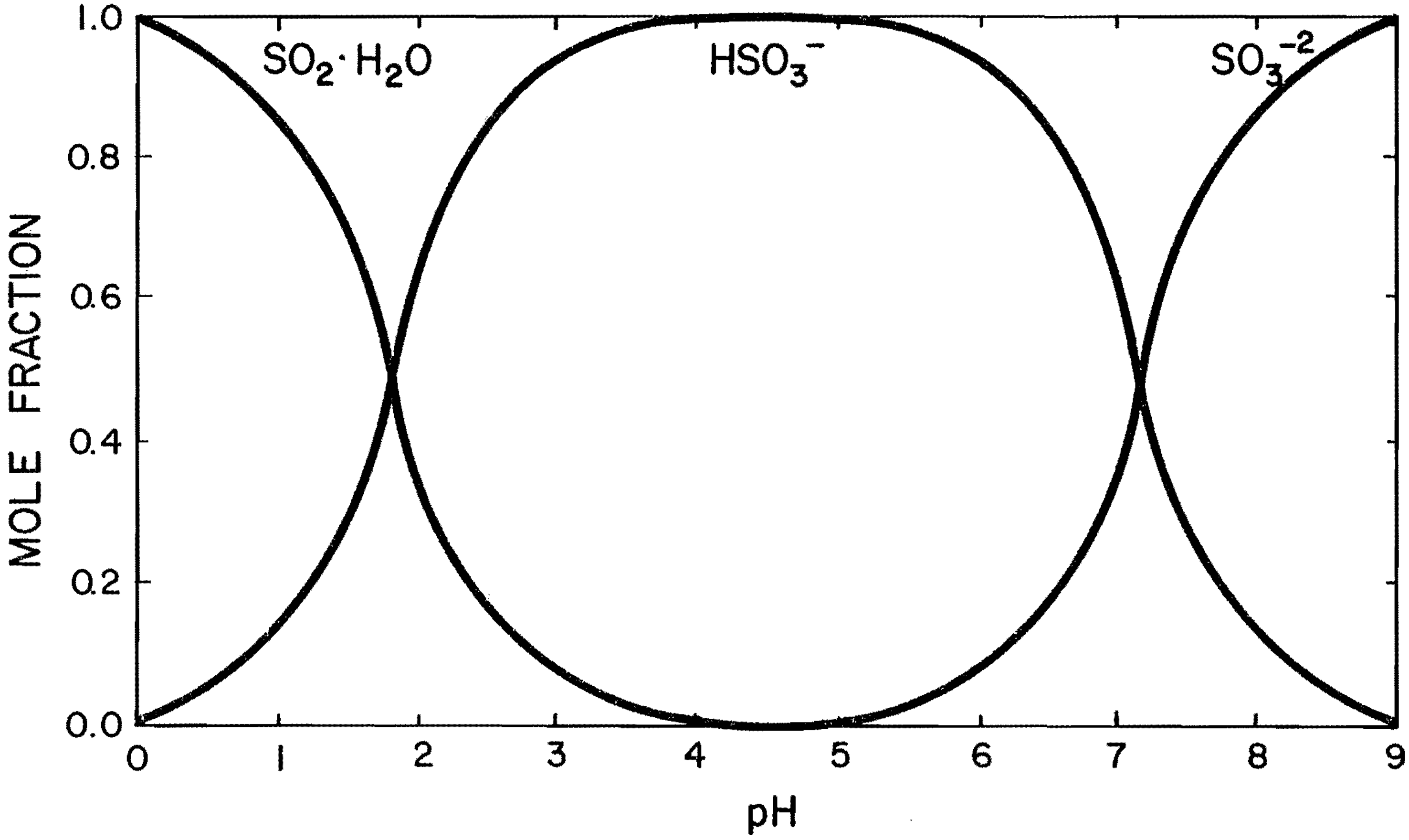


Figure 7. pH versus SO_2 species.

Schmidt (1972) noted that the formation of dithionate is increased at low pH:

$$2HSO_3^- \rightleftharpoons S_2O_5^= + H_2O \qquad (2)$$

$$S_2O_5^= + H_2O \rightarrow S_2O_6^= + 2H^+ + 2e^- \qquad (3)$$

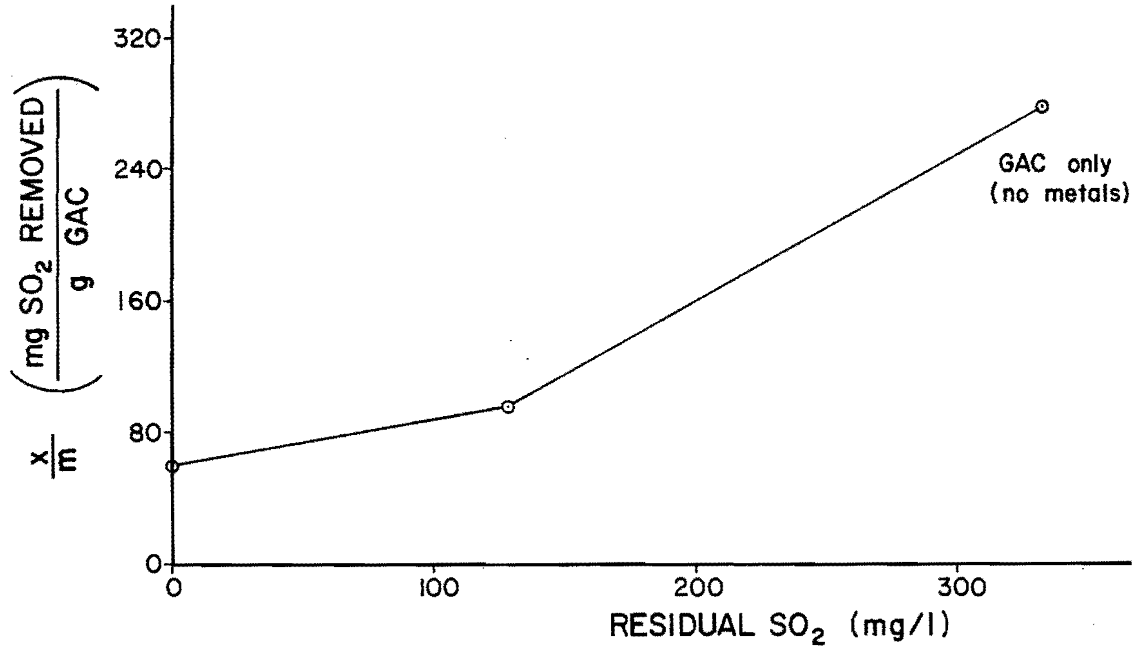
Dithionate is a very stable ion and will not undergo oxidation or reduction very easily. The oxidation state of dithionate (S+V) is not the same as sulfite (S+IV) or sulfate (S+VI). Thus dithionate is not detected by the analytical procedures used to measure sulfite or sulfate. Later discussion of the sulfur mass balance will return to this point.

All sulfur specie concentrations in the following discussion are reported in mg/l as SO_2.

Jar Tests

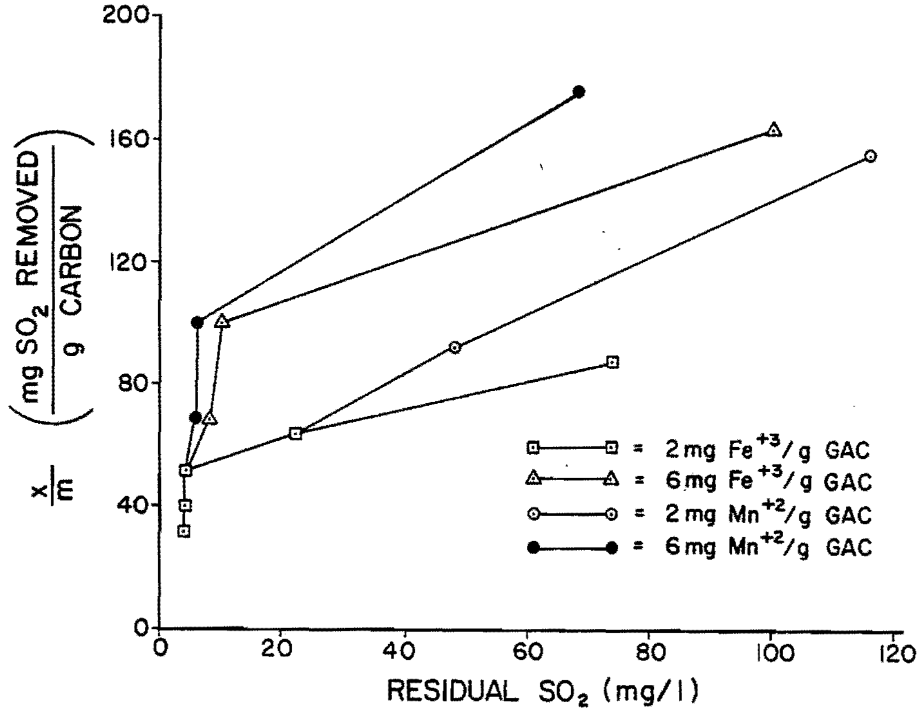
The jar tests clearly indicate the catalytic abilities of activated carbon. The results were plotted as carbon adsorption isotherms. A favorable isotherm is one with an initial steep use at the low carbon masses. The carbon isotherm shown in Figure 8 would be considered unfavorable. The concentration of carbon necessary to completely remove the SO_2 was found to be 40 g/l. The pH increased from an initial 2.6 to 3.6. At higher carbon concentrations, the pH continued to increase, indicating that the activated carbon was removing the products of bisulfite oxidation from solution.

The jar tests involving activated carbon with adsorbed metals produced more favorable isotherms (Figure 9). The metals reduced the carbon concentration necessary for complete removal of SO_2 by



Note: GAC = Granular Activated Carbon

Figure 8. SO_2 removal-jar test results.



Note: Data from Appendix B, Table B-2.

Figure 9. SO_2 removal-jar test results.

half, to 20 g/l. However, the gain in reduced carbon concentration was offset by desorption of the metals from the carbon. For example, the solution containing 50 g/l of carbon with 6 mg/g of iron adsorbed measured 51 mg/l iron at the end of the test. The reason for desorption of the metals is assumed to be the low pH (2.8) of the solution.

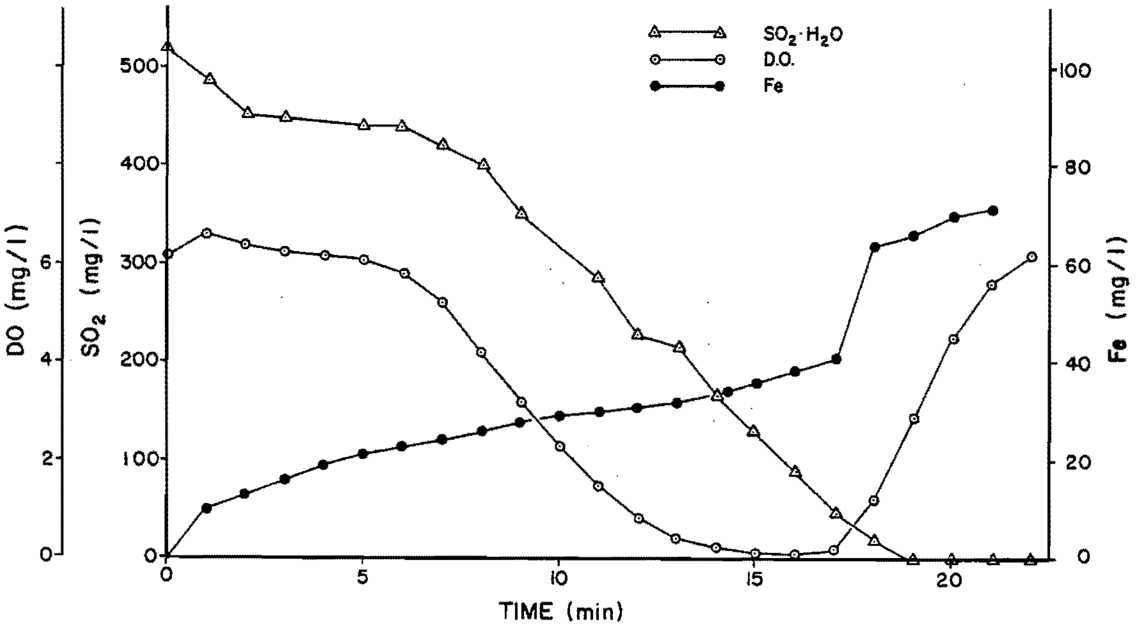
Removal of the bisulfite oxidation products by the carbon was again observed in these experiments. This assumption is proven by considering the mass balance of sulfur species. As shown in Table 3, the effluent sulfur species decrease with increasing carbon concentrations. With no carbon, the data show a loss of 107 mg/l SO_2 after two hours of shaking. Approximately one-third of this loss is due to oxidation to $SO_4^=$; the remainder is assumed to have gone off as gaseous SO_2. As discussed earlier, dithionate may have been formed and would account for some of the missing sulfur.

The results of the carbon jar tests indicate that activated carbon is not very efficient (requiring 40 g/l) at removing SO_2 from wastewater. However, insufficient dissolved oxygen appeared to limit the oxidation of the SO_2 and therefore biased the results. Thus the impetus for column experiments was to further define the catalytic capabilities of carbon.

Jar tests involving raw iron as a catalyst also showed the adverse effects of the acidic solution. As shown in Figure 10, at an iron concentration of 20 mg/l the rate of SO_2 and DO reduction is rapid and constant. Further increases in the iron concentration do not affect the rate of reaction. As the reaction rate did not increase until 20 mg/l of iron was present it can be concluded that iron, as a catalyst, must be dissolved in solution. The catalytic effect is probably not a sur-

Table 3. Typical sulfur mass balance.

Carbon Conc. g/l	Final SO_2 mg/l	Final $SO_4^=$ as SO_2	Total SO_2 mg/l
Initial Solution	500	39	539
0	364	68	432
10	32	448	480
20	6	382	388
30	0	371	371
40	0	278	278
50	0	240	240



Note: Data from Appendix B, Table B-7.

Figure 10. Oxidation of SO_2 using raw iron.

face phenomenon on the iron. Although a good catalyst, the use of raw iron does not appear feasible due to the high concentration (20 mg/l) of iron in the effluent.

Upflow Contactors

Three upflow columns were operated using either iron, manganese, or cobalt adsorbed to activated carbon. The results of the carbon and manganese column are shown in Table 4. The results are very similar to the jar tests, and show activated carbon with metals to be a very efficient catalyst as long as a sufficient stoichiometric amount of oxygen is present to complete the oxidation. The data also show that the acidic nature of the feed solution causes the metal to desorb from the carbon. As with the jar tests, insufficient oxygen did not allow for long term analysis of the catalytic capabilities of activated carbon.

Table 4. Typical upflow column data using activated carbon + Mn^{++} medium.

Time (min)	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Mn^{++} mg/l
Initial	6.8	2.4	548	49	<4
5	2.2	5.0	0	388	178
10	2.2	4.1	0	403	182
15	1.7	3.2	0	388	156
20	0.2	2.5	0	352	105
25	0	2.4	32	395	91
30	0	2.4	48	395	89
35	0	2.4	136	344	55
40	0	2.4	168	358	49

Downflow Contactors

Downflow columns using eight different media were operated for 3-6 hour periods. The purpose of these runs was to make a preliminary assessment of the oxidative capacity of the various media. The results are summarized in Table 5 (raw data are included in Appendix B, Table B-2 through B-5).

None of the alumina base metallic media completely oxidized the SO_2 for any length of time. As excess air (500 ℓ/hr) was being pumped into the column, the extremely large effluent SO_2 concentration should not have been caused by depleted oxygen levels. Insufficient detention time could have caused the breakthrough however. Increasing detention time was not attempted due to the primary reason for dismissing use of these media as catalysts: high metal concentrations in the effluent. Figure 11 shows the manganese catalyst before and after the column run. The removal of the manganese from the base alumina is clearly evident, again, due to the acidic nature of the feed solution.

Study of activated carbon and activated carbon plus metals continued with 24 hour runs. The purpose was to determine the maximum SO_2 breakthrough (if one existed) and the extent of metal desorption from the carbon. Metals used were cobalt, iron and manganese. Excessive air (500 ℓ/hr) was again used to prevent depleted oxygen levels from affecting catalyst evaluation.

SO_2 breakthrough occurred within 2 hours in all columns except the carbon-manganese column which lasted 5 hours (see Appendix B, Tables B-8 through B-16). On the basis of a single run, the carbon-manganese column had a maximum breakthrough of 28 mg/l; 68 mg/l for the

Table 5. Preliminary assessment of oxidation catalysts.

Column Conditions:
Feed Rate = 50 ml/min.
Medium Depth = 25 cm
Feed Soln. pH = 2.5-2.9
Air Flow = 7.2-9.5 ℓ/min.
Run Time = 3 hrs.

Medium	Criteria*				Additional Study
	Oxidative Capacity	Effluent DO	Effluent pH	Effluent Metals	
Activated Carbon	Fair	Good	Poor	N/A	Yes
Fe^{3+} on GAC	Good	Good	Poor	Poor	Yes
Mn^{2+} on GAC	Good	Good	Poor	Poor	Yes
Co^{2+} on GAC	Good	Good	Poor	Poor	Yes
Fe_2O_3 on Alumina	Poor	Good	Poor	Good	No
MnO_2 on Alumina	Fair	Poor	Poor	Poor	No
V_2O_5 on Alumina	Poor	Good	Poor	Poor	No
NiCoFe on Alumina	Poor	Good	Poor	Poor	No

*Oxidative Capacity (Effluent SO_2 Concentration): Good $<$ 50 mg SO_2/l; Fair $<$ 100 mg SO_2/l; SO_2/l; Poor $>$ 100 mg SO_2/lSO_2/l
Effluent DO: Good $\geq$ 2 mg/l; Poor $<$ 2 mg/l
Effluent pH: Good $\geq$ 6.5; Poor $<$ 6.5
Effluent Metals: Good $\leq$ 1 mg/l; Fair $\leq$ 5 mg/l; Poor $>$ 5 mg/l

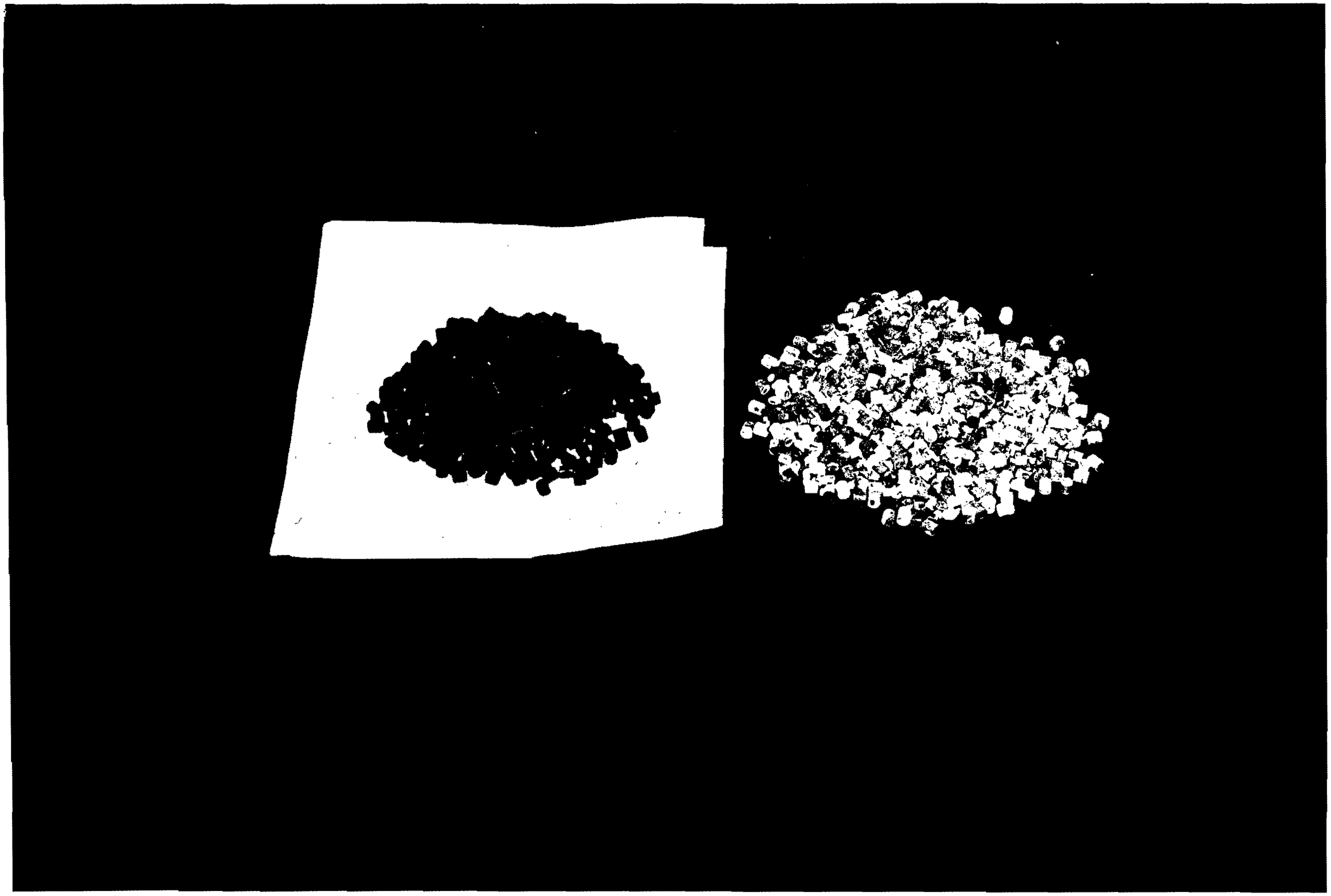


Figure 11. Manganese oxide on alumina before and after column run.

carbon-cobalt column (see Figure 12). Both columns did reasonably well based on metal desorption. The maximum cobalt concentration in the effluent was 5.8 mg/l; the values dropped to less than 1 mg/l after 3 hours. The manganese effluent concentration peaked at 6.1 mg/l and dropped to less than 1 mg/l after 3 hours.

Of three runs using carbon-iron medium two had similar peak SO_2 effluent values of 16 and 38 mg/l. The third run exhibited a much higher breakthrough however (see Figure 13). Iron desorption was higher than the other metals. Concentrations of 60 mg/l were measured at the beginning of the runs. Values decreased to approximately 1 mg/l after 24 hours.

The results of three runs using activated carbon medium are shown in Figure 14. As shown, the results were extremely variable. Five additional runs were completed, with zero air flow, in an attempt to replicate results (Figure 15 and Appendix B, Tables B-18 through B-22). Again, results were variable. As all column parameters were equal for these runs, it was determined that the cause of the variable results was short-circuiting down the glass column walls. Increasing the column diameter from 5 cm to 8.5 cm increased the carbon volume to glass wall area ratio by 70 percent. It also produced much more consistent results (Figure 16 and Appendix B, Tables B-22 through B-26).

At this point it was decided to eliminate the carbon plus metal catalyst from further study and concentrate on activated carbon. This decision was based on the desorption of the metals into the influent. The acidic nature of the feed solution would not allow the activated carbon to retain the metal ions.

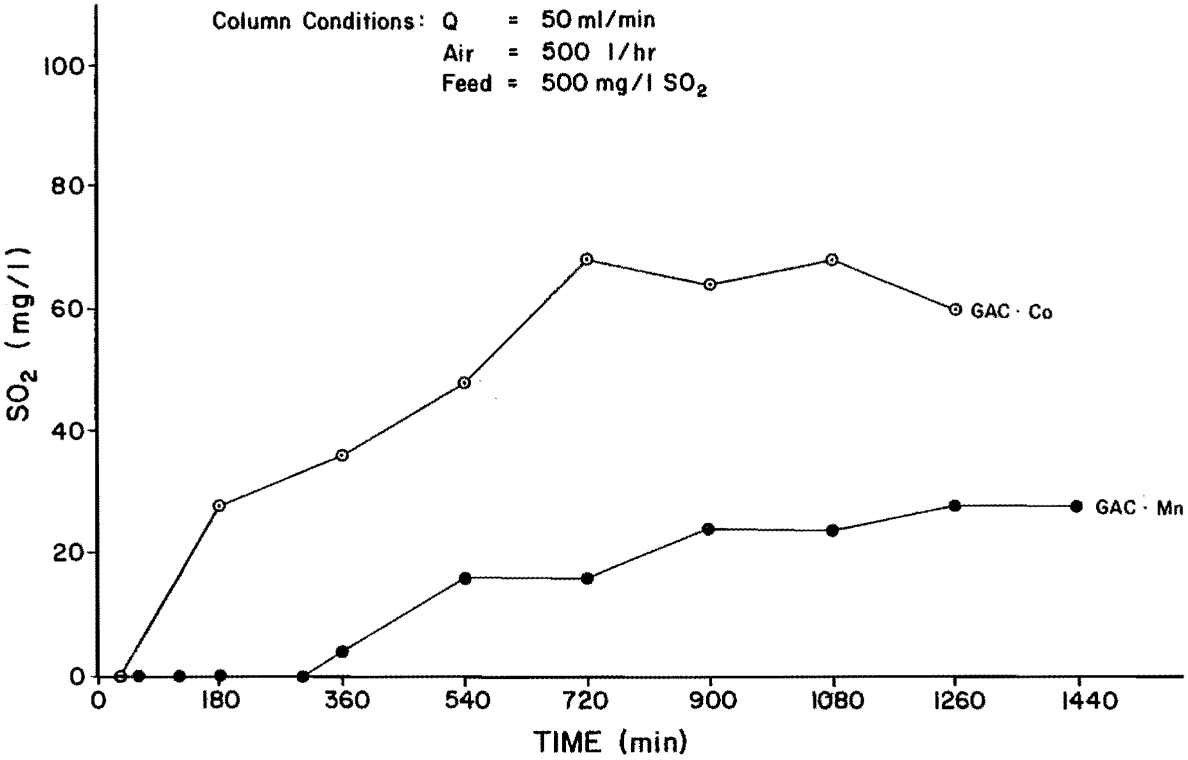
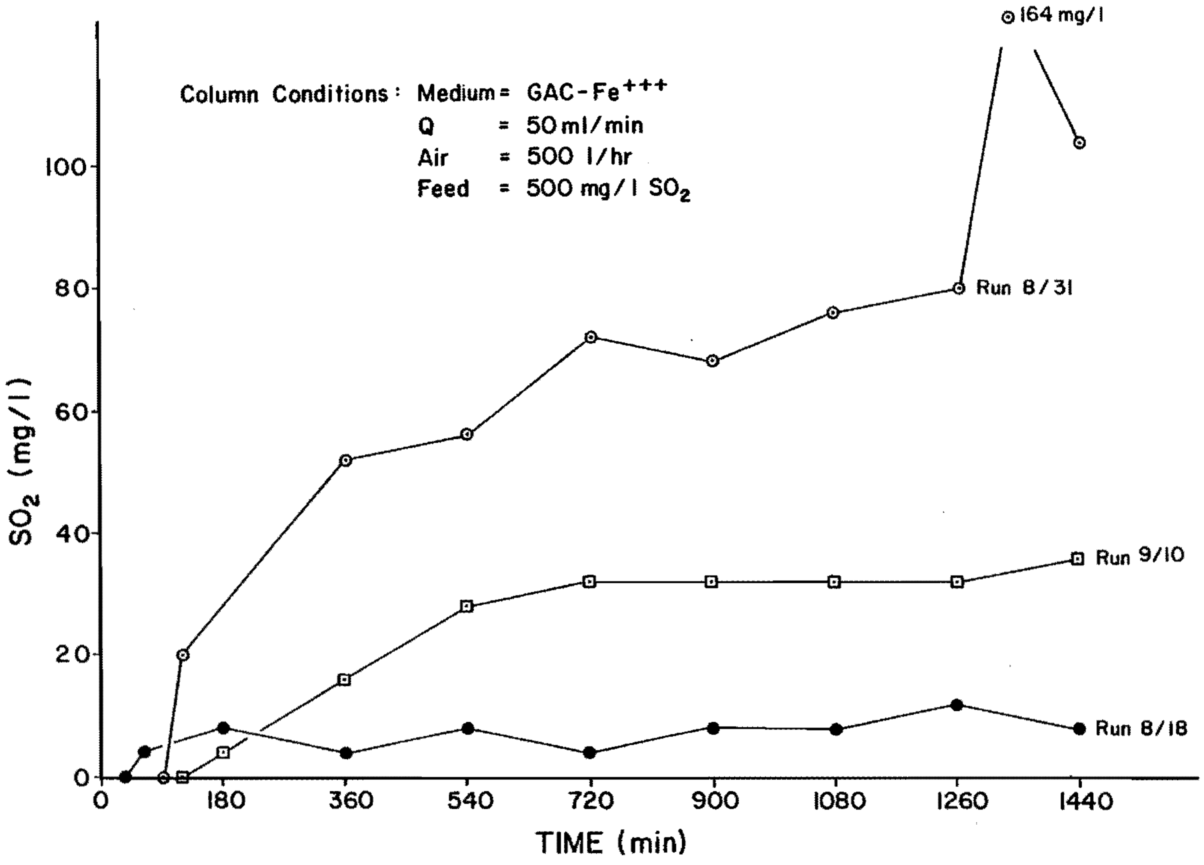


Figure 12. SO_2 breakthrough using activated carbon and metals medium.



Note: 8/31 (i.e.) refers to date of experiment

Figure 13. SO_2 breakthrough using activated carbon + iron medium.

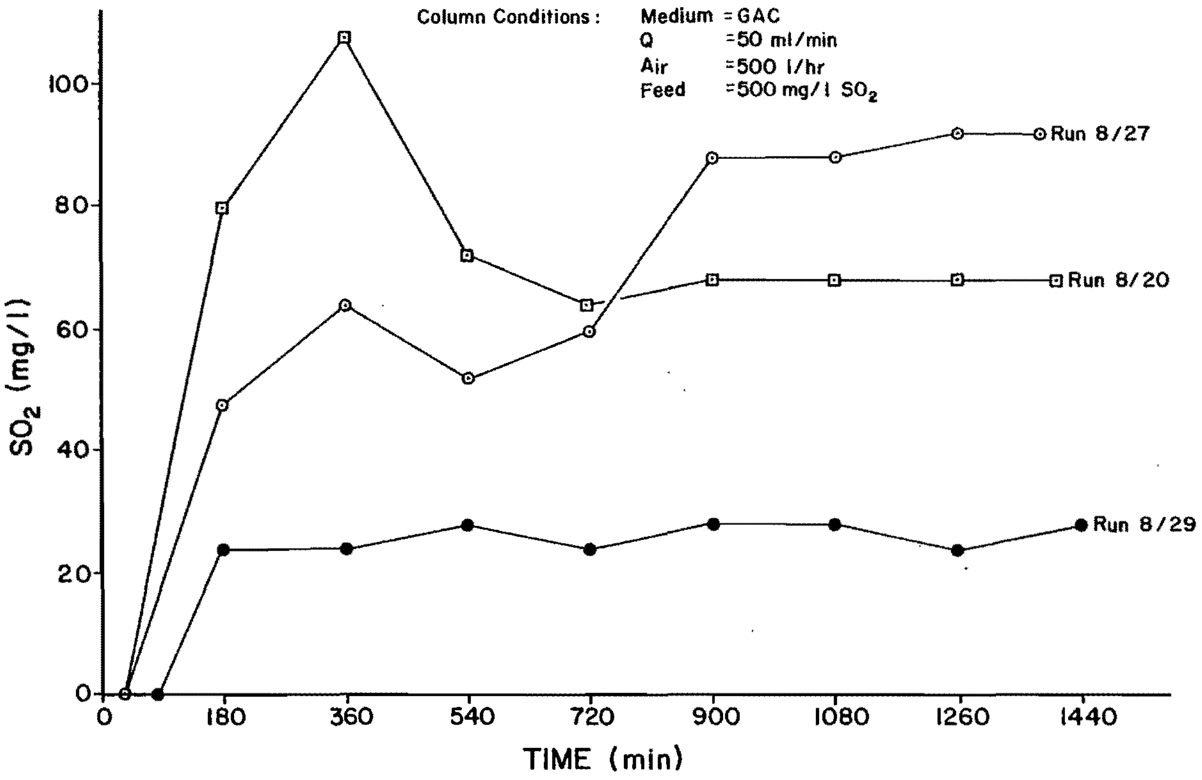


Figure 14. SO_2 breakthrough using activated carbon medium.

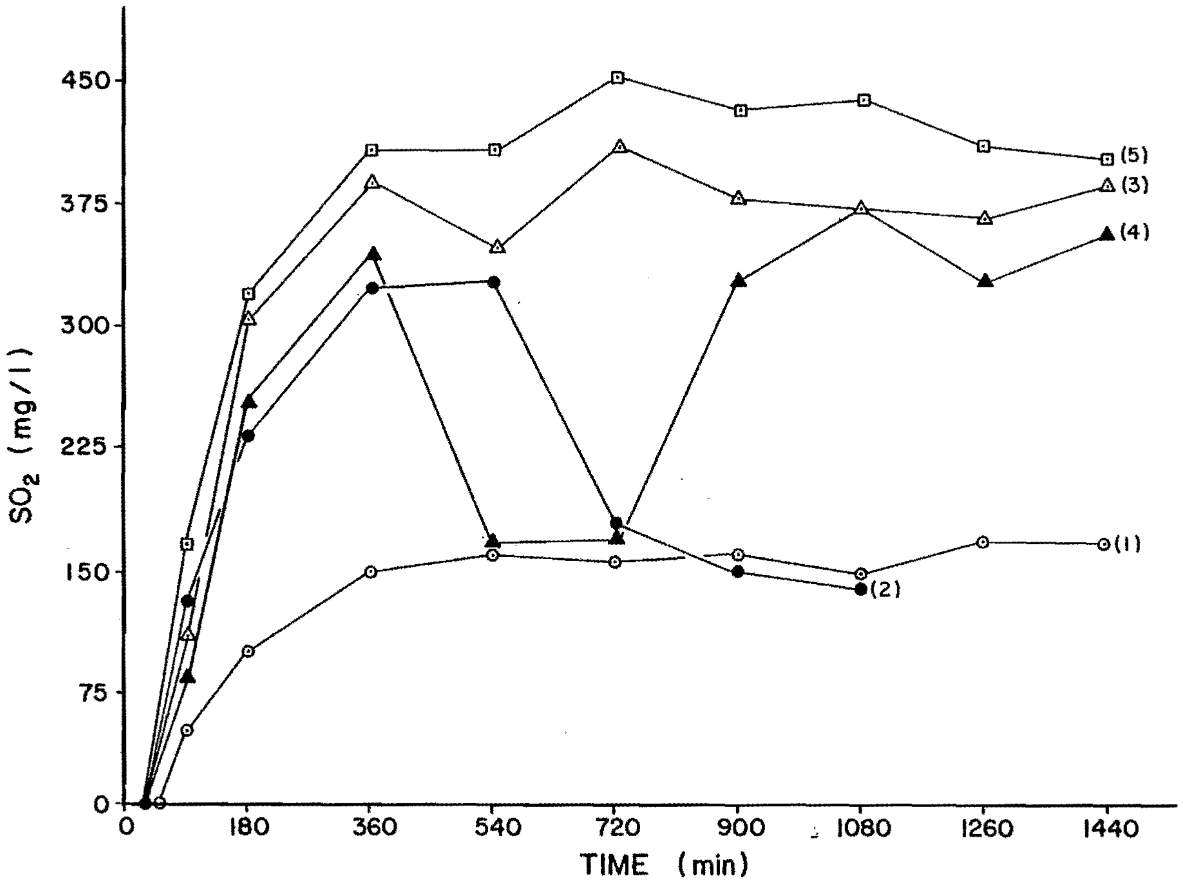


Figure 15. Variation in SO$_2$ breakthrough for 5-24 hour runs (5 cm column).

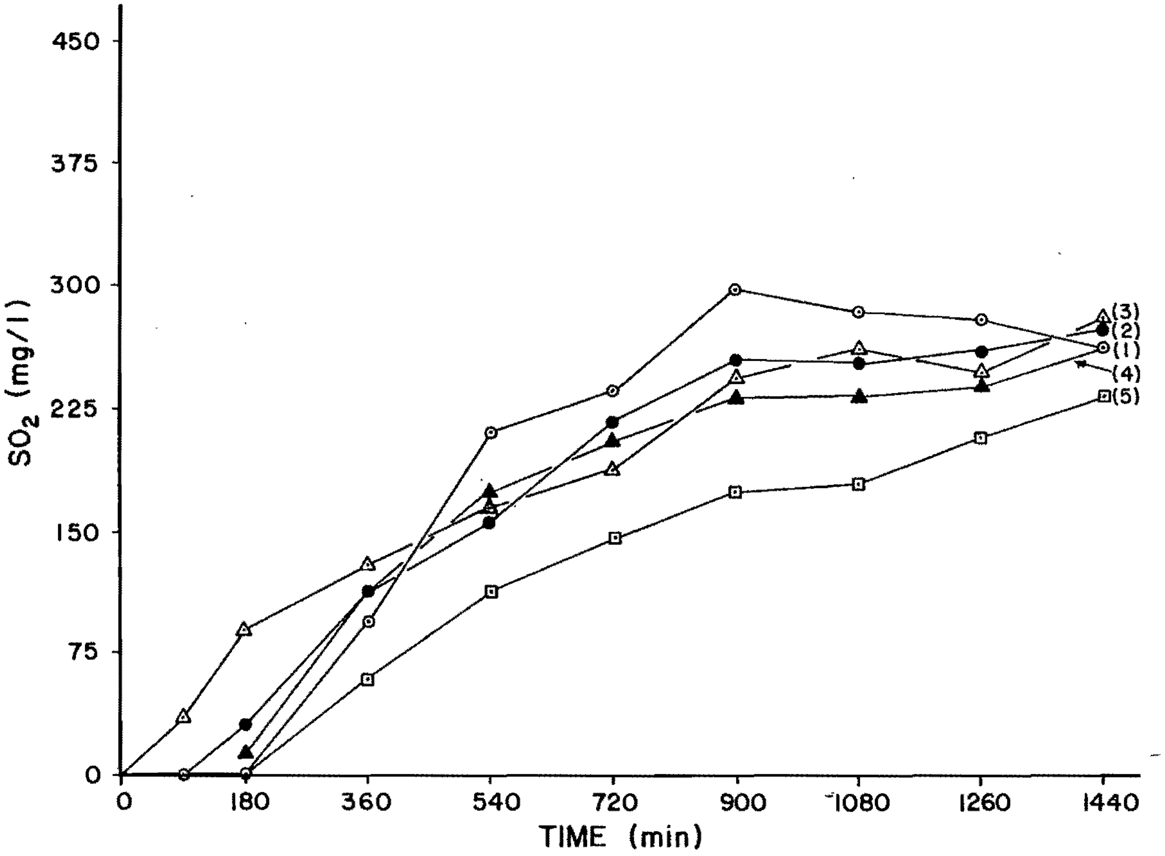


Figure 16. Variation in SO$_2$ breakthrough for 5-24 hour runs (8.5 cm column).

Starting with the 8.5 cm column, other column parameters were varied while the medium was held constant as shown in Table 2. Figure 17 (Table B-24) shows the effects of zero air flow in the column. As before, insufficient oxygen caused column failure indicated by zero dissolved oxygen measurements. The increasing oxygen levels along with increasing SO_2 is indicative of catalyst poisoning. As the activated carbon becomes saturated with sulfuric acid (product of sulfite oxidation) the rate of reaction is decreased. Hence there is insufficient time in the column to utilize all the oxygen available.

Adding a second column in series, identical to the first, produces an effluent with 16 mg/l SO_2 (data in Appendix B, Tables B-27 through B-32). Thus it appears, with minor modifications, two filters in series with 25 cm activated carbon at a liquid loading of 8.8 ml/min per M^2 (50 ml/min) would oxidize the SO_2.

A summary of the various combinations of design parameters used and the ability to remove the influent SO_2 are shown in Table 6 (see Appendix B, Tables B-33 through B-44). As shown, when aerating the column at 140 ℓ/hr a relationship develops, at zero SO_2 breakthrough, between carbon depth and liquid flow (see Appendix B, Tables B-34, B-36, B-38, B-40, B-43, B-46). This proves to be a linear relationship as shown in Figure 18. Using the column with 50 cm of carbon and a flow rate of 150 ml/min for 24 hours, a carbon weight to liquid volume ratio of 5.5 g/l may be computed. Thus with sufficient oxygen available, activated carbon is a far better catalyst than indicated by the 40 g/l ratio determined by the jar tests.

Assuming an 8 percent transfer efficiency between air and water, 63 ℓ/hr of air should be required to oxidize 500 mg/l SO_2 at a flow

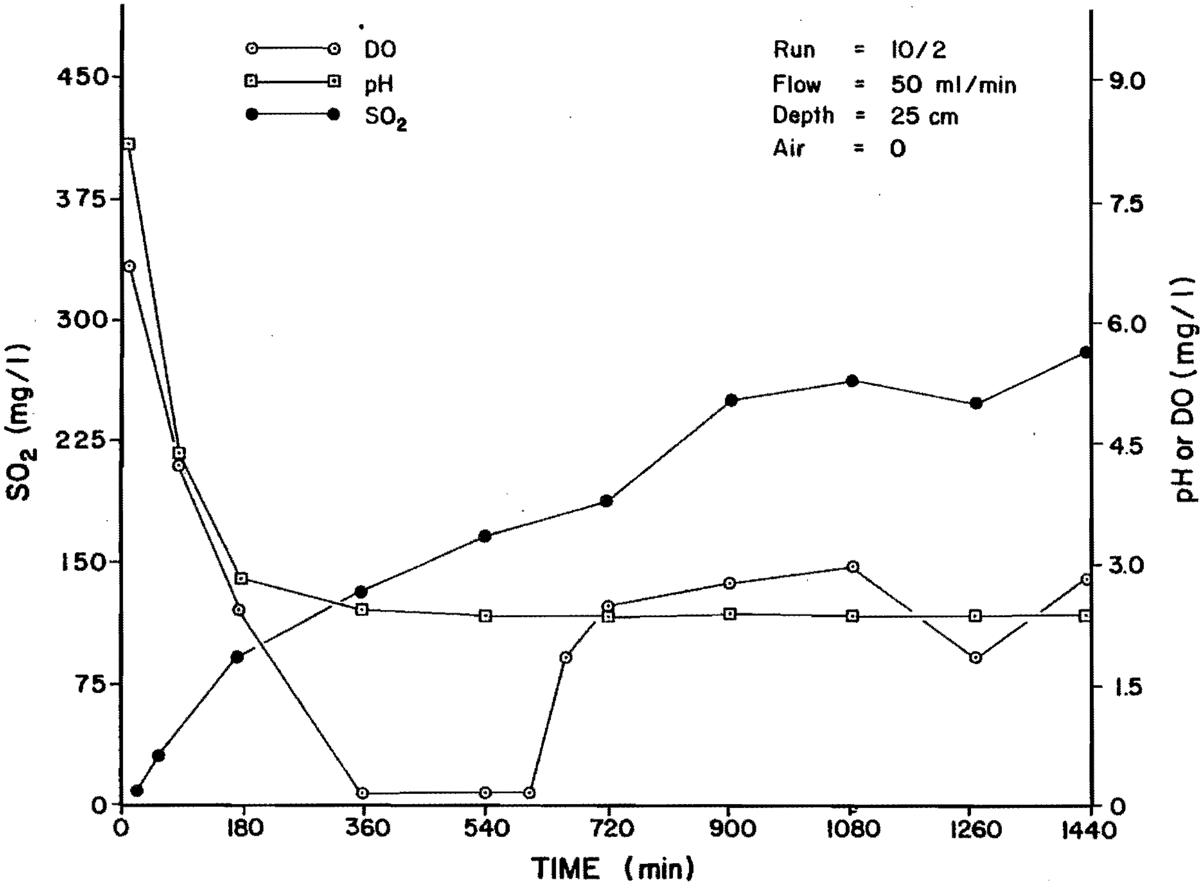


Figure 17. SO_2 oxidation column observations.

Table 6. Summary design parameter variations and SO_2 breakthrough.

Medium Depth (cm)	Air Flow (ℓ/hr)	Liquid Flow (ml/min)	Max. Effluent SO_2 (mg/l)
25	0	50	280
25	140	50	0
25	140	75	0
25	140	100	72
35	140	100	0
35	140	150	128
35	210	150	52
50	0	50	192
50	140	150	0
50	140	175	84
50	70	150	48

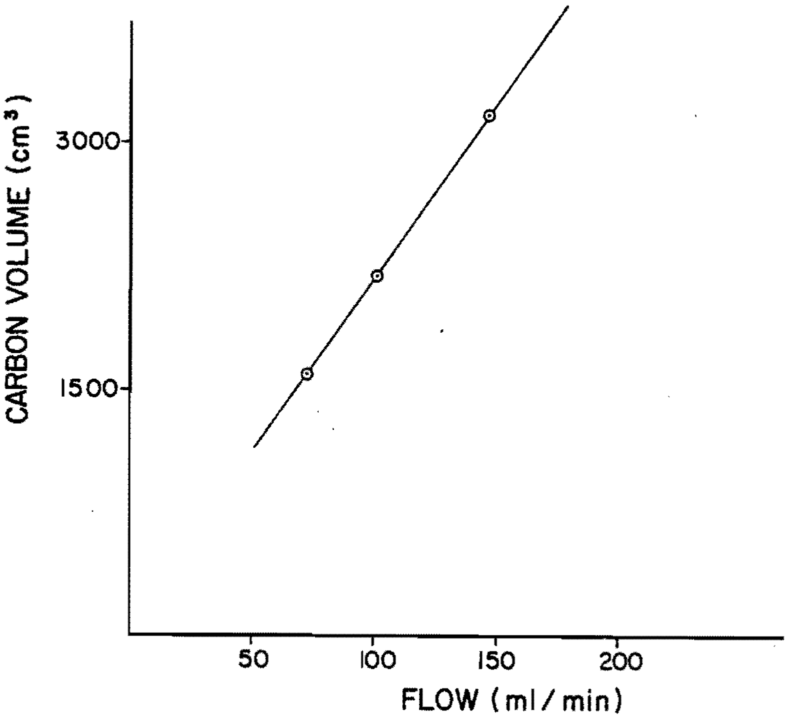


Figure 18. Flow vs. carbon volume for zero SO_2 breakthrough (24 hr runs).

rate of 150 ml/min. Thus it was unexpected to see the column operated at 70 ℓ/hr of air fail. There appears to be several possible reasons. One reason is insufficient detention time in the column. In light of improved performance with increased air flow this explanation does not appear likely. Another reason is that the assumed 8 percent transfer efficiency is too high. This is tied to the air diffuser bubble size and air distribution in the column. Figures 19 and 20 shows the air distribution in a 9.0 cm diameter beaker. At 70 ℓ/hr the air bubbles rise straight up the center of the beaker whereas at 140 ℓ/hr the air bubbles spread out through the entire column. Thus it would appear that the assumed 8 percent transfer efficiency at 70 ℓ/hr is incorrect. More efficient air distribution in a larger system may reduce the required air flow to theoretical values.

Throughout these experiments a milky colored precipitate would form in columns that failed. There is no apparent cause for the formation of this precipitate. The precipitate would form in samples taken from 60 to 720 minutes; dissolved oxygen levels were generally less than 4 mg/l; pH varied from 2.4 to 5.5; and SO_2 concentrations were greater than 4 mg/l. An electron microscopy scan of the precipitate showed the primary elements to be phosphorus and iron. This again gave no clue as to the cause of the precipitation formation. Because the precipitate did not form in samples from successful columns (i.e. no SO_2 breakthrough), investigation of this phenomenon was not pursued.

The column consisting of 50 cm activated carbon, an air flow of 140 ℓ/hr, and a liquid flow of 150 ml/min was run for a period of 96 hours to determine long term catalytic abilities of the carbon (see Figure 21 and Appendix B, Table B-47). Breakthrough of SO_2 began after

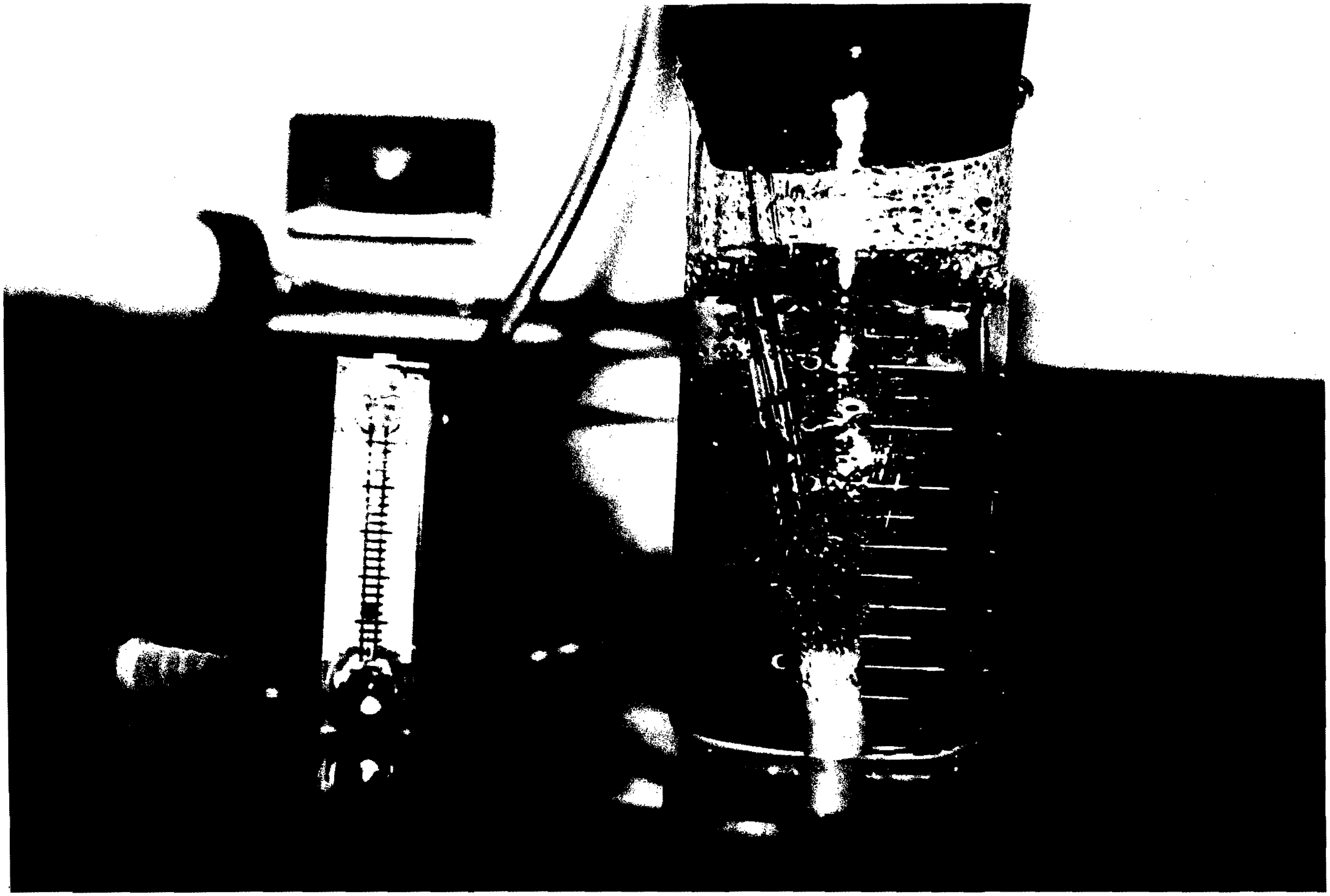


Figure 19. Air distribution at 70 ℓ/hr.

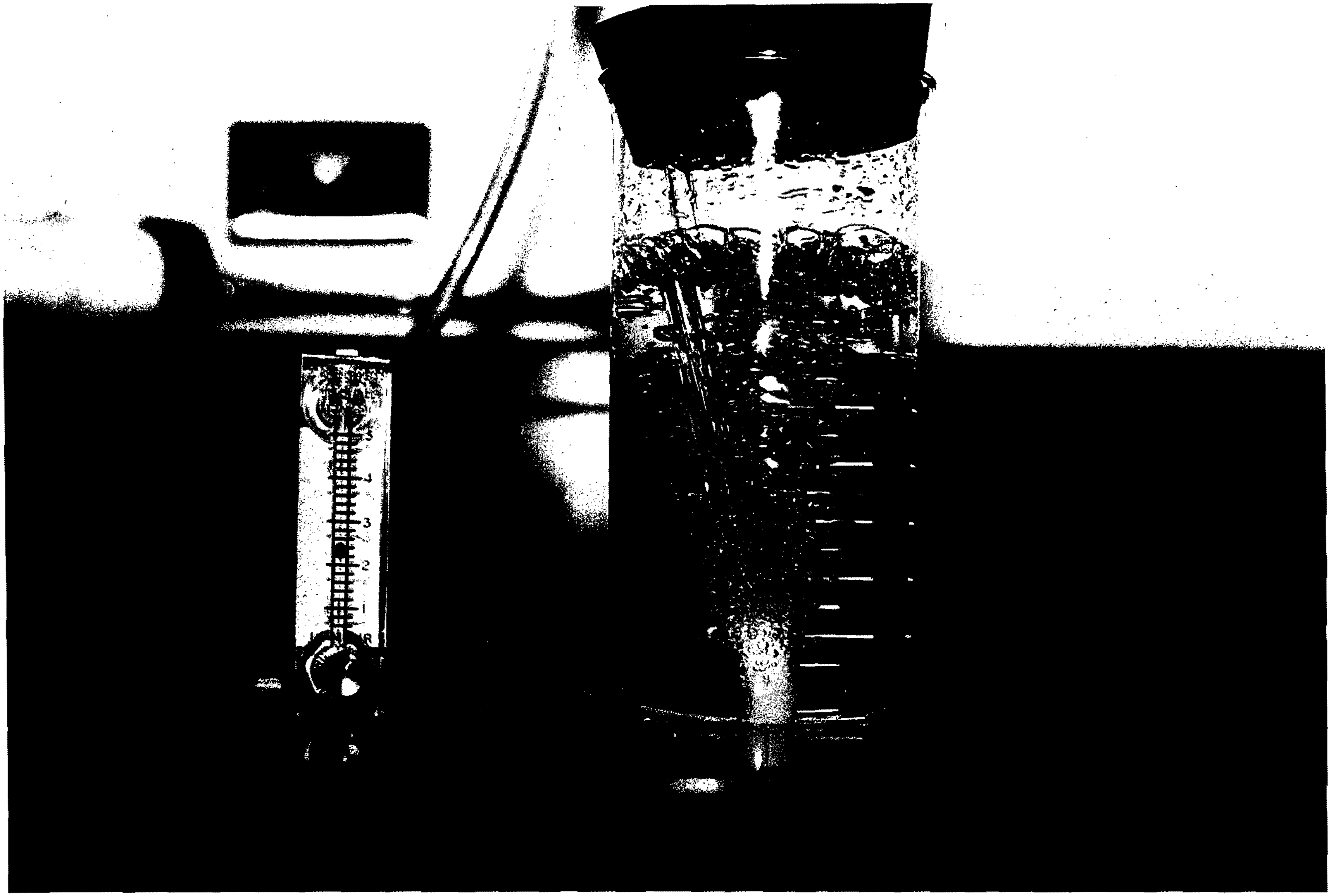


Figure 20. Air distribution at 140 ℓ/hr.

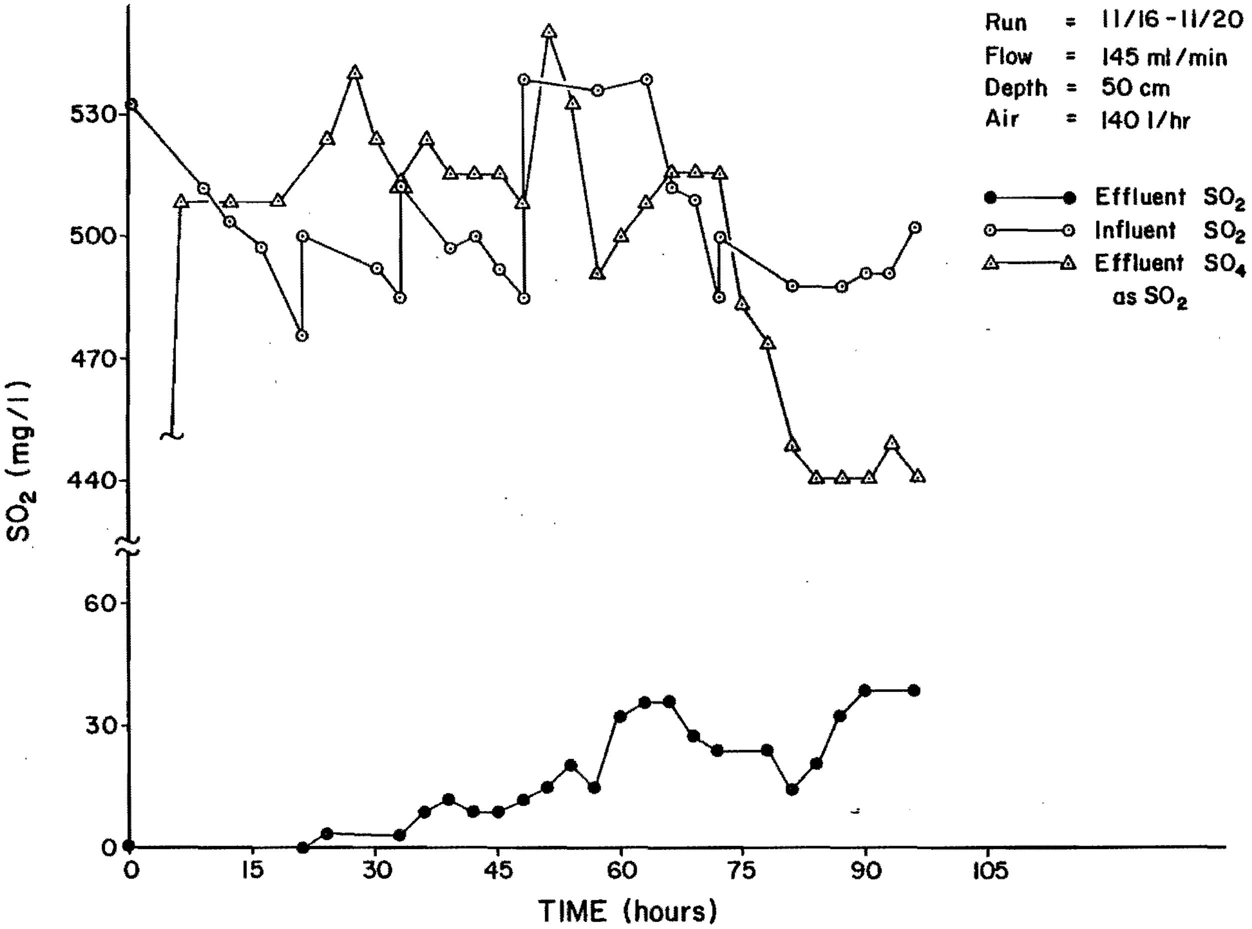


Figure 21. 96 hour column run.

24 hours and increased (in a fluctuating manner) to 40 mg/l after 96 hours, the highest concentration recorded. The cause of the gradual failure is the self-poisoning of the carbon via saturation with sulfuric acid. The removal of the sulfuric acid is necessary for continued oxidation of SO_2. This may be accomplished by flushing the carbon with water (Komiyama and Smith 1975). To test this assumption, a column was run to failure (defined by effluent SO_2 values greater than 20 mg/l), then backwashed with water and the column restarted (see Figure 22 and Appendix B, Table B-48). Backwashing was accomplished by running tap water up through the column, expanding the carbon bed by 20 percent. Forty liters of water were used over a 20 minute period. Initial pH of the backwash water was 2.2; after 4 minutes the pH rose to 6.0. The final backwash pH was 6.8. This increase in pH indicates the flushing out of the acid.

Following backwashing, the carbon bed resettled to 110 percent of its original height. This is due to the strong inter-particle attraction exhibited by wet carbon. The first run failed after 10 hours. The second run, after backwashing, ran for 40 hours without failing (as defined earlier). The most probable cause for the improved performance after backwashing is the increased exposed surface area created by the bridging between carbon particles. Thus it may be concluded that backwashing removes the sulfuric acid and regenerates the catalytic properties of the activated carbon.

The fate of the sulfur species was examined during all 24 hour runs. The results during the 96 hour run are shown in Figure 21. Through the course of the run, 91 percent of the influent sulfur

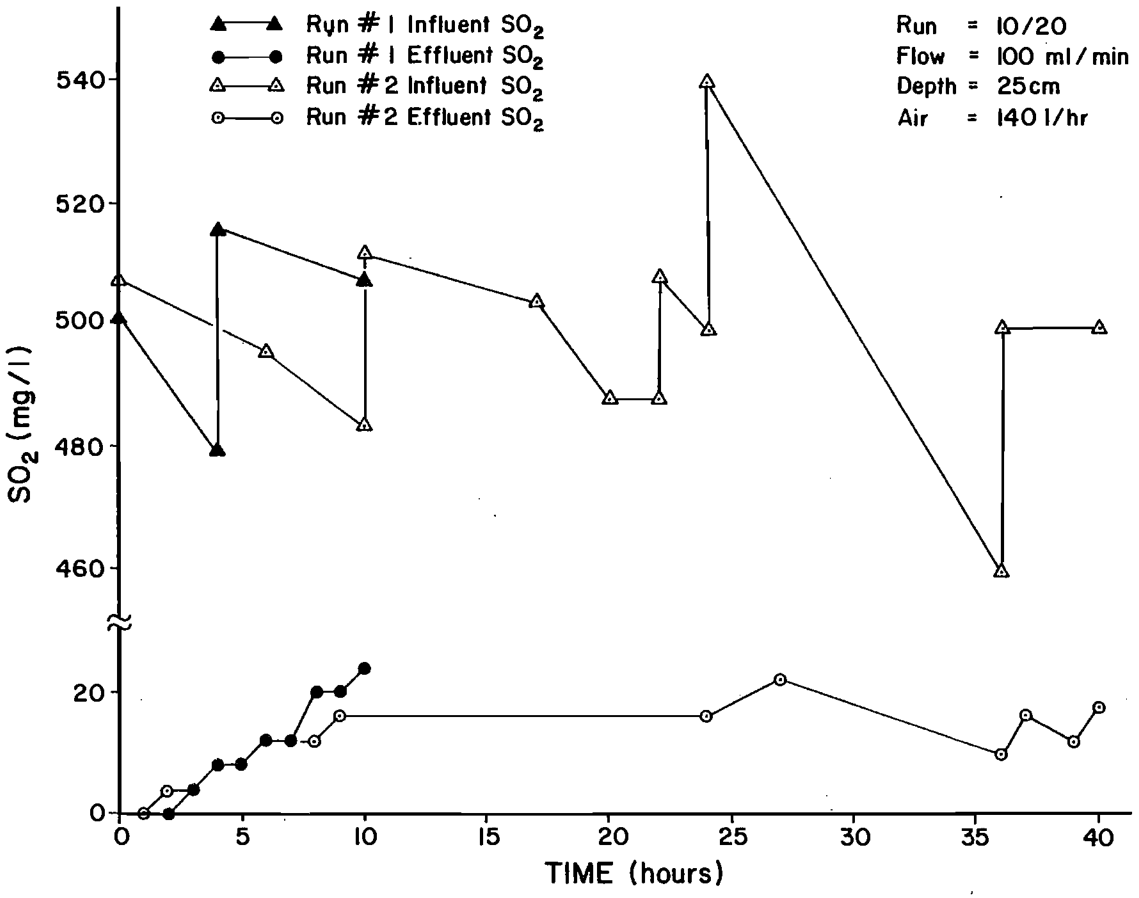


Figure 22. Backwashed column results.

species (+IV and +VI) were accounted for in the effluent. Causes of the missing sulfur may be the formation of dithionate, loss of SO_2 gas in the column, and inaccuracies in the sulfate data due to the analytical procedure used.

COST ANALYSIS

Costs for the sulfur dioxide oxidation system were developed based on reasonable limits in design criteria as shown in Table 7. The worst case design criteria is that developed by the bench scale column. The low surface loading in this case results in a very large filter surface area. By increasing the surface loading and increasing the carbon bed depth (maintaining the carbon volume), the filter surface area and cost may be greatly decreased. For a given carbon volume and flow rate, pilot plant testing must be conducted to optimize surface loading and carbon bed depth.

The worst case also assumes an air requirement equivalent to that used in the bench testing. The best case assumes an air requirement equal to theoretical values.

A capital cost summary for both cases is shown in Table 8. A generalized flow sheet for the SO^2 oxidation system is shown in Figure 23. The filter costs are based on a typical dual media filtration unit (see Appendix D). Included in the filter costs are the feed system, tankage, underdrain system, backwash pump and storage tank, building, and appurtenances necessary for complete operation. The large surface area required for the downflow contactor mode of operation, along with the need for enclosing the filters, makes this system extremely capital intensive.

Annual costs for the SO_2 oxidation system are shown in Table 9. The power costs include feed and backwash pumping, and blowers for aeration. Total power represents only 6-15 percent of the total annual costs indicating a very low-energy use system.

Table 7. Summary of design criteria.

Item	Best Case 3785 m^3/d	Best Case 37850 m^3/d	Worst Case 3785 m^3/d	Worst Case 37850 m^3/d
A. Carbon Filters				
1. No. of units	2	4	2	4
2. Surface area, total, m^2	32	320	100	1000
3. Bed depth, m	1.6	1.6	0.5	0.5
4. Surface loading, $m^3/m^2 \cdot d$	117.2	117.2	37.5	37.5
B. Blowers				
1. No. of units	2	2	2	2
2. Capacity, total, m^3/h	1275	12750	2550	25500
3. kw	7.5	75	7.5	75

Note: $m^3/d \times 2.6417 \times 10^{-4}$ = mgal/day
$m^2 \times 10.7639 = ft^2$
m x 3.2808 = ft
$m^3/m^2 \cdot d \times 24.5424 = gal/ft^2 \cdot d$
$m^3/h \times 0.5886 = ft^3/min$
kw x 1.3410 = HP

Table 8. SO_2 oxidation system capital cost estimate.

Item	Best Case 3785 m^3/d \$	Best Case 37850 m^3/d \$	Worst Case 3785 m^3/d \$	Worst Case 37850 m^3/d \$
1. Filter, Complete Except Medium	612,000	2,720,000	952,000	4,216,000
2. Activated Carbon	50,000	500,000	50,000	500,000
3. Blowers	10,000	48,600	20,000	97,200
4. Corrosion Liner	15,100	84,000	43,200	580,000
Subtotal	\$687,100	\$3,352,600	\$1,065,200	\$5,393,200
5. Electrical & Piping	137,400	670,500	266,300	1,348,300
Total Capital[a]	\$824,500	\$4,023,100	\$1,331,500	\$6,741,500

[a] Construction costs only.

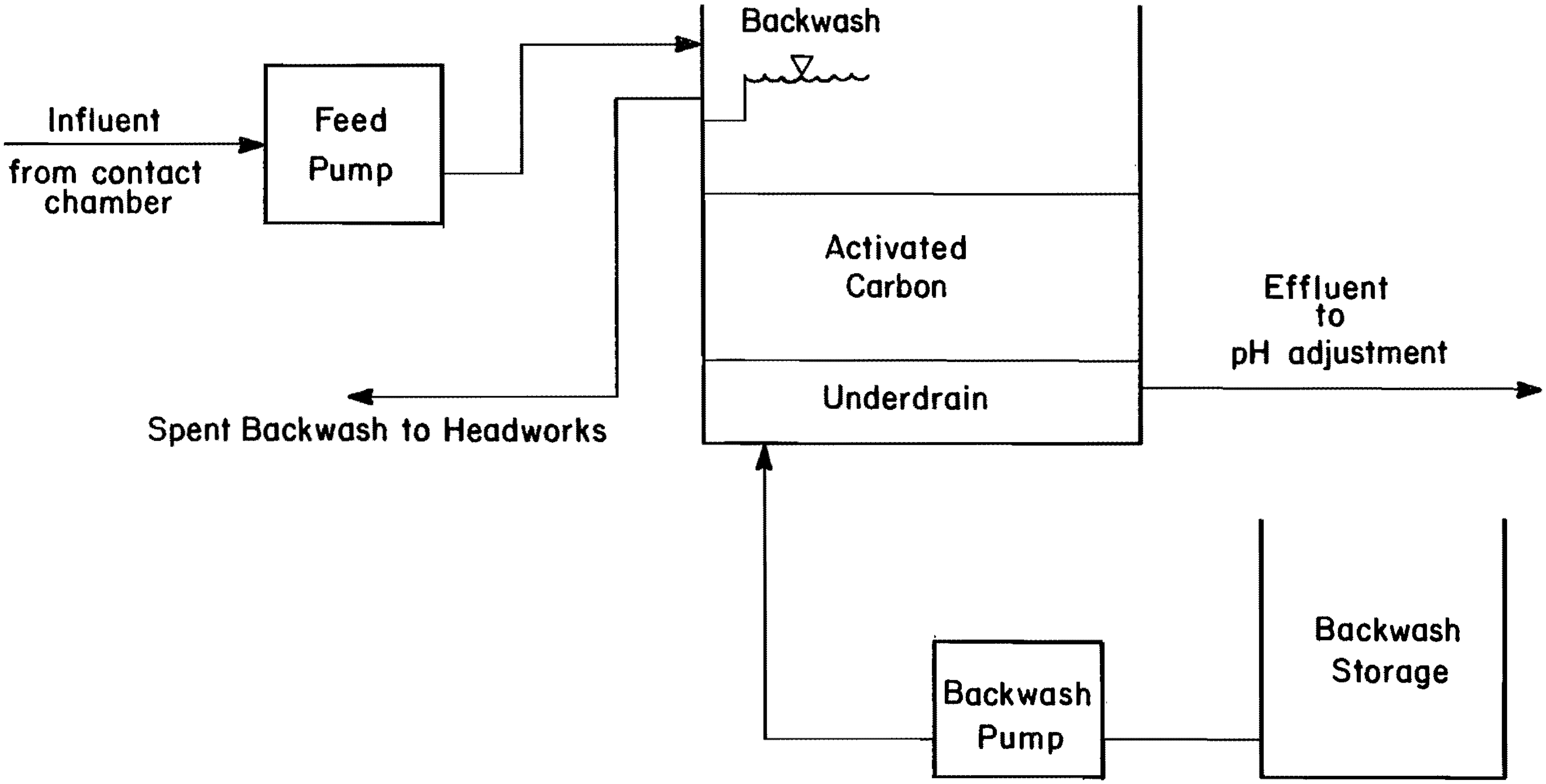


Figure 23. Flow sheet for SO_2 oxidation system.

Table 9. SO_2 oxidation system summary of annual costs.

Item	Best Case 3785 m^3/d \$	Best Case 37850 m^3/d \$	Worst Case 3785 m^3/d \$	Worst Case 37850 m^3/d \$
Capital Cost	\$824,500	\$4,023,100	\$1,331,500	\$6,741,500
Capital Recovery[a]	77,800	379,700	125,700	636,300
Power @ 6.5 ¢/kwh	10,700	97,600	10,700	97,600
Labor @ 13.20/Man hr	5,500	16,000	5,500	16,000
Materials	8,300	40,200	13,300	67,400
Total Annual Cost	\$102,300	\$533,500	\$155,200	\$817,300

[a] 7 percent for 20 years, cost recovery factor = 0.09439.

Labor and material costs were an average of values taken from EPA (1980) cost curves for dual media filtration and trickling filter operations. Labor costs were adjusted to a current rate of \$13.20 per man hour; material costs represent from 1.5-2.5 percent of the capital costs.

Table 10 compares the complete SO_2 disinfection process with other disinfection systems. The costs for the SO_2 disinfection process excluding the oxidation system, along with the other alternative disinfection processes were developed by Nielsen, Maxwell and Wangsgard-Montgomery Inc. (see Appendix D). As shown, when compared to other processes, the SO_2 disinfection process is capital intensive. Total operation and maintenance costs are also significantly higher than for other disinfection processes.

Table 10. Comparison of capital and operation and maintenance costs for various wastewater disinfection processes based on Total Coliform (TC) or Fecal Coliform (FC) standards.

Disinfection Process	Standard = 1000 TC/1000 ml		Standard = 2.2 FC/1000 ml	
	3785 m^3/d	37850 m^3/d	3785 m^3/d	37850 m^3/d
I. Chlorination-dechlorination[a] (without post aeration)				
A. Capital, $	83,000	216,000	124,000	855,000
B. Operation & Maintenance, $/yr	12,600	44,900	15,460	64,060
II. Chlorine Dioxide with SO_2 Reduction[a]				
A. Capital, $	112,000	309,000	160,700	979,400
B. Operation & Maintenance, $/yr	46,430	361,220	80,780	680,600
III. Ultraviolet Light[a]				
A. Capital, $	140,000	1,100,000	3,200,000	26,000,000
B. Operation & Maintenance, $/yr	18,800	187,000	583,300	5,809,000
IV. Ozonation[a]				
A. Capital, $	212,500	914,700	799,500	3,724,700
B. Operation & Maintenance, $/yr	21,025	109,850	96,010	801,200
V. SO_2 Worst Case[b]				
A. Capital, $	1,608,000	7,870,000	1,608,000	7,870,000
B. Operation & Maintenance, $/yr	114,000	955,000	114,000	955,000
VI. SO_2 Best Case[b]				
A. Capital, $	997,000	4,665,000	997,000	4,665,000
B. Operation & Maintenance, $/yr	54,000	408,000	54,000	408,000

[a] Costs developed by Nielsen, Maxwell and Wangsgard-Montgomery, Inc.

[b] Total SO_2 disinfection process, including SO_2 oxidation system.

Costs were also developed for two different coliform discharge standards. The costs for the alternative disinfection systems increase significantly with a more stringent fecal coliform standard. This is due to much greater chemical costs required to meet the higher discharge standards. Larger chemical doses are not necessary with the SO_2 disinfection system, thus costs are not affected by the more stringent standards.

The costs for sulfur dioxide disinfection range from \$0.23 to \$0.73/1000 gallons treated (Table 11). Only for the most stringent coliform standard does the best case SO_2 system prove to be less costly than ozonation or ultraviolet radiation. When compared with other disinfection processes and coliform standards the SO_2 system is more expensive.

Table 11. Summary cost (¢/1000 gallons treated) comparison between sulfur dioxide disinfection and other alternative disinfection systems.

Process	Standard = 2.2 FC/100 ml		Standard = 1000 TC/100 ml	
	3785 m^3/d	37850 m^3/d	3785 m^3/d	37850 m^3/d
Chlorination-Dechlorination (without post aeration)	7.9	4.6	6.0	1.9
Chlorination-Dechlorination (with post aeration)	9.2	5.5	7.3	2.6
Chlorine Dioxide/SO_2 Reduction	27.2	21.9	16.2	10.9
Ozonation	51.7	34.6	12.9	6.1
Ultraviolet Light	261.6	250.7	9.7	8.7
Best SO_2 Case	40.5	23.2	40.5	23.2
Worst SO_2 Case	72.9	46.5	72.9	46.5

Note: ¢/1000 gal x 0.264 = ¢/M^3.

SUMMARY AND CONCLUSIONS

This research dealt with the removal of the oxygen demand created in wastewater disinfected with sulfur dioxide at a concentration of 500 mg/l. The removal mechanism studied was catalyzed oxidation. Catalysts studied included transition metals (Fe^{++}, Mn^{++}, Co^{++}), activated carbon (Calgon Filtrasorb 300), and a combination of the two. It was found that the metals, and activated carbon plus metals were very good catalysts for the oxidation of sulfur dioxide, to sulfate. However, the acidic nature of the disinfected wastewater (pH 2.6) dissolved the metals or caused them to desorb from the carbon. Activated carbon was also shown to be a good catalyst as long as sufficient oxygen levels were maintained. Results showed that the catalytic properties of activated carbon may be maintained over an extended period of time by backwashing the carbon to remove the sulfuric acid produced by the oxidation of sulfur dioxide.

The costs of sulfur dioxide disinfection range from $0.23-$0.73/1000 gallons treated. In general, this is much more costly than other disinfection processes.

Specific conclusions drawn from this research include:

1) The acidic nature of the disinfected wastewater (pH 2.6) will not allow use of transition metals as an oxidation catalyst due to excessive metal transport into solution.

2) Activated carbon does catalyze the oxidation of SO_2 in wastewater.

3) In a downflow contactor with sufficient oxygen, it was found that 5.5 g carbon/l was necessary for complete SO_2 removal over a 24 hour period.

4) Twice the theoretical air flow was found necessary to provide sufficient oxygen for complete SO_2 oxidation, probably caused by poor air distribution in the column.

5) Self-poisoning of the carbon by sulfuric acid (the product of SO_2 oxidation) and/or reduced oxygen solubility in the sulfuric acid saturated column slowly reduced the catalytic effects of the activated carbon.

6) Backwashing the column removed the sulfuric acid and restored the catalytic properties of the activated carbon.

7) Without significant capital cost reductions, SO_2 disinfection cannot compete with other disinfection processes.

ENGINEERING SIGNIFICANCE

The data collected in this study suggest a possible method for the oxidation of sulfur dioxide in wastewater. The development of wastewater disinfection processes, to replace chlorination, is needed in light of increasing evidence of adverse health affects created by chlorination. Sulfur dioxide has been shown to be an effective disinfectant; however, the oxygen demand created by aqueous sulfur dioxide must be eliminated prior to discharge. Oxidation is one means of accomplishing this task.

Activated carbon was shown to be an effective catalyst in the oxidation of sulfur dioxide, with sulfuric acid as a byproduct. The ease of operation of a trickling filter type reactor (downflow contactor) and the sample regeneration of the carbon via backwashing make the system worth further consideration. However a great deal of additional research is necessary to optimize the type of activated carbon used and the process design parameters. Hopefully this research will lead to significant reductions in the preliminary capital costs generated during this study.

RECOMMENDATIONS

1. Conduct pilot plant testing to refine the design parameters developed at bench scale including surface loading, backwashing, and air flows.
2. Further study the role of activated carbon as a catalyst.
3. Further study the fate of other wastewater constituents in the system.
4. Study different system configurations to help reduce costs (e.g., recycle filter effluent to reduce sulfur dioxide requirements).
5. Study several different commercial brands of activated carbon to determine how raw materials affect catalytic properties.
6. Other reactor types, such as a fluidized carbon bed, should be investigated in order to reduce the high costs associated with the downflow contactor arrangement.

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APPENDICES

Appendix A

Manufacturer Information

Activated carbon characteristics

Description.* Filtrasorb activated carbons are manufactured from select grades of bituminous coal to produce a high density, high surface area, durable granular product. They are capable of withstanding the abrasion and dynamics associated with repeated reactivation, hydraulic transport, backwashing, and mechanical handling. Filtrasorb carbons wet readily and do not float, thus minimizing loss during backwash operations.

Physical properties.

	Filtrasorb 300	Filtrasorb 400
Total Surface Area (N_2, BET Method)	950	1050
Bed Density, Backwashed and Drained (lbs/cf)	26	26

Specifications.

	Filtrasorb 300	Filtrasorb 400
Iodine Number (min.)	900	1000
Abrasion Number (min.)	75	75
Moisture (max.)	2.0%	2.0%
Mean Particle Diameter (mm)	1.5-1.7	0.9-1.1
Effective Size (mm)	0.8-0.9	0.55-0.65
Water Soluble Ash (max.)	0.5%	0.5%
U.S. Standard Series Sieve Size:		
Larger than No. 8 (max.)	15%	-
Smaller than No. 30 (max.)	4%	-
Larger than No. 12 (max.)	-	5%
Smaller than No. 40 (max.)	-	4%

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*Calgon Corporation, Product Bulletin 27-33a.

Manufacturers addresses

1) Calgon Corp.
Activated Carbon Division
P.O. Box 1346
Pittsburgh, PA 15230

2) Alfa Products
Thiokol/Ventron Division
152 Andover St.
Danvers, MA 01923

Appendix B

Raw Data

Note:

1. The following tables and graphs may show air flow in units of cubic feet per hour. The conversion to liters per hour is: CFH x 28.32 = ℓ/hr.
2. All sulfur specie concentrations are reported as mg/l as SO_2.

Table B-1. SO_2 oxidation jar test--4/22.

Initial Feed Soln.

DO = 2.8
pH = 1.9
SO_2 = 510 mg/l
$SO_4^=$ = -
Alk = 232

Final Feed Soln.

DO = -
pH = -
SO_2 = -
$SO_4^=$ = -

Jar Test Data:

GAC g/l	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Jar Test Media
0	-	-	420	34	2 mg Fe^{3+}/g GAC
10	0.7	2.3	172	368	
20	0.3	2.5	74	456	
30	0.3	2.6	22	440	
40	0.4	2.8	4	390	
50	0.9	3.1	4	349	
60	1.4	3.5	4	328	
0	6.9	2.6	460	35	6 mg Fe^{3+}/g GAC
10	0.5	2.4	100	534	
20	0.3	2.3	10	480	
30	0.6	2.5	8	436	
40	1.5	2.7	4	380	
50	1.5	3.1	4	329	
60	1.8	3.5	4	291	
0	7.0	2.6	500	37	2 mg Mn^{2+}/g GAC
10	0.3	2.3	118	511	
20	0.3	2.4	48	545	
30	0.2	2.6	22	490	
40	0.1	2.75	4	456	
50	1.1	3.1	4	413	
60	1.4	3.1	4	373	
0	5.6	2.5	412	34	6 mg Mn^{2+}/g GAC
10	0.3	2.3	68	533	
20	0.2	2.3	6	523	
30	0.4	2.6	6	512	
40	1.4	2.9	4	458	
50	1.4	3.2	4	440	
60	1.5	4.4	4	425	

Table B-2. SO_2 oxidation column observations--7/18.

Column Media = Fe·Alumina
Initial Metal = N/A
Final Metal =

Initial Feed Soln.		Final Feed Soln.	
DO =	6.8	DO =	6.7
pH =	2.8	pH =	2.6
SO_2 =	528 mg/l	SO_2 =	496 mg/l
$SO_4^=$ =	98 mg/l	$SO_4^=$ =	54 mg/l
Fe =	175 μg/l		

Column Data: Air Flow = 15-20 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Metal μg/l
0	0.2	6.3	84	197	55	745
10	0.1	5.6	212	168	44	207
20	0.1	4.3	260	155	50	240
30	0.8	3.6	284	184	56	131
40	1.1	3.5	288	371	57	104
50	3.1	3.6	300	151	50	98
60	3.7	3.7	320	177	48	118
90	4.7	3.7	328	186	54	164
120	6.0	3.6	348	175	53	154
150	5.9	3.6	344	212	48	165
180	6.4	3.5	348	169	53	566

Table B-3. SO_2 oxidation column observations--7/19.

Column Media = Mn·Alumina
Initial Metal = N/A
Final Metal =

Initial Feed Soln.		Final Feed Soln.	
DO	6.2	DO	5.7
pH	2.7	pH	2.5
SO_2	532 mg/l	SO_2	496 mg/l
$SO_4^=$	69 mg/l	$SO_4^=$	161 mg/l
Mn	<4 mg/l		

Column Data: Air Flow = 15-20 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Metal mg/l
0	0.2	3.6	108	176	55	39
10	0.4	3.3	108	241	55	76
20	0.2	3.2	108	267	54	91
30	0.6	3.1	108	257	52	96
40	0.5	3.1	104	233	52	99
50	0.1	3.1	100	257	51	105
60	0.1	3.1	100	242	53	100
90	0.1	3.1	104	303	51	105
120	0.1	3.0	100	312	51	105
150	0.1	2.9	80	295	43	110

Table B-4. SO_2 oxidation column observations--7/23.

Column Media = Co, Ni, Fe·Alumina
Initial Metal = N/A
Final Metal =

Initial Feed Soln.
DO = 5.0
pH = 2.6
SO_2 = 540 mg/l
$SO_4^{=}$ = 46 mg/l as SO_2
Co = <3 mg/l
Ni = 16 µg/l
Fe = 49 µg/l

Final Feed Soln.
DO = 5.2
pH = 2.4
SO_2 = 488 mg/l
$SO_4^{=}$ = 37 mg/l as SO_2

Column Data: Air Flow = 15-20 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^{=}$ as SO_2	Flow ml/min	Metal		
						Co mg/l	Ni µg/l	Fe µg/l
0	3.6	3.2	16	30	55	93	1107	395
10	3.6	3.2	52	72	49	45	535	381
20	4.3	3.3	80	53	49	34	371	361
30	4.7	3.3	120	38	54	26	261	357
60	5.5	3.4	172	45	51	17	137	419
90	4.5	3.3	188	50	51	16	94	430
120	4.3	3.3	216	70	51	13	71	479
150	4.3	3.4	208	74	41	15	72	492
180	4.6	3.3	244	66	49	10	52	601
210	4.5	3.2	260	75	52	9	43	596
240	4.8	3.2	268	69	51	7	36	884
270	5.0	3.2	268	71	51	7	36	691

Table B-5. SO_2 oxidation column observations--7/23.

Column Media = V·Alumina and Silica
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 5.8	DO = -
pH = 2.6	pH = -
SO_2 = 552 mg/l	SO_2 = -
$SO_4^=$ = 59 mg/l as SO_2	$SO_4^=$ = -
V = <7 μg/l	

Column Data: Air Flow = 15-20 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Metal μg/l
0	4.5	4.2	280	141	58	85,000
10	5.9	4.1	356	109	45	85,000
20	5.7	3.8	372	109	49	70,200
30	5.8	3.8	388	94	52	64,600
60	6.3	3.7	372	85	52	50,400
90	6.1	3.7	388	79	53	36,600

Table B-6. Preliminary assessment of oxidation catalysts--7/30.

Column Conditions:
Feed Rate = 50 ml/min.
Medium Depth = 25 cm
Feed Soln. pH = 2.5-2.9
Air Flow = 7.2-9.5 ℓ/min.
Run Time = 3 hrs.

Medium	Criteria*				Additional Study
	Oxidative Capacity	Effluent DO	Effluent pH	Effluent Metals	
Activated Carbon	Fair	Good	Poor	N/A	Yes
Fe^{3+} on GAC	Good	Good	Poor	Poor	Yes
Mn^{2+} on GAC	Good	Good	Poor	Poor	Yes
Co^{2+} on GAC	Good	Good	Poor	Poor	Yes
Fe_2O_3 on Alumina	Poor	Good	Poor	Good	No
MnO_2 on Alumina	Fair	Poor	Poor	Poor	No
V_2O_5 on Alumina	Poor	Good	Poor	Poor	No
NiCoFe on Alumina	Poor	Good	Poor	Poor	No

*Oxidative Capacity (Effluent SO_2 Concentration): Good $<$ 50 mg SO_2/l; Fair $<$ 100 mg SO_2/l; SO_2/l; Poor $>$ 100 mg SO_2/lSO_2/l
Effluent DO: Good $\geq$ 2 mg/l; Poor $<$ 2 mg/l
Effluent pH: Good $\geq$ 6.5; Poor $<$ 6.5
Effluent Metals: Good $\leq$ 1 mg/l; Fair $\leq$ 5 mg/l; Poor $>$ 5 mg/l

Table B-7. SO_2 oxidation jar test--8/7.

Raw iron (1/4" nuts) was placed in bottom of 4000 ml beaker. 1700 ml sewage with 500 mg/l SO_2 added to beaker and aerated at 15-20 CFH. pH and DO monitored continuously. Samples taken at 1 min. intervals.

Time Min.	DO	pH	SO_2 mg/l	Metal mg/l	Comments
0	6.2	2.7	516	-	
1	6.6	2.7	492	8	
2	6.4	2.7	456	10	
3	6.3	2.7	456	13	
4	6.2	2.7	408	16	
5	6.1	2.7	440	19	
6	5.8	2.75	440	21	
7	5.2	2.8	424	23	
8	4.2	2.7	400	24	
9	3.2	2.7	352	26	
10	2.3	2.6	-	28	
11	1.5	2.6	292	29	
12	0.8	2.6	232	31	
13	0.4	2.5	224	32	
14	0.2	2.45	172	34	Cloudy
15	0.1	2.4	132	36	Cloudy
16	0.1	2.3	92	39	Cloudy
17	0.2	2.3	48	41	Cloudy
18	1.2	2.3	20	64	Cloudy
19	2.9	2.3	0	66	Cloudy
20	4.5	2.2	0	70	Cloudy
21	5.6	2.2	0	71	Cloudy
22	6.2	2.2	0	105	Cloudy

Table B-8. SO_2 oxidation column observations--8/10

Column Media = Fe^{3+} + GAC
Initial Fe = 500 mg/l
Final Fe = 3.1 mg/l
497 mg = Fe adsorbed/295 g GAC

Initial Feed Soln.
DO = 6.8
pH = 2.75
SO_2 = 472 mg/l
$SO_4^=$ = -
Fe = <0.8 mg/l

Final Feed Soln.
DO = 6.2
pH = 2.7
SO_2 = 416 mg/l
$SO_4^=$ = 51 mg/l as SO_2

Column Data: Air Flow = 15-20 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Fe mg/l
10	7.7	3.9	4	97	47	17
20	7.4	3.5	0	167	49	35
30	7.2	3.0	0	222	49	38
60	7.2	2.5	0	296	52	30
90	7.2	2.3	0	322	54	26
120	7.0	2.3	0	344	47	23
150	7.0	2.2	0	361	51	22
180	6.9	2.2	0	370	49	23
240	6.6	2.25	0	349	50	17
300	6.5	2.2	0	345	50	14
360	6.4	2.2	4	333	53	10.5
420	6.3	2.2	12	335	49	11
540	6.3	2.2	16	328	50	6
600	6.3	2.2	24	322	50	5
660	6.7	2.2	20	327	49	4
720	6.5	2.2	16	316	51	3
1200	7.4	2.5	0	330	56	1.5
1260	7.0	2.2	4	349	52	1.2
1320	6.7	2.2	6	291	50	1.1
1380	6.5	2.2	16	296	49	1.1
1440						

Table B-9. SO_2 oxidation column observations--8/12.

Column Media = Mn·GAC
Initial Mn = 1006 mg/l
Final Mn = 179 mg/l
827 mg = Mn adsorbed/295 g GAC

Initial Feed Soln.
DO = 7.1
pH = 2.8
SO_2 = 488 mg/l
$SO_4^=$ = -
Mn = <39 µg/l

Final Feed Soln.
DO = 5.9
pH = 2.7
SO_2 = 344 mg/l
$SO_4^=$ = 63 mg/l as SO_2

Column Data: Air Flow = 15-20 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Mn µg/l
10	6.6	6.2	0	154	49	58000
20	7.3	6.3	0	210	52	61000
30	7.3	4.3	0	243	52	61000
60	6.8	3.0	0	305	48	53000
90	6.7	2.5	0	326	49	48000
120	6.8	2.3	0	350	49	44000
180	6.7	2.3	0	343	49	7260
240	6.5	2.2	0	350	50	3619
300	6.5	2.2	0	342	50	2090
360	6.25	2.2	4	330	49	1166
460	6.3	2.2	8	326	50	665
540	6.2	2.2	16	316	50	279
600	6.2	2.2	16	311	50	211
660	6.2	2.2	16	301	49	145
720	6.3	2.2	16	301	50	125
780	6.4	2.2	16	314	48	103
840	6.5	2.2	16	314	49	78
900	6.4	2.2	24	310	50	82
960	6.4	2.2	24	308	50	69
1020	6.3	2.2	24	318	48	64
1080	6.4	2.2	24	310	50	54
1140	6.4	2.2	28	310	50	58
1200	6.3	2.2	24	301	49	52
1260	6.5	2.2	28	301	52	45
1320	6.4	2.2	24	310	48	45
1380	6.4	2.2	20	297	48	42
1440	6.1	2.2	28	301	52	42

Table B-10. SO_2 oxidation column observations--8/14.

Column Media = GAC·Co
Initial Co = 732 mg/l
Final Co = 326 mg/l
406 mg = Co Adsorbed/295 g GAC

Initial Feed Soln.		Final Feed Soln.	
DO	= 6.8	DO	= 5.7
pH	= 2.5	pH	= 2.7
SO_2	= 556 mg/l	SO_2	= 316 mg/l
$SO_4^=$	= -	$SO_4^=$	= 56 mg/l as SO_2
Co	= <3 mg/l		

Column Data: Air Flow = 15-20 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Co µg/l	Comments
10	7.8	6.5	0	186	50	52000	
20	7.4	3.6	0	270	50	58000	
30	7.2	3.0	4	324	50	34000	Cloudy
60	6.7	2.6	20	377	50	18000	Cloudy
90	6.6	2.4	24	402	50	14000	Cloudy
120	6.1	2.35	24	427	49	10000	Cloudy
180	6.3	2.3	28	435	50	5000	Cloudy
240	5.5	2.2	36	451	51	3000	
300	5.8	2.2	36	451	49	1000	
360	5.5	2.2	36	427	52	1518	
420	5.4	2.2	48	427	52	814	
480	5.7	2.2	48	402	50	374	
600	6.3	2.2	48	410	47	172	
660	6.3	2.2	56	385	52	133	
720	6.2	2.2	68	402	52	132	
780	6.4	2.2	60	377	51	87	
840	6.4	2.2	64	369	52	43	
900	6.5	2.2	64	369	51	31	
960	6.5	2.2	68	385	50	31	
1020	6.6	2.2	68	361	51	17	
1080	6.6	2.2	68	357	50	17	
1140	6.7	2.2	60	369	50	25	
1200	6.7	2.2	60	348	50	24	
1260	6.6	2.2	60	336	50	28	
1320	6.7	2.2	44	316	50	17	
1350	7.0	2.2	36	303	50	38	

Table B-11. SO_2 oxidation column observations--8/18.

Column Media = GAC·Fe
Initial Fe = 550 mg/l
Final Fe = 10 mg/l
540 mg = Fe Adsorbed/295 g GAC

Initial Feed Soln.
DO = 6.6
pH = 2.6
SO_2 = 496 mg/l
$SO_4^=$ = -
Fe = <0.3 mg/l

Final Feed Soln.
DO = 5.9
pH = 2.7
SO_2 = 292 mg/l
$SO_4^=$ = -

Column Data: Air Flow = 15-20 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Fe mg/l
10	6.7	4.8	0	No Data	53	6
20	6.8	3.8	0		49	38
30	6.8	3.0	0		49	40
60	6.9	2.5	4		51	39
90	6.85	2.35	8		51	35
120	6.8	2.3	8		53	32
180	6.5	2.25	8		54	25
240	6.8	2.3	12		29*	11
300	6.8	2.3	4		28	6
360	6.6	2.15	4		44	6
420	6.7	2.2	4		45	7
480	6.6	2.2	4		43	7
540	6.4	2.2	8		48	8
600	6.5	2.2	4		47	8
660	6.0	2.15	12		53	8
720	6.4	2.2	4		49	6
780	6.2	2.2	4		49	4
840	6.2	2.2	4		49	3
900	6.3	2.1	8		51	3
960	6.5	2.1	8		50	3
1020	6.6	2.1	4		49	2
1080	6.4	2.1	8		52	2
1140	6.6	2.2	4		49	2
1200	6.5	2.2	4		49	2
1260	6.5	2.2	12		53	2
1320	6.5	2.2	12		53	1
1380	6.6	2.2	12		50	0.70
1440	6.5	2.2	8		49	<0.3

*One of the round clear pellets or crystals passed through and must have clogged the flow momentarily.

Table B-12. SO_2 oxidation column observations--8/20.

Column Media = GAC
Initial Metal = N/A
Final Metal =

Initial Feed Soln.		Final Feed Soln.	
DO =	7.3	DO =	5.3
pH =	2.7	pH =	2.8
SO_2 =	460 mg/l	SO_2 =	320 mg/l
$SO_4^=$ =	-	$SO_4^=$ =	-

Column Data: Air Flow = 15-20 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
10	7.2	7.2	0	No	48	
20	7.0	6.5	0	Data	51	
30	6.8	3.4	0		51	
60	5.9	2.7	36		49	Cloudy
90	5.7	2.6	56		51	Cloudy
120	5.5	2.5	68		51	Cloudy
180	5.5	2.5	80		51	Cloudy
240	5.4	2.4	84		51	
300	4.8	2.4	88		51	
360	3.5	2.25	108		53	
420	4.6	2.35	68		54	
480	3.8	2.30	68		55	
540	4.4	2.3	72		52	
600	4.8	2.3	76		52	
660	3.6	2.3	72		52	
720	4.6	2.3	64		51	
780	4.8	2.3	72		52	
840	5.2	2.3	72		51	
900	5.1	2.3	68		50	
960	5.3	2.3	68		50	
1020	5.4	2.3	68		51	
1080	5.3	2.3	68		49	
1140	5.0	2.3	68		51	
1200	5.4	2.3	60		51	
1260	5.4	2.3	68		51	
1320	5.4	2.3	68		50	
1380	5.8	2.3	68		50	
1440	6.3	2.3	24		51	

Table B-13. SO_2 oxidation column observations--8/27.

Column Media = GAC
Initial Metal = N/A
Final Metal =

Initial Feed Soln.
DO = 6.0
pH = 2.6
SO_2 = 508 mg/l
$SO_4^=$ = 71 mg/l as SO_2

Final Feed Soln.
DO = 4.8
pH = 2.5
SO_2 = 380 mg/l
$SO_4^=$ = 67 mg/l as SO_2

Column Data: Air Flow = 15-20 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
10	5.5	6.7	0	206	54	
20	6.6	5.9	0	268	54	
30	6.4	3.4	0	284	52	Cloudy
60	5.8	2.6	24	342	50	Cloudy
90	4.2	2.5	32	362	49	Cloudy
120	5.2	2.5	44	362	51	Cloudy
180	5.6	2.4	48	366	47	Cloudy
240	4.8	2.3	56	387	49	
300	5.4	2.3	56	362	50	
360	5.2	2.2	64	362	52	
420	5.1	2.2	60	354	50	
480	4.9	2.2	56	354	50	
540	4.8	2.2	52	366	49	
600	5.0	2.2	52	354	51	
660	5.1	2.2	52	346	57	
720	4.8	2.2	60	387	53	Feed SO_2 = 368 mg/l
780	5.2	2.2	72	380	50	
840	4.9	2.2	76	395	50	
900	4.9	2.2	88	366	55	
960	5.6	2.2	88	370	52	
1020	5.8	2.2	88	362	51	
1080	5.9	2.2	88	354	51	
1140	6.0	2.2	84	350	52	
1200	6.0	2.2	92	350	52	
1260	6.0	2.2	92	333	52	
1320	6.0	2.3	100	317	53	
1380	6.1	2.3	92	284	51	
1440	6.1	2.3	68	264		

Note: At 720, add 100 ml H_2SO_3, Feed SO_2 = 488 mg/l

Table B-14. SO_2 oxidation column observations--8/29.

Column Media = GAC
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 7.1	DO = 6.0
pH = 2.7	pH = 2.7
SO_2 = 508 mg/l	SO_2 = 432 mg/l
$SO_4^=$ = 75 mg/l as SO_2	$SO_4^=$ = 60 mg/l as SO_2

Column Data: Air Flow = 15-20 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
10	7.3	7.6	0	151	51	
20	7.2	7.5	0	215	52	
30	7.1	6.5	0	267	49	Cloudy
60	6.5	3.0	16	319	52	Cloudy
90	6.0	2.7	24	355	51	Cloudy
120	6.0	2.4	24	375	52	Cloudy
180	6.1	2.3	24	407	50	Cloudy
240	6.0	2.2	28		51	Cloudy
300	5.8	2.2	28	387	50	
360	5.8	2.1	24		51	
420	5.9	2.1	20	390	49	
480	5.6	2.1	28		54	
540	5.9	2.1	28	467	52	
600	6.0	2.1	24		53	
660	5.9	2.1	28	351	54	Feed SO_2 = 440 mg/l
720	6.2	2.1	24	379	52	
780	6.1	2.1	32		53	
840	6.1	2.1	28		52	
900	5.9	2.1	28	363	54	Feed SO_2 = 436 mg/l
960	6.3	2.1	36		53	
1020	6.4	2.1	32	359	50	
1080	6.5	2.1	28		50	Feed SO_2 = 484 mg/l
1140	6.6	2.1	36	375	49	
1200	6.7	2.1	36		51	
1260	7.0	2.1	24	311	50	Feed SO_2 = 436 mg/l
1320	7.0	2.1	32		50	
1380	6.9	2.1	28	319	51	
1440	7.1	2.1	28		51	

Note: At 660, add 48 ml H_2SO_3, Feed SO_2 = 512 mg/l
At 900, add 41 ml H_2SO_3, Feed SO_2 = 512 mg/l
At 1260, add 26 ml H_2SO_3, Feed SO_2 = 520 mg/l

Table B-15. SO_2 oxidation column observations--8/31.

<u>Column Media</u> = GAC·Fe
Initial Metal = 570 mg/l
Final Metal = <0.24 mg/l
570 mg = Adsorbed/295 g GAC

<u>Initial Feed Soln.</u>
DO = 4.8
pH = 2.6
SO_2 = 472 mg/l
$SO_4^=$ = 61 mg/l as SO_2
Fe = <0.25 mg/l

<u>Final Feed Soln.</u>
DO = 5.5 mg/l
pH = 2.6
SO_2 = 440 mg/l
$SO_4^=$ = 61 mg/l as SO_2

<u>Column Data</u>: Air Flow = 15-20 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Metal mg/l	Comments
10	8.1	7.4	0	86	50	<0.24	
20	8.0	4.3	0	159	48	26	
30	7.9	3.5	0	228	51	44	
60	7.7	2.6	0	348	49	55	
90	7.4	2.4	0	386	51	60	
120	6.5	2.4	20	399	51	44	Cloudy
180							
240	5.9	2.3	48	391	50	19	
300	5.5	2.2	44	391	52	16	
360	5.6	2.3	52	374	48	13	
420	5.8	2.2	48	378	50	9	
480	5.8	2.2	60	382	51	7	
540	6.1	2.2	56	356	52	5	
600	6.3	2.2	64	344	51	4	Feed SO_2 = 424 mg/l
660							
720	6.3	2.2	72	361	53	4	
780	6.4	2.2	64	274	50	3	
840	6.5	2.2	72	378	50	2	
900	6.7	2.2	68	382	50	2	Feed SO_2 = 468 mg/l
960	7.0	2.2	68		50	2	
1020	7.1	2.2	68	365	50	1	
1080	7.0	2.2	76		51	1	Feed SO_2 = 484 mg/l
1140	7.1	2.2	84	356	51	0.9	
1200	7.3	2.2	84		49	0.8	
1260	7.2	2.2	80	339	51	0.66	Feed SO_2 = 432 mg/l
1320	6.1	2.2	164		48	4.0	
1380	6.8	2.3	116	305	53	0.50	
1440	6.9	2.2	104		50	<0.25	

Note: At 600, Add 65 ml H_2SO_3, Feed SO_2 = 492 mg/l
At 1260 Add 22 ml H_2SO_3, Feed SO_2 = 488 mg/l

Table B-16. SO_2 oxidation column observations--9/10.

Column Media = GAC·Fe
Initial Metal = No Data
Final Metal =

Initial Feed Soln.
DO = 6.15
pH = 2.5
SO_2 = 544 mg/l
$SO_4^=$ = 64 mg/l as SO_2

Final Feed Soln.
DO = 5.0
pH = 2.6
SO_2 = 446 mg/l
$SO_4^=$ = 64 mg/l as SO_2

Column Data: Air Flow = 15-20 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
10	7.6	4.0	0	130	47	
20	7.4	3.3	0	222	52	
30	7.2	2.8	0	297	51	
60	7.2	2.4	0	355	50	
90	7.2	2.3	0	359	49	
120	7.1	2.3	0	392	48	
180	6.8	2.3	4	380	49	
240	6.7	2.3	12	359	47	
300	6.2	2.25	20	371	49	
360	6.3	2.25	16	355	49	
420	6.5	2.25	20	346	48	
480	6.5	2.25	24	342	50	
540	6.5	2.25	28	334	49	Feed SO_2 = 504 mg/l
600	6.5	2.25	28	322	50	
660	6.5	2.25	28	322	50	
720	6.5	2.25	32	346	49	Feed SO_2 = 492 mg/l
780	6.6	2.25	16	330	45	
840	6.6	2.25	24	317	50	
900	6.6	2.25	32	297	50	Feed SO_2 = 496 mg/l
960	6.6	2.25	16	313	50	
1020	6.6	2.25	32	305	50	
1080	6.6	2.25	32	322	49	Feed SO_2 = 492 mg/l
1140	6.6	2.25	28	313	48	
1200	6.8	2.25	28	305	50	
1260	6.7	2.3	32	288	50	Feed SO_2 = 468 mg/l
1320	6.7	2.3	32	267	50	
1380	6.7	2.3	36	280	51	
1440	6.7	2.3	36	255	50	

Table B-17. SO_2 oxidation column observations--9/14.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.
DO = 6.5
pH = 2.6
SO_2 = 504 mg/l
$SO_4^=$ = 46 mg/l as SO_2
Alk = 277 mg/l

Final Feed Soln.
DO = 5.6
pH = 2.6
SO_2 = 432 mg/l
$SO_4^=$ = 71 mg/l as SO_2

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
10	7.5	7.5	0	202	49	
20	6.6	6.6	0	264	52	
30	5.6	4.7	0	313	49	Cloudy
60	4.4	2.6	32	391	50	Cloudy
90	3.6	2.4	56	440	50	Cloudy
120	3.8	2.2	68	481	49	Cloudy
180	3.5	2.1	100	473	51	
240	4.2	2.1	124	477	48	
300	3.7	2.1	152	452	50	
360	3.6	2.1	152	477	51	
420	3.8	2.0	144	469	50	Feed SO_2 = 512 mg/l
480	3.8	2.0	156	444	50	
540	4.3	2.0	160	461	50	
600	4.5	2.0	168	456	47	
660	4.4	2.0	160	440	51	
720	4.4	2.0	156	428	50	Feed SO_2 = 472 mg/l
780	4.4	2.0	160	436	49	
840	4.0	2.0	148	420	47	
900	3.9	2.05	160	399	50	Feed SO_2 = 488 mg/l
960	4.1	2.0	152	395	47	
1020	4.1	2.0	156	428	49	
1080	4.2	2.0	148	346	50	Feed SO_2 = 460 mg/l
1140	4.0	2.05	164	354	52	
1200	4.3	2.05	160	309	50	
1260	4.0	2.05	172	313	54	Feed SO_2 = 468 mg/l
1320	4.2	2.0	152	272	50	
1380	4.2	2.1	172	321	60	
1440	4.3	2.05	136		48	

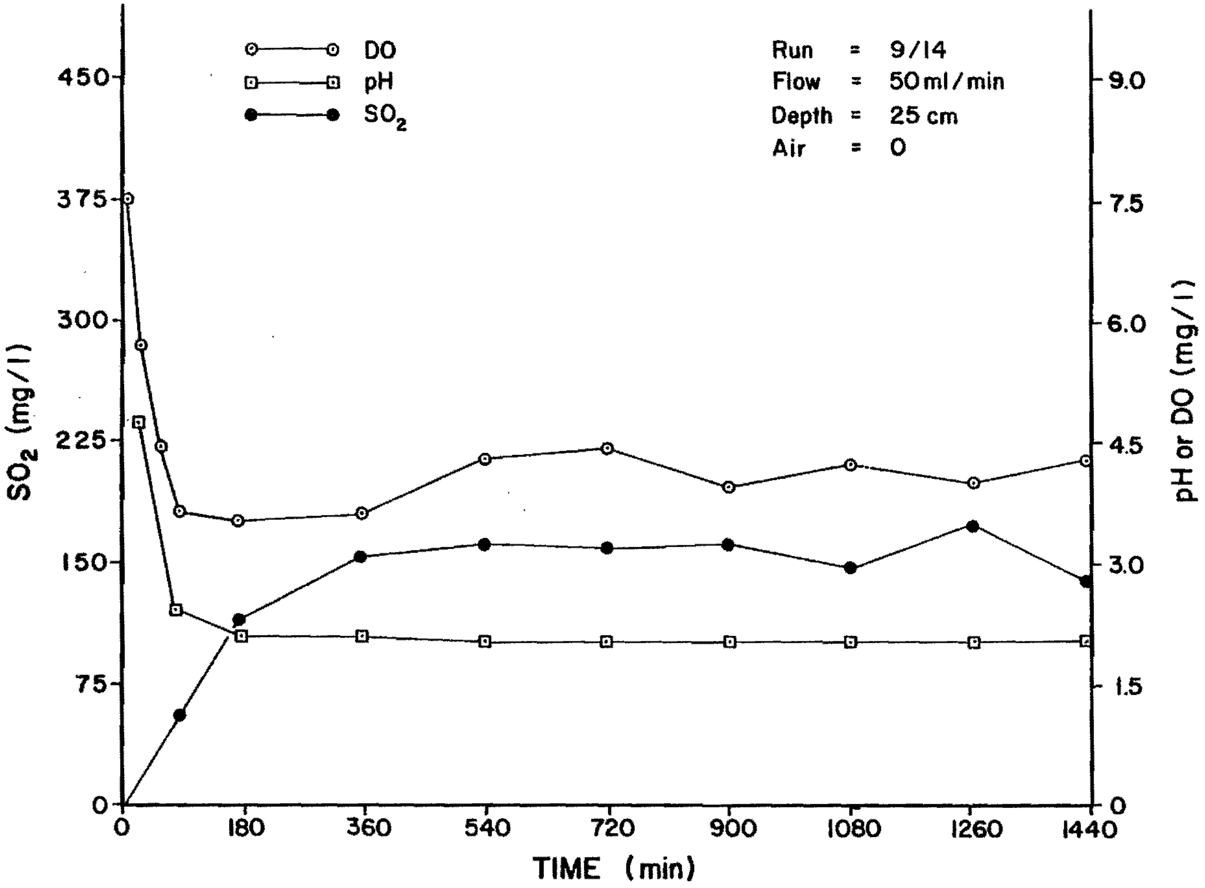


Figure B-1. SO_2 oxidation column observations.

Table B-18. SO_2 oxidation column observations--9/16.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.
DO = 5.6
pH = 2.5
SO_2 = 492 mg/l
$SO_4^=$ = 42 mg/l as SO_2
Alk = 277 mg/l

Final Feed Soln.
DO = 4.9
pH = 2.5
SO_2 = 420 mg/l
$SO_4^=$ = 65 mg/l as SO_2

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
10	6.7	7.1	0	172	49	
20	5.0	5.7	12	261	51	Cloudy
30	3.6	3.2	36	319	50	Cloudy
60	2.2	2.6	100	354	52	Cloudy
90	1.9	2.45	132	381	50	Cloudy
120	1.5	2.4	172	368	49	Cloudy
180	0.1	2.4	236	341	50	Cloudy
240	0.1	2.3	268	314	49	Cloudy
300	0.1	2.35	300	283	50	Cloudy
360	0.1	2.35	324	274	50	Cloudy
420	0.1	2.3	340	252	52	
480	0.1	2.3	348	234	50	Feed SO_2 = 492 mg/l
540	0.1	2.3	328	230	50	
600	1.8	2.3	332	198	50	
660	3.1	2.2	208	341	52	Feed SO_2 = 468 mg/l
720	3.6	2.1	180	377	50	
780	3.9	2.05	172	359	51	
840	4.1	2.1	156	341	50	Feed SO_2 = 460 mg/l
900	4.1	2.1	148	350	48	
960	4.3	2.1	144	328	50	
1020	3.9	2.1	144	310	50	

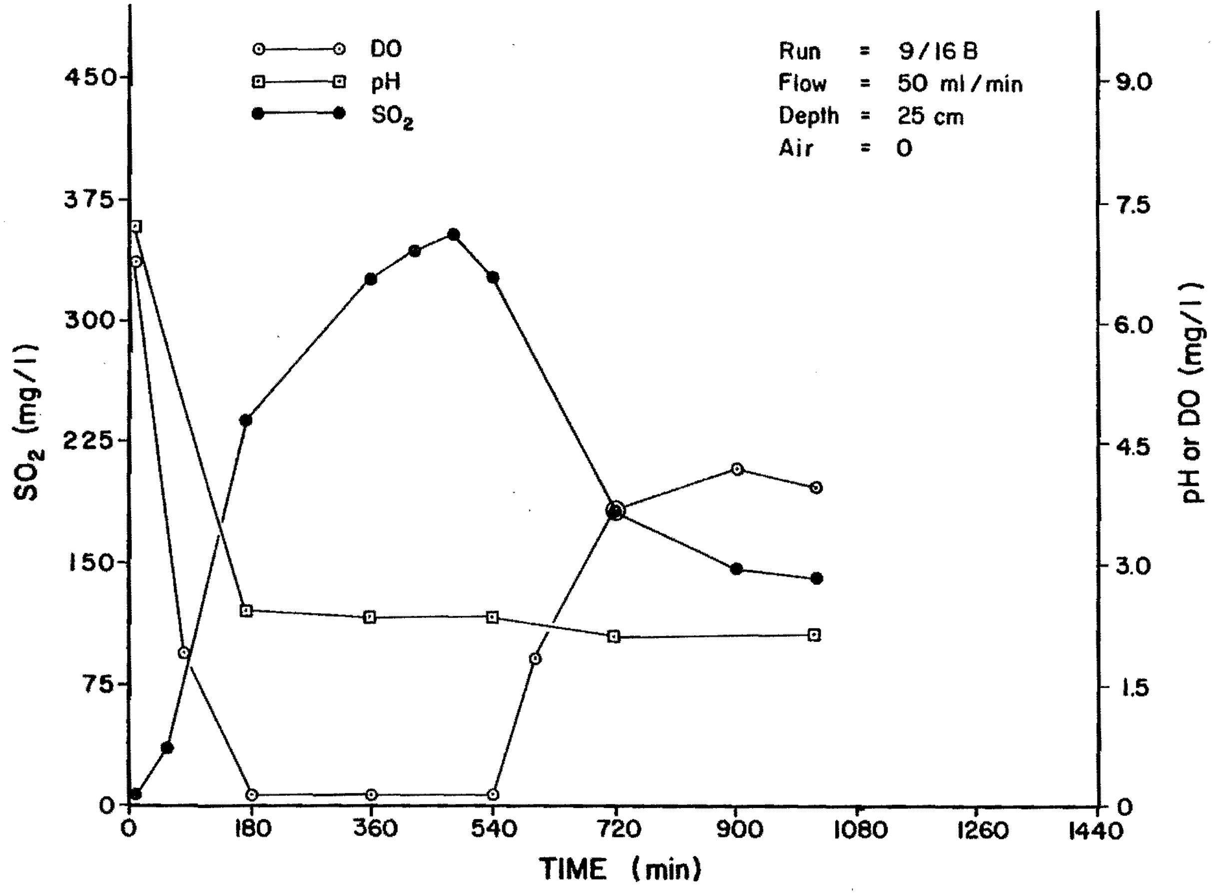


Figure B-2. SO_2 oxidation column observations.

Table B-19. SO_2 oxidation column observations--9/18.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 5.5	DO = 4.8
pH = 2.7	pH = 3.0
SO_2 = 508 mg/l	SO_2 = 448 mg/l
$SO_4^=$ = 46 mg/l as SO_2	$SO_4^=$ = 66 mg/l as SO_2
Alk = 272	

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
10	6.2	8.4	4	182	51	
20	5.5	7.7	0	248	49	
30	4.8	4.1	0	298	51	Cloudy
60	3.0	2.6	44	389	50	Cloudy
90	2.6	2.5	112	381	48	Cloudy
120	0.1	2.5	192	369	50	Cloudy
180	0.1	2.6	304	298	51	
240	0.1	2.6	336	286	50	
300	0.1	2.7	376	257	51	
360	0.1	2.7	388	240	53	
420	0.1	2.7	396	257	50	
480	2.3	2.8	392	257	51	Feed SO_2 = 484 mg/l
540	0.1	2.8	348	232	50	
600	0.1	2.9	360	228	50	
660	0.1	2.9	400	207	49	
720	0.1	2.8	412	198	52	Feed SO_2 = 460 mg/l
780	2.5	2.9	384	186	50	
840	3.6	2.9	356	194	49	
900	2.7	2.9	380	174	47	Feed SO_2 = 464 mg/l
960	3.1	3.0	392	157	50	
1020	3.3	3.0	396	149	50	
1080	3.4	3.1	376	140	50	Feed SO_2 = 452 mg/l
1140	3.2	3.1	372	140	49	
1200	2.5	3.1	368	124	50	
1260	2.7	3.1	348	120	53	Feed SO_2 = 408 mg/l
1320	2.8	3.0	368	107	48	Add 29 ml H_2SO_3
1380	2.5	2.9	376	95	53	Feed SO_2 = 500 mg/l
1440	2.6	2.8	392	107	52	

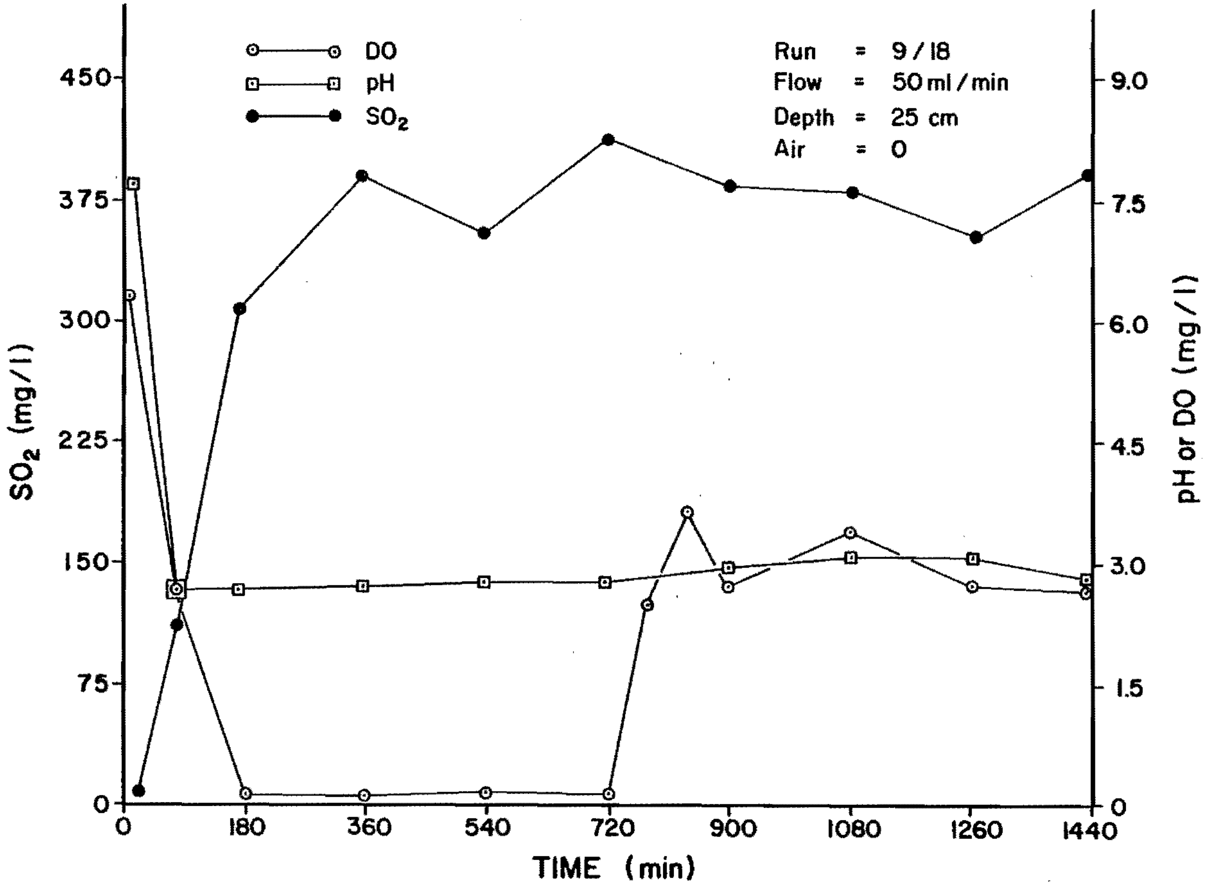


Figure B-3. SO_2 oxidation column observations.

Table B-20. SO_2 oxidation column observations--9/21.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 6.4	DO = 6.0
pH = 2.75	pH = 2.7
SO_2 = 496 mg/l	SO_2 = 448 mg/l
$SO_4^=$ = 46 mg/l as SO_2	$SO_4^=$ = 55 mg/l as SO_2

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
10	6.7	7.7	0	191	48	
20	6.0	6.8	0	263	47	
30	4.8	5.9	0	297	51	Cloudy
60	3.6	2.8	20	344	47	Cloudy
90	2.9	2.7	84	344	49	Cloudy
120	2.4	2.5	144	319	50	Cloudy
180	0.2	2.6	256	221	51	Cloudy
240	0.2	2.6	304	174	50	Cloudy
300	0.1	2.6	336	157	50	
360	0.1	2.55	344	148	51	
420	3.2	2.5	208	250	50	
480	3.8	2.4	188	276	49	Feed SO_2 = 468 mg/l
540	3.3	2.2	156	319	50	
600	4.1	2.3	180	293	52	
660	4.9	2.2	188	293	50	
720	4.5	2.2	172	297	50	Feed SO_2 = 468 mg/l
780	4.7	2.3	252	199	49	
840	3.7	2.4	308	148	50	
900	3.3	2.45	328	131	48	Feed SO_2 = 452 mg/l
960	3.8	2.5	356	131	49	
1020	3.7	2.5	360	110	50	
1080	3.8	2.6	376	113	49	Feed SO_2 = 460 mg/l
1140	3.3	2.6	356	119	50	
1200	3.4	2.55	352	106	50	
1260	2.7	2.6	332	106	48	Feed SO_2 = 436 mg/l
1320	2.8	2.6	372	97	47	Add 21 ml H_2SO_3
1380	3.8	2.5	368	106	51	Feed SO_2 = 476 mg/l
1440	2.8	2.5	364	106	49	

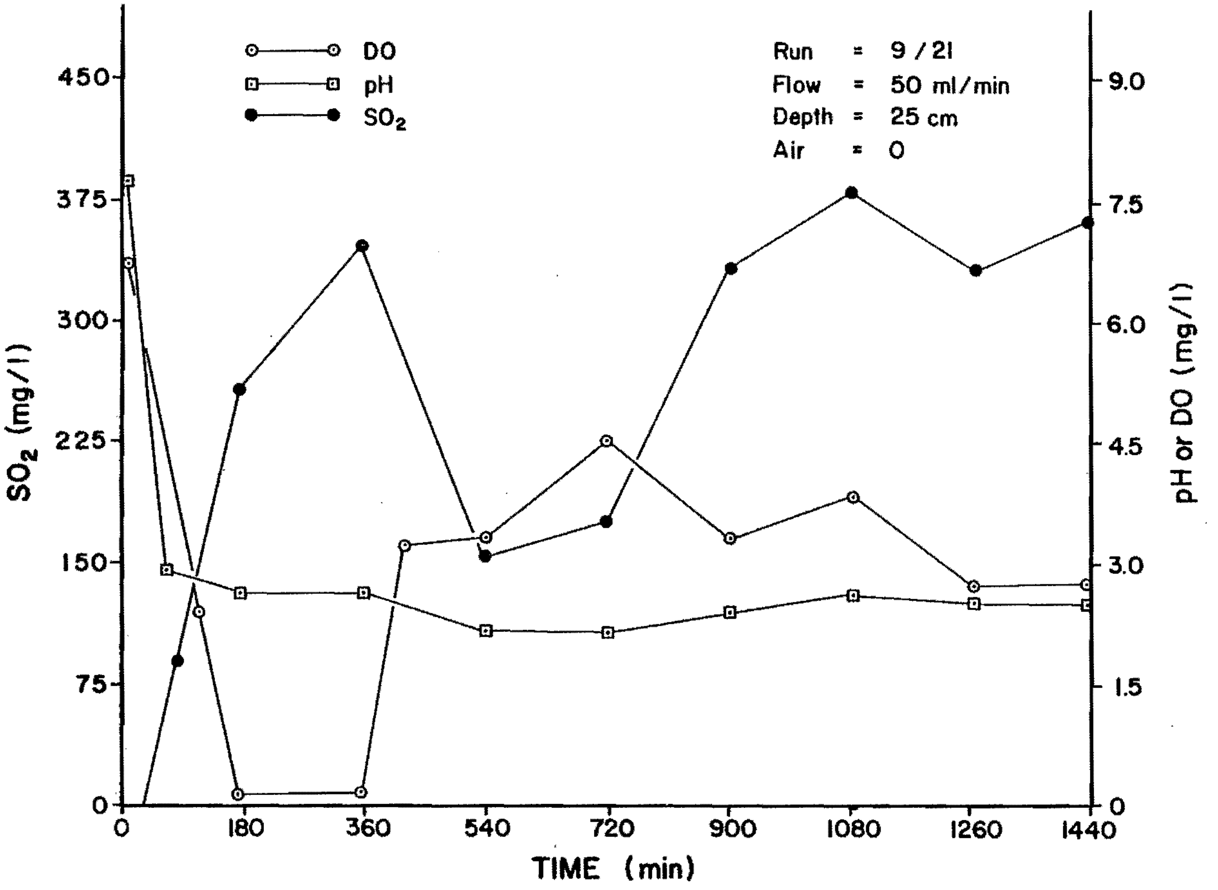


Figure B-4. SO_2 oxidation column observations.

Table B-21. SO_2 oxidation column observations--9/23.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.
DO = 6.1
pH = 2.55
SO_2 = 552 mg/l
$SO_4^=$ = 42 mg/l as SO_2

Final Feed Soln.
DO = 5.3
pH = 2.7
SO_2 = 436 mg/l
$SO_4^=$ = 68 mg/l as SO_2

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	6.7	6.9	0	320	48	
30	5.2	4.3	24	410	52	
60	3.5	2.7	96	447	49	
90	3.0	2.5	168	402	48	
120	2.5	2.5	256	349	49	
180	0.1	2.45	320	272	50	
240	0.1	2.5	356	235	50	
300	0.1	2.45	384	202	50	
360	0.1	2.4	408	186	51	
420	3.0	2.45	432	157	49	
480	2.4	2.4	424	153	49	
540	2.0	2.4	408	143	49	
600	2.3	2.4	432	133	50	
660	3.1	2.4	456	123	48	
720	4.1	2.4	452	121	50	Feed SO_2 = 500 mg/l
780	2.1	2.4	416	137	48	
840	2.4	2.4	412	110	50	
900	2.3	2.4	432	108	49	Feed SO_2 = 504 mg/l
960	3.1	2.45	424	92	49	
1020	3.3	2.4	436	90	50	
1080	3.2	2.45	440	88	50	Feed SO_2 = 500 mg/l
1140	3.0	2.45	436	94	50	
1200	2.6	2.45	436	106	50	
1260	2.9	2.5	412	108	48	Feed SO_2 = 476 mg/l
1320	3.1	2.5	400	88	48	
1380	2.8	2.5	400	84	48	
1440	2.7	2.5	396	96	51	

Note: Inlet change, extend tube directly to surface of carbon

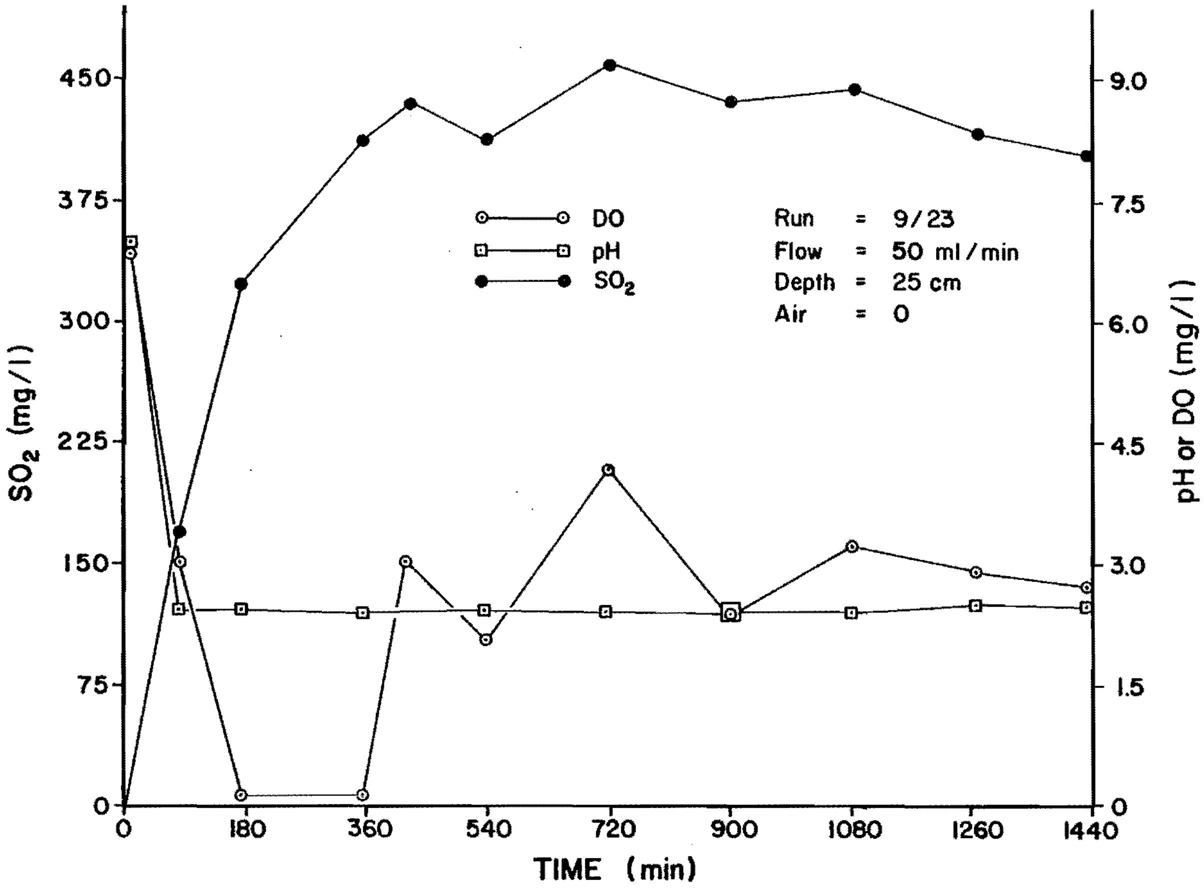


Figure B-5. SO_2 oxidation column observations.

Table B-22. SO_2 oxidation column observations--9/28.

Column Media = GAC, 25 cm , start 85 mm column
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 6.3	DO = 5.9
pH = 2.5	pH = 2.7
SO_2 = 552 mg/l	SO_2 = 404 mg/l
$SO_4^=$ = -	$SO_4^=$ = -

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.3	8.3	0	92	48	
30	6.9	8.2	0	144	49	
60	5.9	7.4	0	229	59	
90	4.0	6.5	0	299	41	Discharged plugged
120	4.1	4.3	0	314	49	
180	3.5	2.5	0	388	50	
240	3.1	2.3	8	433	52	
300	4.2	2.2	52	433	47	
360	2.8	2.2	96	403	50	
420	2.4	2.3	152	348	50	
480	2.8	2.3	180	322	50	
540	0.1	2.2	212	355	50	
600	0.1	2.2	232	281	49	
660	0.1	2.2	232	299	47	
720	2.7	2.2	236	299	50	Feed SO_2 = 520 mg/l
780	3.2	2.2	264	250	50	
840	3.3	2.2	268	218	51	
900	3.6	2.2	300	214	52	Feed SO_2 = 468 mg/l
960	3.3	2.2	276	218	50	
1020	2.8	2.2	284	222	50	
1080	3.4	2.2	288	203	49	Feed SO_2 = 476 mg/l
1140	3.0	2.25	280	214	50	
1200	3.4	2.25	276	196	50	
1260	3.3	2.3	280	188	49	Feed SO_2 = 484 mg/l
1320	3.5	2.3	272	181	46	
1380	3.6	2.4	268	181	51	
1440	3.4	2.3	260	177	51	

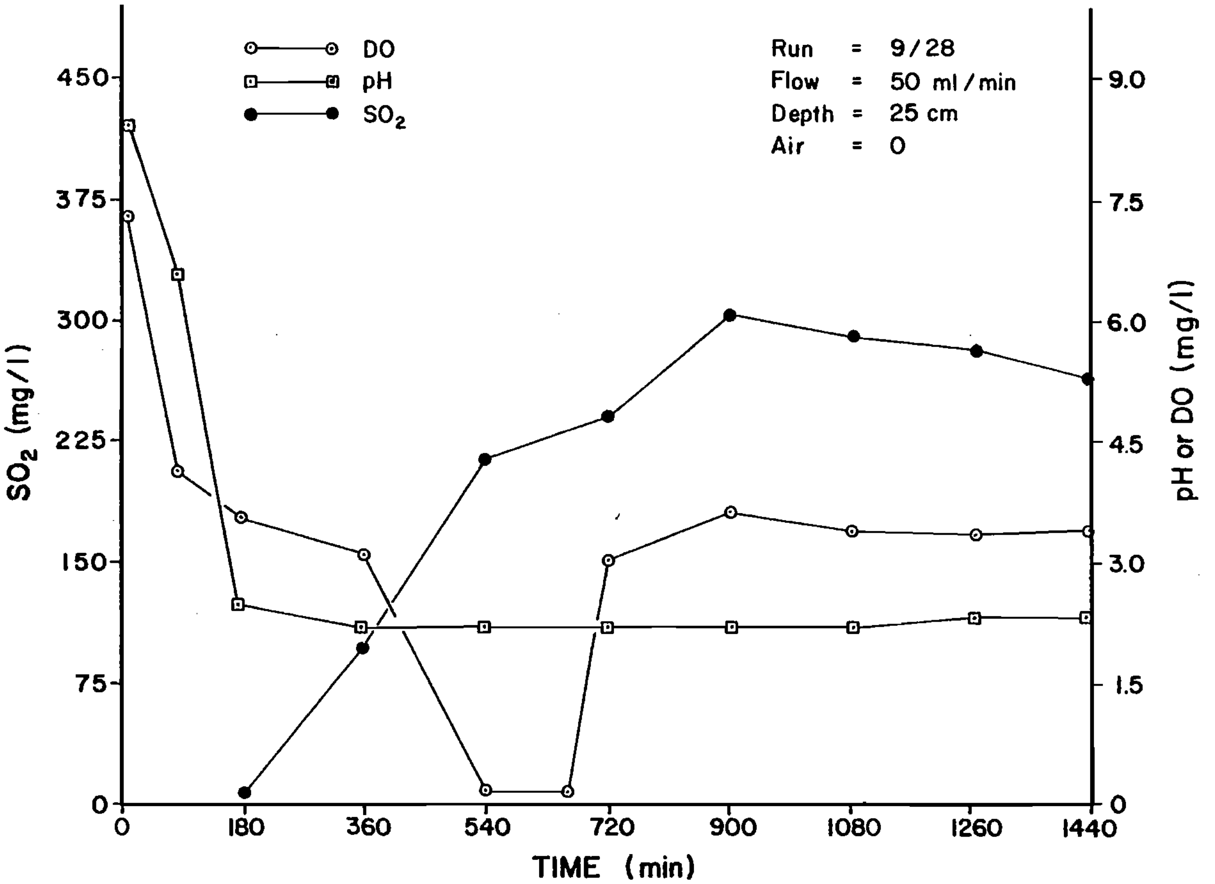


Figure B-6. SO_2 oxidation column observations.

Table B-23. SO_2 oxidation column observations--9/30.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.
DO = 6.5
pH = 2.7
SO_2 = 492 mg/l
$SO_4^=$ = 62 mg/l as SO_2

Final Feed Soln.
DO = 5.8
pH = 2.7
SO_2 = 484 mg/l
$SO_4^=$ = 61 mg/l as SO_2

Column Data: Air Flow = 0

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.7	8.2	0	83	48	
30	7.2	8.1	0	141	48	
60	5.9	7.1	0	217	49	
90						
120	3.8	2.9	8	317	49	Cloudy
180	3.1	2.7	32	333	49	Cloudy
240	3.2	2.6	60	361	48	Cloudy
300	3.0	2.6	88	365	50	Cloudy
360	2.6	2.5	116	341	52	Cloudy
420	2.8	2.5	136	317	49	
480	4.1	2.4	140	333	49	
540	2.6	2.5	152	301	49	
600	0.1	2.4	168	285	50	
660	0.1	2.45	192	289	50	
720	0.1	2.45	216	265	48	Feed SO_2 = 464 mg/l
780	0.1	2.45	236	253	50	
840	2.8	2.4	240	241	50	
900	3.1	2.4	252	213	50	Feed SO_2 = 464 mg/l
960	3.4	2.4	256	221	48	
1020	3.3	2.4	260	201	51	
1080	3.4	2.4	252	197	51	Feed SO_2 = 460 mg/l
1140	3.5	2.4	256	197	49	
1200	3.4	2.45	264	189	50	
1260	2.6	2.4	260	189	50	Feed SO_2 = 456 mg/l
1320	3.1	2.4	264	189	48	Add 16 ml H_2SO_3
1380	2.8	2.4	272	189	48	Feed SO_2 = 500 mg/l
1440	2.7	2.4	272	173	50	

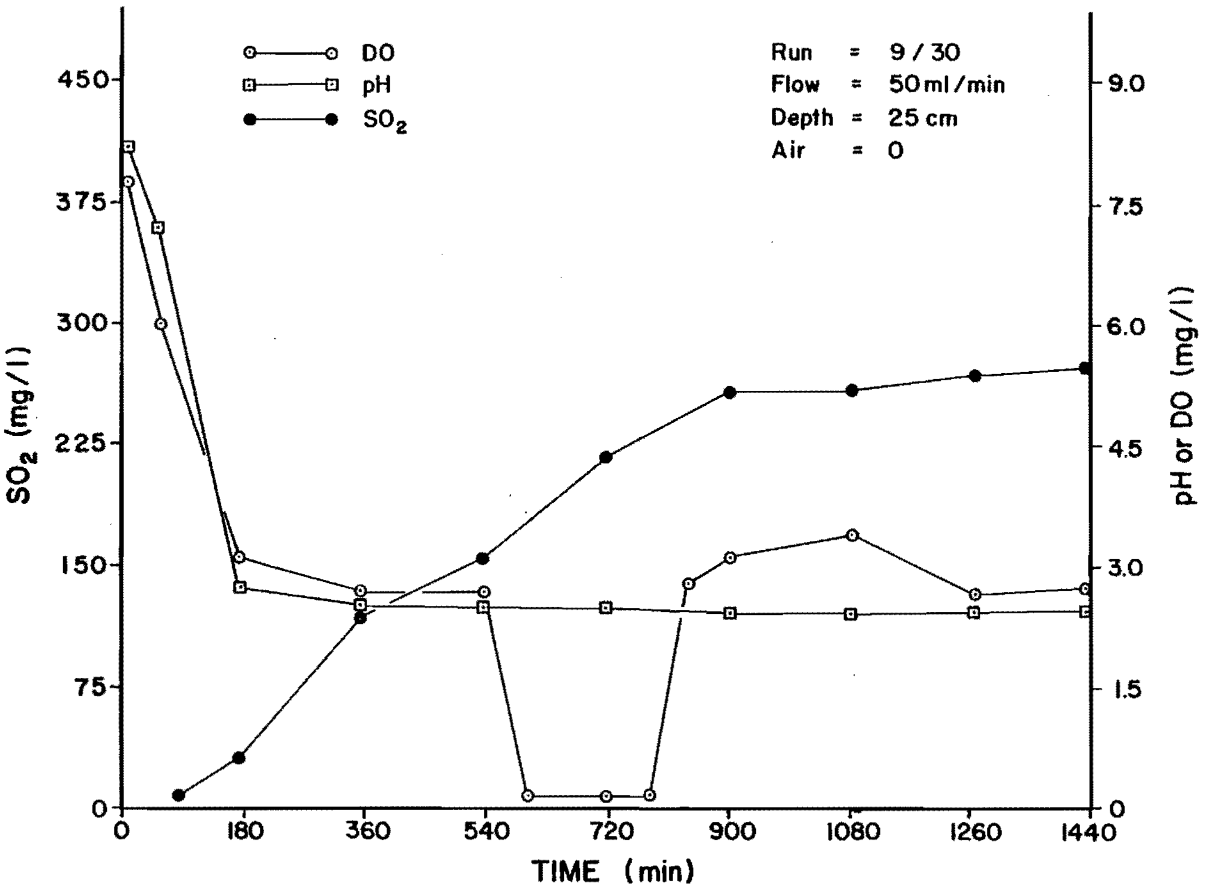


Figure B-7. SO_2 oxidation column observations.

Table B-24. SO_2 oxidation column observations--10/2.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.
DO = 6.6
pH = 2.6
SO_2 = 520 mg/l
$SO_4^{=}$ = 62 mg/l as SO_2

Final Feed Soln.
DO = 5.4
pH = 2.6
SO_2 = 436 mg/l
$SO_4^{=}$ = 67 mg/l as SO_2

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^{=}$ as SO_2	Flow ml/min	Comments
15	6.6	8.1	0	98	47	
30	5.6	7.4	0	171	51	
60	4.2	6.1	20	264	47	Cloudy
90	4.2	4.3	44	287	48	Cloudy
120	4.0	3.4	68	287	50	Cloudy
180	2.4	2.8	92	302	49	Cloudy
240	1.6	2.6	136	302	80	Cloudy
300	0.1	2.5	112	350	48	Cloudy
360	0.1	2.4	128	339	50	Cloudy
420	2.6	2.4	140	328	50	
480	2.6	2.35	156	310	50	
540	0.1	2.35	164	298	50	
600	0.1	2.35	160	283	50	
660	1.8	2.3	168	275	51	
720	2.4	2.3	188	283	50	Feed SO_2 = 480 mg/l
780	2.2	2.3	216	261	50	
840	2.9	2.3	240	257	48	
900	2.7	2.3	248	231	50	Feed SO_2 = 476 mg/l
960	2.6	2.3	240	231	49	
1020	2.6	2.3	252	208	52	
1080	2.9	2.3	260	205	50	Feed SO_2 = 452 mg/l
1140	3.3	2.35	256	201	49	
1200	3.4	2.35	252	208	49	
1260	2.1	2.35	248	197	47	Feed SO_2 = 444 mg/l
1320	2.9	2.3	260	194	50	Add 19 ml H_2SO_3
1380	2.6	2.3	260	190	51	Feed SO_2 = 488 mg/l
1440	2.8	2.3	280	179	47	

Table B-25. SO_2 oxidation column observations--10/5.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 6.6	DO = 5.7
pH = 2.7	pH = 2.6
SO_2 = 520 mg/l	SO_2 = 480 mg/l
$SO_4^=$ = -	$SO_4^=$ = 52 mg/l as SO_2

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	8.4	9.1	0	98	46	
30	7.9	9.0	0	146	47	
60	6.2	8.8	0	220	48	
90	5.1	7.6	0	253	49	
120	4.1	6.4	0	277	49	Cloudy
180	3.6	3.2	12	318	50	Cloudy
240	3.2	2.7	24	351	51	Cloudy
300	4.1	2.5	64	368	51	Cloudy
360	3.3	2.5	100	355	49	Cloudy
420	2.9	2.5	132	335	49	
480	2.9	2.5	156	310	49	
540	2.4	2.45	172	302	50	
600	2.3	2.4	184	294	50	
660	2.4	2.4	200	286	51	
720	2.6	2.4	208	286	50	Feed SO_2 = 496 mg/l
780	2.6	2.4	204	294	51	
840	2.7	2.45	228	269	50	
900	2.6	2.4	232	261	51	Feed SO_2 = 476 mg/l
960	4.3	2.35	228	253	51	
1020	1.9	2.6	224	236	50	
1080	3.8	2.4	236	232	50	Feed SO_2 = 484 mg/l
1140	2.8	2.4	244	236	50	
1200	3.7	2.4	240	-	51	
1260	3.5	2.4	240	212	52	Feed SO_2 = 452 mg/l
1320	3.6	2.4	240	212	52	Add 23 ml H_2SO_3
1380	3.3	2.35	244	203	53	Feed SO_2 = 508 mg/l
1440	3.2	2.3	260	199	51	

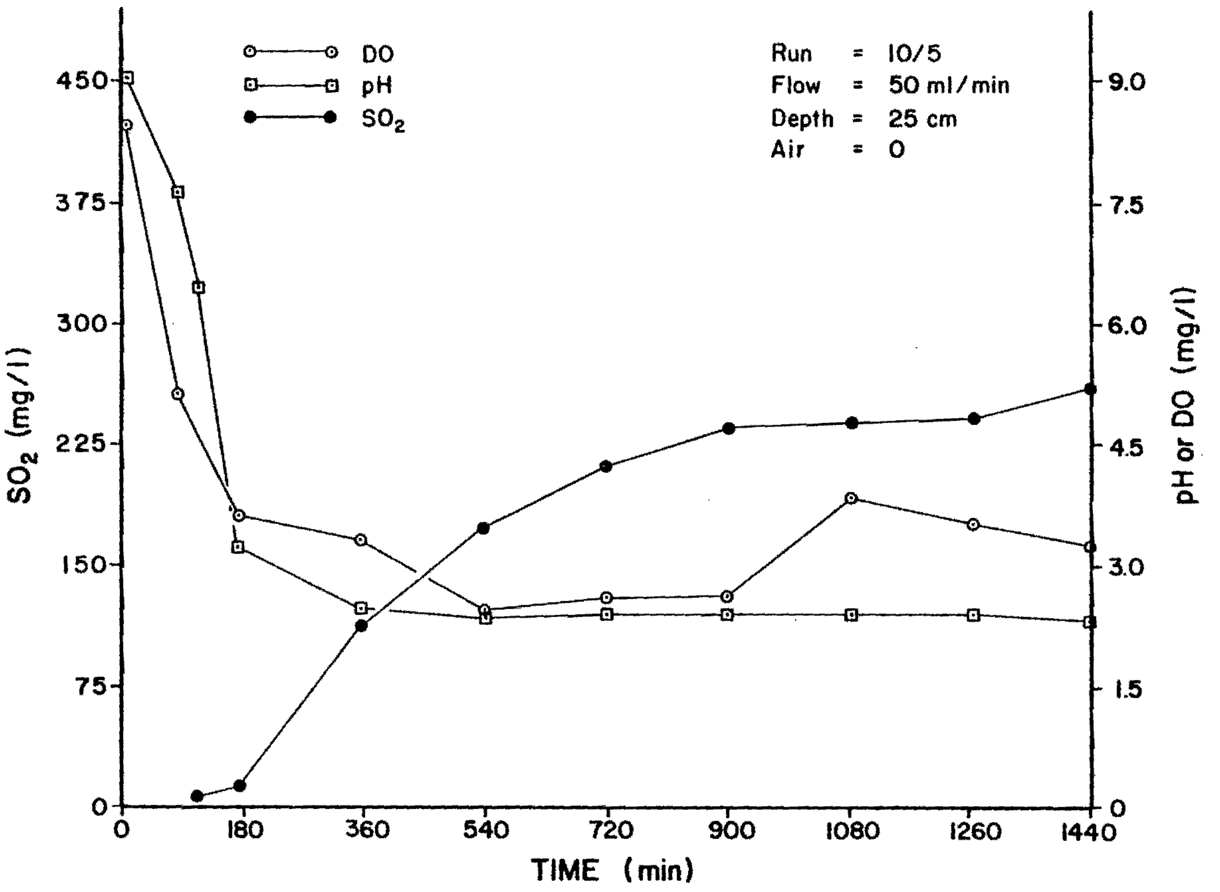


Figure B-8. SO_2 oxidation column observations.

Table B-26. SO_2 oxidation column observations--10/7.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 5.9	DO = 5.5
pH = 2.8	pH = 2.6
SO_2 = 476 mg/l	SO_2 = 456 mg/l
$SO_4^=$ = -	$SO_4^=$ = 33 mg/l as SO_2

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.8	8.7	0	66	51	
30	7.5	8.7	0	120	53	
60	6.3	8.45	0	170	50	
90	5.3	7.4	0	201	50	
120	4.1	6.0	0	224	50	Cloudy
180	2.85	2.85	0	261	51	Cloudy
240	3.15	2.6	16	295	51	Cloudy
300	2.85	2.5	34	291	52	Cloudy
360	3.2	2.45	56	301	50	Cloudy
420	3.3	2.5	80	301	50	Cloudy
480	3.3	2.4	96	308	50	Cloudy
540	3.3	2.4	112	308	50	Cloudy
600	3.1	2.4	120	275	50	Cloudy
660	3.8	2.6	136	261	50	
720	2.4	2.7	148	275	50	Feed SO_2 = 460 mg/l
780	2.1	2.5	148	268	50	
840	3.1	2.45	168	234	50	
900	2.8	2.45	172	221	50	Feed SO_2 = 452 mg/l
960	3.0	2.35	188	218	50	
1020	2.8	2.3	184	207	50	
1080	3.1	2.35	176	207	50	Feed SO_2 = 436 mg/l
1140	3.3	2.4	192	201	50	Add 35 ml H_2SO_3
1200	3.9	2.4	196	201	50	Feed SO_2 = 500 mg/l
1260	3.7	2.35	208	207	50	Feed SO_2 = 504 mg/l
1320	3.2	2.3	224	187	50	
1380	3.9	2.3	236	184	50	
1440	3.3	2.3	236	181	50	

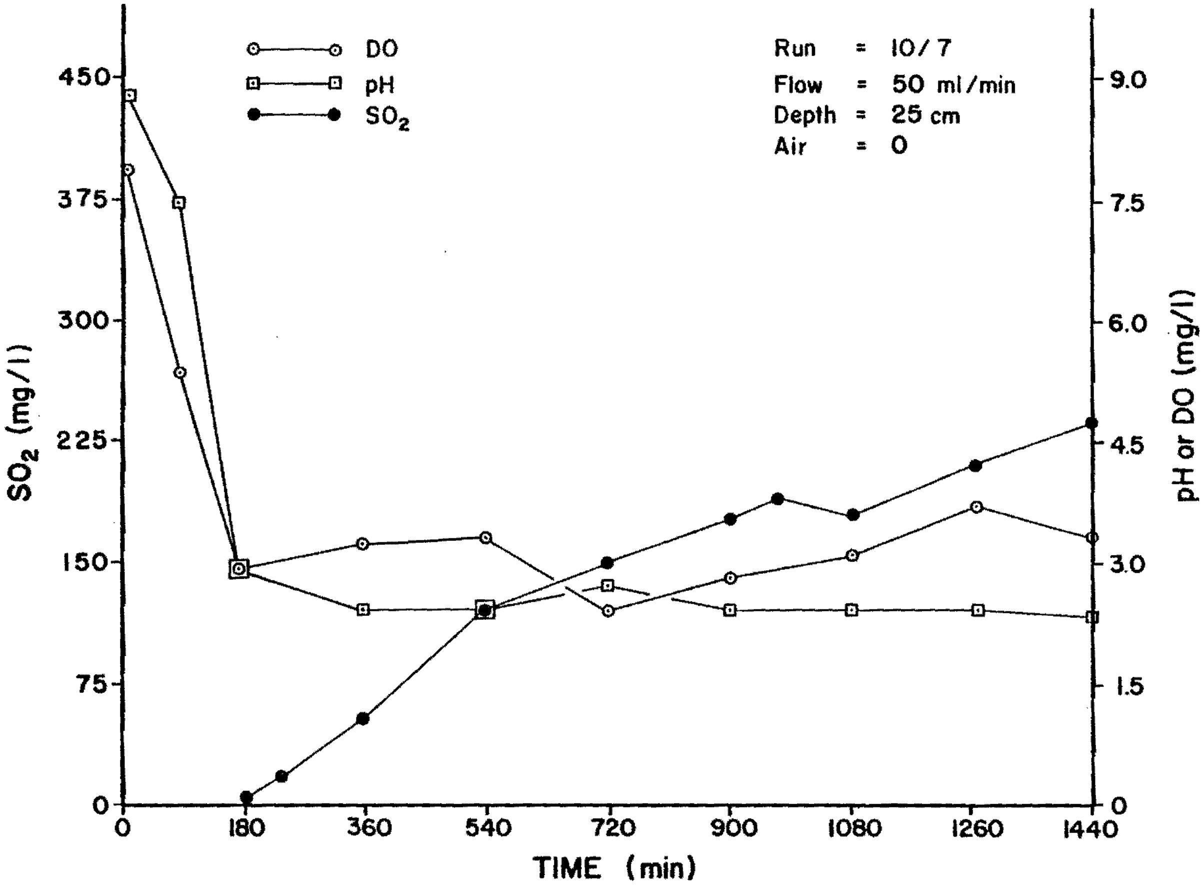


Figure B-9. SO_2 oxidation column observations.

Table B-27. SO_2 oxidation column observations--10/9.

Column Media = GAC, 25 cm, primary column
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 4.8	DO = 4.1
pH = 2.7	pH = 2.5
SO_2 = 486 mg/l	SO_2 = 444 mg/l
$SO_4^=$ = 49 mg/l as SO_2	$SO_4^=$ = 57 mg/l as SO_2

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.4	8.9	0	98	52	
30	7.2	8.8	0	147	50	
60	5.7	8.5	0	244	45	Pump fail
90	4.8	7.4	0	265	49	
120	4.0	5.6	0	306	49	Cloudy
180	3.8	2.9	0	366	50	Cloudy
240	3.6	2.6	20	383	52	Cloudy
300	3.3	2.5	40	391	50	Cloudy
360	1.0	2.4	56	399	46	Cloudy
480	3.1	2.4	140	350	50	Cloudy
600	2.9	2.4	168	318	48	Cloudy
720	3.1	2.3	176	289	52	Feed SO_2 = 460 mg/l
840	2.9	2.3	220	261	53	
960	3.5	2.3	220	285	51	Feed SO_2 = 452 mg/l
1080	3.4	2.3	236	257	49	
1200	3.4	2.1	208	253	51	Feed SO_2 = 424 mg/l Add 29 ml H_2SO_3
1320	3.8	2.2	224	244	52	Feed SO_2 = 486 mg/l
1440	3.9	2.2	248	220	54	

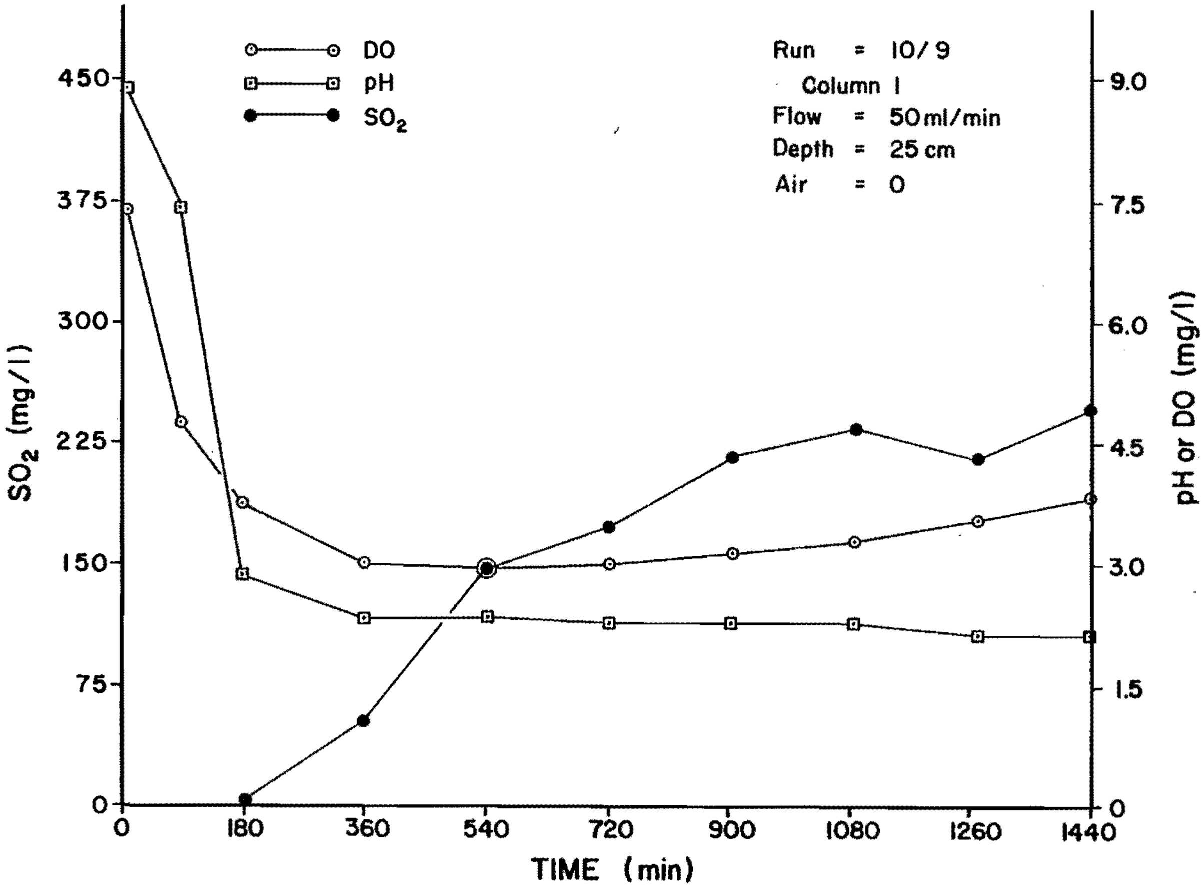


Figure B-10. SO_2 oxidation column observations.

Table B-28. SO_2 oxidation column observations--10/9.

Column Media = GAC, 25 cm, secondary column
Initial Metal = N/A
Final Metal =

Initial Feed Soln.		Final Feed Soln.	
DO =	-	DO =	-
pH =	-	pH =	-
SO_2 =	-	SO_2 =	-
$SO_4^=$ =	-	$SO_4^=$ =	-

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments*
90	7.1	9.2	0	82	49	0
120	6.9	9.1	0	131	49	0
180	6.8	8.9	0	196	46	0
240	6.6	8.6	0	253	46	8
300	5.9	8.0	0	253	52	12
360	5.0	6.7	0	253	47	28
420	4.0	5.0	0	285	48	60
540	4.1	3.0	0	326	49	120
660	4.1	2.55	0	374	50	144
780	4.1	2.2	0	391	50	156
900	4.1	2.1	0	440	50	196
1020	4.1	2.1	0	432	50	188
1140	4.2	2.1	0	432	50	184
1260	2.9	2.1	0	423	50	196
1380	3.9	2.1	0	440	50	204
1500	3.7	2.1	0	476	50	220

*Secondary feed SO_2, mg/l

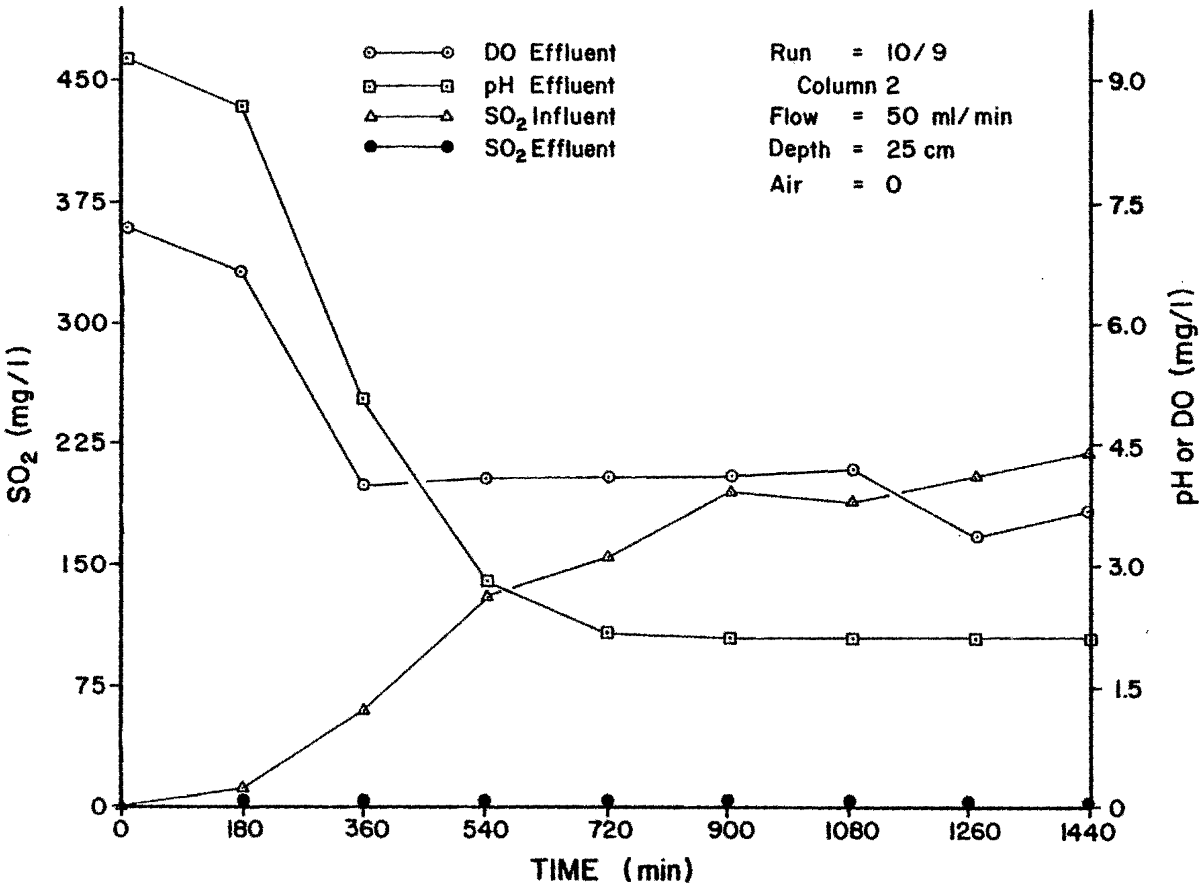


Figure B-11. SO_2 oxidation column observations.

Table B-29. SO_2 oxidation column observations--10/12.

Column Media = GAC, 25 cm, primary column
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 5.1	DO = 4.2
pH = 2.7	pH = 2.6
SO_2 = 500 mg/l	SO_2 = 488 mg/l
$SO_4^=$ = 49 mg/l as SO_2	$SO_4^=$ = 62 mg/l as SO_2

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	4.7	9.3	0		50	
60	1.0	6.8	40		54	
90	0.6	6.5	72	208	48	Cloudy
180	2.0	5.9	188		52	
240	3.2	5.3	216	293	50	Cloudy
300	3.1	3.7	196		50	
360	0.1	3.0	184	293	53	Cloudy
420	0.1	2.8	188		51	
480	0.1	2.6	208	285	54	Cloudy
540	0.1	2.6	216		50	Feed SO_2 = 508 mg/l
600	0.1	2.5	204	277	49	
660	0.1	2.5	228		49	
720	0.1	2.5	240	269	54	Feed SO_2 = 508 mg/l
780	0.1	2.4	208		49	
840	0.1	2.4	216	285	50	
900	0.1	2.4	240		50	Feed SO_2 = 480 mg/l
960	0.1	2.35	236	301	50	
1020	0.1	2.3	224		45	
1080	0.1	2.3	232	281	50	Feed SO_2 = 476 mg/l
1140	0.7	2.4	224		52	
1200	2.4	2.4	248	269	51	
1260	2.9	2.4	256		53	Feed SO_2 = 456 mg/l
1320	3.3	2.3	248	244	55	Add 18 ml H_2SO_3
1380	3.5	2.3	248		54	Feed SO_2 = 496 mg/l
1440	3.3	2.3	248	228	54	

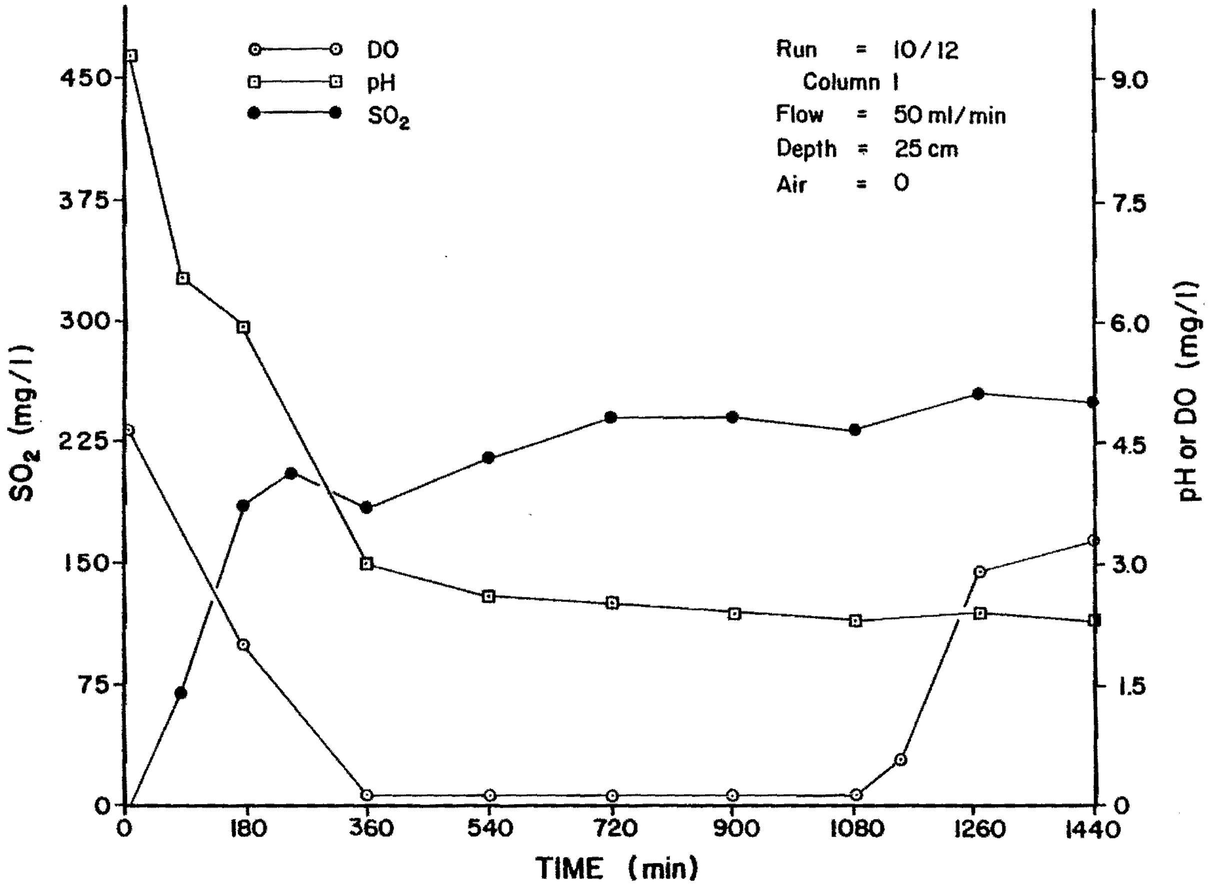


Figure B-12. SO_2 oxidation column observations.

Table B-30. SO_2 oxidation column observations--10/12.

Column Media = GAC, 25 cm, seconday column
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = -	DO = -
pH = -	pH = -
SO_2 = -	SO_2 = -
$SO_4^=$ = -	$SO_4^=$ = -

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments*
15	4.5	9.1	0		52	0
120	4.3	9.3	0	196	52	124
180	3.5	9.0	0	204	48	176
240	4.2	7.8	0		52	
300	4.4	6.5	3.2	277	51	172
360	4.5	5.1	6.4		45	176
420	4.3	3.9	12	326	52	188
480	4.3	3.3	12		51	200
540	4.4	2.9	12	374	51	188
600	4.3	2.75	16		50	172
660	4.5	2.6	16	399	51	200
720	4.4	2.5	20		52	196
780	4.4	2.4	20	415	49	196
840	4.3	2.35	20		49	204
900	4.2	2.35	16	456	50	200
960	4.4	2.3	16		47	208
1020	4.3	2.3	16	448	50	192
1080	4.3	2.3	16		50	196
1140	4.7	2.25	20	423	50	188
1200	4.2	2.25	16		52	188
1260	4.1	2.2	8	456	53	220
1320	4.7	2.2	12		53	220
1380	4.1	2.2	12	448	53	232
1440	4.2	2.1	12		52	224

*Secondary feed SO_2, mg/l

Note: Samples 300-780 were cloudy

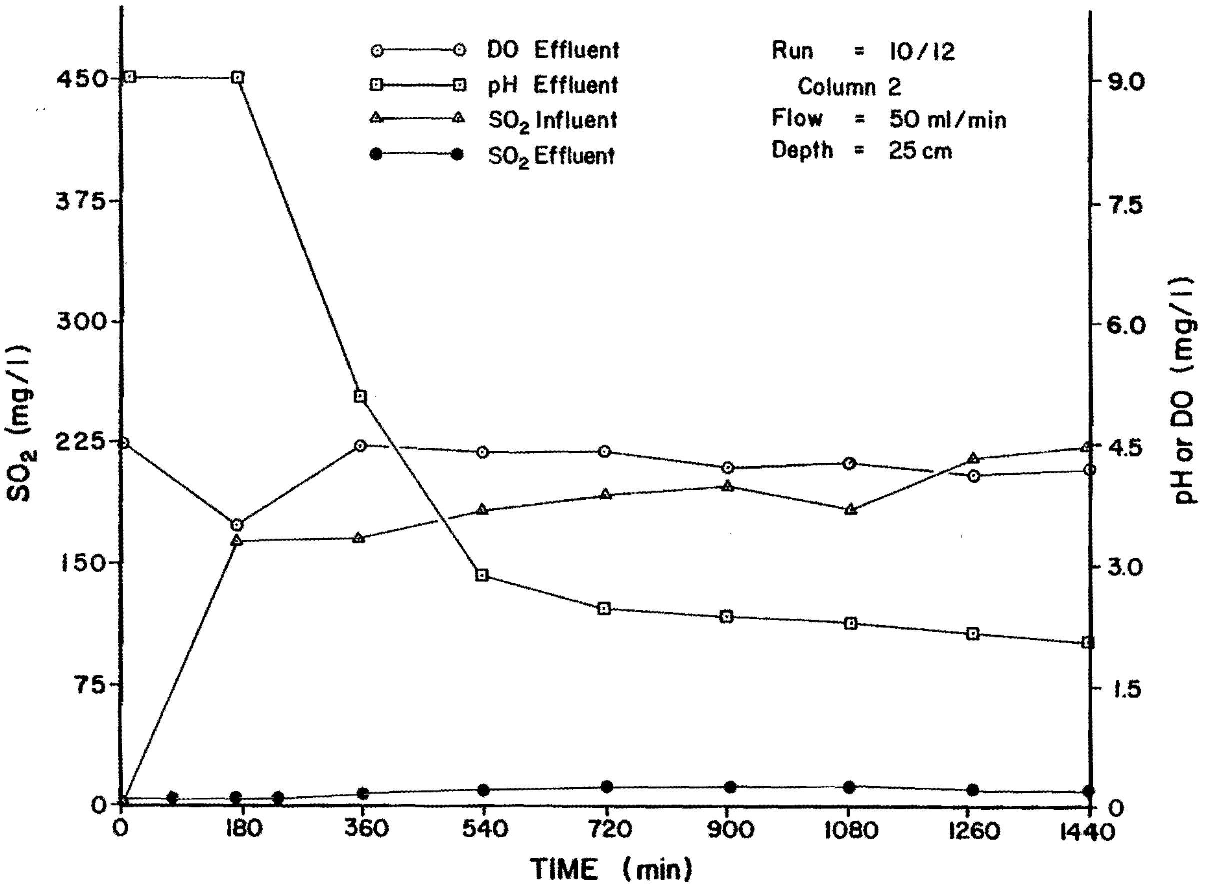


Figure B-13. SO_2 oxidation column observations.

Table B-31. SO_2 oxidation column observations--10/14.

Column Media = GAC, 25 cm, primary column
Initial Metal = N/A
Final Metal =

Initial Feed Soln.		Final Feed Soln.	
DO	= 5.6	DO	= 4.9
pH	= 2.6	pH	= 2.6
SO_2	= 500 mg/l	SO_2	= 460 mg/l
$SO_4^=$	= 49 mg/l as SO_2	$SO_4^=$	= 53 mg/l as SO_2

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.0	9.0	0		52	
60	5.1	7.5	0		50	
90	4.2	5.2	8	310	50	Cloudy
180	3.8	2.7	32		52	
240	3.1	2.6	52	371	48	Cloudy
300	0.1	2.5	88		51	
360	0.1	2.4	104	391	45	Cloudy
420	0.1	2.4	108		51	
480	0.1	2.4	132	346	54	Cloudy
540	2.4	2.3	148		48	Feed SO_2 = 488 mg/l
600	3.5	2.3	156	346	50	
660	3.5	2.3	164		50	
720	3.7	2.3	172	326	49	Feed SO_2 = 468 mg/l
780	3.5	2.3	176		47	Add 26 ml H_2SO_3
840	3.5	2.3	172	326	48	Feed SO_2 = 496 mg/l
900	3.7	2.3	188		50	Feed SO_2 = 500 mg/l
960	2.9	2.25	200	293	50	
1020	3.2	2.25	224		50	
1080	2.9	2.25	232	285	50	Feed SO_2 = 480 mg/l
1140	3.0	2.25	228		51	
1200	3.1	2.25	232	273	51	
1260	3.0	2.3	228		50	Feed SO_2 = 484 mg/l
1320	3.3	2.3	220	232	57	Feed SO_2 = 452 mg/l
1380	3.3	2.3	228		50	Add 17 ml H_2SO_3
1440	3.3	2.3	220	257	43	Feed SO_2 = 492 mg/l

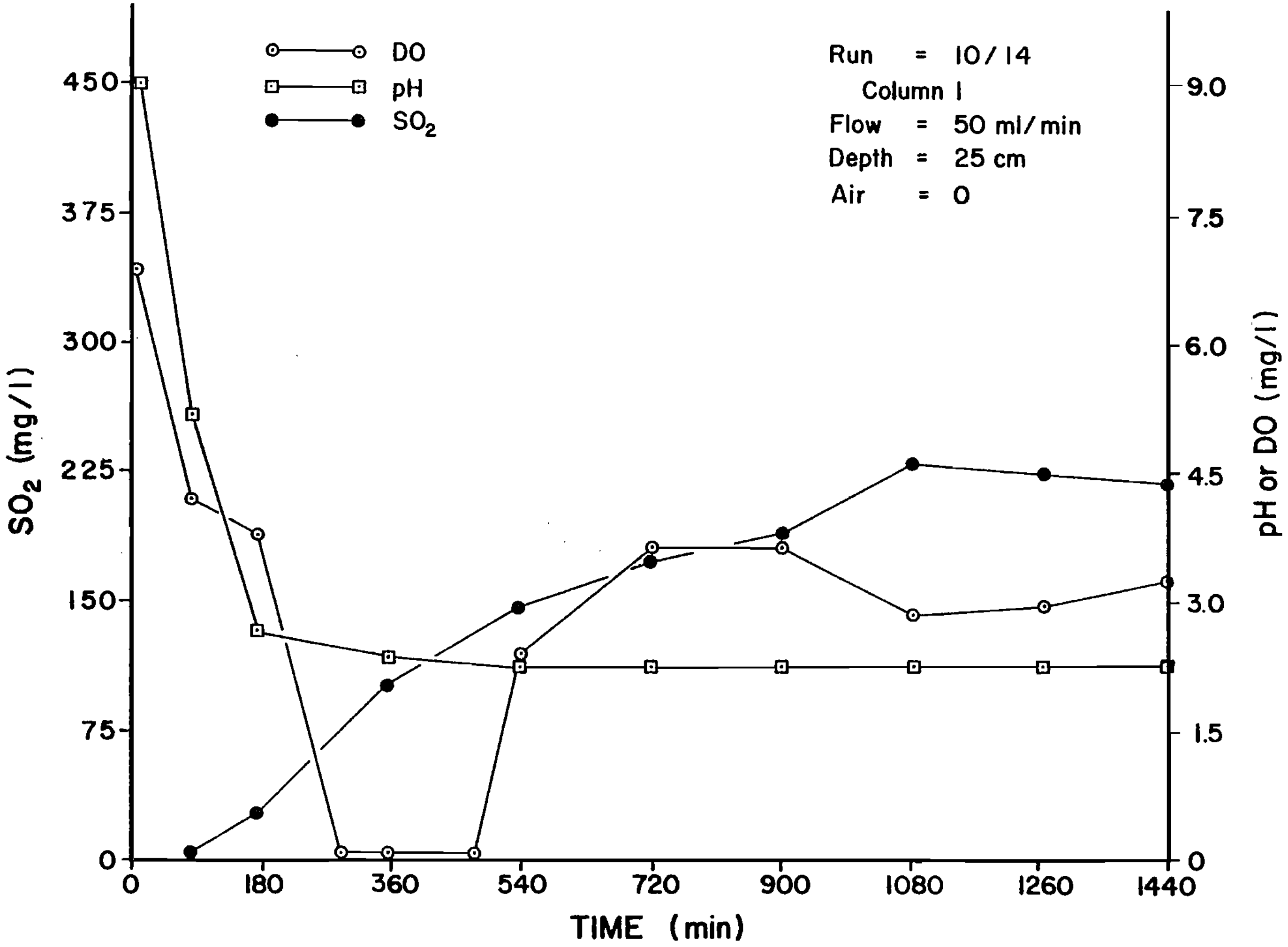


Figure B-14. SO_2 oxidation column observations.

Table B-32. SO_2 oxidation column observations--10/14.

Column Media = GAC, 25 cm, secondary column
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = -	DO = -
pH = -	pH = -
SO_2 = -	SO_2 = -
$SO_4^=$ = -	$SO_4^=$ = -

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments*
15	6.5	9.5	0		48	0
60	6.3	9.35	0		52	4
90	6.25	9.2	0	155	52	10
180	5.75	8.5	0	248	52	24
240	4.8	6.5	0		50	56
300						
360	5.5	6.6	0		48	100
420	4.9	3.2	0	318	51	116
480	4.9	2.9	0		50	116
540	4.8	2.6	0	358	50	120
600	4.9	2.5	0		50	124
660	5.0	2.4	0	403	50	132
720	4.9	2.35	8		51	144
780	4.8	2.35	12	415	48	148
840	4.9	2.35	12		47	168
900	4.5	2.2	12	464	52	184
960	4.7	2.2	12		49	188
1020	4.5	2.2	8	464	49	208
1080	4.5	2.15	4		52	200
1140	4.6	2.15	4	472	51	204
1200	4.6	2.15	8		50	212
1260	4.5	2.1	4	448	50	188
1320	4.5	2.1	6		50	204
1380	4.5	2.1	4	440	50	188
1440	4.5	2.1	4		50	220

*Secondary feed SO_2, mg/l

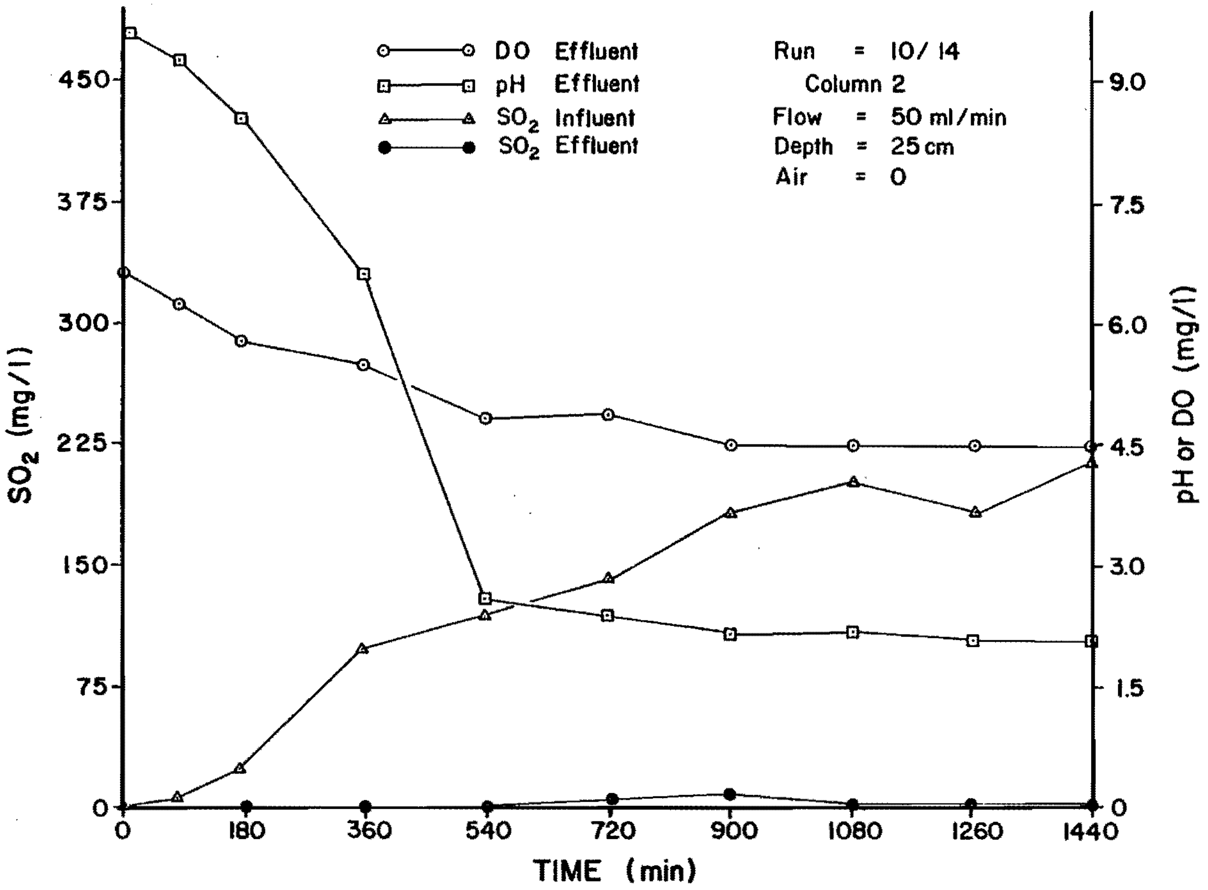


Figure B-15. SO_2 oxidation column observations.

Table B-33. SO_2 oxidation column observations--10/16.

Column Media = GAC, 50 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 4.3	DO = 3.4
pH = 2.6	pH = 2.6
SO_2 = 532 mg/l	SO_2 = 460 mg/l
$SO_4^=$ = 49 mg/l as SO_2	$SO_4^=$ = 53 mg/l as SO_2

Column Data: Air Flow = 0 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	6.8	9.0	0		51	
60	6.1	9.0	0	81	54	
90	5.7	8.9	0		49	
120	4.9	8.8	0	158	50	
180	3.7	6.7	0		50	
240	3.7	5.5	0	266	50	Cloudy
300	3.5	3.0	12		50	
360	3.2	2.8	16	330	50	Cloudy
420	2.7	2.7	40		50	
480	1.6	2.6	56	338	50	Cloudy
540	1.6	2.6	68		50	Feed SO_2 = 512 mg/l
600	0.1	2.5	76	361	50	Cloudy
660	0.1	2.5	84		51	
720	0.1	2.45	88	361	50	Cloudy
780	0.1	2.4	96		50	
840	0.1	2.35	100	330	51	
900	0.1	2.4	108		50	Feed SO_2 = 480 mg/l
960	0.1	2.4	104	330	49	
1020	0.1	2.3	112		50	
1080	0.1	2.3	116	338	50	Feed SO_2 = 464 mg/l
1140	0.1	2.3	120		50	Add 18 ml H_2SO_3
1200						Feed SO_2 = 492 mg/l
1260						
1320	2.0	2.3	156	286	50	
1380	3.0	2.3	188		49	
1440	3.1	2.3	192	258	51	

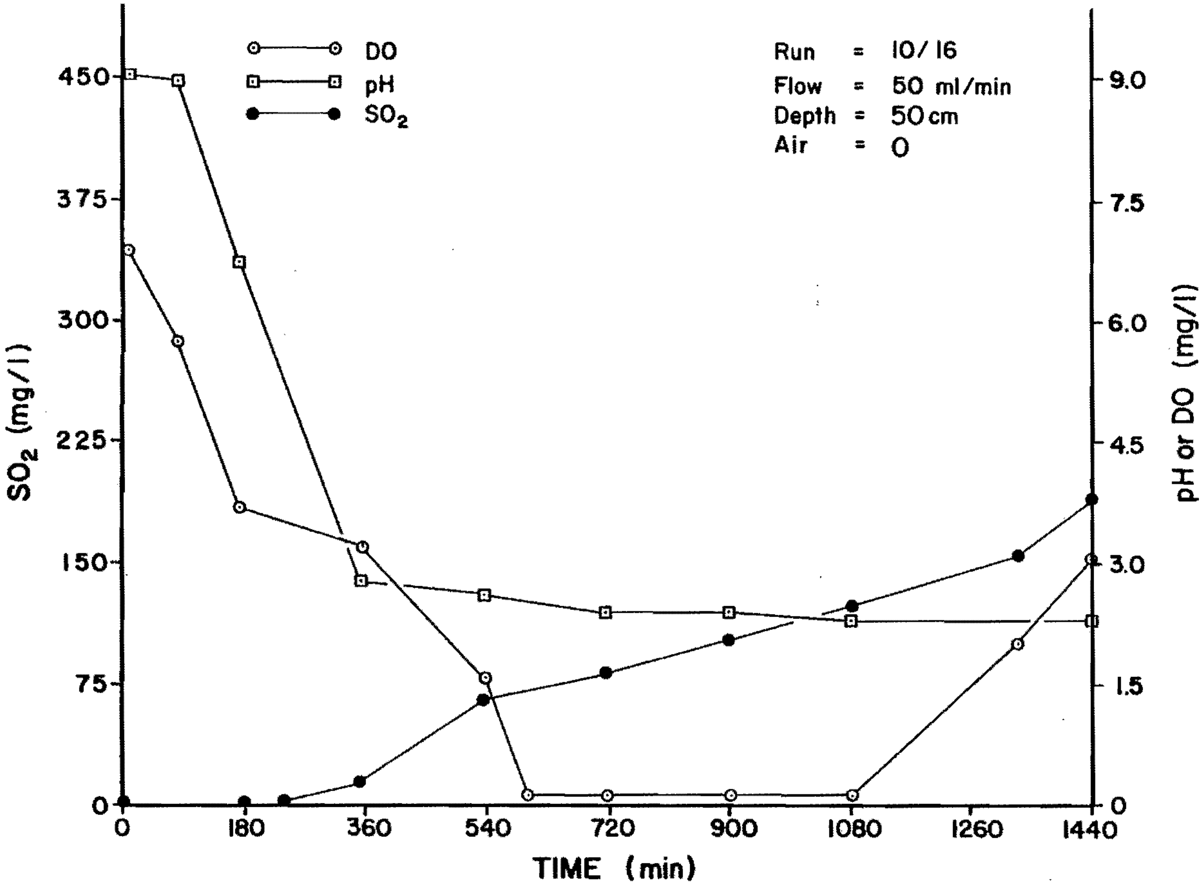


Figure B-16. SO_2 oxidation column observations.

Table B-34. SO_2 oxidation column observations--10/19.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 4.2	DO = 3.5
pH = 2.7	pH = 2.75
SO_2 = 492 mg/l	SO_2 = 460 mg/l
$SO_4^=$ = 49 mg/l as SO_2	$SO_4^=$ = 59 mg/l as SO_2

Column Data: Air Flow = 5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	6.4	8.7	0		49	
60	6.4	8.6	0	173	52	
90	5.6	7.1	0		50	
120	5.5	4.7	0	254	50	
180	5.15	2.9	0		50	
240	5.0	2.7	0	343	51	
300	5.1	2.55	0		51	
360	5.1	2.4	0	392	50	
420	5.2	2.4	0		51	
480	5.4	2.3	0	408	51	
540	5.4	2.3	0		50	Feed SO_2 = 468 mg/l
600	5.5	2.25	0	449	51	Add 34 ml H_2SO_3
660	5.6	2.2	0		51	Feed SO_2 = 524 mg/l
720	5.5	2.2	0	465	50	Feed SO_2 = 464 mg/l
780	5.7	2.2	0		51	Add 32 ml H_2SO_3
840	5.7	2.15	0	498	50	Feed SO_2 = 520 mg/l
900	5.8	2.1	0		50	Feed SO_2 = 488 mg/l
960	5.8	2.1	0	506	50	
1020	5.8	2.1	0		50	
1080	5.9	2.1	0	510	50	Feed SO_2 = 492 mg/l
1140	5.9	2.1	0		49	
1200	5.9	2.1	0	502	48	
1260	5.9	2.1	0		49	Feed SO_2 = 488 mg/l
1320	6.1	2.1	0	498	52	
1380	6.0	2.1	0		52	
1440	6.0	2.1	0	461	52	

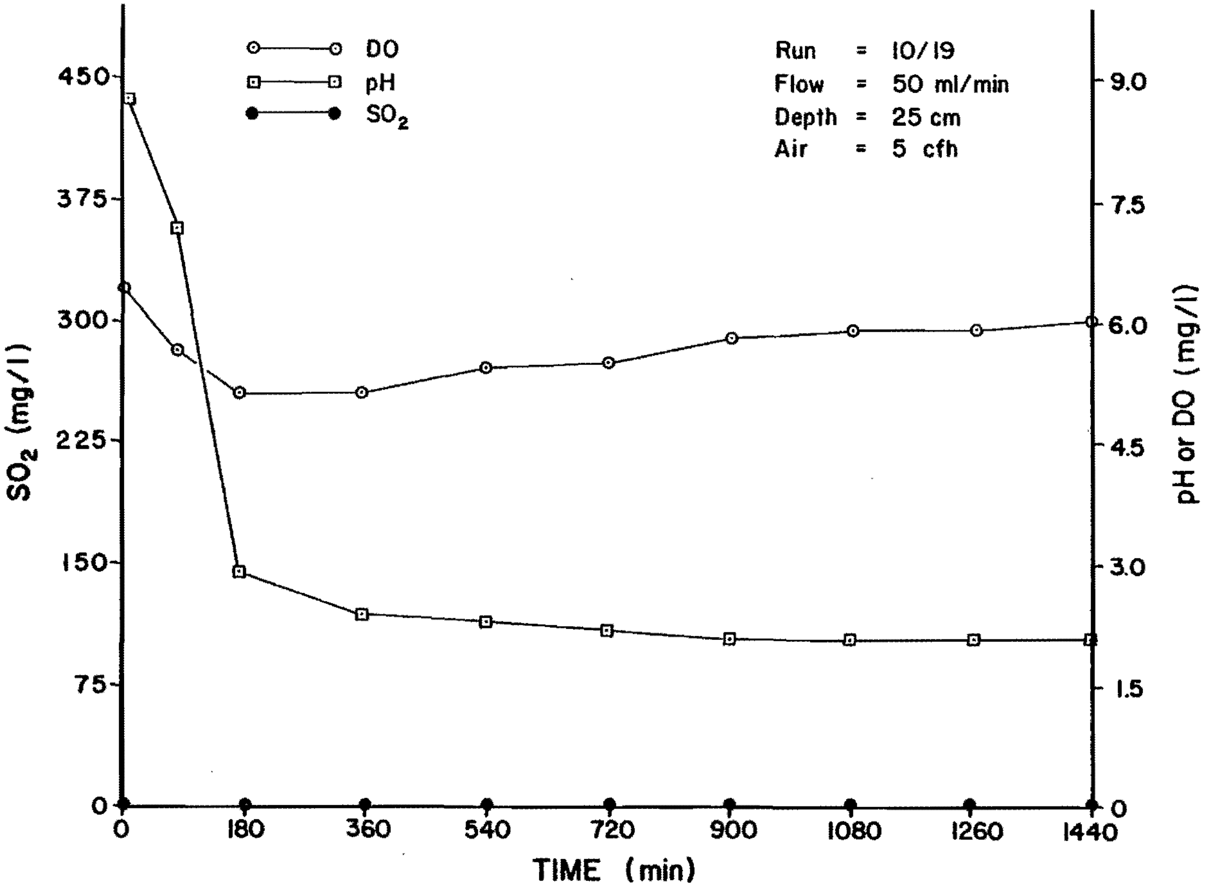


Figure B-17. SO_2 oxidation column observations.

Table B-35. SO_2 oxidation column observations--10/21.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 5.5	DO = 3.2
pH = 2.5	pH = 2.5
SO_2 = 560 mg/l	SO_2 = 488 mg/l
$SO_4^=$ = 45 mg/l as SO_2	$SO_4^=$ = 57 mg/l as SO_2

Column Data: Air Flow = 5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.1	8.8	0		91	
30	6.8	8.4	0		100	
60						
90	4.1	2.9	0	382	100	
120	3.8	2.3	8	456	100	
180						
240						
300	3.5	2.1	24	529	100	
360	3.6	2.1	32	537	100	
420	3.1	2.1	44		100	
480	3.2	2.1	40	529	100	
540	3.2	2.1	48		100	Feed SO_2 = 540 mg/l
600	3.6	2.1	64	496	100	
660	3.8	2.1	68		100	
720	3.7	2.1	64	492	100	Feed SO_2 = 548 mg/l
780	3.5	2.1	72		100	
840	3.6	2.1	68	480	100	
900	3.4	2.1	64		100	Feed SO_2 = 540 mg/l
960	3.3	2.1	72	476	100	
1020	3.2	2.1	68		100	
1080	2.9	2.1	64	472	100	Feed SO_2 = 544 mg/l
1140	3.1	2.1	64		100	
1200	3.5	2.1	64	484	100	
1260	3.3	2.1	60		100	Feed SO_2 = 508 mg/l
1320	3.5	2.0	52	468	100	
1380	3.5	2.0	52		100	
1440	3.5	2.0	50	456	100	

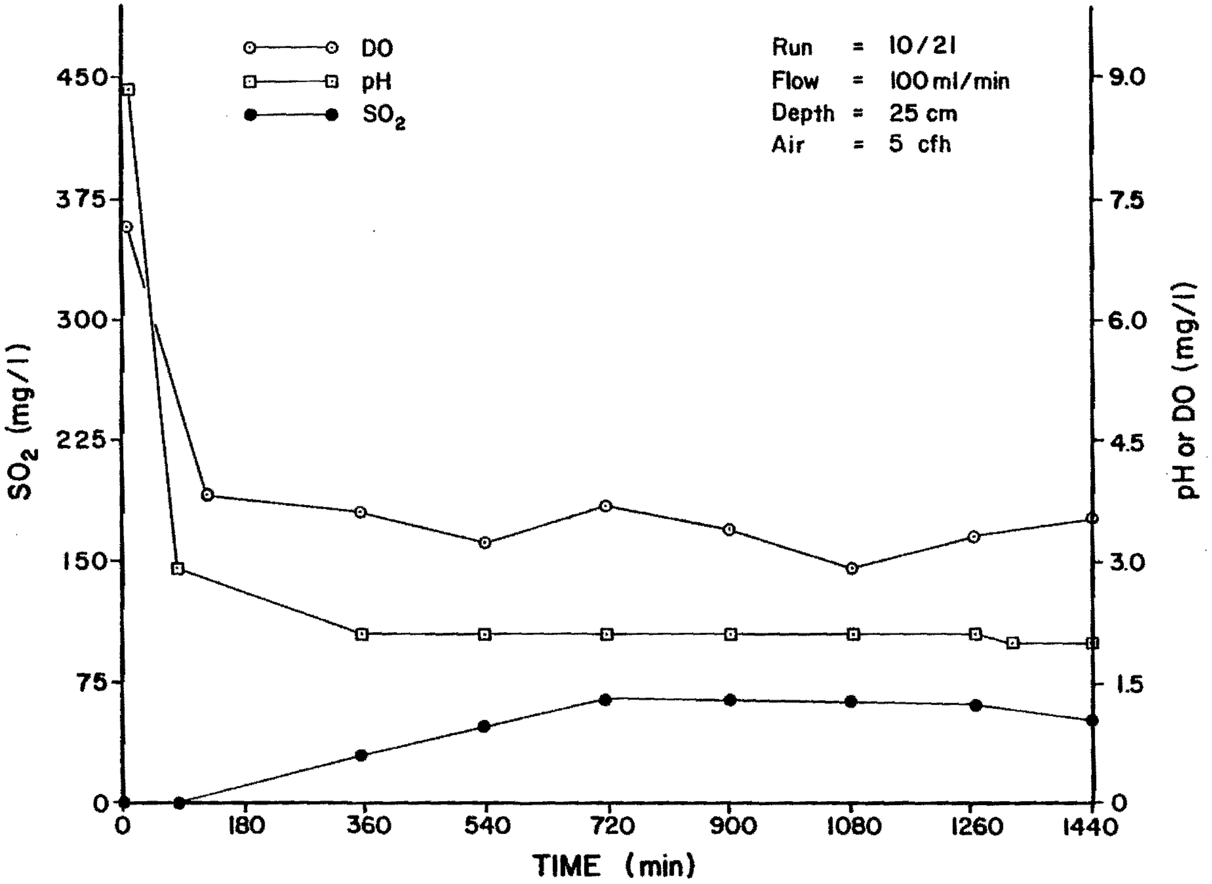


Figure B-18. SO_2 oxidation column observations.

Table B-36. SO_2 oxidation column observations--10/23.

<u>Column Media</u> = GAC, 35 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 5.2	DO = 4.5
pH = 2.6	pH = 2.5
SO_2 = 488 mg/l	SO_2 = 460 mg/l
$SO_4^=$ = 45 mg/l as SO_2	$SO_4^=$ = 62 mg/l as SO_2

<u>Column Data:</u> Air Flow = 5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.2	9.0	0		102	
30	7.2	8.9	0		100	
60	6.9	8.6	0	204	102	
90	6.4	6.9	0		100	
120	5.2	3.6	0	277	100	
180	5.1	2.6	0		98	
240	5.4	2.4	0	391	100	
300	5.5	2.3	0		100	
360	5.6	2.2	0	440	100	
420	5.7	2.2	0		100	
480	5.8	2.1	0	456	100	
540	5.8	2.1	0		100	
600	5.9	2.1	0	488	100	
660	6.0	2.1	0		100	
720	6.0	2.05	0	501	100	Feed SO_2 = 452 mg/l
780	6.0	2.05	0		100	Add 69 ml H_2SO_3
840	5.8	2.0	0	521	100	Feed SO_2 = 512 mg/l
900	5.7	2.0	0		100	Feed SO_2 = 524 mg/l
960	5.6	2.0	0	533	100	
1020	5.7	2.0	0		100	
1080	5.7	2.0	0	533	100	Feed SO_2 = 540 mg/l
1140	5.8	2.0	0		100	
1200	5.7	1.95	0	529	100	
1260	5.7	1.95	0		100	Feed SO_2 = 518 mg/l
1320	5.7	2.0	0	537	100	
1380	5.8	2.0	0		100	
1440	5.8	2.0	0	501	100	

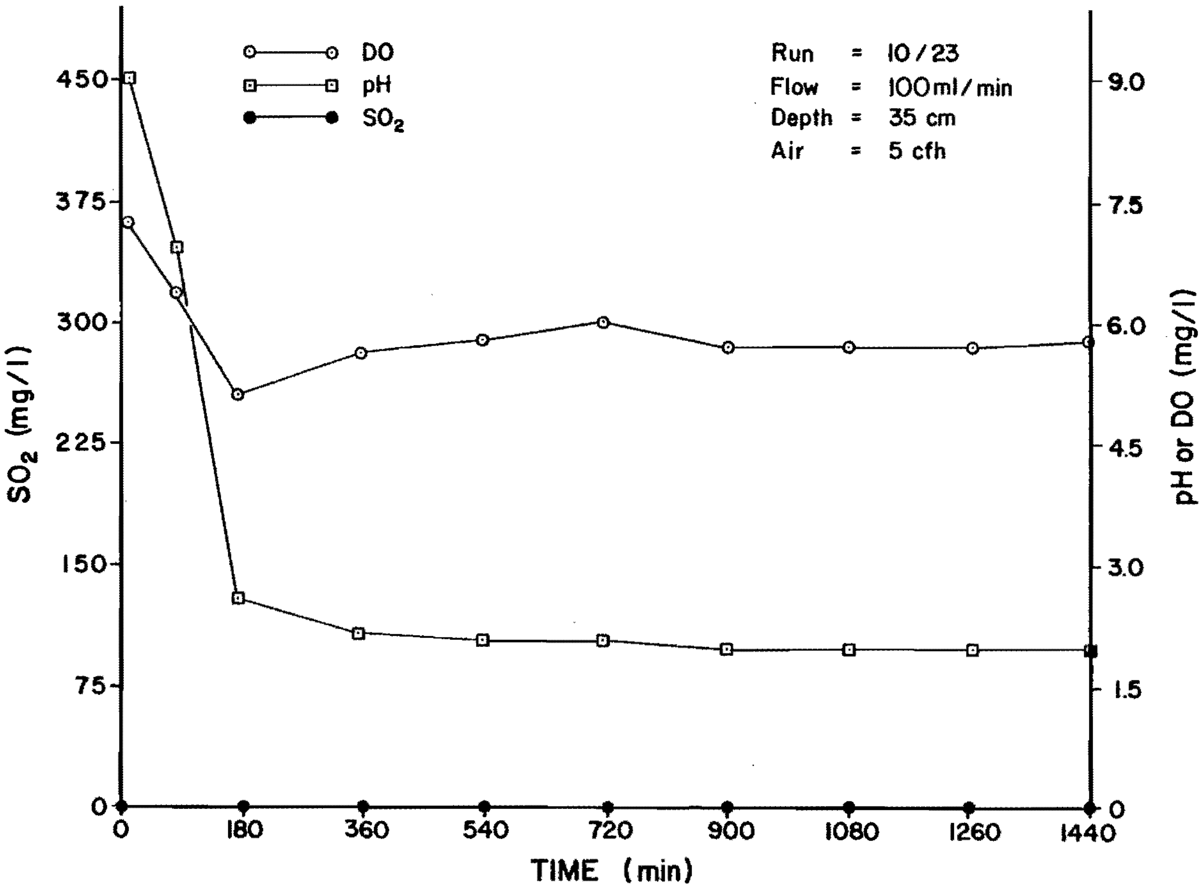


Figure B-19. SO_2 oxidation column observations.

Table B-37. SO_2 oxidation column observations--10/26.

Column Media = GAC, 35 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.
DO = 5.6
pH = 2.7
SO_2 = 496 mg/l
$SO_4^=$ = 45 mg/l as SO_2

Final Feed Soln.
DO = 4.1
pH = 2.7
SO_2 = 456 mg/l
$SO_4^=$ = 60 mg/l as SO_2

Column Data: Air Flow = 5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	6.6	8.7	0	139	150	
30	6.0	7.7	0		154	
60	4.3	3.3	8	326	150	Cloudy
90	3.8	2.7	20		150	
120	3.8	2.5	30	407	150	Cloudy
180	3.3	2.35	56		150	
240	3.2	2.3	64	448	150	
300	2.9	2.2	78		150	
360	3.1	2.2	82	448	150	
420	3.1	2.2	88		150	
480	3.2	2.2	80	460	150	
540	3.3	2.2	84		150	
600	3.5	2.2	104	448	147	
660	3.7	2.2	108		150	
720	3.6	2.15	112	440	150	Feed SO_2 = 492 mg/l
780	3.6	2.15	108		150	
840	3.6	2.15	112	423	150	
900	3.3	2.15	120		150	Feed SO_2 = 508 mg/l
960	3.1	2.15	128	411	150	
1020	3.1	2.15	120		150	
1080	3.1	2.15	116	411	150	Feed SO_2 = 504 mg/l
1140	3.0	2.15	116		150	
1200	3.0	2.15	112	383	150	
1260	3.0	2.15	112		150	Feed SO_2 = 488 mg/l
1320	3.2	2.15	108	383	150	
1380	3.3	2.1	104		150	
1440	3.6	2.1	108	350	150	

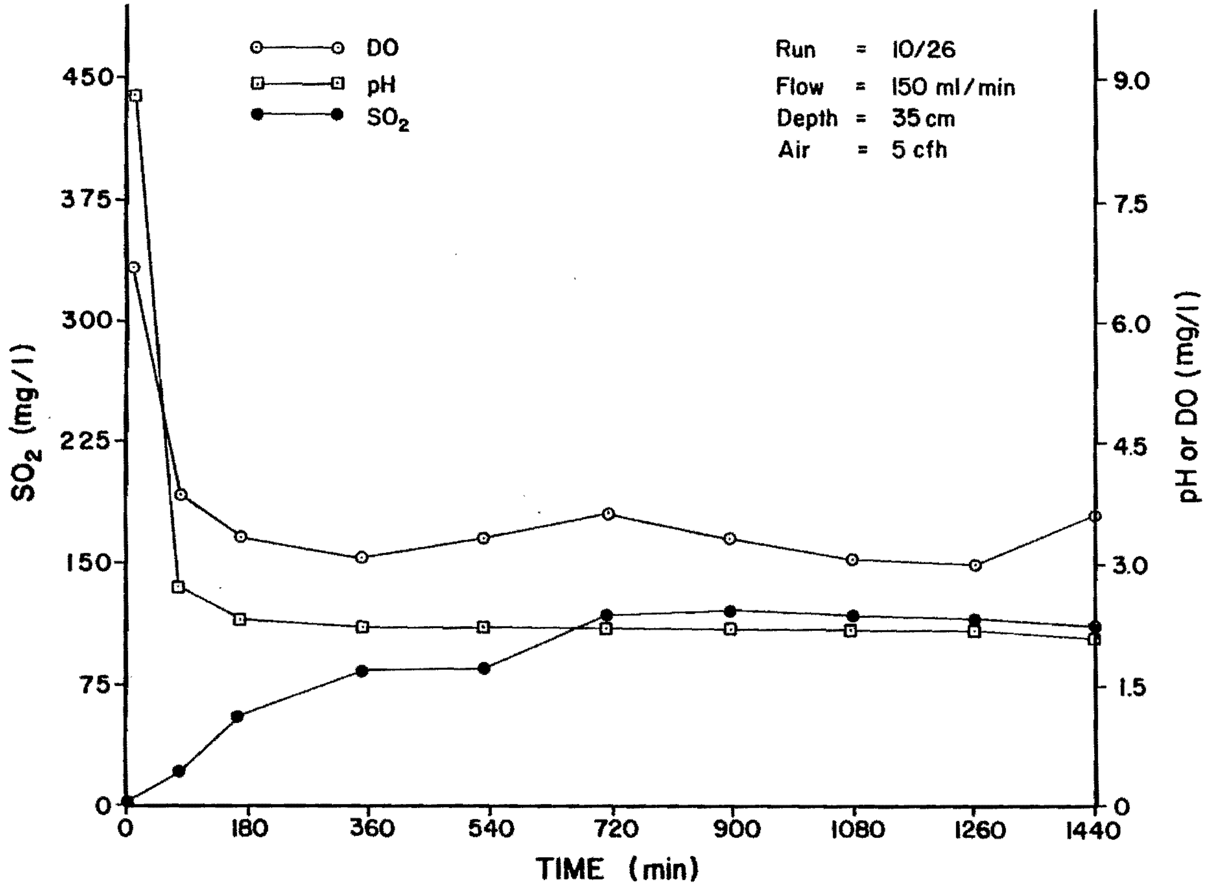


Figure B-20. SO_2 oxidation column observations.

Table B-38. SO_2 oxidation column observations--10/28.

Column Media = GAC, 50 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 4.9	DO = 4.1
pH = 2.65	pH = 2.6
SO_2 = 520 mg/l	SO_2 = 468
$SO_4^=$ = 52 mg/l as SO_2	$SO_4^=$ = 60 mg/l as SO_2

Column Data: Air Flow = 5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.4	9.0	0	52	150	
30	7.2	8.9	0		152	
60	6.9	8.4	0	197	150	
90	5.3	6.5	0		150	
120	4.5	3.4	0	292	150	
180	4.6	2.6	0		150	
240	5.0	2.3	0	400	150	
300	4.8	2.2	0		150	
360	4.8	2.2	0	458	150	
420	4.8	2.2	0		150	
480	4.8	2.1	0	451	150	
540	4.8	2.1	0		150	Feed SO_2 = 512 mg/l
600	4.8	2.05	0	473	150	
660	4.6	2.05	0		150	
720	4.7	2.05	0	458	150	Feed SO_2 = 496 mg/l
780	4.6	2.0	0		150	
840	4.5	2.0	0	451	150	
900	4.3	2.0	0		150	
960	4.4	2.0	0	451	150	
1020	4.4	2.0	0		150	
1080	4.5	2.0	0	465	150	
1140	4.5	2.0	0		150	
1200	4.5	2.0	0	465	150	Feed SO_2 = 460 mg/l
1260′	4.4	2.0	0		150	Add 41 ml H_2SO_3
1320	4.7	2.0	4	480	154	Feed SO_2 = 520 mg/l
1380	4.8	2.0	4		154	
1440	4.6	2.0	4	465	154	

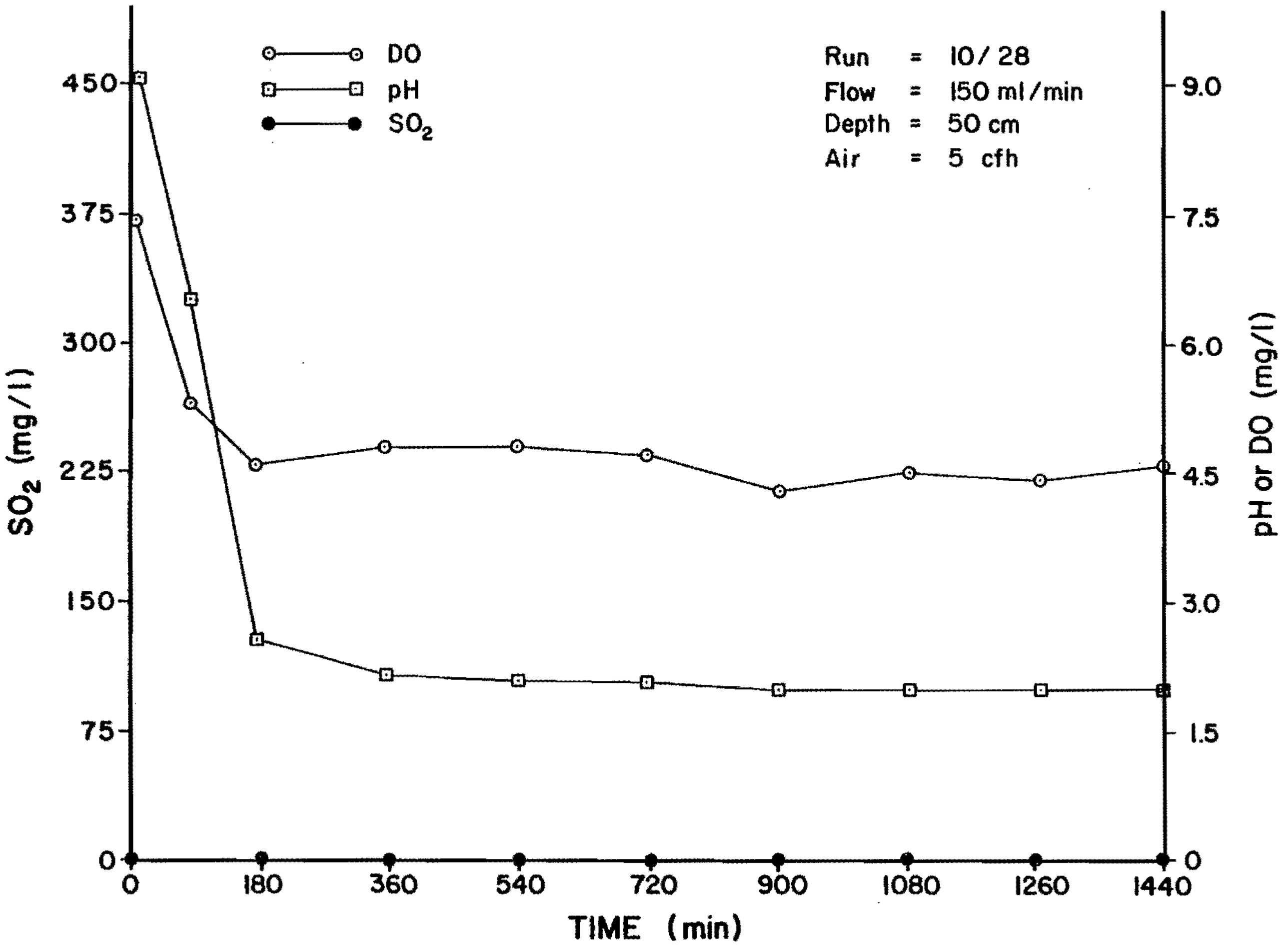


Figure B-21. SO_2 oxidation column observations.

Table B-39. SO_2 oxidation column observations--10/30.

Column Media = GAC, 50 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 6.3	DO = 4.6
pH = 2.5	pH = 2.6
SO_2 = 536 mg/l	SO_2 = 448
$SO_4^=$ = 45 mg/l as SO_2	$SO_4^=$ = 65 mg/l as SO_2

Column Data: Air Flow = 5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.6	8.8	0	110	171	
30	7.2	8.4	0		176	
60	5.1	5.9	0	285	176	Cloudy
90	4.4	2.85	0		176	
120	4.1	2.5	4	383	176	Cloudy
180	4.0	2.2	22		174	
240	3.8	2.2	34	456	174	
300	3.8	2.1	44		174	
360	4.3	2.1	50	456	174	
420	4.1	2.1	54		171	
480	3.8	2.1	64	456	171	
540	3.2	2.1	68		176	Feed SO_2 = 512 mg/l
600	3.1	2.1	76	460	176	
660	3.6	2.1	76		176	
720	3.4	2.05	80	436	176	Feed SO_2 = 512 mg/l
780	3.3	2.05	80		175	
840	3.2	2.05	80	436	175	
900	3.5	2.05	84		175	
960	3.4	2.05	84	415	175	
1020	3.7	2.05	80		176	
1080	3.1	2.05	80	407	174	
1140	3.6	2.05	76		172	
1200	3.7	2.05	76	407	172	Feed SO_2 = 496 mg/l
1260	3.8	2.05	72		175	
1320	3.6	2.05	68	415	175	
1380	4.1	2.05	66		172	
1440	3.2	2.05	62	391	169	

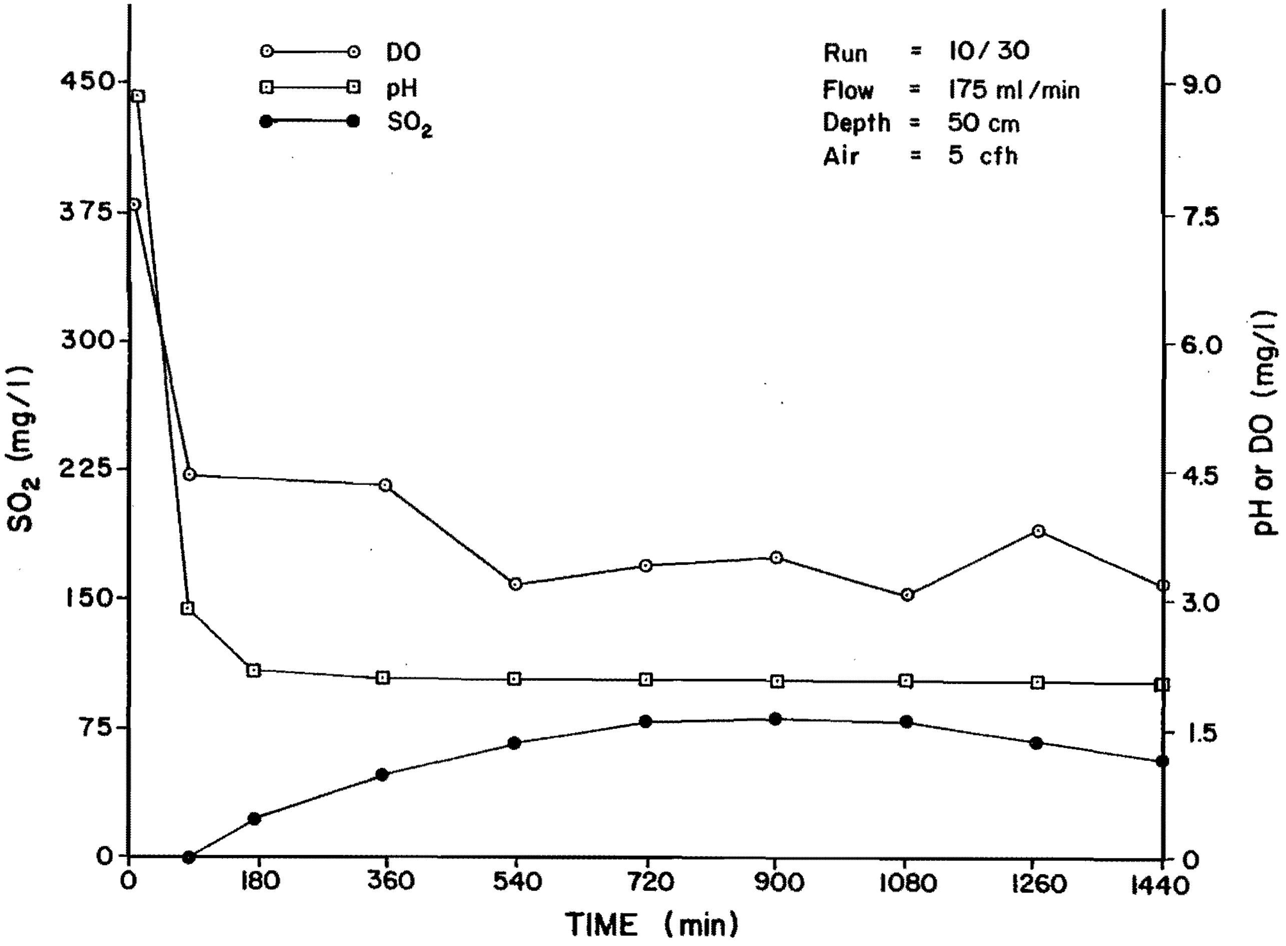


Figure B-22. SO_2 oxidation column observations.

Table B-40. SO_2 oxidation column observations--11/2.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 5.1	DO = 3.6
pH = 2.65	pH = 2.6
SO_2 = 524 mg/l	SO_2 = 428 mg/l
$SO_4^=$ = 45 mg/l as SO_2	$SO_4^=$ = 65 mg/l as SO_2

Column Data: Air Flow = 5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.6	8.6	0	86	76	
30	7.4	8.4	0		78	
60	7.0	6.3	0	231	79	Cloudy
90	5.6	3.9	0		77	
120	4.9	3.0	0	342	75	
180	5.1	2.5	0		76	
240	5.7	2.3	0	453	76	
300	5.3	2.2	0		76	
360	5.2	2.15	0	488	76	
420	5.1	2.1	0		76	
480	5.3	2.1	4	496	76	
540	5.0	2.1	4		76	
600	4.9	2.1	4	479	76	
660	4.8	2.1	4		76	
720	4.9	2.1	4	462	76	Feed SO_2 = 504 mg/l
780	4.9	2.1	4		76	
840	4.8	2.05	4	505	76	
900	4.9	2.05	4		76	
960	4.7	2.05	4	513	76	
1020	4.8	2.05	8		76	
1080	4.7	2.05	8	488	76	
1140	4.8	2.05	8		76	
1200	4.8	2.05	8	492	76	Feed SO_2 = 472 mg/l
1260	4.7	2.05	8		76	Add 17 ml H_2SO_3
1320	4.9	2.0	8	505	76	Feed SO_2 = 504 mg/l
1380	5.1	2.0	8		76	
1440	5.0	2.0	8	470	76	

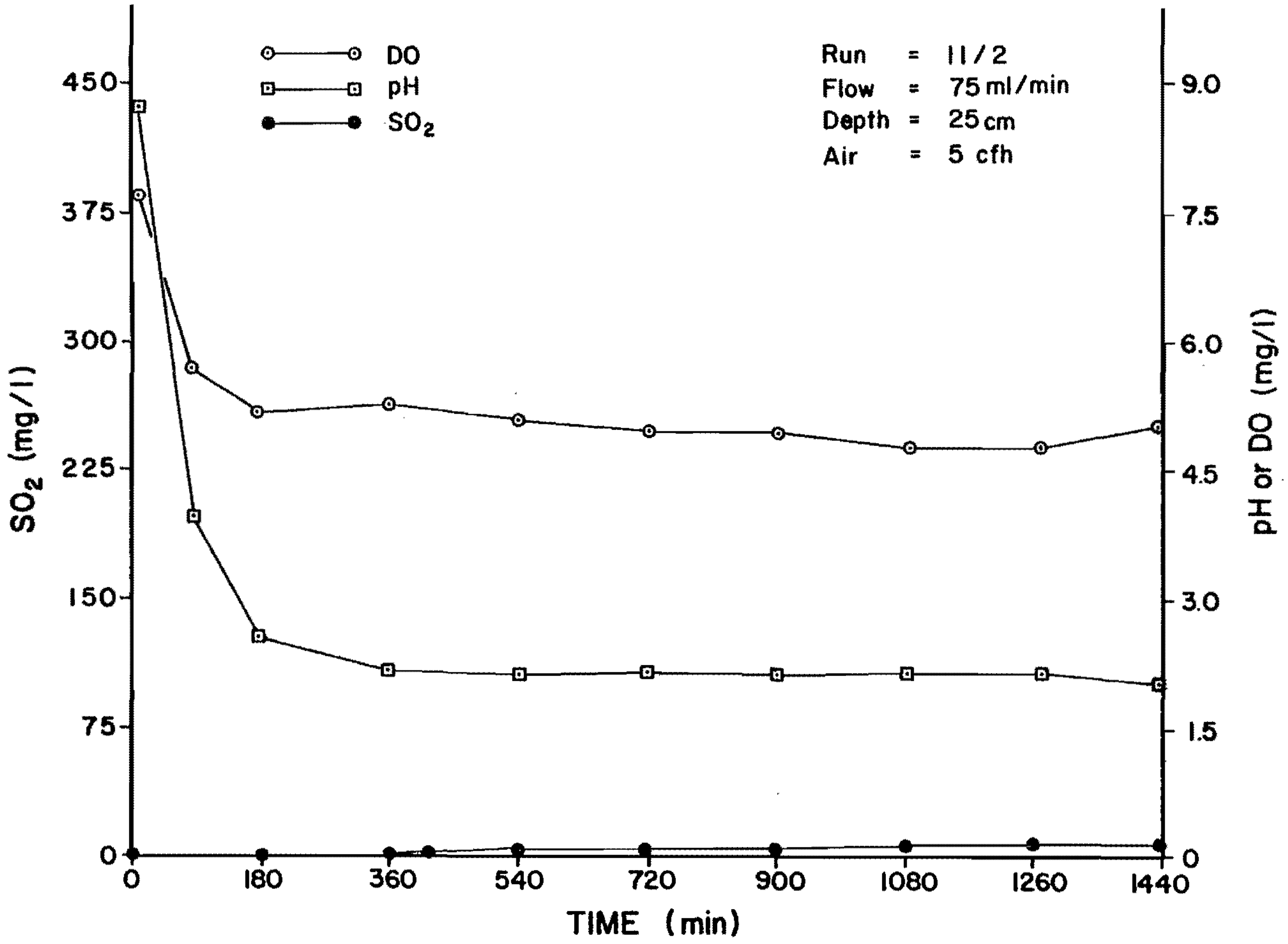


Figure B-23. SO_2 oxidation column observations.

Table B-41. SO_2 oxidation column observations--11/4.

Column Media = GAC, 50 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 4.1	DO = 4.2
pH = 2.7	pH = 2.6
SO_2 = 492 mg/l	SO_2 = 486 mg/l
$SO_4^=$ = 45 mg/l as SO_2	$SO_4^=$ = 66 mg/l as SO_2

Column Data: Air Flow = 2.5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.2	8.7	0	115	154	
30	6.8	8.0	0		150	
60	5.9	6.5	4	251	150	Cloudy
90	5.0	3.35	20		150	
120	4.8	2.9	24	329	150	Cloudy
180	4.5	2.6	34		148	
240	4.5	2.4	36	387	148	Cloudy
300	4.1	2.4	36		150	Feed SO_2 = 464 mg/l
360	4.1	2.3	40	436	150	Add 36 ml H_2SO_3
420	4.1	2.2	48		150	Feed SO_2 = 484 mg/l
480	4.0	2.2	50	448	150	
540	3.9	2.2	56		150	Feed SO_2 = 520 mg/l
600	3.8	2.1	60	477	150	
660	3.5	2.1	64		150	
720	3.6	2.1	72	485	150	Feed SO_2 = 504 mg/l
780	3.7	2.1	80		150	
840	3.6	2.05	80	510	150	
900	3.7	2.05	80		150	
960	3.9	2.05	84	543	150	Feed SO_2 = 512 mg/l
1020	3.9	2.05	84		150	
1080	3.8	2.05	80	485	150	
1140	3.8	2.05	84		150	
1200	3.9	2.05	84	457	150	Feed SO_2 = 496 mg/l
1260	3.8	2.05	76		150	
1320	4.0	2.1	68	444	150	
1380	4.1	2.1	74		150	
1440	3.9	2.1	76	436	150	

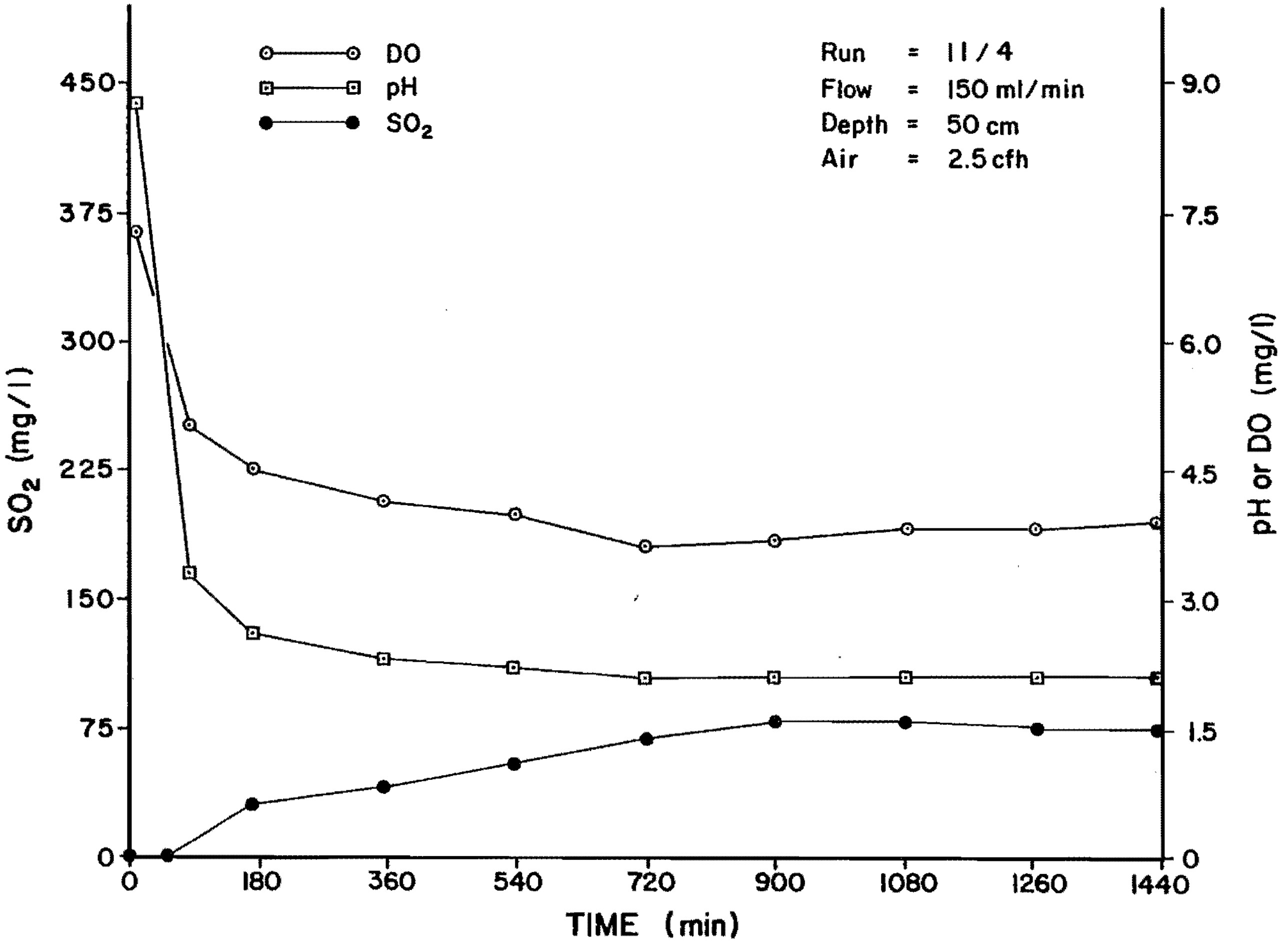


Figure B-24. SO_2 oxidation column observations.

Table B-42. SO_2 oxidation column observations--11/6.

Column Media = Anthracite, 50 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 6.2	DO = 5.7
pH = 2.8	pH = 2.75
SO_2 = 496 mg/l	SO_2 = 484 mg/l
$SO_4^=$ = 45 mg/l as SO_2	$SO_4^=$ = 62 mg/l as SO_2

Column Data: Air Flow = 5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	0.5	2.5	216	476	150	Yellow Effluent
30	0.1	2.5	304	360	150	
60	0.8	2.6	360	299	154	
90	3.0	2.7	384	308	146	Clear
120	4.2	2.7	392	243	146	
180	6.6	2.7	400	211	146	
240	6.6	2.7	400	219	146	
300						
360						
420						
480						
540						
600						
660						
720						

Note: Run ended at 240 due to high breakthrough

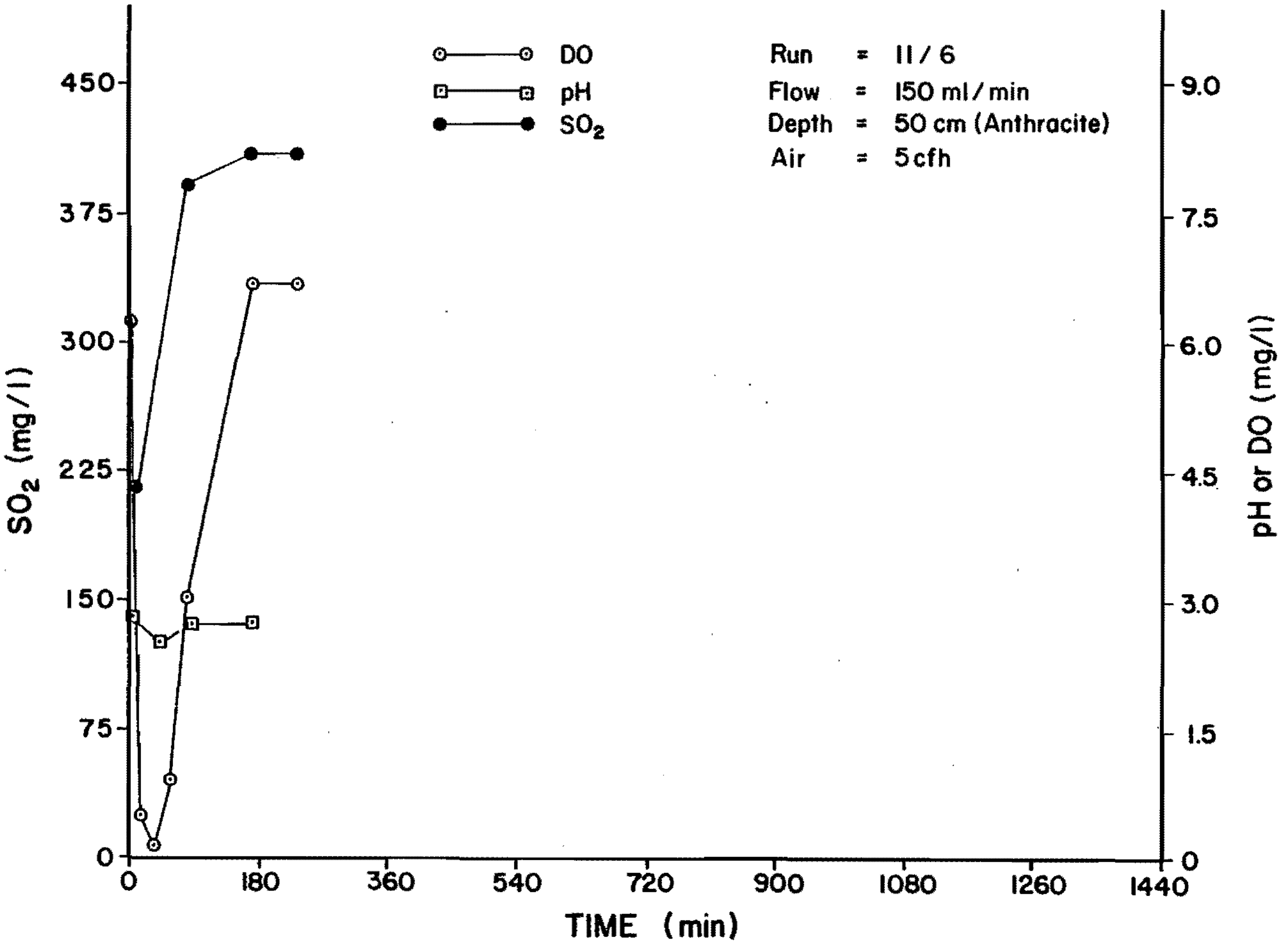


Figure B-25. SO_2 oxidation column observations.

Table B-43. SO_2 oxidation column observations--11/9.

Column Media = GAC, 50 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 3.5	DO = 2.5
pH = 2.7	pH = 2.6
SO_2 = 496 mg/l	SO_2 = 480 mg/l
$SO_4^=$ = 130 mg/l as SO_2	$SO_4^=$ = 146 mg/l as SO_2
Alk = 258 mg/l as $CaCO_3$	

Column Data: Air Flow = 5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.6	8.7	0	170	145	
30	7.4	8.6	0		150	
60	6.8	7.4	0	331	148	
90	6.1	5.8	0		148	
120	5.9	3.5	0	428	145	Cloudy
180	5.8	2.6	0		145	
240	5.6	2.4	0	529	145	
300	5.4	2.35	4		144	
360	5.6	2.3	0	565	145	
420	5.4	2.25	6		145	
480	5.3	2.2	4	590	145	
540	5.5	2.2	6		146	
600	5.4	2.15	6	638	146	
660	5.0	2.1	8		145	
720	5.3	2.1	12	646	146	Feed SO_2 = 500 mg/l
780	5.4	2.1	16		145	
840	5.1	2.1	16	630	145	
900	5.5	2.1	16		146	
960	5.3	2.1	12	650	145	Feed SO_2 = 492 mg/l
1020	5.2	2.1	16		146	
1080	5.3	2.1	16	646	146	
1140	5.0	2.1	16		145	
1200	5.4	2.1	16	646	145	Feed SO_2 = 472 mg/l
1260	5.4	2.1	16		145	Add 27 ml H_2SO_3
1320	5.3	2.1	20	662	145	Feed SO_2 = 496 mg/l
1380	5.2	2.1	16		145	
1440	5.1	2.1	20	646	145	

Note: Sewage from Salt Lake City

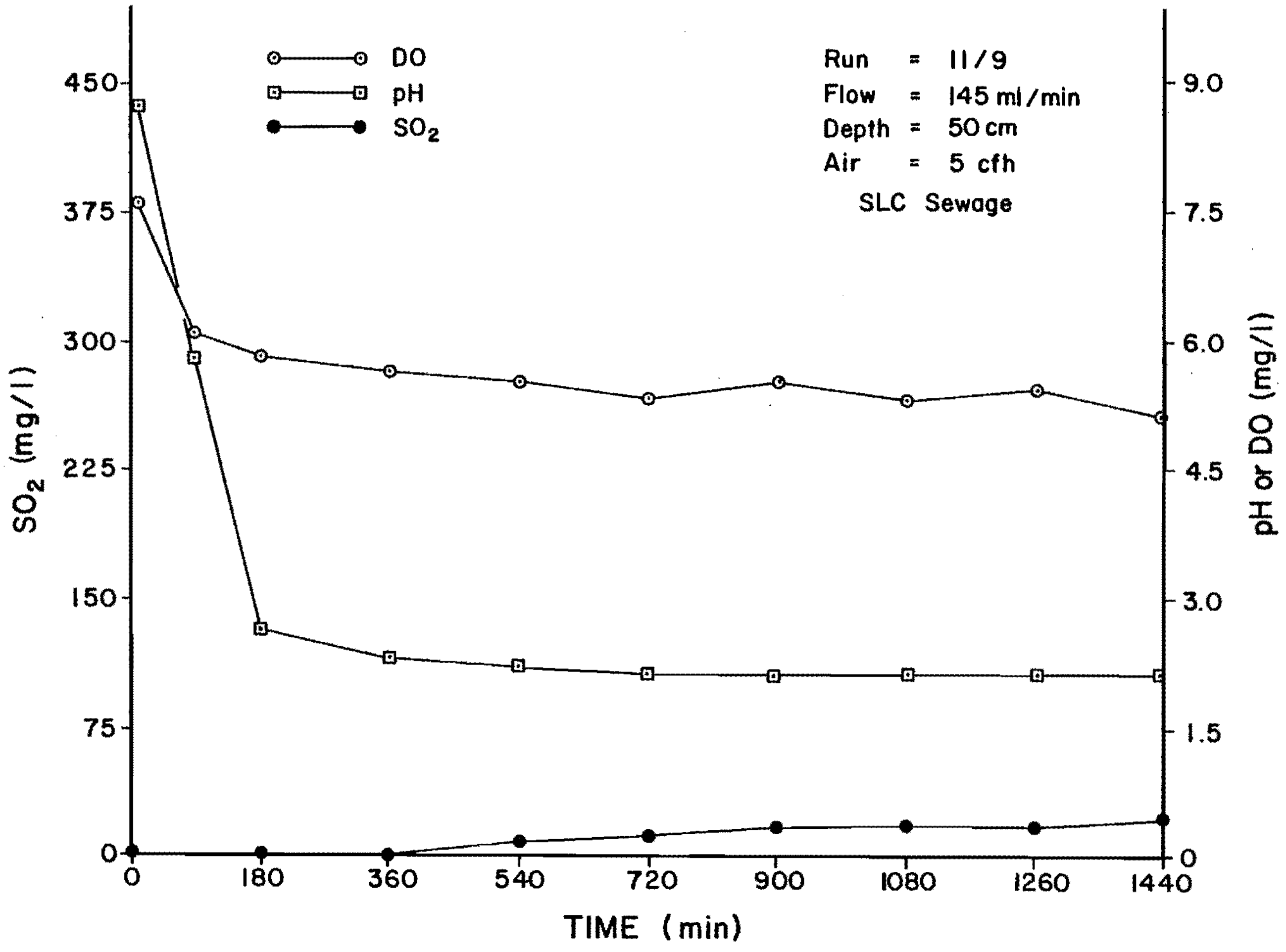


Figure B-26. SO_2 oxidation column observations.

Table B-44. SO_2 oxidation column observations--11/11.

Column Media = GAC, 35 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 6.0	DO = 4.8
pH = 2.6	pH = 2.7
SO_2 = 568 mg/l	SO_2 = 456 mg/l
$SO_4^=$ = 45 mg/l as SO_2	$SO_4^=$ = 55 mg/l as SO_2
Alk = 271 mg/l	

Column Data: Air Flow = 7.5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.4	8.6	0	172	150	
30	6.9	7.6	0		152	
60	5.2	5.0	0	284	150	Cloudy
90	4.5	3.1	4		152	
120	4.8	2.7	0	372	146	Cloudy
180	5.4	2.3	8		154	
240	4.2	2.2	18	480	154	
300	4.8	2.2	22		146	
360	3.7	2.15	30	505	148	
420	3.7	2.15	36		146	
480	3.7	2.1	44	489	148	
540	4.1	2.1	40		152	Feed SO_2 = 532 mg/l
600	4.5	2.1	48	480	150	
660	4.2	2.1	44		150	
720	3.9	2.1	44	465	150	Feed SO_2 = 508 mg/l
780	3.7	2.1	48		150	
840	3.6	2.1	48	457	150	
900	3.8	2.1	48		150	
960	3.8	2.1	52	457	150	Feed SO_2 = 516 mg/l
1020	3.7	2.1	52		150	
1080	3.5	2.1	48	441	150	
1140	3.8	2.1	52		150	
1200	3.6	2.1	52	457	150	Feed SO_2 = 508 mg/l
1260		2.1	48		150	
1320	4.1	2.1	44	441	150	
1380	4.2	2.1	40		150	
1440						

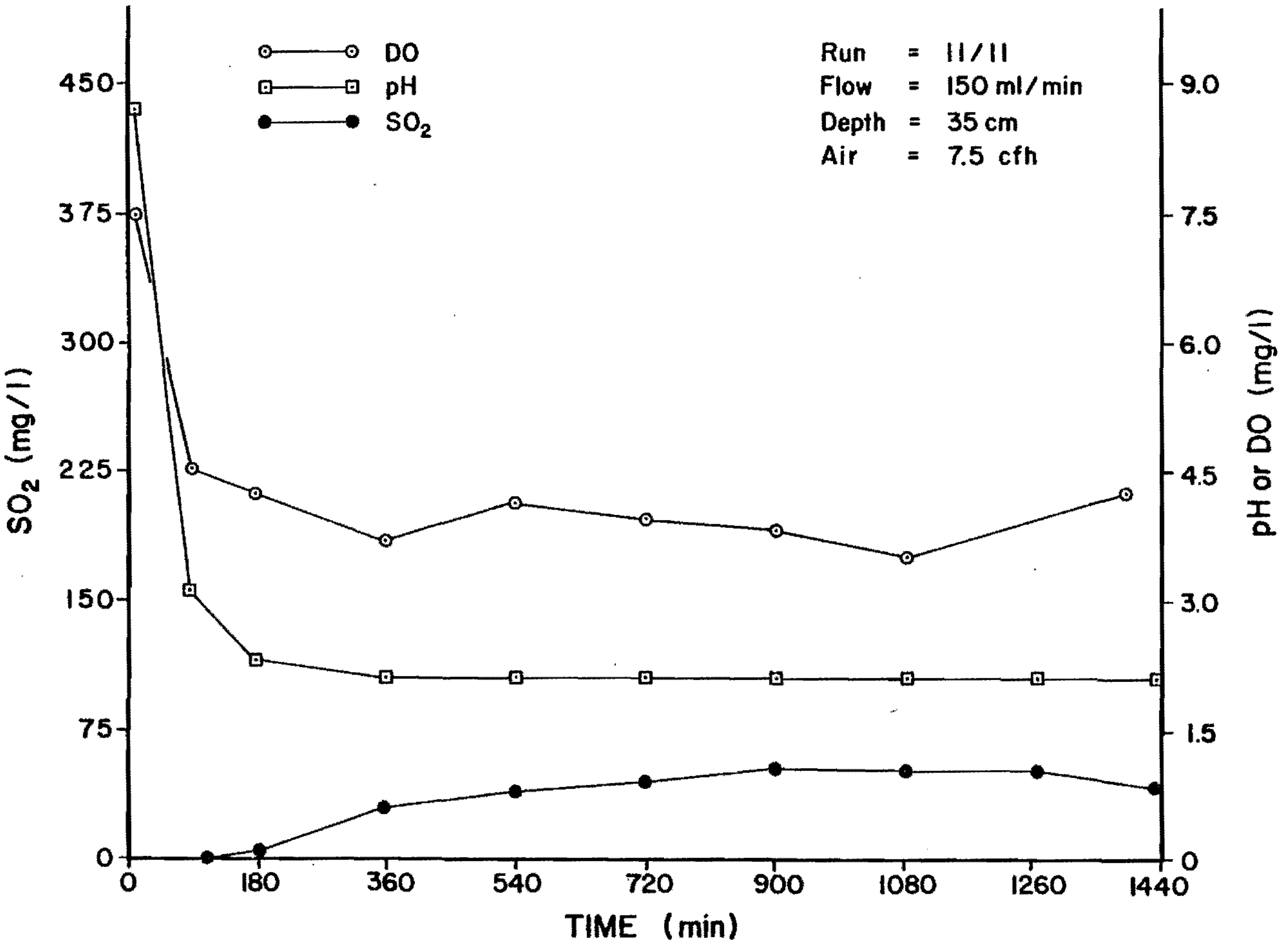


Figure B-27. SO_2 oxidation column observations.

Table B-45. SO_2 oxidation column observations--11/13.

Column Media = GAC, 50 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 4.4	DO = 4.2
pH = 2.7	pH = 2.6
SO_2 = 520 mg/l	SO_2 = 464 mg/l
$SO_4^=$ = 45 mg/l as SO_2	$SO_4^=$ = 53 mg/l as SO_2

Column Data: Air Flow = 5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.6	8.8	0	110	143	
30	7.4	8.6	0		145	
60	5.5	4.9	0	262	146	Cloudy
90	5.3	3.0	6		146	
120	4.7	2.7	16	358	146	Cloudy
180	5.1	2.5	26		146	
240	4.8	2.4	34	400	146	
300	4.5	2.3	36		144	
360	4.6	2.3	40	434	144	
420	4.5	2.2	40		144	
480	4.5	2.2	42	461	145	
540	4.7	2.2	40		145	Feed SO_2 = 528 mg/l
600	5.2	2.2	44	483	145	
660	4.8	2.2	44		146	
720	4.6	2.15	48	499	146	Feed SO_2 = 496 mg/l
780	4.5	2.1	48		146	
840	4.5	2.1	48	480	146	
900	4.6	2.1	48		146	
960	4.5	2.1	48	491	146	Feed SO_2 = 512 mg/l
1020	4.4	2.1	48		146	
1080	4.7	2.1	52	483	146	
1140	4.6	2.1	44		144	
1200	4.6	2.1	48	499	146	Feed SO_2 = 504 mg/l
1260	4.7	2.1	48		146	
1320	5.0	2.1	44	461	146	
1380	4.9	2.1	44		146	
1440	4.9	2.1	40	444	146	

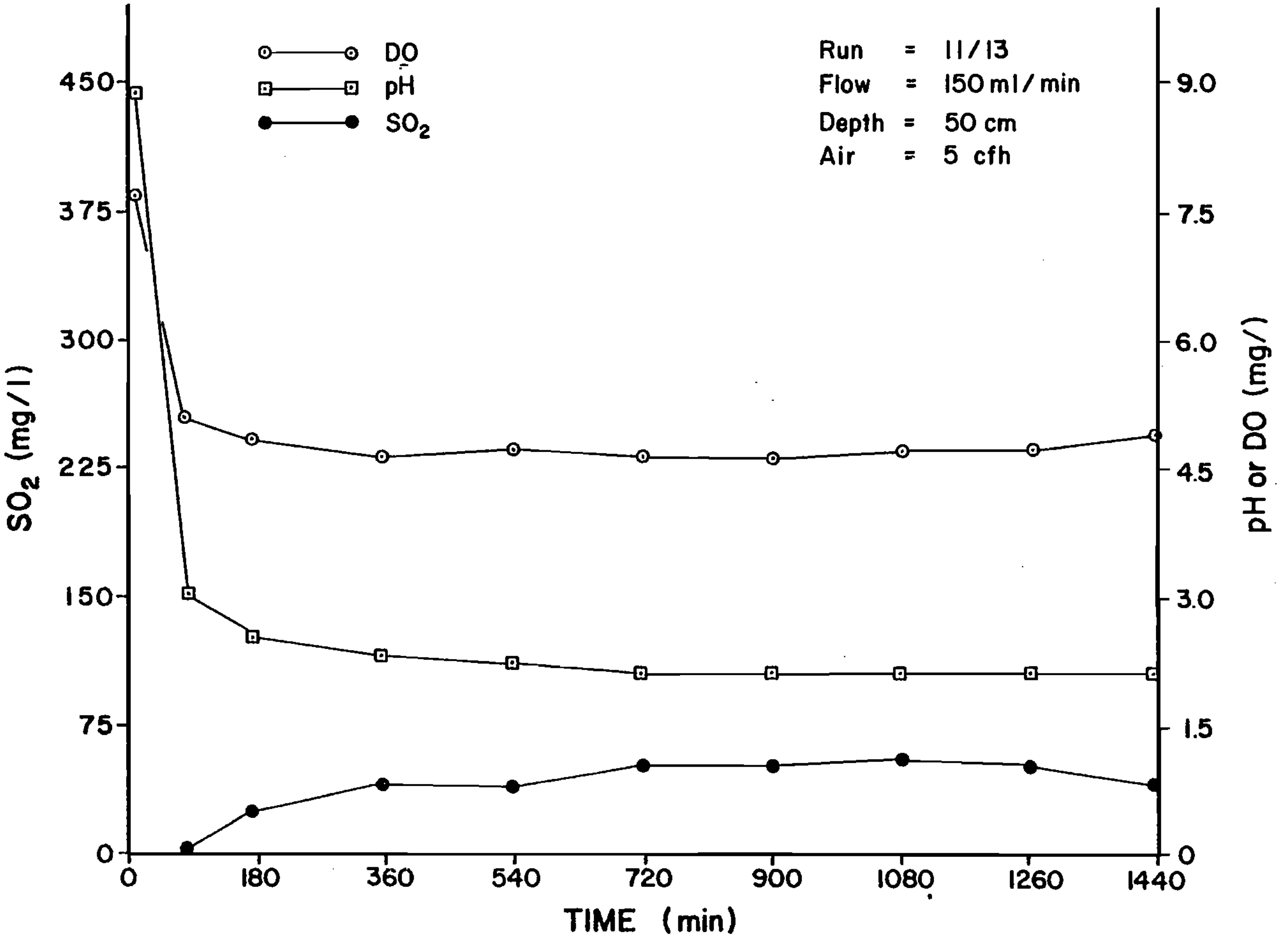


Figure B-28. SO_2 oxidation column observations.

Table B-46. SO_2 oxidation column observations--11/16.

Column Media = GAC, 50 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 6.0	DO = 5.9
pH = 2.6	pH = 2.6
SO_2 = 532 mg/l	SO_2 = 508 mg/l
$SO_4^=$ = 52 mg/l as SO_2	$SO_4^=$ = 62 mg/l as SO_2

Column Data: Air Flow = 5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.2	8.7	0	75	146	
30	7.2	8.6	0		145	
60	7.1	8.0	0	194	146	
90	5.8	6.6	0		145	
120	4.3	3.5	0	271	145	
180	4.7	2.7	0		146	
240	5.4	2.4	0	370	144	
300	5.4	2.25	0		145	
360	5.6	2.2	0	417	145	
420	5.5	2.2	0		145	
480	5.9	2.2	0	423	145	
540	6.1	2.2	0		145	Feed SO_2 = 512 mg/l
600	6.0	2.1	0	430	145	
660	5.9	2.1	0		145	
720	5.9	2.1	0	417	145	Feed SO_2 = 504 mg/l
780	5.8	2.1	0		145	
840	5.8	2.1	0	430	145	
900	5.7	2.1	0		145	
960	5.8	2.05	0	423	145	Feed SO_2 = 496 mg/l
1020	5.7	2.05	0		145	
1080	5.9	2.05	0	417	145	
1140	5.8	2.05	0		143	
1200	5.9	2.05	0	397	145	Feed SO_2 = 476 mg/l
1260	5.8	2.05	0		145	Add 23 ml H_2SO_3
1320	5.7	2.05	4	423	146	Feed SO_2 = 500 mg/l
1380	6.0	2.05	0		146	
1440	5.4	2.0	4	430	146	

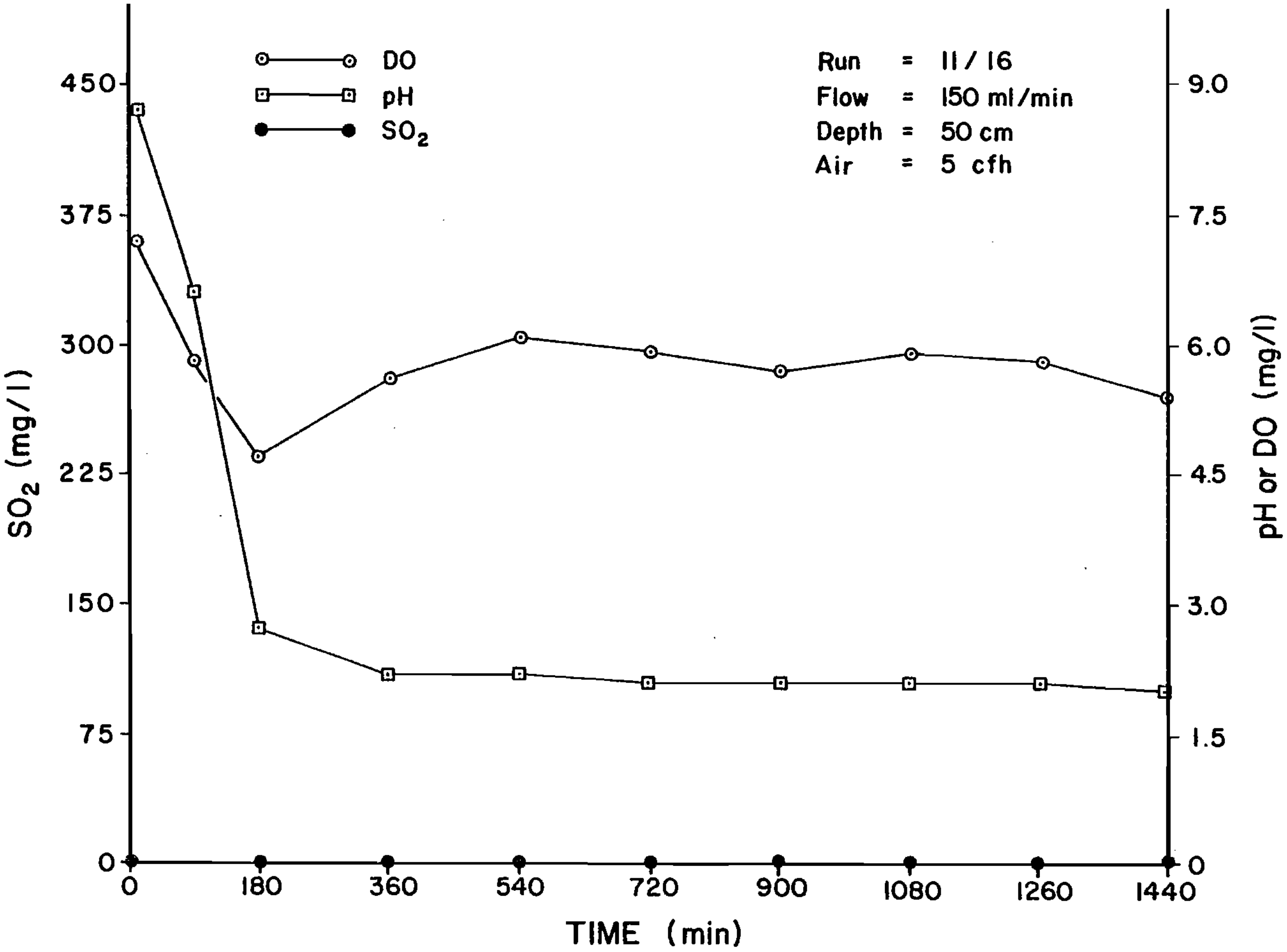


Figure B-29. SO_2 oxidation column observations.

Table B-47. SO_2 oxidation column observations--11/17.

Column Media = GAC, Cont. 11/16
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = -	DO = 6.4
pH = -	pH = 2.6
SO_2 = -	SO_2 = 502 mg/l
$SO_4^=$ = -	$SO_4^=$ = 65 mg/l as SO_2

Column Data: Air Flow = 5 CFH

Time Hrs.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
27	5.4	2.05	4	541	146	
30	4.9	2.0	4	525	146	Feed SO_2 = 492 mg/l
33	5.1	2.05	4	512	144	Feed SO_2 = 484 mg/l
36	4.8	2.05	8	525	144	*512 mg/l
39	4.4	2.05	12	516	145	Feed SO_2 = 496 mg/l
42	4.9	2.0	8	516	145	Feed SO_2 = 500 mg/l
45	4.4	2.0	8	516	144	Feed SO_2 = 492 mg/l
48	4.8	2.0	10	508	145	Feed SO_2 = 484 mg/l
51	4.8	2.0	16	550	145	*540 mg/l
54	4.3	2.0	20	533	145	
57	4.7	2.1	16	491	145	Feed SO_2 = 536 mg/l
60	4.6	2.0	32	499	145	
63	4.0	2.05	36	508	145	Feed SO_2 = 540 mg/l
66	3.9	2.0	36	516	144	Feed SO_2 = 512 mg/l
69	3.8	2.05	28	516	144	Feed SO_2 = 508 mg/l
72	3.9	2.0	24	516	144	Feed SO_2 = 484 mg/l
75	3.9	2.05	24	483	144	*500 mg/l
78	3.9	2.1	24	474	144	
81	4.7	2.1	16	449	145	Feed SO_2 = 488 mg/l
84	4.1	2.1	20	441	145	
87	4.4	2.05	32	441	145	Feed SO_2 = 488 mg/l
90	3.8	2.05	40	441	145	Feed SO_2 = 492 mg/l
93	3.5	2.05	40	449	145	Feed SO_2 = 492 mg/l
96	3.6	2.1	40	441	146	

*Start new feed tank

Table B-48. SO_2 oxidation column observations--11/20.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.
DO = 6.4
pH = 2.6
SO_2 = 502 mg/l
$SO_4^=$ = 52 mg/l as SO_2

Final Feed Soln.
DO = 5.1
pH = 2.5
SO_2 = 500 mg/l
$SO_4^=$ = 105 mg/l as SO_2

Column Data: Air Flow = 5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.2	8.4	0	190	103	
30	7.1	7.9	0		98	
60	5.8	4.7	0	261	100	
90	5.1	3.0	0		100	
120	5.1	2.7	0	345	100	
180	4.9	2.4	4		100	
240	4.6	2.2	8	424	100	Feed SO_2 = 480 mg/l
300	4.5	2.1	8		100	Add 27 ml H_2SO_3
360	4.6	2.1	12	466	100	Feed SO_2 = 500 mg/l
420	5.0	2.1	12		100	
480	4.5	2.1	20	483	100	Feed SO_2 = 516 mg/l
540	4.5	2.1	20		100	
600	4.4	2.1	24	449	100	
BW						See Note
15	6.2	4.9	0	249	102	
30	5.6	2.7	0		100	
60	5.2	2.35	0	374	100	
90	5.3	2.25	4		100	
120	5.1	2.2	4	441	100	
180	5.1	2.2	4		100	
240	5.2	2.15	8	449	100	
300	5.7	2.15	8		100	
360	5.3	2.15	12	466	100	Feed SO_2 = 496 mg/l
420	5.1	2.25	12		100	
480	5.3	2.15	12	449	100	
540	5.6	2.1	16		100	
600	5.3	2.1	16	437	100	Feed SO_2 = 484 mg/l
660	5.1	2.1	16		100	Add 30 ml H_2SO_3
720	5.4	2.1	16	458	100	Feed SO_2 = 512 mg/l
780	5.2	2.1	16		100	
840	5.1	2.1	16	453	100	
900	5.2	2.1	16		100	

Table B-48. Continued.

Column Media = GAC, 25 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.	Final Feed Soln.
DO = 6.4	DO = 5.1
pH = 2.6	pH = 2.5
SO_2 = 502 mg/l	SO_2 = 500 mg/l
$SO_4^=$ = 52 mg/l as SO_2	$SO_4^=$ = 105 mg/l as SO_2

Column Data: Air Flow = 5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
960	5.1	2.1	16	458	100	
1020	5.2	2.1	16		100	Feed SO_2 = 504 mg/l
1080	5.1	2.1	16	479	100	
1140	5.1	2.1	16		100	
1200	5.0	2.1	16	472	100	Feed SO_2 = 488 mg/l
1260	5.1	2.1	16		100	
1320	5.1	2.1	16	472	100	Start New Feed Tank
1380	5.3	2.1	16		100	Feed SO_2 = 508 mg/l
1440	5.3	2.1	16	464	100	Add 50 ml H_2SO_3
27 hrs	5.6	2.1	22	472	100	Feed SO_2 = 540 mg/l
36 hrs	5.2	2.05	10	472	95	Feed SO_2 = 460 mg/l
37 hrs	5.1	2.05	16	479	100	Add 20 ml H_2SO_3
39 hrs	5.1	2.05	12	488	95	Feed SO_2 = 500 mg/l
40 hrs	5.1	2.0	18	488	100	

Note: Backwashing:

Run tap water up through column, 120 ℓ/hr for 20 min., monitor pH and time.

pH	Time (min.)
5.0	3.5
6.0	4.0
6.8	20.0

Column expanded 20% (5 cm)
Bed resettled only 2.5 cm, new bed depth = 27.5 cm

Table B-49. SO_2 oxidation column observations--11/23.

Column Media = GAC, 50 cm
Initial Metal = N/A
Final Metal =

Initial Feed Soln.
DO = 6.0
pH = 2.6
SO_2 = 508 mg/l
$SO_4^=$ = 52 mg/l as SO_2

Final Feed Soln.
DO = 6.6
pH = 2.6
SO_2 = 504 mg/l
$SO_4^=$ = 73 mg/l as SO_2

Column Data: Air Flow = 2.5 CFH

Time Min.	DO	pH	SO_2 mg/l	$SO_4^=$ as SO_2	Flow ml/min	Comments
15	7.4	8.4	0	105	143	
30	7.2	8.2	0		146	
60	5.6	6.3	0	244	146	Cloudy
90	5.1	3.3	6		145	
120	5.3	2.7	14	336	145	Cloudy
180	4.7	2.5	24		145	
240	4.6	2.4	30	400	145	
300	4.4	2.3	36		145	
360	4.5	2.2	36	448	145	
420	4.7	2.2	32		145	
480	4.7	2.2	40	448	145	Feed SO_2 = 520 mg/l
540	4.6	2.2	36		145	Start New Feed Tank
600	4.2	2.2	44	448	145	Feed SO_2 = 536 mg/l
660	4.1	2.15	48		145	
720	4.3	2.1	48	479	145	Feed SO_2 = 520 mg/l
780	4.0	2.1	48		145	
840	4.1	2.1	48	504	145	
900	4.1	2.1	44		145	
960	4.0	2.1	44	488	145	Feed SO_2 = 508 mg/l
1020	4.0	2.1	44		145	
1080	4.2	2.05	44	504	145	
1140	4.2	2.05	44		145	
1200	4.0	2.05	40	488	145	Feed SO_2 = 504 mg/l
1260			40		145	
1320	4.2	2.05	36	488	145	
1380						
1440	4.4	2.05	36	479	145	

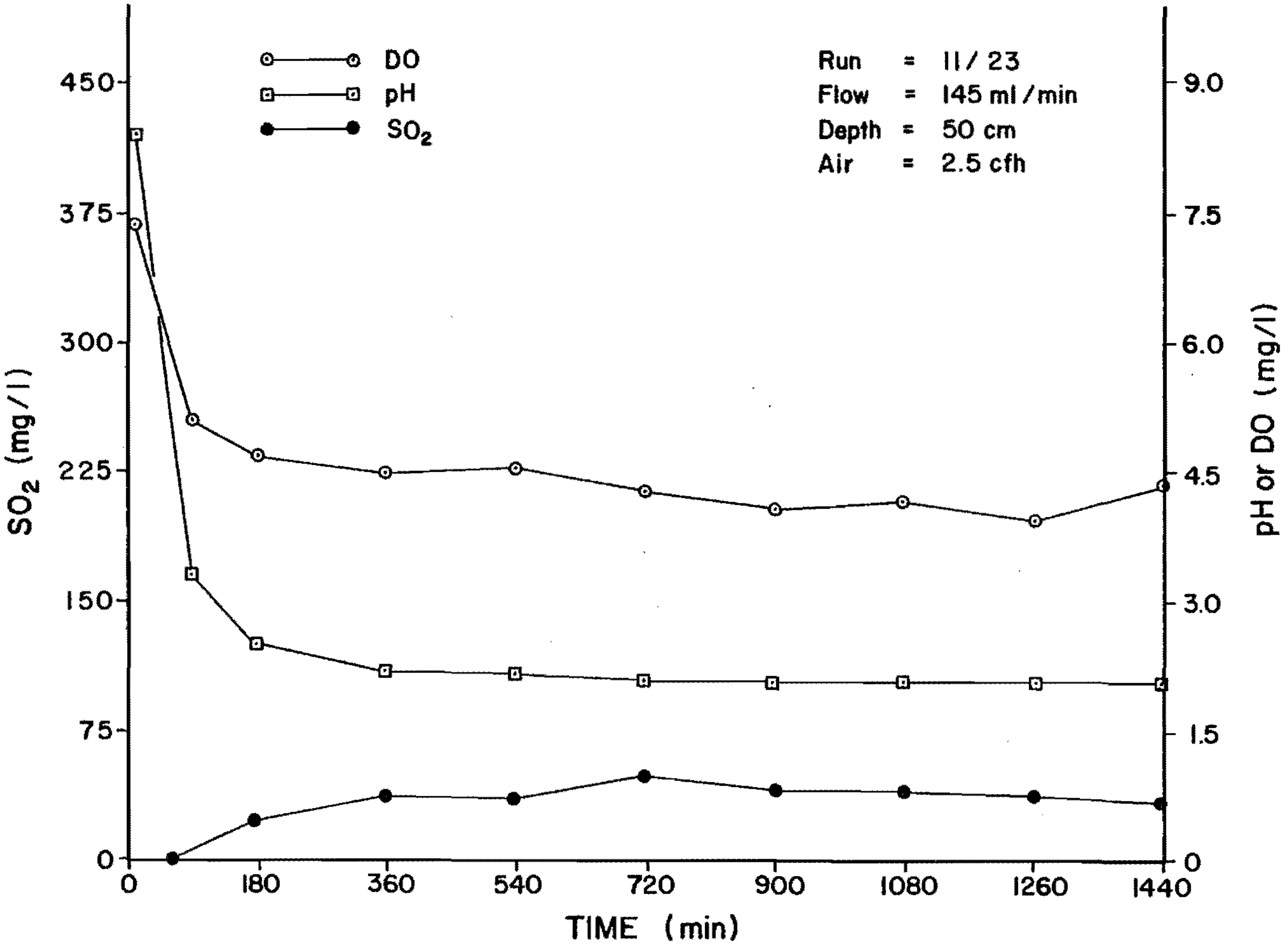


Figure B-30. SO_2 oxidation column observations.

Appendix C

Oxygen Requirements

M. W. SO_2 = 64

M. W. HSO_3^- = 81

M. W. O_2 = 32

500 mg/1 SO_2 $\left(\frac{81}{64}\right)$ = 633 mg/1 HSO_3^-

At pH 2.5, all aqueous SO_2 is in HSO_3^- form

$HSO_3^- + \frac{1}{2}O_2 \rightarrow SO_4^=$

O_2 required = 633 $\left(\frac{16}{81}\right)$ = 125 mg/1

Air flow for 150 ml/min.:

Assume: Air = 21% O_2

1 ℓ air = 1.06 g

8% air to water oxygen transfer efficiency

125 mg/1 x 0.00015 x 10^6 ml/min. x 1 g/ml = 0.01875 g O_2/min.

0.01875 g O_2/min. x 1/0.21 x 1 ℓ/1.06 g air x 1/0.08 x 60 min./h = 63 ℓ/hr

Appendix D

Cost Data

Assumptions for estimating costs of filters

1) Use EPA cost curves for dual media filters. (EPA 1980, Innovative and Alternative Technology Assessment Manual)
2) Use ENR cost index 3357 (November 1980).
3) To enter EPA construction cost curves, multiply flows by 4 for worst case and by 2 for best case to account for different filter loading rates.
4) Add cost of activated carbon media; ignore cost of sand and anthracite (used to make up cost of influent feed modifications).
5) Carbon cost equal for best and worst case.
6) Add cost to epoxy line concrete structures.
7) Add cost of forced draft blowers.

Activated carbon requirements

- Assume: 0.046 lbs/gal (5.5 g/l)
- Mass Required per MGD = 46,000 lbs
- A.C. Cost = $0.83/lb, FOB Kentucky

  Use $1.085/lb Installed

FILTRATION, DUAL MEDIA

FACT SHEET 3.1.7

Description - Dual media filtration-gravity is one of the most economical forms of granular media filtration. Granular media filtration involves the passage of water through a bed of filter media with resulting deposition of solids. Eventually, the pressure drop across the bed becomes excessive or the ability of the bed to remove suspended solids is impaired. Cleaning is then necessary to restore operating head and effluent quality. The time in service between cleanings is termed the run length. The head loss at which filtration is interrupted for cleaning is called the terminal head loss, and this head loss is maximized by the judicious choice of media sizes.

Dual media filtration involves the use of both sand and anthracite as filter media, with anthracite being placed on top of the sand. Gravity filters operate by either using the available head from the previous treatment unit, or by pumping to a flow split box after which the wastewater flows by gravity to the filter cells. Pressure filters utilize pumping to increase the available head.

Normally filter systems include multiple filter compartments. This allows for the filtration system to continue to operate while one compartment is being backwashed.

A filter unit generally consists of a containing vessel, the filter media, structures to support the media, distribution and collection devices for influent, effluent and backwash water flows, supplemental cleaning devices (see "Common Modifications"), and necessary controls for flows, water levels and backwash sequencing.

Common Modifications - Filtration systems can be constructed out of concrete or steel, with single or multiple compartment units. Steel units can be either horizontal or vertical and are generally used for pressure filters. Systems can be manually or automatically operated.

Backwash sequences can include air scour or surface wash steps. Backwash water can be stored separately or in chambers that are integral parts of the filter unit. Backwash water can be pumped through the unit or can be supplied through gravity head tanks.

Technology Status - Has been used for many years in the potable water industry, and has been used in the wastewater treatment field for 10 to 15 years.

Typical Equipment/No. of Mfrs. (23) - Dual media filters/20; blowers/7; controls/29.

Applications - Removal of residual biological floc in settled effluents from secondary treatment and removal of residual chemical-biological floc after alum, iron, or lime precipitation in tertiary or independent physical-chemical waste treatment.

In these applications filtration may serve both as an intermediate process to prepare wastewater for further treatment (such as carbon adsorption, clinoptilolite ammonia exchange columns, or reverse osmosis) or as a final polishing step following other processes.

Limitations - Economics are highly dependent on consistent pretreatment quality and flow modulations. Increasing suspended solids loading will reduce run lengths, and large flow variations will deleteriously effect effluent quality in chemical treatment sequences.

Performance -

Filter Influent	Filter Effluent mg/l
High Rate Trickling Filter	10 to 20
2-Stage Trickling Filter	6 to 15
Contact Stabilization	6 to 15
Conventional Activated Sludge	3 to 10
Extended Aeration	1 to 5

Chemicals Required - Alum and iron salts, and polymers can be added as coagulant aids directly ahead of filtration units. This, however, will generally reduce run lengths.

Residuals Generated - Backwash water, which generally approximates two to ten percent of the throughput. Backwash water can be returned to the head of the plant.

Design Criteria (99) -
Filtration rate 2 to 8 gal/min/ft^2; bed depth 24 to 48 inches (depth ratios of 1:1-4:1 sand to anthracite); backwash rate 15 to 25 gal/min/ft^2; air scour rate 3 to 5 stdft^3/min/ft^2; filter run length 8 to 48 hours; terminal head loss 6 to 15 ft.

Unit Process Reliability- Dual media filtration systems are very reliable from both a process and unit standpoint.

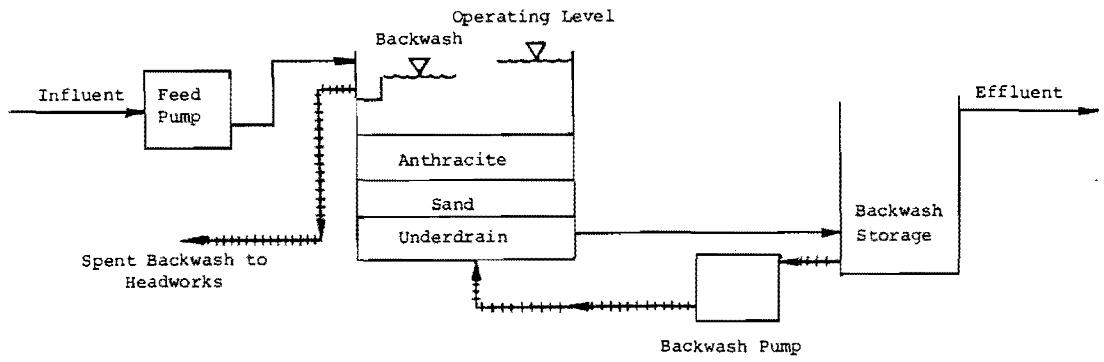
Environmental Impact - Requires relatively little use of land. Backwash water will need further treatment, with an ultimate production of solids which will need disposal. Air scour blowers usually need silencers to control noise. No air pollution generated.

References - 23 26, 39, 44, 99

FILTRATION, DUAL MEDIA

FACT SHEET 3.1.7

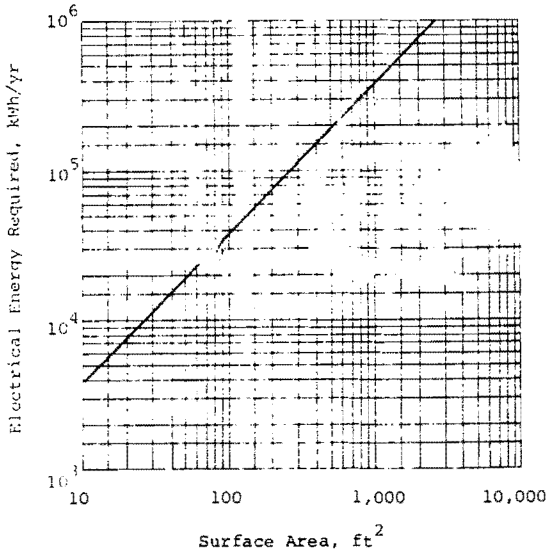
FLOW DIAGRAM -



ENERGY NOTES - If sufficient head available, no influent pumping required. However, usually a feed pump is employed to provide necessary head.

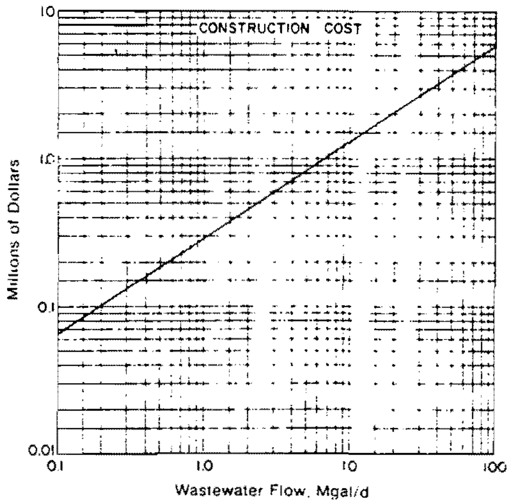
Assumptions:

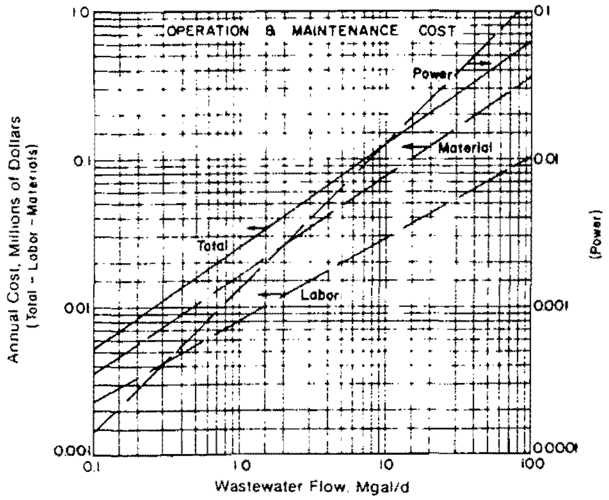
1. Gravity filters @ 4 gal/min/ft^2
   - a. TDH for backwash and feed pumps 14 ft
   - b. Run length = 12 h; 15 min backwash @ 15 gal/min/ft^2
   - c. Pump efficiency 70%; motor efficiency, 93%
2. Centrifugal pumps



COSTS* - Assumptions: ENR Index = 2475

1. Same as above, with air scour assist for backwash
2. Backwash holding tank = capacity of two backwash cycles.
3. Construction cost includes facilities for backwash storage, all feed and backwash pumps, piping, and building.
4. Power at $.02/kWh.
5. Labor at $7.50/h, including fringe benefits.





REFERENCES - 3, 4, 39

*To convert construction cost to capital cost see Table A-2.

Corrosion lining costs, worst case

For 1 MGD,

Assume two filters, 23' sq x 6' deep, ea

Total wall area = (23 x 6) x 8 = 1104 ft^2

Total floor area = (23 x 23) x 2 = 1058

Total = 2162 ft^2

For 10 MGD,

Assume four filters, 74' sq x 6' deep, ea

Total wall area = (74 x 6) x 16 = 7104

Total floor area = (74 x 74) x 4 = 21904

Total = 29000 sq ft

Lining costs, use $10/SF

Double costs to account for lining backwash storage tank

Corrosion lining costs, best case

For 1 MGD,

Assume two filters, 14' sq x 10' deep, ea

Total wall area = (14 x 10) x 8 = 1120 ft^2

Total floor area = (14 x 14) x 2 = 392

Total = 1512 ft^2

For 10 MGD,

Assume four filters, 30' sq x 10' deep, ea

Total wall area = (30 x 10) x 16 = 4800

Total floor area = (30 x 30) x 4 = 3600

Total = 8400 ft^2

Lining costs, use $5/SF

Double costs to include backwash storage tank

1) Horsepower requirements for blowers

Headloss through activated carbon by air

Superficial Velocity fpm	Headloss in. of water per foot of bed
10	2
20	4.2
50	11.5
100	28

Air Flow cfm	Media Area ft^2	Velocity fpm	H_L, in. of Water			H_L psi	HP
			Media	Water Flow	Total*		
750	347	2.2	2	60	64	2.4	10
7500	3470	2.2	2	60	64	2.4	100
1500	1080	1.4	0.5	20	21	0.8	10
15000	10800	1.4	0.5	20	21	0.8	100

*Assume underdrain headloss = 2 x media H_L

2) Annual power cost for blowers

kw*	kwh/yr**	$
10	87600	5700
100	876000	57000

*Assume: 90% motor eff.

85% power factor

$\therefore$ 1 HP ≅ 1 kw

**24 hrs/day, 365 days/yr

Table D-1. Summary of capital costs for sulfur dioxide disinfection systems.*

Unit	Best Case		Worst Case	
	1 MGD ($)	10 MGD ($)	1 MGD ($)	10 MGD ($)
1. SO$_2$ Equipment including installation	20,000	20,000	20,000	20,000
2. Absorption Tower complete w/fan				
a. Equipment	22,983	190,561	28,728	236,551
b. Installation	4,596	38,112	11,491	94,620
3. Contact Basin (30 min)				
a. Materials including lining	16,169	150,080	30,518	281,960
b. Installation, miscellaneous	4,850	45,024	15,259	140,980
4. Pumps				
a. Absorption tower pump	3,000	3,000	3,000	3,000
5. Oxidation Process, complete	687,100	3,352,600	1,065,200	5,393,200
6. Lime Process				
a. Equipment	46,250	73,550	75,050	84,050
b. Installation	9,250	14,710	37,525	42,025
SUBTOTAL	$814,198	$3,887,637	$1,286,771	$6,296,386
7. Electrical & Piping	162,840	777,527	312,693	1,574,096
TOTAL CAPITAL**	$997,000	$4,665,000	$1,608,000	$7,870,000

*Nielsen, Maxwell & Wangsgard-Montgomery. 1981. Preliminary report for sulfur dioxide disinfection pilot plant.

**Values rounded to nearest $1,000.

Table D-2. Summary of O&M costs for sulfur dioxide disinfection systems excluding SO_2 oxidation.

Item	Best Case		Worst Case	
	1 MGD ($)	10 MGD ($)	1 MGD ($)	10 MGD ($)
Chemicals	15,464	154,640	57,904	579,040
Power	7,457	81,936	12,752	134,857
Maintenance	3,049	12,841	8,309	33,869
Labor	3,300	4,620	5,665	25,800
Σ O&M	$29,270	$254,037	$84,630	$773,566