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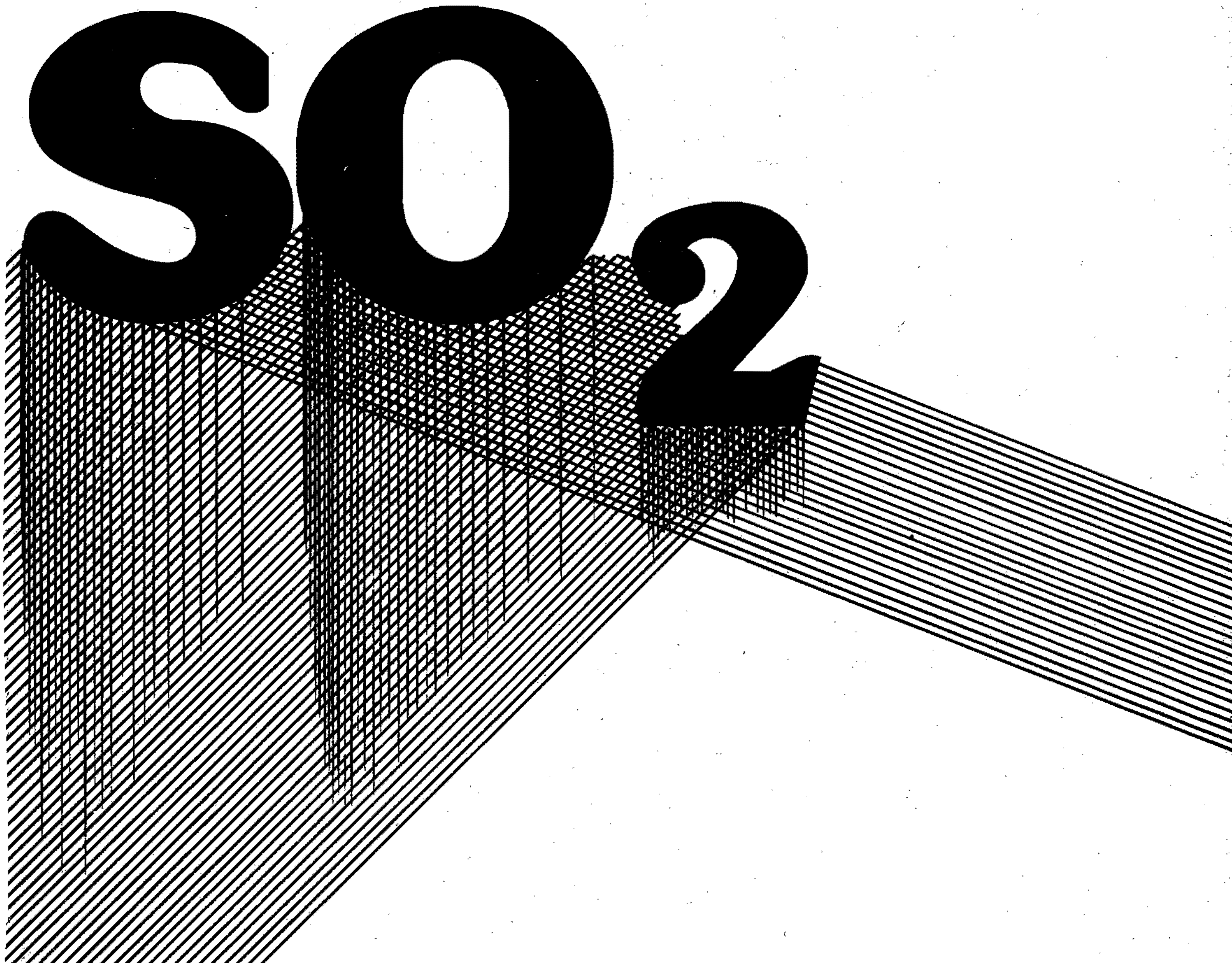

Report to:

International Environmental, Inc.
Salt Lake City, Utah

pH NEUTRALIZATION AND PHOSPHORUS REMOVAL FROM A SULFUR DIOXIDE (SO_2) TREATED WASTEWATER USING LIME ($Ca(OH)_2$) ADDITION

by

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Report to

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Submitted by

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Phosphorus Removal

Use of lime for the treatment of wastewater dates back to the mid-1880s. It was observed that calcium formed a precipitate both with hardness and with phosphates (EPA 1976).

There is extensive literature dealing with phosphorus precipitation and adsorption associated with lime addition. Metcalf and Eddy (1979) stated that phosphorus is removed from the liquid phase through a combination of precipitation, adsorption, exchange, and agglomeration. The two primary mechanisms, precipitation and adsorption, are discussed below.

Metcalf and Eddy (1979) described the mechanism of calcium phosphate (apatite) precipitation associated with lime addition in wastewater. When lime is added to water it reacts with the natural bicarbonate alkalinity to precipitate $CaCO_3$:

$$Ca(OH)_2 + H_2CO_3 \rightleftharpoons CaCO_3 + 2H_2O \quad \quad (1)$$

$$Ca(OH)_2 + Ca(HCO_3)_2 \rightleftharpoons 2CaCO_3 + 2H_2O \quad \quad (2)$$

When calcium ions are added in excess of what is required to react with the natural bicarbonate alkalinity (reactions in Equations 1 and 2) the excess calcium ions will then react with phosphate, as shown in Equation 3, to precipitate hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$:

$$10Ca^{+2} + 6PO_4^{-3} + 2OH^- \rightleftharpoons Ca_{10}(PO_4)_6(OH)_2 \quad \quad (3)$$

Therefore, the quantity of lime required will, in general, be independent of the amount of phosphate present and will depend primarily on the alkalinity of the wastewater. In low-alkalinity wastewaters, smaller quantities of lime are required for neutralization and phosphorus precipitation, with smaller quantities of sludge being formed.

A number of studies have been performed dealing with phosphorus adsorption onto calcium carbonate crystals (i.e., calcite). Boischot et al. (1950) found surface adsorption of phosphorus on calcium carbonate particles at low concentrations, and a precipitation reaction at higher concentrations. Cole et al. (1953) investigated calcium carbonate-phosphorus interactions by placing crystalline calcium carbonate in a range of phosphate concentrations. They found that at low phosphate concentrations, phosphate adsorption was proportional to the concentration of calcium carbonate. At high concentrations of phosphate the amount of phosphate adsorbed was not a function of the amount of calcium carbonate present. However, this reaction proceeded until phosphate levels were reduced below a critical value. Cole et al. (1953) concluded that at low phosphate concentrations a monolayer of phosphorus was adsorbed on the calcium carbonate surface, and theorized that at high phosphate concentrations, calcium carbonate acted as a calcium source for the precipitation of calcium phosphate. The transition between the monolayer adsorption and calcium phosphate precipitation generally occurred at a concentration of 3×10^{-4} M phosphate, but was found to vary with pH.

Griffin and Jurinak (1973) found two regions in their Langmuir adsorption isotherm plots dealing with phosphorus adsorption onto calcite, and concluded that phosphorus adsorption occurred as a multilayer phenomenon on the calcite surface. Griffin and Jurinak (1973) also concluded that the type of nucleation which formed on the calcite surface is dependent upon the calcium to phosphorus ratio and the various species of calcium phosphate. They further found that if the concentrations of phosphate and calcium are high enough that the solubility product of dicalcium phosphate is exceeded, this specie will form on the calcite surface by the process of heterogeneous nucleation. An intermediate phosphate concentration that does not exceed the solubility product of dicalcium phosphate will result in the nucleation of octacalcium phosphate on the calcium carbonate surface. When neither the solubility product of dicalcium phosphate nor octacalcium phosphate are exceeded, hydroxyapatite is formed on the calcite surface.

An experimental investigation using lime treatment of raw wastewater to remove phosphorus was carried out in New York. Feeding 300 mg/l of slaked lime to a domestic wastewater removed 94 percent of the phosphorus to an effluent concentration of 0.6 mg/l, reduced suspended solids (SS) by 95 percent to 4 mg/l, and reduced the biochemical oxygen demand (BOD) by 71 percent to an average of 101 mg/l (Karanik and Nemerow 1965).

King et al. (1979) discussed the use of alum, iron chloride, and lime for phosphorus removal prior to primary sedimentation and as a tertiary treatment application. In all cases, the effluent total phosphorus was below 1.0 mg/l.

Ketchum and Liao (1979) showed phosphorus removal in excess of 90 percent in a synthetic wastewater using a lime dose of 80 mg/l.

A number of other studies have also established that lime addition to wastewater is a viable process for phosphorus removal, but large quantities of chemical sludges are formed in the process.

Lime Requirements for Neutralization of SO_2 Treated Wastewater

Addition of lime to SO_2 treated wastewater appears to be a potential method for raising the pH of the treated wastewater and also give an additional benefit of phosphorus removal. A series of experiments were designed to determine the amount of lime required to raise SO_2 treated wastewater at a low pH to a neutral pH. Additional lime was also added to raise the pH to higher values to determine phosphorus removal and sludge production.

Methods and Procedures

Wastewater was collected between 8:30 AM and 9:30 AM the morning of the experimental run from the secondary clarifier of the Hyrum City wastewater treatment plant. The sulfur dioxide source was concentrated sulfurous acid (H_2SO_3) titrated to determine the concentration of H_2SO_3 as SO_2 (APHA; Standard Methods, 1975, p. 508). Secondary effluent (1000 ml) was poured into 2 ℓ beakers and sulfurous acid was added to a final concentration of 500 mg/l $SO_2 \pm 10$ percent. The pH of the sample was then adjusted to the desired pH using 25 percent HCl or a 5N NaOH solution. The sample was then titrated to neutral pH with a 15 g/l $Ca(OH)_2$ slurry. The titration was made as quickly as possible to avoid settling of the $Ca(OH)_2$ in the buret. Later experiments performed used a less concentrated slurry due to operational problems. When the desired pH was reached the sample was stirred using a conventional jar test stirrer at 20 rpm for 20 minutes. After stirring, the mixture was allowed to settle for 30 minutes after which total phosphorus (APHA 1975) was measured on the supernatant. The sludge produced was measured on the remaining solution and solids using vacuum filtration and gravimetric procedures (APHA 1975).

Results and Discussion

The neutralization and phosphorus removal experiment was performed 13 times (data in the Appendix). Due to error and operation problems some of the replicate experiments were not used in calculating the mean lime ($Ca(OH)_2$) neutralization requirements.

The mean lime requirement data listed in Table 1, and expressed in mg/l $Ca(OH)_2$, indicate that when wastewater samples treated with 500 mg/l SO_2 and pH adjusted to 2 are neutralized with lime a large quantity of lime is required. These values include 670 mg/l lime and 742 mg/l lime for pH adjustments from 2 → 6.5 and 2 → 7, respectively. When the pH was raised above 7, successively higher amounts of lime were required to reach higher pH levels. For example, approximately 60 mg/l lime were required to reach pH 8 over pH 7, approximately 80 mg/l lime were required to reach pH 9 over pH 8, and about 20 mg/l lime were required to reach pH 10 over pH 9.

Approximately half the amount of lime was required to reach neutrality when wastewater samples treated with 500 mg/l SO_2 were initially pH adjusted to 2.5 rather than pH 2.0. Mean values for reaching neutrality with lime were 306 mg/l and 366 mg/l when the pH adjustments were

Table 1. Mean lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted.

Initial Adjusted pH of SO_2 Treated Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Mean Lime Requirement (mg/l $Ca(OH)_2$)
2	6.5	670 (6)[a]
2	7	742 (9)
2	8	800 (9)
2	9	876 (9)
2	10	893 (3)
2.5	6.5	306 (6)
2.5	7	366 (9)
2.5	8	431 (9)
2.5	9	481 (9)
2.5	10	523 (9)
3.5	6.5	133 (6)
3.5	7	203 (6)
3.5	8	276 (6)
3.5	9	346 (6)

[a]The numbers in parentheses are the number of data points used in determining the mean values.

2.5 → 6.5 and 2.5 → 7, respectively. Approximately 50 mg/l lime were required to reach each successive pH unit above 7.

A substantial decrease of approximately 43 percent of the lime requirement was noted when the wastewater sample treated with 500 mg/l SO_2 was pH adjusted to 3.5 instead of 2.5. The lime requirement for the pH adjustment 3.5 → 6.5 was 133 mg/l lime. The pH adjustment of 3.5 → 7 required a significant increase in lime to 203 mg/l.

It appears that near pH 2 SO_2 and other weak acids act as buffers, resisting a change to higher pH by $Ca(OH)_2$ when it is added. However, near pH 3.5 there is little buffering capacity, and $Ca(OH)_2$, when added, quickly raises the pH.

Phosphorus remaining in solution and removal data for the experimental runs of June 11, 16, and 23 are shown in Tables 2 and 3. Figures 1 and 2 indicate that very little phosphorus was removed when lime was added to pH 6.5 and pH 7. However, when lime was added to pH 8 approximately 2 mg/l total phosphorus was removed, with approximately 1 mg/l total phosphorus remaining. When the pH was raised to 9 with lime,

Table 2. Phosphorus remaining in the supernatant from SO_2 treated wastewater following lime treatment.

Initial Adjusted pH of SO_2 Treated Wastewater	pH of SO_2 Treated Wastewater by Lime Addition	Total Phosphorus in Supernatant (mg/l TP)			
		June 11, 1980	June 16, 1980	June 23, 1980	Mean
2	6.5	2.99	3.27	3.10	3.12
2	7	2.54	2.93	2.86	2.78
2	8	0.69	0.833	0.549	0.69
2	9	0.130	0.104	0.092	0.109
2.5	6.5	2.78	3.08	3.16	3.01
2.5	7	2.57	3.10	2.99	2.89
2.5	8	1.10	0.961	0.797	0.953
2.5	9	0.124	0.162	0	0.143
3.5	6.5	2.82	3.21	3.24	0.09
3.5	7	2.80	3.23	3.13	3.05
3.5	8	1.32	1.30	1.24	1.29
3.5	9	0.280	0.241	0.180	0.23
Secondary Sewage		3.02	3.44	3.54	3.33

Table 3. Phosphorus removed from SO_2 treated wastewater following lime treatment (using data in Table 2 and initial total phosphorus values).

Initial Adjusted pH of SO_2 Treated Wastewater	pH of SO_2 Treated Wastewater by Lime Addition	Total Phosphorus Removed (mg/l TP)			
		June 11, 1980	June 16, 1980	June 23, 1980	Mean
2	6.5	0.03	0.17	0.44	0.21
2	7	0.48	0.51	0.68	0.56
2	8	2.33	2.61	2.99	2.64
2	9	2.89	3.34	3.45	3.23
2.5	6.5	0.24	0.36	0.38	0.33
2.5	7	0.45	0.34	0.55	0.45
2.5	8	1.92	2.48	2.74	2.38
2.5	9	2.90	3.28		3.09
3.5	6.5	0.2	0.23	0.3	0.24
3.5	7	0.22	0.21	0.41	0.28
3.5	8	1.7	2.14	2.3	2.05
3.5	9	2.74	3.20	3.36	3.1

greater than 90 percent of the total phosphorus was removed with mean values of 0.109 mg/l TP, 0.143 mg/l TP, and 0.23 mg/l TP remaining for samples with initial pH adjustments of 2.0, 2.5, and 3.5, respectively. Data in Appendix Table A-14 give the mean total phosphorus remaining in the supernatant of from five to eight experimental runs. The trends are similar to those shown in Table 2.

Sludge production data from the experimental runs of June 11, 16, and 23 are presented in Table 4 and Figure 3. Small amounts of sludge production occurred as lime was added to pH 6.5 and pH 7. At pH 8, however, 80-90 mg/l sludge was formed (depending upon initial pH adjustment of titration) and at pH 9 approximately 200 mg/l to

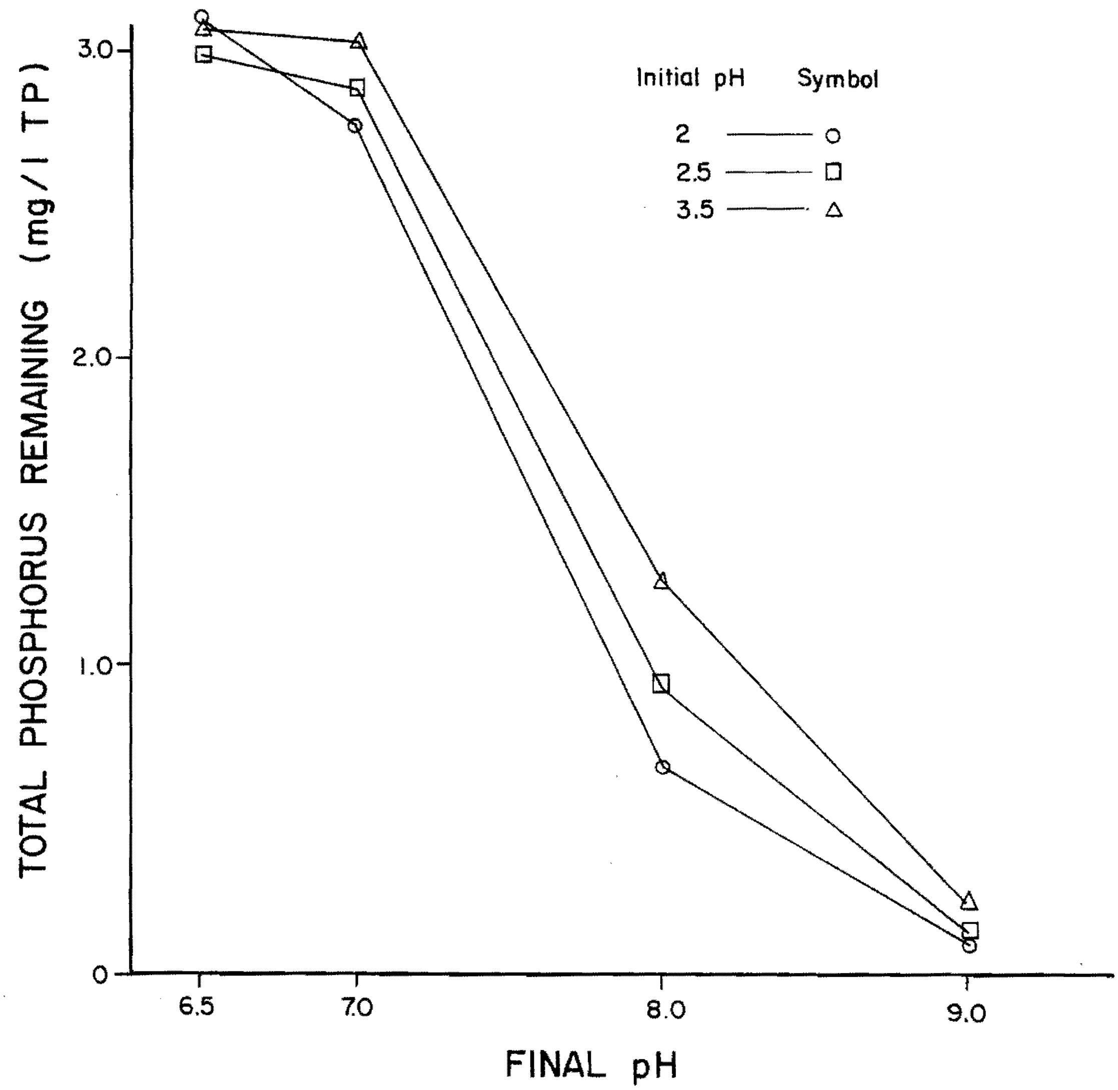

Figure 1. Total phosphorus remaining in the SO_2 treated wastewater vs final pH as a function of lime addition (mean values plotted from data Table 2 where n = 3).

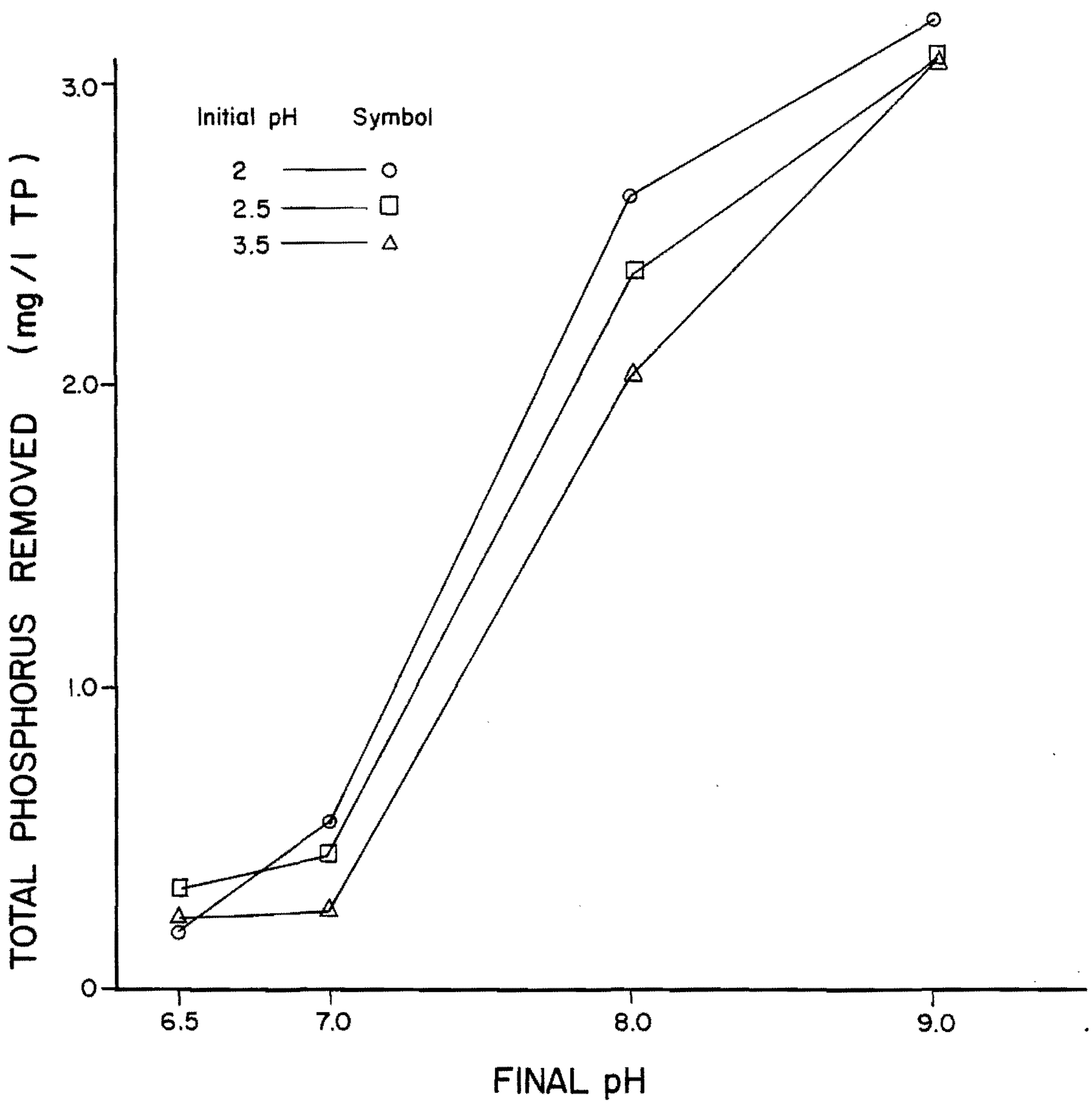

Figure 2. Total phosphorus removed from the SO_2 treated wastewater vs final pH after lime addition (mean values plotted from data Table 3 where n = 3).

Table 4. Sludge production from lime ($Ca(OH)_2$) addition to SO_2 treated (500 mg/l SO_2) wastewater.

Initial Adjusted pH of SO_2 Treated Wastewater	pH of SO_2 Treated Wastewater by Lime Addition	Sludge Production (mg/l)			
		June 11, 1980	June 16, 1980	June 23, 1980	Mean
2	6.5	0.10	1.8	1.5	1.1
2	7	6.7	6.7	3.7	5.7
2	8	89.9	82.0	101	90.8
2	9	292	215	309	272
2.5	6.5	0	0	1.0	0.33
2.5	7	11.5	8.1	1.6	7.1
2.5	8	73.7	107	92.3	91.1
2.5	9	290	195	266	250
3.5	6.5	0	0	0.2	0.07
3.5	7	0	2.9	3.0	2.0
3.5	8	74.3	95.4	67.5	79.1
3.5	9	200	214	179	198

270 mg/l sludge was formed. Treatments where lime titration began at pH 2.0 experienced higher sludge production than those started at pH 2.5. Similarly, treatments where lime titration began at pH 2.5 formed more sludge than those started at pH 3.5.

Mean data in Appendix Table A-14 for sludge production indicate that little sludge is formed in neutralization of SO_2 treated wastewater for all initial pH values to 6.5 or 7.0. Sludge production upon raising the pH to 8.0 or 9.0 gives values of approximately 70 mg/l and 170 mg/l of sludge, respectively. There appears to be little difference in the amount of sludge produced whether the initial pH was pH 2 or pH 3.5.

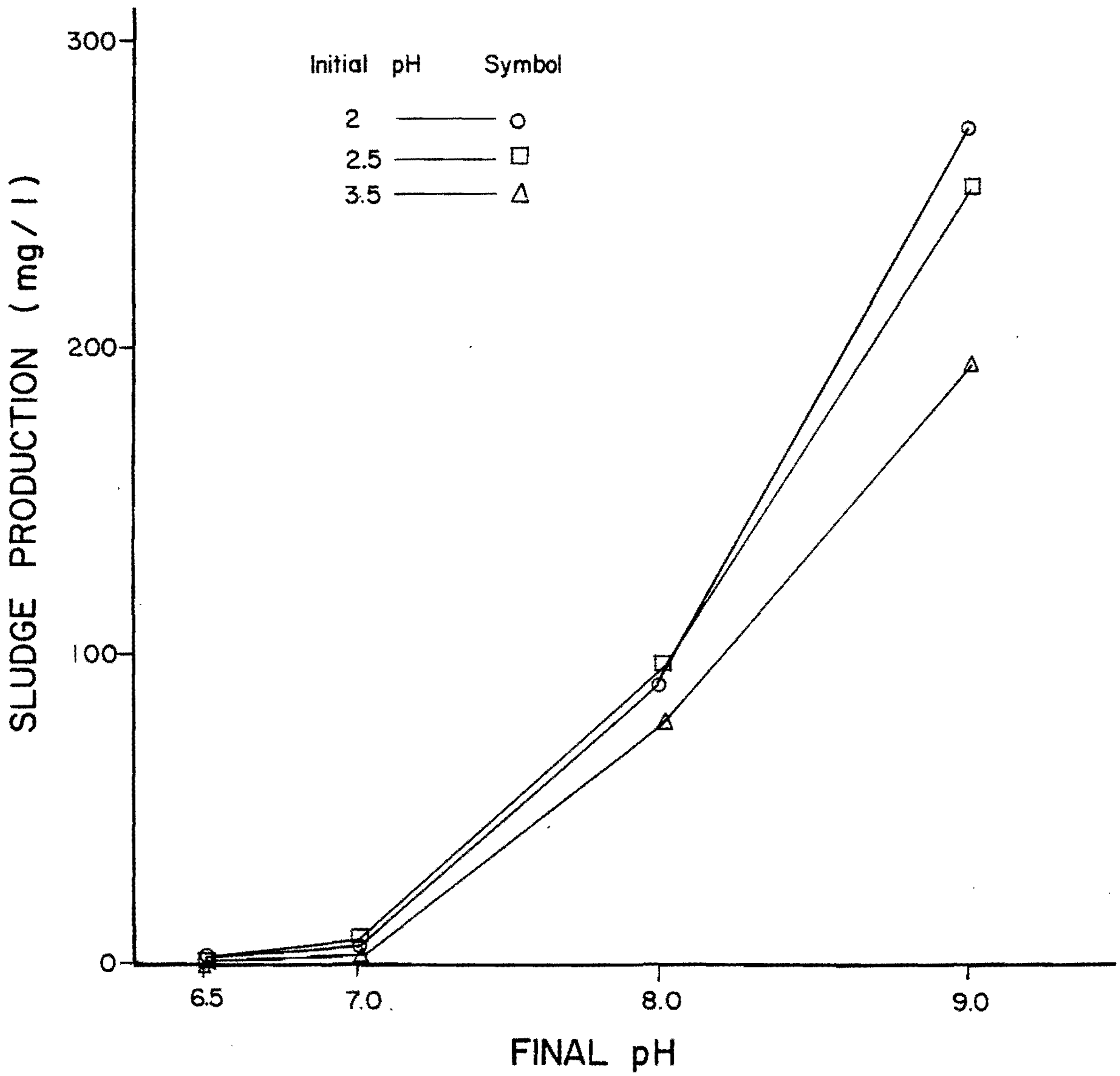

Figure 3. Sludge produced vs final pH after lime addition to SO_2 treated wastewater.

The phosphorus removal graph (Figure 2) and the sludge production graph (Figure 3) are quite similar. This suggests that phosphorus removal is closely associated with the sludge produced, possibly hydroxyapatite precipitation (Metcalf and Eddy 1979) and/or adsorption of phosphorus onto calcite particles (Griffin and Jurinak 1973). As lime was added to the wastewater to neutralize H_2SO_3 to HSO_3^- and $SO_3^=$, calcium carbonate precipitated as lime reacted with H_2SO_3 and the "natural alkalinity" as depicted by Equations 1 and 2. Various species of phosphorus may be adsorbed onto these calcium carbonate crystals (Griffin and Jurinak 1973). As the "natural alkalinity" was consumed by the reaction with calcium, hydroxyapatite precipitated, removing larger quantities of phosphorus. The pK_{a2} of the carbonate equilibrium system, as shown in Equation 4, regulates the mole fraction of $CO_3^=$ in solution relative to other carbonate species. This value is generally pH 8.3

$$HCO_3^- + OH^- \rightleftarrows CO_3^= + H_2O \qquad \ldots\ldots\ldots\ldots \quad (4)$$

$pK_a = 8.3$ (Sawyer and McCarty 1978). This pH must be approached for efficient $CaCO_3$ formation. Thus there is little sludge production and, consequently, little phosphorus removal at the more neutral pH values.

In summary, as lime was added to wastewater treated with 500 mg/l SO_2, calcium carbonate, calcium sulfite, or calcium sulfate appear to be formed as the pH is raised. This resulted in high sludge formation. Concomitant with the sludge formation, however, was adsorption of phosphorus species onto the calcium carbonate or other crystals and hydroxyapatite formation may have occurred after the natural alkalinity in the wastewater was consumed. Thus, phosphorus removal is achieved only at the expense of the copious sludge production. Metcalf and Eddy (1979), in response to such a problem, stated that the use of lime for phosphorus removal is limited because lime produced low phosphorus levels only at high pH values.

Conclusions

Conclusions reached in this study are:

1) When pH-adjusted SO_2 is titrated to neutrality with lime 100 percent more lime is required when beginning the titration at pH 2.0 instead of pH 2.5. Over 100 percent more lime is required when titrating from pH 2.5 instead of pH 3.5.

2) Phosphorus removal is most prevalent when the wastewater solution is titrated to pH 9, with very little phosphorus removal occurring at pH 6.5 and pH 7.

3) There is little sludge produced when lime titrations proceed to pH 6.5 and pH 7. However, succeedingly increasing amounts of sludge are formed at pH 8 and pH 9.

4) Phosphorus removal appears to be intimately associated with sludge production.

5) There is little difference in the amount of sludge produced during lime treatment of SO_2 treated wastewater whether the initial pH was pH 2 or pH 3.5.

Future Required Studies

Important studies required for the future includes:

1) Evaluate the bicarbonate-carbonate-alkalinity system with respect to sulfur dioxide addition to wastewater.

2) Determine if after SO_2 addition to wastewater and air stripping there remains any "natural alkalinity."

3) Determine lime requirements of SO_2 treated and air stripped wastewater.

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APPENDIX

Table A-1.* Lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted (April 4, 1980). Data for the total phosphorus remaining in solution and the sludge produced after lime treatment are also presented.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	7	382	2.98	16.5
2	8	518	1.90	62.7
2	9	540	0.650	142
2	10	738	0.110	493
2.5	7	225	3.11	17.2
2.5	8	242	1.95	101
2.5	9	585	0.699	254
2.5	10	471	0.202	489
Secondary Sewage Alkalinity 255 mg/l as $CaCO_3$			3.18	

*Data not used in mean calculation of lime requirements, total phosphorus or sludge produced.

Table A-2. Lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted (April 8, 1980). Data for the total phosphorus remaining in solution and the sludge produced after lime treatment are also presented.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	7	805	5.62	9.7
2	8	880	2.12	58.1
2	9	930	0.762	110
2	10	994	0.097	392
2.5	7	410	5.96	11.3
2.5	8	462	2.72	92.0
2.5	9	529	0.911	100
2.5	10	624	0.526	312
Secondary Sewage Alkalinity 288 mg/l as $CaCO_3$			6.16	

Table A-3. Lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted (April 9, 1980). Data for the total phosphorus remaining in solution and the sludge produced after lime treatment are also presented.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	7	638	7.50	17.6
2	8	730	4.08	93.1
2	9	791	0.298	163
2	10	837	0	502
2.5	7	384	8.11	9.2
2.5	8	457	5.43	48.0
2.5	9	488	0.358	199
2.5	10	540	0.103	486
Secondary Sewage Alkalinity 287 mg/l as $CaCO_3$			8.32	

Table A-4.* Lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted (April 15, 1980). Data for the total phosphorus remaining in solution and the sludge produced after lime treatment are also presented.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	7	244	3.25	
2	8	304	3.03	
2	9	285	1.06	
2	10	321	0.228	
2.5	7	165	3.16	
2.5	8	286	2.97	
2.5	9	178	2.01	
2.5	10	410	2.52	
3.5	7	93.0		
3.5	8	118.5		
3.5	9	135.0		
3.5	10	163.5		
Secondary Sewage Alkalinity 286 mg/l as $CaCO_3$			3.40	

*Data not used in mean calculation of lime requirements, total phosphorus or sludge produced.

Table A-5.* Lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted (April 16, 1980). Data for the total phosphorus remaining in solution and the sludge produced after lime treatment are also presented.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	7	1878	3.40	3.6
2	8	1900	1.78	59.7
2	9	1845	0.302	112
2	10	1957	0.290	253
2.5	7	802	3.54	3.0
2.5	8	890	2.74	62.1
2.5	9	622	0.648	97.8
2.5	10	825	0.108	190
Secondary Sewage Alkalinity 305 mg/l as $CaCO_3$			4.08	

*Data not used in mean calculation of lime requirements, total phosphorus or sludge produced.

Table A-6.* Lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted (April 18, 1980). Data for the total phosphorus remaining in solution and the sludge produced after lime treatment are also presented.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	7	975	5.74	
2	8	1032	1.36	
2	9	1117	0.064	
2	10	1275	0.061	
2.5	7	466	6.79	
2.5	8	541	0.467	
2.5	9	616	0.169	
2.5	10	776	0.095	
Secondary Sewage Alkalinity 310 mg/l as $CaCO_3$			8.30	

*Data not used in mean calculation of lime requirements, total phosphorus or sludge produced.

Table A-7. Lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted (April 25, 1980). Data for the total phosphorus remaining in solution and the sludge produced after lime treatment are also presented.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	7	764	2.87	3.7
2	8	789	2.60	13.7
2	9	810	0.276	98.1
2	10	848	0.190	226.0
2.5	7	305	2.90	3.1
2.5	8	350	2.60	40.8
2.5	9	377	0.291	97.6
2.5	10	406	0.151	191
Secondary Sewage		285	3.10	

Table A-8. Lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted (May 16, 1980). Data for the total phosphorus remaining in solution and the sludge produced after lime treatment are also presented.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	6.5	771	2.80	4.4
2	7	798	2.72	13.4
2	8	818	1.18	53.0
2	9	888	0.160	98.1
2.5	6.5	311	3.58	3.1
2.5	7	352	3.15	12.7
2.5	8	388	2.32	40.2
2.5	9	406	0.258	80.5
3.5	6.5	115	3.35	3.3
3.5	7	178	3.35	2.8
3.5	8	226	2.80	36.5
3.5	9	316	0.422	114
Secondary Sewage Alkalinity 273 mg/l as $CaCO_3$			3.58	

Table A-9. Lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted (May 18, 1980). Data for the total phosphorus remaining in solution and the sludge produced after lime treatment are also presented.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	6.5	617	3.10	0
2	7	649	2.98	8.6
2	8	746	1.27	73.4
2	9	908	0.163	222
2.5	6.5	282	3.44	0.6
2.5	7	328	2.35	9.3
2.5	8	346	1.65	61.8
2.5	9	376	0.27	94.4
3.5	6.5	102	3.35	0.1
3.5	7	132	3.17	3.0
3.5	8	214	1.71	51.3
3.5	9	240	0.25	94.3
Secondary Sewage Alkalinity 262 mg/l as $CaCO_3$			3.46	

Table A-10. Lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted (May 19, 1980). Data for the total phosphorus remaining in solution and the sludge produced after lime treatment are also presented.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	6.5	702		
2	7	738		
2	8	756		
2	9	786		
2.5	6.5	274		
2.5	7	308		
2.5	8	341		
2.5	9	366		
3.5	6.5	131		
3.5	7	152		
3.5	8	177		
3.5	9	216		

Secondary Sewage
Alkalinity 278 mg/l as $CaCO_3$

Table A-11. Lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted (June 11, 1980). Data for the total phosphorus remaining in solution and the sludge produced after lime treatment are also presented.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	6.5	641	2.99	0.10
2	7	772	2.54	6.7
2	8	832	0.69	89.9
2	9	930	0.130	292
2.5	6.5	345	2.78	0
2.5	7	399	2.57	11.5
2.5	8	543	1.10	73.7
2.5	9	622	0.124	290
3.5	6.5	144	2.82	0
3.5	7	248	2.80	0
3.5	8	345	1.32	74.3
3.5	9	446	0.280	200
Secondary Sewage			3.02	
Alkalinity 287 mg/l as $CaCO_3$				

Table A-12. Lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted (June 16, 1980). Data for the total phosphorus remaining in solution and the sludge produced after lime treatment are also presented.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	6.5	626	3.27	1.8
2	7	762	2.93	6.7
2	8	796	0.833	82
2	9	921	0.104	215
2.5	6.5	308	3.08	0
2.5	7	435	3.10	8.1
2.5	8	519	0.961	107
2.5	9	585	0.162	195
3.5	6.5	158	3.21	0
3.5	7	270	3.23	2.9
3.5	8	368	1.30	95.4
3.5	9	450	0.241	214
Secondary Sewage Alkalinity 309 mg/l as $CaCO_3$			3.44	

Table A-13. Lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted (June 23, 1980). Data for the total phosphorus remaining in solution and the sludge produced after lime treatment are also presented.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	6.5	662	3.10	1.5
2	7	750	2.86	3.7
2	8	846	0.549	101
2	9	916	0.092	309
2.5	6.5	316	3.16	1.0
2.5	7	378	2.99	1.6
2.5	8	472	0.797	92.3
2.5	9	585	0	266
3.5	6.5	146	3.24	0.2
3.5	7	240	3.13	3.0
3.5	8	324	1.24	67.5
3.5	9	410	0.180	179
Secondary Sewage Alkalinity 302 mg/l as $CaCO_3$			3.54	

Table A-14. Mean lime requirements ($Ca(OH)_2$) for neutralization of secondary wastewater effluent treated with 500 mg/l SO_2 and pH adjusted. Data for the mean total phosphorus remaining in solution and the mean sludge produced after lime treatment are also presented. This is a compilation of all the data in Tables A-1 to A-13 unless otherwise specified.

Initial Adjusted pH of SO_2 Treated (500 mg/l as SO_2) Wastewater	pH of SO_2 Treated Wastewater Neutralized by Lime Addition	Lime Requirement (mg/l $Ca(OH)_2$)	Total Phosphorus in Supernatant (mg/l TP)	Sludge Produced (mg/l)
2	6.5	670 (6)[a]	3.10 (5)	1.6 (5)
2	7.0	742 (9)	2.75 (8)	8.8 (8)
2	8.0	800 (9)	1.66 (8)	70.5 (8)
2	9.0	876 (9)	0.248 (8)	188 (8)
2	10.0	893 (3)	0.096 (3)	382 (3)
2.5	6.5	306 (6)	3.21 (5)	1.0 (5)
2.5	7.0	366 (9)	2.89 (8)	8.4 (8)
2.5	8.0	431 (9)	2.20 (8)	69.5 (8)
2.5	9.0	481 (9)	0.297 (8)	169 (8)
2.5	10.0	523 (3)	0.260 (3)	330 (3)
3.5	6.5	133 (6)	3.19 (5)	0.7 (5)
3.5	7.0	203 (6)	3.14 (5)	2.3 (5)
3.5	8.0	276 (6)	1.67 (5)	65.0 (5)
3.5	9.0	346 (6)	0.275 (5)	160 (5)
Secondary Sewage			4.33 (8)	
Alkalinity 286 mg/l as $CaCO_3$ (9)				

[a]The numbers in parentheses are the number of data points used in determining the mean values.

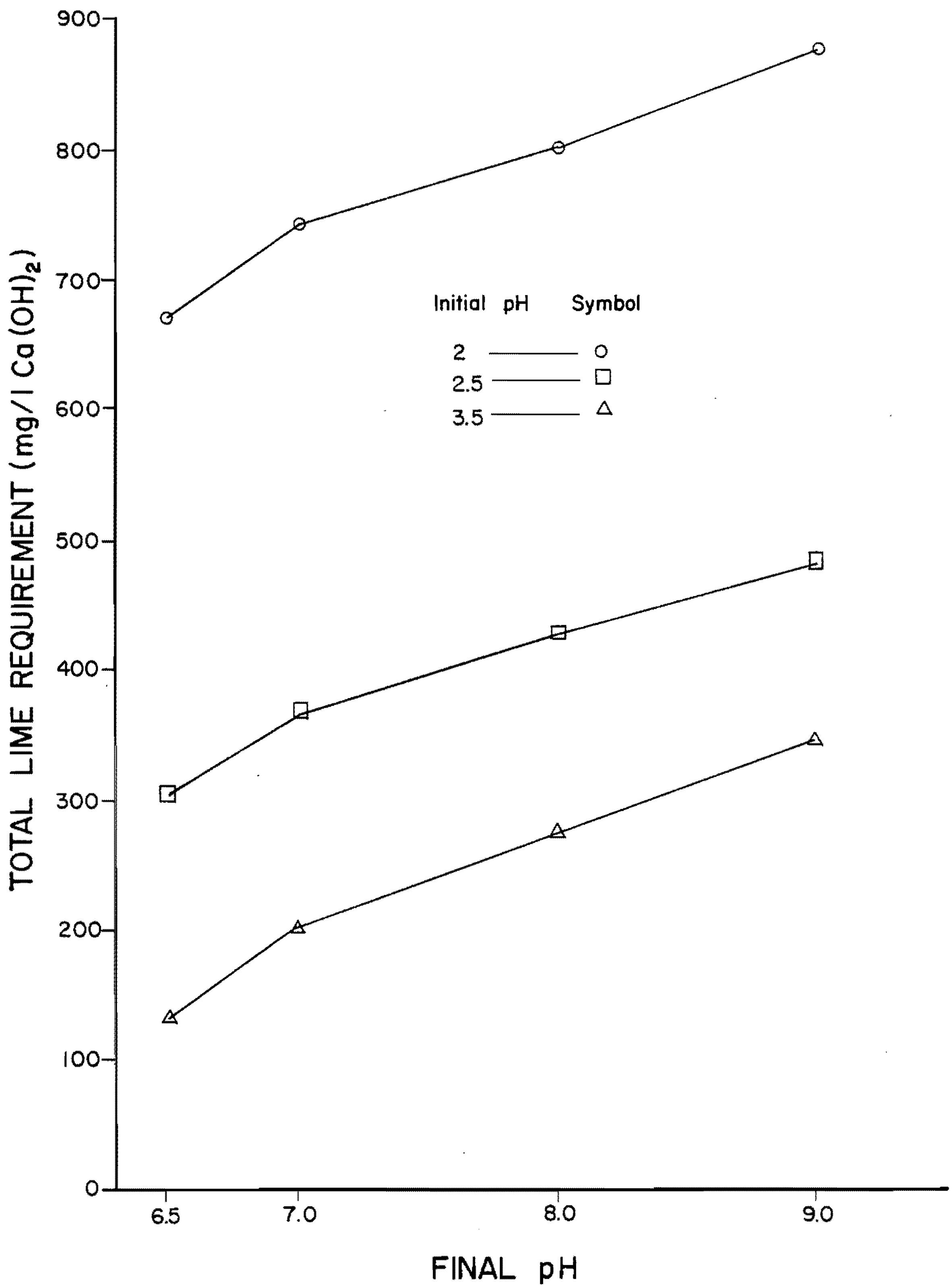

Figure A-1. Mean total lime requirement for neutralization of SO_2 treated wastewater vs final pH (data from Table A-14).

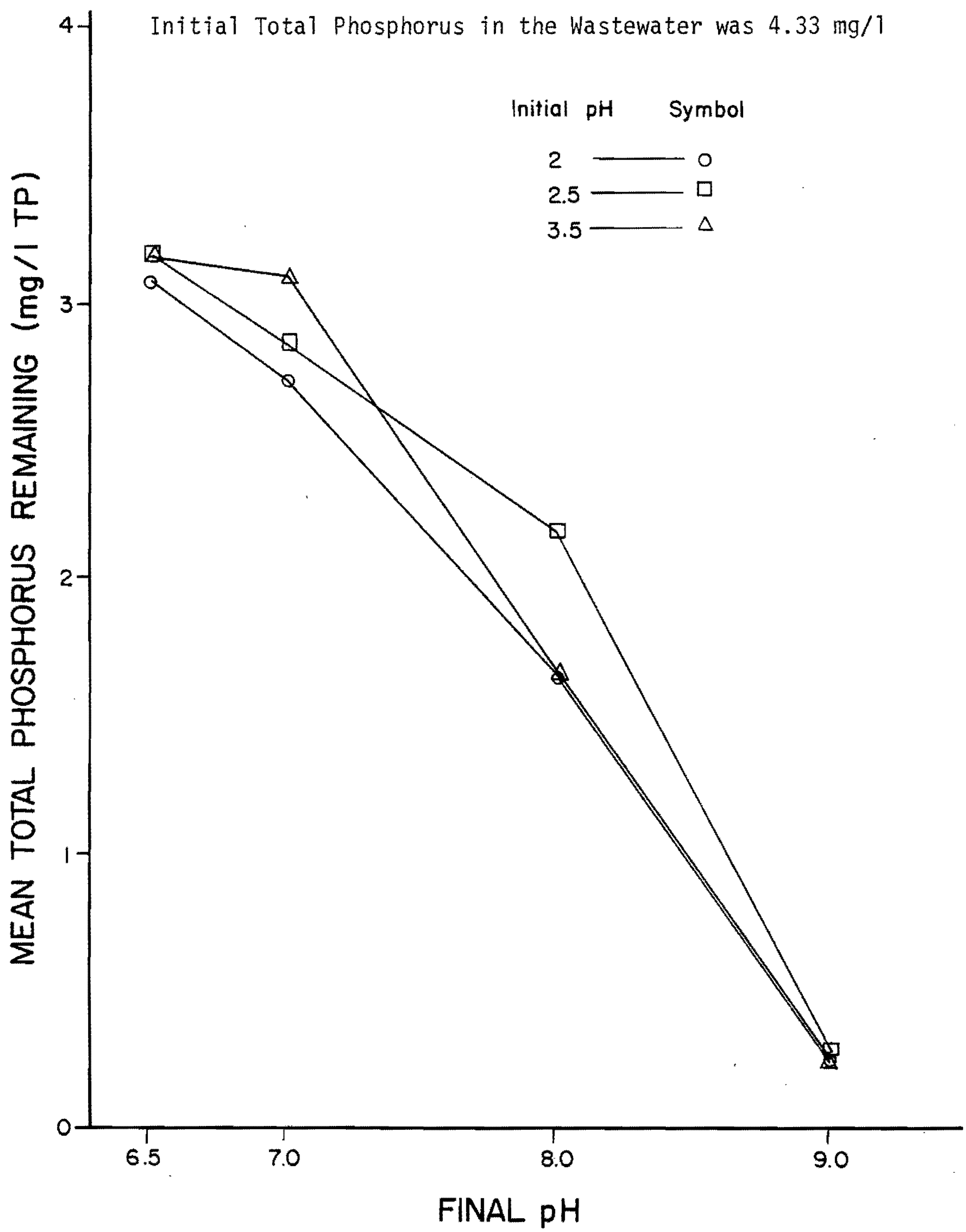

Figure A-2. Mean total phosphorus remaining in the SO_2 treated wastewater vs final pH as a function of lime addition (data from Table A-14).

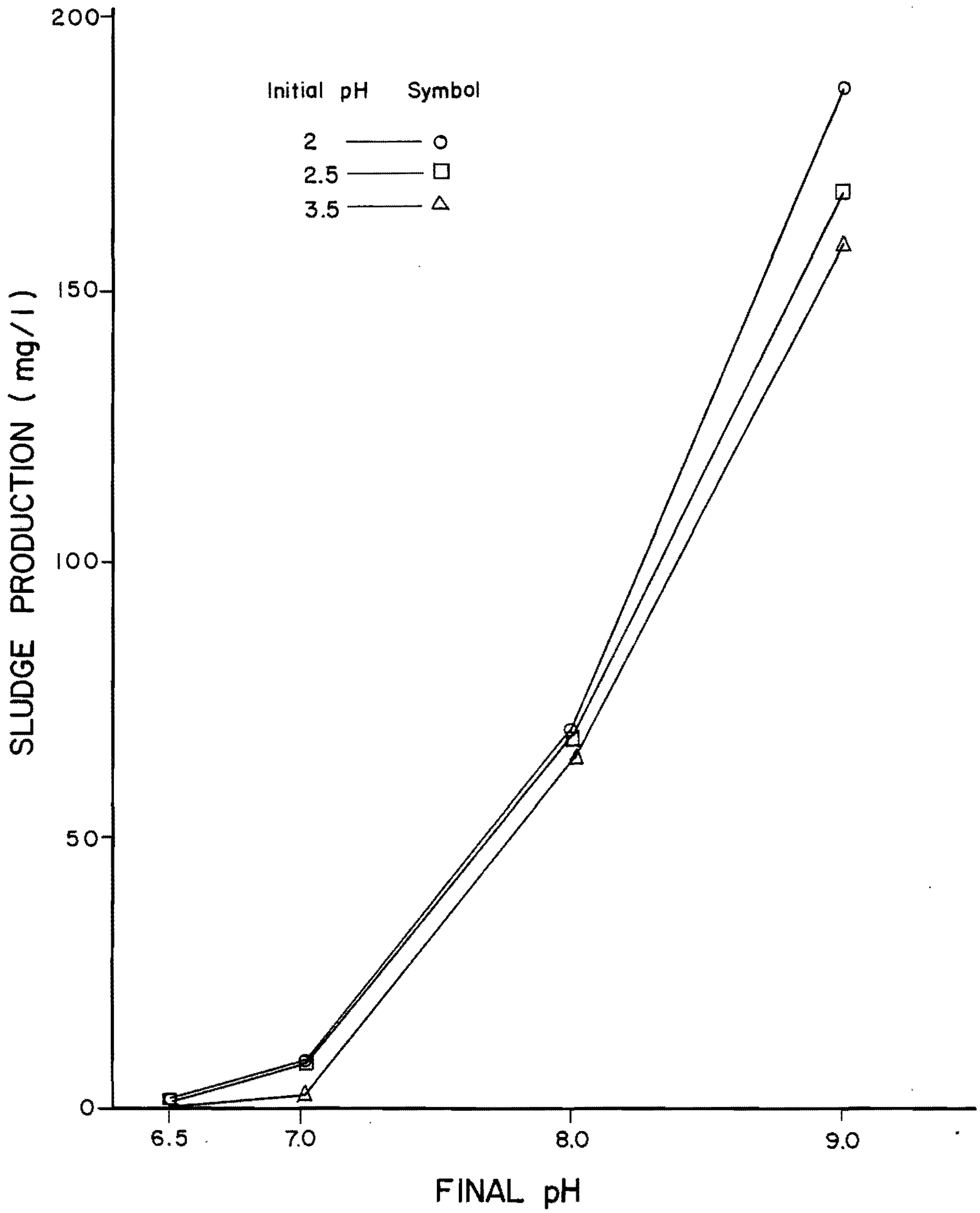

Figure A-3. Mean sludge production vs final pH after lime addition to SO_2 treated wastewater.