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Leaching Rates for the HCl Extraction of Aluminum From Calcined Kaolinitic Clay

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LEACHING RATES FOR THE HCl EXTRACTION OF ALUMINUM FROM CALCINED KAOLINITIC CLAY

By R. S. Olsen,[1] S. J. Bullard,[2] W. G. Gruzensky,[2] R. V. Mrazek,[3]
and J. L. Henry[4]

ABSTRACT

The Bureau of Mines is engaged in research to recover aluminum from kaolinitic clay and other nonbauxitic domestic resources. As part of this work, calcined Georgia kaolin was prepared by a process that prevents slime formation and makes the leached residues fast settling and easy to filter. The leaching reaction for calcined kaolinitic clay in a 5 pct stoichiometric excess of boiling 23- to 26-pct HCl was found to be zero order. Rate constants based on the weight-fraction of aluminum in the clay were found to be between 0.095 and 0.15 min^{-1} depending on feed preparation and leaching parameters. The mathematical relationships between aluminum extraction and time for both batch and continuous, stirred-tank operations were derived and verified experimentally.

INTRODUCTION

The scarcity of bauxite in this country suggests abundant kaolinitic clay as an alternative source of aluminum for metal production. The Bureau of Mines is examining methods for extracting aluminum from kaolinitic clay and other nonbauxitic domestic resources. Determination of the kinetics of leaching kaolinitic clay with hydrochloric acid (HCl) was part of this effort.

A study of leaching rates for calcined kaolin in nitric, sulfuric, and hydrochloric acids was done by Hulbert and Huff.[5] This work was done in batch process at 90° C and below. They made no effort to extend their rate relationships to continuous, stirred-tank leaching. A major objective of the present Bureau of Mines work, therefore, was to determine the kinetics of leaching clay in boiling solutions and to relate the batch process to continuous operations.

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[5] Hulbert, S. F., and D. E. Huff. Kinetics of Alumina Removal From a Calcined Kaolin With Nitric, Sulphuric and Hydrochloric Acids. J. Clay Miner. Group, Miner. Soc., v. 8, No. 3, 1970, pp. 337-345.

PROCEDURES

FEED PREPARATION

Easy separation of leached residues from their pregnant liquors is a key to efficient extraction of aluminum from kaolinitic clay. This objective was attained with development of a clay feed preparation method in which a fine mist of water is applied to the crushed clay prior to calcining.[6] Calcined clays used in the present work were prepared by this misting process, which consisted of the following steps: As-received clay containing about 19 pct free water was crushed by passing through a jaw crusher and then a roll crusher, with progressively closer settings of the rolls. The crushed clay was screened between stages to recover the sized material, usually minus 20 mesh, and to minimize the generation of fines. After crushing and screening, the clay contained about 18 pct free water. The crushed clay then was dampened with a fine mist of water while tumbling on an inclined, rotating disk, to wet the surfaces of the crushed clay but not to form pellets. The misting operation caused any fines to adhere to the larger particles and also caused the rough, feathery surfaces of the larger particles to become smooth and hard after calcining. Misted clay contained about 19.5 pct free water. The misted clay was calcined at 750° C in either a muffle furnace or a continuous, fluidized-bed calciner. In some of the fluidized-bed tests, coal was added with the clay to simulate proposed industrial practice, in which coal would be burned directly in the fluidized bed to provide the necessary heat. Coal additions had no noticeable effect on the quality of the calcined clay other than leaving it dark gray rather than its normal light-yellow color. For this investigation, a typical Georgia kaolin, containing 19.6 to 20.5 pct Al, was obtained from Thiele Kaolin Co., Sandersville, Ga. (Pure kaolinite ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$) contains 20.9 pct Al.)

LEACHING

Leaching tests were conducted in either batch or continuous, stirred-tank reactors. Both batch and continuous tests were done to determine and verify a kinetic model that would describe clay leaching and to demonstrate that extractions in continuous equipment can be predicted from the more easily obtained batch extraction data.

Batch tests were made by adding the calcined clay to 2 L of boiling reagent-grade HCl in a 5-L, round-bottom flask equipped with a heating mantle, a low-speed paddle stirrer, a thermometer, and a condenser. Calcined clay was added in amounts to provide a 5 pct stoichiometric excess of acid. The reaction starting time was taken as the time at which boiling resumed, usually about 30 sec after the feed was added. Leaching was then allowed to proceed for a predetermined length of time. For longer reaction times, more than 5 min, when the reaction was nearing completion, the heating mantle was removed and replaced by a pan of ice water to cool the flask and stop the reaction. In this way, samples from the longer runs could be taken for settling and filtration tests as well as for aluminum extraction determinations. For shorter reaction times, 5 min or less, when the reaction was still proceeding vigorously, a liter of ice water slurry was added to stop the reaction by both cooling and dilution. In both cases, the residues were separated from the pregnant liquor by filtration and washed immediately with water until no chloride was indicated in the wash water by silver nitrate. The quenching procedure was based on the findings of Hulbert and Huff[7] that the leaching reaction rate

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[6] Olsen, R. S., W. G. Gruzensky, S. J. Bullard, and J. L. Henry. Effects of Feed Preparation on HCl Leaching of Calcined Kaolinitic Clay To Recover Alumina. BuMines RI 8618, 1982, 24 pp.

[7] Work cited in footnote 5.

decreases rapidly at temperatures below the boiling point.

Continuous leaching tests were done in a 5-L, round-bottom flask equipped with heating mantle, thermometer, stirrer, condenser, and overflow port that maintained a slurry volume of 2 L. Clay and acid were fed continuously with a screw feeder and a metering pump, and leached slurry was allowed to overflow through a water-cooled side arm. Samples were taken after a startup period of four or five residence times, filtered immediately, and washed until free of chloride. Continuous, multiple-stage tests were carried out in a train of two or three 5-L flasks equipped with stirrers, heating mantles, and condensers. In these tests, the slurry overflowed from one reactor to the next. The overflow ports were positioned such that each flask contained 2 L. Boiling was maintained in each flask. Samples were taken by pumping a portion of slurry from each stage onto a separate Buchner vacuum filter after steady-state operation had been established.

ANALYSES

Samples of the washed solid residues were analyzed by dissolving them in HNO_3-HF solution and determining aluminum and silicon by atomic absorption spectrophotometry. Since essentially no silicon was leached from the clay, aluminum extraction (X) was calculated on the basis of aluminum-to-silicon ratios in the feed and residue as

$$X = \frac{(Al/Si)_f - (Al/Si)_r}{(Al/Si)_f}, \qquad (1)$$

where $(Al/Si)_f$ is the aluminum-to-silicon weight ratio in the feed and $(Al/Si)_r$ is the aluminum-to-silicon ratio in the leached residue. Use of the aluminum-to-silicon ratio removed any uncertainty due to water absorption gain or loss by the clay feed or leached residue samples. It also removed the need for overall mass balances on the leaching tests and allowed samples to be taken for residue settling and filtration tests as well as for chemical analyses.

RESULTS AND DISCUSSION

BATCH TESTS

Aluminum in kaolinitic clays becomes acid-soluble when the clay is calcined at 600° to 900° C to remove its water of formation. Initially, the misted clay feeds were calcined by heating them to 750° C in a muffle furnace, holding them at 750° C for 2 hr, and cooling them in the furnace. Batch leaching results for these feeds are shown in table 1 and figure 1. The figure shows that, for particle sizes of minus 20 mesh and smaller, particle size had no effect on reaction rate. It also shows that slightly lower reaction rates and lower aluminum recoveries were obtained with 26-pct HCl than with 23-pct HCl. Lower reaction rates are probably due to the higher viscosity and, consequently, lower diffusion rates of aluminum and hydrogen ions in the aluminum chloride solutions derived from 26-pct HCl. The incomplete extraction was due to the escape of HCl from the more concentrated boiling reaction slurry. Even when an initial 10 pct excess of HCl was provided in the 26-pct runs, the final leached slurry was free of HCl at the end of the leaching cycle. For both the 23- and 26-pct HCl tests, the reaction was rapid up to about 80 pct extraction and showed a linear relationship between aluminum extraction and time. The straight line relationship demonstrates the zero-order kinetics typical of diffusion-controlled reactions, as explained by Levenspiel.[8] The slopes of the initial parts of the extraction curves were 0.105 min^{-1} and 0.095 min^{-1} for the tests done with 23- and 26-pct HCl, respectively. The aluminum extraction curve for the 23-pct HCl series becomes asymptotic with $X = 0.965$. This is due to the presence of acid-insoluble aluminum compounds in the clay.

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[8] Levenspiel, O. Chemical Reaction Engineering. John Wiley & Sons, Inc., New York, 1967, p. 322.

TABLE 1. - Batch leaching tests for misted kaolin calcined in muffle furnace 2 hr at 750° C

Run	Clay size, Tyler mesh	Acid concentration, pct	Leaching time, min	Aluminum extraction, pct	Rate constant (k/C_{A_o}),[1] min^{-1}
1	Minus 10	26	9.1	69.8	0.077
2	Minus 10 plus 14	26	9.1	73.6	.081
3	.....do	26	29.2	84.1	NAp
4	.....do	26	4.3	50.2	.117
5	Minus 20 plus 28	26	9.3	84.0	.090
6	.....do	26	2.3	19.5	.085
7	.....do	26	4.3	36.3	.084
8	Minus 35 plus 48	26	1.8	18.1	.101
9	.....do	26	9.1	87.0	.096
10	Minus 28 plus 35	26	14.1	90.1	NAp
11	.....do	26	4.1	33.8	.082
12	.....do	26	8.9	86.3	.097
13	.....do	26	2.2	20.7	.094
14	.....do	26	29.1	90.5	NAp
15	Minus 20 plus 28	26	14.0	88.4	NAp
16	Minus 35 plus 48	26	14.1	89.6	NAp
17	Minus 20	26	9.1	85.4	.094
18	.....do	26	29.1	91.1	NAp
19	.....do	26	14.1	89.3	NAp
20	.....do	26	1.75	16.3	.093
21	.....do	26	3.9	35.9	.092
22	Minus 10	23	9.3	83.1	.089
23	.....do	23	14.5	89.8	NAp
24	Minus 10 plus 14	23	4.0	42.5	.106
25	.....do	23	14.0	84.0	NAp
26	.....do	23	9.0	73.0	.081
27	Minus 20 plus 28	23	14.5	93.7	NAp
28	Minus 28 plus 35	23	14.3	94.4	NAp
29	.....do	23	4.4	46.8	.106
30	.....do	23	29.4	96.4	NAp
31	Minus 35 plus 48	23	9.3	90.2	.097
32	Minus 10	23	4.3	40.9	.095
33	Minus 28 plus 35	23	8.8	89.1	.101
34	.....do	23	2.4	25.7	.107
35	Minus 20 plus 28	23	3.8	48.6	.127
36	Minus 10	23	29.5	93.1	NAp
37	Minus 20 plus 28	23	9.4	88.4	.094
38	Minus 20 plus 28	23	2.3	27.4	.119
39	Minus 35 plus 48	23	14.4	94.6	NAp
40	Minus 20	23	9.4	90.5	.096
41	Minus 35 plus 48	23	2.6	20.7	.080
42	Minus 20	23	4.6	47.6	.103
43	.....do	23	14.4	93.8	NAp
44	Minus 35 plus 48	23	4.5	53.8	.119
45	Minus 20	23	2.5	22.3	.089
46	.....do	23	29.5	96.7	NAp
47	.....do	23	29.4	94.1	NAp
48	.....do	23	14.0	92.1	NAp
49	.....do	23	59.2	96.5	NAp
50	.....do	26	59.3	93.9	NAp

NAp Not applicable.

[1] Runs with longer holding times are not applicable to calculation of rate constants.

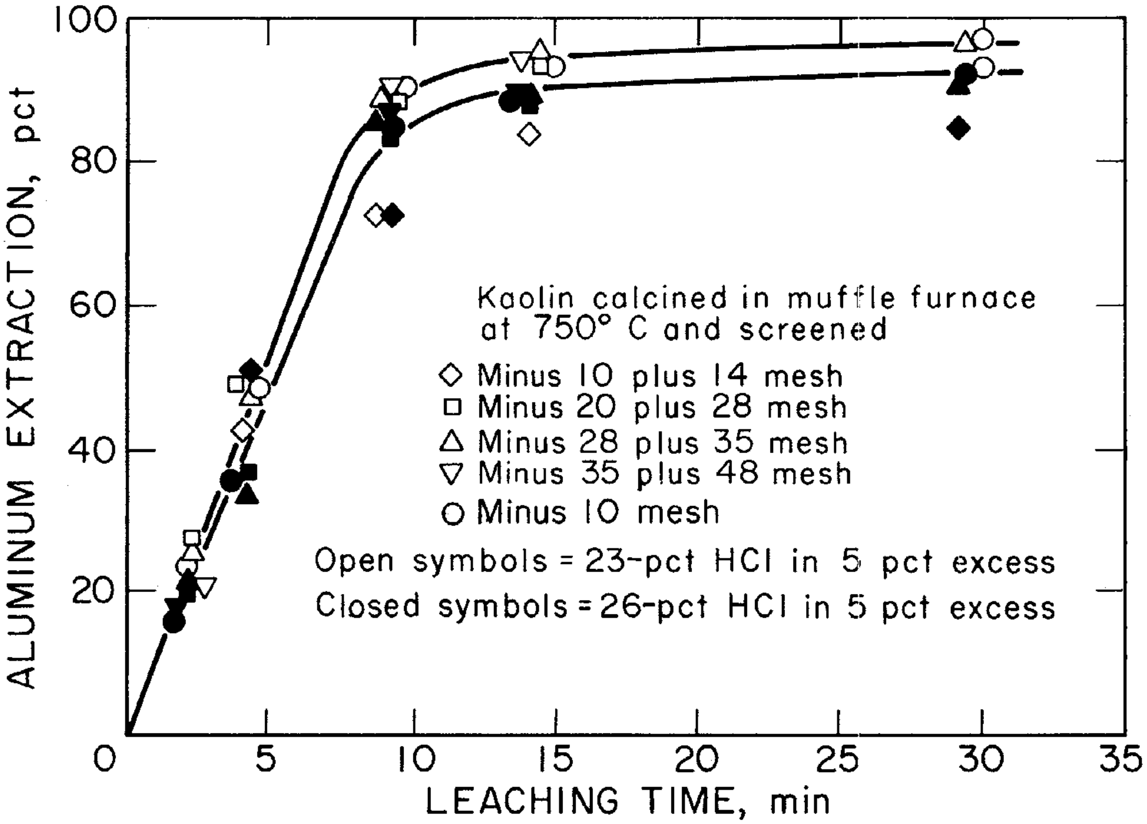

FIGURE 1. - Aluminum extraction as a function of leaching time, clay particle size, and acid concentration for misted clay calcined in a muffle furnace and leached in a batch, stirred-tank reactor.

Further work on feed preparation showed that crushed and misted clay could be calcined in a fluidized-bed calciner. In this case, the misted clay, with or without 5.7 pct coal, was injected directly into a 750° C bed of clay particles fluidized with air. Leaching results for these samples are shown in table 2 and figure 2. Figure 2 shows aluminum extraction as a function of time for minus 20-mesh clay calcined for 30, 60, and 100 min in the fluidized bed. Calciner holding times between 30 and 100 min showed no effect on aluminum extraction. However, aluminum extraction was again slower and less complete when 26-pct HCl was used. Slopes for the initial parts of the extraction curves were 0.150 min^{-1} and 0.145 min^{-1} for the tests done with 23- and 26-pct HCl, respectively. The 23-pct HCl curve was again asymptotic with X = 0.965.

In a diffusion-controlled, zero-order reaction, the reaction rate is independent of concentration, or

$$dC_A = -k\ dt, \tag{2}$$

where k is a rate constant and C_A is the weight-fraction of aluminum in the calcined clay at time t after leaching begins. Integration of equation 2 gives

$$\frac{C_A}{C_{Ao}} = 1 - \frac{kt}{C_{Ao}}, \tag{3}$$

where C_{Ao} is the weight-fraction of aluminum in the calcined clay prior to leaching. In terms of fractional conversion or extraction,

$$X = \frac{C_{Ao} - C_A}{C_{Ao}} = \frac{kt}{C_{Ao}}. \tag{4}$$

TABLE 2. - Batch leaching tests for misted kaolin calcined in fluidized bed at 750° C

(Clay size: minus 20 Tyler mesh, except as indicated)

Run	Calcining conditions			Acid concentration, pct	Leaching time, min	Aluminum extraction, pct	Rate constant (k/C_{Ao}), min^{-1}
	Dried[1]	Time, min	Coal, pct				
51	No	102	5.7	23	14.4	93.1	NAp
52	No	102	5.7	23	59.5	94.1	NAp
53	No	102	5.7	23	4.5	67.6	0.150
54	No	102	5.7	23	9.4	91.7	.097
55	No	102	5.7	23	2.5	43.3	.173
56	No	102	5.7	26	9.3	88.9	NAp
57	No	102	5.7	26	59.2	92.9	NAp
58	No	102	5.7	26	2.2	35.1	.160
59	No	102	5.7	26	4.2	63.5	.151
60	No	102	5.7	26	14.2	89.7	NAp
61	No	68	5.7	23	9.4	92.8	.099
62	No	68	5.7	23	59.4	96.9	NAp
63	No	50	5.7	23	59.4	96.4	NAp
64	No	50	5.7	23	4.3	72.3	.168
65	No	50	5.7	23	2.4	47.0	.196
66	No	102	5.7	23	7.3	86.2	.118
67	No	30	5.7	23	14.5	94.4	NAp
68	No	30	5.7	23	4.6	74.7	.162
69	No	30	5.7	23	59.9	96.0	NAp
70	No	30	5.7	23	9.5	91.9	NAp
71	No	30	5.7	23	9.6	92.6	NAp
72	No	30	5.7	23	59.5	96.8	NAp
73	No	30	5.7	23	4.5	75.7	.168
74	No	30	5.7	23	14.5	95.0	NAp
75	Yes	63	5.7	26	3.96	59.0	.149
76	Yes	63	5.7	23	4.22	60.7	.144
77	Yes	63	5.7	24	4.24	60.2	.142
78	Yes	63	5.7	25	4.22	56.9	.135
79	No	30	0	23	60	95.7	NAp
80	No	30	0	23	4.43	66.1	.149
81[2]	Yes	30	6	23	4.35	58.2	.134
82[2]	Yes	30	6	23	60	95.1	NAp
83	No	60	6	23	60	96.2	NAp
84	No	60	6	23	4.07	59.6	.146
85[2]	Yes	60	0	23	60	95.0	NAp
86[2]	Yes	60	0	23	4.36	55.5	.127
87[2]	No	60	6	23	60	96.2	NAp
88[2]	No	60	6	23	4.41	58.7	.133
89	Yes	60	0	23	60	96.2	NAp
90	Yes	60	0	23	4.28	55.3	.129
91[2]	No	30	0	23	60	95.6	NAp
92[2]	No	30	0	23	4.90	71.6	.146
93	Yes	30	6	23	60	94.8	NAp
94	Yes	30	6	23	4.22	61.5	.145

NAp Not applicable. [1] Dried prior to calcining. [2] Minus 14 Tyler mesh.

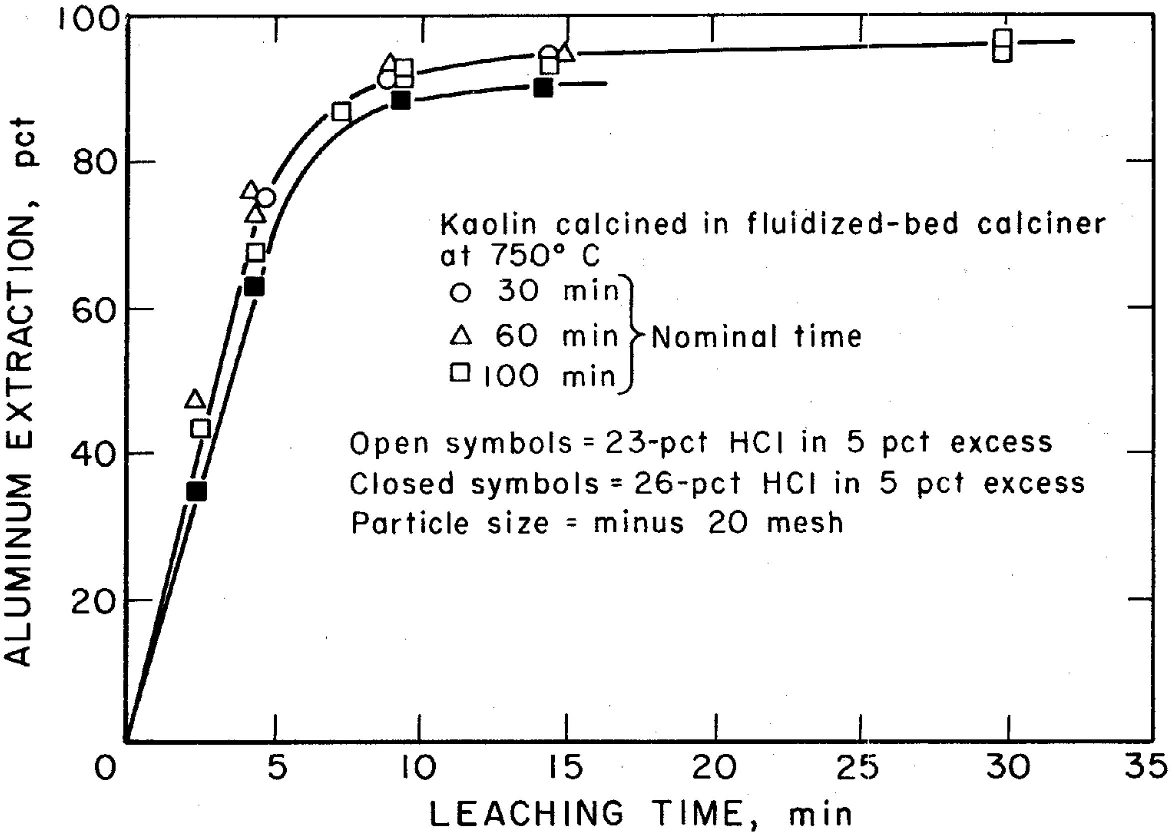

FIGURE 2. - Aluminum extraction as a function of leaching time, calcining time, and acid concentration for misted clay calcined in a fluidized-bed calciner and leached in a batch, stirred-tank reactor.

Equation 4 represents a straight line through the origin as shown during the initial rapid reaction phase of the batch leaching tests. As shown by equation 4, the slopes of the extraction-versus-time curves give the values of the rate constant k/C_{Ao}.

CONTINUOUS TESTS

If one is to apply the rate data obtained in batch leaching tests to continuous operation, the reaction mechanism must be considered. Zero-order reactions are independent of concentration, and a homogeneous, zero-order reaction would be expected to give the same time-extraction response irrespective of reactor type or whether it was operated batchwise or continuously. However, this is not the case with clay leaching. In clay leaching, the reaction is not homogeneous and a heterogeneous system prevails. The probability that a clay particle will leave the reactor immediately, reside there for a given time, or be held there indefinitely must also be considered.

In a continuous, stirred-tank heterogeneous reaction, the two factors that cause the disappearance of component A are the chemical reaction of A in the particles and the loss of particles containing A at the reactor outlet. Disappearance of A in the particles because of chemical reaction is governed by equation 3; the probability function, E_t, that particles will remain in a single, stirred tank is governed by

$$E_t = \frac{1}{\bar{t}} e^{-\frac{t}{\bar{t}}}, \qquad (5)$$

where t is the time considered and $\bar{t}$ is the mean residence time in the tank.

For a series of n equal-sized tanks in series,[9]

$$E_t = \frac{1}{\bar{t}}\left(\frac{t}{\bar{t}}\right)^{n-1}\frac{n^n}{(n-1)!}\,e^{-nt/\bar{t}} \qquad (6)$$

(Note: By definition, 0! = 1)

where $\bar{t}$ is the mean residence time for the entire series of n tanks. Combination of equations 3 and 6 and integration gives the overall average concentration of A as a function of holding time for a reactor made up of n equal-sized stirred tanks in series:

$$\frac{\bar{C}_A}{C_{Ao}} = \int_0^{\infty}\left(\frac{C_A}{C_{Ao}}\right)(E_t)\,dt, \qquad (7)$$

where $\bar{C}_A$ is the overall averaged weight-fraction of aluminum in all the particles of clay leaving the reactor with a residence time $\bar{t}$. Substituting the expression in equations 3 and 6 in equation 7 gives

$$\frac{\bar{C}_A}{C_{Ao}} = \frac{1}{\bar{t}}\int_0^{C_{Ao}/k}\left(1-\frac{kt}{C_{Ao}}\right)$$

$$\left(\frac{t}{\bar{t}}\right)^{n-1}\frac{n^n}{(n-1)!}\,e^{-nt/\bar{t}}\,dt. \qquad (8)$$

For reactions of order other than zero, an expression such as equation 8 would be integrated from zero to infinity. However, in the zero-order case, the reaction is theoretically complete when time is equal to C_{Ao}/k, which then becomes the upper limit of integration.[10]

Equation 8 can be integrated analytically to give the extraction behavior for one or more equal-volume stirred tanks in series:

$$\bar{X}_1 = \left(1-\frac{\bar{C}_A}{C_{Ao}}\right)_1 = R(1-e^{-1/R}); \qquad (9)$$

$$\bar{X}_2 = R(1-e^{-2/R}) - e^{-2/R}; \qquad (10)$$

$$\bar{X}_3 = R(1-e^{-3/R}) - \left(2+\frac{3}{2R}\right)e^{-3/R}; \qquad (11)$$

$$\bar{X}_4 = R(1-e^{-4/R})$$

$$-\left(3+\frac{4}{R}+\frac{8}{3R^2}\right)e^{-4/R}. \qquad (12)$$

In equations 9 through 12

$$R = \frac{k\bar{t}}{C_{Ao}}.$$

The leaching results from batch tests in figures 1 and 2 show that extraction begins to deviate from ideal zero-order behavior at around 80 pct extraction. They also show that for long holding times no more than about 96 pct of the aluminum will ever be extracted. This is due to the presence of small amounts of acid-insoluble aluminum-bearing minerals such as micas. If the expressions in equations 9 through 12 are to correlate the continuous leaching data, they must be modified to account for the acid-insoluble aluminum. This can be done by multiplying them by a correction factor, X_{max}, which will then make the curves asymptotic to the value corresponding to the amount of acid-soluble aluminum present in the calcined clay. Figures 1 and 2 show that X_{max} is 0.965 for the kaolinitic clay used in this study.

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[9] Page 282 of work cited in footnote 8.

[10] Rietema, K. Heterogeneous Reactions in the Liquid Phase: Influence of Residence Time Distribution and Interaction in the Dispersed Phase. Chem. Eng. Sci., v. 8, No. 1/2, 1958, pp. 103-112.

TABLE 3. - Continuous leaching tests for minus 20-mesh misted kaolin calcined in muffle furnace at 750° C

Run	Leaching time, min	Aluminum extraction, pct	R[1]	Rate constant (k/C_{Ao}), min^{-1}
95	60	90.9	7.5	0.125
96	30	83.4	3.4	.113
97	30	83.6	3.45	.115
98	15	74.8	1.9	.127

[1] R values derived from curve of R versus $\bar{\bar{X}}$ where X_{max} = 0.965 in equation 13.

Table 3 and figure 3 show continuous leaching data for misted clay calcined in a muffle furnace and leached with 23-pct HCl in 5 pct excess. The curve corresponds to X_{max} = 0.965 and k/C_{Ao} = 0.105 min^{-1}. Table 3 shows values of R and k/C_{Ao} for the continuous runs made with feed calcined in a muffle furnace. Values of R were found from a graph of R versus $\bar{X}_1$, constructed by evaluating the equation

$$\bar{X}_1 = X_{max} R(1-e^{-1/R}), \qquad (13)$$

where X_{max} = 0.965. The R value corresponding to the aluminum extraction $\bar{X}_1$ for a given experiment was then used to evaluate the reaction rate constant. Since the reactor holding time was known, the rate constant was calculated as

$$k/C_{Ao} = R/\bar{t}. \qquad (14)$$

The average value of k/C_{Ao} in table 3 is 0.12 min^{-1}. Although there is some deviation between the rate constants obtained from the batch and continuous data, figure 3 shows that the continuous leaching results are quite adequately predicted by a rate constant obtained from the batch tests and equation 9.

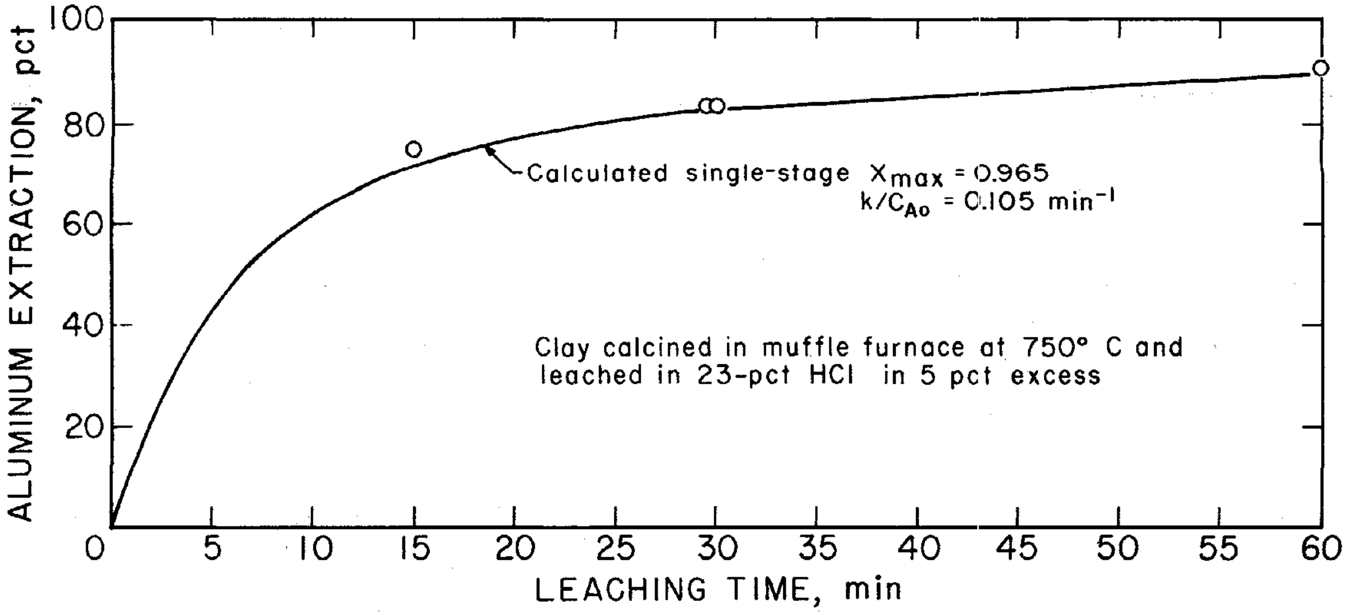

FIGURE 3. - Aluminum extraction as a function of leaching time for misted clay calcined in a muffle furnace and leached in a continuous, stirred-tank reactor.

TABLE 4. - Continuous leaching tests for misted kaolin calcined in fluidized bed at 750° C

(Clay size: minus 20 Tyler mesh, except as indicated)

Run	Calcining conditions			Leaching time, min	Aluminum extraction, pct	Number of stages	R[2]	Rate constant (k/C_{Ao}), min^{-1}
	Dried[1]	Time, min	Coal, pct					
99	No	68	5.7	30	83.8	1	3.6	0.120
100	No	68	5.7	15	80.5	1	2.6	.173
101	No	102	5.7	10	71.7	1	1.8	.180
102[3]	Yes	60	5.7	60	89.2	1	8.0	.133
103[3]	No	85	5.7	60	91.4	1	10.0	.167
104[3]	No	85	5.7	120	95.6	2	14.0	.117
105	No	63	5.7	60	94.3	2	7.0	.117
106	Yes	105	0	30	86.0	1	4.4	.147
				60	95.4	2	10.0	.167
107	Yes	105	0	15	80.2	1	2.75	.183
				30	91.9	2	3.5	.117
				15	79.6	1	2.6	.173
				30	90.1	2	2.9	.097
108	Yes	49	5.7	10	73.3	1	1.8	.180
				20	89.0	2	2.6	.130
				30	92.9	3	2.8	.093
				10	74.1	1	1.85	.185
				20	87.7	2	2.3	.115
				30	92.7	3	2.65	.083
109	Yes	49	5.7	5	51.0	1	.72	.144
				10	76.8	2	1.3	.130
				15	89.1	3	1.9	.127

[1] Dried prior to calcining.

[2] R values derived from curves of R versus $\bar{X}$ where X_{max} = 0.965.

[3] Minus 14 Tyler mesh.

Leaching tests were also done on misted clay calcined in the fluidized-bed reactor. These leaching tests, done in single, double, and triple tank reactors, are shown in table 4 and figure 4. The curves in figure 4 correspond to equations 9, 10, and 11 when values of X_{max} = 0.965 and k/C_{Ao} = 0.15 min^{-1} are used. Figure 4 shows that a good correlation of the continuous, stirred-tank leaching data results when the parameters derived from batch tests are applied to the appropriate correlating analytical relationships. The values of R and k/C_{Ao} shown in table 4 were again derived from values of R corresponding to a given aluminum extraction and the reactor holding time. In this case the $\bar{X}$-versus-R relationship depended on the number of stages corresponding to equations 9, 10, and 11. In the case of the clay activated in the fluidized-bed calciner, a value of X_{max} = 0.965 and k/C_{Ao} = 0.15 min^{-1} gave a fairly good correlation of the continuous single- and multiple-stage leaching data.

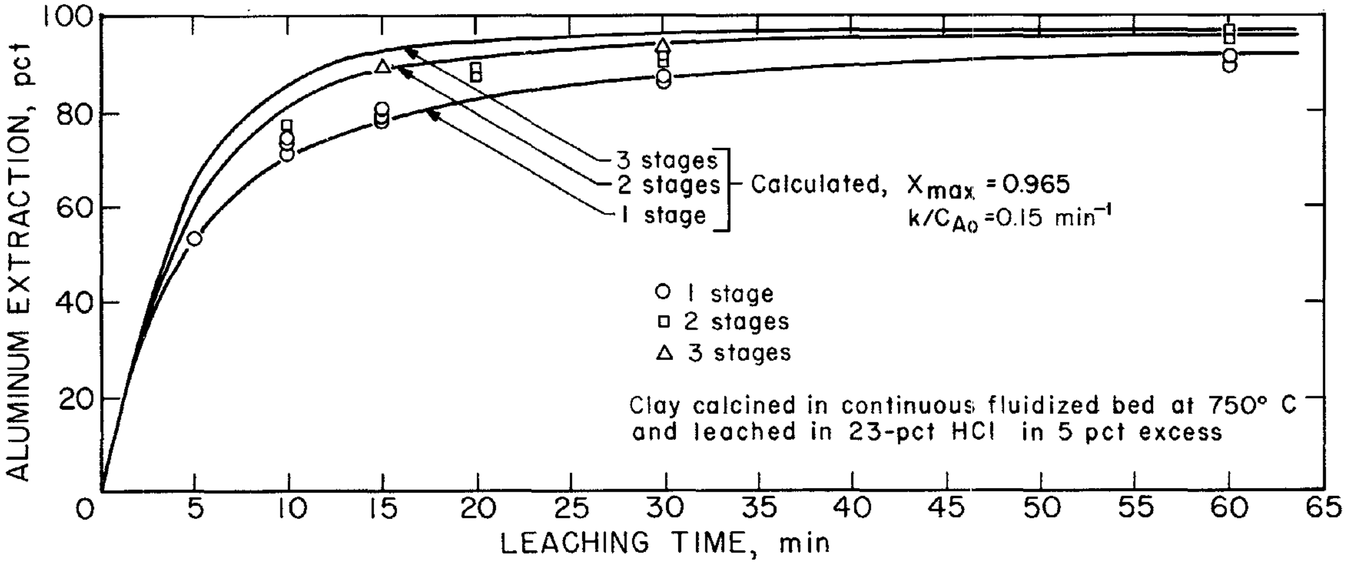

FIGURE 4. - Comparison of experimental and calculated aluminum extraction as a function of leaching time for misted clay calcined in a fluidized bed and leached in single- and multiple-tank, continuous, stirred-tank reactors.

CONCLUSIONS

Leaching tests on calcined clay with boiling HCl showed that rapid extraction of aluminum was obtained and that clay calcined in a fluidized bed reacted 50 pct faster than clay calcined in a muffle furnace. The leaching reaction was fast enough that diffusional resistances became rate controlling and a zero-order kinetic relationship adequately described the leaching process.

Continuous, stirred-tank leaching tests also showed a zero-order relationship between aluminum extraction and holding time. Leaching reactors made up of one, two, and three tanks produced results that were adequately correlated by the zero-order kinetic relationships. This shows that a continuous operating clay leaching system could be designed by obtaining the zero-order rate constants from a few batch tests. The required holding time in a continuous, single or multitank reactor then could be obtained with equations 9 through 12 and the data from the batch tests. The size and number of tanks to produce a given aluminum extraction at a given throughput could be determined fairly accurately. This would prevent the unnecessary expense of using too many or oversized tanks in a leaching system and, more importantly, would prevent the slurry from being held for excessively long times in the leaching reactor. Excessive leaching time causes degradation of the calcined clay particles and leads to filtration problems when the leached residue is separated from the product slurry.

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