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The Elimination of Channeling and Foam Overturning in Continuous Mode Adsorbing Colloid Flotation with a Sodium Dodecylsulfate/Dodecanoic Acid Mixture

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ABSTRACT

The effect of hydraulic loading, surfactant concentration, and air flow rate on the removal of Cr(III), Ni(II), and Zn(II) from chromium stream electroplating wastewater by adsorbing colloid flotation using a sodium dodecylsulfate/dodecanoic acid mixture was investigated. Typically, heavy metal concentrations of 81 ppm Cr(III), 55 ppm Ni(II), and 3.3 ppm Zn(II) were reduced to 1.2 ppm Cr(III), 3.2 ppm Ni(II), and 0.05 ppm Zn(II) at a hydraulic loading of 22.9 $m^3/m^2 \cdot h$ (3 $L \cdot min^{-1}$), an air flow rate of 45.8 $m^3/m^2 \cdot h$ (6 $L \cdot min^{-1}$), 40 ppm dodecanoic acid, and 80 ppm sodium dodecylsulfate, and using a 10-cm inner diameter column. A novel mode of operation (high liquid carryover) was used whereby a large proportion of the liquid entering the column leaves the column with the foam.

Key Words. Channeling; Foam overturning; Adsorption; Removal; Coprecipitation; Flotation; Surfactant; Bubble; Heavy metal; Iron hydroxide; Sodium dodecylsulfate; Dodecanoic acid; Colloid.

INTRODUCTION

Adsorbing colloid flotation is known to be an effective method for removal of metal ions from solution. A number of extensive reviews of the subject are available (1–4). In an earlier paper (5) we pursued the work of Allen et al. (6), Gannon et al. (7), and Sarker et al. (8) through the development of adsorbing colloid flotation using a dual surfactant mixture

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consisting of a strongly adsorbing surfactant and a carrier surfactant. We found that a 2:3 mole ratio of dodecanoic acid (DA) to sodium dodecylsulfate (SDS) was considerably more efficient and effective for removal of Cr(III), Ni(II), and Zn(II) from industrial wastewaters than SDS alone. This was attributed to the decreased interferences associated with the use of a more strongly adsorbing surfactant than SDS. Preliminary work with a small scale (4.5 cm inner diameter column) continuous flotation apparatus using electroplating wastewaters revealed that flotation with this dual surfactant mixture was sufficiently rapid to make it industrially feasible.

A number of detailed pilot-plant studies for adsorbing colloid flotation of metals exist (9–12). In general, such pilot plants demonstrate that the concentrations of some toxic heavy metals, such as Cr(III), Cu(II), Zn(II), and Pb(II), in simulated wastewaters could be reduced by adsorbing colloid flotation (using SDS alone) to very low concentrations (<1 ppm) at considerable hydraulic loadings (6.9–13.8 $m^3/m^2 \cdot h$).

Wilson et al. (9) found that channeling and foam overturning in the flotation column were the major determinants of effluent quality. Channeling and foam overturning were both found to occur, using a 10-cm inner diameter column, at high hydraulic loadings (greater than 4.8 $m^3/m^2 \cdot h$) and low gas flow rates (less than 15 $m^3/m^2 \cdot h$). At air flow rates greater than this it is possible to obtain a somewhat higher hydraulic loading without sacrificing effluent quality; however, this leads to a very wet foam. For a 10-cm inner diameter column operating at an air flow rate of 2 $L \cdot min^{-1}$, the collapsed foamate was approximately 3% of the influent volume. Increasing the air flow rate to 4 $L \cdot min^{-1}$ resulted in a collapsed foamate volume approximately 9% of the influent volume.

During our earlier flotation work on industrial wastewater samples with DA/SDS mixtures it was found that under appropriate conditions the resultant foam had two extremely desirable characteristics:

1. The volume of the foam produced was considerably less than that observed when SDS alone was used under the same conditions.
2. The foam does not readily give up its load of heavy metals on drainage.

When the foam has these characteristics it is possible to avoid the problems of channeling and foam overturning by increasing the gas flow rate such that a large proportion of the liquid entering the cell is carried over with the foam and allowing simple drainage of the foam to generate clean water. Operating the column in this mode (high liquid carryover, HLC) allows the use of much higher hydraulic loadings, potentially leading to a much smaller and less expensive treatment plant.

In this paper we define the operating conditions under which low volume, clean draining foams are produced. We then test the feasibility of operation in the HLC mode on a larger scale where channeling and foam overturning were found in previous work by Wilson et al. (9) to be major determinants of effluent quality.

EXPERIMENTAL SECTION

Reagents

Stock solutions were prepared as follows: 40,000 ppm Fe(III) (0.716 M) from AR Grade $Fe(NO_3)_3 \cdot 9H_2O$ (Ajax Chemicals), 5000 ppm SDS (0.017 M) from LR Grade sodium dodecylsulfate (BDH Chemicals), and combined surfactant solution (0.012 M DA, 0.017 M SDS) from LR Grade dodecanoic acid (BDH Chemicals) dissolved in warm alkaline solution.

Industrial Electroplating Wastewater

Bench-Scale Foam Characteristics Study (4.5 cm i.d. flotation column)

Chromium stream electroplating wastewater (150 L) was sampled and stored in 25 L polythene carboys (pH 2.9) over the duration of the study (approximately 2 months). The concentrations of heavy metals in this sample were determined by atomic absorption spectroscopy to be 19.4 ppm Cr, 3.3 ppm Ni, and 12.5 ppm Fe.

Semibench-Scale Foam Flotation Study (10.0 cm i.d. flotation column)

The collection of chromium stream electroplating wastewater samples was carried out in 150 L lots (6 × 25 L carboys) as required over the duration of this study (approximately 6 months). The concentration of heavy metals in these samples was found to be in the following ppm ranges: Cr, 50–100; Ni, 20–70; Zn, 1–3.

Equipment and Procedure

Bench-Scale Foam Characteristics Study (4.5 cm i.d. flotation column)

A schematic representation of the equipment is shown in Fig. 1. A 4-L quantity of industrial wastewater was pretreated by dosing with stock Fe^{3+} (0.716 M ferric nitrate solution) to give 25 ppm added Fe^{3+} and raising the pH to the required value with NaOH. A 30-minute aging period with constant stirring was allowed for the equilibration of all adsorption/coprecipitation processes prior to pumping the wastewater to the flotation

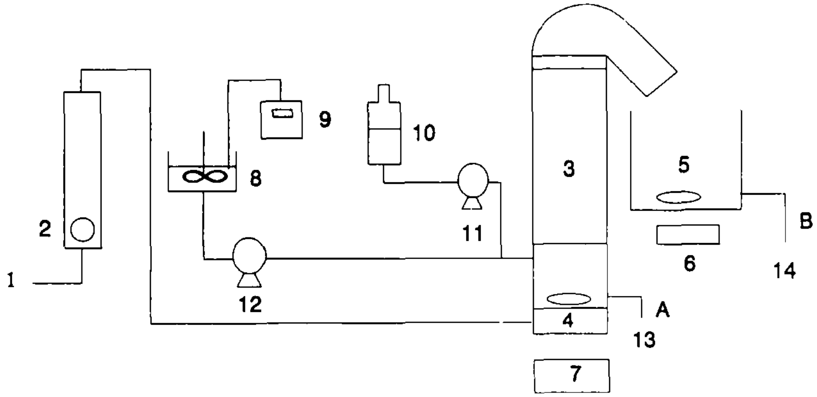

FIG. 1 Flotation apparatus used for the study of foam characteristics. (1) Air inlet, (2) rotameter, (3) 4.4 cm inner diameter flotation column (29 cm in height), (4) porous glass frit (porosity 3), (5) foam collection vessel, (6, 7) magnetic stirrer, (8) water pretreatment reservoir with stirrer, (9) pH meter, (10) surfactant reservoir, (11, 12), pump, (13) treated wastewater outlet A, (14) treated wastewater outlet B.

column. The surfactant mixture was pumped into the wastewater lines immediately prior to entry into the flotation column. Air was introduced into the column through the fritted glass disk (porosity 3) at the bottom of the column. The diameter of the bubbles generated in the pool of liquid at the bottom of the flotation column was determined photographically to be in the range 0.2 to 2.0 mm. The majority of bubbles were less than 0.5 mm in diameter.

For the lower air throughput runs the treated wastewater outlet A was regulated such that the liquid pool at the bottom of the column was maintained at 200 mL. At higher air throughputs, where the quantity of liquid leaving the column with the foam was equal to the quantity being pumped into the column, the treated effluent drain was turned off. The foam produced was collected in a large beaker which had been fitted with a sampling port at the bottom. The liquid draining from the foam was sampled at regular intervals over a 2-hour period with a syringe after gentle stirring with a magnetic stirrer. The liquid leaving the cell at treated wastewater outlet B was also sampled at regular intervals. The volume of foam and liquid was recorded over the 2-hour duration of the experiment.

Semibench-Scale Foam Flotation Study (10 cm i.d. flotation column)

A schematic representation of the plant is shown in Fig. 2. A 25-L quantity of industrial wastewater was pretreated by dosing with stock

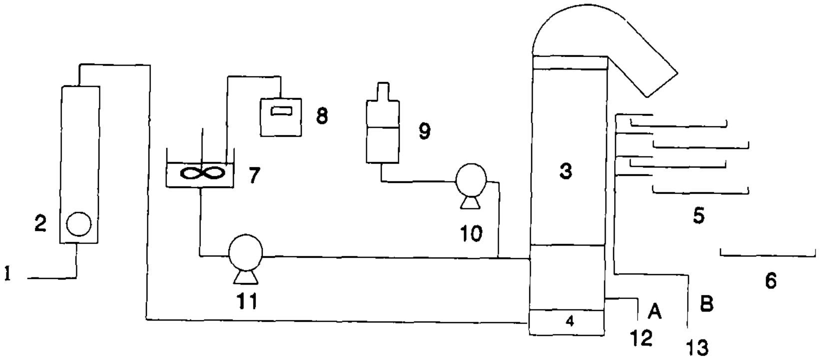

FIG. 2 Flotation apparatus used for "continuous" flotation experiments including modification for total liquid carryover mode. (1) Air inlet, (2) rotameter, (3) 10 cm inner diameter flotation column (1.6 m in height), (4) porous glass frit (porosity 3), (5) foam dewatering/concentration vessels, (6) dewatered foam collection vessel, (7) water pretreatment reservoir with stirrer, (8) pH meter, (9) surfactant reservoir, (10, 11) pump, (12), treated wastewater outlet A, (13) treated wastewater outlet B.

Fe^{3+} (0.716 M ferric nitrate solution) to give 25 ppm Fe(III) and raising the pH to 8.0 with NaOH. A similar 30-minute aging period with constant stirring was allowed for equilibration of all adsorption/coprecipitation processes prior to pumping the wastewater to the flotation column. The surfactant mixture was pumped into the wastewater lines immediately prior to entry into the flotation column. Air was introduced into the column through a fritted glass disk (porosity 3) at the bottom of the column. The flow rate through the treated effluent drain (12) was regulated such that the volume of liquid pool at the bottom of the column was maintained at 2 liters.

Sample Characterization

Wastewater samples were analyzed for Cr, Ni, and Zn by using atomic absorption spectroscopy.

RESULTS AND DISCUSSION

Carboxylic acids are powerful collectors which are used extensively in the field of mineral processing. They usually exhibit poor foam properties and hence a frother is often employed. The frother used in this work with dodecanoic acid (DA) was sodium dodecylsulfate (SDS). SDS was employed not only because of its relatively low cost and toxicity but also due its very well characterized behavior in flotation generally (4).

Most pilot scale investigations published in the literature use SDS as both collector and frother since this surfactant has an affinity for both the hydroxide/water interface and the air/water interface. Similarly, dodecanoic acid can also act as both collector and frother at high pH values where the alkali metal soap is formed. The precise role of each surfactant in a mixed surfactant system has not been clearly defined, particularly when one considers the complexity of the dodecanoic acid chemical and phase behavior. Dodecanoic acid can, depending on solution conditions, exist as dodecanoic acid, heavy metal soap(s), alkali metal soap(s), and/or ionic dimers or trimers (13–16), each of which has its own solubility and surface activity. To aid in the interpretation of data obtained from flotation with this dual surfactant system, comparison with a simpler and better known system (i.e., flotation with SDS alone) was employed. The industrial sample chosen for the investigation was one which gave good removal of heavy metals over a wide range of pH values for both DA/SDS and SDS alone.

Batch mode flotation tests using the 4.5-cm internal diameter cell were performed in order to determine the operational pH range under which

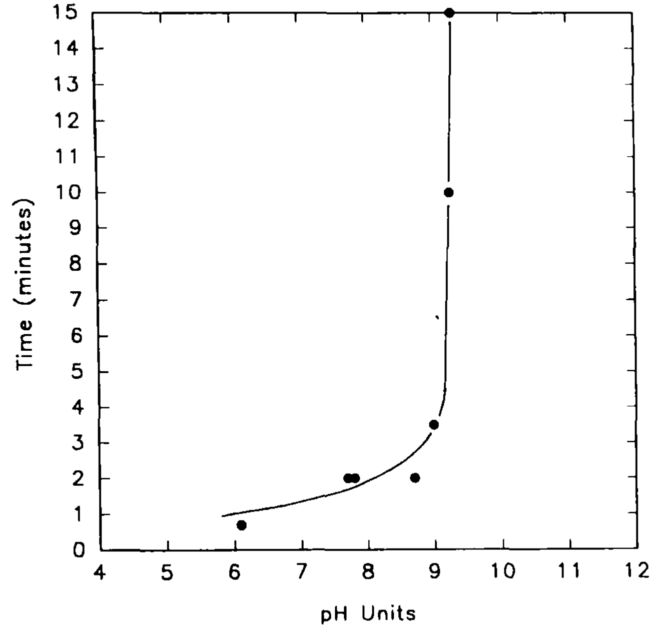

FIG. 3 Time required for flotation cell to appear clear and colorless as a function of pH for flotation with SDS alone.

continuous mode flotation would be feasible. Two criteria were used. The first was the time taken for the flotation cell to clear of the turbidity originally present due to the metal hydroxides. The second was the flotation effectiveness as measured by the percentage removal of chromium, nickel, and iron.

Figure 3 shows the removal time and Fig. 4 shows the flotation effectiveness, each as a function of pH, for flotation using SDS only. Figure 5 shows the removal time and Fig. 6 shows the flotation effectiveness, again as a function of pH, for flotation using the surfactant mixture. Flotation with SDS alone was found to be rapid and effective up to approximately pH 8.5. Flotation with the surfactant mixture is rapid and effective up to approximately pH 9.5. These results are in agreement with the results we presented in an earlier paper (5) where we showed that the interferences expected in real industrial samples can be overcome by the use of a more strongly adsorbing surfactant (than SDS). The higher ranges of pH values for each system were used for the bench-scale foam characteristics study, i.e., 6.5 to 9.0 for SDS and 7.5 to 10.0 for DA/SDS. The flotation apparatus shown in Fig. 1 was operated in a continuous mode with a range of pH

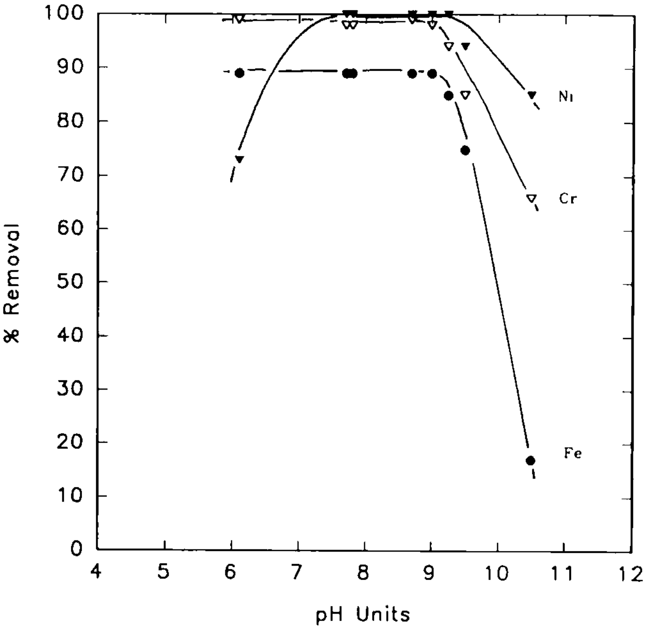

FIG. 4 Removal of heavy metals achieved as a function of pH for flotation with SDS alone.

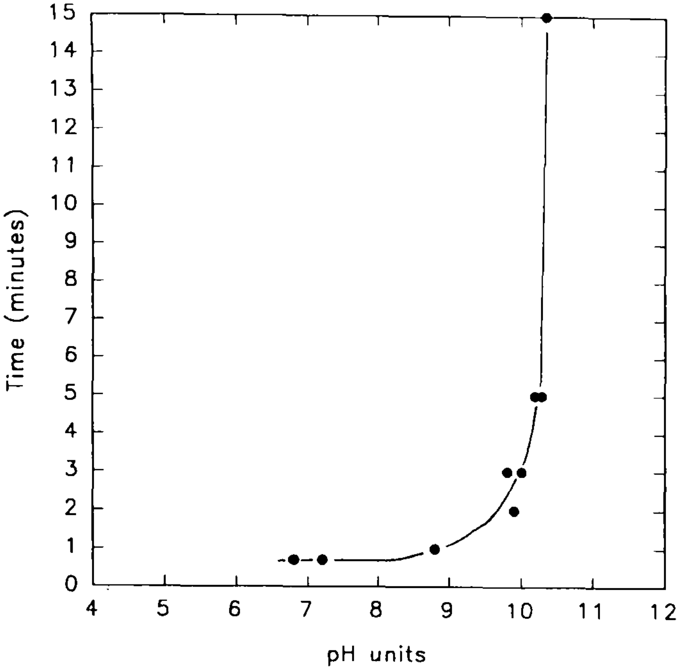

FIG. 5 Time required for flotation cell to appear clear and colorless as a function of pH for flotation with DA/SDS mixture.

values, surfactant concentrations, air flow rates, and wastewater flow rates. The results are presented in Tables 1 to 4.

Table 1 contains foam and liquid volume data readings at the end of each run (i.e., at the end of foam production) as well as the average metal concentrations in the flotation cell during the run. Table 2 contains the metal concentration in the liquid pool beneath the foam sampled at 30, 60, and 120 minutes from the beginning of operation. Table 3 contains calculations of the percentage of the metals originally present in the foam which were released over the 2-hour duration of the experiment as the foam decayed and drained. Table 4 contains the calculated total percentage removal achieved by the flotation process taking into account the concentration of metals in the liquid collected from the treated wastewater outlet A (Fig. 1) as well as the concentration of metals in the liquid draining from the foam (outlet B, Fig. 1).

Foam stability and the influence of solid particles on foam stability are complex phenomena. Livshitz and Dundekov (17) demonstrated an

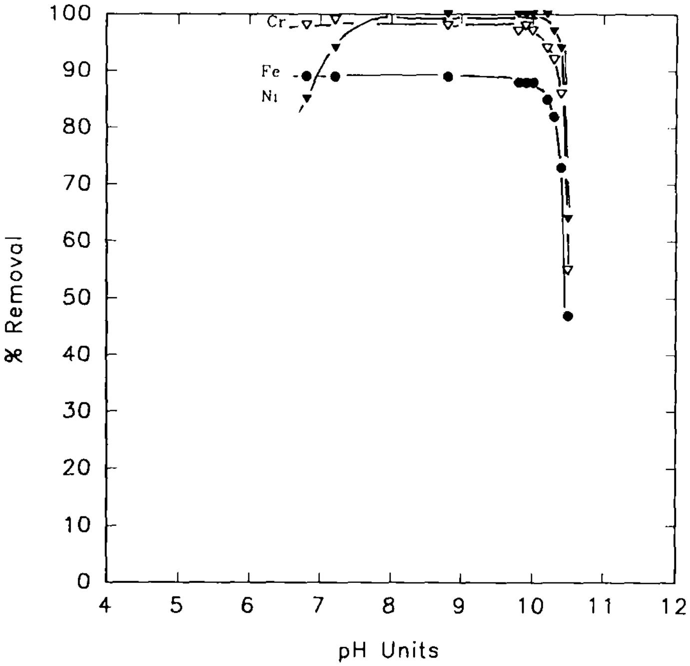

FIG. 6 Removal of heavy metals achieved as a function of pH for flotation with DA/SDS mixture.

optimum hydrophobic particle size range that destabilize foams. They, however, also demonstrated that if particles are large enough, they can stabilize a foam by physically separating the lamellae. This effect is more pronounced with increasing particle hydrophobicity. They also showed that froth instability was associated with the presence of the hydrophobic particles and not with the reduction of aqueous surfactant concentration. More recently, these results have been explained by the protruding particle theory (Hemmings, 18). This theory details the mechanisms by which particle size (of discrete particles or floccules), hydrophobicity, particle concentration, and zeta potential or state of aggregation affect froth stability.

One measure of the *initial* stability of a foam is the maximum volume the foam reaches as it is being produced. When the foam production rate is greater than the decay rate, the foam accumulates and an increase in volume results. The maximum volume reached by the foam within a set time period is hence a measure of the difference between the foam produc-

TABLE 1
Volume Readings, Average Metal Concentrations in Cell During Run, % of Influent Volume Carried Over with Foam[a]

							$[M]_c$					
F_w	F_g	pH	[S]	V_a	V_c	V_d	Fe	Cr	Ni	V_{Fm}	V_T	$\%V_i$
100	200	7.5	20/40	3150	300	550	4.2	1.3	0.4	150	4.0	15
100	200	8.5	20/40	3100	300	600	10.8	4.9	0.8	400	4.0	16
100	200	9.5	20/40	2800	300	900	9.7	3.7	0.4	1100	4.0	24
100	200	10.0	20/40	3021	300	680	25.6	12.8	1.9	850	4.0	18
100	600	8.5	20/40	2750	300	950	1.3	0.5	0.2	500	4.0	26
100	900	8.5	20/40	0	500	3500	1.9	0.8	0.1	200	4.0	100
100	1100	8.5	20/40	0	500	3500	2.6	1.4	0.2	100	4.0	100
200	1100	8.5	20/40	0	600	3400	2.0	1.5	0.2	500	4.0	100
275	600	8.5	20/40	3480	300	220	5.6	2.5	0.5	500	4.0	6
275	1100	8.5	20/40	1000	300	2700	1.8	0.6	0.2	500	4.0	73
275	1400	8.5	20/40	0	400	3700	2.0	0.5	0.2	500	4.0	100
275	1900	8.5	20/40	0	600	3400	2.0	0.2	0.3	350	4.0	100
275	1100	7.5	20/40	800	500	700	4.0	1.2	0.5	20	2.0	47
275	1100	9.5	20/40	750	300	950	4.2	1.4	0.2	1400	2.0	56
100	1100	8.5	30/60	0	500	3500	3.1	0.9	0.1	100	4.0	100
100	200	8.5	30/60	2500	300	1200	3.7	0.7	0.2	650	4.0	32
100	200	8.5	40/80	2550	300	1150	4.7	2.3	0.3	700	4.0	31
100	200	6.5	0/60	3250	400	350	8.3	3.6	2.0	950	4.0	10
100	200	7.5	0/60	3100	300	600	8.6	2.9	0.4	1820	4.0	16
100	200	8.5	0/60	2950	300	750	19.7	6.9	1.5	1900	4.0	19
100	200	9.0	0/60	2950	300	750	14.3	5.6	0.7	2000	4.0	20
100	1100	8.5	0/60	0	100	900	3.4	0.2	0.1	3820	1.0	100
275	1100	7.5	0/60	0	500	650	4.0	0.4	0.2	2550	1.15	100
275	1100	8.5	0/60	0	300	1250	9.2	3.8	0.6	4100	1.65	100

[a] F_w = Influent wastewater flow rate (mL/min)
F_g = Gas flow rate (mL/min)
[S] = Surfactant concentrations (ppm DA/ppm SDS)
V_a = Liquid volume exiting outlet A (mL)
V_c = Liquid volume left in cell at end of run (mL)
V_d = Volume of drainage liquor
$[M]_c$ = Metal concentration in liquid exiting the cell (ppm)
V_{Fm} = Maximum volume of foam (mL)
V_T = Total volume of wastewater treated (mL)
$\% V_i$ = Percentage of total volume of wastewater carried over with foam

TABLE 2
Metal Concentrations in Liquids Drained from Foam[a]

				Metal concentration at end of foam production (ppm)			Metal concentration t = 30 min (ppm)			Metal concentration t = 70 min (ppm)			Metal concentration t = 120 min (ppm)		
F_w	F_g	pH	[S]	Fe	Cr	Ni	Fe	Cr	Ni	Fe	Cr	Ni	Fe	Cr	Ni
100	200	7.5	20/40	—	—	—	29.9	15.4	2.7	31.2	15.8	2.9	33.1	16.1	2.9
100	200	8.5	20/40	—	—	—	1.9	0.4	0.3	11.1	5.2	1.1	12.8	6.5	1.3
100	200	9.5	20/40	—	—	—	2.4	0.3	0.1	3.7	0.7	0.1	4.1	1.4	0.2
100	200	10.0	20/40	—	—	—	2.6	0.3	0.1	3.5	0.9	0.2	4.2	1.4	0.2
100	600	8.5	20/40	—	—	—	1.3	0.4	0.1	1.6	0.4	0.1	1.6	0.5	0.1
100	900	8.5	20/40	—	—	—	3.6	2.0	0.4	3.7	2.0	0.4	3.8	2.0	0.4
100	1100	8.5	20/40	—	—	—	7.3	4.2	0.3	7.3	4.0	0.3	7.9	4.3	0.3
200	1100	8.5	20/40	2.3	—	0.1	2.3	1.0	0.2	2.3	—	—	2.9	1.3	0.2
275	600	8.5	20/40	8.2	4.4	0.6	7.2	3.6	0.6	6.2	3.6	0.6	7.6	3.8	0.7
275	1100	8.5	20/40	1.0	0.2	0.1	1.7	0.5	0.2	2.2	0.8	0.2	2.4	0.9	0.2
275	1400	8.5	20/40	2.1	0.5	0.5	2.1	0.8	0.8	2.3	0.8	0.8	2.4	0.9	0.9
275	1900	8.5	20/40	3.7	1.3	0.3	3.9	1.3	0.3	3.8	1.4	0.3	4.1	1.5	0.3
275	1100	7.5	20/40	29.7	18.4	3.3	29.7	18.4	3.3	29.7	18.4	3.3	29.7	18.4	3.3
275	1100	9.5	20/40	4.5	1.5	0.3	5.7	2.3	0.3	5.8	—	0.3	5.9	2.5	0.4
100	1100	8.5	30/60	—	—	—	8.8	4.9	0.8	9.5	5.5	0.9	10.7	5.8	0.9
100	200	8.5	30/60	—	—	—	3.6	0.8	0.2	4.0	0.9	0.2	4.1	0.9	0.2
100	200	8.5	40/80	—	—	—	5.3	1.4	0.2	5.3	1.3	0.2	5.6	1.6	0.3
100	200	6.5	0/60	—	—	—	4.3	1.0	2.2	4.7	1.2	2.3	4.8	1.3	2.3
100	200	7.5	0/60	—	—	—	3.3	0.4	0.1	4.7	1.0	0.3	6.4	1.9	0.4
100	200	8.5	0/60	—	—	—	3.8	0.4	0.1	6.5	2.0	0.4	27.9	14.1	2.6
100	200	9.0	0/60	—	—	—	3.9	0.5	0.1	5.5	1.4	0.4	24.4	12.4	1.0
100	1100	8.5	0/60	—	—	—	3.5	0.3	0.1	4.9	1.1	0.1	13.8	7.1	1.2
275	1100	7.5	0/60	3.9	0.4	0.1	5.2	1.2	0.2	6.0	1.7	0.3	17.7	9.5	1.6
275	1100	8.5	0/60	—	—	—	—	—	—	11.3	5.5	0.9	18.9	10.4	1.7

[a] F_w = Influent wastewater flow rate (mL/min)
F_g = Gas flow rate (mL/min)
[S] = Surfactant concentrations (ppm DA/ppm SDS)

tion rate and decay rate, i.e., its stability. It should be noted that this criterion of foam stability only applies to fresh foams as they are being produced. It does not imply persistence of the foam over a long time period after foam production has ceased. It does, however, serve as a useful probe of the surface chemistry involved.

The pH dependence of the maximum foam volume is plotted for both the SDS and DA/SDS mixture in Fig. 7, where it is seen that SDS foams

TABLE 3
Metal Release by Foam[a]

				Metal release at end of foam production (ppm)			Metal release t = 30 min (ppm)			Metal release t = 70 min (ppm)			Metal release t = 120 min (ppm)		
F_w	F_g	pH	[S]	Fe	Cr	Ni	Fe	Cr	Ni	Fe	Cr	Ni	Fe	Cr	Ni
100	200	7.5	20/40	—	—	—	12.4	11.8	12.7	12.9	12.1	13.7	13.7	12.3	12.7
100	200	8.5	20/40	—	—	—	1.0	0.3	1.8	6.1	4.2	6.6	7.1	5.3	7.8
100	200	9.5	20/40	—	—	—	1.9	0.4	0.8	3.0	1.0	0.8	3.3	2.0	1.5
100	200	10.0	20/40	—	—	—	3.8	0.8	1.2	5.2	2.3	2.4	6.2	3.6	2.4
100	600	8.5	20/40	—	—	—	0.8	0.5	0.8	1.0	0.5	0.8	1.0	0.6	0.8
100	900	8.5	20/40	—	—	—	8.4	9.0	10.6	8.7	9.0	10.6	8.9	9.0	10.6
100	1100	8.5	20/40	—	—	—	17.1	18.9	21.2	17.1	18.0	21.2	18.5	19.4	21.2
200	1100	8.5	20/40	5.2	—	2.6	5.2	4.4	5.2	5.2	—	—	6.6	5.7	5.2
275	600	8.5	20/40	1.4	1.4	1.2	1.2	1.1	1.2	1.0	1.1	1.2	1.3	1.2	1.4
275	1100	8.5	20/40	2.0	0.7	2.2	3.5	1.8	4.3	4.5	2.8	4.3	4.9	3.2	4.3
275	1400	8.5	20/40	5.5	2.4	3.1	5.5	3.8	5.0	6.0	3.8	5.0	6.3	4.3	5.6
275	1900	8.5	20/40	8.7	5.7	7.7	9.2	5.7	7.7	9.0	6.2	7.7	9.7	6.6	7.7
275	1100	7.5	20/40	31.3	35.3	41.	31.3	35.3	41.1	31.3	35.3	41.1	31.3	35.3	41.1
275	1100	9.5	20/40	5.7	4.0	4.6	7.2	6.1	4.6	7.4	—	4.6	7.5	6.6	6.1
100	1100	8.5	30/60	—	—	—	20.6	23.2	21.9	22.3	26.1	24.6	25.1	27.5	24.6
100	200	8.5	30/60	—	—	—	3.2	1.2	1.9	3.6	1.4	1.9	3.7	1.4	1.9
100	200	8.5	40/80	—	—	—	4.7	2.4	1.9	7.7	2.2	1.9	5.0	2.7	2.9
100	200	6.5	0/60	—	—	—	1.2	0.5	14.9	1.4	0.6	15.6	1.4	0.72	15.6
100	200	7.5	0/60	—	—	—	1.7	0.4	0.6	2.4	0.9	1.7	3.3	1.7	2.3
100	200	8.5	0/60	—	—	—	5.1	1.9	1.0	8.7	9.4	3.9	37.5	66.1	25.5
100	200	9.0	0/60	—	—	—	3.2	0.7	1.5	4.5	1.9	6.0	19.8	16.9	15.1
100	1100	8.5	0/60	—	—	—	9.3	1.4	2.7	13.0	5.1	2.7	36.6	32.9	32.7
275	1100	7.5	0/60	3.9	0.4	0.1	8.8	3.6	3.6	10.2	5.2	5.5	30.1	28.9	29.1
275	1100	8.5	0/60	—	—	—	—	—	—	50.5	26.4	25.2	84.4	50.0	47.6

[a] F_w = Influent wastewater flow rate (mL/min)
F_g = Gas flow rate (mL/min)
[S] = Surfactant concentrations (ppm DA/ppm SDS)

were initially more stable than DA/SDS foams, and that this stability increases with pH, although in the case of DA/SDS foams there was a decrease in stability at the highest pH. The increase in foam volume with increasing pH can be attributed to the indirect influence of pH on particle hydrophobicity. Figure 8 shows the electrokinetic behavior of the mixed heavy metal flocs resulting from the increase in pH of the wastewater. At pH values below and near the isoelectric point (7.5), adsorption of the anionic surfactant is favored and the floc would be expected to be

TABLE 4
Total Metal Removal from Electroplating Wastewater[a]

				Total removal at end of foam production (%)			Total removal at t = 30 min (%)			Total removal at t = 60 min (%)			Total removal at t = 120 min (%)		
F_w	F_g	pH	[S]	Fe	Cr	Ni	Fe	Cr	Ni	Fe	Cr	Ni	Fe	Cr	Ni
100	200	7.5	20/40	—	—	—	79	83	78	79	83	77	78	83	77
100	200	8.5	20/40	—	—	—	75	78	78	71	74	74	70	73	73
100	200	9.5	20/40	—	—	—	78	85	90	78	84	90	77	84	90
100	200	10.0	20/40	—	—	—	42	45	51	41	44	51	41	44	51
100	600	8.5	20/40	—	—	—	96	97	95	96	97	95	96	97	95
100	900	8.5	20/40	—	—	—	91	90	89	91	90	89	91	90	89
100	1100	8.5	20/40	—	—	—	82	80	91	82	81	91	81	80	91
200	1100	8.5	20/40	—	—	—	94	94	94	94	—	—	93	93	94
275	600	8.5	20/40	85	87	85	85	87	85	85	87	85	85	87	85
275	1100	8.5	20/40	97	98	96	95	97	94	94	96	94	94	96	94
275	1400	8.5	20/40	94	97	95	94	96	77	93	96	77	93	96	74
275	1900	8.5	20/40	91	94	91	90	94	91	90	94	91	90	94	91
275	1100	7.5	20/40	65	81	77	65	62	77	65	63	77	65	62	77
275	1100	9.5	20/40	87	96	96	87	91	96	87	—	96	87	91	96
100	1100	8.5	30/60	—	—	—	78	77	78	77	75	76	74	73	76
100	200	8.5	30/60	—	—	—	90	96	94	90	96	94	90	96	94
100	200	8.5	40/80	—	—	—	87	90	92	87	90	92	87	90	91
100	200	6.5	0/60	—	—	—	79	83	39	79	82	39	79	82	39
100	200	7.5	0/60	—	—	—	79	87	89	78	86	88	78	86	88
100	200	8.5	0/60	—	—	—	67	71	62	54	69	61	43	57	48
100	200	9.0	0/60	—	—	—	67	76	82	67	75	80	56	65	77
100	1100	8.5	0/60	—	—	—	91	98	97	88	95	97	67	33	67
275	1100	7.5	0/60	89	98	96	87	96	94	86	94	92	68	71	70
275	1100	8.5	0/60	—	—	—	73	—	—	70	75	76	47	56	58

[a] F_w = Influent wastewater flow rate (mL/min)
F_g = Gas flow rate (mL/min)
[S] = Surfactant concentrations (ppm DA/ppm SDS)

hydrophobic. As the pH is raised past a pH of approximately 8.0, the increasing negative charge would inhibit surfactant adsorption and result in a less hydrophobic surface. The increase in foam volume with an increase in pH shown in Fig. 7 reflects this decreasing hydrophobicity. The decrease in foam volume exhibited at very high pH with the DA/SDS mixture could be due to either a change in particle size and/or an increase in particle hydrophobicity. Although the increase in surface charge with

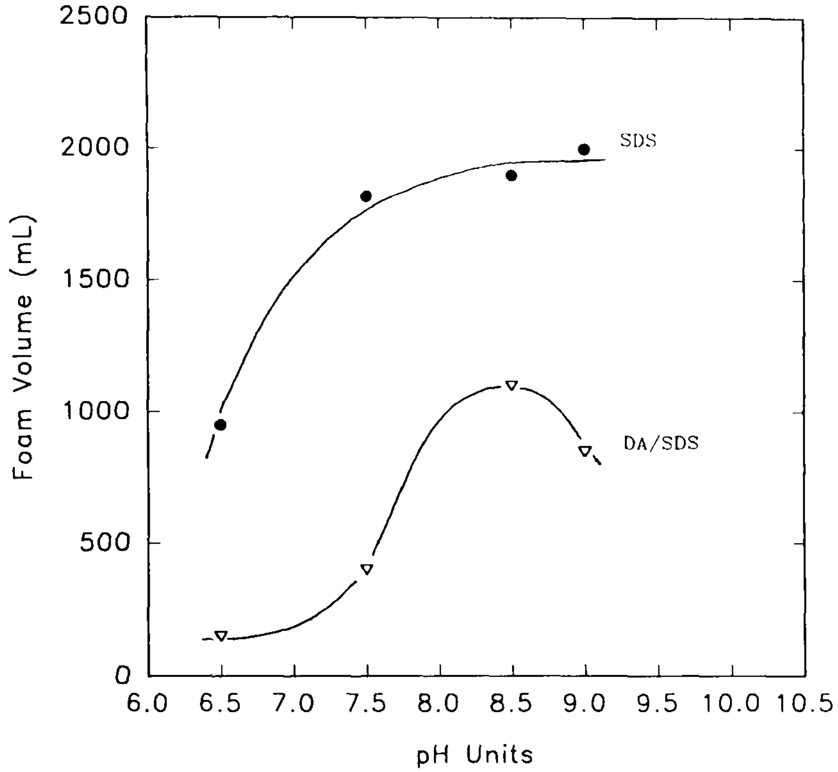

FIG. 7 Maximum volume of foam achieved during foam production stage of experiment as a function of pH.

increase in pH should decrease the floc size due to increased repulsive forces between the particles (i.e., result in a shallower primary minimum in DLVO theory), the increasing surface charge would tend to also provide an increasing electrostatic barrier to adsorption and thus decrease hydrophobicity. To attain an increase in hydrophobicity, a new, more surface active collector species may be envisaged that is formed at the higher pH values (e.g., the alkali metal soap, the acid soap, or the ionic dimer). Thus the data for DA/SDS foams at high pH shown in Fig. 7 suggests that the upper pH level for effectiveness illustrated by the data in Fig. 6 does not necessarily result from poor hydrophobicity as might be intuitively expected. Other factors, such as adsorption kinetics associated with differing surface sites, presumably also play a role.

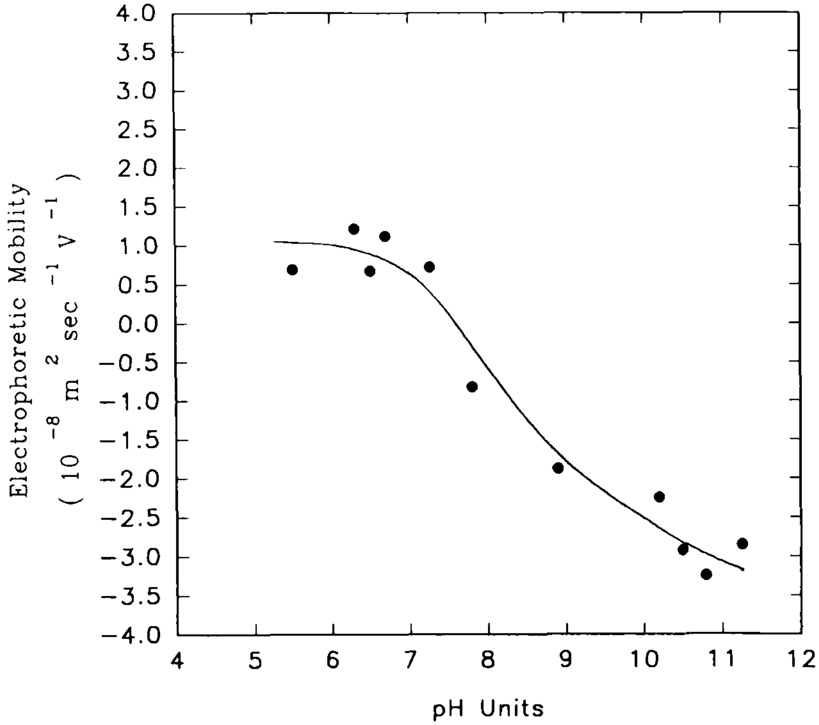

FIG. 8 Electrophoretic mobility of mixed heavy metal flocs as a function of pH.

The effect of gas flow rate on foam volume for flotation with the DA/SDS mixture at pH 8.5 is shown in Fig. 9. There appears to be an optimum air flow rate for maximum volume. For a wastewater throughput of 100 mL/min, the optimum air flow rate for maximum foam volume is 600 mL/min. Air flow rates higher than this result in less foam production, i.e., foam instability. The high turbulence conditions resulting from high air throughput would be conducive to the break-up of loosely held flocs, thus resulting in a larger number of smaller particles or flocs which, if sufficiently hydrophobic and of appropriate size, would have a destabilizing effect on the foam. This is in agreement with results obtained by Dudenkov (19) and Dippenaar (20) who found that well-dispersed hydrophobic particles have a greater foam destabilizing effect than flocculated fine particles. The possibility also exists that the break-up of flocs under conditions of high turbulence could expose more particle surface area which,

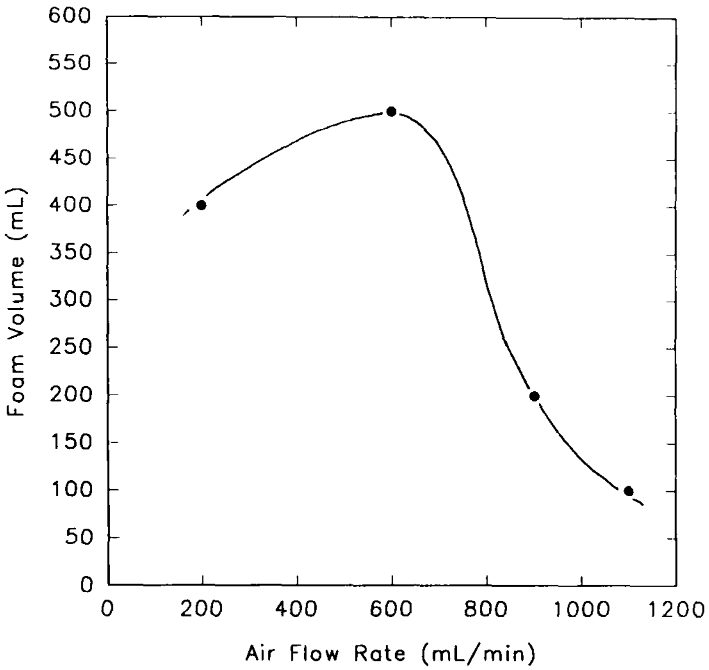

FIG. 9 Maximum volume of foam achieved during foam production stage of experiment as function of air flow rate for flotation with DA/SDS mixture.

due to adsorption, could decrease the amount of surfactant in solution. This, however, does not appear to be the case since an increase in surfactant concentration from 20 ppm DA, 40 ppm SDS to 30 ppm DA, 60 ppm SDS does not improve foam stability (see Table 1). Conversely, the foam instability seen at high air throughputs may be caused by an increase in effective particle size through air entrapment and/or heteroflocculation of bubbles and particles. Dukhin (21) calculated the floatability limits of fine particles with flocculation in the secondary minimum as a function of the potentials of the particle and the bubble. From his calculations it is evident that the range of particle concentrations at which flocculation in the secondary minimum occurs, increases as the product of the potentials of bubble and particle decreases. Hence, as one might expect, heteroflocculation is likely to be favored by low floc (and bubble) surface charge. The effect in the presence of adsorbed surfactant, however, is not clear from these calculations.

Microscopic examination of the flocs in the foam supports the latter mechanism of destabilization of the foam. A large number of small bubbles can be observed in these flocs, as shown in Fig. 10. The effect of increasing wastewater throughput seems to also support the latter mechanism of destabilization. An increase in the number of heavy metal flocs brought about by increasing the wastewater throughput results in larger foam volumes (see Table 1), presumably due to the production of a larger number of smaller bubble/particle aggregates with the available air bubbles. It should be noted that the increase in liquid volume in the foam is not the cause of the greater stability at high water throughputs. This can be seen by the volume of liquid left in the cell at the end of the run (see Table 1). The unstable foams at low water throughput contain more water than the more stable foams at higher wastewater throughput.

The presence of entrapped air bubbles in the heavy metal floc in sufficient quantities renders them sufficiently buoyant to cream at the waterline. This phenomenon has also been observed by Wilson et al. (9) in the clarifier after foam destruction. Slapik et al. (22) encountered the same phenomenon in their study of surfactant recovery from the collapsed foamate. Both groups used spinning disk foam breakers which could be the stage at which air entrapment took place. Little importance was placed

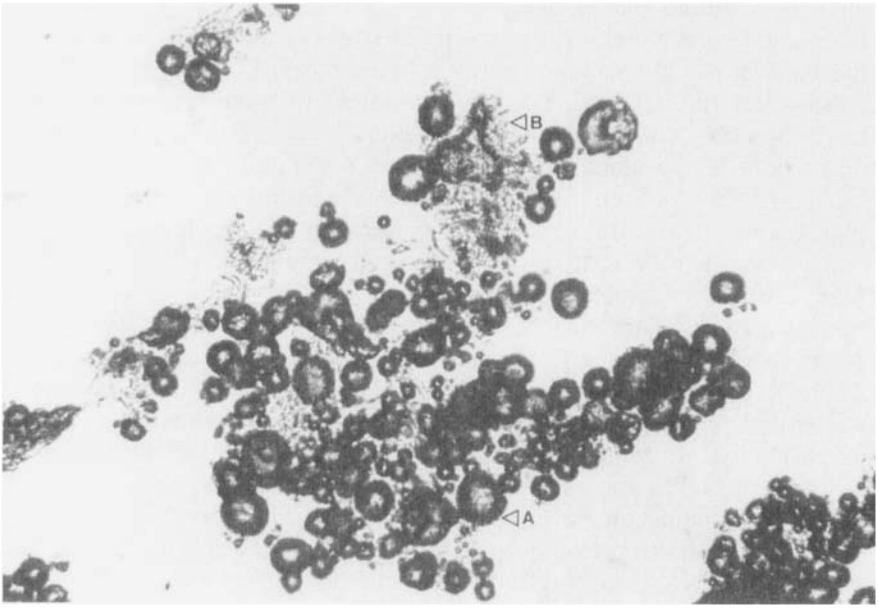

FIG. 10 Mixed heavy metal hydroxides sampled from DA/SDS, pH 8.5 foam at t = 120 minutes. (A) Air bubble, (B) metal hydroxide floc.

on the phenomenon of air entrapment in these studies. We, however, recognize air entrapment as a prerequisite for the complete elimination of the two major factors limiting flotation effectiveness and efficiency: channeling and foam overturning.

Channeling and foam overturning are primarily caused by foam instability, which is the result of the excessive dewatering from drainage resulting from high foam residence times in the column. Increasing the water content of the foam by increasing the air flow rate results in larger volumes of foam *which drain cleanly*. This can be seen from the heavy metal concentrations in the drainage from the foam formed with flotation using SDS alone at $t = 30$ minutes (see Table 2). The water content of these foams was found to depend on pH (see Table 1). Foams of similar water contents were produced by Wilson et al. in their pilot-plant study (9). It was successfully shown that channeling and foam overturning could be eliminated at a given wastewater throughput by using a higher gas flow rate. Using a 10-cm i.d. flotation apparatus with an air flow rate of 4 $L \cdot min^{-1}$, the resulting foamate was 9% of the influent volume. Since it was considered that a smaller volume of collapsed foamate aided disposal, a drier foam was sought, and hence lower air flow rates and lower wastewater throughput were used. Had the foam not been immediately collapsed, it would have been found that the foam drains cleanly at these higher air flow rates and that the inclusion of a separate dewatering stage prior to foam destruction would have allowed them to operate the plant at much higher wastewater throughputs. The larger volumes of foam produced at high gas flow rates with SDS would, however, require large equipment size and would hence make the flotation process much less attractive as a technology for the removal of heavy metals from industrial waste. The high foam volume problem can be minimized by working at lower pH values where the floc hydrophobicity and air entrapment causes *some* foam instability (see Fig. 7). This is, however, not always possible when metals such as Ni are present in the wastewater. The concentration of Ni found in the cell during flotation at pH 6.5 using SDS only is shown in Table 1 to be significant. At this pH nickel is neither fully precipitated nor completely adsorbed onto the carrier floc. Some remains in solution as Ni(II)(aq). Its removal would then only be via ion flotation, and not by the more rapid and efficient precipitate flotation mechanism.

The high foam volume problem can also be minimized by the use of the DA/SDS mixture. Comparison of foam volume results at high gas and water flow rates where high foam volume would be expected (e.g., 275 mL/min wastewater throughput, 1100 mL/min air throughput, pH 8.5) for the two surfactant systems reveals that flotation with SDS alone results in a much larger volume of foam. It is important to note that although excessive foam volume is undesirable, excessive instability during foam production is also undesirable. Hence the drainage from DA/SDS foams with the lowest metal concentrations is observed when the foam volume is the greatest, i.e., under conditions of maximum foam stability (compare foam volume results in Table 1 with the heavy metal concentration in Table 2).

Direct comparison of the data in Table 2 can be misleading since each foam carried over different quantities of liquid and contained different quantities of heavy metal flocs. The ability of the foam to retain metals is characterized by the percentage of heavy metals originally contained in the foam which, during the drainage and decay process, were released to the drained liquid. I.e.,

% Metal release

$$= \frac{\text{quantity of metal in drained liquid}}{\text{quantity of metals originally present in the foam}} \times 100$$

$$= \frac{V_d \times [\mathrm{M}]_d}{[\mathrm{M}]_0 \times V_T R} \times 100 = \mathrm{M}_R$$

where V_d = volume of liquid drained from the foam at the end of the run
$[\mathrm{M}]_d$ = metal concentration in the drained liquid
$[\mathrm{M}]_0$ = metal concentration prior to treatment
V_T = total volume treated
R = removal ratio = $\dfrac{\text{metal concentration in flotation cell } [\mathrm{M}]_c}{\text{metal concentration prior to flotation } [\mathrm{M}]_0}$

The values of percentage metal release over a 2-hour period were calculated and are presented in Table 3. In the interpretation of this data, some distinction must be made between the magnitude of the % metal release (M_R) and the change in % metal release with time [$\Delta \mathrm{M}_R(t)$]. The former can be directly related to the fresh foam volume and stability, the latter is an approximate measure of the persistence of the foam in the drained state. For example, at pH 7.5, influent wastewater flow rate of 275 mL/min, air flow rate of 1100 mL/min, and 20 ppm DA/40 ppm SDS, there is no change in the percentage of metals released into the drained liquid over time. Thus $\Delta \mathrm{M}_R(t)$ under these conditions would be close to zero, indicating a foam which is persistent in its drained state but which was unstable in the initial stages (i.e., drains very cleanly over time despite an initial relatively large release of metal hydroxide).

The data for SDS foams reveals that these foams, when initially formed, drain very cleanly. They are also persistent in the drained state at low pH values (less than isoelectric point). Microscopic examination of the heavy metal flocs remaining in the partially collapsed pH 8.5 SDS foam 2 hours after collection revealed the presence, as was found for the DA/SDS foams at all pH values, of a large number of small bubbles (see Fig. 11). Examination of the flocs released into the drained water by this foam revealed much less air entrapment (Fig. 12). The flocs containing small air bubbles appear to stabilize the foam. A combination of both the buoyancy and high floc concentration results in physical separation of the surfactant films, thus preventing coalescence rather than destroying foam structure as is observed at lower floc concentrations. The low $\Delta M_R(t)$ values achieved for SDS foams at low pH and for DA/SDS foams at all pH values show that, provided the lamellae persist in the formation stage (i.e., the foam is sufficiently stable), they persist as unbroken films in the drainage stage and retain their load of heavy metals. This is in contrast to the results obtained for SDS foams at high pH where high $\Delta M_R(t)$ values are observed, i.e., large amounts of metal flocs are released as the foam decays. These results suggest that there is a threshold value of hydrophobicity and/or low floc surface charge necessary for air entrapment and/or heteroflocculation to take place. This is further suggested by the batch mode data presented in Figs. 3 and 5 where the rate of removal is much greater at low pH values where we also see low $\Delta M_R(t)$ results.

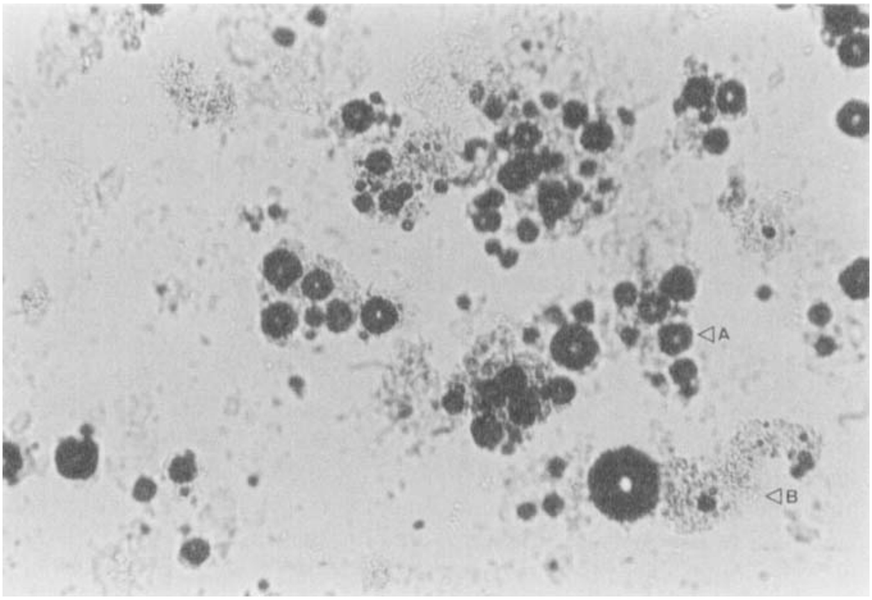

FIG. 11 Mixed heavy metal hydroxides sampled from SDS, pH 8.5 foam at t = 120 minutes.

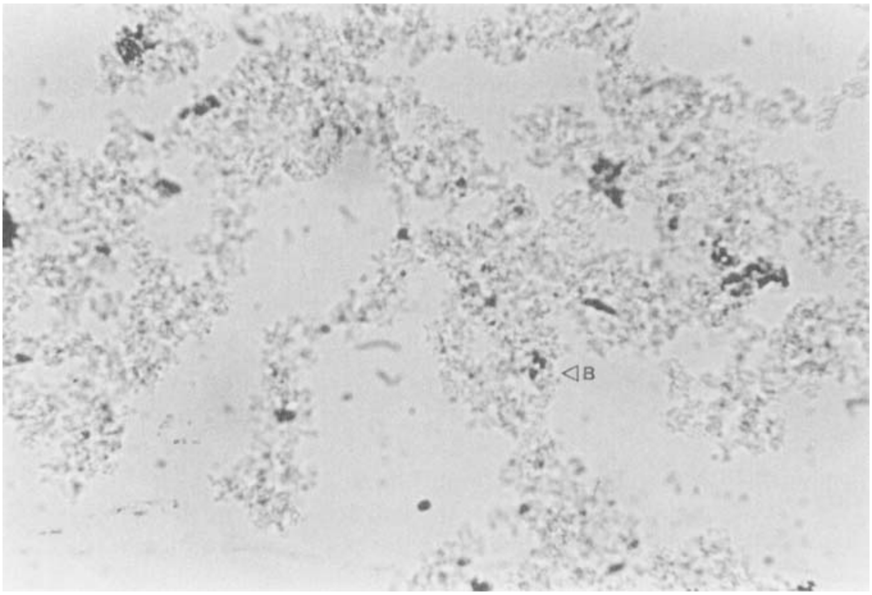

FIG. 12 Mixed heavy metal hydroxides sampled from SDS, pH 8.5 drainage liquor at t = 120 minutes.

Such a pattern is consistent with an increase in effective particle size resulting from the heteroflocculation of particles and bubbles and hence greater collision efficiency in the flotation cell at these pH values. Further work of a more fundamental nature is required to accurately define these parameters in a well-characterized model system. It should be emphasized that low $M_R(t)$ and $\Delta M_R(t)$, and high removal rate, are seen at pH values which correspond to the lowest foam stability (see Table 3, flotation using SDS alone, Fig. 3). If the foam stability is so low as to result in a large release of heavy metals during foam formation in the flotation column (e.g., with the DA/SDS mixture at low pH, Table 3), it may be necessary to decrease the removal rate (i.e., operate at pH values where removal is slower) to accomplish better foam stability (e.g., at pH 9.5 for flotation with the DA/SDS system at 100 mL/min influent wastewater, 200 mL/min air flow rate, 20 ppm DA/40 ppm SDS—see Table 3). If high removal rates are then required, it is possible to increase the rate of removal by increasing the air flow rate. Since foam water content is not a limiting factor, this is not a constraint. The maximum air flow rate which can be used, however, is governed by the foam stability at the higher air flow rates (see Fig. 9).

The data in Table 3 also show that under some conditions very low M_R and $\Delta M_R(t)$ values are achievable. When the foam has these properties it is possible to increase the air flow rate sufficiently to completely eliminate channeling and foam overturning. The high water content of the resulting foam can then be reduced through drainage in a separate stage before foam destruction. Once channeling and foam overturning have been eliminated, two outputs from the flotation column are possible, i.e., from the bottom of the column or from the foam drainage stage. The total heavy metal removal achieved by the flotation column operating in the high liquid carryover mode is thus a function of the volumes and metal concentrations of the two outputs.

$$\text{Total \% removal} = \left(1 - \frac{[M]_c V_c + [M]_c V_a + [M]_d V_d}{[M]_0 V_T}\right) \times 100$$

where $[M]_c$ = metal concentration of liquid exiting the cell
V_c = liquid volume left in the cell at the end of the run
V_a = volume of liquid exiting the cell through outlet A
$[M]_d$ = metal concentration in the drainage liquor
V_d = volume of drainage liquor
$[M]_0$ = metal concentration before treatment
V_T = total volume of wastewater treated

The total % removal for each run was calculated according to the above equation. The results are presented in Table 4. Not surprisingly, it can be seen that the optimum air throughput increases with increasing wastewater throughput. For low water throughputs (100 mL/min), only a moderate quantity of air is required (600 mL/min). Hence, only 26% of the influent volume is carried over with the foam (see Table 1). An increased wastewater throughput to 275 mL/min requires an air flow rate of 1100 mL/min. At this air flow rate, 73% of incoming liquid volume is carried over with the foam. A further increase in wastewater throughput would require air flow rates which result in even greater liquid carryover. Further work is required to determine the maximum attainable wastewater throughput for a given cell geometry and size. This is likely to suggest improvements to be made to existing wastewater treatment plant technology to fully take advantage of flotation in HLC mode.

As stated earlier, channeling and foam overturning are primarily due to foam instability brought about by excessive foam drainage. Foam drainage in flotation is promoted by wider column dimensions, thus the channeling and overturning problems are likely to be accentuated in the scale-up process. Indeed, Wilson et al., in their pilot plant work, found it necessary to increase the number of baffles in the column from 4 to 7 when scaling from 10 cm i.d. to 30 cm i.d. columns. The results presented so far in this paper were obtained using a 4.5-cm i.d. column. With such a narrow column, channeling and foam overturning are rarely seen except under conditions of extreme foam instability. Although there is no doubt that operating at high gas flow rates will alleviate these problems in wide diameter columns, it is not known whether the desirable foam characteristics observed in the small scale (low volume, clean draining), which make operation in HLC mode practically feasible, are reproducible on the larger scale. To test this and begin to investigate the most efficient mode of handling of the foam produced from the adsorbing colloid flotation process, a 10-cm i.d. column was employed (see Fig. 2).

The effect of influent wastewater flow rate, gas throughput, and surfactant concentration on the percentage removal achieved in the liquid sampled from the treated wastewater outlet A (Fig. 2) is shown in Table 5.

TABLE 5
Heavy Metal Removal Achieved in Liquid Sample from Treated Wastewater Outlet A (Fig. 2)

		Initial metal ion levels (ppm) Cr (50–100) Ni (20–70) Zn (1–3)									
		Surfactant concentration (ppm DA/SDS)									
		20/40			30/60			40/80			
Influent flow rate (mL/min)	Gas flow rate (mL/min)	Cr (%)	Ni (%)	Zn (%)	Cr (%)	Ni (%)	Zn (%)	Cr (%)	Ni (%)	Zn (%)	% Volume of influent leaving with foam
100	950	84	75	78	81	72	77	92	83	83	0
100	1400	90	87	91	91	81	90	93	83	92	0
100	1900	97	96	92	95	95	96	96	95	96	0
250	950	75	61	78	85	73	83	85	75	83	0
250	1400	84	67	85	84	80	85	83	79	83	0
250	1900	82	79	85	89	73	88	92	74	91	0
400	950	55	65	64	62	66	70	57	61	54	0
400	1400	70	58	69	78	75	78	77	64	73	—
400	1900	83	83	84	86	84	85	84	82	85	—
400	2300	—	—	—	—	—	—	88	84	90	70
600	2300	—	—	—	—	—	—	82	84	85	—
600	2750	—	—	—	—	—	—	85	84	85	50
1000	4500	—	—	—	—	—	—	81	79	77	60
1000	5000	—	—	—	—	—	—	77	84	83	100
1500	3600	—	—	—	—	—	—	83	79	83	60
1500	4500	—	—	—	—	—	—	86	81	80	100

As may be expected, optimal results were obtained at low influent wastewater flow rates and high gas throughput. Increasing the surfactant concentration from 20/40 to 40/80 ppm DA/SDS has little influence on the removal of metals at high gas flow rates. However, at lower gas flow rates, an increase in surfactant concentration results in a more clearly marked increase in percentage removal. Increasing the influent wastewater flow rate from 100 to 400 mL/min results in a marked decrease in percentage removal for all cases. This trend is minimized by the use of high gas flow rates and/or high surfactant concentrations.

Increasing the influent wastewater flow rate further necessitates the use of higher gas throughputs for good floc removal. This, however, leads to the production of a very wet foam, indicating that much of the influent volume was being carried over with the foam, as shown in the last column of Table 5. Gas flow rates greater than approximately 2 $L \cdot min^{-1}$ were found to result in extremely wet foams. At these high gas throughputs the majority of the water is carried over with the foam, suggesting that the purity of the water draining from the foam (treated wastewater outlet B, Fig. 2) will be more important than that of water remaining in the column (treated wastewater outlet A, Fig. 2).

Liquid draining from the foam (outlet B) during flotation was sampled and analyzed for Cr, Ni, and Zn. The results are given in summary form in Table 6. Comparison of Tables 5 and 6 shows that liquid draining from the foam contains a much lower level of all aqueous heavy metals than

TABLE 6
Heavy Metal Removal Achieved in Liquid Drained from the Foam (Outlet B, Fig. 2)[a]

		Metal		
Effluent flow rate (mL/min)	Gas flow rate (mL/min)	Cr (%)	Ni (%)	Zn (%)
400	950	95	85	90
400	1400	95	82	92
400	1900	94	91	96
400	2300	97	91	98
600	2300	92	92	98
600	2750	98	94	96
1000	4500	97	94	95
1000	5000	95	93	94
1500	3600	97	93	99
1500	4500	99	92	99

[a] Surfactant concentration 40/80 (ppm DA/ppm SDS), initial metal ion levels: 50–100 ppm Cr, 20–70 ppm Ni, and 1–3 ppm Zn.

the liquid from the pool at the bottom of the column. Improved metal removal and higher influent wastewater flow rates can be achieved by closing off the treated wastewater outlet A (Fig. 2) and increasing the gas throughput until all the liquid entering the column exits with the foam. Operating the column in this mode (high liquid carryover, HLC), influent wastewater flow rates as high as 3 L·min^{-1} with a 10-cm i.d. column (hydraulic loadings = 22.9 m^3/m^2·h) were still able to result in excellent removal of heavy metals. The residual metal concentrations after treatment at some of these very high hydraulic loading runs are summarized in Table 7. It should be noted that, due to practical considerations (i.e., pump and reservoir capacities), 3 L·min^{-1} is the highest influent wastewater flow rate attempted with this column. Higher influent wastewater flow rates may still be possible at this scale. Heavy metal concentrations well below the 10 ppm indicative regulatory discharge limits for discharge to metropolitan drains were consistently achieved. Further reductions in these levels may be possible by adopting a two-stage flotation process as outlined and tested by us in an earlier paper (5), but using the HLC mode.

A considerable advantage in operating in the HLC mode is the possibility of a reduction in plant size allowed by operating at such high hydraulic

TABLE 7
Water Quality after Treatment at High Hydraulic Loadings[a]

Metal	Concentration of metals in untreated wastewater (ppm)	Concentration of metals in treated wastewater (ppm)	Influent flow rate (L/min)	Air flow rate (L/min)
Cr	52.5	1.4	1.0	5.0
Ni	23.5	1.3	1.0	5.0
Zn	1.54	0.07	1.0	5.0
Cr	78.5	1.1	1.5	4.5
Ni	54.9	4.4	1.5	4.5
Zn	3.11	0.04	1.5	4.5
Cr	80.5	4.7	2.0	4.8
Ni	58.3	6.6	2.0	4.8
Zn	2.32	0.14	2.0	4.8
Cr	74.2	2.8	2.5	4.8
Ni	52.3	2.7	2.5	4.8
Zn	2.21	0.11	2.5	4.8
Cr	80.8	1.2	3.0	4.8
Ni	55.3	3.2	3.0	4.8
Zn	3.27	0.05	3.0	4.8

[a] HLC mode, 10 cm inner diameter column, surfactant concentration 40/80 ppm DA/ppm SDS.

loadings. However, concomitant with this advantage is the requirement for larger, more complicated collection vessels. Other potential disadvantages of operation in the HLC mode are the increased difficulty of automation of the process and the operating costs that may be associated with the use of surfactants in the concentration range 60 to 120 ppm.

The rapidity of operation in the HLC mode requires an equally rapid mode of foam dewatering (e.g., natural drainage, centrifugation, filtration). The feasibility of the natural drainage mode of dewatering was investigated here. Wide, shallow collection vessels are the most effective in dewatering and concentrating the foam product since they facilitate the drainage process. A stack-type arrangement of trays was employed which would allow the foam to progressively overflow from higher to lower trays while draining. This is shown diagrammatically in Fig. 13. Results obtained with this configuration indicate that dewatering and concentration of the foam resulting from operation of the flotation column in the HLC mode is very efficient. A tray surface area of approximately 0.3 m^2 (2 trays, 35 × 45 cm) was sufficient to achieve a foam product of approximately 5% (by weight) solids content from foam being produced by operating the 10-cm i.d. column at 1 $L \cdot min^{-1}$ for 60 minutes. It is, however, recognized that such a mode of dewatering may be difficult to automate

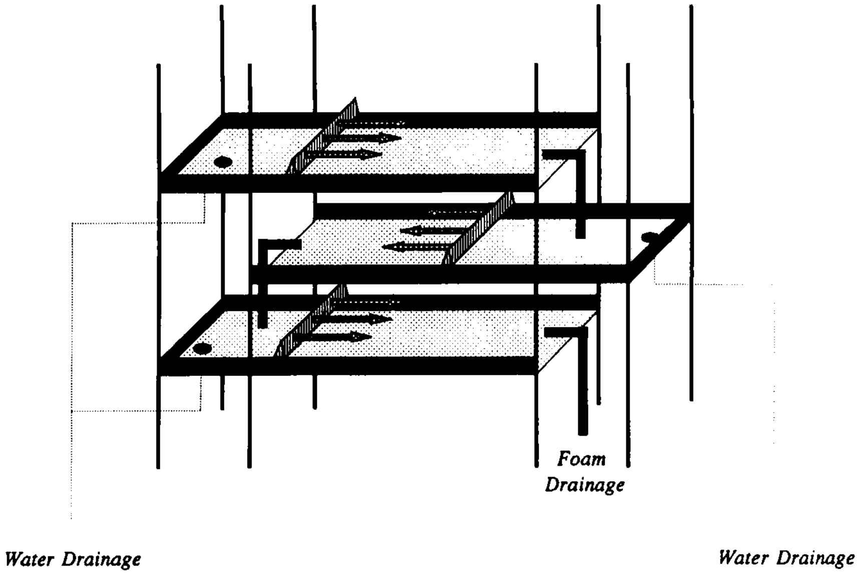

FIG. 13 Tray arrangement used for continuous foam drainage studies.

on a large scale. Long duration runs are required to determine how the automation of the natural drainage process may be controlled.

CONCLUSION

The laboratory-scale continuous flotation data presented in this paper indicates that typical electroplating wastewater samples can be treated by adsorbing colloid flotation with a mixed surfactant system (40 ppm DA/80 ppm SDS) to give aqueous metal ion concentrations well below 5 ppm. A novel mode of operation for the continuous flotation column (high liquid carryover, HLC) was used to avoid channeling and foam overturning, and thus achieve these levels at considerably higher hydraulic loadings than is possible by conventional continuous mode operation using SDS.

Further work is required to determine the most economically feasible mode of foam dewatering and the maximum hydraulic loading, for a given column capacity, that results in good removal rates.

On the basis of the results presented in this paper, adsorbing colloid flotation increases the process options for treating electroplating wastewaters.

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