Floe Foam Flotation of Chromium(VI) with Polyelectrolytes

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Abstract

The separation efficiency of the floc foam flotation of chromium(VI) with Fe(II) from aqueous solutions with high ionic strength can be improved by adding a very small amount of polyelectrolyte (either cationic or anionic polymer) as an activator. The possible mechanisms by which flotation is affected by polyelectrolytes are discussed. The effects of the order of the addition of the reagents (polyelectrolyte and base) on flotation and sedimentation are also studied. It was found that effective separation of chromium(VI) by floc foam flotation with Fe(II) can be achieved for a rather wide range of initial chromium(VI) levels by using the same treatment parameters.

INTRODUCTION

Foam separation techniques have been found to be very effective for removing various heavy metal ions from dilute aqueous solutions. A number of excellent reviews on foam separation are available (1–5). These techniques are based on the fact that surface-active material tends to concentrate at the gas–liquid interface. By bubbling the air through the solution, the surface-active materials, adsorb at the surface of the rising bubble, which then separates it from the solution. The substance to be removed, if not surface active, can be made surface active through union with or adsorption of a surface-active material. Foam separation techniques are subdivided into froth flotation (floc foam flotation), in which particulates

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are removed; and foam fractionation, in which soluble surface-active substances are removed from the solution by adsorption at gas–solvent interfaces. Froth flotation (floc foam flotation) is further divided into a number of somewhat overlapping areas. For instance, adsorbing colloid flotation involves the addition of a coagulant (alum or ferric chloride) to produce a floc. The dissolved metal ion is adsorbed onto the floc particle and/or coprecipitated with it. A surfactant is then added, adsorbs onto the floc particle, and renders it hydrophobic, and the floc (with adsorbed metal) is removed by air flotation. In precipitate flotation a precipitate is formed and then foamed off. The work in this paper involved removing chromium(VI) from aqueous solutions by reducing chromium(VI) to chromium(III) with Fe(II); the resulting precipitate [mainly a mixed precipitate of $Fe(OH)_3$, $Cr(OH)_3$, and possibly some coprecipitated chromium(VI), chromium(III), and Fe(II) with the floc] was foamed off with sodium lauryl sulfate. Because both precipitate flotation (or mixed precipitate flotation) and adsorbing colloid flotation are involved in this separation process, the general term "floc foam flotation" will be used to describe the separation technique used in this study.

When dealing with dilute waste, foam flotation apears to possess some distinct advantages: low residual metal concentrations, rapid operation, low space requirements (important where land costs are high), flexibility of application to various metals at various scales, production of small volumes of sludge highly enriched with the contaminant, and moderate cost. The chemical costs and capital costs of wastewater treatment by adsorbing colloid flotation have been estimated and compared with those of lime precipitation (6–8). Economics appear to favor adsorbing colloid flotation by a substantial margin (7, 8).

There is one distinct disadvantage of precipitate flotation and adsorbing colloid flotation; this is that the separation efficiency decreases with increasing inert salt concentration of the solution (7–12). We have shown that the effect of increasing inert salt concentration on the separation efficiency of adsorbing colloid flotation with $Fe(OH)_3$ as the adsorbing floc can be compensated to quite a large extent with the aid of activators [such as Al(III), Zn(II), and Mg(II) ions] (9–13).

Chromium is widely used as a scratch and corrosion-resistant decorative finish for metals, onto which it is electroplated. Chromium in industrial wastes often occurs in the hexavalent form as chromate (CrO_4^{2-}) and dichromate ($Cr_2O_7^{2-}$) or acid chromatic ($HCrO_4^{-}$). The most commonly used method of hexavalent chromium disposal is its reduction to the trivalent state with a chemical reducing agent such as sulfur dioxide, sodium bisulfite, or ferrous sulfate. The trivalent chromium is then

removed by precipitation, usually with lime (*14*). Wilson's group removed trivalent chromium by adsorbing colloid flotation (*15*).

Foam separations of hexavalent chromium have been developed by a number of investigators (*16–24*). A number of variations of the technique have been used, including foam fractionation, ion flotation, precipitate flotation, and adsorbing colloid flotation; these have been reviewed by Grieves (*19*) and Huang et al. (*12*). Ion flotation has an advantage over foam fractionation in that for ion flotation the precipitation reaction between the surfactant and the metal ion colligend generally requires a surfactant concentration only slightly above stoichiometric, while foam fractionation requires surfactant concentrations well in excess of stoichiometric. Surfactant utilization may be reduced even further by first precipitating the colligend and then floating the precipitate. Grieves et al. removed chromium(VI) from aqueous solution by reducing it with $NaHSO_3$ followed by precipitation of chromium(III) with NaOH, and then the precipitate was removed by flotation with sodium lauryl sulfate (*19*). Huang et al. reported on the removal of chromium(VI) by adsorbing colloid flotation with $Fe(OH)_3$ or $Al(OH)_3$ (*12*). Chromium(VI) was also removed by reducing it to chromium(III) with $FeSO_4$. The resulting precipitate [of $Fe(OH)_3$, $Cr(OH)_3$, and possibly some coprecipitated chromium(VI)] was then removed by a batch foam flotation system (*12*) and by a continuous-flow flotation pilot plant (*24*). The effect of increasing inert salt concentration on the separation efficiency of floc foam flotation of chromium(VI) with Fe(II) can be compensated for somewhat by using Al(III) and Zn(II) as the activators (*9, 12, 13*).

Ore flotation sometimes involves the use of polymers along with surfactants (*25–30*). Usoni et al. (*27*) showed that polymers can enhance or depress flotation depending on the nature, concentration, and duration of contact of the polymers with the mineral. Somasundaran and Lee examined the role of polymer–surfactant interactions on the flotation of quartz by using both anionic and cationic polymers and surfactants; the possible mechanisms by which flotation was affected by the polymers were discussed (*31*).

Sasaki et al. reported a series of studies of ion flotation of cations and anions with polyelectrolytes (*32–34*). In the case of ion flotation of Fe(III) and Cu(II), they remarked that the metallic ions removed by this process were presumably in the state of large metallic hydroxide aggregates carrying a few residual positive charges (*34*). Therefore, this process is precipitate flotation instead of ion flotation.

In this paper we report that the separation efficiency of the floc foam flotation of chromium(VI) with Fe(II) from aqueous solutions with high

ionic strength can be improved by adding very small amounts of polyelectrolyte (either cationic or anionic) as the activator. The possible mechanisms by which flotation is affected by polyelectrolytes are discussed. The effects of the order of the addition of the reagents (polyelectrolyte and base) on flotation and sedimentation are also studied. We report here also the allowed range of the initial chromium(VI) concentration which can yield effective separation (with residual chromium levels less than 0.5 ppm and residual iron levels less than 10 ppm) by using the same set of foam flotation treatment parameters (such as Fe(II) dosage, pH, etc.). These studies are very important for the design of wastewater treatment plants using foam flotation, but have seldom been studied by the investigators of foam separation techniques.

EXPERIMENTAL

The foam flotation system used was similar to that described in earlier reports (*9, 12, 13*). Figure 1 depicts the apparatus used for the batch separations. A soft glass column 90 cm in length with an inside diameter of 3.5 cm was used for the flotation. There was a side arm with a rubber septum near the bottom to inject the collector. The bottom of the column was closed with a rubber stopper with holes for a gas sparger and a stopcock to take samples and to drain the column. The gas sparger was a commercially available gas dispersion tube. A lipped side arm near the top of the column served as a foam outlet.

Compressed air was generated from an air pump, and the gas flow was adjusted with a Hoke needle valve with micrometer control and measured with a soap film flowmeter. The air was purified by passing it through glass wool to remove particulates, Ascarite to remove carbon dioxide, and distilled water for controlled rehumidification.

Laboratory grade sodium lauryl sulfate (SLS) was used as the collector and frother without further purification. The polyelectrolytes used were from Betz (practical grade). Betz 1100 is a weakly anionic acrylamide copolymer. Betz 1160 is a strongly cationic acrylamide copolymer. Both of them are in powder form. 100 ppm polyelectrolyte stock solutions were prepared by adding 0.1 g polyelectrolyte slowly into 1000 mL distilled water with rapid stirring. Fresh stock solution was prepared each week. Reagent grade $Na_2Cr_2O_7 \cdot 2H_2O$, $FeSO_4$, $NaNO_3$, and $NaOH$ were used for sample preparation. The effect of ionic strength variation was studied by adding $NaNO_3$ solution. The air flow rate was maintained at 90 mL/min.
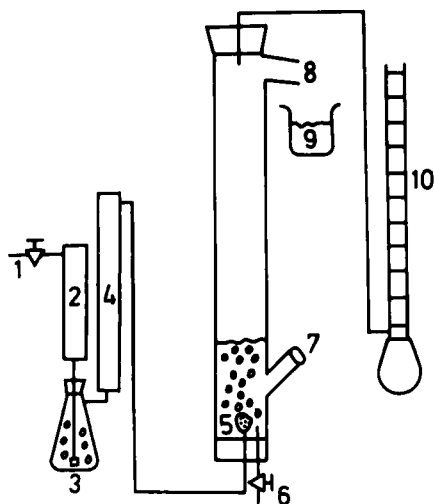
FIG. 1. The apparatus for foam separation. (1) Air needle valve, (2) Ascarite tube for CO_2 removal, (3) humidifier, (4) glass wool column, (5) fritted glass sparger, (6) drain, (7) reagent syringe, (8) foam discharge port, (9) discharged foam, (10) soap film flowmeter.

All experiments were run using 250 mL solution. The initial concentration of chromium was 50 ppm unless specified otherwise. The dosage of Fe(II) was 175 ppm for all runs.

Floc foam flotation of chromium(VI) was performed by reducing chromium(VI) with Fe(II). The solution was stirred for 10 min to allow the redox reaction to go to completion. The duration of all flotation runs was 10 min. The effects of polyelectrolytes on flotation and sedimentation were studied by adding the polyelectrolyte solutions to the sample solutions (before or after the addition of base) with rapid stirring. For the sedimentation experiments the solution was poured into a 250-mL graduated cylinder. 20 mL solution was taken from a point 40 cm below the liquid surface after 30 min. The residual chromium and/or iron levels in the solutions were analyzed.

The pH measurements were made with a Radiometer PHM63 digital pH meter. Concentrations of iron and chromium were measured with a Perkin-Elmer 5000 atomic absorption spectrophotometer (detection limit: 0.01 ppm for iron and 0.004 ppm for chromium).

RESULTS AND DISCUSSIONS

Table 1 shows the influence of pH on chromium removal by floc foam flotation with Fe(II). Residual chromium levels were less than 0.5 ppm for the solutions in the pH range of 5.0 to 8.0 after 10 min of flotation. The higher residual chromium level at pH 4.0 is presumably due to the incomplete precipitation of $Cr(OH)_3$ at lower pH values. The effect of $NaNO_3$ on separation efficiency is shown in Table 2. The residual chromium level was less than 0.5 ppm for the solution containing $NaNO_3$ at concentrations no greater than 0.05 M. The poor chromium removal from solutions containing high concentration of $NaNO_3$ is presumably due to the decrease of the surface potential of the floc by the nitrate ion such that the surface potential of the floc is no longer positive enough for anionic surfactant adsorption.

The effects of adding Betz 1160, the cationic polyelectrolyte, was studied. The effect of the order of the addition of reagent on the floatability is shown in Table 3. The polymer was added either before the addition of base [Cr(VI) + Fe(II) + polymer + OH^- + SLS] or after the addition of base [Cr(VI) + Fe(II) + OH^- + polymer + SLS]. The addition of polymer to the system followed by the addition of base shows better floc floatability than the addition of the reagents in the reverse order. The effect of the order of the addition of the reagents on the sedimentation behavior is shown in Table 4. The residual chromium level in the supernatant (after 30 min standing) was much less if the polymer was added after the addition of base than if the polymer was added before the addition of base. The explanation proposed for the effects of the order of the addition of the polymer and the base on floatability and sedimentation is as follows: When the polymer is added after the formation of the floc by

TABLE 1

The Effect of pH on Floc Foam Flotation of Chromium(VI)[a]

pH	4.0	5.0	5.5	6.0	7.0	8.0
Residual Cr (ppm)	0.70	0.05	0.11	0.08	0.15	0.30

[a]SLS = 60 ppm, initial chromium(VI) = 50 ppm, Fe(II) = 175 ppm, duration of run = 10 min.

TABLE 2
The Effect of NaNO$_3$ on Floc Foam Flotation of Chromium(VI)[a]

NaNO$_3$ (M)	pH	Residual Cr (ppm)				
		4.5	5.0	5.5	6.0	6.5
0		—	0.05	—	0.05	0.08
0.05		0.64	0.30	0.09	0.13	0.17
0.10		0.70	0.55	0.79	0.58	1.10
0.20		3.21	1.30	1.59	1.01	1.57
0.30		—	2.20	2.04	3.06	4.16

[a]All other conditions the same as those in Table 1.

the addition of base, a higher degree of crosslinking of the floc by the polymer can yield larger floc size (which was observed in the experiment), and thus the floc settles faster. The increased size of the floc may also cause the floc to be less floatable if the floc is too heavy. When the polymer is added before the floc is formed, each polyelectrolyte molecule is adsorbed onto a smaller floc particle and causes the floc to be more positively charged, resulting in greater affinity for the anionic surfactant and better floatability. Note that the floatability decreased when too much polyelectrolyte was added, presumably due to the extention of part of the hydrophilic chain into the aqueous solution (part of the polymer chain

TABLE 3
The Effect of the Order of the Addition of Betz 1160 and Base on Floatability[a]

pH	Betz 1160 (ppm)	NaNO$_3$ (M)	Residual Cr (ppm)	
			(+Polymer + OH$^-$)	(+OH$^-$ + Polymer)
5.0	0	0.2	1.13	1.13
5.0	0.3	0.2	0.40	1.58
5.0	0.5	0.2	1.15	1.91
5.0	0.8	0.2	1.55	—
5.0	1.0	0.2	1.70	—
6.5	0.1	0.3	3.60	—
6.5	0.2	0.3	2.69	>5

[a]All other conditions the same as those in Table 1.

TABLE 4

TheEffect of the Order of the Addition of Betz 1160 and Base on Sedimentation[a]

Betz 1160 (ppm)	Cr in supernatant (ppm)	
	(+Polymer + OH$^-$)	(+OH$^-$ + Polymer)
0	0.66	0.66
0.2	0.30	0.14
0.3	0.38	0.11
0.5	0.42	0.20
0.8	0.39	0.11
1.5	0.20	0.10

[a]$NaNO_3$ = 0.2 M, pH = 6.0, initial chromium(VI) = 50 ppm, Fe(II) = 175 ppm, duration of standing = 30 min.

was adsorbed onto the floc) such that the surface of the floc becomes hydrophilic and less floatable.

The effect of dosage of the cationic polyelectrolyte, pH, and ionic strength of the solution on separation efficiency of chromium by floc foam flotation is shown in Table 5. Betz 1160, the cationic polyelectrolyte, was added before the addition of base. Both the average values and standard deviations of the residual chromium levels are given in the table for duplicate runs. For the solutions containing 0.2 M $NaNO_3$, the residual chromium levels were larger than 1.0 ppm if no polymer was added. With the aid of the cationic polyelectrolyte, the residual chromium levels were reduced to levels of less than 0.5 ppm. Note that as little as 0.3 ppm of Betz 1160 was required for effective separation. Separation efficiency was also improved by the addition of Betz 1160 from solutions containing 0.3 M or 0.4 M $NaNO_3$, but the residual chromium levels were greater than 0.5 ppm. Larger amounts of polymer were required for systems with a higher pH. For instance, 0.3 ppm Betz 1160 was required for optimum separation at pH 5.0, while 0.8 and 1.5 ppm Betz 1160 were required for optimum separation at pH 5.5 and 6.0, respectively. This effect may be explained as follows: The surface potential of the floc is less positive (or more negative) with increasing pH of the solution, and therefore a larger amount of cationic polyelectrolyte is required to make the surface potential of the floc positive enough for anionic surfactant adsorption at higher solution pH.

TABLE 5
The Effect of Betz 1160, pH, and $NaNO_3$ on Flotation[a]

			Residual Cr (ppm)		
$NaNO_3$ (M)	Betz 1160 (ppm)	pH:	5.0	5.5	6.0
0.2	0.0		1.31 ± 0.11	1.24 ± 0.11	1.01
0.2	0.2		0.87	—	—
0.2	0.3		0.44 ± 0.05	0.92	—
0.2	0.4		1.06	—	—
0.2	0.5		1.16 ± 0.03	0.67 ± 0.13	—
0.2	0.8		1.48	0.45 ± 0.04	—
0.2	1.0		1.70	1.16	—
0.2	1.5		—	—	0.36
0.3	0.0		2.10	2.04	3.06
0.3	0.2		—	1.88	—
0.3	0.3		2.05	—	—
0.3	0.5		1.20	—	—
0.3	0.8		1.55	1.82	—
0.3	1.0		1.71	—	3.49
0.3	1.5		1.39	—	2.36
0.3	2.0		1.59	—	>5
0.4	0.0		2.97	—	—
0.4	0.2		2.08	—	—
0.4	0.5		2.40	—	—
0.4	0.8		2.70	—	—

[a]Initial chromium(VI) = 50 ppm, Fe(II) = 175 ppm.

The effect of the anionic polyelectrolyte, Betz 1100, was also studied. The effect of the order of the addition of Betz 1100 and base on sedimentation behaviors is shown in Table 6. Larger floc size and less residual chromium levels were found when Betz 1100 was added after the addition of base than when the addition of the reagents was made in the reverse order. The reason for this effect is similar to that for the effect of the order of the addition of Betz 1160 and base to the systems. Adding polyelectrolyte after the formation of the floc (by the addition of base) resulted in a higher degree of crosslinking of the floc by the polyelectrolyte. Note that both anionic and cationic polyelectrolyte can be adsorbed onto the floc

TABLE 6
The Effect of the Order of the Addition of Betz 1100 and Base on Sedimentation [a]

		Cr in supernatant (ppm)	
$NaNO_3$ (M)	Betz 1100 (ppm)	(+Polymer + OH^-)	(+OH^- + Polymer)
0.2	0.0	0.65	0.65
0.2	0.2	0.37	0.08
0.2	0.3	0.37	0.14
0.2	0.5	0.62	0.12
0.2	0.8	0.57	0.10
0.3	0.0	0.32	0.32
0.3	0.2	0.37	0.08
0.3	0.3	0.33	0.09
0.3	0.5	0.71	0.11
0.3	0.8	0.61	0.12

[a]pH = 6.0, duration of standing = 30 min, initial chromium(VI) = 50 ppm, Fe(II) = 175 ppm.

particle and cause the floc to coagulate, presumably due to the inhomogeneity of the charge distribution on the floc surface.

The effects of dosage of Betz 1100, ionic strength, and pH on the separation efficiency of chromium by flotation with Fe(II) are shown in Table 7. Betz 1100, the anionic polyelectrolyte, was added after the addition of base. Somewhat surprisingly, the separation efficiency of chromium from solutions of high ionic strength can also be improved by the addition of a suitable amount of anionic polyelectrolyte. For instance, effective separation with a residual chromium level of less than 0.5 ppm was achieved from a solution containing 0.2 M $NaNO_3$ at pH 6.0 by adding 0.3 ppm Betz 1100. The separation efficiency was also improved for a solution containing 0.3 M $NaNO_3$ by adding Betz 1100. The reason for the improvement in separation of chromium by floc foam flotation with the addition of Betz 1100 is proposed to be as follows: The surface potentials of the floc particles are rather variable; some of the floc may have a net negative charge on the surface even through the average surface potential of the floc is positive (this is especially true if the average surface potential of the floc is not high). During the flotation process, the positively charged floc is floated with the anionic surfactant, while the negatively charged (or less

TABLE 7
The Effect of Betz 1100, pH, and $NaNO_3$ on Flotation[a]

NaNO₃ (M)	Betz 1100 (ppm)	pH:	5.0	5.5	6.0	6.5
				Residual Cr (ppm)		
0.2	0		1.36	1.32	1.10	—
0.2	0.2		1.54	1.40	0.59	—
0.2	0.3		1.58	1.15	0.48	—
0.2	0.5		1.62	—	1.12	—
0.3	0		2.04	2.23	3.59	4.06
0.3	0.2		2.18	1.62	2.20	5.97
0.3	0.3		2.24	1.58	1.04	4.79
0.3	0.4		—	1.61	1.97	—
0.3	0.5		2.14	1.67	1.94	4.77
0.3	0.6		—	—	1.96	6.72
0.3	0.8		2.10	1.54	2.98	—

[a]Initial chromium(VI) = 50 ppm, Fe(II) = 175 ppm, SLS = 60 ppm, duration of runs = 10 min.

positively charged) floc remains in solution. With the addition of Betz 1100, the negatively charged floc (or less positively charged floc) may be coagulated with other positively charged floc by the mechanism of crosslinking by the polyelectrolyte; the coagulated floc is then carried out from the solution by flotation and results in better separation efficiency. Furthermore, Betz 1100 is a weakly anionic organic polymer; the hydrophobic part of the polymer may increase the surface activity of the floc and improve its floatability when the polymer is adsorbed onto the floc. The addition of a large excess of Betz 1100 results in poor separation, presumably due to a decrease in the surface potential of the floc caused by the adsorption of the anionic polyelectrolyte, and therefore the affinity for anionic surfactant on the floc surface is decreased. Coagulation of the floc by the addition of Betz 1100 may also result in poor separation if the floc is too heavy.

The effect of varying the initial chromium(VI) and $NaNO_3$ concentrations on the separation efficiency is shown in Table 8. The dosage of Fe(II) was 175 ppm for all the runs. The residual chromium levels were

less than 0.5 ppm for solutions containing 10 to 65 ppm chromium initially when the flotation was run at pH 5.0. Note that 175 ppm Fe(II) is not enough to reduce as much as 65 ppm chromium(VI) to chromium(III); some of the chromium is carried out in the hexavalent state by the mechanism of coprecipitation with the floc, as we proposed in an earlier paper (*12*). The allowed range of initial chromium levels that can achieve effective separation with residual chromium levels of less than 0.5 ppm decreases with increasing $NaNO_3$ concentration of the solution. The residual iron levels after flotation are shown in Table 9. The residual iron levels increase with decreasing initial chromium(VI) concentrations. This is presumably due to the high solubility of Fe(II). The residual iron level will be high if the Fe(II) added is not completely oxidized to Fe(III) by the chromium(VI) in the solution. The allowed range of initial chromium(VI) levels that can be effectively separated to residual chromium levels of less than 0.5 ppm and residual iron levels of less than 10 ppm by flotation with 175 ppm Fe(II) and 60 ppm SLS at various pH values is summarized in Table 10. It appears that effective separation can be achieved for a rather wide range of initial chromium(VI) levels by using the same treatment conditions.

CONCLUSION

The separation efficiency of the floc foam flotation of chromium(VI) with Fe(II) from aqueous solutions of high ionic strength can be improved

TABLE 8
The Effect of Initial Chromium(VI) and $NaNO_3$ Concentration on Flotation of Chromium[a]

					Residual Cr (ppm)					
$NaNO_3$ (*M*)	pH	Initial Cr (ppm):	10	20	30	35	40	50	60	65
0	5.0		0.17	0.16	0.12	0.15	0.16	0.05	0.22	0.22
0	6.0		0.10	0.12	0.06	0.04	0.04	0.05	0.34	0.94
0	6.5		0.03	0.05	0.03	0.08	0.04	0.09	0.79	2.33
0.05	6.0		0.06	0.10	0.12	0.17	0.11	0.13	0.31	0.86
0.05	6.5		—	0.18	0.23	0.31	—	0.27	1.57	2.89
0.10	6.0		—	0.22	0.09	0.28	0.40	0.53	0.76	2.47
0.10	6.5		—	0.21	0.43	0.52	0.64	0.10	1.58	3.82

[a]Fe(II) = 175 ppm, SLS = 60 ppm, air flow rate = 90 mL/min.

TABLE 9

The Effect of Initial Chromium(VI) and $NaNO_3$ Concentration of Flotation of Iron[a]

NaNO₃ (M)	pH	Initial Cr (ppm):	10	20	30	35	40	50	60	65
0	5.0		113.1	88.9	49.2	23.7	20.4	4.8	0.2	0.2
0	6.0		68.2	23.6	3.7	0.4	0.4	0.3	0.2	0.1
0	6.5		10.0	8.4	6.2	0.2	0.2	0.1	0.1	0.1
0.05	6.0		—	—	13.3	5.7	0.4	0.2	0.2	0.1
0.05	6.5		—	14.6	0.8	1.0	—	0.2	0.7	0.8
0.10	6.0		—	58.4	25.3	10.1	2.8	0.6	0.2	0.1
0.10	6.5		—	6.8	5.2	1.6	1.8	1.6	1.1	0.8

Column header spanning 10–65: Residual Fe (ppm)

[a]Fe(II) = 175 ppm, SLS = 60 ppm, air flow rate = 90 mL/min, duration of runs = 10 min.

TABLE 10

The Allowed Range of Initial Chromium(VI) for Effective Separation by Flotation[a]

NaNO₃ (M)	pH:	5.0	6.0	6.5
0		50–60	30–60	10–50
0.05			35–60	10–50
0.10			35–40	20–35

Column header spanning 5.0–6.5: Initial Cr (ppm)

[a]Fe(II) = 175 ppm, residual Cr less than 0.5 ppm, residual Fe less than 10 ppm, NLS = 60 ppm, duration of flotation = 10 min, air flow rate = 90 mL/min.

by adding very small amounts of polyelectrolytes (either Betz 1160, a cationic polyelectrolyte, or Betz 1100, an anionic polyelectrolyte). Because as little as 0.3 ppm polymer is needed to improve separation from a solution containing $0.2\,M\,NaNO_3$, the amount of sludge produced by the addition of polymer will be less than that produced by using Al(III) and Zn(II) as activators (9, 12, 13).

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