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Alternating Current Electrocoagulation for Superfund Site Remediation

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Alternating Current Electrocoagulation for Superfund Site Remediation

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The Superfund Innovative Technology Evaluation (SITE) Emerging Technology (ET) Program, authorized under the Superfund Amendments and Reauthorization Act (SARA) of 1986, implements the goal of the SITE Program to promote, accelerate the development of, and make commercially available alternative innovative treatment technologies for use at Superfund sites.

Under this program, the technical and economical feasibility of alternating current electrocoagulation (ACE) developed by Electro-Pure Systems, Inc., was evaluated for a two-year period. ACE is an electrochemical technology where highly-charged aluminum polyhydroxide species are introduced into aqueous media for the removal of suspended solids, oil droplets and soluble ionic pollutants. ACE can break stable aqueous colloidal suspensions of up to 10 percent total solids and stable emulsions containing up to 5 percent oil.

Major operating parameters have been defined for different classes of effluents based on experimental results using complex synthetic soil slurries and metals. Test results indicate that ACE produces aqueous and solid separations comparable to those produced by chemical flocculent additions, but with reduced filtration times and sludge volumes. The technology has application where removal of soluble and suspended pollutants from effluents is required, and in the recovery of fine-grained products from process streams. The technology, however, has not yet been demonstrated at full-scale for Superfund site remediation. The principal results of the SITE research program, and results of ACE treatment on some different classes of industrial effluents not part of the SITE Program, are summarized.

Alternating current electrocoagulation (ACE) was originally developed in the early 1980s to break stable aqueous suspensions of clays and coal fines produced in the mining industry.¹⁻⁴ The technology was developed as a replacement for primary chemical coagulant addition to simplify effluent treatment, realize cost savings and facilitate recovery of fine-grained coal.⁵

Traditional treatment (chemical coagulation) of such effluents and other colloidal suspensions entails the addition of inorganic salts (e.g., aluminum or ferric sulfate) and sometimes, organic polymers to prompt flocculation of fine particulates. The salt disassociates and the cations form polyhydroxide species with available

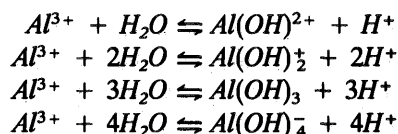
hydroxide ions in the solution. Destabilization occurs by the polyhydroxide species neutralizing the negative charges associated with these particles at neutral or alkaline pHs. This enables the particles to overcome repulsive forces and come in close enough proximity that van der Waals attractive forces prompt their aggregation.^{6,7} The flocculated materials are then separated by sedimentation or filtration. A disadvantage of traditional chemical coagulation is that voluminous sludges, with high boundwater content, which are slow to filter and difficult to dewater are often generated.

The ACE technology differs from chemical coagulation by the manner in which the aluminum polyhydroxide

species are generated and introduced into the waste stream to be treated. Controlling this process are the following mechanisms:

1. Electrocoagulation, whereby the suspended particles are stripped of surface charges under an alternating electrical field in a highly turbulent stream.
2. Electroflocculation, whereby minute quantities of metal hydroxide are formed from the dissolution of the electrodes to assist in the flocculation of suspended particles.

The metal used to produce the polyhydroxides for electroflocculation is aluminum supplied in the form of small elemental pellets through which the solution passes. The aluminum metal dissolves slowly, producing aluminum ions. These ions can then combine with water to form the aluminum hydroxide species⁸ listed below:



No extraneous ions are added to the waste and only minor amounts of hydrogen are generated.

The charged hydroxide species are responsible for neutralizing the surface charges associated with suspended or precipitated solids. All hydroxide species may participate in the precipitation of other metal ions in solution. Although the electroflocculation mechanism resembles chemical coagulation in that cationic species are re-

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sponsible for the neutralization of surface charges, the characteristics of the electrocoagulated floc differ dramatically. Electrocoagulated flocs tend to contain less bound water, are more shear resistant, and are more readily filterable.⁹ Additional theoretical information on the electrocoagulation process can be found in the references.

The ACE Technology can be configured by one of two designs of the ACE Separator™: (1) a parallel electrode unit in which a series of parallel, vertically-oriented aluminum electrodes form a series of monopolar electrolytic cells through which the effluent passes (Figure 1), and (2) a fluidized bed unit with nonconductive cylinders equipped with nonconsumable metal electrodes between which a turbulent fluidized bed of aluminum alloy pellets is maintained (Figure 2).^{10,11} Test results indicate the fluidized bed unit dissolves aluminum at least one order of magnitude more efficiently than the parallel unit. Thus, results reported here are from experiments with the fluidized bed ACE Separator™.

Within the fluidized bed unit, application of an alternating current (AC) electric field to the electrodes induces dissolution of the aluminum pellets and the formation of the polymeric hydroxide species. Charge neutralization and particle growth is initiated within the electrocoagulation cells, and continues following discharge of the aqueous medium from the apparatus. (In this way, product separation into solids, water and oils may be achieved.) Compressed air injection into the electrocoagulation cells can be used to assist in maintaining the turbulent fluidized bed, and enhancing the aluminum dissolution efficiency by increasing the anodic surface area.

Experimental Design

Preliminary laboratory testing of the ACE technology on solutions of various compositions of clays, metals and petroleum constituents were encouraging. These experiments indicated that electrocoagulation operating conditions were highly dependent upon the chemistry of the aqueous medium, especially the conductivity. Other influent characteristics such as pH, particle size and chemical constituent concentrations were found to influence attainment of the optimum operating conditions. Treatment generally required the application of low voltage (<150 VAC) to the electrocoagulation cell electrodes; current usage is typically 1 to 5 amp-min/L.

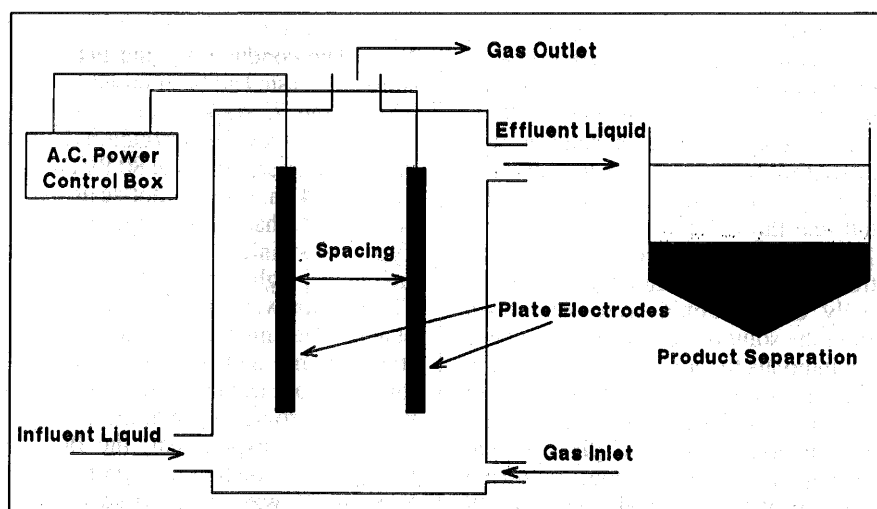


Figure 1. Schematic of a parallel electrode ACE Separator used in alternating current electrocoagulation.

Based on the findings from laboratory experiments, bench-scale testing was undertaken with the principal focus on evaluating and defining optimal operating variables for specific waste types. To provide a comparison with conventional alum (aluminum sulfate) treatment, aqueous waste solutions were split and subjected to treatment by the ACE technology and alum coagulation. A description of the bench tests performed are presented below.

The bench-scale fluidized bed ACE Separator™ was fabricated from eight horizontally-oriented 32.00-mm (1.25-in diameter), 51-mm (2-in.) high segments of 316 stainless steel separated by 13.0-mm (0.5-in.) segments of 32.00-mm (1.25-in.) inside diameter translucent polyethylene tubing. Hose clamps were used to secure the polyethylene tubing overlap onto the stainless steel electrodes. Alternate electrodes were connected to the same polarity such that at any instant the electrodes would be powered in the configuration: positive, negative, positive, etc. Pieces of plastic window screen (nominal opening 1 mm) were installed at the base and top of the electrocoagulation cell to support and maintain a bed of aluminum pellets (-8 to +16 mesh Sphery Shot manufactured by Reynolds Metals Company, Richmond, Virginia) within the electrode cell. At the top of the electrocoagulation cells a 25-mm (1-in.) diameter, 15-cm (6-in.) long glass pipe was installed to provide sufficient headspace to allow the fluidized bed to surge upwards and to fall backwards down into the cell. The total height of the apparatus, including the inlet and outlet glass ports, was 91.5 cm (36.0 in.). The electrocoagulation cells contained 600 g of aluminum shot and ap-

proximately 0.5 L of solution. During an experiment, the solution undergoing electrocoagulation is pumped by means of a peristaltic pump in an up-flow mode through the electrocoagulation cells at a rate sufficient to fluidize the aluminum pellets, but slow enough not to jam the fluidized bed pellets against the upper screen. Typical solution throughput rates may vary between 0.75 and 1.0 L/min. Following the discharge from the top of the electrocoagulation cell, the treated solution flows down by gravity into the treated solution reservoir.

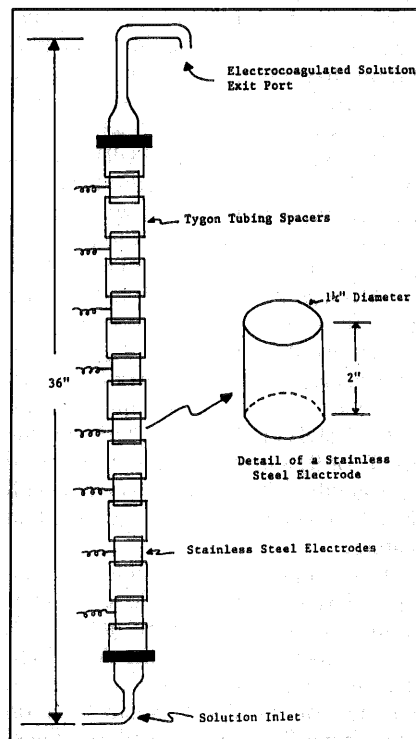


Figure 2. Schematic of a fluidized bed ACE Separator used in alternating current electrocoagulation.

Initially, separate stock solutions of zinc, copper and nickel were prepared by dissolving metal salts to produce a metal ion concentration of 100 mg/L. The conductivity of each solution was adjusted to 1500 or 3000 micro-Siemens per centimeter ($\mu\text{S}/\text{cm}$) to determine the effect of conductivity. A 16 L volume of each solution was electrocoagulated and aliquots of the partially treated liquid were withdrawn from the solution reservoir at two minute intervals to monitor the progressive reduction of the metal contaminant from the aqueous phase. In some instances, a reduction in solution pH occurred during electrocoagulation, requiring adjustment to neutral pH. The current density (amperes) and retention time were recorded and the resultant supernatant metal and aluminum concentrations mapped with respect to these variables. From this, the optimal current densities and retention times were determined.

Bench-scale tests were then performed on surrogate waste streams containing varying proportions of emulsified diesel fuel, metals and clay. These surrogate wastes were prepared to resemble those that might be expected as a result of leaking underground storage tank (UST) remediation or from soil washing operations. The primary objective of such testing was to establish the optimum operating conditions for the ACE Separator™ to break the oil/water emulsion and achieve reductions in the clay suspended solids and soluble metal pollutant loadings. Experiments were conducted on surrogate wastes prepared by mixing 0.2 to 3.0 wt. percent of the 230 mesh (clay and silt) fraction of the U.S. EPA's Synthetic Soil Matrix (SSM) with 0.5 to 1.5 wt. percent Number 2 diesel fuel, 0.05 to 0.10 wt. percent of an emulsifier (Titon-100X or Alconox soap), and 10 to 100 mg/L of one or more of the following contaminants: copper, nickel, zinc, orthophosphate, or fluoride. The pH of each surrogate mixture was adjusted with either NaOH or CaO to the desired value (5, 7, or 9) and the conductivity raised to roughly 1200 to 1500 $\mu\text{S}/\text{cm}$ with NaCl to simulate values expected in nature.

Using operating parameters developed during the bench-scale tests, pilot-scale test conditions were defined. A 12 hr experiment using the ACE Separator™ was conducted on 208 L batches of surrogate waste solution containing 0.2 wt. percent SSM fines, 0.5 wt. percent diesel fuel, 0.05 wt. percent Alconox surfactant, and 10 mg/

L each of Cu^{2+} , Zn^{2+} , PO_4^{3-} , F^- , and Ni^{2+} . The conductivity and pH of the surrogate waste had been raised to 1200 $\mu\text{S}/\text{cm}$ and 7, respectively. This surrogate was recycled through a 10 cm (4 in.) diameter, Schedule 80 PVC pipe, 61 cm (24 in.) high pilot-scale ACE Separator™, that was equipped with two Type 316 stainless steel electrodes (61 cm [24 in.] high, 6.5 cm [2.5 in.] wide). The interior was filled with aluminum pellets. The unit was powered at a constant 20 amp and the voltage was allowed to vary as the electrocoagulation treatment progressed over the 12 hr period. In this experiment, the flow of the surrogate solution through the ACE Separator™ was varied from 4 to 23 L/min (1 to 6 gpm) and the quantity of compressed air introduced into the solution feed line ranged up to a maximum of 10 psig. Samples of the surrogate solution were collected at various times throughout the experiment to document the rate of aluminum ion generation, and the reductions in concentration of the metal contaminants, chemical oxygen demand (COD) and total suspended solids (TSS).

The pilot-scale experimental apparatus consisted of a 100 L Nalgene tank equipped with a heavy-duty shear mixer that served as the surrogate waste reservoir. A centrifugal pump fed the surrogate waste from the Nalgene reservoir to the base of the ACE Separator™, where it would flow upwards between the stainless steel electrodes and fluidize the aluminum particles. A bypass line from the pump discharge line could be valved to direct a portion (or all) of the pumped surrogate back into the Nalgene reservoir. This piping arrangement allowed the flow rate of the surrogate solution into the ACE Separator™ to be regulated. The ACE Separator™ was placed on a laboratory bench to allow the electrocoagulated solution to flow by gravity from the top of the electrocoagulation cell back into the Nalgene reservoir tank. A copper heat exchange coil was placed into the reservoir tank to circulate cold tap water through the partially treated surrogate solution in the reservoir for temperature control. The ACE Separator™ was powered with a Powerstate

Type 3PN136B variable output (0-140 VA) transformer.

Finally, a demonstration model, capable of treating 57 L/min (15 gpm) was developed to more rigorously test the technology. This unit had four electrocoagulation cells and was equipped with a 24 KVA transformer for downstepping input power of 240 VAC-100 amp/460 VAC-50 amp to the desired operating ranges. The waste streams treated in this demonstration unit were effluents produced from treatment of titanium dioxide (TiO_2) from a paint manufacturing operation. The objective was to recover the TiO_2 .

Results and Discussion

Based upon the bench-scale experiments conducted on the surrogate wastes, the following findings were reported:

- Electrocoagulation provided approximately 83 percent less sludge volume and a 76 percent improvement in filtration rate compared to alum treatment.
- Aluminum or stainless steel may be used as electrode material for the fluidized bed configuration with comparable results.
- The agglomerated particles tend to disaggregate with both increased frequency for the AC current and increased retention time.

Optimum operating conditions resulting from these studies are shown in Table I.

Pilot-scale studies conducted on the surrogate waste reported the following findings: electrocoagulation reduced the TSS (220 mg/L to 4.5 mg/L), total organic carbon (TOC) (130 mg/L to 6.6 mg/L) and spiked metal concentrations (Table II). For example, copper was reduced by 72 percent, cadmium by 70 percent, chromium by 92 percent, and lead by 88 percent. No appreciable change in total solids (TS) loadings in the supernate resulted from electrocoagulation. These results are shown in Table II.

Particle size analyses confirm the appreciable enhancement of this parameter in the clay fraction as a result of electrocoagulation. The mean par-

Table I. Optimum operating conditions as a result of bench-scale tests.

Parameter	Value
current	4 amp
electrode spacing	13.0 mm (0.5 in.)
retention time	3 to 5 min.
frequency	10 hz
submergence	fully submerged

Table II. Electrocoagulation of metals-spiked soil slurries.

Analytical Parameter	Untreated Slurry (mg/L)	ACE Separator™ Treated		
		Supernate (mg/L)	Filtrate (mg/L)	Filter Cake (µg/g)
Total Solids	1870	1480	*NA	<1,000,000
Total Suspended Solids	220	4.5	*NA	*NA
Total Organic Carbon	130	6.6	*NA	*NA
Total Metals: Cadmium	0.50	0.150	0.28	290
Chromium	0.31	0.024	0.01	720
Copper	0.30	0.085	0.44	650
Lead	0.72	0.90	0.16	3700

* Note: NA = parameter not analyzed

ticle diameters of the ACE Separator™ treated particulates both in the supernate and the filtrate (188 µm and 230 µm, respectively) have increased by a factor of approximately 85 and 105, respectively, over that in the original slurry (2.2 µm).

The experimental data indicated that after 30 min of treatment, in excess of 90 percent of the metals and phosphate were removed. The data also showed that the aluminum generation rates are highest when the throughput flow rate is <15 L/min (4 gpm). This upper flow limit may reflect compaction of the fluidized bed aluminum pellets against the upper screen of the electrocoagulation cell, thus placing them out of the range of the electrodes. As the emulsion is destabilized, the surrogate solution likely becomes less resistive to ion mobility, thereby improving the operational efficiency of the ACE Separator™.

As a part of these pilot-scale efforts, a comparison of the effectiveness of ACE Separator™ treatment, alum addition, and polymer coagulation was made. The comparison included such parameters as:

- **TSS:** ACE Separator™ treatment and the polymer treatment yielded equivalent results for the reduction of TSS and TS in the treated supernates. TSS values for alum treatment were 4 to 5 times greater than for ACE Separator™ treatment or polymer treatment.
- **COD:** ACE Separator™ treatment resulted in the highest COD reductions of the three methods. Removal efficiency for COD was considerably higher (from 2 to 4 times higher) than removal efficiency for either alum treatment or polymer treatment.
- **Lead:** ACE Separator™ treatment achieved approximately 66 percent removal of lead in the high metals runs, while polymer treatment showed a slightly higher removal (71 percent). Some

difficulties were experienced with the alum treatment, thereby invalidating these test results. Further ACE Separator™ treatments of low metals concentration slurries yielded the highest lead removal (96 percent).

- **Copper:** Copper in the supernate achieved dramatic removal by electrocoagulation in both the high (90 percent reduction) and low (99 percent reduction) metals concentration experiments. However, in the former, polymer and alum addition achieved greater removal (approximately 100 percent reduction).
- **Chromium:** ACE Separator™ treatment resulted in good removal for total chromium (87 percent and 94 percent reductions for the high and low concentrations). Alum and polymer addition accomplished similar results.
- **Cadmium:** Cadmium levels in the supernates dropped as a result of ACE Separator™ treatment: 14 percent in the high metals runs and 99 percent in the low metals tests. The inconsistency between these two sets of experiments, as well as the high concentrations remaining in the supernates and filtrates, raise questions about the accuracy of the high metals concentration experimental results. For the low metals tests, the cadmium concentrations in both ACE Separator™ filtrates were much lower than for either alum or polymer treatment.

Field Demonstration - A Case Study

An industrial waste stream was selected for the field demonstration of the ACE Separator™. The following discussion presents the results of this effort.

In the manufacturing of high-grade TiO₂ pigment, rotary drum vacuum filters are used for final product recovery.

The filtrate produced in this operation is moderately conductive (7,000 to 12,000 µS/cm), has a neutral pH (6 to 8), and typically contains several thousand mg/L of fine-grained pigment (<0.30 µm in diameter). The filtrate is generally transferred to a clarifier sized to provide sufficient retention time (approximately 12 hr) to enable a majority of the suspended TiO₂ to settle out of solution. The operating efficiency of such clarifiers depends on several parameters, including the influent solids loading and its chemical nature. Generally, 70 to 80 percent of the pigment in the influent stream will settle out and be captured in the clarifier underflow stream. Polymer or metal salt addition to the clarifier itself (or to its overflow), to encourage settling of the remaining entrained TiO₂, is not practiced due to the adverse effect on the quality of the settled pigment.

Electrocoagulation of a 115-L/min stream of the clarifier overflow (11,050 µS/cm conductivity, pH 6.7) containing approximately 1100 mg/L TiO₂ with an ACE Separator™ at 60 VAC, 77 amp with a current usage of 2.1 amp-min/L coagulated essentially all of the entrained TiO₂ to produce an effluent stream containing from 10 to 35 mg/L TSS. Recoveries from 85 percent to >99 percent were achieved, depending on the extent of electrocoagulation. Recovery of 90 percent of the overflow pigment required low electrical energy (1.5 to 3 kWh/1000 L of overflow) and low consumption of the fluidized bed aluminum pellets (10 to 25 g Al/1000 L of overflow).

This treatment required dissolution and introduction of 15 to 30 mg/L of aluminum, essentially all of which was found in the coagulated pigment phase. The alumina (Al₂O₃) content of the coagulated pigment increased from 4 to 7 percent; however, blending of the coagulated pigment solids with freshly manufactured pigment was able to reduce the Al₂O₃ content such that it fell

within the TiO₂ product quality specifications. Use of high-purity aluminum pellets (1-cm nominal diameter, >99.9 percent Al) minimized the introduction of undesirable metal contaminants (Fe, V, Cr, Ni) into the pigment.

Electrocoagulation increased the mean size of the TiO₂ by a factor of 4 to 5, and increased the percentage of particles having a mean size >10 μ m in diameter from 1 to approximately 75 percent (Table III). Sonic treatment was performed to evaluate the structural integrity of the formed flocs (thus providing an evaluation of resistance to filter shear). The tests showed that following 10 min of sonic treatment, agglomerated pigment particles (diameter = 11.65 μ m) retained their integrity, and were an average of 17 times larger than untreated pigment particles (diameter = 0.68 μ m). Results of these studies are summarized in Table III.

The mixture of ACE-treated overflow and untreated clarifier overflow on a 1:1 volume basis provided some interesting results. The median particle diameter prior to sonic treatment is nearly as large as that produced for ACE-treated overflow alone. This may be the result of introducing minute neutrally or positively charged particles (seeds) in the ACE-treated overflow which have not yet increased in size to settle out of solution under gravity. Alternatively, the combination of the two waste streams may produce a stream with a pH more conducive to precipitation of the TiO₂ solids in the untreated overflow.

It was also observed that the particles produced from mixing the ACE-treated overflow and the untreated overflow tend to be more susceptible to shearing. This would suggest that the particles produced had contained boundwater within the particles typical of an alum treated sludge. Additional studies are required to verify this contention.

Finally, this experiment suggests that electrocoagulation of a portion of the effluent, followed by remixing of the treated portion back into the untreated

overflow, may allow treatment of the entire overflow stream (1300 L/min) at a low cost. Vacuum filtration rates for the two pigment samples indicated that electrocoagulated solids did not blind the filter medium (8 μ m spacing) and improved the filtration rate by a factor of three.

Other experiments performed in conjunction with this research effort suggested that filtration rate for solids coagulated by electrocoagulation were much less than for solids formed by chemical coagulation. This was verified for a 1 percent slurry of TiO₂. Samples of untreated, ACE Separator™-treated and alum-treated slurries were subjected to filtration tests. These tests indicated that the filtration time for 100 mL slurry was 3.27 min, 1.20 min and 21.08 min for untreated, ACE Separator treated and alum-treated, respectively.

The treatment costs (including electrical power, aluminum pellets and labor) to achieve an 85 to 90 percent recovery of TiO₂ from an influent stream of 1100 mg/L TiO₂ was estimated to be \$0.10 to \$0.15/1000 L of overflow. With the value of TiO₂ at market prices equal to approximately \$0.20/kg (\$0.45/lb), it was projected that TiO₂ recovered would be \$0.90 to \$1.00/1000 L of overflow treated. Capital cost for a standard ACE Separator™ with a nominal throughput of 190 L/min (50 gpm) is estimated to be \$80,000, and for a 950 L/min (250 gpm) unit, \$300,000. (The degree of automation and the need for electrical transformation can affect the total capital cost.)

Operating Costs

The operating cost (electricity, aluminum pellets, operation and maintenance) for the treatment of each waste tested at bench- and pilot-scale levels were also developed as part of the overall effort. Using a cost typical for alum treatment of \$0.79/1000 L (\$3.00/1000 gal), cost comparisons were made. It was estimated that the operating costs would vary from \$0.13 to \$0.26/1000

L (\$0.50 to \$1.00/1000 gal) for treatment of dilute clay-water suspensions; and from \$1.30 to \$2.60/1000 L (\$5.00 to \$10.00/1000 gal) for treatment of oily emulsions containing surfactants and/or stabilizers. Treatment costs for metals-containing waste streams and oily emulsions that did not contain surfactants varied, but typically were equal to or less than that of alum treatment. As would be expected, the operating and maintenance costs are also a function of the degree of phase separation required. In many applications, use of the ACE Separator™ to break a majority of the emulsions/suspensions followed by the addition of a small quantity of polymer to complete clarification was found to be a more prudent treatment alternative.

Conclusions

ACE offers an economically competitive and technically simple method for achieving solid-liquid separations in aqueous-based waste streams. The technology relies on the introduction of low concentrations of aluminum ionic species, the majority of which will be removed in the coagulated solid phase by standard filtration practices. Treatment does not entail addition of chemicals (polymers, metal salts, polyelectrolytes) the accumulation of which might inhibit reuse of the effluent.

Aluminum pellets used in the ACE technology can be of two types. For remediation or effluent treatment, the use of lower purity aluminum pellets produced from recycled scrap or beverage containers is acceptable. For product recovery installations in which contaminant introduction is a serious concern (e.g., TiO₂ recovery), the use of high-purity pellets is required.

Electrocoagulation has been demonstrated to achieve significant reductions in TSS loadings of particulate slurries and in the concentrations of metals (Pb, Cu, Zn, Cr), fluorides and phosphates under certain pH conditions. ACE can break stable aqueous suspensions containing submicron-sized particles up to 10 percent TSS and stable aqueous emulsions containing up to 5 percent oil. It has been demonstrated to enhance filtration and dewatering rates for solids removed from an effluent; such enhancements are prompted by increase in mean particle size from <0.3 μ m in diameter to as much as 150 μ m, depending upon the degree of electrocoagulation.

ACE is effective in recovering fine-grained products that would otherwise

Table III. TiO₂ particle size growth.

Treatment Method	Median Particle Diameter (μ m)		
	No Sonic Treatment	Sonic Treatment*	% Particles < 10 μ m
Untreated	3.10	0.68	99.1
ACE Separator™	16.12	11.65	24.5
ACE Separator™†	14.83	2.12	28.9

* Evaluation of resistance to filter shear

† Mixture of treated overflow with untreated clarifier overflow

be lost from centrates, filtrates and clarifier overflows, and whose discharge might result in noncompliance with effluent limits. Electrocoagulation can reduce the volume of potentially hazardous slurry by concentrating precipitated pollutant metals and particulates into a readily dewaterable and filterable solid phase.

The ACE technology is applicable where product recovery is the objective and alum addition cannot be tolerated. Other applications of the ACE Separator™ include: (1) remediation of groundwater and leachates (metals, COD/BOD removal), (2) enhancement of clay separation from aqueous suspensions/emulsions resulting from soil-washing operations, (3) breakage of oil-water emulsions produced in the pumping of hydrocarbon contaminated groundwater, and (4) removal of TSS from stormwater runoff. Possible industrial applications include fine-grained product recovery (pigments, PVC) and extraction of TSS from waste streams which contribute to high BOD and COD loadings.

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