



Project Summary

Sludge Demetalization by the Union Carbide Corporation Electrochemical Process

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This study was undertaken to evaluate an electrochemical sludge demetalization process developed by Union Carbide Corporation for removing toxic metals such as cadmium, nickel, and zinc from municipal wastewater sludges. The process deposits metals on the surface of an electrode when sludge having a pH of about 3 is placed in an electrochemical cell and a controlled electric potential is applied.

A laboratory-scale apparatus was designed and constructed to determine the most desirable electrode and cell operating conditions for the process tests and to investigate the various phenomena that occur during electrolysis. These tests were conducted using several reference electrode systems in a solution of distilled water and ions so that the process could be observed without the complications attendant to sludge. Dropping mercury and solid electrodes were used to generate linear polarization plots of current versus applied voltage to establish the plating potential appropriate for removing metal ions. This potential was determined to be -1.45 volts versus the Cu-CuSO₄ reference electrode.

An existing bench-scale apparatus was modified to hold about 17 liters of fluid, and batch tests were conducted using both sludge and metal ion solution as the electrolyte. Efforts centered on achieving a balance of metals during the experiments and on improving metal removal rates and coulombic efficiencies. Coulombic efficiencies remained below 10 percent and metal removal performance was erratic. The use of the Cu-CuSO₄ reference electrode system

to control total cell voltage and thus, indirectly, the current density did appear feasible. The quality and quantity of data obtained did not allow a strong correlation to be made between system design, operating parameters, and process performance.

This Project Summary was developed by EPA's Water Engineering Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The use of sewage sludge as a soil amendment has been practiced for many years in certain parts of the world. In the United States, recent studies reveal that up to 25 percent of the Nation's sludge production is disposed of on land. This statistic does not include disposal in designated landfills, but rather it applies to reclamation of marginal or drastically disturbed land as well as the use of sludge as a fertilizer for croplands.

As population and the degree of wastewater treatment sophistication increases, the quantity of sewage sludge produced by each community can be expected to multiply dramatically. Furthermore, economic and environmental pressure may shift the emphasis from presently preferred methods of disposal (ocean dumping, 15 percent; landfill, 25 percent; incineration, 35 percent) to land application. Naturally, such a shift in emphasis will be accompanied by an increased demand for suitable land disposal sites. This problem is expected to reach critical proportions in certain

localized areas (such as in the north-eastern United States), when large populations are confronted with a relative scarcity of land. In these areas, the disadvantages of land application (lack of public acceptance, odors, pathogens, toxic metals, and the possible presence of industrial chemicals) will become greatly magnified. Concern over the fate of such pollutants in the soil and groundwater and their impact on vegetation and the food chain is well placed and must be definitively answered in the future.

The purpose of this study was to investigate an electrochemical process for the removal of heavy metals directly from sewage sludge without previous dewatering. Sludge does contain macronutrients useful to plant growth such as nitrogen, phosphorus, and potassium. But it may also contain substantial quantities of metals, some of which (most notably Cd, Zn, Ni, Cu, and Cr) have been found to be toxic to vegetation at elevated concentrations and may accumulate in the human food chain. Concern over the migration of these elements into the food chain has resulted in the proliferation of many guidelines that recommend limits on the amount of sludge applied to farmland based on the amount and species of metal contaminants involved. The objective of the Union Carbide demetalization process is to reduce the concentrations of such metals sufficiently to allow an increase in the amount of sludge that may be applied to the available acreage.

Process Description

The Union Carbide demetalization process involves the direct electrowinning of metals from aerobically digested, acidified municipal sludge. Work done by other investigators and in bench-scale experiments at Union Carbide's Tonawanda Laboratories have confirmed that the bulk of metals in municipal sludge are locked in the solid phase rather than the aqueous. These solid phase metals are held primarily in two forms: insoluble organometallic complexes and insoluble hydroxide, carbonate, or sulfide compounds. To reduce their concentration in sewage sludge, metals must first be liberated from this solid phase and dissolved in aqueous solution.

The proposed sludge demetalization process solubilizes the metal ions in sewage sludge through a pair of pretreatment steps. First, the sludge is aerobically digested to oxidize organic material and convert insoluble heavy metal sulfides to the soluble sulfate form. Thermophilic

(greater than 45°C) aerobic digestion with high purity oxygen for 1 day is sufficient to convert the metal sulfides to their soluble forms. The temperature increase in the sludge is produced by heat liberated by the oxidation of organic material in the sludge and is self-sustaining as long as oxygen and sludge are fed to the digester in appropriate amounts.

The second step involves a shift in the equilibrium that exists between the dissolved heavy metals and the insoluble metallic complexes contained in the sludge solid phase. This shift is produced by adding acid, which lowers the solution pH and causes the displacement of metal ions by H^+ ions. The extent of metal solubilization by this method is a function of the pH to which the sludge is acidified. The shift in metal complex equilibrium occurs relatively rapidly upon acid addition and is usually complete in 5 to 20 minutes.

At this point the proposed demetalization process diverges from other published metal removal methods for sludge, which advocate the separation of the solid and liquid phases by a dewatering step followed by treatment of the liquid supernatant by chemical precipitation, electrolysis, or some other means. This approach is limited by the efficiency of sludge dewatering technology and by the fact that no further metal transfer from the solid to the liquid phase may occur after separation. The proposed sludge demetalization process involves the continuous stripping of metal ions directly from the sludge in an electrolytic cell. This cell may consist of a series of parallel plates arranged in electrode pairs across which an electric potential is applied. A reference electrode situated in the bulk solution provides the set point for control of the voltage applied between the electrodes. The positive electrode of each pair (the electron acceptor) is defined as the anode, and the negative (electron donor) is known as the cathode. Aerated sludge is circulated between the plates to enhance mass transfer of metal ions from the bulk solution to the surface of the cathodes, where they are removed by electrodeposition. The equilibrium between the solid and aqueous phase metal ion concentration acts to replenish the soluble metal concentration by releasing more metals from the solid phase. Thus through the judicious choice of operating conditions for the electrolytic cell (voltage, pH, and temperature), the metal species of interest may be substantially removed. The demetalization process provides a stabilized, pasteurized, metal-depleted

sludge that is ready for disposal except for lime treatment to neutralize pH. Furthermore, when the useful life of the cathodes has been reached, they may be regenerated, sold as scrap, or disposed of along with any metal-concentrated deposits in an environmentally secure manner.

Laboratory Tests

Experimental Apparatus and Procedures

Stock sample solutions were prepared containing 10 to 100 ppm each of cadmium, zinc, copper, and other metals in varying combinations. The pH of these aqueous solutions were depressed by the addition of H_2SO_4 , and then deaeration was achieved through agitation with nitrogen. In some instances, suppressants such as methyl-red or gelatin were added to act as maxima suppressants or to simulate the effect that organic matter might have on the shape of the current potential curves. These sample solutions were placed in an electrochemical cell (Figure 1) to obtain current-potential relationships for the various metal ions being investigated. The apparatus consisted of an Aardvark potentiostat, potential scanner, current integrator, reference electrode system, and various pieces of recording equipment. The cell can be used with either a dropping mercury electrode or a stationary electrode.

Polarographic tests were conducted by varying the potential and measuring the current that results from the reactions at the electrodes. The solution pH, metal ion species, and concentration were varied between test runs, and the results were recorded as a series of sigmoidal waves, each representing a different reaction. Reference electrodes determined the potential between the working electrode (or cathode) and the electrolyte, whereas potentiostats controlled this potential during the course of a test. Only a very small current is tolerated between the working and reference electrodes.

Samples were analyzed by Union Carbide's Analytical Services Laboratory at Tonawanda. Electrodes were washed with a solution of nitric acid, and the metals in the resulting solution were measured by means of atomic absorption. A microprocessor was used to analyze absorption data and determine the metal species. Electrodes and electrolyte were analyzed for Cu, Zn, Pb, Ni, Cd, and Cr.

Laboratory Results

Small-scale (about 1 liter) tests were conducted to make controlled electro-

chemical measurements of electrode potentials and to investigate the conditions required for metal deposition. Particular attention was paid to determining the extent to which unwanted side reactions might reduce the coulombic efficiency of the process. Laboratory-scale tests were grouped in three main categories: Polarographic, electrode, and plating studies.

Polarographic Reduction Spectrum

These experiments determined the actual half-wave potentials of metals in solution. Because of the possibility of chemical complexation, these potentials

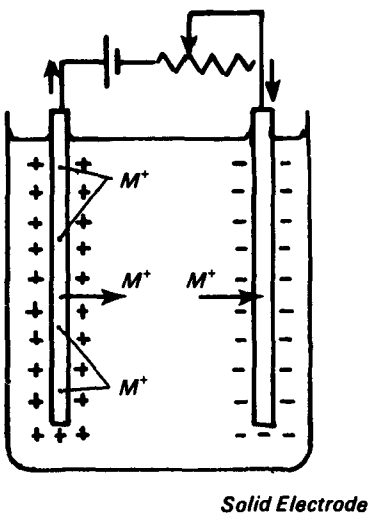
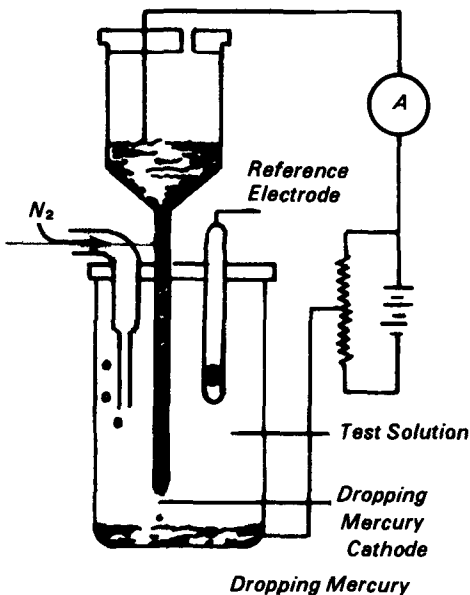


Figure 1. Typical electrochemical cells.

could be very different from reference values of the standard reduction potential. To obtain the current-potential curves (polarograms) for the reactions of interest, a dropping mercury electrode apparatus was designed and constructed. Tests were performed with dilute aqueous solutions of metal sulfates adjusted to a pH of 4.0 with sulfuric acid. Dilute solutions (10^{-5} to 10^{-2} M) of Cu^{+2} , Cd^{+2} , and Zn^{+2} were studied extensively with some additional testing of Ni^{+2} , Cr^{+2} and Fe^{+2} solutions.

The recorded polarograms were of the shape anticipated, with currents remaining low until the reduction potential was approached, whereupon the current then rose in a sigmoidal wave and reached a plateau. This level remained reasonably flat until the next reduction wave or until H_2 evolution occurred. The shape of a typical test polarogram is illustrated in Figure 2. The measured half-wave potentials of Cu^{+2} , Cd^{+2} , and Zn^{+2} were close to the values of the standard reduction potentials calculated for these ions with respect to HgSO_4 , Hg_2Cl_2 , and CuSO_4 reference electrodes, whereas the reductions of Cr^{+3} , Ni^{+2} , and Fe^{+2} were considerably more cathodic than their standard reduction potentials. Cr^{+3} gave a broad wave between Cd^{+2} and Zn^{+2} , and Ni^{+2} gave a very broad wave more cathodic than Zn^{+2} . With Fe^{+2} , a wave could just be observed superimposed on the final hydrogen wave.

The Zn^{+2} ion, the most difficult to reduce based on standard hydrogen electrode (SHE) potentials, can be reduced to concentrations of 10^{-7} equivalents per liter by the following potential/reference combinations:

Potential (Volts)	Reference Electrode
-1.00	normal hydrogen electrode
-1.25	saturated Hg_2Cl_2
-1.32	saturated CuSO_4
-1.64	saturated Hg_2SO_4

Hydrogen gas evolution was observed at approximately -2.1 volts, indicating that this reaction does not compete in a major way for metals removed under conditions suitable for plating zinc. The concentrations of metal ions more electronegative than zinc would be expected to be reduced even further under these conditions.

The major conclusion of this test series is that the best cathode potential for controlled potential deposition is approximately -1.45 volts versus the Cu-CuSO_4 reference electrode.

Electrochemical Cell Experiments - Electrode Tests

Attention was shifted in this series of experiments to the reduction and plating of metals on solid cathodes. Exploratory tests were made with 3003-F aluminum and various steel cathodes plating Cd^{+2} and Zn^{+2} ions at a pH of 4. Multiple potentiometric scans (cyclic voltammetry)

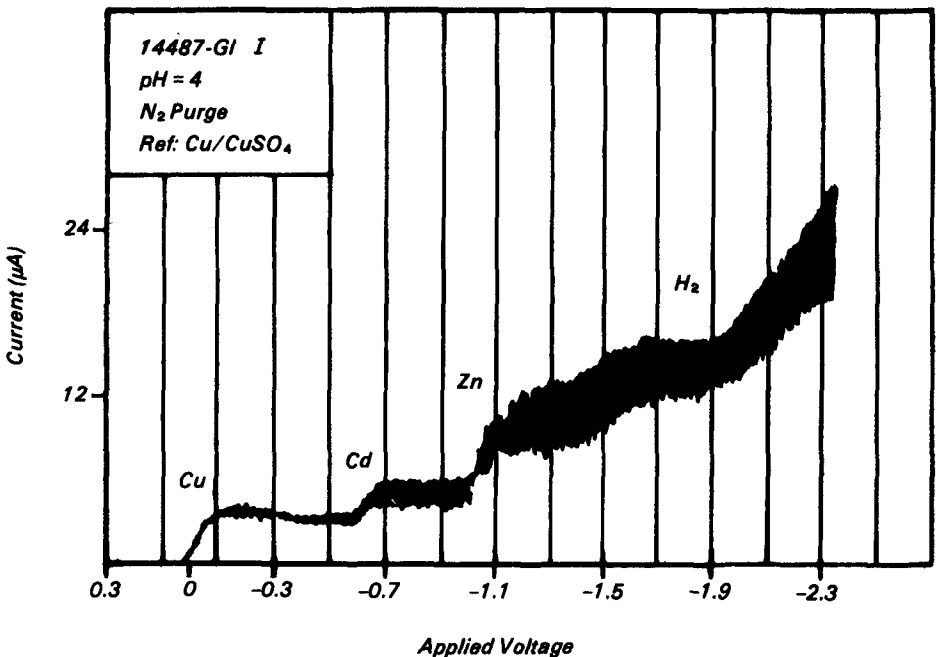


Figure 2. Typical polarogram (current versus voltage plot).

showed a distinct wave and plateau corresponding to the reduction of Cd^{+2} to Cd, followed by a current rise (probably a result of H_2 evolution). On sweeping in the anodic direction, a peak corresponding to the stripping of Cd from the cathode was observed at a potential somewhat below the reduction potential. The aluminum cathodes appeared to behave satisfactorily, but with the steel cathodes, a substantial anodic current was observed at potentials below about -0.7 volts versus the Cu-CuSO₄ reference because of the corrosion of iron. Iron or steel are therefore not satisfactory cathode materials.

Graphite anodes were used extensively during these experimental runs. But the solution was observed to darken as plating progressed because of the partial dissolution of the graphite. Since the cost of using a noble metal as an anode material would be prohibitive, aluminum or sulfated lead anodes were tested as alternatives to graphite. The aluminum anode exhibited areas of highly promoted general attack and crevicing at its surface. The sulfated lead anode tests were marked by very poor mechanical adherence of metallic deposits on the aluminum cathode. The rate of metal removal was also poor for the lead anode.

Electrochemical Cell Experiments - Plating Studies

Plating studies were initiated using a 1-liter test apparatus manufactured by Princeton Applied Research.* The test solutions nominally contained 100 ppm concentrations of cadmium and zinc ions adjusted to pH 4 by dilute sulfuric acid. All the solutions were deaerated before testing with nitrogen and stirred using a Teflon-coated magnetic stirrer. The surface area of the aluminum cathodes was 5 cm². A pair of high-density graphite rods served as anodes. The open-circuit potential of the aluminum in this environment was -0.76 volts versus Cu-CuSO₄ reference.

Previous polarographic tests on 10⁻³ M Cd^{+2} and Zn^{+2} solutions indicated a diffusion current density of about 2 amps/m². Comparable current densities with the solid aluminum cathodes were anticipated, with current decreasing as plating progressed as a result of metal ion depletion in the solution. The current measured during the plating studies was initially in the range expected; but as electrolysis proceeded, the current

greatly increased. The reason is believed to be a large increase in the effective cathode surface area. With Cd^{+2} and Zn^{+2} ions, a somewhat denser deposit was formed. In all cases, the deposit was very porous and apparently has a large surface area.

When cadmium was selectively plated at an applied potential of -0.80 volts versus the Cu-CuSO₄ reference, the coatings were not very adherent. Large portions of the coating would detach completely or partially from the cathode surface. The observed current density fluctuated with these events. The plated solids that detached from the cathode did not immediately redissolve, and they appeared to have a long residence time in solution. When both cadmium and zinc were plated from solution at an applied potential of -1.45 volts versus the Cu-CuSO₄ reference, the coatings were more adherent and uniform. The pores in the coating surface were approximately 0.076 cm in diameter, and the cathode substrate was visible through these pores.

Though the mass balances in the above tests were greater than 95 percent, the coulombic efficiencies were relatively poor at less than 20 percent. These test results are summarized in Table 1.

Bench Scale Tests

Experimental Apparatus and Procedures

The demetalization test apparatus (Figure 3) consisted of a 7-liter, rectangular, Plexiglas vessel equipped with nine parallel plate electrodes being alternately made of 1100 aluminum cathodes and graphite anodes. A 2.5-cm diameter copper sulfate reference electrode was placed into solution near the electro rack. Power was provided by a constant voltage (or constant current) supply by means of a network of switches and wires (not shown) and a Magnar model 4700M research potentiostat and its associated meters and recorders. A gas sparger was located at the bottom of the electrolytic cell to allow oxygen or other gas to be bubbled into solution. A separate holding vessel connected to the electrolytic cell by a common channel at the vessel bottom contained a mixer and temperature controller. A variable-speed pump forced the fluid to recirculate from the holding vessel back to the top of the electrolytic cell where it again flowed downward between the parallel plate electrodes. A Plexiglas manifold distributed the fluid evenly over the electrode channels. After initial testing, some modifications were

made to the apparatus to improve performance. The nature of these improvements were as follows:

1) A small Plexiglas shield was constructed around the tip of the reference electrode to prevent interference by rising gas bubbles.

2) Metal components (such as screws, gauges, etc.) in the apparatus structure were identified as a source of metal contamination and were removed.

3) The stainless steel rotor of the recirculation pump was replaced by equivalent drive coated with GE Glyptol 1201-A insulating enamel to prevent corrosion.

4) Alligator clips that had been used to make anode connections were found to be a source of cadmium contamination in early tests. These clips were replaced by insulated copper wire adhesive bonded into a hole drilled into the carbon anode. A silicone rubber cement was used to seal the connection from the electrolyte.

5) Additional gas space volume was added to the electrolytic reactor to prevent foam overflow. Because of a desire to operate without chemical antifoam addition, the apparatus was provided with a rotating paddle above the liquid level, which beat down any foaming that did occur.

Secondary sludge was obtained from the Lockport, New York, Wastewater Treatment Plant on a weekly basis and kept in refrigerated storage. When ready for use, the sludge was gravity-thickened and fed to two 14-liter Microform fermenters equipped with variable speed mixers, a gas sparger, and heating coil. In these reactors, the sludge was aerobically digested at 50 to 55°C for a period of about 1 day. The sludge was then screened through a 0.60-cm mesh and fed to the demetalization reactor. The recirculation pump, mixers, and sludge heaters were adjusted to their desired points and turned on. The pH of the sludge was adjusted by the addition of 10N H₂SO₄. Gas purge from a regulated cylinder provided agitation between the electrodes.

After approximately 5 minutes of operation to allow for homogeneity to develop throughout the system, a sludge sample was withdrawn as the initial sample. The electrical current was then applied, and the total cell voltage was adjusted to maintain the desired reference voltage. Readings and samples were then taken at intervals during the course of each test. Total cell voltage, reference voltage, and total cell amperage were recorded continuously while the following

*Mention of trade names or commercial products does not imply endorsement or recommendation for use.

Table 1. Electrochemical Cell - Plating Studies

Test ID	pH Initial	pH Final	Metal in Initial Solution	Metal in Final Solution	Metal Removed from Solution	Weight of Solids Filtered	Metals Analyzed from Filtered Solids	Mass Balance	Total Time	Coulombs to Remove (Cd/Zn)	Total Coulombs	Coulombic Efficiency	Anodes
I	4	2.9	0.1337g	0.0721g	0.0616g	—	0.0602g	97.7%	22.8 hrs	114	—	—	graphite
II	4	2.9	0.1433	0.0099	0.1334	0.1810*	0.1380	96.7	17.7	308	2851	10.8%	graphite
III	4	—	0.1295	0.0567	0.0728*	0.0760*	—	—	—	—	—	—	graphite
IV	4	4.3	0.1410	0.0019	0.1391	0.4199*	0.0780	56.1	28.5	330	1641	20.1	A1
V	4	2.7	0.1260	0.0503	0.0757	0.0694	0.0606	80.1	24.0	154	1221	12.6	PbSO ₄

* includes weight of graphite filtered

* includes weight of aluminum filtered

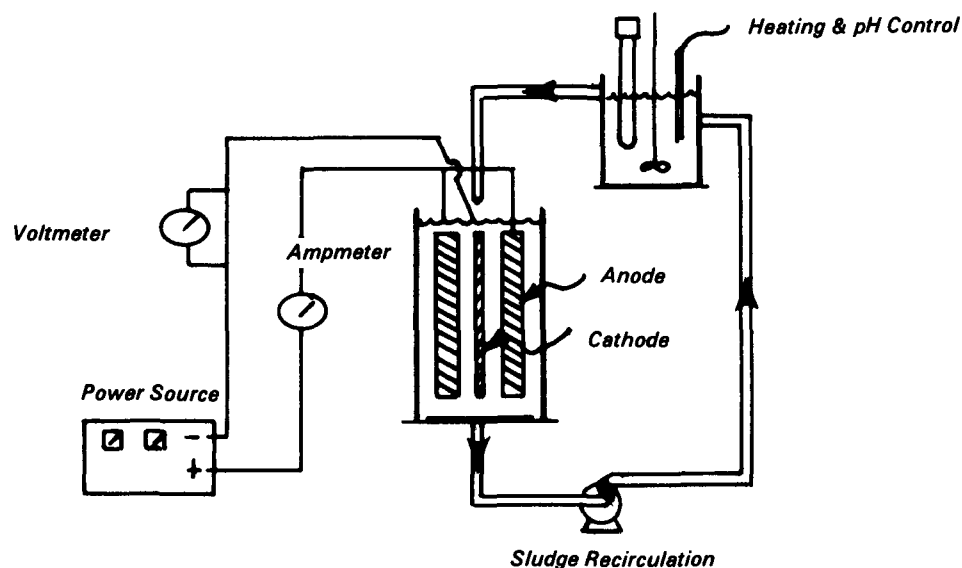


Figure 3. Demetallization test apparatus.

data were hand recorded: time, gas-flow rate, sludge recirculation rate, temperature, pH, reactor volume, and the amount of acid addition (if any). The volume of each sludge sample was recorded, and at the conclusion of each test, the reactor was emptied, its contents were measured and any water loss due to evaporation was made up by the addition of distilled water. The electrodes were removed, any observations as to the condition of the metal deposits were noted, and then each was sent to the laboratory in a separate beaker for analysis. All metals were analyzed on a Perkin-Elmer 460 Atomic Adsorption Spectrophotometer with flame technique.

Bench-Scale Results

Upon completion of initial tests, several important conclusions were made. First, the total cell voltage was considerably lower than that normally used in previous tests, despite reference potentials (versus

the Cu-CuSO₄ electrode) in the -1.0 to 1.5-volt range. This observation suggested that much of the power input of previous tests may have been wasted on unwanted side reactions. The second important conclusion was that the most electro-negative metal, zinc, could indeed be plated out at these low cell voltages. Third, the amount of material plated (as determined by removing and analyzing electrode deposits) was substantially more for certain metals than the amount of metal removed (as determined by a metals balance and solution concentrations). This discovery led to an extensive search for possible contamination sources in the bench-scale apparatus.

The bulk of the remaining sludge tests were oriented toward eliminating various sources of contamination such as reactor screws, fitting, recirculation pump, and electrode clips. That this program was fairly successful is shown by a change in the metal balances from negative to

positive in later tests, indicating contamination-free operation. Unfortunately the coulombic efficiencies, defined as (coulombs metals plated/coulombs input to electrodes) x 100, were all extremely low, with the highest being less than 10 percent. Furthermore, the percentage of metals removed from solution was also disappointingly low.

After the eighth demetallization test, the electrolyte was changed to a synthetic solution of cadmium, copper, zinc, and nickel ions in distilled water. The purpose of this change was to allow a more accurate determination of a reactor metal balance and to provide visual monitoring of the electrodes during testing. Despite the elimination of any possible interference from the sludge solids, the metal removals and plating efficiencies still remained low. This observation suggested that a shortcoming of the electrochemical process itself may prevent the attainment of better performance rather than any characteristics of the sludge.

Results obtained from the laboratory-scale apparatus during this time allowed hope for the improved metal removal. These small-scale tests showed that a porous, dendritic structure of plated metals formed on the cathode, and that the composition and structure of the deposit depended on the electrode materials used. During the course of a test, some pieces of the metal deposit were found to spall off the cathode because of agitation of the bath. This spalled material remained suspended in the bath solution as particles or chips of metals and was not counted as plated metal. Furthermore, these particles acted as points of high metal concentration in the solution, making it nonhomogeneous and increasing the difficulty of withdrawing representative liquid samples for analysis. This problem was addressed in Tests 14 through 17. In these tests, sampling procedures were modified to account for the plated materials that spalls off the electrodes and back into bulk solution. This step was accomplished

by filtering each sample, the final reactor fluid, and each reactor wash to collect any particulate matter. The liquid and electrode samples were then analyzed in the usual way, and the filtered solids were analyzed for their metal content. Such procedures did improve metal balances in the 17-liter reactor to within 25 percent, which may be a reasonable limit given the accuracy of the large-scale analysis.

Conclusions

The sludge demetalization process successfully removed metals from sewage sludge without previous dewatering. Copper, zinc, cadmium, nickel, chromium and (to a smaller extent) lead were shown to be removed from solution and to accumulate on the electrodes. Unfortunately, the metal concentration reductions and the coulombic efficiency of the plating process were low, resulting in projected treatment costs that were higher than most methods of sludge disposal currently in use. Furthermore, attempts to correlate metal removal performance with system operating parameters were largely unsuccessful. Thus many improvements and additional developmental work must be done before the process can be commercially successful. Other important conclusions developed as a result of this study are as follows:

1) The Cu-CuSO₄ reference electrode was a useful tool in controlling total cell voltage and thus, indirectly, current density. Operating voltages in the 2 to 3 volt range were observed at a reference voltage of 1.4 to 1.45 volts. Such potentials were shown to be capable of plating very electronegative ions (such as zinc) at lower values than the 3 to 4 total cell volts that were used when operating without the reference electrode.

2) The identification and elimination of possible sources of metal contamination in the reactor design was a critical step in attaining reasonable metal removals and approaching a metal balance around the reactor.

3) Despite the elimination of possible metal contamination and a change in process fluid from sludge to synthetic metal ion solution, process performance remained below expectations. This result suggests that obstacles to higher metal removals and coulombic efficiency lie in the electrodeposition process itself rather than in interferences from the sludge solids.

4) In both laboratory and bench-scale tests, flakes and particles of deposited metal can spall off the electrodes and remain suspended in the agitated electro-

lyte. This agitation is necessary to reduce the boundary layer thickness at the electrode surface and to enhance the transport of metal ion species from the bulk solution to that boundary layer. Thus some compromise must be made between the improvement of mass transport from bulk agitation and the difficulty of recovering the spalled-off metal that results. Bench-scale testing indicates that this resuspended material can account for up to 10 percent of the metal deposited on the electrodes.

5) Gas aeration plays a significant role in improving bulk agitation, but performance does not seem to be sensitive to the quantity of gas used within the range tested. Nitrogen or air seem to be interchangeable as the aeration gas.

6) Aluminum is the preferred material for the cathode, and graphite for the anode. Stainless steel was also tried out as a cathode material, but it was deemed unsuitable because of extensive corrosion at low voltages. Aluminum was found to be a poor anode, since it slowly dissolved into solution. A sulfated lead electrode with low solubility was also tried out as an anode material, but the cathode deposits formed during its use were less adherent than those experienced with graphite anodes under the same conditions.

7) Laboratory-scale tests revealed that deposits formed from cadmium solution were less adherent than those formed from a solution containing both cadmium and zinc ions. Furthermore, as metals plated out on the cathode, its surface area increased, resulting in an increase in current until the metal ions were depleted from the solution.

8) In the bench-scale tests with sludge, the solution pH was initially dropped to the 3 to 4 range by the addition of 10N H₂SO₄. During the course of the experimental runs, small amounts of acid solution often had to be added to maintain this low pH. Our hypothesis is that the reduction of metal ions at the cathode shifts the acid hydrolysis equilibrium, causing more H⁺ ions to be consumed.

9) Sludge foam, when it did occur, was successfully suppressed, either through the addition of small amounts of anti-foaming agent or by a flat-bladed impeller rotating in the gas space above the fluid.

Recommendations

At present, the direct electrochemical treatment of sewage sludge does not seem to offer an economical means of metal removal. But since the removal of heavy metals from both municipal and industrial sludges is becoming increasingly

critical in today's environment and since alternatives are not plentiful, further investigation of the process to improve its performance may be warranted. The relatively low metal removals and low coulombic efficiency of this process seem to be tied to the electrolytic cell performance rather than to any interference from the sludge. Thus future experiments should be undertaken to identify and eliminate these obstacles to improved performance.

The full report was submitted in fulfillment of Contract No. 68-03-2968 by Union Carbide Corporation under the sponsorship of the U.S. Environmental Protection Agency.

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The complete report, entitled "Sludge Demetalization by the Union Carbide Corporation Electrochemical Process," (Order No. PB 85-137 347; Cost: \$14.50, subject to change) will be available only from:
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