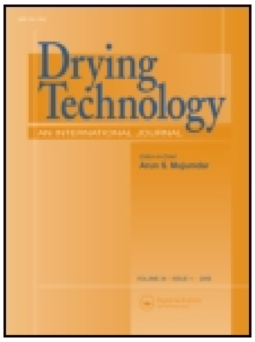

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# WATER REMOVAL FROM MINE SLIMES AND SLUDGE USING DIRECT CURRENT

D. J. Kelsh and R. H. Sprute
Spokane Research Center, U.S. Bureau of Mines
Spokane, WA 99207

Key Words and Phrases: electro-osmosis; electrophoresis; electrokinetic dewatering; mine tailings; coal wastes; fine-particle slurries; zeta potential; electrical conductivity; tailings pond consolidation.

## ABSTRACT

Recent tests by the U.S. Bureau of Mines have demonstrated the effectiveness of electrokinetic dewatering to consolidate a variety of coal and mineral slimes. Material properties and application methods that affect performance are briefly reviewed, and some operating and proposed field installations are described. Application of the method to other slimes and sludges can best be determined through laboratory testing, but certain physical properties can be helpful predictors of responsiveness.

## INTRODUCTION

Sludge consolidation and drying are industrial problems of major importance, particularly in coal and mineral processing. Low-grade ores must be crushed to a fine consistency to permit efficient separation and extraction of the valued material, and the voluminous sludge waste created gives testimony to the present

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scarcity of high-grade deposits. Taconite, tar sands, oil shale and coal are raw materials whose processing will generate hundreds of millions of tons of waste annually, much of it in the form of slimes. Troublesome sludges are also created as by-products of stack-gas scrubbing, municipal sewage treatment, and other mining and industrial production. Safe and permanent disposal of these unwanted legacies is essential for our continued technological and environmental well-being.

Fine particles dispersed in water are difficult to consolidate by techniques based on differences in specific gravity, e.g., sedimentation or centrifugation. The particles are small enough to be sensitive to the stirring action of thermal gradients, and capillary action (surface tension) prevents drainage of water from the small pore spaces between sedimented particles. Polymeric flocculants can be effective aids to dewatering in specific instances, especially when used in conjunction with vacuum-or belt-filters, but cost often reduces their attractiveness.

Traditional reliance on the mill pond for sludge disposal has been called into question because of a number of tragic occurrences. Poorly engineered earth dams have collapsed catastrophically, resulting in considerable property damage and loss of life. The 1975 failure at Buffalo Creek, West Virginia, stimulated enactment of tougher legal standards, but a 1981 Corps of Engineers study suggests that hundreds of existing dams are still structurally unsafe. Consolidation of the impounded sludge to a firm, solidified soil would remove this threat and also permit reclamation of pond sites. Treatment methods which do not require total reprocessing of pond contents would be most desirable.

As an alternative to mechanical and chemical methods of dewatering fine-particle suspensions, the Bureau of Mines Spokane Research Center (SRC) has studied consolidation caused by electrophoresis and electro-osmosis. Electrophoresis is the motion of charged particles induced by an imposed electric field, and is useful for consolidating electrically charged fine particles in dilute water suspension. When these particles are concentrated in a thick slurry and are relatively immobile, water can be drawn out of the pores by an electric field (electro-osmosis). Because these electrokinetic phenomena are relatively insensitive to particle and pore sizes, they are technologically attractive for dewatering sludges that are unresponsive to hydraulic methods (centrifugation, etc.) Because the electric field can be imposed by burying electrodes in the sludge, the method also is advantageous for treating old impoundments without requiring major reprocessing of the waste.

A simple model of how water is removed during electro-osmosis envisions a pore space as being a capillary tube with negatively-charged walls, with ions in solution distributed so as to counter-balance this negative charge (Figure 1). Positive and

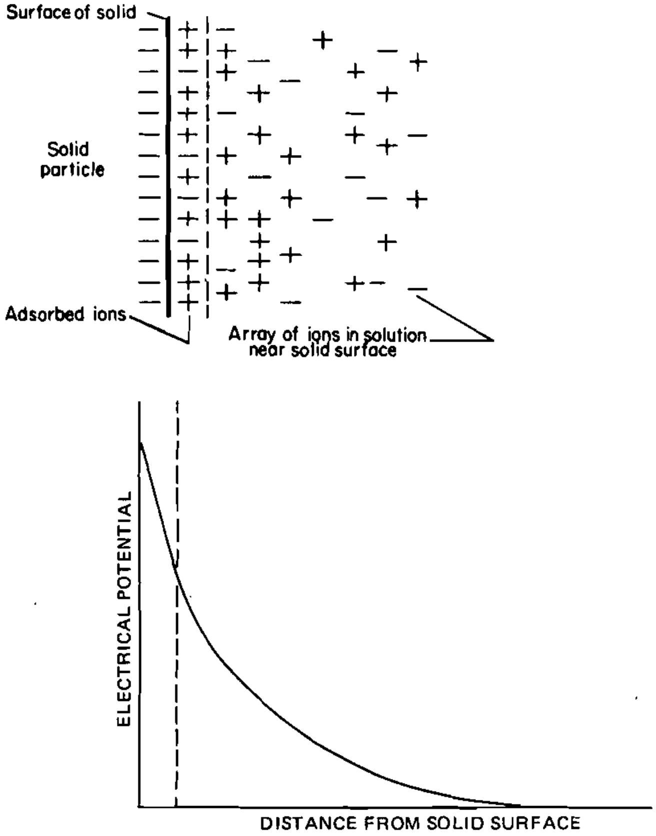

Figure 1. - Schematic distribution of ions in vicinity of solid surface.

negative ions in solution move in opposite directions in a direct current field imposed along the length of the tube, but since the concentration of positive ions is in considerable excess near the wall, their motion will dominate, and viscous drag will carry water with them. A kind of plug flow results because the electrical driving force is concentrated along the tube wall, precisely where interfacial drag (hydraulic resistance) is greatest. This mechanistic explanation nicely accounts for the nondependence of electro-osmotic flow on capillary diameter. The process is therefore most attractive for treating fine-grained slimes and sludges, where hydraulic flow resistance is very high in the small-diameter capillaries.

Suitable electric fields can be created by imposing a dc potential between metal electrodes immersed in the slurry. Electric power requirements are governed by the conductivity of the slurry and the applied current density. Current can be adjusted within limits, depending on the dewatering responsiveness of the slurry and the time available for treatment. Effects of these and other variables can be determined experimentally in small-scale laboratory tests.

Electrokinetic phenomena have intrigued scientists and inventors for over one hundred years, and the technical literature is filled with descriptions of devices and methods for electrical dewatering of slurries. Recent examples of these come from Poland (Ukleja, 1979 and 1981), Switzerland (Porta and Kulhanek, 1980), Japan (Hayakawa, 1980 and 1981), England (Sunderland, 1976 and 1977), and Australia (Lockhart, 1981). Industrial firms in North America which are known to have an active interest in the process include Westinghouse, Monsanto, Dorr-Oliver, and Champion International. Electro-osmosis has also been used by civil engineers to stabilize soils during excavation (Casagrande, 1953).

Discussion in this paper will be limited to a brief review of Bureau of Mines work. Details can be found in the referenced reports which describe successful treatment of siliceous mine tailings from north Idaho metal mines (Sprute and Kelsh, 1974, 1975, and 1976a-b), mine drainage sediment in a Colorado molybdenum mine (Sprute and Kelsh, 1980), thickener underflow from two Appalachian coal preparation plants (Sprute and Kelsh, 1976c), and material from a large coal mine sediment pond in western Washington state (Sprute and Kelsh, 1982).

## LABORATORY EVALUATION

The complex interaction of factors affecting efficiency of the electrical dewatering process has prevented the use of physical properties alone as reliable predictors of performance. Change in application methods, such as current density, current reversal, electrode configuration, and settlement time, also can have unique and important effects on slurry response. However, the following physical properties have been found to be useful indicators of probable success for the method: 1) Zeta potential (zp). It has become customary to infer the potential difference between the solid particle and the suspending liquid ("zeta potential") by measuring the electrophoretic mobility of the particle, ie., the rate of movement as a function of applied field strength. Instruments for making such measurements are commercially available; the "Laser Zee" used at SRC permits relatively rapid determination of the average zp of dilute fine-particle suspensions.[1] Slurries which are responsive to electrical dewatering usually have zp more negative than about -16 millivolts. Conversely, for suspensions where zp is anywhere between +5 and -5 mv (often the case with chemically-treated sludges), electrokinetic dewatering is ineffectual, and only modest response can be expected when zp is between -5 and -16 mv. We have not encountered any solids having high positive charge in our own work, but electrical treatment would presumably be effective if zp exceeded +16 mv.

Some caution must be advised when making and interpreting zeta potential measurements. Considerable dilution of sludge is required to permit individual particles to be tracked microscopically. Decant water from the parent sludge should be used in making dilutions, or considerable change in zp (and conductivity) may result. Also, since the large particles settle out quite rapidly, their zp will probably not be measured; the measured value may therefore not be truly representative of the entire distribution of particles.

2) Soil resistivity. For successful electrokinetic dewatering, enough ions must be present in soil water to establish a zeta potential and allow ionic transport through solution to be

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[1] Reference to specific trade names does not imply endorsement by the Bureau of Mines.

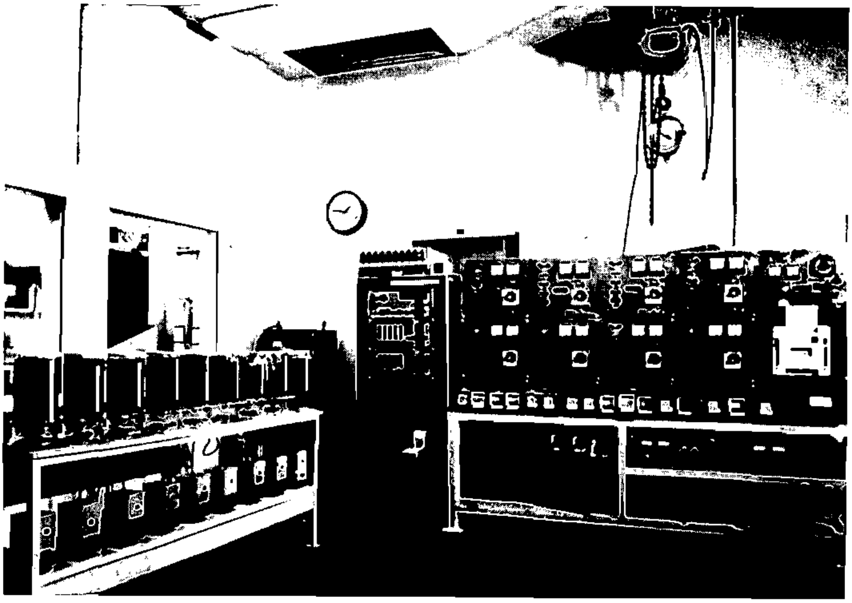


Figure 2. - Electrokinetic testing facilities.

the principal current-carrying mechanism. Power efficiency is poor if ionic strength is too great, however, because water removal depends on the excess concentration of positive ions over negative ions near the solid surfaces. Current carried by ions in bulk water (where ionic concentrations are balanced) does not contribute to dewatering, and this "wasted" current will increase in proportion to electrolyte concentration. Responsive soils typically have resistivities between 1,000 and 4,000 ohm-cm.

Addition of small amounts of salt easily reduces resistivity that is too high. The more frequently encountered cases of low resistivity are harder to treat, unless one is willing to use very low current densities and thereby extend the treatment time (as proposed for the WIDCO pond to be discussed later in this paper; resistivity of that sludge is about 800 ohm-cm.)

Figure 2 shows the laboratory equipment at the Spokane Research Center for evaluating electrokinetic response. Nine samples can be tested simultaneously, with different conditions of treatment individually programmed. Data are printed out automatically every half hour. One or two runs on this apparatus are usually sufficient to determine dewatering efficiency, power consumption, and preferred treatment method. However, before designing operational systems, additional tests for more specific data are performed in bench-scale models more nearly simulating expected field conditions.

## FIELD APPLICATIONS

### Idaho, unclassified tailings.

Underground field tests of electrokinetic dewatering were first performed in 1974 in two Idaho metal mines operated Hecla Mining Company. Both of these cut-and-fill mines backfill with hydraulically placed classified tailings. The slimes fraction is separated from the coarser material using hydrocyclones or settlement basins and deposited in larger aboveground tailings ponds. The classified fraction used for backfill is coarse, quick-settling sand with a significant amount of unwanted fine particles that resist settlement.

Our first test was in the Star mine on tailings taken directly from the concentrator with little classification (the slimes remained mixed with the coarser fraction).

The stope was filled to the top of the watertight sand wall, and after complete settlement of solids, surface water was decanted, leaving deposits of soupy slime up to 41-cm deep near the top of the fill (Figure 3).

The three-electrode system in this test divided the fill into two layers: 1) the upper layer containing the slimes that resist dewatering, 2) a 80-cm-deep layer of relatively coarse, easily drained material. Direct current at 55 amperes and up to 350 volts was alternately applied to the two layers. The cycle consisted of applying potential to the upper pair of electrodes for 25 minutes, drawing water to the negatively charged middle electrode; 1 minute of no power; 3.5 minutes of potential on the lower electrodes, drawing water to the bottom of the fill; and 30 seconds of no power. This 30-minute cycle was repeated throughout the dewatering period.

After 2.5 hours, material had hardened sufficiently to permit walking on the surface. Continued treatment for an additional 13 hours yielded a dry, firm surface whose average hardness, measured by a surface penetrometer, was $3.34 \times 10^5$ kg/m$^3$ on the slimes and $8.8 \times 10^4$ kg/m$^3$ on the coarser sand. Three hundred kilowatt-hours of power had been used, but treatment could have been stopped much earlier. Approximately 7 cubic meters of slimes and 35 cubic meters of coarse sand had been treated.

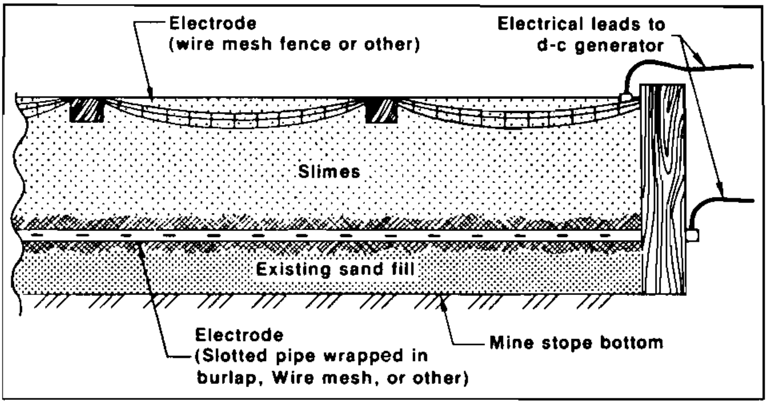


Figure 3. - Simplified diagram of electrokinetic densification of mine slimes.

Miners reported that the electrokinetically consolidated slimes provided better-than-normal working surface for later mining. An even better fill could be obtained, however, if slimes and sand would not separate during settling. Such segregation can be minimized by reducing the water content of the slurry before placement. Our laboratory tests show that slurries of unclassified tailings from north Idaho can be densified by settlement to 70-percent solids by weight (47 percent solids by volume). The resultant material when reslurried is thixotropic, resists further settlement, yet flows quite easily under mild agitation. Electrokinetic dewatering of these dense slurries is most effective, yielding a firm, homogeneous fill with little segregation. Although there has been no opportunity to test this concept in the field, recommendations have been made for detailed studies of rheology, pumping requirements, tendency for pipeline plugging, etc., on dense, well-graded slurries. If the transport properties are favorable, considerably more water could be removed from tailings before transporting them underground, thus reducing underground water accumulation and pumping requirements while creating a superior fill material through electokinetic treatment.

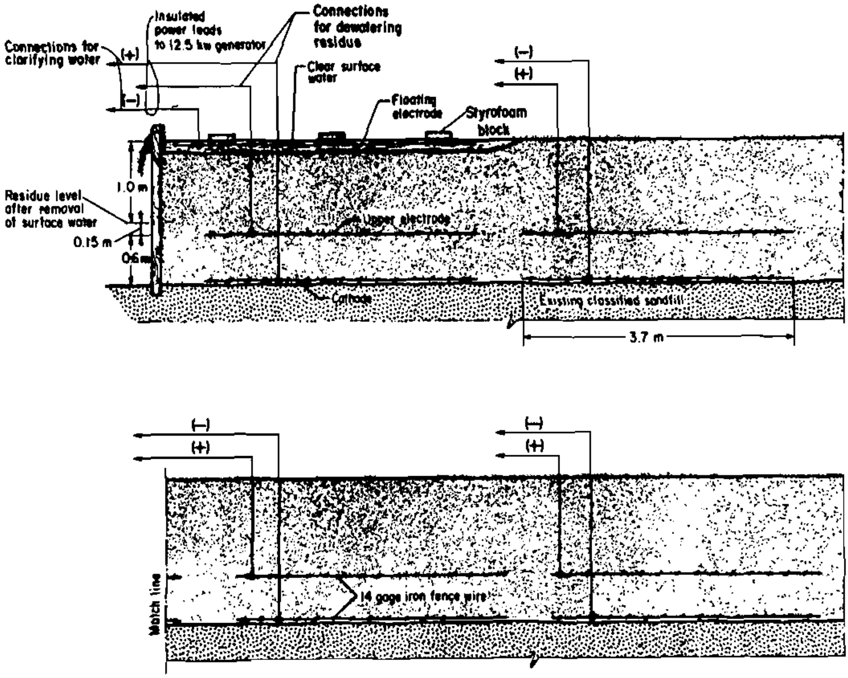
Idaho, slimes.

To minimize the time required for placing hydraulic backfill, operators decant surface water as fast as settlement of the classified sand will allow. Consequently, a significant amount of fine particles remains suspended in the decant water, which is directed to large underground sumps. Here, with sufficient time, the solids gradually settle into a "thick soup" consistency (slimes), and the clear surface water is pumped out of the mine. Removal of slimes from deep mines is impractical, thus requiring underground disposal methods. The common procedure of burying thickened slimes under classified sand has been unsatisfactory; the slimes remain liquefied and tend to return to the fill surface as they are displaced by the denser coarse sand.

Field tests in the Star and Lucky Friday mines demonstrated the effectiveness of electrokinetic treatment on both old and new deposits of thickened slimes. A one-year-old deposit (85 percent finer than 20 micrometers) impounded behind a timber bulkhead in an unused tail drift on the 4,050-level of the Lucky Friday mine, was about 46 meters long by 3 meters wide by 1.5 meters deep.

Panels of iron fence wire, 76-cm wide, placed on the surface of the soft, mushy material served as the cathode. Existing ore-car rails on the drift floor were used for anodes. Water was brought to the top by electro-osmosis and routed over the end of the dam via small channels scratched on the surface. Treatment for 53 hours with intermittent power (25 minutes on, 5 minutes off) of 225 volts (8.4 amp/$m^2$ of the horizontal area between electrodes) consolidated the material sufficiently to permit removal with a mucker. The slimes had been considerably enriched while flowing to the collection sumps through haulage areas where ore spillage occurs; consequently, the dewatered muck was reprocessed for mineral recovery. Power cost for dewatering was about 46 kWh/$m^3$ of densified material. The mine operator plans to use this process for other deposits as the need arises.

Newly thickened slimes from an underground sump were treated in a specially prepared stope off the 7,500-level of the Star mine. Fence-wire electrodes were suspended as shown in Figure 4. A watertight, 1.8-meter-high sandwall was constructed, and the stope was filled with 115 cubic meters of thickened slimes from a collection sump (65 percent of the solids were finer than 20 micrometers). Immediately after filling, a floating fence-wire electrode suspended on styrofoam logs was placed on the fill surface and energized by a 12.5-kW motor-generator. Electrophoretic settlement was immediate compared with settlement by gravity, which takes days or weeks; application of 55 amperes



**Longitudinal Cross Section**

Figure 4. - Test layout, 7500-level, Star Mine.

at 150 volts allowed removal of 19 cubic meters of clear surface water in 4.5 hours. Thirty-seven killowatt-hours of power were required.

After the floating electrode was removed, power was applied to the buried electrodes to draw water to the bottom cathode. The small 12.5-kW generator limited treatment to 24 square meters, requiring division of the stope into four 4.3-meter lengths that were individually treated. Treatment for a total of 51 hours (492 kWh) yielded 46 cubic meters of consolidated slimes that were sufficiently dry and firm to be covered with normal backfill.

Henderson mine.

The Henderson mine in Colorado, operated by Climax Molybdenum Company, has recently installed an electrokinetic dewatering system in two large sump pits on the 7,500-level. All mine drainage (about 9.5 $m^3$/minute) is clarified in these settling basins, and consolidated slimes are removed by loaders and ore cars. Electrical treatment can increase the solid content of sludge from an initial 25 percent to about 70 percent, yielding a firm claylike product. Increasing the applied voltage will accelerate dewatering, but more power per ton of dewatered material will then be needed.

Ultrafine Coal Waste.

Under a cost-sharing cooperative agreement, the Bureau and the Clinchfield Coal Company, Dante, Va., will determine technical and economic feasibility of consolidating coal-waste sludge electrokinetically.

Sludge for the test is from an abandoned 50,000 $m^2$ pond at the company's Moss 3 preparation plant near Clinchfield, Va. The 6-to 9-meter-deep pond has 0.6 to 0.9-meter firm crust over relatively thick sludge with a 50 weight-percent water content and 1,750-ohm-cm resistivity. Nearly 100 percent of the particles are less than 74 micrometers in diameter, 50 percent are smaller than 20 micrometers and electrical surface charge is -26 millivolts. Heating value is 24,000 Joule/gram (dry basis) and ash and sulfur contents are 29 and 0.5 percent, respectively.

Laboratory tests that guided the cooperative agreement and field demonstration design indicate that this sludge can be converted into a firm-to-hard cake with a 19 weight-percent moisture content for a power expenditure of 0.041 kWh per kilogram of final product.

The demonstration includes two phases. The first phase will consolidate sludge in electrokinetic dewatering cells installed on the bank of the pond, and the second phase will attempt to dewater sludge in the pond.

Facilities for phase 1 that have been installed, as shown in Figure 5, include two 150-cubic meters reinforced concrete tanks supported on concrete and steel pilings on the west bank of the pond. Each tank has removable wooden bulkheads on one end to allow entry of equipment and a slot and timbers at the opposite end for decanting surface water before applying treatment. Cathodes are 8-cm-diameter iron pipes, gravel-covered in 15-cm-deep floor trenches with drain ports on the bottom. The upper electrode for each cell includes three 4-by 4.5-meter rectangular grids fabricated from 3.8-cm-diameter pipes. Direct current power is supplied by two 300-kW solid-state rectifiers that provide constant current (as preset) regardless of changing resistance of material between electrodes.

Operational shakedown testing in November 1979 dewatered seven cell loads of sludge. Treatment reduced water content from 55 weight-percent to about 23 weight-percent, with power

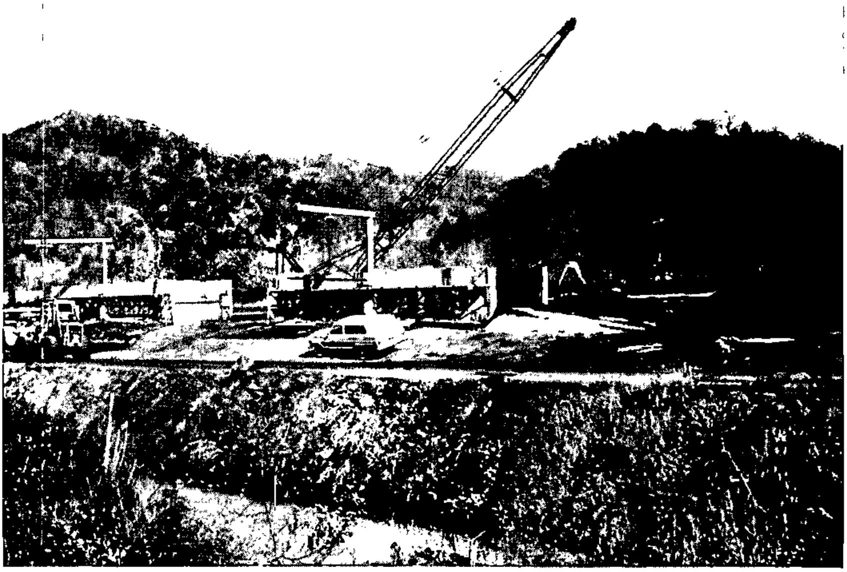


Figure 5. - Field test facilities, Clinchfield Coal Company.

consumption ranging from 44 to 77 kWh/$m^3$ of cake. Ineffective drainage caused these results to fall significantly below laboratory results. The drain systems have therefore been modified, and additional switchgear has been installed to permit periodic reversal of current for improved electrical efficiency.

The planned 24-hour cycle is to fill the cells in the afternoon with a clamshell, apply power throughout the night, and remove the consolidated product with a front-end loader in the morning. Production from both cells is expected to be $10^6$ kg of cake per week. Operation in this manner, expected to continue for 6 to 8 weeks, should develop a semicircular pit near the pond bank.

The second phase of the Clinchfield demonstration will dewater sludge in the pond using an electrode system on or near the face of the semicircular pit and two concentric rings of vertically inserted electrodes around the pit perimeter. Power will be sequentially applied by automatic switching equipment, first to the outer pair of rings and then to the inner pair. Thus, in the first step of the sequence, with the middle ring of electrodes at negative potential, water will be drawn from the outer ring to the middle ring. The second step with the middle ring now positive will draw water into the pit for removal by a pump. Switching periods are adjustable but will probably be set at about 15 minutes.

Treatment will continue until material in the electrical field is sufficiently consolidated for removal with loaders. Dewatered material will be evaluated for suitability as fill and for possible resource recovery.

Washington Irrigation and Development Company (WIDCO) has a pond covering 4 x $10^5$ $m^2$ at the coal processing plant near Centralia, Washington. The pond typically receives 10,000 $m^3$ of thickener underflow per day. Suspended particles settle slowly into a thick soup--a thixotropic and noncohesive sediment of 25 to 35 weight-percent solids. Company records indicate that 3,200 $m^3$ of storage volume is required for each day of operation. Pond depth is over 34 meters in some locations, and filled capacity will soon be reached.

There are two compelling reasons for examining methods to consolidate ultrafine mineral waste in existing tailings ponds:

1. Pond contents would be stabilized and ultimately capped for total reclamation, thereby eliminating potential dike failure and ecological problems.

2. Pond capacity can be extended, thus reducing the need to acquire and develop new disposal sites (which require new permits, approval of regulatory agencies, etc.)

Laboratory and field tests performed by the Bureau of Mines under terms of a cooperative agreement with the company have shown that electrokinetic densification can reduce WIDCO sludge volume by a factor of two, and can be economically attractive if low current densities are used (50 to 65 $mA/m^2$) at low applied potential (20 to 30 volts). Water is brought to the surface by attraction to floating cathodes. Surface water can then be decanted continuously and recycled to the preparation plant as the thickening sludge consolidates around anodes buried in the pond's bottom sediment.

The process was demonstrated to WIDCO officials in small-scale field tests performed September 1979, in a 30-by 15-meter pond adjacent to the $4 \times 10^5$ $m^2$ impoundment. Results supported those obtained in previous laboratory studies; substantial consolidation occurred, with greatest efficiency at low current density. Figure 6 illustrates final conditions in the test pond; the original depth of 142-cm was reduced to 79 cm.

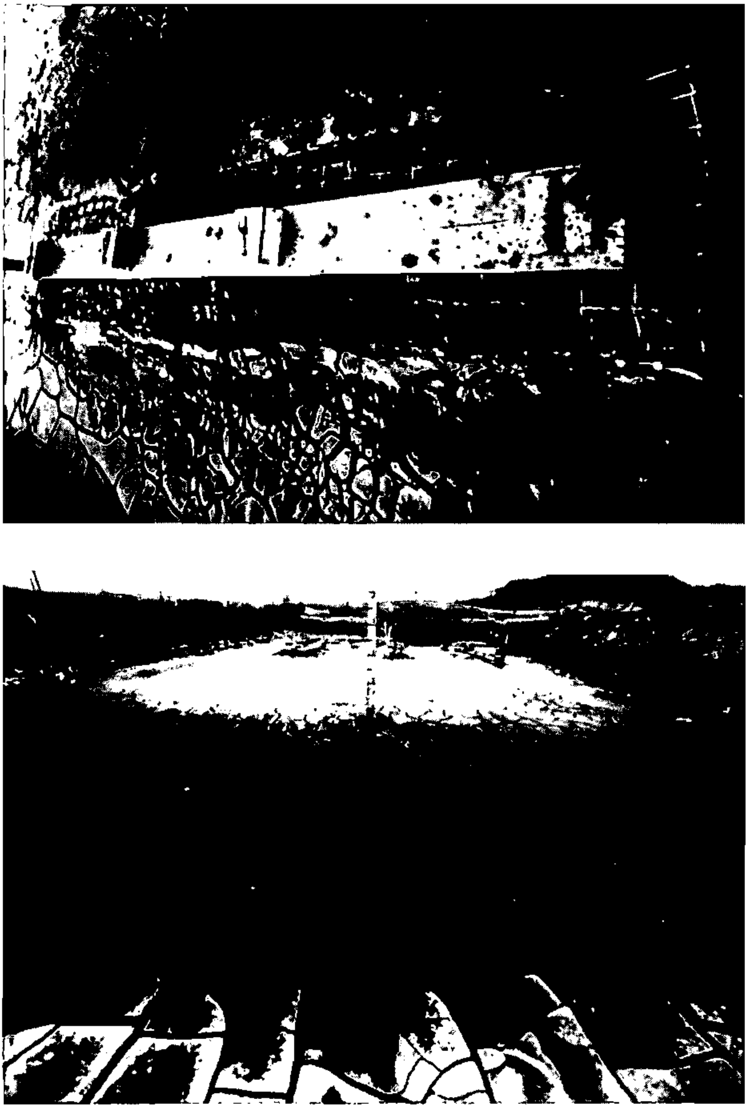


Figure 6. - Electrokinetic consolidation test in an earthen pond.

Material directly between electrodes consolidated to a cohesive, stiff clay; that near the pond edge and the outer edge of electrodes was noticeably softer and less dense.

A full-scale operational system, designed on the basis of laboratory and field test results, is fully discussed in a publication under preparation. An artist's concept drawing of the facility is shown in Figure 7. Power is applied through a rectifier that can be adjusted to supply any regulated current between 120 and 12,000 amperes. Voltage is adjustable between 7 and 70 volts. Imput power comes from the company's 5,000-volt system and is converted to 480-volt, three-phase power by stepdown transformers. To minimize the large and expensive dc bus, all power equipment would be mounted on a floating platform in the center of the electrode array.

One thousand six hundred and eighty four pairs of electrodes are arranged to cover 8.5 x $10^4$ $m^2$ of the deepest part of the pond. About 11 x $10^4$ $m^2$ will be directly affected by electrokinetic treatment. Outlying areas will dewater significantly by natural drainage into the consolidated pit under the cathode. All cathodes are connected to aluminum feeder cables, as are the anodes. Cathodes consist of 3.0-by 0.9-meter pieces of 14-gage iron fence wire kept afloat with 2-cm timber and styrofoam blocks (which also support the aluminum feeder cables). Cathodes do not deteriorate with use, making the small-gage fence wire adequate for the entire treatment period.

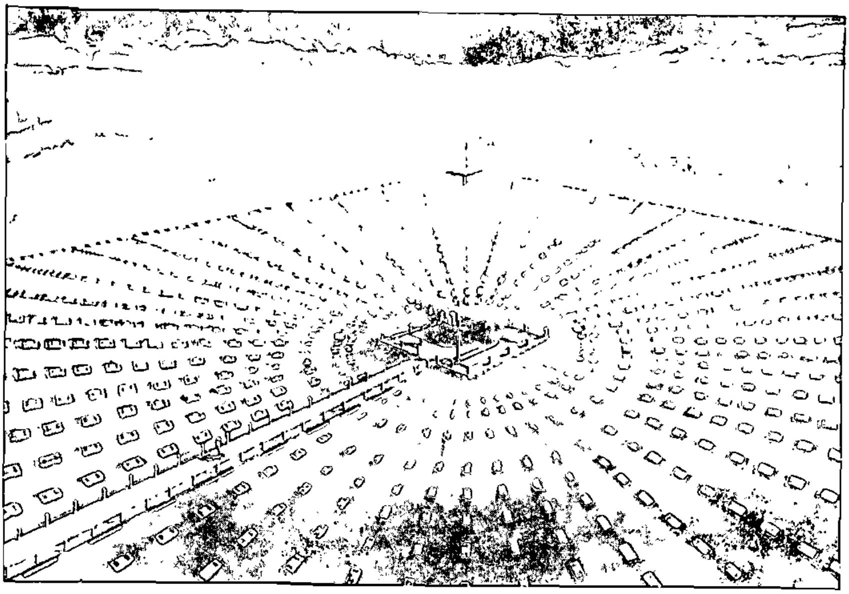


Figure 7. - Electrokinetic consolidation concept for WIDCO's disposal pond.

Anodes can be made of any relatively large piece of scrap iron of sufficient size to withstand the electrochemical corrosion that occurs at a rate of 0.9 grams per ampere-hour. Each anode would be lowered to the pond bottom so as to lie below a cathode; a small insulated wire would connect the anode to the appropriate aluminum feeder cable.

WIDCO engineers have evaluated this plan and have recommended it to management as being technically and economically feasible.

## SAFETY HAZARDS

Although extensive precautions have been exercised in all of the electrokinetic procedures with which we have been involved, concern exists (particularly for underground applications) about possible hazards in various situations--for example, generation of flammable or noxious gas, stray ground currents in proximity of electric blasting, electrochemical corrosion, danger to personnel from possible stray voltages, and resaturation or liquefaction of dewatered slimes. The Waterways Experiment Station at Vicksburg, Miss., has determined the hazards of using this process in underground mines and has developed guidelines and safety procedures for minimizing their occurrence (Green, 1979).

## CONCLUSIONS

Laboratory and field tests have shown that responsive slurries can be dewatered and densified safely and economically using this technique. Power consumption can be reduced significantly by decreasing the applied current density, but this lengthens the time required for treatment. Costs are, therefore, sensitive to how much treatment time is available.

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