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Electrokinetic Densification of Solids in a Coal Mine Sediment Pond—A Feasibility Study

(In Two Parts)

2. Design of an Operational System

By R. H. Sprute, D. J. Kelsh, and S. L. Thompson

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	kg/g	kilogram per gram
A/ft^2	ampere per square foot	kV	kilovolt
A•h	ampere hour	kV•A	kilovolt ampere
A/in^2	ampere per square inch	kW	kilowatt
cm	centimeter	kW•h	kilowatt hour
cm^2	square centimeter	lb	pound
c/s	cycle per second	lb/ft^3	pound per cubic foot
d/yr	day per year	lb/kg	pound per kilogram
deg	degree	lin ft	linear foot
ft	foot	µA/ft^2	microampere per square foot
ft^2	square foot	mA	milliampere
ft^2/acre	square foot per acre	mA/ft^2	milliampere per square foot
ft^3	cubic foot	MW	megawatt
g	gram	ohm•cm	ohm centimeter
g/(A•h)	gram per ampere hour	ohm/cm^2	ohm per square centimeter
gal	gallon	ohm•m	ohm meter
gal/(A•h)	gallon per ampere hour	pct	percent
gal/d	gallon per day	s	second
gal/h	gallon per hour	st	short ton
gal/min	gallon per minute	rad	radian
h	hour	V	volt
h/d	hour per day	W	watt
Hz	Hertz	wt pct	weight percent
in	inch	yr	year

ELECTROKINETIC DENSIFICATION OF SOLIDS IN A COAL MINE SEDIMENT POND A FEASIBILITY STUDY

(In Two Parts)

2. Design of an Operational System

By R. H. Sprute,[1] D.J. Kelsh,[2] and S. L. Thompson[3]

ABSTRACT

The Bureau of Mines conducted a feasibility study and designed an operational system for consolidating waste coal sludge in a 110-acre pond by applying direct current between buried and floating electrodes. Consolidation would reduce the sludge to half its present volume, thereby extending the working life of the pond as well as creating a safe, stable impoundment. The project was conducted by the Bureau under an agreement with the Washington Irrigation and Development Co. (WIDCO), located near Centralia, WA. Part 1 of this report, published as Report of Investigation 8666 in 1982, covers the results of laboratory tests at the Bureau's Spokane Research Center and of a small-scale field test at WIDCO's coal preparation plant. Test results show the process is efficient and cost-effective when power is applied at low current density. Part 2 (this paper) describes a detailed design for an electrokinetic system to dewater WIDCO's 110-acre pond with a 27.4-acre electrode array. Densification of the inactive sludge pond will require 3.6 yr of treatment for a total cost of $1,450,000. The study and design are site specific, but design procedures and analyses are sufficiently detailed to serve as a guide for applying the process to any sludge pond.

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[3]Electrical engineer, Washington Water Power Company, Spokane, WA.

INTRODUCTION

Washington Irrigation and Development Co. (WIDCO) operates a large surface mine in western Washington State to supply coal for a 1,400-MW steam-electric generating plant near Centralia, WA. The mine's preparation plant typically charges the pond with about 2,600 gal/min, or 11.6 acre-feet of waste per day. Suspended solids are extremely resistant to natural settlement forces, and after a few years, sediment consolidation by natural means is slow to nonexistent, resulting in a soft, thixotropic product containing 25 to 35 wt pct solids. Since startup in 1970, the pond has grown to 110 acres with a center depth of 110 ft. Plant records show that the average accumulation rate in the pond has been 2.5 acre-feet per day. The pond is now nearly filled, and WIDCO management is searching for future storage space. Electrokinetic dewatering to consolidate the pond contents, thereby increasing the life of the pond, was one of a number of alternatives under consideration by the company at the time of this study.

For the electrokinetic option, electric power is applied to a 27.4-acre array of submerged anodes (positive potential) and floating cathodes, causing suspended solids to migrate downward while water in the thickening sediment moves upward. The relatively clear surface water is then decanted and normally recycled for plant use. Previous laboratory and field tests indicate that treatment in this manner at low current density will economically reduce the sludge between electrodes to about half its original volume. Outlying areas also will densify significantly, but to an unknown extent. In the lower 85 to 90 pct of the volume of the electrode area, the final product will be a very firm, claylike material. The top 10 to 15 pct will also consolidate but will be soft, ranging from soupy to moderately cohesive. Outlying areas will be soft but cohesive (1).[4]

Bureau of Mines personnel, with engineering assistance from WIDCO, designed a system for electrokinetically consolidating existing pond contents. The process will consolidate all of the sludge sufficiently so that the pond can be capped with coarse refuse for total reclamation. This project qualifies as an acceptable modification to an existing process already listed on the original Office of Surface Mining application; therefore, new environmental impact statements are not required. Safety features are included to minimize electrocution hazards that will exist in the bare bus area, where the maximum phase-to-phase potential will be 137 V (RMS) during the first 10 days and 96 V thereafter. The hazard due to the potential between bare bus and earth is minimal because all conductors are tightly connected to earth.

The complete design package, including drawings, analyses, specifications, costs, and an executive summary, was formally presented to mine management at a September 1984 meeting of representatives from the Bureau and WIDCO at their offices in Centralia, WA. WIDCO management enthusiastically accepted the proposal as a viable solution. However, they had hoped to receive some Government funding to help defray the costs of demonstrating this new technology; receiving none, they decided to pursue other options. WIDCO may eventually reclaim the old pond using electrokinetics, but there is no immediate plan to do so.

This report describes in detail the design specifications for the WIDCO pond. The WIDCO site is presented as an example of how this technology can be applied to dewater sludge ponds. Although some of the design criteria are site specific, this report provides a guide for other companies planning electrokinetic dewatering systems for sludge ponds.

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[4]Underlined numbers in parentheses refer to items in the list of references preceding appendix A.

ACKNOWLEDGMENTS

The cooperation and technical assistance contributed by WIDCO, Centralia, WA, are gratefully acknowledged, with particular thanks to Roger Paul, engineering geologist, and David Frankovitch, electrical engineer. Successful completion of the project has been in large measure due to the efforts of Ray Anderson, lead engineering technician at the Bureau's Spokane Research Center (SRC), for field sampling and conducting the laboratory tests; John White, electrical power engineer, Bonneville Power Administration, for furnishing electrode grounding technology; Doug Tesarik, SRC mathematician, for the computer work; and Donald Corson, SRC research supervisor, for his insightful comments and suggestions.

THE PROBLEM

WIDCO, owned by Washington Water Power Company, operates a large, multiseamed surface mine in western Washington to supply coal for a 1,400-MW steam-electric generating plant near Centralia, WA. The mine's preparation plant thickener typically discharges about 2,600 gal/min (11.6 acre-feet per day) of underflow. Disposal is made unusually difficult by (1) the large volume of materials, (2) suspended particles that are extremely resistant to natural settlement, and (3) physical properties that change significantly and unpredictably as mining progresses. From 1981 to 1984, disposal was accomplished by flocculating with polymers, followed by dewatering with a belt press, placement in mined-out areas, and finally covering with coarse refuse. The high cost of reagents and equipment maintenance makes this procedure no longer satisfactory.

From plant startup in 1970 until installation of the belt presses, the watery underflow was pumped into a pond where solids settled slowly and surface water was decanted for reuse in the plant. At the time of the Bureau's study, the pond was nearly full, covered about 110 acres, and was up to 110 ft deep. Most of the sediment was soft, thixotropic, and noncohesive with a 25- to 35-pct solids content. Company records indicated that about 2.5 acre-feet of storage volume was required for each day of operation. Results of laboratory and field tests conducted under an agreement between the Bureau and WIDCO showed that pond contents could be economically reduced in volume by up to 50 pct with electrokinetic treatment if current was applied at very low density over a relatively long period of time.

In order to abandon the belt press procedures, WIDCO management sought space to safely store waste coal sludge (thickener underflow) that would accumulate from the coal preparation plant over a 3-yr operating period. The volume of pond needed to contain this addition is about 2,740 acre-feet, and the impoundment for this soupy material must be licensed and must meet all State and Federal regulations for safety. A plan to consolidate sludge in the existing pond while simultaneously adding new sludge was developed by the Bureau, but this option was later foregone by WIDCO in favor of constructing new space. Consequently, the design description that follows assumes that no new material will be added to the old pond during electrokinetic dewatering treatment.

AN ELECTROKINETIC CONSOLIDATION SYSTEM FOR WIDCO SLUDGE

An artist's concept of the electrokinetic system designed for consolidating existing sludge in the WIDCO waste pond is shown in figure 1. The total system includes five major components:

1. The cathode is the electrode through which negative electric potential is applied to the upper level of the sludge body. The cathode array covers 27.4 acres over the deepest part of the

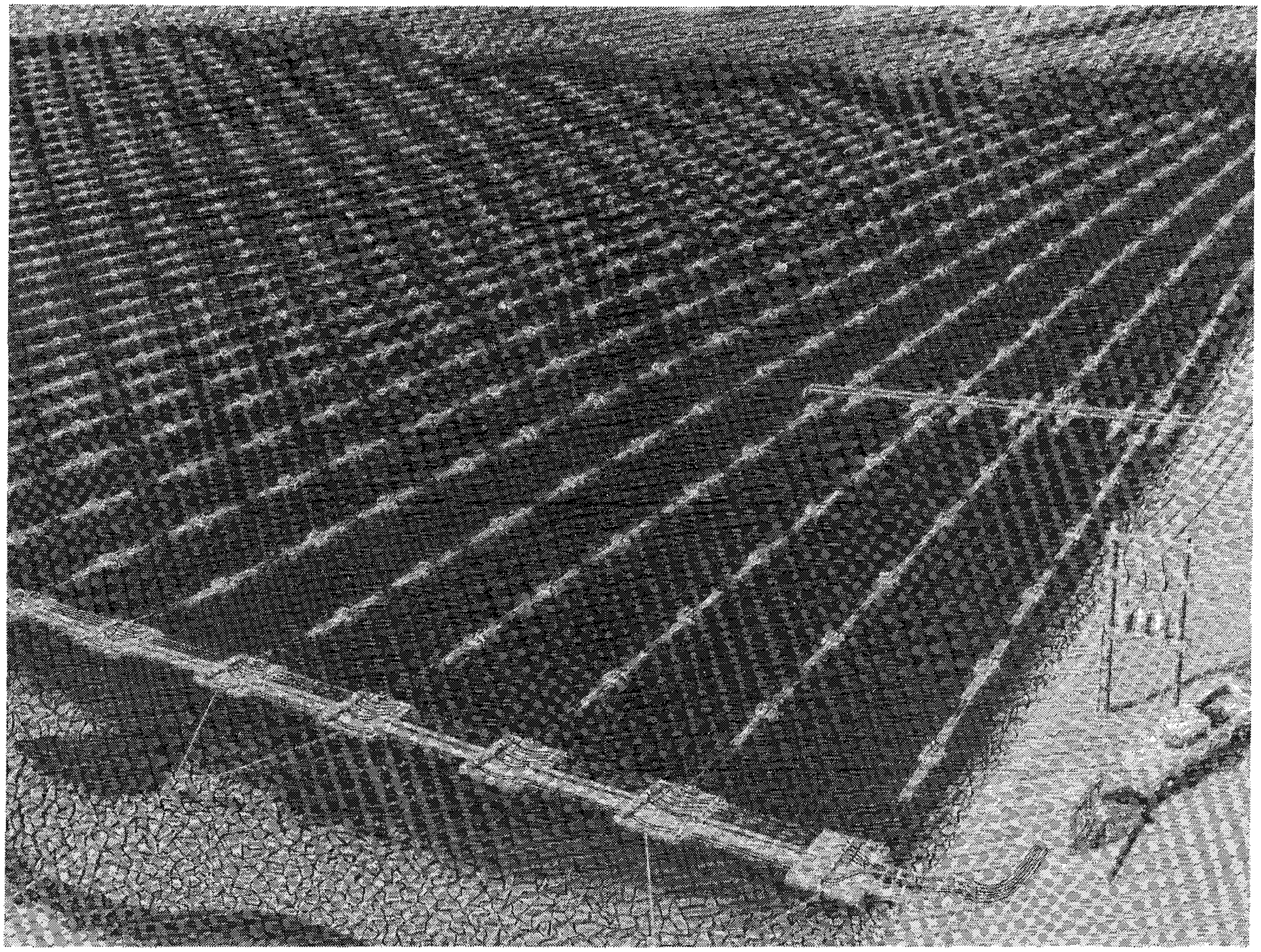

FIGURE 1.—Electrokinetic dewatering system—an artist's concept.

pond and consists of 1,135 pieces of galvanized iron fence wire (hog wire), each measuring 14 by 2.67 ft. The fence panels are suspended from floating Styrofoam[5] blocks and timbers so that they float 3 to 4 in below the pond surface water. Horizontal orientation of the panels is maintained by the electrical feeder cables and guy wires anchored to shore. The guy wires are coated to prevent electrochemical corrosion. During operation, decanting of electrokinetically developed surface water is regulated to maintain 8 to 12 in of clear surface water above the sediment in order to effectively float and operate the cathode. The cathode is always at a negative electrical potential relative to the submerged electrodes (anodes) and its immediate environment and thus will not corrode; i.e., it is cathodically protected. Therefore cathodes, connectors, and feeder cables could be salvaged in good condition if economically justified.

2. The anode is the electrode that imparts positive (direct current) potential to the sludge being treated. For this design, four relatively large pieces of any available iron are submerged beneath each of the 1,135 cathodes at a depth of about 36 ft. Each anode is connected by its individual, small, insulated wire to a large, insulated

[5]Reference to specific products does not imply endorsement by the Bureau of Mines.

aluminum feeder cable suspended above the pond surface on Styrofoam blocks. Connection of the copper wire to the iron must exclude moisture to prevent corrosion of the small electrical feeder wire and of connecting devices such as screws and terminal clips. This is accomplished by recessing the connection in a carefully selected location, usually the most massive area of the anode, and covering the connection with sealant as shown in the design analysis section of appendix A (fig. A-6). Extensive laboratory testing for corrosion has shown that this will protect the connection until the anode is essentially depleted. Of the three materials tested to find the best anode material to use with this project, DSA (dimensionally stable anode, a patented electrode) and iron performed about equally well, and both performed significantly better than aluminum. DSA was attractive because it does not corrode, and, therefore, a relatively small quantity is required compared to that of iron, which corrodes severely. However, DSA is more expensive, and there would be particular installation problems in that DSA is a rather light, screenlike material that would not naturally sink sufficiently into the sludge, which thickens with distance below the surface. Because of these considerations and the ready availability of scrap iron at the mine and elsewhere, iron was selected as the preferred anode material.

Laboratory tests show that an iron anode dissipates by electrochemical corrosion in WIDCO pond refuse at a rate of 1.15 g/(A•h). The amount of current that each anode transfers varies with its size and shape as well as with the level of applied potential and sludge resistance. Therefore, as discussed in appendix A, each of the 1,135 anodes consists of 550 lb of iron, divided into four equal units symmetrically positioned beneath the cathode. A total of 313 st of iron is required for the anode array. Splitting the anode into smaller units improves the current distribution pattern in the sludge body. The smaller electrodes are also much easier to handle and install.

Anode shape contributes to the efficiency of current conduction through the sludge. For example, as shown in appendix A, a piece of iron would be most effective (offer least resistance) if formed into a straight rod or wire and buried horizontally. Conductivity of that rod would decrease by 5 pct if it were reshaped into an equilateral, equal-legged Y-shape, and would be reduced by 39 pct if formed into an eight-point star. Therefore, for this project, miscellaneous pieces of iron such as dragline cable, pipes, construction steel, drill steel, etc., were fabricated into straight-, L-, or Y-shaped anodes.

Consideration was also given to the potential impediments of coatings such as oils, conventional paints, and creosotes, as well as to the oxidation coating normally present on scrap iron. Performance testing in the laboratory and field by SRC has shown that normal coatings of this type present no problem because they corrode away relatively soon after the iron is energized. Iron with unusually impervious coatings, such as the epoxies and silicons, requires special preparation to expose the metal for sludge contact and should, therefore, be avoided.

3. The <u>electrical power system</u> includes an incoming distribution line to furnish 480-V, three-phase power; a specialized rectifier for converting 480-V alternating current (ac) power to direct current (dc) power; a high-current-capacity, low-voltage distribution system for transferring power from the rectifier to the electrodes; and a system of docks to support the large dc conductors. In order to connect the 715-kW rectifier at the WIDCO treatment site with the nearest source, new construction of 0.25 mile of three-phase, 2/0 ASCR, 5-kV primary distribution line is required. In addition, 0.5 mile of existing primary line must be converted from single phase to a three-phase, 2/0 ASCR, 5-kV system. A platform-mounted transformer bank at the treatment site will reduce three-phase, 4,160-V primary voltage to three-phase, 480-V secondary

output. The primary side of the transformer is protected with fused cutouts, pole-mounted disconnects, and lightning arrestors. Secondary output will be fed through a manual, nonfused safety disconnect switch to the input terminal box on the rectifier.

The rectifier for the project must be specially built with unique features to power the selected electrode system effectively. First of all, as discussed in appendix A, laboratory tests at SRC show that treatment with pulsing half-wave dc power (that is, sinusoidal pulses) rather than the normally used pure dc power produces somewhat superior results. Specifically, for WIDCO sludge, a given amount of current applied in pulses rather than in a constant flow should increase final consolidation by 3 to 4 wt pct. A much greater advantage has been claimed by other researchers, but their results have not been substantiated in this work. In any case, the rectifier's three-phase output will be arranged to supply six individual, time-separated, half-wave potentials. This circuitry arrangement is easily accomplished and allows the primary treatment area in the WIDCO pond to be separated into six separate areas, each covering about 5.5 acres and having an individual electrode system and pulsed dc supply of power. Such zoning will tend to equalize current distribution through the sludge and alleviate the possibility of current hogging by an area that for some unforeseen reason has a lower electrical resistance.

Special circuitry is included to suppress the peaks of the output pulses; i.e., 14 pct of the peak of each pulse will be blocked off. This degree of suppression, selected after evaluating a number of other values, significantly reduces electrical heating loss in the distribution system with a relatively small reduction in the water removal rate, which is directly proportional to the ampere hours of applied current.

A control switch permits operation in either of two modes--constant current or constant voltage. In the first mode, current output can be maintained within 5 pct of any set value as changes occur in load resistance; i.e., voltage varies within the unit's capacity, and current remains constant. Similarly, in the second mode, voltage remains within 5 pct of a selected value, and current output varies with changes in load resistance.

The required maximum output rating of the rectifier is calculated as 715 kW continuous duty and 70 V RMS, with reference to the neutral value for each of the six half-wave output circuits. The maximum current output rating per pulse is 3,475 A RMS, and the combined maximum from the six outputs expressed in terms of a constant current is 8,886 A.

The rectifier unit should be weatherproof, pad mounted, and equipped with all required safety devices, including overload protection for individual diodes, transformers, and the overall system.

Salvage value will be minimal for this specially designed unit unless a similar need arises, e.g., another large waste coal or phosphate impoundment.

4. The <u>dc electrical distribution</u> system shown in appendix figures A-1, A-3, and A-12 through A-18 employs a rather complicated circuit of large and small conductors along with a few large diodes to prevent flow of current in the wrong direction. The distribution system is complex because a large quantity of current must be delivered over relatively long distances. Also, the six individual dc potentials from the electrical power source (two half-wave outputs per each phase) must each be delivered by a separate circuit to six individual areas. The pulse in each of these circuits is a flat-topped sinusoid (fig. A-20) with a frequency of 60 c/s and equal on-off times of 1/120 s. The amplitude of the pulses varies according to area requirements, ranging from 2,967 A RMS for zone 5 to 3,479 A for zone 2. In normal operation, an adjustable current regulator will automatically raise or lower the output voltage as necessary to compensate for changes in resistance so as to maintain the selected level of current flow. Circuitry for delivering power includes one run of aluminum tubing for each of the six output circuits and one additional run, or neutral, which serves as a

common return. The size of the tubing increases with distance from the rectifier and with the amperage. The bus is routed along the east side of the treatment area and ranges in size from 4-in-OD pipe with 1/4-in walls for zone 1 to 8-in-OD pipe with 3/8-in walls for zone 6. Large, insulated aluminum feeder cable distributes the dc power laterally from the bus across the treatment areas, and finally, small insulated wires for the branch circuits carry power from the feeder cables to the electrodes.

The bus system is supported 12 to 15 in above the pond surface by 43 wooden docks aligned along the east boundary of the treatment zone. Each dock has enough Styrofoam logs to give a net support capacity of about 3,600 lb per dock. The 24-ft-long aluminum tubes, with diameters ranging from 4 to 8 in (bus), span the open space. Their ends are solidly fixed to wooden crossbars, which are in turn attached to the docks midway between the dock edges and the centerline. One of the crossbars on each dock is fastened solidly, while the other is free to swivel horizontally about its center point; i.e., this bar is attached with one large center pin, which allows horizontal flexibility. The 6-ft gap between bus ends on the dock (the space between the fixed and swivel bars) is bridged by insulated aluminum jumper cables in sufficient number and size to provide the necessary current-carrying capacity. The jumper cables provide necessary flexibility and also provide a convenient means for connecting the feeder cables that cross the pond with simple T-splices.

The ramp also can be used as staging space for construction (perhaps supplemental to a relatively large, mobile, winch-powered, construction dock) and could support a 2-ft catwalk to provide access for construction, operation, and salvage when electrokinetic treatment has been completed.

The dock guy system includes an electrical cable system anchored to the west bank as discussed earlier, and a nonelectrical, steel cable system attached to the east shore. The nonelectrical cables require particular attention because they will be in contact with earth potential on the shore and, possibly, with sludge in the pond. The pond sludge near the surface will probably be negative in potential with respect to the surface of the host earth. Such a difference in potential, even if slight, would soon corrode and destroy the cable if a conducting path were available. Cathodic protection procedures were considered, but coating the wire with coal tar enamel was chosen because of simplicity, adequacy, and lowest cost.

During normal operation, the maximum potential on the aluminum phase bus (with respect to neutral) will be about 48 V RMS, but it can be as high as 69 V during the first 10 days after startup. Corresponding potentials measured from phase bus to phase bus are 166 and 239 V RMS. Therefore, electrocution hazards are present in the aluminum bus area. Another danger is the possibility of accidentally dropping a conducting object, such as a large pipe wrench, across the energized, uninsulated aluminum buses. Such an accident could draw a sustained, several-thousand-ampere arc that would probably vaporize the wrench while causing personnel injury from burns via flying molten metal, blindness from excessive radiant energy, fires, etc. The final design should include provisions to alleviate these hazards by making certain that power to the buses is off before allowing personnel to enter the dock or catwalk areas. Such provisions should be automatically activated; e.g., a gate across the ramp access should be electrically interlocked with the rectifier so as to automatically disconnect power when the gate is opened.

5. The <u>decant</u> system is required to remove electrokinetically clarified surface water from the pond surface for return to the plant and reuse. The system, as indicated in the right center of figure 1, includes two 8-in polyvinyl chloride pipes supported above the pond's surface with Styrofoam and timber buoys. The pipes extend up the inside of the dam surface, through the dam a few feet below the roadway, and then down the face of the dam to a creek below the toe. (The creek flows into a holding pond, which is

the source of process water for the preparation plant.)

The intake ends of the pipes are located over the deepest part of the disposal pond and are equipped with screens and foot valves. Each pipe also has two capped standpipes located near the highest point just off the roadway. These pipes are used to fill the decant lines with water while evacuating air for initial syphoning, or to reestablish the process if vacuum is inadvertently lost.

The combined discharge rate of the two 8-in pipes is about 900,000 gal/d--246 pct greater than the maximum predicted extraction rate of 365,000 gal/d, which includes both natural and electrokinetic dewatering. The excess decant capacity is required to remove rain water and to allow accelerated removal of accumulated surface water when necessary.

The discharge end of each pipe is equipped with a manual valve that is used to regulate the decant rate. An operator can periodically monitor and adjust these valves to maintain an 8- to 12-in layer of water on the pond surface so that the electrode system floats.

The decant lines must be somewhat flexible to adapt to changes in contour and elevation of the pond surface with decantation, sludge consolidation, and rain water accumulation. This is achieved through the natural flexibility of the pipe itself and by using flexible couplings instead of standard fittings in some of the joints.

SYSTEM OPERATION

The following paragraphs describe operational procedures for using the electrokinetic equipment outlined in the foregoing paragraphs, as well as anticipated results. The WIDCO system must consolidate a large amount of existing sludge (perhaps 5,000 acre-feet). At treatment end, it must leave the pond contents sufficiently consolidated to allow eventual capping with coarse refuse and topsoil for total reclamation or, alternatively, to provide additional storage space for up to 3 yr of plant operation.

Treatment consists of applying electric power between submerged anodes and floating cathodes. At WIDCO, these electrodes (1,135 pairs of anodes and cathodes) would have been installed in a regular pattern covering 27.4 acres over the deepest part of the pond. Electrode theory shows that this array will actually cause current to flow throughout the entire sludge body, but the intensity or current density will diminish rapidly with distance from the electrode. Laboratory and field tests do show that the field is very effective for a distance beyond the perimeter of 1.25 times the separation distance between electrodes. At WIDCO, this would have equaled 5.6 acres. The total area affected, the actual area of the array plus the additional area around the perimeter, is called "the primary treatment zone." At the WIDCO site, it would have equaled 33 acres.

Application of power, with the upper electrode negative, will cause particles in the upper region (muddy water) to move downward while water in the sediment migrates upward to the cathode. In addition, significant flocculation occurs in the muddy water zone, probably induced by the hydroxide ions generated at the cathode.

Surface water separates as a result of several factors. Continued treatment gradually dilutes the muddy water through electrophoresis or downward particle migration, but stops short of total clarification. Meanwhile, the depth of surface water gradually increases with electro-osmosis, i.e., the upward migration of surface water in the sediment and consequent consolidation.

Soon after treatment starts, a precisely defined layer of very clear water develops at the cathode and continues to grow in depth with treatment. The water in this layer does not clear gradually, but rather is a clear layer that grows in depth. This clear-layer phenomenon is attributed to coagulation at the cathode; i.e., small particles coalesce into larger units that are sufficiently massive to settle under the influence of gravity without being hindered by thermal convection or diffusion.

Coalescence at the cathode may be caused or enhanced by the electrode reaction:

$$2H_2O + 2e^- \longrightarrow H_2(g) + 2OH^-(aq).$$

The hydroxide ions can react chemically with the suspended solids, thereby altering composition and/or surface charge, and the increased electrolyte concentration can compress the electrical double layer of charge that surrounds each particle, thereby reducing the charge repulsion that normally keeps the particles from making contact with each other. When the repulsion barrier is sufficiently small, cohesive contacts between colliding particles are frequent, and sedimentation is appreciably enhanced as the particles grow larger.

The electrode array is divided into six roughly equal zones of 5.5 acres, as shown in appendix figure A-3. Each zone is energized by its own individual half-wave direct current potential. Thus, in sequence, each of the six zones is pulsed 60 times per second with a sinusoidal potential of 1/120 s followed by an equal period of zero potential. The ratio of peak potential (flat-topped sinusoidal crest) to an equivalent average value of constant current, assuming a perfect rectifier, is about 2.8. The postulated reason for improved results with pulsed power compared to constant dc is that, for a given quantity of charge passed through the circuit, the much higher potential, even though brief, imparts a greater force for particle movement and/or water transport.

A critical point in the design process is selecting a current density that will be applied to the sludge. This number is important and must be carefully determined because it must produce effective and efficient results and is also a key factor in designing and selecting equipment. Based on consistent results from a variety of laboratory and field tests, the average current for treating WIDCO sludge is specified to be 6 to 7 mA per square foot of horizontal cross-sectional area in the 33-acre primary treatment zone. Thus, typically, each square foot of the primary area will be treated with current that constantly pulses from zero A to a peak value and back to zero over 1/120 s, followed by an equal off period. The total applied current expressed as a constant value (dc) is about 8,886 A.

Generally, the water clarification rate with a 6- to 7-mA/ft^2 current density achieves a high of more than 1 gal/(A·h) shortly after treatment begins. This is maintained through 60 to 65 pct of the entire treatment time, but then begins to decline slowly, reaching a very low value near the final stage.

Overall, as discussed in the analysis and calculations section of the appendix to this report, the average water clarification rate over the entire 3.6-yr period is conservatively estimated at 0.75 gal/(A·h). Therefore, electrokinetically produced clear water in the primary zone will range from a high of 213,000 gal/d through much of the treatment to a minimal amount near the end, and will average about 160,000 gal/d.

The outlying area of 77 acres will also dewater as a result of receiving a small amount of current from the electrode array and because a gradually increasing slope toward the electrodes will develop as the pit in the primary area deepens with treatment. The outlying area is expected to yield an average of 152,000 gal/d of surface water. Additional surface water will also result from rainfall, which is quite heavy at times.

The decant line intakes will be located over the deepest part of the pond, where treatment should ultimately lower the sludge level by nearly 20 ft. Thus, when treatment is complete, the primary zone will serve as a sump with the up-slope gradient directed toward the pond boundaries, similar to conditions achieved in the small test pond shown in figure 14 of RI 8666 (1).

Valves on the discharge end of the decant lines should be periodically adjusted to remove surface water continuously as it develops while maintaining an 8- to 12-in layer of water on which to properly support surface electrodes. This layer will also allow occasional relocation of the cathodes, if warranted, to minimize mounds and valleys. As treatment nears completion, all of the surface water can be removed, allowing the cathodes to rest in the sediment.

As outlined in the appendix A calculations, during the 3.6-yr treatment period, the depth of sludge in the primary area between electrodes is expected to be reduced by 16.4 ft. During this period, material in the 20-ft layer beneath the anode will also be consolidated by about 2.5 ft. Thus, the level in the primary zone will be lowered by 18.9 ft, creating 626 acre-feet of new storage space. When treatment has been completed, i.e., water extraction ceases, all of the sediment in the primary zone should be a firm, claylike product, except for a shallow surface layer, possibly averaging 12 in, which will remain soft. This entire 33-acre zone could probably be capped immediately with coarse refuse and topsoil.

An accurate quantitative prediction of consolidation in outlying areas is not possible in the absence of test data. On the basis of electrode theory, some current will certainly be present in every portion of the pond. It will diminish with distance from the electrode and thus will be very small at the outermost edges--perhaps about 1 $\mu A/ft^2$. Even such low density, applied for 3.6 yr, should cause significant densification. In addition, as the depth of the pit in the primary zone increases with continued treatment and decanting of surface water, the slope of sediment surface in the outlying area will also increase. This increasing slope should aid both natural and electrokinetic dewatering. Shrinkage cracks will develop on the exposed sediment to assist in drying. The entire procedure is conservatively expected to increase solid content of sediment in the outer zone by an average of 6 pct, to a total of 31 wt pct solids. This consolidation will result in 608 acre-feet of new storage.

Thus, with treatment complete, the 77 acres of sediment in the outlying area would be soft but cohesive with a 31-pct solids content. It would slope into the primary treatment area and be liberally crisscrossed with large shrinkage cracks to allow air drying along with very slow natural dewatering.

Available storage in the pond after completion of the treatment process is as follows:

	Acre-feet
New storage developed in the 33-acre primary area.........	626
New storage developed in the 77-acre outside area.........	608
Additional available space from the existing sludge level of 384 ft to maximum fill capacity of 391 ft......	770
Total available space after treatment..........	2,004

Plant records show a sludge accumulation rate of 2.5 acre-feet per day. Therefore, the project would provide storage space for only 2.19 yr of plant operation--0.81 yr short of the 3-yr goal. It should be recognized, however, that the calculated value of 2,004 acre-feet of available storage after treatment is considered conservative for the following reasons:

1. Consolidation of sludge in the 77-acre secondary area will probably significantly exceed the 6-pct figure used in this design.
2. Storage space calculations did not take into account a small amount of settling that can be expected in the lowermost 54 ft of sludge in the primary area.

In addition, it appears that the given sludge accumulation rate of 2.5 acre-feet per day may be high. Therefore, completion of the project would result in at least 2,004 acre-feet of storage for 2.19 yr or more of plant operation.

Assessment of sludge conditions throughout the pond will obviously have to be carefully made at the end of the treatment period before selecting post-treatment procedures. Two procedures are possible:

1. Immediately cap the primary zone and other areas, such as deltas, with coarse refuse and topsoil. Maintain a drainage channel from the secondary zone into the decant point in the primary zone. Sludge in the secondary zone will continue to dewater by natural forces. Selected areas can be capped as feasible. Total reclamation in this manner would probably require several years with relatively low cost.

2. Immediately cap the primary area of 33 acres with coarse refuse and topsoil, being careful to preserve the heavy aluminum bus. Maintain drainage channels from the secondary zone into the decant point in the primary zone. For the second step, select 5 or 10 acres of the outlying zone and install a simple electrokinetic densification system (vertically installed pipes) specifically engineered for particular existing conditions. The treatment period could be reduced by using a greater current density, but with proportionally higher cost if such increased cost can be justified. When consolidated, this plot could be capped and reclaimed, and a second section could be selected and dewatered. This sequence could continue until the entire pond is densified, with 120 acres of real estate reclaimed and available for normal use.

The electrical energy requirements and cost estimate, described in detail in appendix A and excluding reclamation option 2, are summarized as follows:

Energy requirements (3.6 yr), kW•h:

Power consumed by electrodes and sludge	6,601,000
Power consumed as heat in distribution system	3,491,000
Power consumed in rectifier, as inefficiency	1,121,000
Total power consumption	11,213,000

Cost estimate:

Substation, 800 kV•A, and primary line	$45,000
Rectifier installation and fabrication, 715 kW	52,000
Dock system, 43 each, with catwalks, hardware to mount bus, and anchors	221,400
Direct current distribution system, complete	288,221
Anode array, complete	123,400
Cathode array, complete	47,900
Decant system, complete	15,000
Engineering cost to finalize design	30,000
Contingencies and omissions, 10 pct	79,291
Contractor profit, 10 pct	90,221
Total installation cost	992,433
Electric power cost (3.60 yr)	313,954
Maintenance and operation--includes testing, sampling, decanting, and equipment upkeep	144,000
Total estimated project cost	1,450,387

SUMMARY AND CONCLUSIONS

Large tailings ponds can be densified and dewatered by applying direct current between floating and submerged electrodes. The process is especially recommended for very finely divided solids in suspension and is effective for many types of materials, provided that sufficient electrical charge is naturally present on the particle surface and that electrical conductivity of the slurry is not too high. Laboratory evaluations should always be done on candidate materials before proceeding with plans for a field installation.

This report has described an electrical dewatering process for a particularly difficult slurry of ultrafine coal and clay. Other slurries will have their own unique characteristics, and optimum levels of current density, electrode placement, etc. must be determined on a case-by-case basis. However, the use of half-wave rectified power is thought to be generally more efficient than straight dc, and should be applicable to any type of electrokinetic dewatering system.

REFERENCES

1. Sprute, R. H., and D. J. Kelsh. Electrokinetic Densification of Solids in a Coal Mine Sediment Pond —A Feasibility Study (In Two Parts). 1. Laboratory and Field Tests. BuMines RI 8666, 1982, 32 pp.

2. Eaton, J. R. Grounding Electric Circuits Effectively. James G. Biddle Co., Bull. 2ST2 (undated), 19 pp.

3. Sprute, R. H., and D. J. Kelsh. Electrokinetic Densification of Hydraulic Backfill—A Field Test. BuMines RI 8075, 1975, 20 pp.

4. Kelsh, D. J. Water Electrolysis: A Suprising Experiment. J. Chem Education, v. 62, No. 2, 1985, p. 154.

5. Tagg, G. F. Earth Resistance. Pittman Publ. Corp., 1964, 205 pp.

6. Swartz, S. J. Analytical Expressions for the Resistance of Grounding Systems. AIEE Proc., Aug. 1954, pp. 1011-1016.

APPENDIX A.--DESIGN PROCEDURES

The use of electric power to dewater and consolidate watery slimes and sludges in ponds and underground mine stopes is essentially a new concept for which established design procedures and manuals do not exist. Much more experience in both research and use is necessary before comprehensive time-tested procedures for this technology will be available. Therefore, this appendix is included to show design considerations, calculations, computer programs, etc., used in preparing the WIDCO system. It will be a helpful technical guide to anyone involved in planning an electrokinetic dewatering system.

GIVEN DATA AND ASSUMPTIONS

Current elevation of pond surface............ ft..	384
Surface area of pond at current elevation (approximate)............acres..	110
Elevation of filled pond surface............ft..	391
Surface area of pond at maximum fill level (approximate)............acres..	120
Maximum depth, current............ft..	110
Average depth (approximate)[1]............ft..	45
Volume of existing sludge (approximate)............acre-feet..	5,000
Volume required to accommodate disposal needs of the preparation plant's waste for the ensuing 3 yr[2]............acre-feet..	2,740
Average moisture content of the sludge in the primary zone from the surface to a depth of 36.3 ft............wt pct..	68.9
Average moisture content in the primary zone from a depth of 36.3 to 56 ft wt pct..	58.6
Average moisture content of sludge outside the primary zone............wt pct..	81
Average grain size, pct:	
Smaller than 0.074 mm............	91
Smaller than 0.020 mm............	67
Specific gravity of solids............	201
Average resistivity of sludge in the primary zone from the surface to a depth of 36.3 ft............ohm•cm..	1,050
Average resistivity of sludge in the primary zone from a depth of 36.3 to 56 ft............ohm•cm..	1,100
Average resistivity of the sludge outside the primary zone............ohm•cm..	1,010

[1]As shown in figure A-1, depth varies from 110 ft in the front area to a few feet along the outermost perimeter. Approximate average is 45 ft.

[2]Based on plant records.

Moisture contents and resistivities shown above are based on three samplings. The first sampling (1979) included 22 samples taken from depths between 3 and 9 ft within 100 ft of shore, generally in the northwest area. This material was assumed to be representative of much of the perimeter area sludge. Moisture content varied only about 3 wt pct in this 6-ft sampling zone. Resistivities of samples showed a variation of only 2 percentage points.

The second sampling (1981) extracted samples from various locations in the primary zone from depths of 3 to 30 ft beneath the surface. Moisture contents for 22 samples ranged from 74.3 to 68.4 wt pct; moisture generally decreased with depth, although not in direct proportion. Average moisture content for this layer was 71 wt pct.

The third sampling (also 1981) included numerous extractions from various locations in the primary zone at depths ranging from 1 to 56 ft below the surface. For this layer, water content generally decreased with depth from 98 wt pct at 1 ft, to 62 wt pct at 36 ft, to 45.1 wt pct at 56 ft. Average moisture content of the sludge was estimated to be 68.9 wt pct from the surface to a depth of 36.3 ft and 58.6 wt pct in the zone from

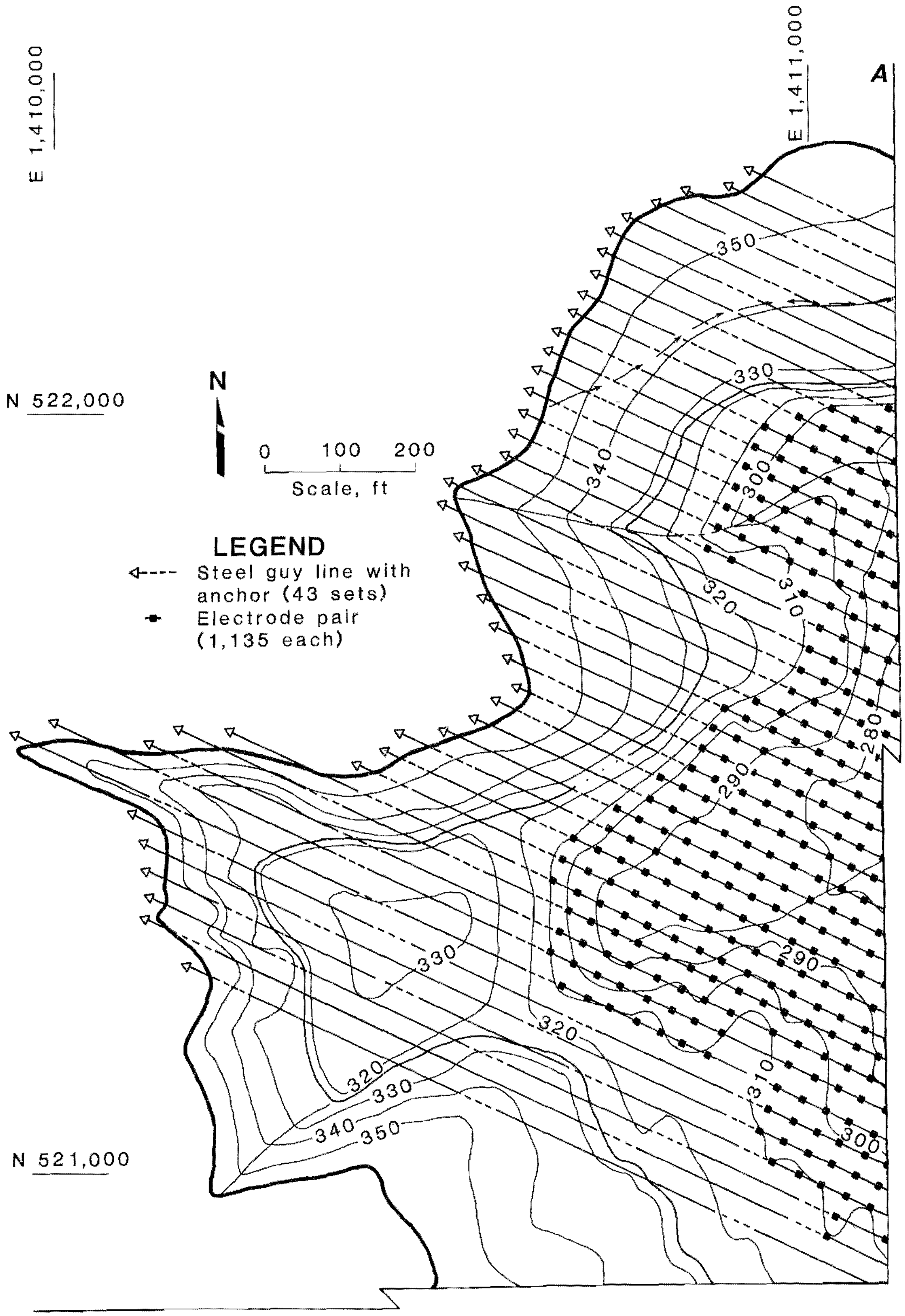

FIGURE A-1.—Electrokinetic system location plan.

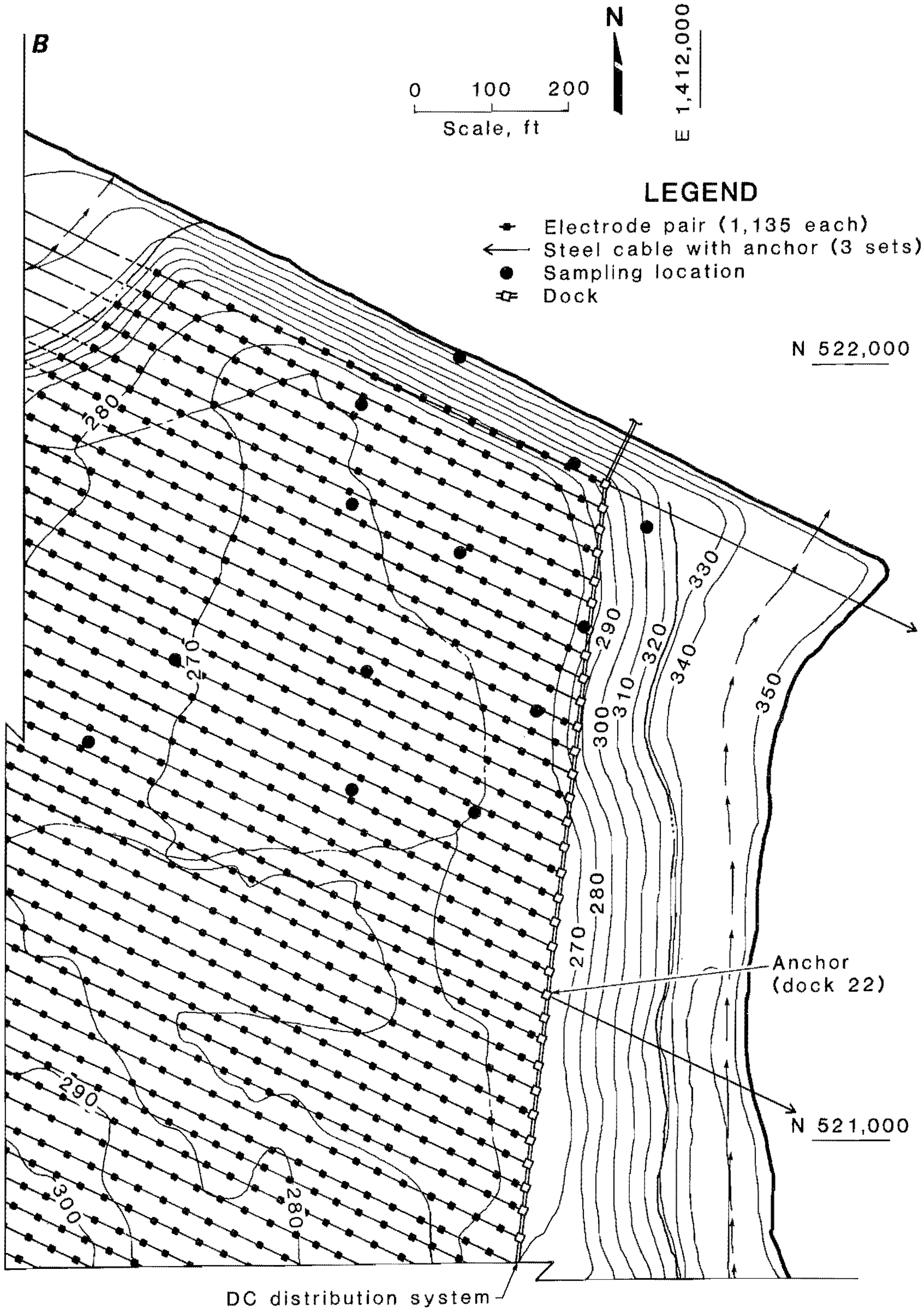

FIGURE A-1.—Electrokinetic system location plan—Continued.

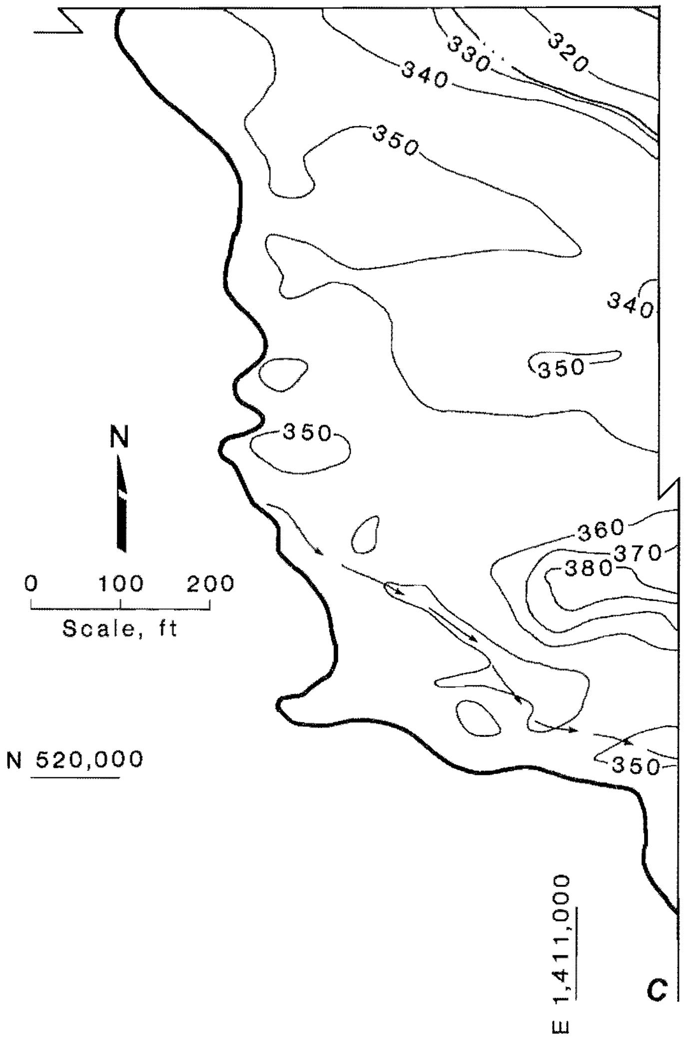

FIGURE A-1.—Electrokinetic system location plan—Continued.

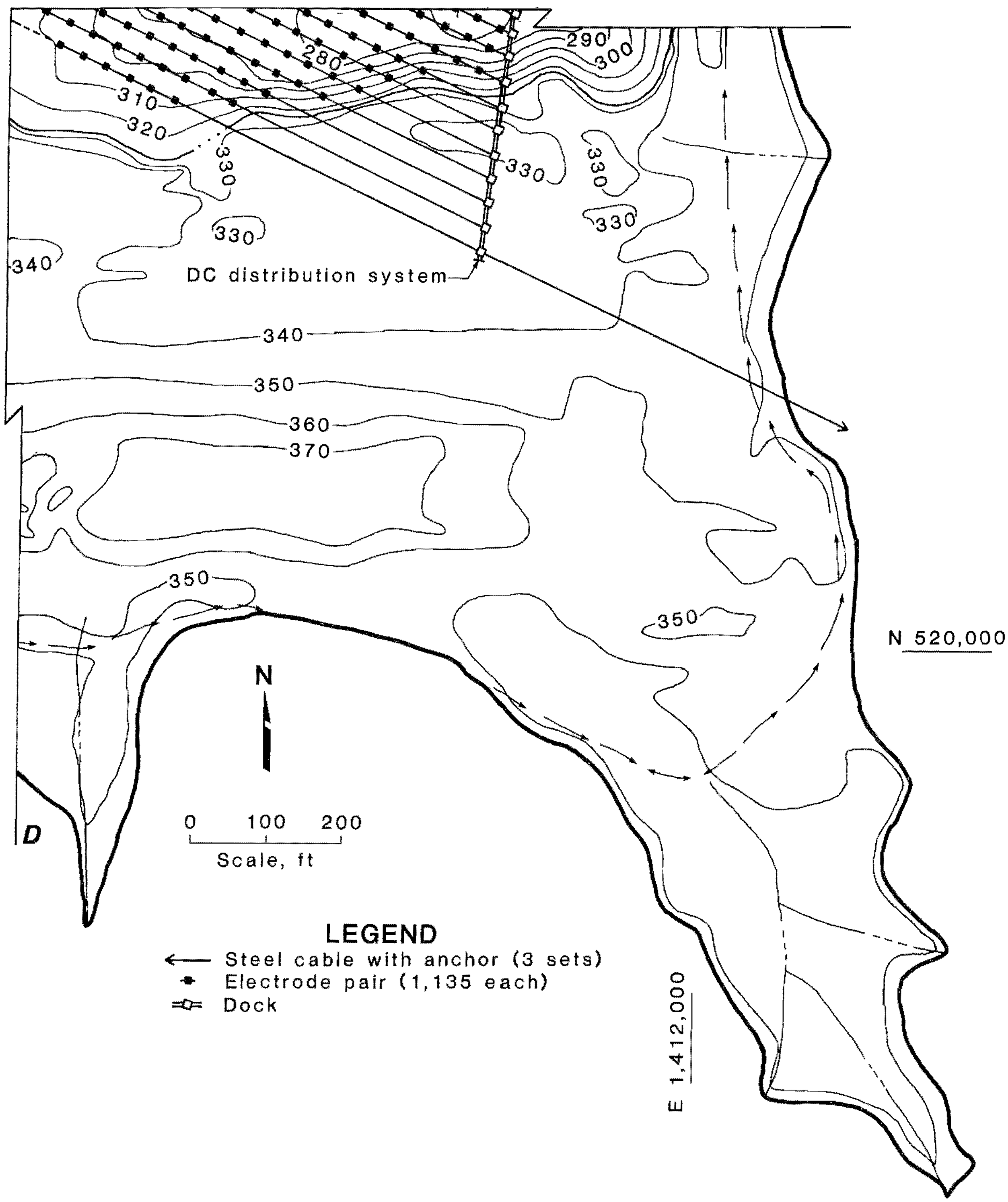

FIGURE A-1.—Electrokinetic system location plan—Continued.

36 to 56 ft. Resistivity definitely increased with depth, although somewhat erratically, averaging 1,050 ohm•cm in the upper layer and 1,100 in the lower level.

The first two sets of samples were representative portions taken from each of twenty-two 50-gal drums of sludge extracted by lowering the suction line intake of a pump to a specific level. The third set of samples was collected with an Alpha sampler, which is designed to extract essentially intact samples from any desired level. The number of samples is relatively small for such a large and quite old pond, particularly for the outside area. Nonetheless, the data are assumed to be adequately representative and are used in the following design calculations.

Laboratory and field tests have consistently shown that this particular sludge can be dewatered by the electrokinetic process to a maximum of 54 wt pct solids. At this point, the material is a hard, claylike product which is stable and suitable for capping with coarse refuse for total reclamation. While the maximum limit of 54 wt pct has been used in this design, greater dewatering is in fact possible, based on previous Bureau work in underground mining, where results significantly improved with upscaling from laboratory efforts.

The Bureau has not to date used half-wave dc power for dewatering waste. Nevertheless, based on unpublished results by others and on laboratory results from SRC, this design assumes that such power will produce results better than those achieved by constant dc power.

During installation, the anodes will sink until completely impeded by mechanical resistance of the sludge, which becomes more dense with depth. Field tests indicate that large pieces of iron will probably sink to a depth of about 36.3 ft. If they do not sink by gravitation, they will be driven to this depth by application of negative dc potential. Field tests elsewhere have shown this process to be very effective. Therefore, the initial depth of the anode for the primary zone is placed at 36.3 ft below the surface elevation of 384 ft.

Treatment in the WIDCO pond would use a horizontal layer of anodes 36.3 ft below the surface, and cathodes suspended 3 or 4 in below the surface (figs. 1 and A-1). Application of power (surface electrodes negative) would draw water from the thickening sediment to the surface for decanting. The rate and final degree of dewatering between the electrodes can be reliably predicted. As demonstrated by small-scale laboratory tests, material beneath the anode will also dewater to some extent. For example, in a 5-1/2-in-diam by 10-in-deep test cell filled with WIDCO coal sludge where the cathode is located on the upper surface and the anode from 2 to 6 in below the surface, the material below the anode dewatered to an average solids content of 54 wt pct. Whether this occurs because of electro-osmosis, by negative pore pressure, or by a combination of these influences has not been determined. No research is known that provides data for predicting results in this zone. It is confidently assumed for purposes of this design that the material in the 20-ft layer beneath the anode in the primary zone will dewater by an average of 5 wt pct points.

Results of the tests in the small earthen pond (1)[1] will be used to predict consolidation in the outlying area--an assumed average final solids content of 31 wt pct for this sludge at the conclusion of treatment.

Development of clean surface water will essentially occur by two processes: particles will migrate downward, and water in the sediment will move upward. Laboratory and small-scale field tests (with WIDCO sludge) have consistently shown that clear, decantable surface water develops at an average rate of 0.75 gal/(A•h) of applied current over the entire dewatering process.

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[1] Underlined numbers in parentheses refer to items in the list of references preceding this appendix.

DESIGN CALCULATIONS AND ANALYSES

Development of Electrode Arrangement

An efficient electrode system design will take advantage of specific existing conditions when possible. Three design concepts were evaluated:

1. Vertical electrodes: Perforated iron pipe (6- to 8-in-diam) wrapped with filter cloth to exclude entry of solids would extend from pond floor to surface and be spaced on 150- to 200-ft centers. Water would be removed from each of these cathodes with a system of pumps. An array of iron rods (anodes), also vertically installed, would encircle each catholde.

Satisfactory installation of numerous large, fabric-covered cathodes with a reliable water removal system would be costly and technically difficult. Clogging at cathode perforations and pump failures are also probable. The final condition of the sediment would be less than desirable--large, firm mounds of cake around each anode and a significant quantity of soupy product surrounding each mound and cathode.

2. Horizontal electrodes with upper electrode positive: Large, perforated iron pipe, burlap-covered and equipped with pumps and nonmetallic discharge pipes, would be lowered to the pond floor to form a horizontal grid (cathode) covering about 27.5 acres. The anode, made from any available scrap iron to allow for severe corrosion during treatment, is held on the pond surface with a flotation system.

This arrangement, using gravity electro-osmosis (drawing water to the bottom), should be electro-osmotically efficient. It does not take advantage of electrophoresis, i.e., the electrically driven downward migration of suspended particles that would clarify surface water. Installation would be costly because of the need for numerous pumps and a large quantity of perforated, fabric-covered, iron pipe on a pond floor. Severe operational problems could be expected from filter cloth failure, silting in the pipes, or pump failure.

3. Horizontal electrodes with upper electrode negative: The bottom electrode, made up of pieces of any available iron (old drill rod, cable, etc.), would serve as the anode. It would be sized to be dissipated by electrochemical corrosion at the conclusion of treatment. Heavy electric bus and cables used for distributing power to the electrodes could be salvaged. Because no corrosion would occur at the cathode, the upper electrode (cathode) can consist of a number of light iron grids (with maximum surface area per unit weight). Material would consolidate at the bottom of the pond, and clear water would develop at the surface for removal by decanting or pumping.

With careful design, the final sediment surface can be fairly flat--a desirable feature if the pond is to be abandoned or converted into a recreational lake. Maintaining an effective and adequate anode throughout the treatment cycle is seen as the major problem because severe electrochemical dissolution will occur.

The third approach is obviously the best in terms of technical and economic feasibility.

The number, shape, and arrangement of individual pieces of iron and grids are discussed later in this appendix.

Density Versus Water Content

To calculate density (d) at various water contents, assume 100 lb of sludge at 70 wt pct water and 30 pct solids, and the specific gravity of solids = 2.01. Therefore,

$$\text{Volume } H_2O = \frac{70 \text{ lb}}{62.4 \text{ lb/ft}^3} = 1.122 \text{ ft}^3;$$

$$\text{Volume solids} = \frac{30 \text{ lb}}{(62.4)(2.01) \text{ lb/ft}^3} = 0.239 \text{ ft}^3;$$

$$\text{Total volume} = 1.361 \text{ ft}^3;$$

$$\text{d at 70 pct water} = \frac{100 \text{ lb}}{1.361 \text{ ft}^3} = 73.48 \text{ lb/ft}^3.$$

Similarly--

d at 90 pct water = 65.72 lb/ft^3,

d at 85 pct water = 67.50 lb/ft^3,

d at 80 pct water = 69.37 lb/ft^3,

d at 75 pct water = 71.36 lb/ft^3,

d at 65 pct water = 75.70 lb/ft^3,

d at 60 pct water = 78.07 lb/ft^3,

d at 55 pct water = 80.66 lb/ft^3,

d at 50 pct water = 83.36 lb/ft^3,

d at 45 pct water = 86.24 lb/ft^3,

and d at 40 pct water = 89.34 lb/ft^3.,

A graph of the foregoing is shown in figure A-2.

Water Removal Versus Ampere Hours

Water production rates (gallons of clear surface water per ampere hour of applied current) achieved in numerous large and small laboratory tests on WIDCO sludge range from slightly greater than 1 gal/(A•h) at the beginning of the process, when water content is high, to less than 0.01 gal/(A•h) near the end of the process, when the electrokinetic effect approaches insignificance. The average throughout a given dewatering process in which the horizontal configuration is used in WIDCO sludge has been fairly well established at about 0.75 gal of clear surface water per ampere hour. It should be recognized that this rate of 0.75 gal/(A•h) produces essentially crystal-clear surface water. For the operational system at WIDCO, however, surface water can be decanted in a significantly less clarified condition because it will be returned to the plant for reuse. Consequently, the actual dewatering rate for the WIDCO project should turn out to be greater than 0.75 gal/A•h). This ensures a margin of safety because the 0.75 value will be used in the design calculation even though the final value could be much greater.

The time and power required to reduce the moisture to 50 wt pct can be determined as follows:

The average existing moisture contents for sludge above and below the anode are given as 68.9 and 58.6 wt pct, respectively. Therefore, density of sludge with 68.9 wt pct moisture = 73.97 lb/ft^3, water content at 68.9 wt pct (73.97) (0.689) = 50.96 lb/ft^3, and solids content at 68.9 wt pct (74.97) (0.311) = 23.01 lb/ft^3.

The dewatering goal is to reduce average moisture to 50 wt pct, i.e., 23.01 lb of solids and 23.01 lb of water. Therefore, water to be removed from each cubic foot of material above the anode = (50.96-23.01) = 27.95 lb/ft^3, (3.350 gal/ft^3), density of sludge with 58.6 wt pct moisture = 78.80 lb/ft^3, water content at 58.6 pct (78.80) (0.586) = 46.18 lb/ft^3, and solids content at 58.6 pct (78.80) (0.414) = 32.62 lb/ft^3.

The dewatering goal is to reduce the moisture in the 20-ft layer beneath the anode by 5 wt pct, i.e., from 58.6 to 53.6 wt pct moisture. Thus, for water (w_1) in sludge at 53.6 wt pct,

$$0.536 = \frac{w_1}{w_1 + 32.62},$$

where w_1 = 38.51 lb/ft^3.

Therefore, water to be removed from each existing cubic foot of material beneath the anode = (46.18 - 38.51) = 7.67 lb/ft^3 (0.921 gal/ft^3.

Total water to be removed from each 1- by 1- by 36.3-ft column of material above the anode = (36.3) (3.350) = 121.6 gal.

Total water to be removed from each 1- by 1- by 20-ft column of material beneath the anode = (20) (0.921) = 18.4 gal.

Total amount of water to be removed from each square-foot column in the primary zone from the surface to a depth of 20 ft beneath the anode = (121.6 + 18.4) = 140.0 gal.

Total treatment current required, for each square-foot column, at the extraction rate of 0.75 gal/(A•h) of applied current = 140.0/0.75 = 186.7 A•h.

Total required ampere hours for the primary zone (186.7 $A{\cdot}h/ft^2 \times 33$ acres $\times$ 43,560 $ft^2/acre$) = 2.68×10^8 A.h.

Rate of current application (at a density of 6.5 mA/ft^2) expressed in terms of constant dc = 9,343 A.

Total hours of treatment, including an arbitrary assumption that 5 pct of the current applied to the electrodes travels through the sludge in the secondary zone = (1.05) (2.68×10^8/9,343) = 30,110 h (3.44 yr).

The values for current density (6.5 mA/ft^2), total continuous current (9,343 A), and treatment time (3.44 yr) are close approximations. The final design numbers will be designated later in this study after evaluation of resistances, power losses, and costs.

The range of the current density suitable for this design is 0.006 to 0.007 A/ft^2. Densities lower than 0.006 have been shown to be ineffective in a Bureau large-scale laboratory test. Values higher than 0.007 are undesirable because electrical efficiency decreases rapidly with increase of current density. The application rate is tentatively set at 0.0065 A/ft^2, but it must be coordinated with other factors such as array size, bus size, costs, etc.

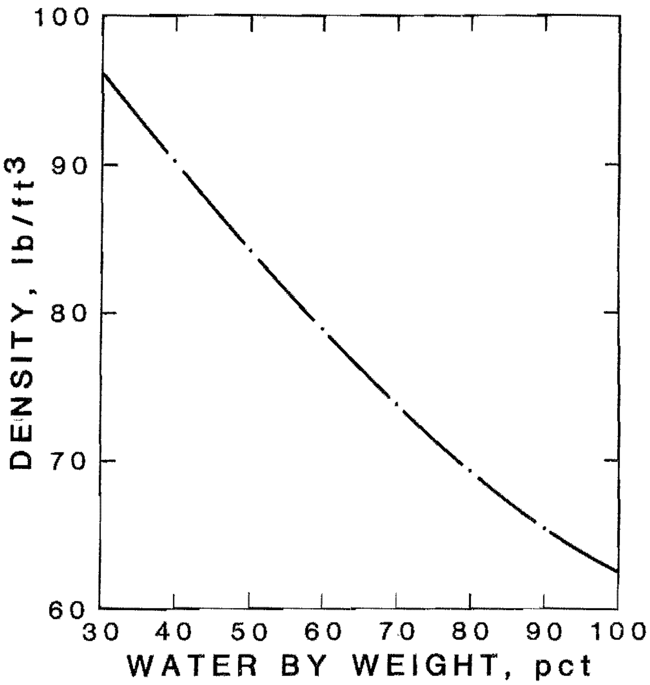


FIGURE A-2.—Water content versus density, WIDCO coal sludge, 1981.

Size and Shape of Array

Selecting the best electrode array in terms of size, shape, and location in the pond is a difficult problem. For the horizontal electrode configuration to be used in this pond, one must consider such factors as the portion of the contents that should be consolidated into a dense product, any cost limitations, the follow-on plan for the dewatered pond, the time factor, etc.

No specific follow-on plans are assumed in this design. The void developed by treatment may be refilled with waste sludge or filled with fresh water to serve as an artificial freshwater lake. The consolidated material could also be capped with coarse mine refuse and topsoil to form useful land. In any case, cost must be minimized wherever possible, and treatment should eliminate the potential hazards that normally exist with a large mass of unconsolidated sludge.

If the entire pond--a horizontal area of 110 acres--were to be covered with electrodes, problems would arise because of the great variation in depth, from 110 ft in the front area to only a few feet near the perimeter, as shown in figure A-1. One solution might be to size individual anodes, in accordance with the dissipation rate of 1 g/(A•h) of applied current, to last only long enough to accomplish the desired results. With the anode corroded away, current to that area would be minimal. The depth variation problem could also be solved either by applying current density in proportion to sludge depth or by disconnecting circuits to areas when consolidation is completed. The principal advantage of the 110-acre array would be effective and expeditious consolidation of all the sludge in the pond. The main disadvantages would be a very high cost due to a mammoth electrical bus and distribution system and the low cost effectiveness of the equipment installation in the shallow areas.

Another approach uses a relatively small array, on the order of 5 acres. The array would be installed off the dam heel in a corner of the impoundment. Treatment would consist of consolidating the 5-acre block and then capping the area with coarse refuse and perhaps topsoil. The reclaimed area would serve as a platform for repeating the process on a second 5-acre plot. The process would continue until the entire pond area was reclaimed. The main disadvantages of this method are a long overall treatment time, the loss of the option to immediately generate additional space for storing the plant's current waste sludge, and a relatively high cost. The advantages include design flexibility which can accommodate various circumstances, the ability to monitor the success of various design configurations, and the development of comprehensive technology.

The third approach would use a floating cathode constructed so that it could be relocated when consolidation in a particular area is complete. The size of the array would probably be limited to about 1.5 acres or less. Building larger arrays sturdy enough to withstand occasional relocation by winch power would be very costly. If structural, electrical power supply, and relocating problems could be satisfactorily solved, this concept could be quite efficient, allowing use in areas of greatest need and where electrokinetic efficiency is high.

The principal problem, aside from construction, is that two or three of these arrays may be required to densify the pond contents in a reasonable period of time, and five or six arrays would be required if the new storage space is to be developed in the pond (by densification of existing sludge) rapidly enough to provide space for the plant's current waste sludge. The cost of construction and operation would probably be excessively high.

A fourth and final concept had an array installed as one unit over the deepest part of the pond. This system would be large enough to reclaim a major portion of the pond area in a reasonable period of time and/or allow for sufficiently rapid dewatering to provide necessary storage for the preparation plant's current sludge (thickener underflow) disposal needs. This system was selected as the most feasible, and its design is discussed in the following paragraphs.

The array selected as the most practical after an evaluation of several other configurations is shown in figures A-1 and A-3. The most important considerations in its development were -

1. The electrode arrays and the electrical bus system, the most costly features of the project, become more expensive as the treatment area increases. Therefore, separation between the upper and lower arrays should be large to allow treatment of a relatively large volume for a given horizontal area.
2. The separation between upper and lower electrodes should be reasonably uniform throughout the primary treatment area. This ensures that the resistance between electrodes is close to uniform throughout the grid.
3. If the pond were being filled during treatment, the electrode array must cover enough pond surface to provide dewatering rates in excess of 2.5 acre-feet per day, to keep pace with refuse input from the preparation plant, but not be so large that extension into the more shallow regions reduces vertical separation of the electrodes to an undesirable degree.

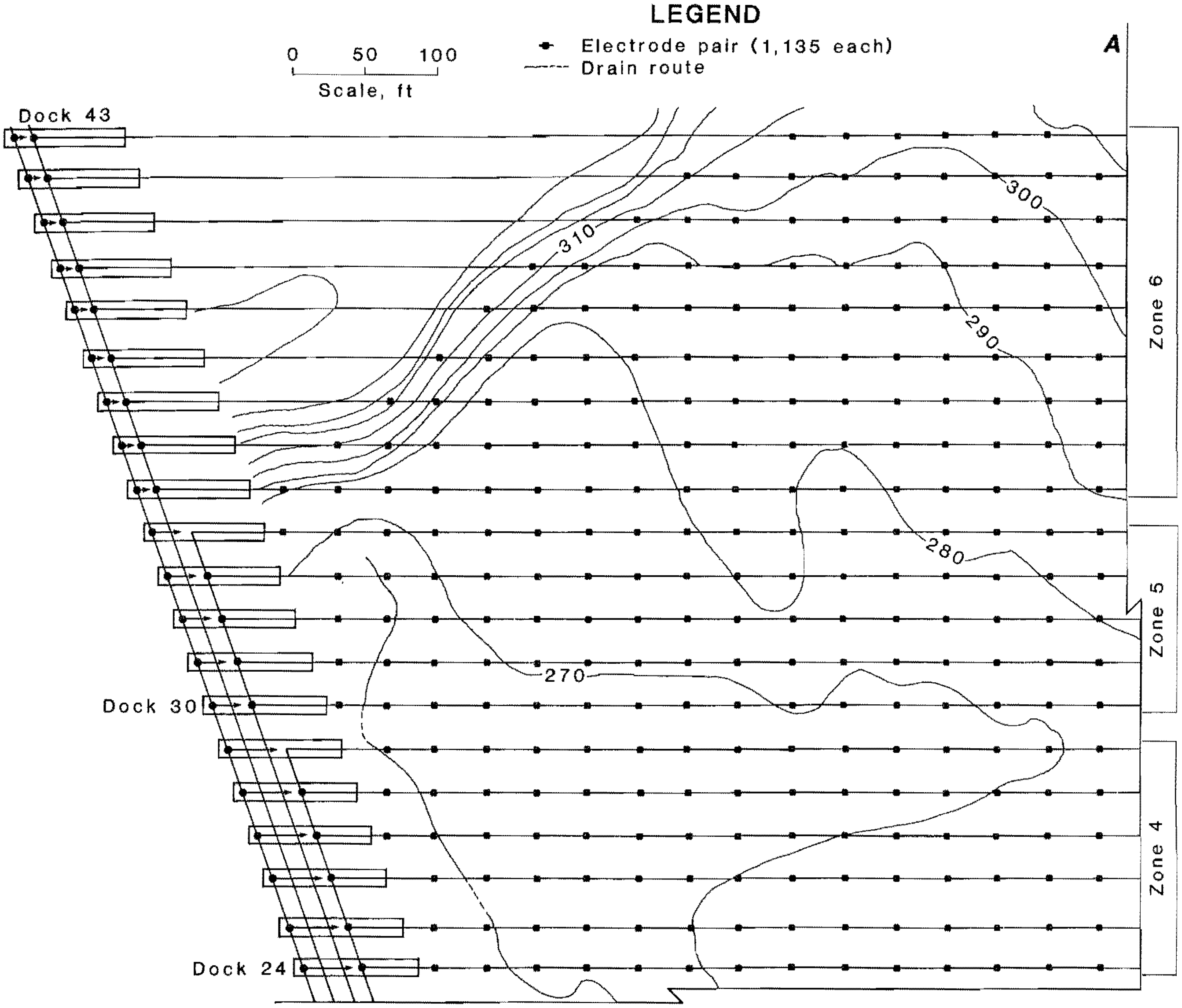
Field tests have shown that large compact iron shapes will sink to a depth of about 36 ft throughout most of the deepest part of the WIDCO pond. Field tests also show that if an electrode should fail to achieve the 36.3-ft depth, it can readily be driven to the desired depth by applying a relatively high negative potential of 50 to 75 V dc for a few minutes. Thus, for this design, the separation between the upper and lower electrodes is set at 36.3 ft.

Test results indicate that, where the existing sludge depth is 75 ft or more, the iron electrodes can be rather easily placed to a level 36 ft beneath the surface. However, in shallower depths, installation to 36 ft is moderately difficult. Each individual electrode in the shallower areas would probably require electro-osmotic assistance. The pond surface is now at an elevation of 384 ft. The boundary of the proposed array approximately coincides with the 310-ft contour line shown in figure A-1, and the area of the electrode array is about 27.4 acres. The size of the array can be increased if the 27.4-acre unit proves to be inadequate during the design process.

Each iron anode is paired with a cathode which floats at the surface of the pond. Each pair of electrodes in the array exerts its principal effect on its immediate vicinity, but each pair also induces a very small amount of current in each of the other electrodes. The effect is somewhat more pronounced with pulsating current, and it also causes a very small amount of current to flow into every part of the sludge body. However, in calculating the number of electrode pairs that will be needed, such minor effects are ignored.

The number of electrode pairs required for a functional system is determined by the following criteria:

1. The electrical resistance of the total electrode system (all pairs of anodes and cathodes considered as a unit) must be very low so that the heating (I^2R) does not waste energy or impede the electrokinetic process. For electrodes



Notes: 1. 12- by 12-ft docks not drawn to scale for sake of clarity
2. Amperes in terms of equivalent constant current
3. Electrode pairs per lateral are shown in parentheses

FIGURE A-3.—Electrokinetic system layout plan.

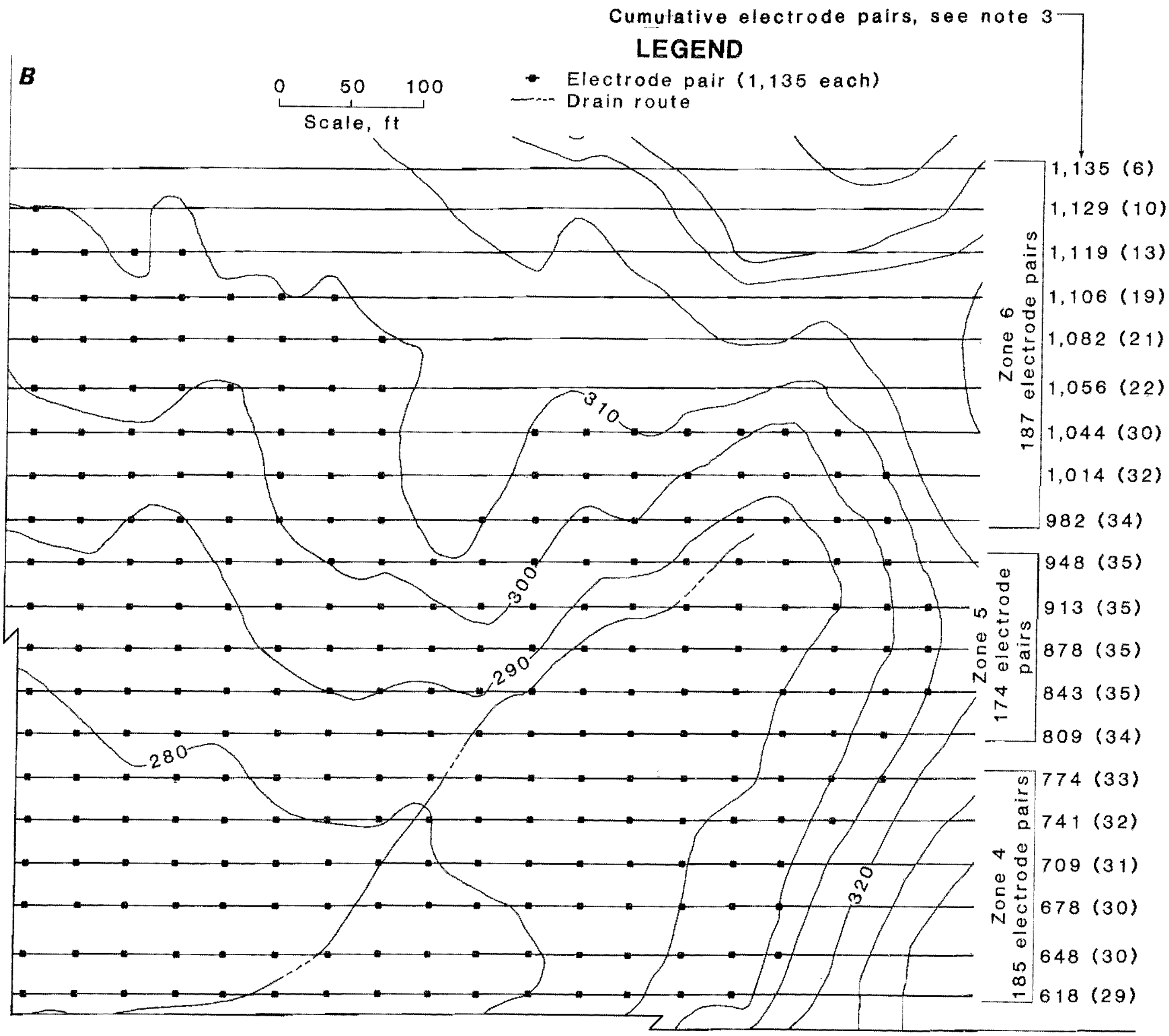


FIGURE A-3.—Electrokinetic system layout plan—Continued.

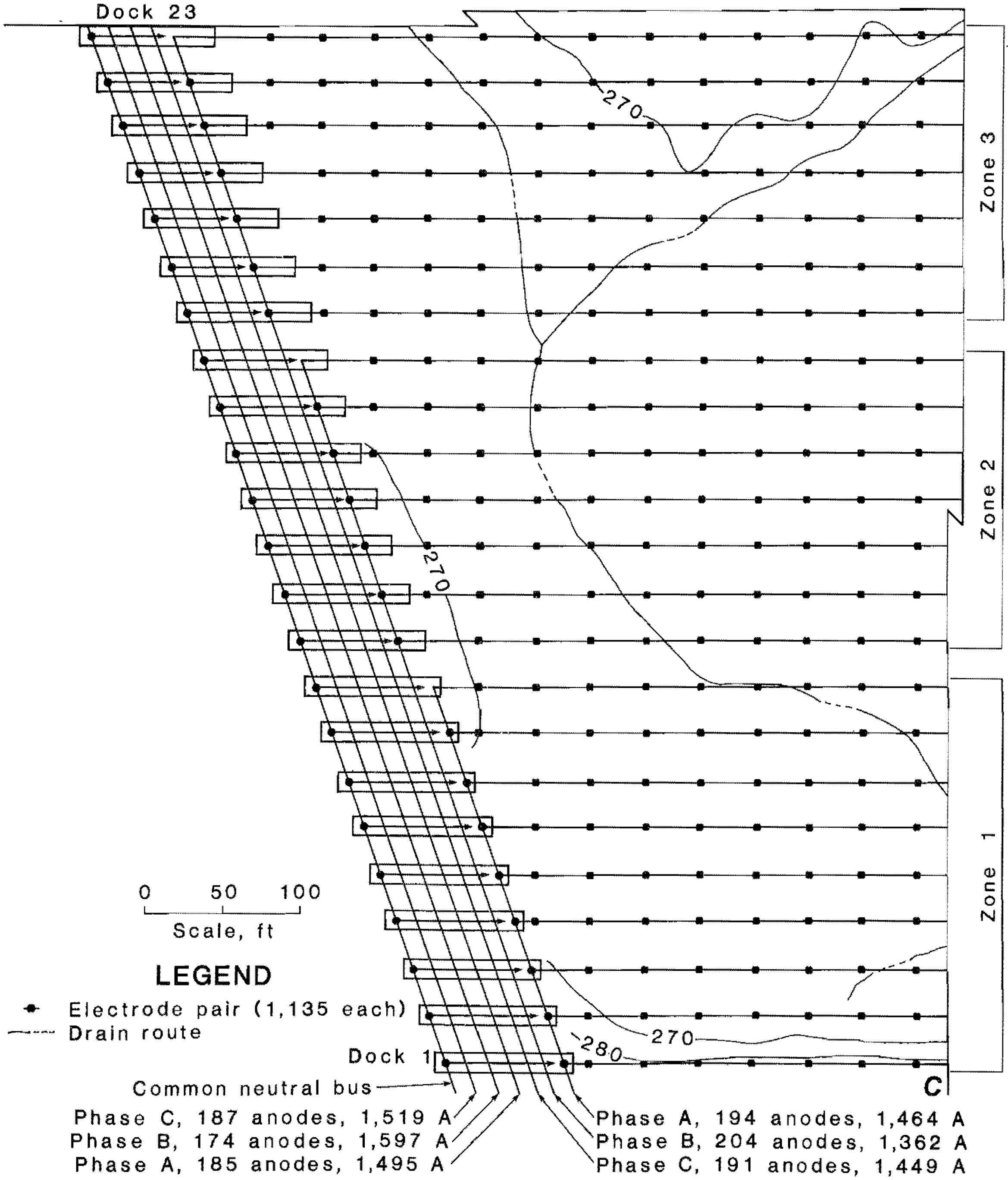


FIGURE A-3.—Electrokinetic system layout plan—Continued.

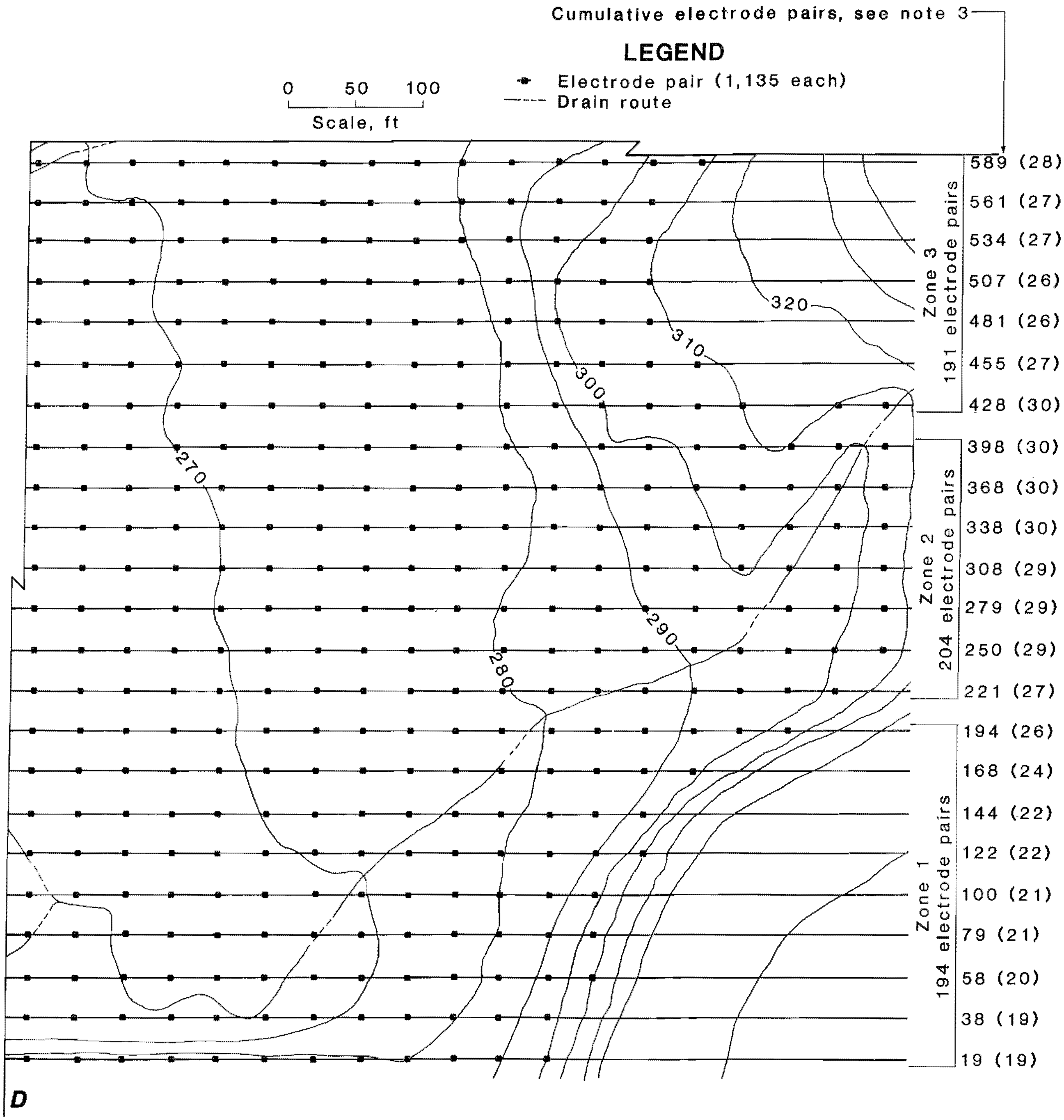


FIGURE A-3.—Electrokinetic system layout plan—Continued.

in sludge (or earth), resistance is always highest at the iron-sludge interface because the cross-sectional area of conducting sludge, which has conductivity much lower than that of metal, is relatively small, and gas bubbles may also be present. Resistance at such interfaces is reduced by increasing the surface areas and by dispersing the contact points over a broad range rather than clustering electrodes in one location. Therefore, during the design process, it is very important to analyze a selected electrode system for total electrical resistance. Such an analysis is included later in this report.

2. Each pair of electrodes exerts a dewatering effect throughout the entire pond. The effect is greatest directly between the electrodes and in their immediate vicinity and falls off rapidly with distance from the electrodes. Laboratory and field tests indicate that effective dewatering for such a system extends horizontally and radially to a distance of 1.25 times the vertical separation. Thus, if electrodes are spaced too sparsely, aside from possible electrical resistance problems, treatment will leave mounds of consolidated material about each electrode pair with valleys of unconsolidated sludge between the mounds. Too many pairs will cause uniform consolidation and provide good electrical resistance, but the cost would unnecessarily high.

Based on successful applications in previous Bureau dewatering projects, galvanized iron fence wire panels (hog wire) were selected for the design. These rectangular units would be held about 4 in below the surface with light, wooden timbers and Styrofoam blocks. The tentative panel size is 2.67 ft wide by 15 ft long. This size must satisfy electrical resistance requirements as determined (via electrical resistance calculations) later in this report.

Various electrode patterns were drawn to scale and evaluated to determine adequate electrical coverage based on the fact that each electrode's field balloons out horizontally. The pattern selected (fig. A-3) spaces the cathodes laterally and longitudinally at 35 and 30 ft, respectively. In every case, the open space between grids will be almost totally encompassed in the electrical field from each of the bordering electrodes. This possibly excessive electrical coverage is justified by the improved efficiency at the electrode-sludge interface, by the improved level of final consolidation in regions between electrodes, and by the insertion of an insurance factor in case individual electrode performance falls below expectations. With this placement, primary coverage for each electrode equals 35 by 30 ft, or 1,050 ft^2. Therefore, the targeted area of 27.4 acres will be equipped with 1,135 sets of electrodes.

Individual Anode Design

Each of the 1,135 individual anodes more or less dewaters its own specific area. The following factors must be taken into consideration in the design of the anodes:

1. Type of material used for the electrodes.
2. Quantity of water to be extracted per anode.
3. Quantity of current applied per anode and required treatment time.
4. Electrochemical dissipation rate for anodes and weight of metal required for completion of the procedure.
5. Most efficient shape of the anode.
6. Uniform erosion of anodes and continuous contact with electrical circuit throughout treatment.
7. Manner of placing anode, i.e., in one piece versus several pieces advantageously distributed.
8. Adequate connection of electrical feeder wire to the anode so that it is maintained until the anode corrodes away.
9. Appropriate electrical resistance across anode-sludge interface to minimize energy consumption.
10. Evaluation of possible adverse effect of coatings (rust, oil, creosote, etc.) usually present on scrap metals.

The three types of material tested for use as anodes in the WIDCO project were aluminum, iron, and dimensionally stable anode (DSA), a commercial electrode made of titanium coated with an oxide that prevents corrosion.

Each of these was tested with various current densities and in combination with cathodes fabricated from iron, aluminum, DSA, and galvanized iron fence wire. An aluminum anode was the least desirable because of its excessive dissipation rate and its past performance in densifying solids and producing clear surface water. DSA and iron anodes performed about equally well in developing clear surface water and solid sediment regardless of the material in the cathode. Dissipation was relatively high with iron anodes, but nonexistent for DSA.

If iron were to be used, a large proportion of the required amount is available at the mine site in the forms of scrap drag-line cable, drill steel, railroad rail, construction steel, etc. Additional scrap is readily available from various salvage operations in the immediate vicinity. In contrast, DSA anodes are a licensed product and are available from only one source in the general form of lightweight screen (i.e., expanded metal about 1/16 in thick). If iron anodes are used, a very large quantity of inexpensive scrap metal will be required. On the other hand, the DSA option will use a manufactured product of relatively small mass which is quite expensive per unit weight. Although the comparison was only approximate, neither option was found to be clearly preferable in terms of cost.

DSA is attractive because only a relatively small quantity of material is required, and it has an acceptable cost, good performance, and resistance to anodic dissipation. A DSA anode could be used indefinitely. The main disadvantage is the difficulty of installation. This screenlike material, with its large surface area and small weight, would be difficult to submerge to a depth of 36 ft where the sludge is relatively dense.

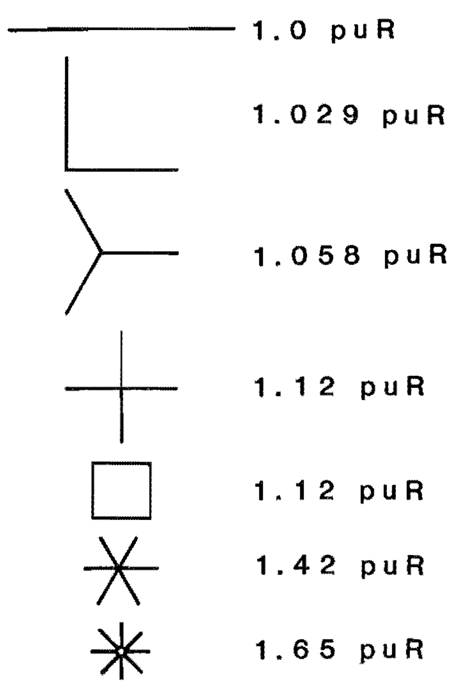
Using iron for anodes is acceptable in terms of cost, performance, and availability. Also, most of the electrodes would probably sink by gravitation to the required 36-ft depth. The high corrosion rate and the consequently large amount of metal required for completion of the project are the principal disadvantages.

After evaluating all the pertinent factors, iron was selected as the anode material for this project.

As determined earlier, each electrode pair is expected to dewater a horizontal area of 1,050 ft^2 with a current density of 6.4 mA/ft^2 over a treatment period of 3.49 yr. Corrosion of iron anodes has been calculated to occur at a rate of 1.15 g/(A•h). Thus, the amount of iron required for each of the 1,135 anodes is (1,050 ft^2)(0.0064 A/ft^2)(3.49 yr)(365 d/yr)(24 h/d) (1.15 g/(A•h)) (10^{-3} kg/g) (2.205 lb/kg) = 521 lb. This allows for dissolution, assuming that current is distributed uniformly throughout the array and that the iron is completely dissolved away. However, because of variations in water content and other properties, some anodes could carry more current than others. Also, further design changes could probably slightly alter current values. Finally, it is probable that at least some pieces of iron will break off before complete dissolution. To compensate for these factors, the weight of required anode should be increased to 550 lb each. Thus, a total of about 313 st of iron is required for anode iron.

Miscellaneous scrap iron will probably be found in all shapes and conditions. Generally, such random material must be cut and welded into advantageous configurations to create minimum electrical resistance to sludge, to ensure easy installation, and to minimize the chances that pieces will break off from corrosion.

As shown in figure A-4, for a given length of wire, straight, horizontally buried wire has the lowest resistance. The resistance of a 500-ft-long, 1-in-OD conductor buried 3 ft in 100 ohm•m earth was calculated to be 1.38 ohms (or 1.0 puR). The resistance of the L-configuration was 1.029 times that of the horizontal, straight wire, and the resistance of the eight-point star configuration was 1.65 times that of the



The puR number compares earth resistance for a given length of conductor installed in various shapes

FIGURE A-4.—Effect of electrode shape.

horizontally buried conductor (2). Therefore, compact electrodes will require either more material or a greater number of electrodes to achieve the desired low resistance.

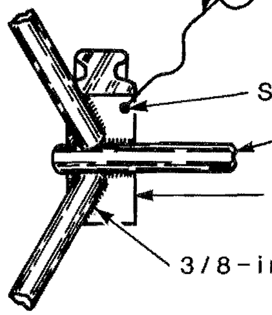
To alleviate breakage problems induced by corrosion, anodes should probably be shaped somewhat like a tree, i.e., the point where the electrical power lead is connected is the most massive while branches are smaller and taper away from the trunk. The central portion of the anode (where the electrical lead wire is attached) must be massive enough to withstand corrosion for the life of the project. Typical examples are shown in figure A-5. These configurations were tested in the laboratory. A relatively high current of 5 to 6 A applied for 15 to 20 days in a 3.5-ft^3 body of sludge showed the following:

1. The shapes shown in figure A-5, examples 1 and 2, corroded away without premature severance in the legs. The electrical connection also remained competent. Although not completely evaluated, the transfer of current from a unit area of the anode surface appears to be greatest in the outermost zone because of the relatively lower current density in adjacent sludge, which results in decreased interfacial resistance. Thus, total disappearance of metal proceeds from the outermost points into the control connecting plate (rail). Based on the laboratory results, either of these shapes is adequate. Therefore, both shapes are preferred for use on this project.

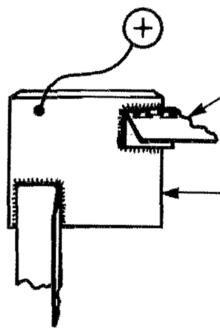
2. The shape shown in example 3 is also acceptable if the anode is carefully fabricated. The mass of metal must generally taper down with distance from the connecting points, as shown in the example. Laboratory tests showed that if the limbs have a uniform cross section, such as in iron rod, random breakage will occur.

Each anode is connected by a small insulated wire to a large, insulated, aluminum feeder cable suspended above the pond surface on Styrofoam blocks. To prevent corrosion of the small electrical feeder wire and of the connecting hardware, moisture must be excluded from the connection of the copper wire with the iron. Consequently, in this design, the connection is released in a carefully selected location in the central area of the anode, and a sealant is used, as shown in figure A-6. Laboratory corrosion testing has shown that this method protects the connection until the anode is essentially depleted.

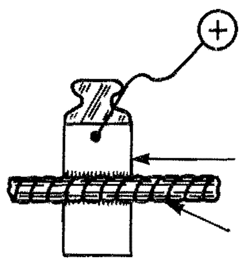
The impediments that might arise due to the presence of coatings such as oils, conventional paints, creosotes, and oxides, some of which are normally present on scrap iron, must also be considered. Performance testing by the Bureau in the laboratory and the field has shown that normal coatings of this type present no problem because they dissolve away, leaving a bare, shiny surface soon after the iron is energized. Iron with specialized waterproof coatings, such as epoxies and silicons, must be specially treated to expose the metal to contact with the



EXAMPLE 1



EXAMPLE 2



EXAMPLE 3

FIGURE A-5.—Anode construction.

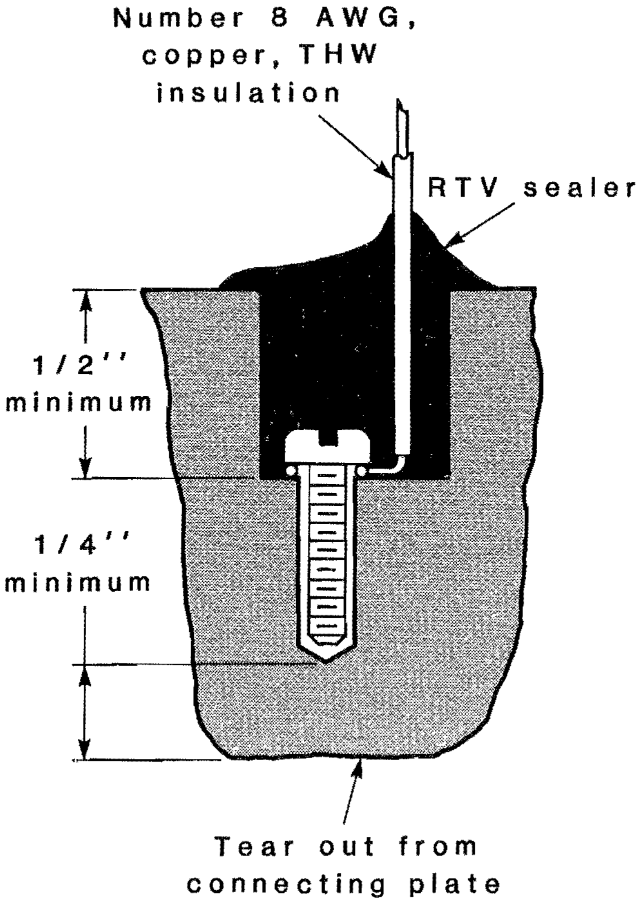


FIGURE A-6.—Wire connection to anodes.

sludge and should therefore be avoided.

As indicated earlier, each anode must include 550 lb of iron. This amount of iron, whether straight or Y-shaped, is difficult to handle. To make handling easier and also to improve electrical efficiency, in this design the anode for each electrode pair is instead composed of four separate pieces weighing about 140 lb each. These pieces are arranged around their companion cathode in a regular pattern. This procedure will distribute 313 st of iron (4,540 individual electrodes) uniformly at a depth of 36 ft throughout the primary treatment area. As shown in figure A-7, the maximum horizontal separation between the iron anodes is only 17.5 ft. The even distribution and close spacing (relative to the vertical spacing between the anode and the cathode) should yield good results. However, the design may have to be changed if its electrical resistance is found to be inadequate.

Individual Cathode Design

Earlier in the design process, each cathode was assumed to consist of a 32-in by 14-ft panel of galvanized iron fence wire held just below the surface with timber and Styrofoam blocks. This selection had been made in order to allow first-order calculations of other important design characteristics, such as the required number of pairs of electrodes, the ampere hours of current, etc. The selection was based primarily upon satisfactory experiences with similar configurations in previous Bureau projects (1, 3). However, final selection in this or any comparable project must also consider other factors, as discussed below.

Four different cathode materials were tested in the laboratory. Iron, DSA, and galvanized iron fence wire had essentially the same efficiency in developing clear surface water, densifying residue, and resisting corrosion. Aluminum, on the other hand, was found to corrode in proportion to the density of current transfer across the interface between the electrode and the sludge. With a current of 67 mA/ft^2, an appropriate level for the procedure, the aluminum corroded at a rate of 0.08 g/(A•h) of current. Thus, this project would consume nearly 19 st of aluminum. The reasons for this consumption are believed to be as follows.

Aluminum is a chemically reactive substance, easily oxidized to the +3 state. When it is exposed to air or another oxidizing environment, a tough surface coating of aluminum oxide forms, which protects the metal from further attack. However, when an aluminum cathode is submerged in the sludge pond, the reducing environment quickly destroys the oxide coating, exposing the bare aluminum metal to chemical attack by water and by hydroxide ion. The following reactions describe a plausible sequence which can account for the observed cathodic corrosion of aluminum. "Normal" cathodic reaction:

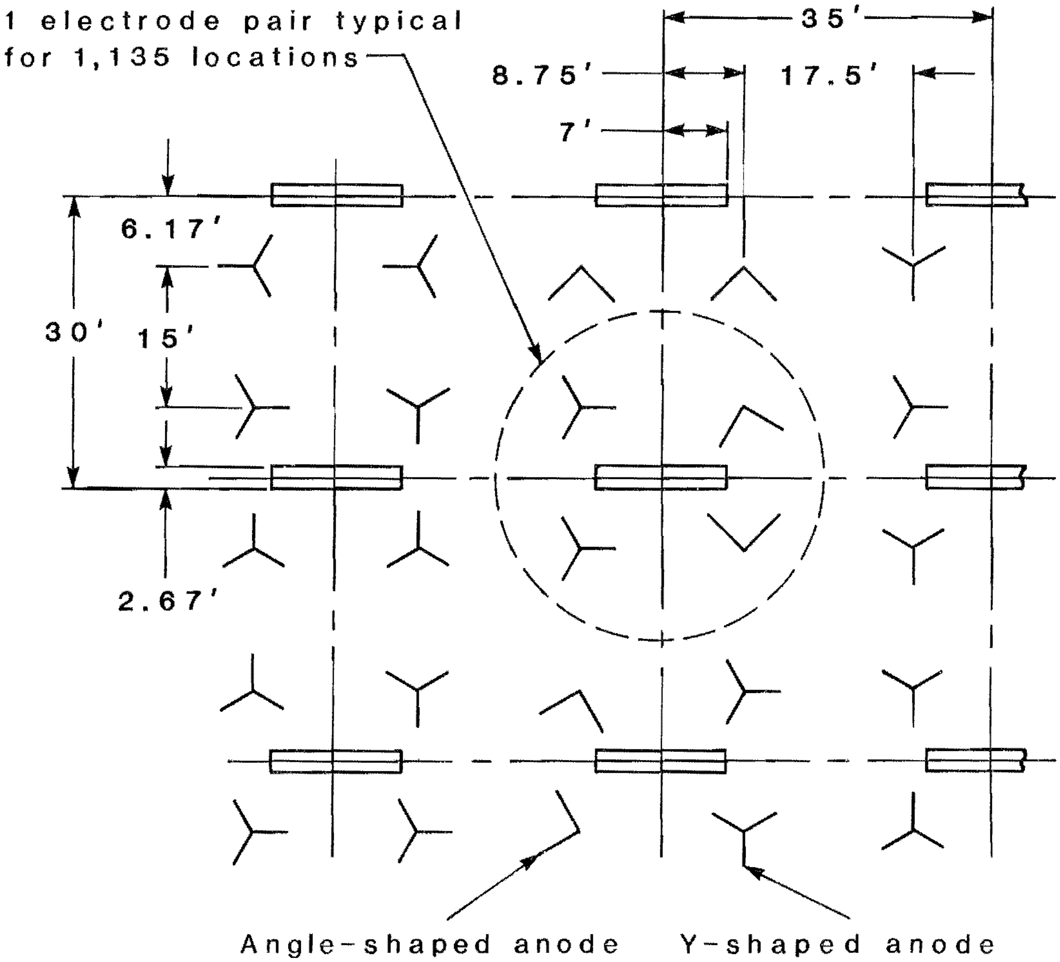


FIGURE A-7.—Electrode placement pattern.

$$2H_2O + 2e^- \longrightarrow H_2(g) + 2OH^- \qquad (A)$$

Destroys Al_2O_3 protective coating:

$$Al_2O_3 + 3H_2 \longrightarrow 2Al + 3H_2O$$

and/or

$$Al_2O_3 + 2OH^- + 3H_2O \longrightarrow 2Al(OH)_4^- \qquad (B)$$

Electrochemical dissolution of exposed aluminum:

$$2Al + 6H_2O + 2OH^- \longrightarrow 2[Al(OH)_4]^- + 3H_2(g) \qquad (C)$$

The $Al(OH)_4^-$, once formed, migrates toward the anode. The increased concentration of hydrogen (formed by reaction C) can be verified by collecting the gases generated during electrolysis; the "extra" hydrogen is directly proportional to the loss of aluminum from the cathode (4).

One possible design would have used stranded bare aluminum cables stretched across the treatment area and held just beneath the surface with Styrofoam blocks. If 500-MCM cable (0.81-in-diam) were used and if a 15-pct "insurance" factor were added on, approximately 21.9 st of cable would be required to obtain 73,000 lin ft of aluminum cathode (73 lines spaced about 15 ft apart). This design was rejected because of high cost and somewhat reduced performance, as well as the probability that such cable would suffer breakage due to uneven corrosion.

DSA cathodes were eliminated because they would have been significantly more expensive and would not have been more efficient or easier to install. Bare or galvanized iron fence wire performed as well as DSA. Galvanized fence wire is readily available as stock material, while bare fencing must be specially ordered. For the relatively small total requirement of 16,000 lin ft (32 in wide), stock galvanized wire is the least expensive. While paint and other coatings are not a problem on anodes, they do impede performance when present on cathodes. However, galvanized fencing is new and has excellent surface condition.

The wire fencing is also easily prefabricated into individual units (fig. A-8), which are easily handled and installed. We expect that the units will be mechanically sound and durable, with a more-than-adequate service life. While many functional cathode systems can be devised, this design uses the configuration shown in figure A-8. Final selection, particularly in regard to size, still depends on the evaluation of the electrical resistance.

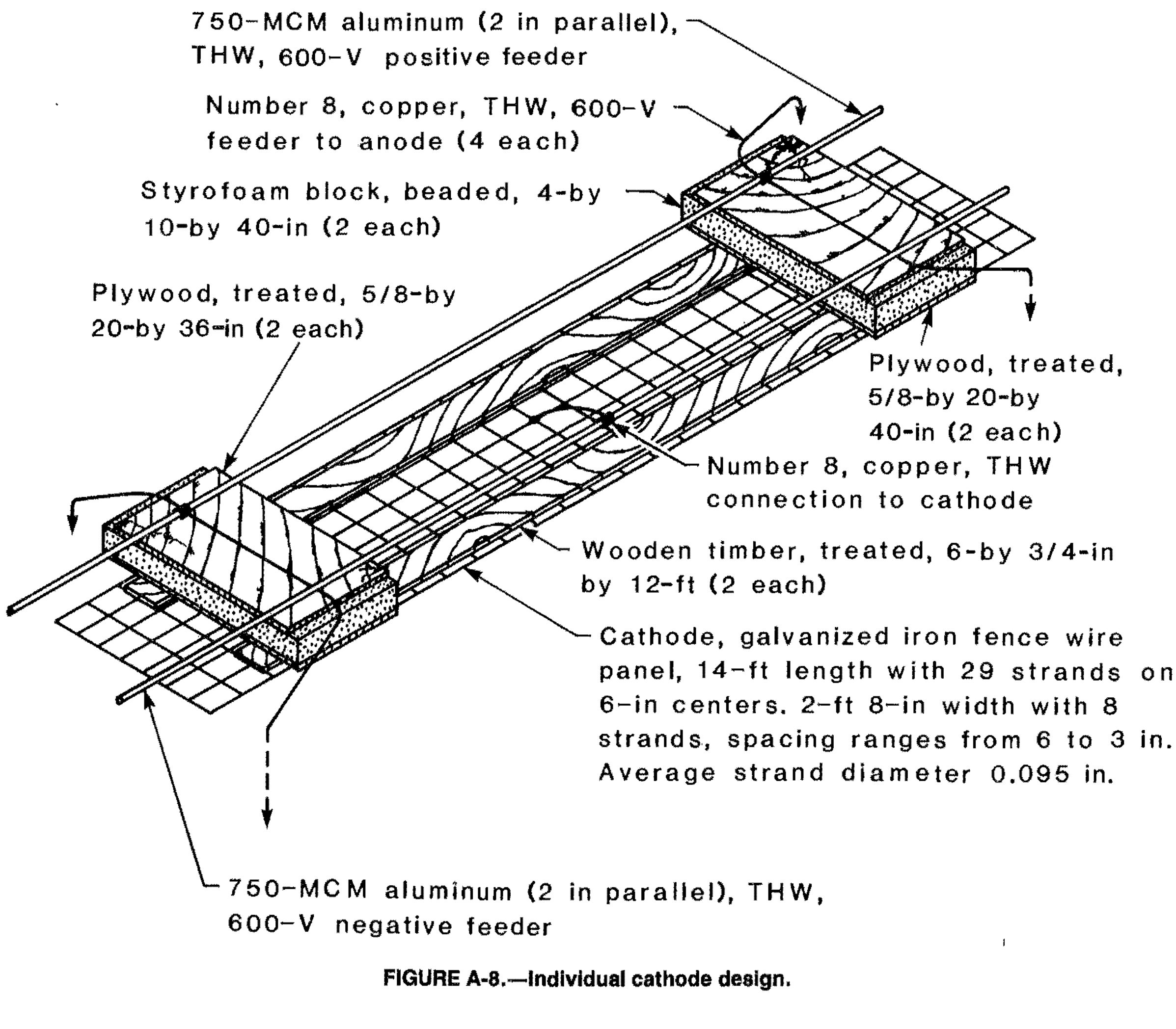


FIGURE A-8.—Individual cathode design.

Treatment With Half-Wave Direct Current

Laboratory test results at SRC show that for a given amount of power, treatment with half-wave dc potential (i.e., sinusoidal pulses), rather than the normally used constant dc power, produces somewhat superior results. Specifically, if such treatment were applied to WIDCO sludge, the final consolidation would be increased by 3 to 4 wt pct. Much greater advantages have been claimed by other researchers (personal communication), but such results have not been published and remain speculative. There is an added and more important advantage to using half-wave in this project, because a three-phase rectifier can readily be arranged to produce six individual, sequential, half-wave potentials, as shown in figure A-9. This feature is used in this design to separate the WIDCO treatment area into six 5.5-acre zones, each of which is equipped with a separate electrode system and voltage. Thus, even in the unlikely event that a low-resistance spot in the treatment area should occur (e.g., if a salt solution was deposited at some point in the treatment zone), problems with the sludge treatment would be confined to that area.

As shown in figure A-9 *A*, each of the three phases produces two continuously pulsating potentials--one positive and the other negative. Each of the pulses is sinusoidal and has a frequency of 60 c/s with an equal on-off time of 1/120 s. When such potentials are applied to resistive loads, such as electrodes in sludge, the resulting current will also be sinusoidal and in phase with the driving potentials. The amplitude of the current pulse will be inversely proportional to the load resistance (anode to cathode resistance) and directly proportional to the level of applied voltage. In actual operation, individual regulators will maintain the current to each zone at a constant value and will automatically raise or lower output voltage as necessary to compensate for changes in load resistance.

The circuit arrangement for the half-wave concept, as shown in figure A-9, requires seven output terminals at the rectifier. Each of six serves a specific zone, while the seventh (neutral) is a common return for all six zones. As indicated in figure A-9, when all phase currents are equal (i.e., resistance and applied voltage are uniform in all six zones), the system is balanced. Under such a condition, the currents for regular sinusoidal pulses are always algebraically equal to zero, and normally there is no current in the neutral leg at the transformer connection. However, owing to the space arrangement and to possible charge imbalance, some sections of this bus will have very high current. This will be discussed later in this report.

As previously discussed, the current to each of the six zones in the treatment area consists of sequential sinusoidal pulses lasting 1/120 s alternating with equal periods of zero flow. Thus, at any given instant, there will be unique and changing current patterns, as shown in figures A-10 and A-11. Figure A-10 shows the pattern at the instantaneous time t_1 when the phase A potential is at its maximum value (positive with respect to neutral) and phases B and C are each at half of their maximum negative values (negative with respect to neutral). Resulting current flow in the neutral bus from phase A is in the opposite direction to current flow from phases B and C. For a three-phase transformer with balanced outputs and identical phase-to-phase loads, the current will be equal to zero at all times.

Most electron flow in the six zones of the electrode array will occur between electrodes within each respective zone, i.e., from anodes in zone 1 to cathodes in zone 1. Electrodes in immediately adjacent zones will be sufficiently close to offer an alternative conduction path, however. For example, referring to figure A-3, the least resistance (shortest distance) between cathode 1 and 2 occurs between docks 9 and 10. Here the distance is about 47 ft, and current flow will be significant. At the far end of

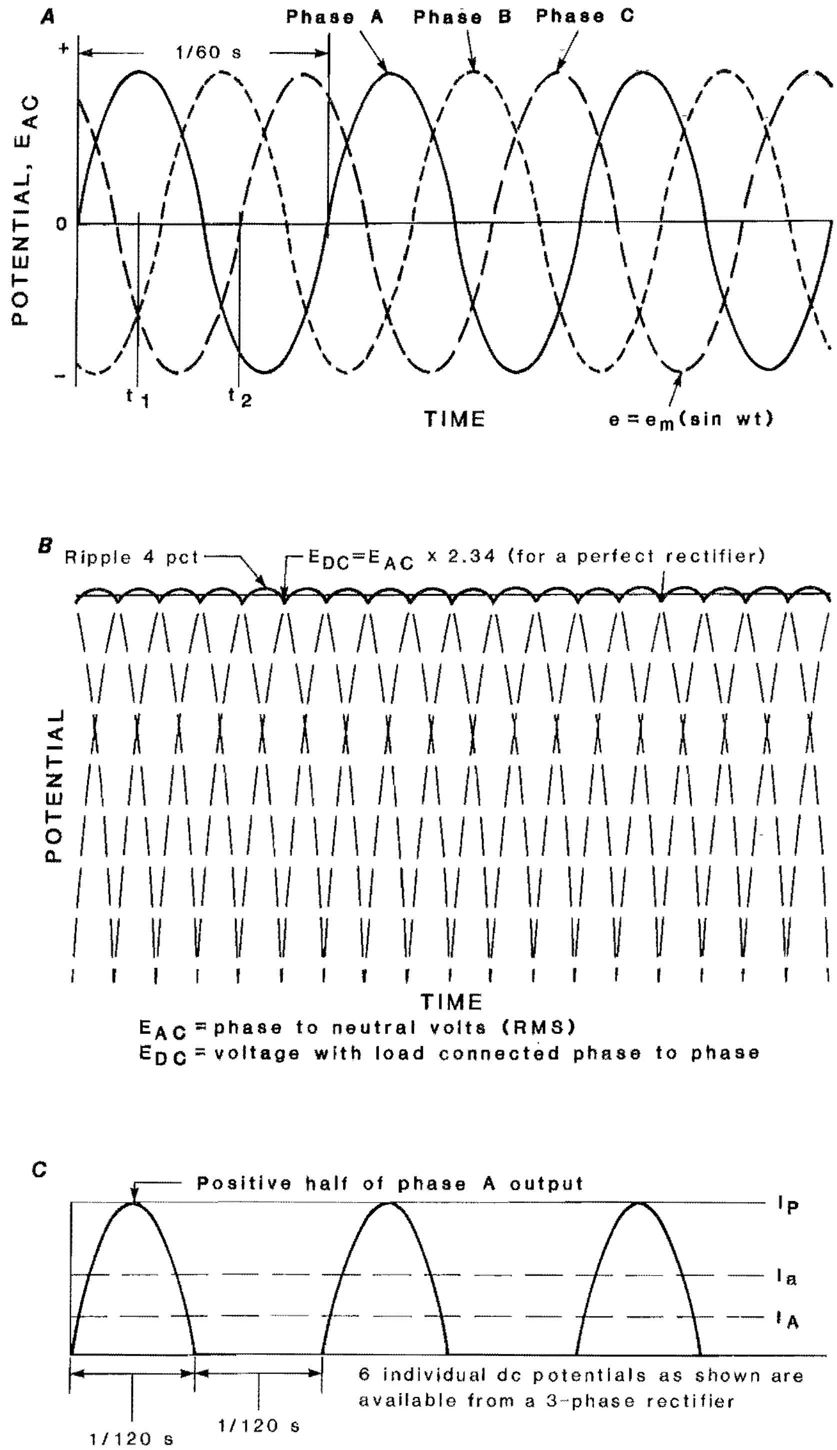
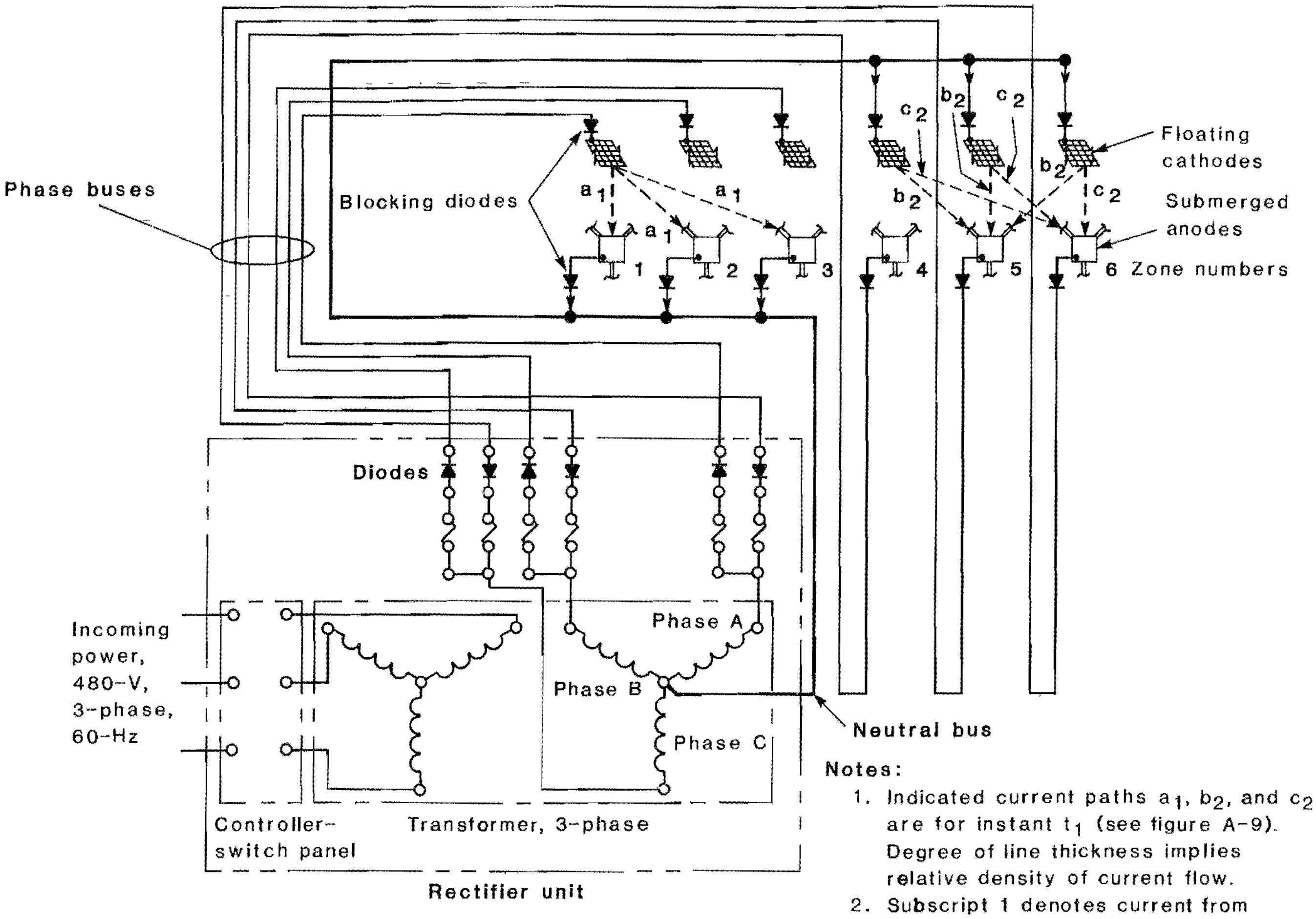


FIGURE A-9.—Pulsed potential from a three-phase rectifier.



Notes:

1. Indicated current paths a_1, b_2, and c_2 are for instant t_1 (see figure A-9). Degree of line thickness implies relative density of current flow.
2. Subscript 1 denotes current from positive half of a phase potential, and subscript 2 denotes negative half.
3. Main electrode reactions are–
   cathode: $2e^- + 2H_2O \rightarrow H_2 + 2OH^-$
   anode: $4OH^- \rightarrow 2H_2O + O_2 + 4e^-$
   overall: $2H_2O \rightarrow 2H_2 + O_2$

FIGURE A-10.—Current flow pattern at time t_1.

zone 2, the anodes connected to dock 16 are approximately 213 ft from the nearest cathodes in zone 1, and current flow between these electrodes will be much smaller. Spacing between nonadjacent zones (240 to 420 ft) is so large that current flow between electrodes in these zones will be negligibly small. However, the interaction of electrodes in adjacent zones, illustrated in figure A-10, will significantly increase overall dewatering efficiency.

Figure A-11 shows current flow at time t_2, when current in C phase is zero and currents in A and B phases are equal and opposite. Again, there is significant interaction between electrodes from zone to zone.

The blocking diodes shown in figures A-10 and A-11 are incorporated in the design to prevent damage or counterproduction by current flow in the wrong direction. For example, at t_1, cathodes 1, 2, and 3 (fig. A-11) are positive with respect to cathodes 5 and 6. Without blocking diodes, current could flow between cathodes 1, 2, and 3 (acting as anodes) and cathodes 5 and 6. If this occurred, the small fence wire would soon be corroded away.

As shown in figure A-9*C*, each of the six circuits will carry continuously pulsating power. At the anticipated current density of 0.0065 A/ft^2, the required current per zone will be equal to

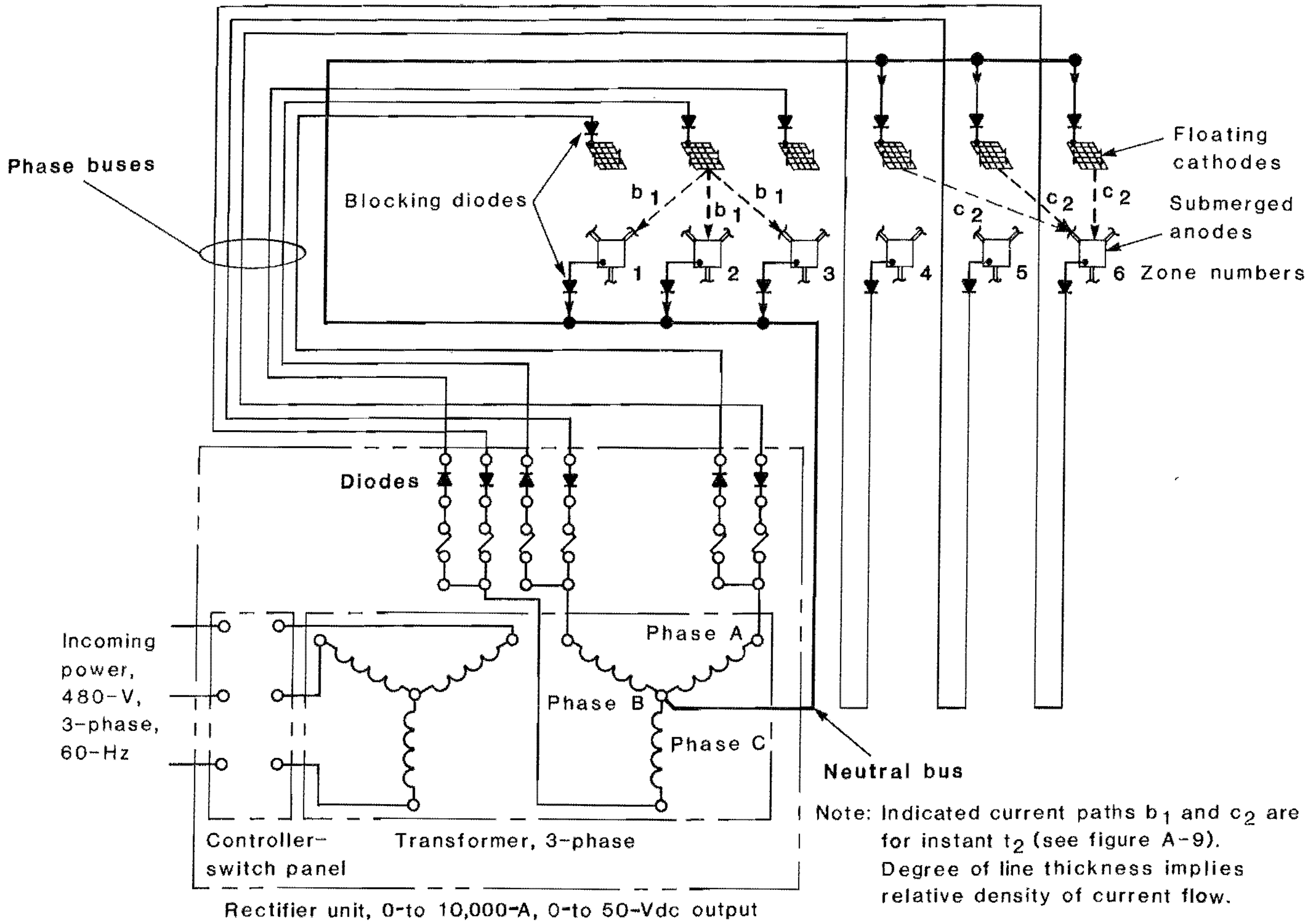


FIGURE A-11.—Current flow pattern at time t_2

(5.5 acres/zone)(43,560 ft^2/acre)(0.0065 A/ft^2), or 1,557 A in terms of constant dc. However, the ratio of the peak value of half-wave sinusoidal pulses to an equivalent constant current is 3.14 to 1. Thus, instead of a constant flow of 1,557 A, the current will continuously pulsate from an instantaneous peak of 4,889 A to 0 A. Apparently, this relatively high peak, even though brief, is largely responsible for the superior results that occur with use of half-wave power. Obviously, the increased effectiveness must be weighed against the increased rate of power consumption. Power consumption increases in proportion to the RMS of the current flow. Therefore, it may be necessary to flatten the top of the sinusoidal wave via transistor elements to achieve acceptable power losses. Such a modification of the applied pulse might be incorporated into this design, depending upon results obtained in the design calculations for the dc bus, the electrode resistance, and the power consumption.

Direct Current Distribution System

The dc distribution system, illustrated in figures A-3 and A-12 through A-18, is complex because the six individual dc potentials generated by the rectifier (i.e., two half-wave outputs per phase) must each be delivered to a specific area. The problem is intensified by the large quantity of current to be delivered, the numerous electrodes that must be connected, and the relatively long distribution lines to some of the zones. The extraordinarily high current rates will cause large heat losses in the conductors (I^2R), which must be offset by increasing the size of the system

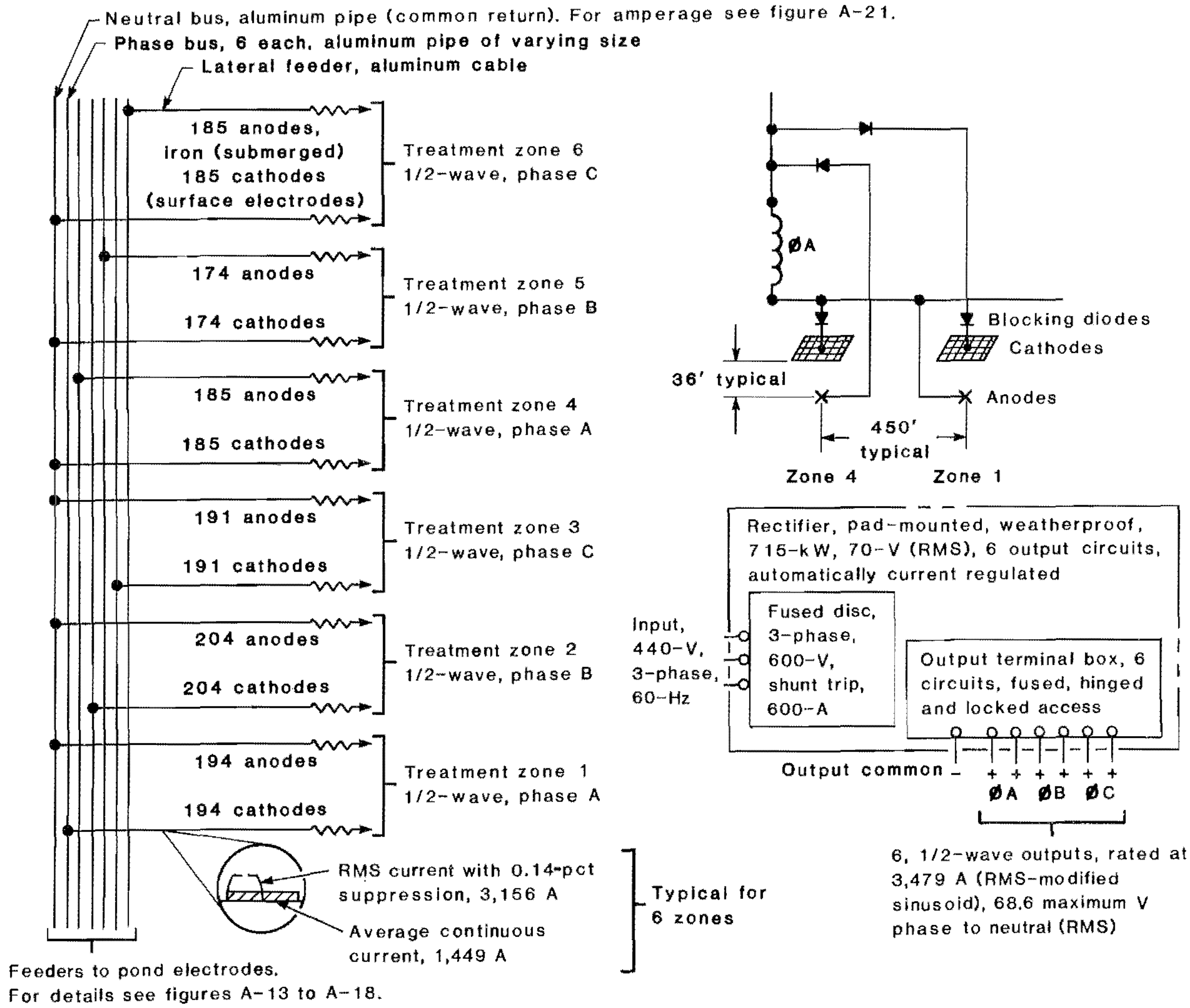
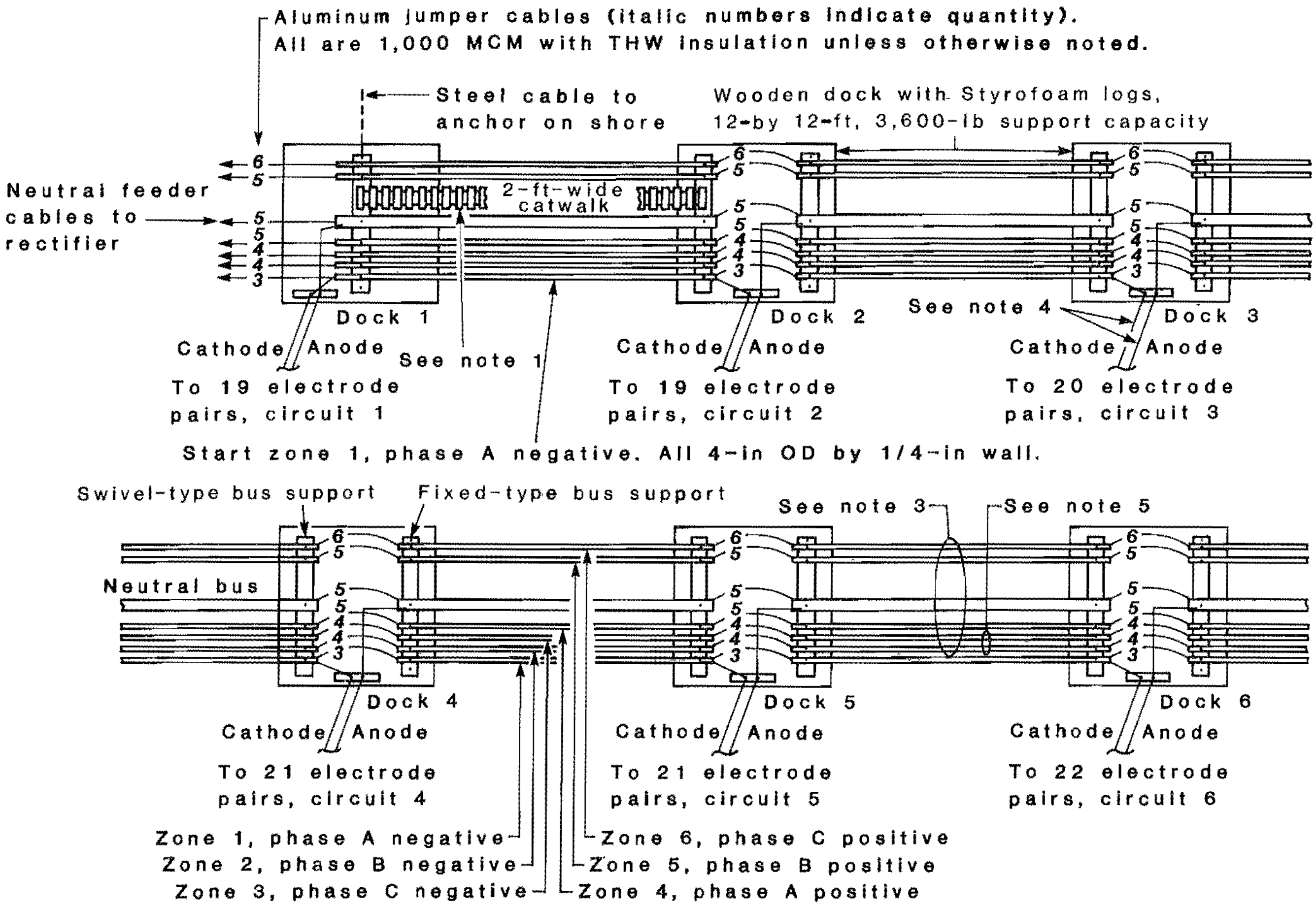


FIGURE A-12.—Electrical diagram.



Notes:
1. All docks joined with catwalks as shown above
2. All docks spaced on 30-ft centers unless otherwise noted
3. All tubing is round aluminum, 8-in OD with 3/8-in wall unless otherwise noted
4. Each lateral includes 2, 750-MCM, THW aluminum conductors in parallel
5. All buses for zones 2 and 3 are 8-in OD with 1/4-in wall

FIGURE A-13.—Distribution system, docks 1 through 6.

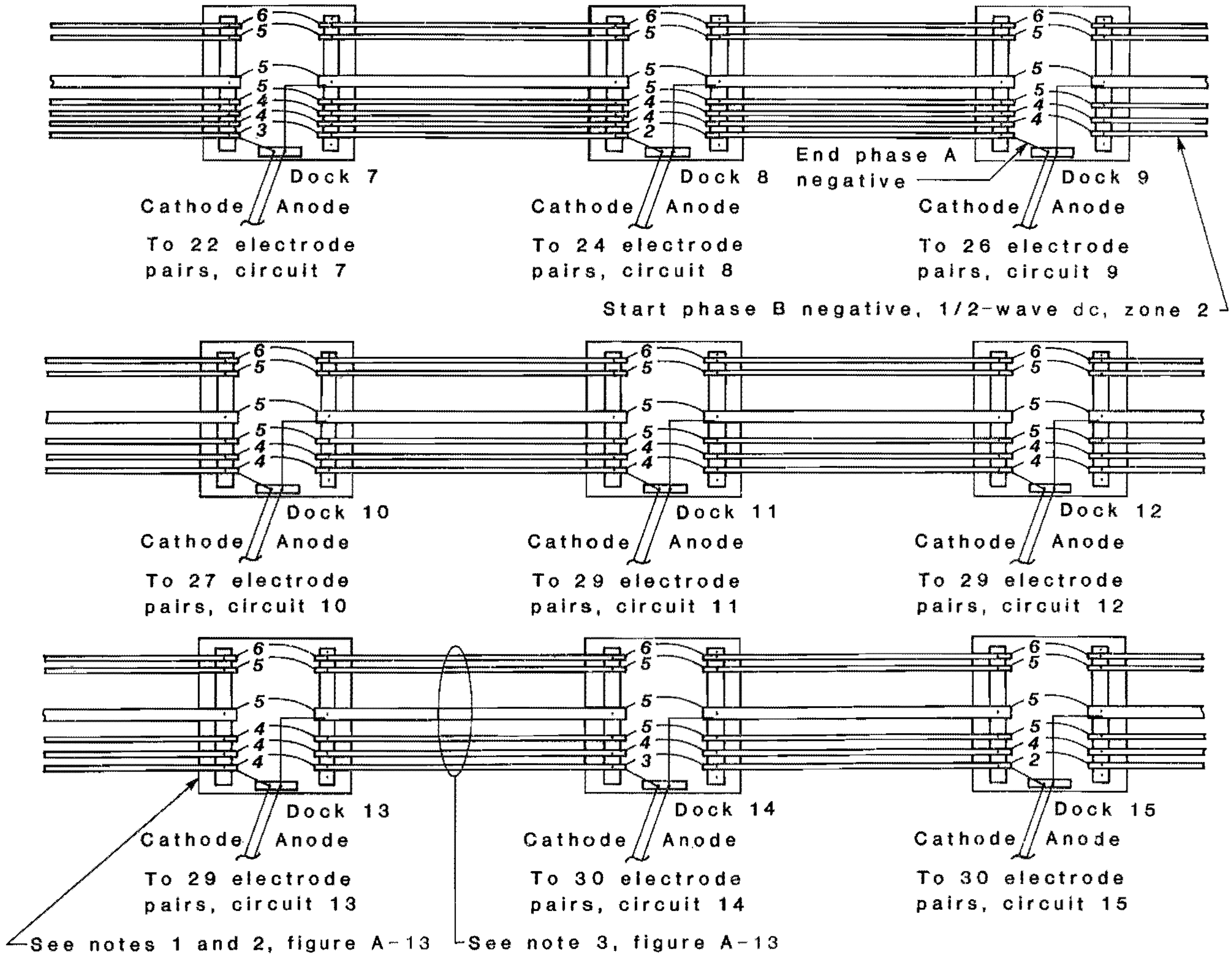


FIGURE A-14.—Distribution system, docks 7 through 15.

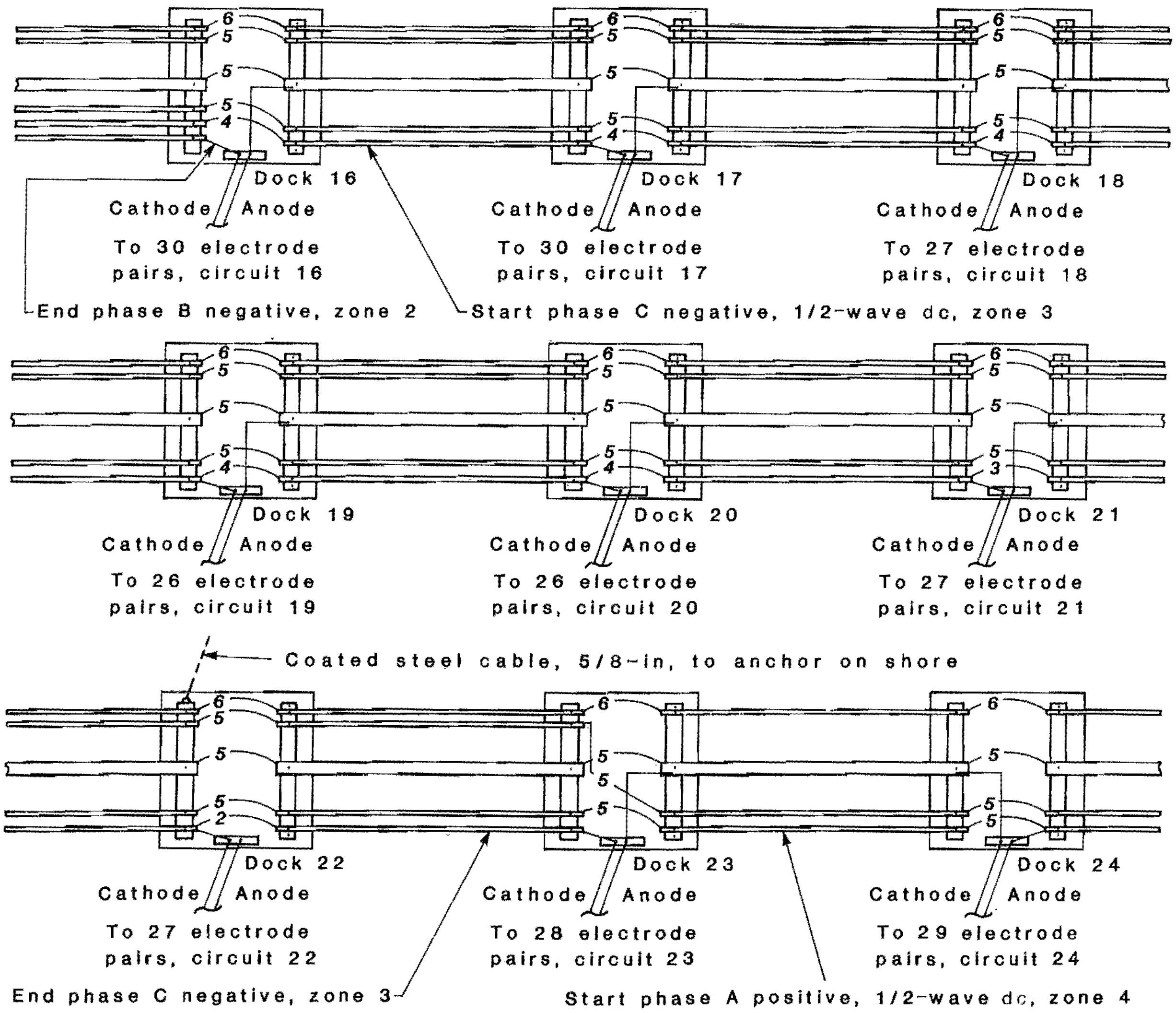


FIGURE A-15.—Distribution system, docks 16 through 24.

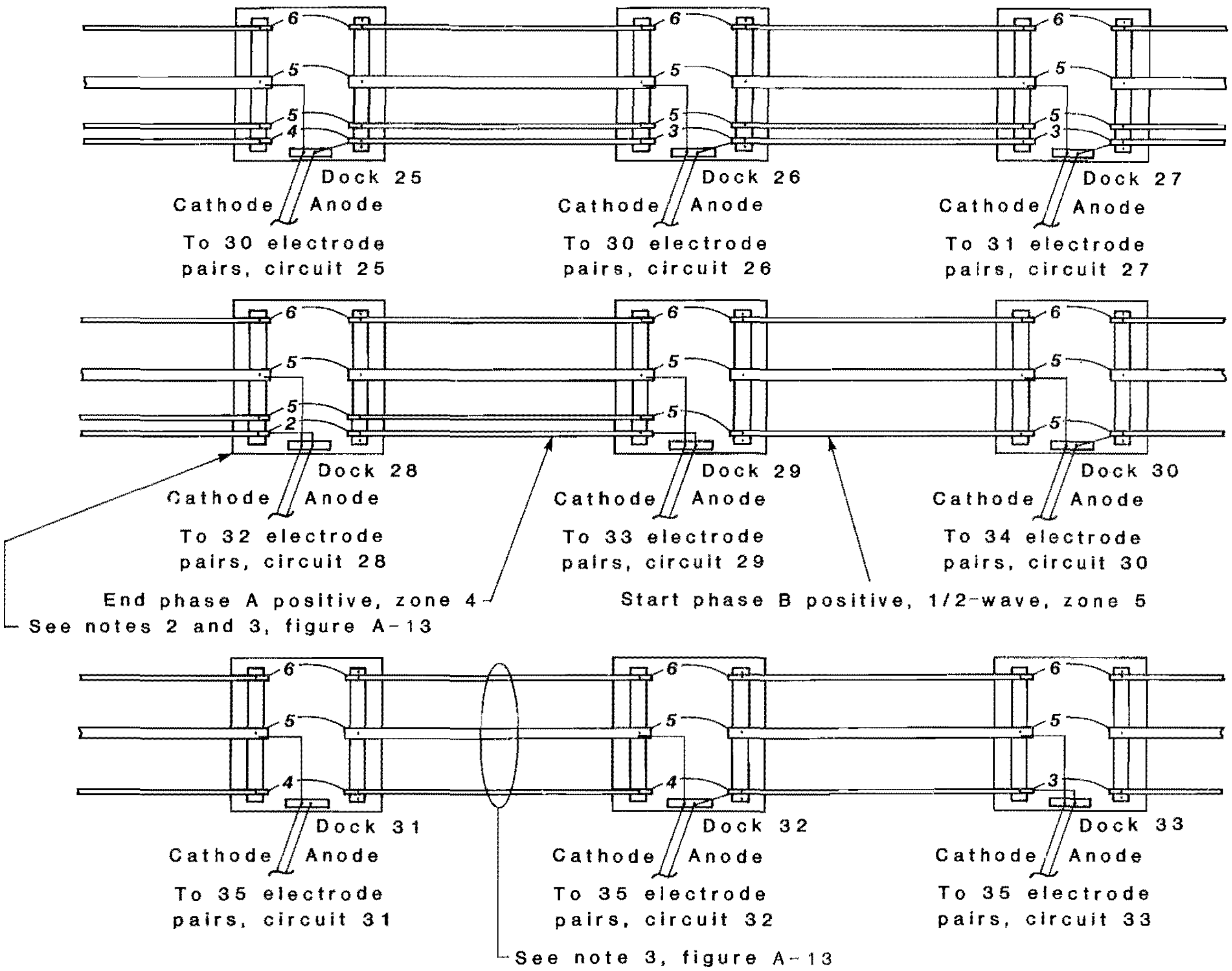


FIGURE A-16.—Distribution system, docks 25 through 33.

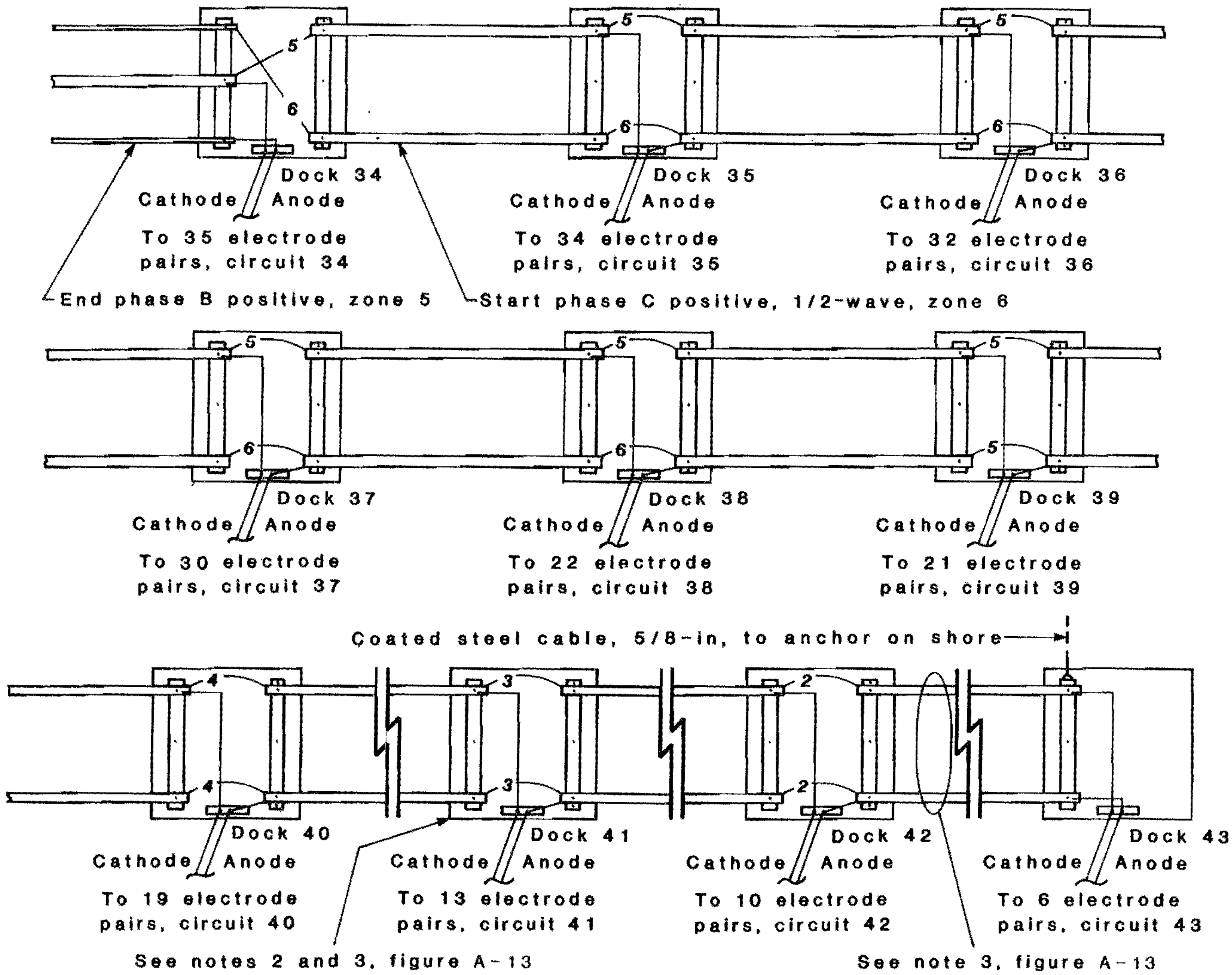


FIGURE A-17.—Distribution system, docks 34 through 43.

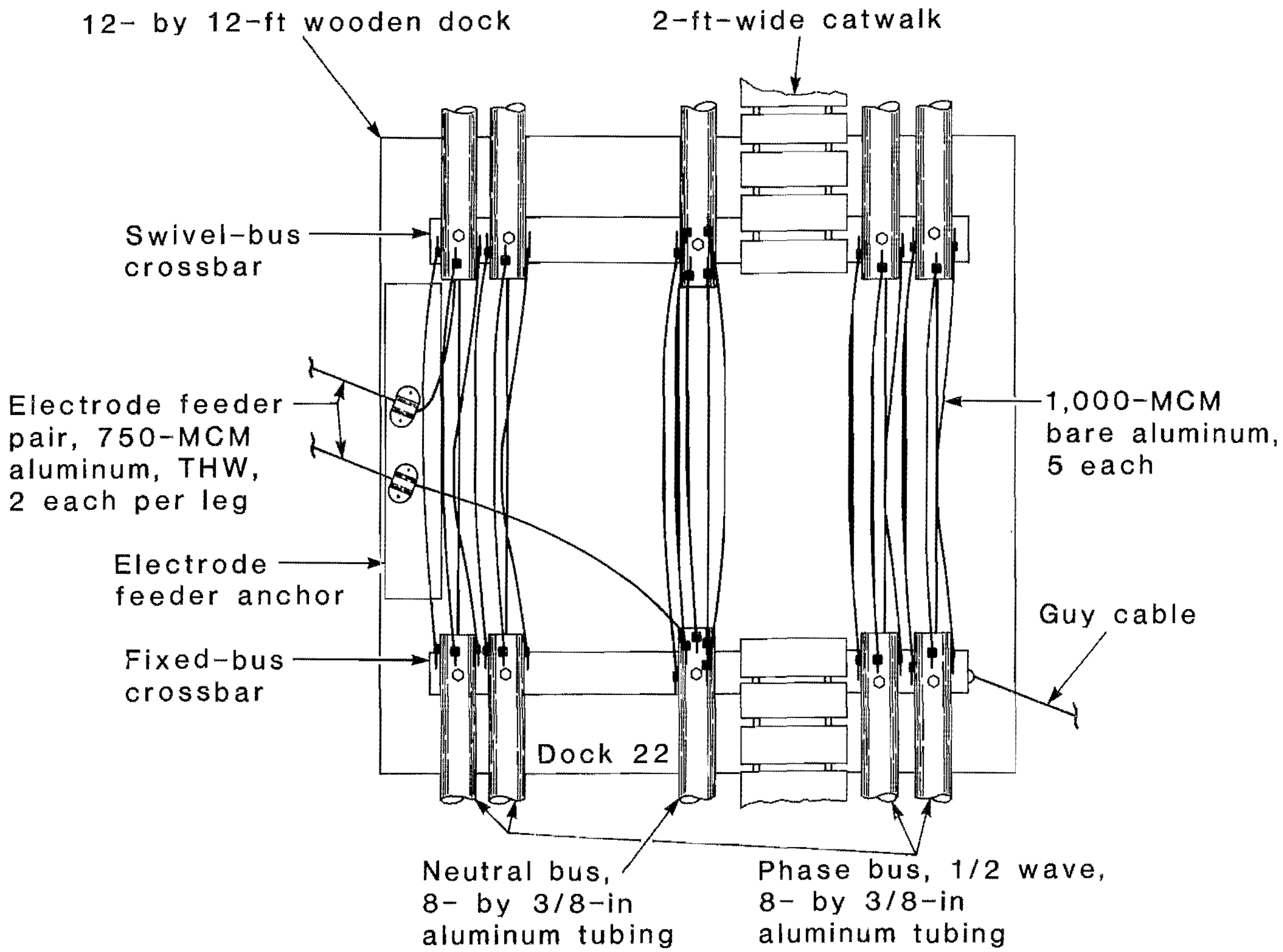


FIGURE A-18.—Typical layout of distribution system dock.

(i.e., the cross-sectional area of conductors) as much as is economically feasible. Therefore, the design described here attempts, through iterative calculations, to achieve a favorable balance between the costs of wasted heat losses and those of system installation.

The components of the complete dc circuit are shown in figure A-12. They are shown in sequence, starting at the rectifier. The components include -

1. Phase and neutral cables: Single-conductor, insulated (THW) aluminum cable, in multiple parallel as necessary for electrical capacity, connects the rectifier with the aluminum tubing on the first dock (fig. A-13). Cables are fastened to wooden crossbars on the surface of the ground, and are attached to the tubing by arc welds and to the rectifier by mechanical pressure devices.
2. Phase bus: Each zone is fed with a set of aluminum tubes (bus) supported 12 to 15 in above the pond surface by a system of 43 wooden docks aligned along the east boundary of the treatment zones. The 24-ft lengths of round tubing span the 18-ft spaces between docks. Resistance calculations for the aluminum pipe are based on an ALCOA resistivity value of 3.13×10^{-6} ohm/cm^2.
3. Phase and neutral bus junpers: The gaps between the 24-ft lengths of tubing, i.e., across the top of the docks (fig. A-18), are bridged with a sufficient number of insulated (THW) aluminum cables in parallel to achieve the desired capacity. Jumper conductors are arc-welded to the tubing.
4. Lateral cables: One set of relatively large insulated (THW) aluminum cables per zone carries current laterally across the treatment zone from the phase bus to one side of the electrode pairs. An identical set carries return current from the second side of the electrode pairs to the neutral bus. Guy wires off the far end of each lateral cable hold the entire array in place. Lateral conductors are fixed to the aluminum tubing by arc welds.
5. Connector wires: Small insulated (THW) copper wires connect the individual electrodes to the large lateral cables.
6. Electrode resistance: The electrical resistance between the sets of cathodes and anodes for each zone includes resistive effects of the two sludge-electrode interfaces, the sludge body, and the reflective effect, in a given zone, from electrodes in all other zones. Electrode resistance differs somewhat for the various zones and also can be expected to change significantly as treatment progresses.
7. The neutral bus is connected to the neutral point of the three-phase transformer in the rectifier and serves as the common return path from all electrodes. It consists of 24-ft lengths of aluminum tubing, in series, as described above for the phase bus. The neutral current is proportional to the phase current imbalance. This is very large in some portions of the bus, primarily because of the large physical separations between the six half-phase loads. Neutral current will be different in each span, ranging from a very high to a relatively low value, as shown by calculations later in this study.

As established earlier, to fulfill the dewatering objective will require application of an average dc of about 0.0065 A/ft^2 over the primary treatment area, or a total of 9,344 A. This study will assume equal distribution of this current to all electrode pairs. Thus, each electrode pair will conduct 9,343/1,135, or 8.23 A. This value multiplied by the number of electrode pairs in a given zone establishes the approximate current for that area in terms of continuous dc. However, the actual current is in the form of regular 60-cycle sinusoidal pulses which may be altered and somewhat reduced by suppressing the peaks to moderate I^2R losses. The relationships between continuous dc and half-wave sinusoidal pulses of both the standard and an altered version are shown in figures A-19 and A-20. Applied current flow to each zone is shown in table A-1. The

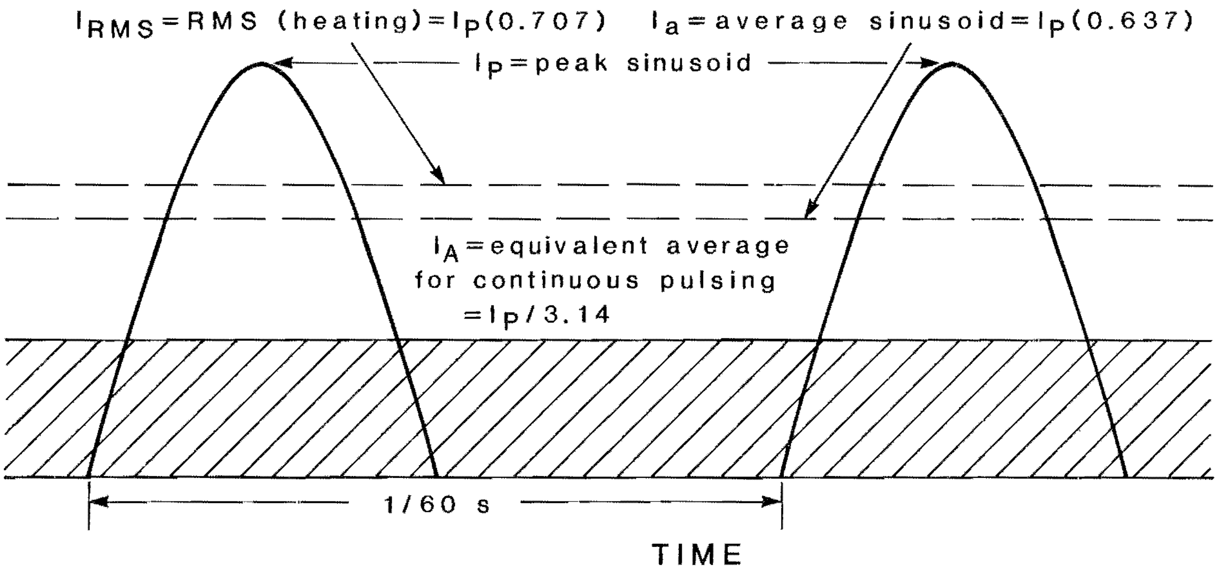


FIGURE A-19.—Continuous current versus sinusoidal pulses.

values for current, with subscripts 1 through 6, are values for the sinusoidal pulses for which the peak values have been suppressed by transistor control. As shown in table A-1, such suppression causes a substantial reduction in power consumption for a relatively small decrease in the average current. For example, as shown by lines 12 and 13 (fig. A-20), suppression of the top 14 pct decreases the average quantity of current by 4.9 pct while decreasing power consumption by 12.8 pct.

Four combinations of various distribution system components were evaluated with regard to efficiency, voltage drop, and cost. The cases were considered sequentially, i.e., reasonable estimates of item requirements were made in case 1, and after calculations had forecast the consequences of those assumptions, they were modified for case 2 and the calcualtions were repeated, etc. Given the impossibility of optimizing a system for more than one variable at a time, this is a reasonable approach, and we believe results of the fourth case study are not far different from the best that could be achieved with additional "tinkering."

Calculations were performed to relate average and RMS currents for various levels of peak suppression. The area bounded by a truncated wave with an original amplitude of one unit was calculated. This calculation was repeated for truncated amplitude of 0.84 to 0.94 as shown in table A-2. The RMS value was obtained by using the computer program in appendix B, and the area under one curve was found by integrating sin θ from 0 to $\sin^{-1}$ (truncated amplitude) and adding this to the area of the rectangle. For example, suppose the amplitude is truncated to 94 pct of its maximum value. The area under the truncated curve from 0 to $\pi/2$ is given by

$$\sin^{-1}(0.94) = 70.05° = 1.223 \text{ rad}$$

$$\text{Area of rectangle} = (\pi/2 - 1.223)(0.94) = 0.327$$

$$\text{Total area} = \int_{0°}^{70.05°} \sin\theta \cdot d\theta + 0.327 = -[\cos(70.05°) - \cos 0°] = 0.327$$

$$= -0.341 + 1.0 + 0.327$$

$$= 0.986$$

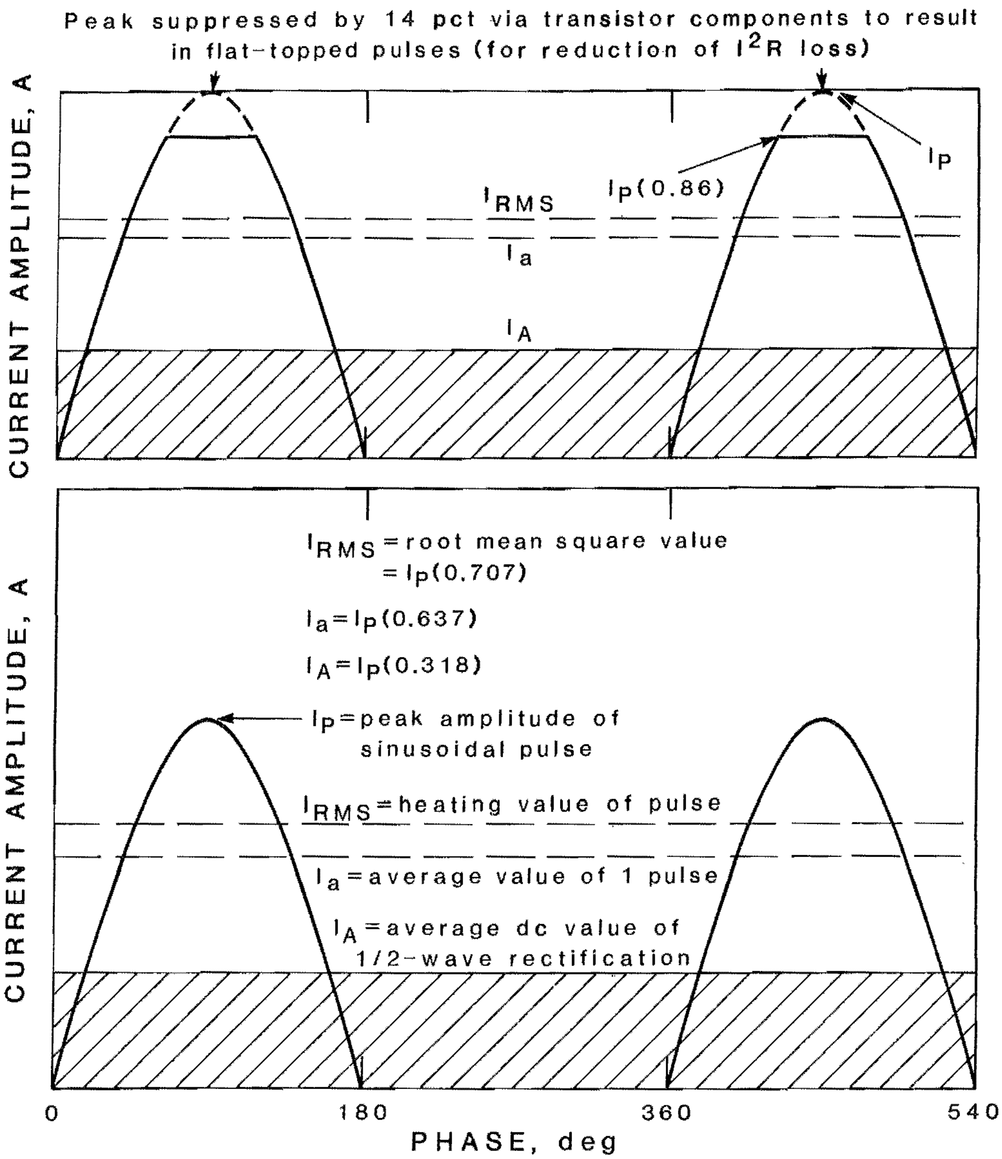


FIGURE A-20.—Altered sinusoidal pulse.

The area under the nontruncated curve from 0 to $\pi/2$ is 1, and the percentage of the total area is (0.986/1.0)(100 pct) = 98.6 pct.

Calculation procedures for losses in individual components are simple but tedious, and therefore are not included here. However, for the neutral leg, calculations are quite unusual and procedures are presented in more detail. Results for the first three cases are presented briefly. Greater detail is given for the fourth and final case, which is the one selected for installation. Both regular and altered sinuosical pulses were evaluated for this case.

TABLE A-1. - Applied current to individual zones, amperes

Item	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
I_A --Required amperes expressed as an average constant value..............	1,597	1,679	1,572	1,523	1,432	1,539
I_p --Peak value of sinusoidal pulse, with half-wave rectification to achieve I_A..................................	5,015	5,272	4,936	4,782	4,497	4,833
I_R --RMS[1] value of sinusoidal pulse (i.e., I_R=heating effect)..................	3,545	3,727	3,490	3,381	3,179	3,417
I_{R_1} --RMS with 6 pct clipped clipped from pulse peaks.........................	3,468	3,646	3,414	3,307	3,110	3,342
I_{A_1} --Average constant calue with 6 pct suppression.........................	1,575	1,656	1,550	1,502	1,412	1,518
I_{R_2} --RMS current with 8-pct suppression...	3,469	3,647	3,415	3,308	3,111	3,343
I_{A_2} --Average constant value with 8-pct suppression.........................	1,564	1,644	1,539	1,491	1,402	1,507
I_{R_3} --RMS with 10-pct suppression..........	3,409	3,584	3,356	3,251	3,059	3,286
I_{A_3} --Average constant value with 10-pct suppression.........................	1,549	1,628	1,525	1,477	1,389	1,493
I_{R_4} --RMS with 12-pct suppression..........	3,359	3,532	3,307	3,204	3,012	3,237
I_{A_4} --Average constant value with 12-pct suppression.........................	1,533	1,612	1,509	1,462	1,375	1,477
I_{R_5} --RMS with 14-pct suppression..........	3,309	3,479	3,257	3,156	2,967	3,189
I_{A_5} --Average constant value with 14-pct suppression.........................	1,519	1,597	1,495	1,449	1,362	1,464
I_{R_6} --RMS with 16-pct suppression..........	3,259	3,426	3,209	3,108	2,922	3,142
I_{A_6} --Average constant value with 16-pct suppression.........................	1,500	1,577	1,476	1,430	1,345	1,445

[1]RMS = root mean square.

TABLE A-2. - Average and RMS values for various levels of suppression

Suppression of peak value, pct	RMS value	Area, pct
94	0.69	98.6
92	.69	97.9
90	.68	97.0
88	.67	96.0
86	.66	95.1
84	.65	93.9

Each of the 20-ft lengths of the neutral bus along the east boundary carries a different level of current, as shown in figure A-21, ranging from very low to very high amperage. The neutral bus accumulated return current from all the individual electrode pairs, each of which is fed with sinusoidal pulses. Thus, starting from the far end of zone 6, dock 43, the neutral bus receives (from lateral 43) a sinusoidal pulse with an RMS

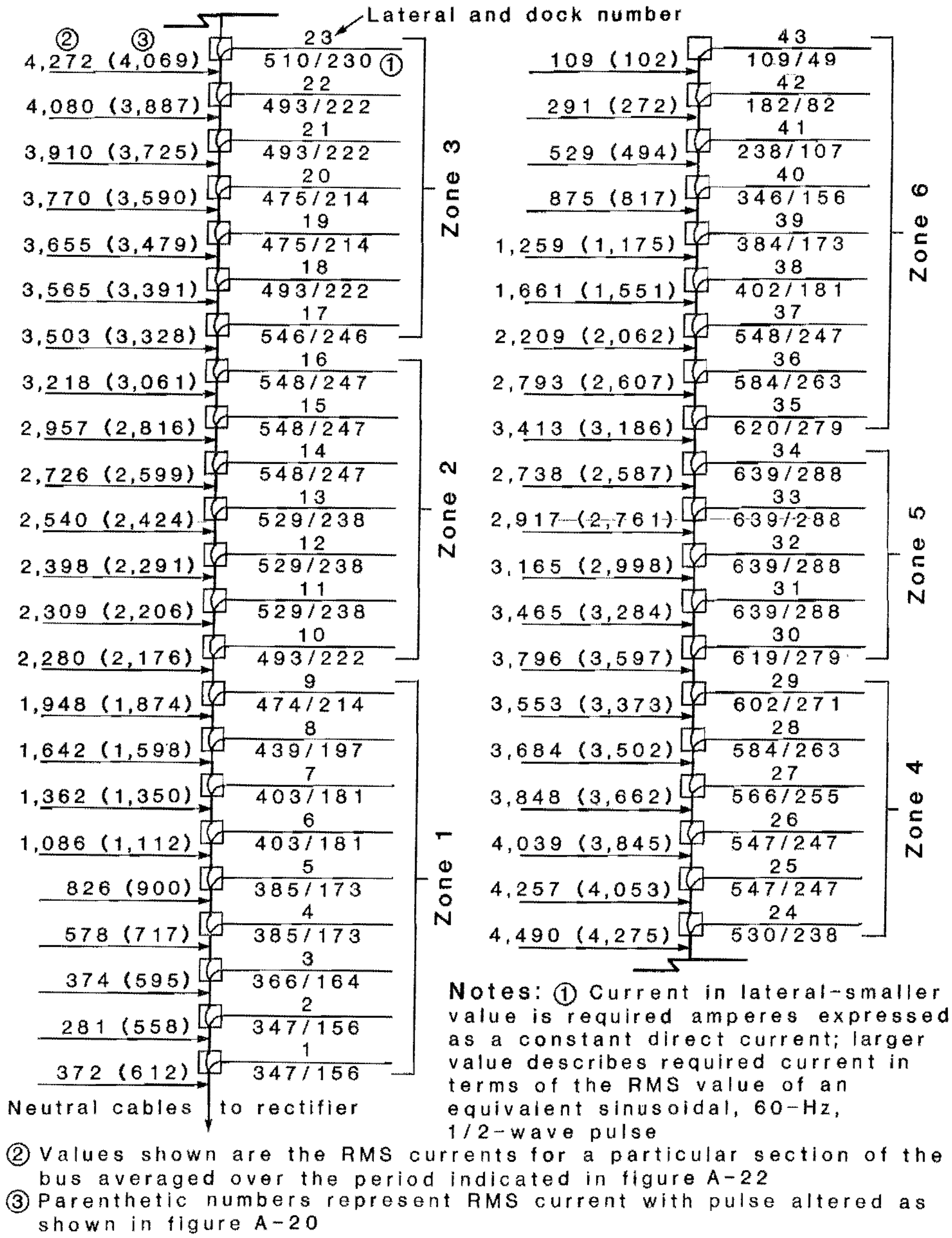


FIGURE A-21.—Neutral bus current, individual sections.

current (i.e., root mean square or heating effect) of 109 A. From dock 43 through 35, the pulses from the laterals are all in phase with one another and add directly, as denoted by figure A-22, diagram *B*, resulting in a gradually increasing sinusoidal pulse. Starting at dock 34, the pulses from zone 5 are added 120° out of phase to the single large pulse emanating from the bus at dock 34. This develops an irregular pulse, gradually increasing in average amplitude as shown in diagram *C*, figure A-22. Pulses from zone 4 are added 120° out of phase to the pulse from dock 30 (summation of pulses from zones 5 and 6), resulting in pulses as shown in diagram *D*, figure A-22. Across zones 3, 2, and 1, the pulses are subtractive and result in the patterns shown in figure A-22. A short computer program (appendix C) was used to calculate current for each individual section of pipe as an RMS current, for a normal as well as an altered pulse, averaged over the pulse time period, e.g., 180°, 300°, etc. Results are shown in figure A-21. The home run current represents system imbalance and amounts to a

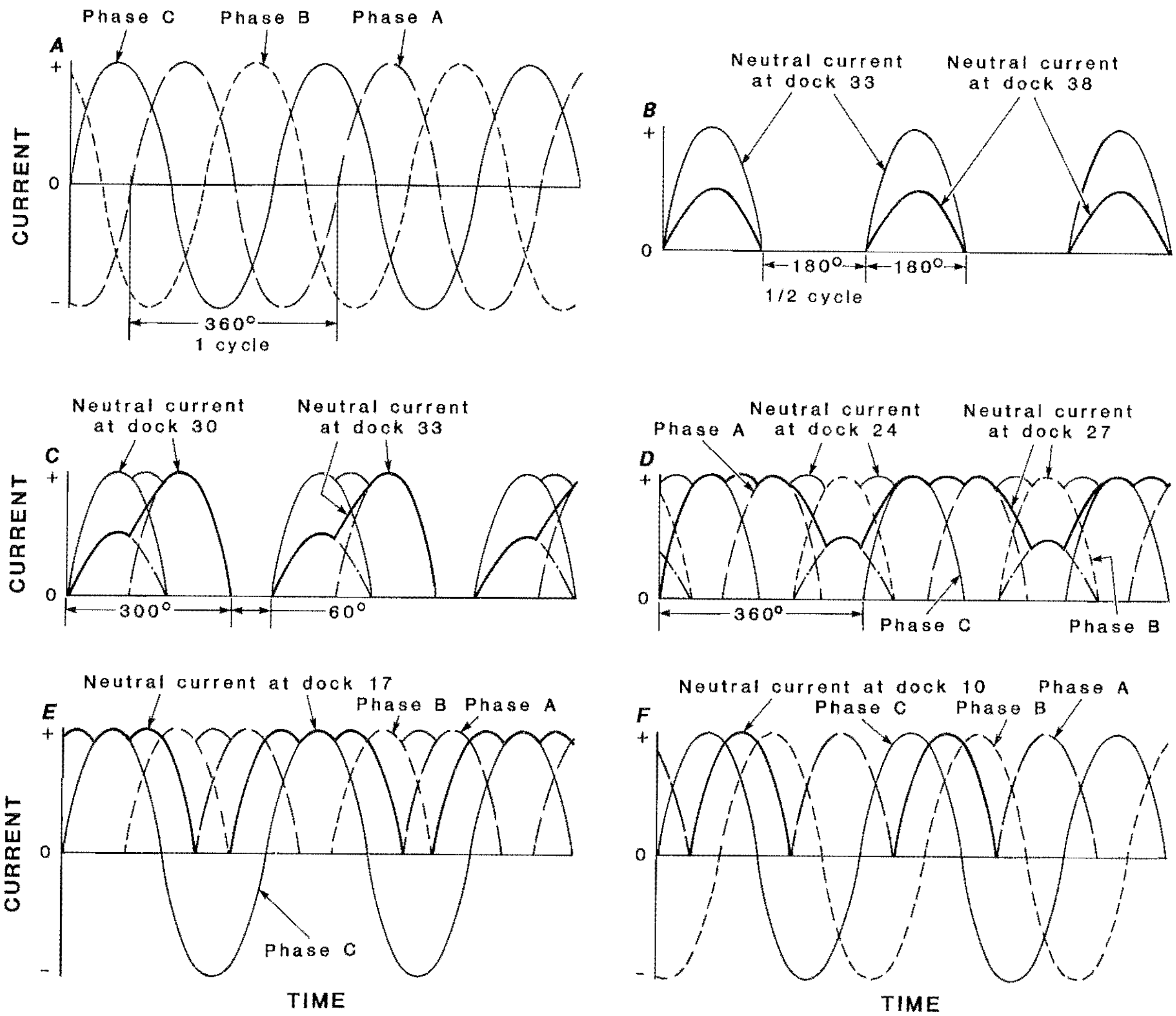


FIGURE A-22.—Current pulses in neutral bus.

372-A sinusoidal pulse expressed as constant current or 612 A RMS, altered pulses. Heating loss in the bus is equal to the product of the RMS current squared and the bus resistance and is summarized in table A-3.

Case 1 considered 4-in-OD by 3-1/2-in-ID pipe for the phase bus, a set of four 1,000-MCM cables in parallel for each phase bus for the run from the rectifier to the first dock, a set of four 500-MCM conductors in parallel for each phase bus jumper, one 500-MCM conductor for each lateral across the treatment area, one No. 10 AWG copper wire to connect each individual electrode to a lateral cable, a 6-in-OD by 5-1/2-in-ID pipe for a neutral bus and a set of five 500-MCM cables for each neutral bus jumper, and five 1,000-MCM conductors for the run connecting the rectifier to the neutral pipe on the first dock.

TABLE A-3. - Heating loss in neutral bus across various zones per case study, watts

Zone	Regular sinusoidal pulses		Altered sinusoidal pulse, case 4
	Cases 1-3	Case 4	
1...	859	440	465
2...	6,561	3,316	3,016
3...	16,433	8,301	7,522
4...	15,281	7,724	6,993
5...	6,984	3,530	3,166
6...	2,381	1,206	1,053

Case 1 results are summarized as follows:

Heating loss in the distribution system, exclusive of electrodes.......kW..	285
Approximate cost for installing the distribution system (exclusive of docks and electrodes) plus the cost of energy loss in the distribution system conductors:	
Estimated cost for installation..	$136,000
Approximate cost for energy loss...	210,000
Total..	346,000
Typical voltage drop across the treatment zones, i.e., difference in voltage applied to the nearest and most remote electrodes............V, RMS..	13

The principal objections to this system are excessive power loss and voltage drop; case 2 will therefore enlarge some of the system components.

Case 2 evaluated a combination of various pipe sizes for the phase bus (increasing in diameter with distance from the rectifiers) including 4-, 5-, and 6-in OD (all 1/4-in wall), a set of five 1,000-MCM cables from the rectifier to each phase bus on dock 1, four 1,000-MCM cables from the rectifier to each phase bus on dock 1, four 1,000-MCM conductors in parallel for each set of phase bus jumpers, one 1,000-MCM conductor for each lateral across the treatment zones, one No. 10 AWG copper conductor for connecting each electrode to a lateral, one 6-in-OD pipe (1/4-in wall thickness) for the neutral bus, five 500-MCM conductors in parallel for each set of neutral bus jumpers, and five 1,000-MCM conductors in parallel for connecting the rectifier to the neutral bus on the first dock.

Case 2 results are summarized as follows:

Heating loss in the distribution system, exclusive of electrodes.......kW..	204,000
Approximate cost for installing the distribution system (exclusive of docks and electrodes) plus the cost of energy loss in the distribution system conductors:	
Estimated cost for installation..	$185,000
Approximate cost for energy loss...	150,000
Total..	335,000
Typical voltage drop across the treatment zones, i.e., difference in voltage applied to the nearest and most remote electrodes............V, RMS..	6.73

Results for this study show higher-than-desirable heat loss and voltage drops. Therefore, some component sizes will be increased for case 3.

Case 3 considered 4-in-OD by 1/4-in-wall-thickness pipe for phase bus to zone 1, 8-in-OD by 1/4-in pipe to zone 2, and 8-in-OD by 1/2-in pipe to zones 3 through 6; a set of six 1,000-MCM conductors in parallel from the rectifier to each phase bus on the first dock; for phase bus jumpers, four 1,000-MCM conductors to zone 1, five 1,000-MCM conductors per set to zones 2 through 5, and six 1,000-MCM conductors for zone 6; one 1,000-MCM conductor per lateral across zone 1 and one 1,250-MCM conductor per lateral across zones 2 through 6; connection from laterals to individual electrodes with No. 8 AWG copper conductor in zones 1 through 5 and one No. 6 AWG copper conductor in zone 6; one 6-in-OD by 1/4-in-wall-thickness pipe for the neutral bus; five 500-MCM conductors for the neutral bus jumpers; and five 1,000-MCM conductors for the run connecting the rectifier with the neutral bus on the first dock.

Case 3 results are summarized as follows:

Heating loss in the distribution system, exclusive of electrodes.......kW..	142,000
Approximate cost for installing the distribution system (exclusive of docks and electrodes) plus the cost of energy loss in the distribution system conductors:	
Estimated cost for installation....................................	$347,000
Approximate cost for energy loss....................................	105,000
Total..	452,000
Typical voltage drop across the treatment zones, i.e., difference in voltage applied to the nearest and most remote electrodes...........V, RMS..	5.40

This case study shows adequate efficiency but excessive installation costs. A lower voltage drop across the treatment zones would be desirable. Generally, case 4, as indicated below, reduces the size of some components used in case 3 but increases the size of others to stem losses and voltage drops.

Case 4 considered the following components:

Phase cables, rectifier to phase pipes on first dock; six each 1,000-MCM conductors per phase pipe: resistance is 0.0029 ohm/1,000 ft.

Phase bus, aluminum pipe:
Zone 1--4-in-OD by 1/4-in walls, 0.0065 ohm/1,000 ft.
Zones 2 and 3--8-in-OD by 1/4-in walls, 0.0033 ohm/1,000 ft.
Zones 4, 5, and 6--8-in-OD by 3/8-in walls, 0.0022 ohm/1,000 ft.
Jumpers, phase bus:
Zone 1--three each 1,000-MCM conductors in parallel, 0.0059 ohm/1,000 ft.
Zones 2 and 3--four each 1,000-MCM conductors in parallel, 0.0044 ohm/1,000 ft.
Zones 4 and 5--five each 1,000-MCM conductors in parallel, 0.0035 ohm/1,000 ft.
Zone 6--six each 1,000-MCM conductors in parallel, 0.0029 ohm/1,000 ft.

Note: The number of conductors per set is reduced by one per set near the end of each phase run (and the neutral run), such that the last jumper set uses no more than two conductors, the second to the last no more than three, etc.

Laterals across the treatment zones: Two each 750-MCM conductors in parallel for each lateral run, 0.0118 ohm/1,000 ft.

Connector wires, laterals to individual electrodes: All No. 8 AWG copper, 0.653 ohm/1,000 ft.

Neutral bus, aluminum pipe: All 8-in-OD by 3/8-in-thick walls, 0.0022 ohm/1,000 ft.

Jumpers, neutral bus: Each set includes five each 1,000-MCM conductors, 0.0035 ohm/1,000 ft. (See note under Jumpers, phase bus.)

Neutral cables, rectifier to neutral pipe on first dock: Five each 1,000-MCM conductors in parallel, 0.0035 ohm/1,000 ft.

Case 4 was evaluated with regular sinusoidal pulses and pulses for which the peak was suppressed (or truncated) to 86 pct of the original value with the following results; results for altered pulses are in parentheses.

Heating loss in distribution components, watts:		
Phase bus and jumpers	65,336	(56,949)
Laterals across treatment zones	23,250	(20,267)
Connecting leads (laterals to electrodes)	6,142	(5,354)
Phase cables (rectifier to first dock)	24,516	(22,215)
Neutral cables to first dock	6	(39)
Total	124,484	(111,257)
Cost estimate for installation of the distribution system (exclusive of docks and electrodes) plus the cost of energy loss via conductor heating at $0.0028/kW•h:		
Installation	$260,500	($265,000)
Energy (3 yr)	92,336	(81,132)
Total	352,836	(346,132)

Voltage drops in the distribution system for the worst and best case, exclusive of drops in electrodes, are shown in table A-4.

The combination of components selected for case 4 shows an acceptable balance between installation and power loss costs.

Table A-4 shows zone 5 as the worst case in terms of difference between applied voltage for the electrodes most remote from and nearest to the power supply, i.e., 26.3 and 14.7 V (full sinusoidal pulse). These values assume that each electrode pair will draw equal amperage. In the reality of operation, however, such voltage differences will be greatly moderated because the sludge body between the upper and lower electrodes will tend to demand a rather uniform distribution of current. Also, if large differences were to occur between the near and far end of a lateral, the region of high current density will dewater faster and become more resistive, thus moderating unequal current density. Therefore, the difference between the nearest and most remote electrodes should be no more than 2 or 3 V for any of the six zones. Consequently, the case 4 components are selected for this preliminary design along with application of the altered sinusoidal pulse with 14-pct suppression.

TABLE A-4. - Voltage drop per zone

Item	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Most remote electrode in zone	10.3	15.2	19.0	22.9	26.3	23.0
	(9.7)	(14.3)	(17.9)	(21.5)	(24.8)	(21.0)
Electrode nearest to rectifier	0.2	5.1	9.3	11.6	14.7	17.4
	(.1)	(4.9)	(8.9)	(11.0)	(13.9)	(16.4)
Difference	10.2	10.1	9.7	11.3	11.6	5.6
	(9.5)	(9.4)	(9.0)	(10.5)	(10.9)	(4.6)

NOTE.--Numbers in parentheses represent drops for pulses with peaks suppressed to 86 pct of a full sinusoidal wave.

Thus, the selected operating current is 8,886 A (expressed as continuous current in table A-1) and is 4.9 pct less than the initially assumed rate of 9,343 A, owing to peak suppression. This reduction will extend dewatering time proportionally as specified later in this design.

In final design, the foregoing calculations should be repeated with a higher current to achieve the initially selected dewatering rate. The considerable time and effort required for that adjustment are not warranted for this preliminary design effort.

Electrical Resistance of Electrode Arrays

The use of electrodes to dewater sludge and slime in ponds or mine stopes is an essentially new procedure. There are no verified data for specifically predicting the electrical resistance of an electrode array immersed in a sludge deposit such as that proposed for the WIDCO pond.

The problem is complicated because the treatment area is divided into six separate zones with various areas and shapes. Each zone requires a large number of individual electrodes formed into a specific array, and two layers of material should be considered--the sludge with comparatively low resistivity and the host earth with a much higher resistivity.

The solution to the problem must be reliable because resistance is the primary factor in specifying and purchasing power supplies, bus systems, transformers, etc. While some tolerance can be obtained by purchasing equipment with some margin or adjustability, a major mismatch of electrode systems and power supply equipment would cause serious problems.

Although the use of electrodes in the densification process differs significantly from the electrical grounding of power systems, the basic equations for electrodes and the theory of current flow through earth should apply. The analysis that follows develops a tractable anode-cathode model and an earth model using a two-layer earth, and discusses the effects of individual electrode shape on resistance.

Anode or cathode resistance (R_a or R_c) is determined by the self-resistance of each individual electrode plus the mutual resistance of all electrodes in the configurations. Anode-to-cathode resistance is determined by

$$R_{ac} = R_a + R_c - 2R_m$$

where R_m = sum of the mutual resistances between all anode electrodes and each cathode electrode divided by the number of cathode electrodes (average mutual).

The dewatering anode and cathode are arranged in a regular pattern and consist of a multiplicity of individual conductors. For example, the anode might include hundreds of individual units, each made up of dragline cables welded into Y-shapes, right angles, etc. Such a large number and variety of units complicate development of mathematical formulas to calculate anode-to-cathode self- and mutual resistance. Therefore, the anode and cathode are modeled as a "parallel conductor," which involves a relatively small number of horizontal parallel conductors whose distribution, total length, and diameter simulate an array of numerous small electrodes uniformly distributed throughout the treatment zone. Results obtained with the model should be a close and somewhat conservative approximation of the resistance of the actual installation.

When the anode and cathode are installed in low-resistivity sediment surrounded by much higher resistivity earth, the resistance equation requires that the two-layer earth contribution be included. The formulas used to calculate each of the components of the anode-to-cathode equation for the parallel conductor model, included at the end of this section, are derived from those developed by Tagg and Swartz (5-6).

Figure A-23 shows the parallel conductor configuration used for the model's anode and cathode. The anode conductors are located at the average pond depth of 36.3 ft (d_a), and the cathode conductors are supported by floats at a depth of 0.3 ft (d_c). Model calculations are made by assuming either a homogeneous earth with a resistance of 10.5 ohm•m or a two-layer earth with a resistance of 10.5 ohm•m in the top layer (36.3 ft deep) and 390 ohm•m in the bottom layer. The latter more nearly approximates pond-host earth conditions. When pond resistivity differs from 10.5 ohm•m, calculated anode-to-cathode resistance values can be prorated by multiplying by the ratio of actual resistivity to the calculated resistivity (10.5).

The model is first applied to zone 2, which has been arbitrarily selected, to determine its electrode resistance and the effect of varying the number of conductors with various anode diameters. Calculations are then performed and tabulated for electrodes in the remaining five zones.

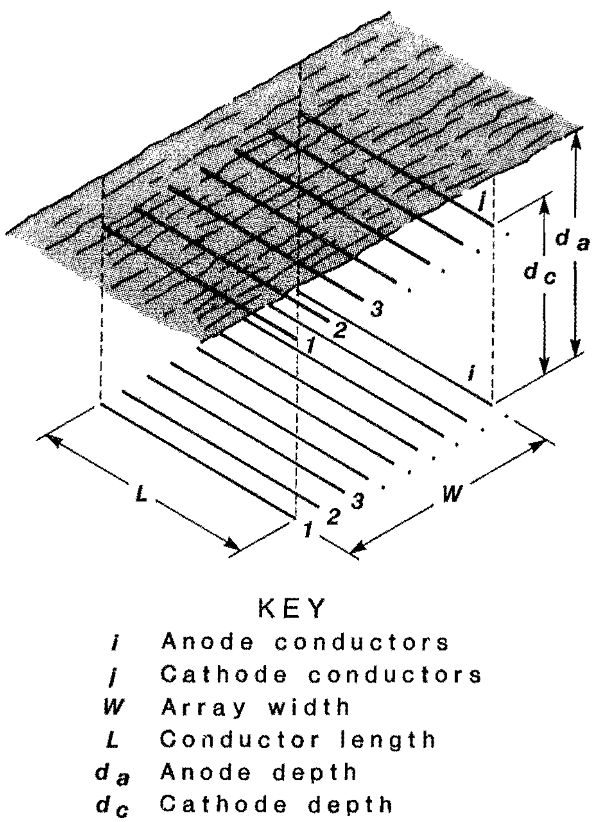


FIGURE A-23.—Anode-to-cathode resistance model.

The electrode array for zone 2 covers an area of about 1,020 by 180 ft, with 204 wire fence panels constituting the cathode and 816 iron shapes constituting the anode. These electrodes are approximated in figure A-24 by curve 9/9. This means nine each 2/0 AWG conductors, 1,020 ft long, are connected in parallel for the cathode, and nine each 2.25-in-OD conductors, 1,020 ft long, are connected in parallel for the anode. The number and size of the parallel conductors for this approximation were determined as follows:

1. Each fence wire panel has eight 14-ft-long strands and 29 crosswise strands each 32 in long. The diameter of the strands is 0.095 in. Thus, total strand length per panel is 189.3 ft with a surface area of 678 in^2. An equivalent surface area of 2/0 AWG cable (0.418-in-OD) for 204 panels requires 8,777 ft of nine parallel cables, each 1,020 ft long.
2. As determined earlier, 313 tons of anode iron are required for the entire treatment area in order to have sufficient iron to compensate for corrosion. This means that 52.2 tons are required for zone 2. Use of 2-1/4-in-OD dragline cable at 12.31 lb/lin ft for all anodes would require a total length of 9,130 ft (nine parallel conductors at 1,020 ft each).

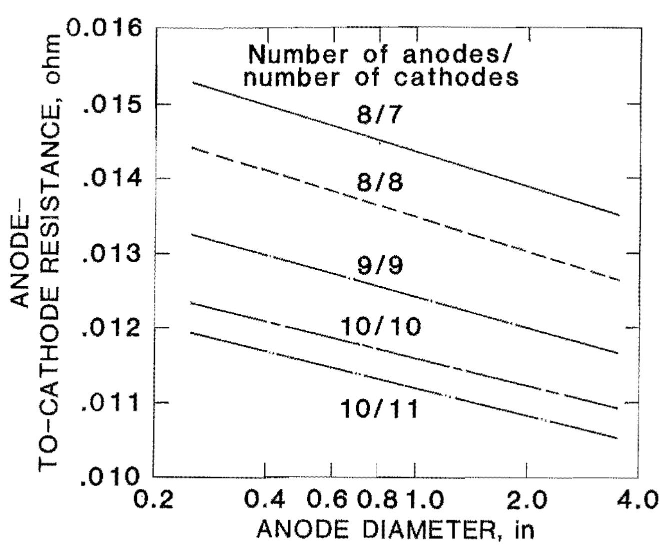


FIGURE A-24.—Anode-to-cathode resistance for various number of parallel circuits.

The effect of parameter changes on anode-to-cathode resistance was determined for 2/0 copper cathode conductors by a computer program (appendix D). The number of parallel conductors was varied for five different anode conductor diameters: 1/4 in, 1/2 in, 1 in, 2 in, and 3.5 in. Assuming an average pond depth of 100 ft, a cathode depth of 4 in, and an anode depth of 36.3 ft, anode-to-cathode resistance values are plotted against anode conductor diameter in figure A-24.

The electrode with 204 wire fence panels for the cathode and 816 iron shapes for the anode is approximated in figure A-24 by curve 9/9.

Table A-5 and figure A-24 show the variation in anode-to-cathode resistance relative to the variation in the number of parallel conductors and anode diameters. Generally the change in circuit resistance is small relative to large increases in diameter and a moderate increase in the number of parallel electrodes. Therefore, the electrode array, represented by the parallel conductor arrangement of nine anodes and nine cathodes, is generally an acceptable system.

Table A-6 shows array resistance for each zone for the selected electrode patterns.

It must be realized that these values are not exact resistances but can be accepted as good, conservative approximations.

Finally, SRC'S extensive previous experience with electrode configurations in various types of sludges has shown repeatedly that careful installation of a reasonable pattern will result in an anode-to-cathode resistance that readily falls within 65 pct of the resistance of the block of sludge between the upper and lower electrodes. Using the model presented here, 65 pct of the resistance of the sludge body in zone 2 (1,050 by 180 by 36 ft) is calculated to be 0.0104 ohm.

This result provides verification that the calculated values are conservative resistances—a desirable position for a design of this nature. Therefore, the values shown in table A-6 will be used for this design.

TABLE A-5. - Cathode-to-anode resistance with variation in number of electrodes and diameters

Number of parallel conductors		Electrode resistance, ohms (top entry is for 2-layer earth; bottom entry is for 1-layer earth)				
Anode	Cathode	0.25-in anode	0.50-in anode	1-in anode	2-in anode	3.5-in anode
8	7	0.0152753	0.0148148	0.0143491	0.0138834	0.0135075
		.0152584	.0147980	.0143323	.0138666	.0134907
8	8	.0144064	.0139460	.0134803	.0130146	.0126386
		.0143924	.0139320	.0134663	.0130006	.0126247
9	9	.0132466	.0128373	.0124233	.0120094	.0116752
		.0132323	.0128230	.0124091	.0119951	.0116610
10	10	.0123437	.0119753	.0116028	.0112302	.0109295
		.0123292	.0119609	.0115883	.0112158	.0109150
10	11	.0119448	.0115765	.0112039	.0108313	.0105306
		.0119316	.0115633	.0111907	.0108181	.0105174

TABLE A-6. - Electrode array resistance per zone

Item	Anode-to-cathode parameters					
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Conductor length...ft..	780	1,020	940	1,065	1,220	980
Array width........ft..	240	180	180	150	120	125
Number of anodes, parallel conductors...	11	9	9	8	6	8
Number of cathodes (2/0 cables)..........	11	9	9	8	6	8
Anodes-to-cathode resistance, ambient temp, ohm:						
1-layer earth..........	0.0125815	0.0119278	0.0129805	0.0129828	0.0145161	0.0149034
2-layer earth..........	.0125948	.0119421	.0129961	.0129996	.0145336	.0149254

NOTE.--The following conditions are present in all zones:

Anode diameter - 2.25 in.
Depth of anodes - 36.3 ft.
Cathode diameter - 0.418 in.
Depth of cathode - 0.33 ft.
Sludge resistance - 10.50 ohm·m.
Host earth resistance - 3.90 ohm·m.
Average pond depth in treatment area - 100 ft.

Equations used to calculate each of the terms in the anode-to-cathode resistance equation are given in figures A-25 and A-26.[2] Terms are defined as follows:

L = conductor length

W = parallel array width

n_a = number of anode conductors

i = anode conductors 1, 2, 3,...,n_a

r = 1, 2, 3,...

S_a = spacing between anode conductors

$S_a = W/(n_a-1)$

$X_i = (i-1)S_a$

$X_{ra} = (r-1)\ S_a$

OD_a = diameter of anode conductors

d_a = depth of anode

[2]Computer program appears as appendix D.

n_c = number of cathode conductors

j = cathode conductors 1, 2, 3,...,n_c

S_c = spacing between cathode conductors

$S_c = W/(n_c-1)$

$Xj = (j-1)S_c$

$X_{rc} = (r-1)S_c$

OD_c = diameter of cathode conductors

d_c = depth of cathode

P_1 = average resistivity of pond

P_2 = average resistivity of earth outside pond

$k = (P_2-P_1)/(P_2+P_1)$, reflection factor

n = number of images for series convergence

D = depth of top layer (average depth of pond)

$$
\begin{aligned}
R_a = \frac{P_1}{2\pi L n_a^2} \Bigg\{ \sum_{r=1}^{n_a} \sum_{i=1}^{n_a} \Bigg[& \ln \left(\frac{L + \sqrt{(X_{ra}-X_i-OD_a/2)^2+L^2}}{\sqrt{(X_{ra}-X_i-OD_a/2)^2}} \right. \\
& \left. \left(\frac{L + \sqrt{(X_{ra}-X_i-OD_a/2)^2+L^2+4d_a^2}}{\sqrt{(X_{ra}-X_i-OD_a/2)^2+4d_a^2}} \right) \right) - \frac{\sqrt{(X_{ra}-X_i-OD_a/2)^2+L^2}}{L} + \frac{\sqrt{(X_{ra}-X_i-OD_a/2)^2}}{L} - \\
& \frac{\sqrt{(X_{ra}-X_i-OD_a/2)^2+L^2+4d_a^2}}{L} + \frac{\sqrt{(X_{ra}-X_i-OD_a/2)^2+4d_a^2}}{L} \Bigg] + \sum_{r=1}^{n_a} \sum_{i=1}^{n_a} \sum_{1}^{n} k^n \\
& \Bigg[\ln \left(\frac{L + \sqrt{(X_{ra}-X_i)^2+L^2-4(nD-d_a)^2}}{\sqrt{(X_{ra}-X_i)^2+4(nD-d_a)^2}} \left(\frac{L + \sqrt{(X_{ra}-X_i)^2+L^2+4(nD)^2}}{\sqrt{(X_{ra}-X_i)^2+4(nD)^2}} \right)^2 \right. \\
& \left. \frac{L + \sqrt{(X_{ra}-X_i)^2+L^2+4(nD+d_a)^2}}{\sqrt{(X_{ra}-X_i)^2+4(nD+d_a)^2}} \right) - \frac{\sqrt{(X_{ra}-X_i)^2+L^2+4(nD-d_a)^2}}{L} + \frac{\sqrt{(X_{ra}-X_i)^2+4(nD-d_a)^2}}{L} - \\
& \frac{2\sqrt{(X_{ra}-X_i)^2+L^2+4(nD)^2}}{L} + \frac{2\sqrt{(X_{ra}-X_i)^2+4(nD)^2}}{L} - \frac{\sqrt{(X_{ra}-X_i)^2+L^2+4(nD+d_a)^2}}{L} + \\
& \frac{\sqrt{(X_{ra}-X_i)^2+4(nD+d_a)^2}}{L} \Bigg] \Bigg\}
\end{aligned}
$$

FIGURE A-25.—Equation for anode resistance.

To calculate cathode resistance, substitute

n_c for n_a

j for i

X_{rc} for X_{ra}

X_j for X_i

OD_c for OD_a

Dc for d_a.

Electrical Power Supply

General Description. - The overall system for this project includes a three-phase 5-kV primary line to bring power to the site, an 800-kV•A substation to transform 5-kV power into three-phase 480-V power, a specialized rectifier to convert 480-V ac power to pulsating dc power, a high-capacity, low-voltage distribution system (bus) to carry dc power from the rectifier to the electrode array, and a system of docks to support the large distribution bus system.

$$R_m=\frac{P_1}{\pi L n_a n_c}\left\{\sum_{j=1}^{n_c}\sum_{i=1}^{n_a}\left[\ln\frac{L+\sqrt{(X_j-X_i)^2+L^2+d_a^2}}{\sqrt{(X_j-X_i)^2+d_a^2}}-\frac{\sqrt{(X_j-X_i)^2+L^2+d_a^2}}{L}+\frac{\sqrt{(X_j-X_i)^2+d_a^2}}{L}\right]+\right.$$

$$\sum_{j=1}^{n_a}\sum_{i=1}^{n_a}\sum_{1}^{n}k^n\left[\ln\left(\frac{L+\sqrt{(X_j-X_i)^2+L^2+(2nD+d_a)^2}}{\sqrt{(X_j-X_i)^2+(2nD+d_a)^2}}\left(\frac{L+\sqrt{(X_j-X_i)^2+L^2+(2nD-d_a)^2}}{\sqrt{(X_j-X_i)^2+(2nD-d_a)^2}}\right)\right)-\right.$$

$$\frac{\sqrt{(X_j-X_i)^2+L^2+(2nD+d_a)^2}}{L}-\frac{\sqrt{(X_j-X_i)^2+L^2+(2nD-d_a)^2}}{L}+\frac{\sqrt{(X_j-X_i)^2+(2nD+d_a)^2}}{L}+$$

$$\left.\left.\frac{\sqrt{(X_j-X_i)^2+(2nD-d_a)^2}}{L}\right]\right\}$$

FIGURE A-26.—Equation for mutual resistance, anode-to-cathode.

Primary Distribution Line. - Connection of the rectifier unit at the treatment site with the nearest source requires constructing 0.25 mile of new three-phase, 2/0 ASCR, 5-kV primary line and converting 0.5 mile of existing primary line from single phase to a three-phase, 2/0 ASCR, 5-kV system.

Substation. - A platform-mounted transformer bank at the treatment site will reduce the primary voltage to three-phase, 480 V. The primary side of the transformer is protected with fused cutouts, pole-mounted disconnects, and lightning arrestors. Secondary output, at three-phase, 480 V, will be fed through a nonfused manual safety disconnect switch to the input terminal box at the rectifier.

Rectifier Unit. - The rectifier unit converts alternating current to direct current and, as the heart of the system, its capacities and performance characteristics should be carefully specified.

Table A-7 lists power consumption demands for each zone and phase. The total power consumption rate, with pulses modified to suppress the top 14 pct of the sinusoidal peak, is 525 kW, which includes 110.3 kW to offset distribution system losses and 414.8 kW to power all of the electrodes.

The RMS voltage requirement per zone and phase is shown in table A-8.

For construction practicality, each of the six output capacities should be equal and should meet the highest individual zone demand for current and voltage outputs. Thus, with the altered sinusoidal pulse, output capacity for each half-wave circuit should be (1/2)(68.6 V) (3,479 A) = 119 kW, or 715 kW of total output capacity for the rectifier unit.

It should be recognized at this point that the rectifier capacity is based on sludge resistance in an ambient state and could be reduced if two constraints were accepted. That is, as power is applied to electrodes in almost any type of sludge, resistance decreases very significantly with elapsed time. As discussed later, electrode resistance for this design decreases by a factor of 2 within 10 days after power is first applied. Consequently, the rectifier capacity for this project could be reduced accordingly under the following operating conditions. During system startup, maximum available current at the electrodes must be reduced in proportion to the voltage capacity reduction. Availability of higher current would occur gradually, over 20 to 30 days, with rising temperature of the sludge adjacent to the electrodes. For

TABLE A-7. - Power requirements per zone, watts[1]

Zone	Power consumption	Phase A	Phase B	Phase C
	POSITIVE HALF OF CYCLE			
6.............	Distribution system loss..........	NAp	NAp	20,501
6.............	Power to electrodes...............	NAp	NAp	75,894
5.............	Distribution system loss..........	NAp	20,234	NAp
5.............	Power to electrodes...............	NAp	63,970	NAp
4.............	Distribution system loss..........	22,614	NAp	NAp
4.............	Power to electrodes...............	64,740	NAp	NAp
	NEGATIVE HALF OF CYCLE			
3.............	Distribution system loss..........	NAp	NAp	23,363
3.............	Power to electrodes...............	NAp	NAp	68,931
2.............	Distribution system loss..........	NAp	16,291	NAp
2.............	Power to electrodes...............	NAp	72,270	NAp
1.............	Distribution system loss..........	7,254	NAp	NAp
1.............	Power to electrodes...............	68,953	NAp	NAp
Total cycle....................................		163,561	172,765	188,689

NAp Not applicable.
[1]Total required output from the rectifier = 525,015 w.

TABLE A-8. - Rectifier output voltage requirements, neutral to phase, volts, RMS

Zone	Phase	Half of cycle	Sinusoidal pulse without suppression	Altered sine wave 14-pct suppression)
1.............	A	Negative	53.6	51.3
4.............	A	Positive	66.9	62.5
2.............	B	Negative	59.8	55.8
5.............	B	Positive	72.7	67.9
3.............	C	Negative	64.5	60.2
6.............	C	Positive	73.5	68.6

final design, evaluation and acceptability of this aspect and associated cost reduction should be considered. For this preliminary design, however, selected rectifier capacity remains at 715 kW continuous duty and 70 V RMS.

Treatment of sludge normally requires application of constant current at selected rates, such as 0.006 to 0.007 A/ft^2 of area between the electrode arrays. The preset rate must be maintained at a constant value using automatic regulators, regardless of the changes that occur throughout the treatment process, e.g., reduced resistance between cathode and anode arrays because of temperature increase at electrode interfaces, decrease of water content, etc. There may also be circumstances where application of constant voltage for short periods could be advantageous, e. g., testing the performance of such a mode. Therefore, the rectifier specification should include the provision that by control switch operation, the unit can be placed in either of two modes--constant current or constant voltage. In the first mode, current output must be maintained within 5 pct of any set value regardless of changes in load resistance, i.e., voltage output will vary while current remains constant. Similarly, in the second mode, voltage will remain within 5 pct of a selected value, and current output will vary with changes in load resistance.

The rectifier must also include the necessary circuitry to suppress the top 14 pct of the sinusoidal pulses from each of the six half-wave circuits.

The rectifier must be weatherproofed for outdoor service, mounted on a pad, and equipped with all required safety devices, including overload protection of individual diodes, transformers, reactors, and the overall system. In addition, for personnel safety, the unit should have provisions for automatic shutdown whenever the access gate to the treatment area is opened. A manual restart at the rectifier would be required after such a shutdown.

Dewatering and Consolidation Results

The following paragraphs describe procedures used for predicting operational performance of the electrokinetic equipment described in the previous section. The system must sufficiently consolidate a large quantity of existing sludge in a nearly filled impoundment so that additional storage is provided for up to 3 yr of plant operation. If the pond is to be abandoned, the final product should be totally stable, safe, and suitable for eventual capping with coarse refuse and topsoil for total reclamation.

The electrode array, comprising 1,135 sets of electrodes, would be installed in a regular pattern covering 27.4 acres over the deepest part of the pond. According to the principles of electrode theory, this array would actually cause current to flow throughout the entire sludge body, but the intensity or current density would attenuate rapidly with distance from the electrode. Laboratory and field tests do show that the field is very effective for a distance beyond the perimeter of 1.25 times the separation between electrodes. The sum of this additional 5.6 acres and the actual area of the array is designated (for this design) as the primary treatment zone; it encompasses 33 acres.

The application of power, with the upper electrode negative, causes particles in the upper region (muddy water) to move downward while water in the sediment migrates upward to the cathode. In addition, a significant amount of electrokinetic flocculation occurs in the muddy water zone.

Consolidation in the 36.3-ft Layer Above the Anode (Primary Treatment Area)

Initial water content, average..........wt pct..	68.9
Initial density..........lb/ft^3..	73.97
Initial depth..........ft..	36.3
Water removed via treatment..........lb/ft^3..	27.96
Anticipated final water content, average..........wt pct..	50
Final density..........lb/ft^3..	83.4
Final depth of material above anode..........ft..	19.86
Volume reduction with treatment (36.3-19.86)(33)..........acre-feet..	542.5

Consolidation in the 20-ft Layer Beneath the Anode (Primary Treatment Area)

Initial water content, average..........wt pct..	58.6
Initial density..........lb/ft^3..	78.80
Initial depth..........ft..	20
Water removed via treatment..........lb/ft^3..	7.69
Anticipated final water content, average..........wt pct..	53.6
Final density..........lb/ft^3..	81.37
Final depth of 20-ft layer..........ft..	17.5
Volume reduction with treatment (20-17.5)(33)..........acre-feet..	82.5

Consolidation in the Outlying Area (Secondary)

An accurate quantitative prediction of the amount of consolidation in the outlying areas is not possible in the absence of relevant test data. Although some current will certainly be present in every portion of the pond, it will diminish rapidly with distance from the electrode and thus will be very small at the outermost edges--probably less than 1 μ/ft^2. However, applied for 3 to 4 yr, even such a low density should cause significant densification.

In the absence of more definitive and confirmed information, the results of the tests in the small earthen pond (1) can be used to predict consolidation in the outer zone. This seems reasonable since, proportionally, the distances from the electrodes to the sludge perimeter are similar for both cases. These results indicate that, at the conclusion of treatment, the outer zone will have an average solids content of 31 wt pct after about 56 days of treatment. In contrast, the average consolidation to be expected by natural settlement might only equal about 25 wt pct solids, which was the average value of a large number of samples obtained from throughout the upper 25 ft of the pond sludge. Thus electrokinetic treatment for 3 to 4 yr should increase solid content of sediment in the outer zone by an average of 6 pct to a total of 31 wt pct solids. At that time, the material in the outer zone would be cohesive but quite soft.

As treatment progresses, material in the primary area consolidates, and surface water is decanted. At the WIDCO pond, a 33-acre pit with a final depth of about 20 ft would develop. The area outside the electrode perimeter, when free of surface water, should slope gently into the pit. This gradient should significantly improve natural dewatering, with additional assistance from the slight electrical field.

Also, many large shrinkage cracks should develop, and this would enhance evaporation. If enough time were allowed after completion of the treatment process, the outlying material would be sufficiently dewatered to allow capping with coarse refuse for total reclamation. Total reclamation could be expedited if a simplified second array were installed after final treatment of the primary zone.

The average water content of the outlying, or secondary treatment, area is estimated to be equal to the averaged values of the samples collected from the upper 36-ft layer of sludge and from the layer 36 to 56 ft below the surface, or in this case, (1/2)(75.5 + 60) = 67.8 wt pct. As discussed earlier, this material is expected to consolidate by an average of at least 6 wt pct during the proposed treatment period.

Approximate Area of the Secondary Zone--77 Acres

Initial depth of secondary zone, average............................ft..	42
Initial water content, average..............................wt pct..	67.8
Initial density, average lb/ft^3..............................lb/ft^3..	74.4
Water to be removed...gal..	197,094,500
Final water content, average................................wt pct..	61.8
Final density...lb/ft^3..	77.2
Final depth of secondary zone, average............................ft..	34.1
Volume reduction (77 acres)(42 ft-34.1 ft)...................acre-feet..	608

Storage Space Available After Completion of Treatment

	Acre-feet
New volume between electrodes in primary zone	543
New volume beneath the anode in primary zone	82
New volume in secondary zone	608
Additional space from existing level to full capacity (elevation 384 to 391 ft)	770
Total available space after treatment	2,003

According to plant records, sludge accumulates at the rate of 2.5 acre-feet per day. Therefore, the 2,003 acre-feet calculated to be available after treatment provides storage for only 2 yr and 71 days--735 acre-feet short of the 3-yr goal.

It is possible that the estimate of the required storage space, 2.5 acre-feet per day, is too high, because the estimated existing deposit of 6,000 acre-feet, which has accumulated over about 10 yr of operation, presents a calculated rate which is lower than 2.5 acre-feet per day. Nevertheless, this figure can be used to calculate the minimum amount of available storage space at the conclusion of treatment. This is summarized as follows:

1. After treatment, a minimum of about 2,003 acre-feet of space will certainly be available. based on a waste accumulation rate of 2.5 acre-feet per day, this would accommodate the wastes generated in 2.2 yr of plant operation.
2. It is probable that treatment will generate up to 62 acre-feet of additional space. This estimate is based on the assumption that greater dewatering will occur in the secondary zone than was assumed in the calculations. With this additional space, treatment would yield sufficient space to accommodate the wastes from 2.26 yr of plant operation.
3. Available storage capacity, in terms of years of plant operation, may be significantly greater than that calculated because the assumed waste accumulation rate of 2.5 acre-feet per day may be larger than the actual rate.

The water clarification rate with a 6- to 7-mA/ft^2 current density applied to WIDCO sludge achieves a high of more than 1 gal/(A·h) shortly after treatment begins and continues at this rate through 60 to 65 pct of the entire treatment time. It then begins to decline slowly, reaching a very low value near the final stage. For this project, the average rate for the entire treatment period is estimated at 0.75 gal/(A·h) of applied current. These values assume that the surface water is essentially clear before it is decanted. For this operation, however, surface water is routed to the plant for reuse; therefore, total clarification is not required or economically justified. In the interest of being conservative, this design will use the rate of 0.75 gal/A·h), although the actual rate may be significantly greater.

Thus, with an applied constant current of 8,886 A (equivalent), surface water develops in the primary zone at a maximum rate of 8,886 gal/h and averages 6,665 gal/h.

Total water extraction from the secondary 77-acre zone, as derived earlier, amounts to over 197 million gal after 3.6 yr of treatment. For want of better evidence, this production rate is assumed to be constant throughout the treatment time, at 6,338 gal/h. With these assumptions, the total maximum rate for surface water development is placed at 15,224 gal/h, and the average is 13,003 gal/h. The decant lines must be sufficiently large to remove this accumulation as well as additional water from rainfall that occurs frequently at the project site.

The decant system includes two 8-in pipes with a combined discharge capacity of 37,500 gal/h--240 pct greater than the maximum predicted rate. The excess capacity may be required for periods of heavy rain and to provide some flexibility in decanting operations.

The selected operating current of 8,886 A amounts to a reduction of 4.9 pct from the initially assumed level of 9,343 A and its corresponding dewatering period of 3.44 yr. The reduced operating current increases treatment time to 3.6 yr. Average current density for 8,886 A is 6.18 mA/ft^2. Final design should test the practicality of increasing density to at least 6.5 mA/ft^2.

Power Consumption

The rate of power consumption is dependent upon (1) electrical resistance of the electrodes and the distribution system and (2) amperage and pattern of current flow (i.e., pulsating versus constant) and is given by the following equation: power = I^2R. For this design, computer programs were used to calculate resistances for the electrode array and the distribution system in each zone.

However, electrode resistance changes during operation. Resistance between the electrodes and the sludge decreases soon after treatment begins. This is caused by the I^2R heating effect that occurs across the electrode-to-sludge interface; i.e., sludge resistivity decreases with temperature rise. This temperature rise is most pronounced in the thin skin (and successive thin layer) immediately next to the metal electrode. Even though the layer may be relatively thin, the total "electrode-to-earth" resistance is significantly reduced because much of the resistance of an earth electrode is concentrated immediately adjacent to the electrode.

The power dissipation of 150 to 175 W at each individual anode and cathode will cause some increase in temperature. The amount of increase with distance from the electrodes cannot be easily calculated or measured. Its effect, however, could be easily determined by a field test with a pair of electrodes installed in the WIDCO pond. Circuit resistance would be monitored for a period of time while applying 6 A of current, i.e., 0.0064 A × 1,050 ft^2. This would quantify the relationship between resistance and elapsed time after initiation of treatment. Sometimes, electrode resistance will decrease by a factor of 3 within a few days, depending upon the size of the anode and the current. Field test data are not available, so the results of a somewhat similar laboratory test will be used as a guide. Sprute and Kelsh (3, table 3) showed that after 200 h of treatment, resistance had decreased by a factor of 2.1. The dimensions of the test cell were 48 by 10 by 10 in. Current density at the cathode was 0.004 A/in^2, compared with 0.0094 A/in^2 for the cathode selected for use in the pond. The anode current in the model was 0.0012 A/in^2 of surface, as compared to 0.0017 in the pond system. Thus, for both the test cell and the pond, current density at the sludge-iron interface is similar, although it is somewhat greater in the pond electrodes. Both heating and the consequent decrease in resistance should also be somewhat greater in the proposed operational system. Normally in the sludge dewatering cycle, resistance decreases with elapsed treatment time and then increases abruptly near the end of the process. The latter effect has not been a significant factor in dewatering WIDCO sludge. Therefore, in the following power consumption calculations, the resistance factor is incorporated as follows:

1. For the first 10 days, resistance of electrodes is assumed to be as shown in table A-6.
2. For the remainder of the treatment period, electrode resistance is assumed to be the values shown in table A-6 reduced by a factor of 2.

Power consumption and cost per zone are shown in table A-9.

The calculated value for the total power consumed by the distribution system and the electrodes equals 10,091,376 kW·h. According to a leading rectifier manufacturer, rectifier efficiency is equal to 90 pct. Therefore, the calculated total power requirement for the expected project life of 3.6 yrs is 11,212,640 kW·h, for a cost of $313,954.

COST ESTIMATE

Table A-10 is a summary of a detailed project cost estimate (not included in this report). The costs of equipment and materials are based on 1985 quotations from manufacturers and suppliers; labor costs are based on an engineering estimate for required installation times. Installation costs are based on the use of skilled workers (25 pct) and ordinary labor (75 pct).

TABLE A-9. - Power consumption and cost

Item	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Power consumption, kW•h:						
Electrodes[1]..........	1,097,101	1,150,005	1,097,388	1,029,939	1,018,201	1,208,171
Distribution system...	229,651	515,749	739,637	715,925	640,578	649,031
Total..............	1,326,751	1,665,754	1,837,025	1,745,864	1,658,779	1,857,202
Cost for power consumption at $0.028/kW•h....	$37,149	$46,641	$51,437	$48,884	$46,446	$52,002

[1]Power consumption at the electrodes is based on the 2-layer earth resistance values shown in table A-6.

TABLE A-10. - Project cost estimate

Item	Labor	Material	Item total
Substation, 800 kV•A, and the 4-kV primary line.......	$15,000	$30,000	$45,000
Rectifier, 715 kW, furnish and install................	6,000	46,000	52,000
Dock system: Includes 43 units, 12 by 12 ft each, with catwalks, hardware to mount bus, anchors, and guys..	80,900	140,500	221,400
DC distribution system: Includes phase and neutral bus lines, laterals across treatment zones, electrical connections to aluminum bus and electrodes, guys from lateral ends to shore, and connections to electrodes..	89,335	198,885	288,220
Anode system: 4,548 iron anodes using 313 st of scrap iron..	38,400	85,000	123,400
Cathode system: 1,135 floating grids.................	27,500	20,400	47,900
Decant line: 2 8-in polyvinyl chloride lines with foot valves, fill standpipe, intake screen, discharge valves..	4,000	11,000	15,000
Subtotal (labor and material)....................	261,135	531,785	792,920
Engineering cost to finalize design..................			30,000
Contingencies to missions at 10 pct..................			79,292
Subtotal...			902,212
Profit (10 pct)......................................			90,221
Total installation cost..........................			992,433
Electric power cost for 3.6 yr of operation...........			313,954
Maintenance: Includes testing sampling, and decanting (estimated at an average of $40,000/yr..............			144,000
Total estimated cost for project[1]................			1,450,387

[1]Salvage and removal not included (salvage assumed equal to removal costs).

APPENDIX B.--COMPUTER PROGRAM FOR CALCULATING NEUTRAL BUS CURRENT

```
C
C  THIS PROGRAM CALCULATES THE RMS FOR ALTERNATING CURRENT
C  WITH AMPLITUDE TRUNCATION OPTION
C
C  AMPL     AMPLITUDE OF SIN FUNCTION
C    EN     NUMBER OF DATA POINTS THAT ARE USED TO AVERAGE
C  PERC     PERCENT OF AMPLITUDE TO TRUNCATE WAVES (DECIMAL)
C TRUNC     TRUNCATED AMPLITUDES
C
      DIMENSION AMPL(6),EN(6),TRUNC(6)
      DATA PI/3.14159265/
      DATA EN/181,301,361,361,361,361/
      DATA AMPL/6*0.0/
C
C  INPUT PERCENT OF AMPLITUDE OF WAVE TO TRUNCATE (DECIMAL)
C
      WRITE(6,450)
  450 FORMAT(' INPUT PERCENT OF AMPLITUDE TO TRUNCATE WAVES (DECIMAL)')
      READ(5,/) PERC
C
C  INPUT AMPLITUDE OF WAVES
C
      WRITE(6,500)
  500 FORMAT(' INPUT NUMBER OF WAVES')
      READ(5,/) NP
      DO 530 I=1,NP
      WRITE(6,510) I
  510 FORMAT(' INPUT AMPLITUDE OF WAVE NUMBER',I5)
      READ(5,/) AMPL(I)
C
C  CALCULATE PERCENTAGE OF AMPLITUDE
C
      TRUNC(I) = PERC * AMPL(I)
  530 CONTINUE
C
C  CONVERT 120 DEGREES AND 240 DEGREES TO RADIANS
C
      R120 = 120. * PI/180.
      R240= 2*R120.
C
C  CALCULATE FUNCTION VALUE, SQUARE, AND SUM
C
C
C  SET CUMULATIVE SUM TO ZERO
C
      SUM = 0.0
       DO 1000 I=0,360,1
C
C  CONVERT I DEGREES TO RADIANS
C
```

```
      RAD = I * PI /180.
      P1 = AMPL(1)*SIN(RAD)
C
C  SET P1, P2, AND P3 TO ZERO IF NEGATIVE
C
      IF(P1 .LT. 0.) P1 = 0.0
      P2 = AMPL(2) * SIN(RAD-R120)
      IF(P2 .LT. 0.) P2 = 0.0
      P3 = AMPL(3) * SIN(RAD-R240)
      IF(P3 .LT. 0.) P3 = 0.0
      P4 = AMPL(4) * SIN(RAD-R240)
C
C  SET P4, P5, AND P6 TO ZERO IF POSITIVE
C
      IF(P4 .GT. 0.0) P4 = 0.0
      P5 = AMPL(5) * SIN(RAD-R120)
      IF(P5 .GT. 0.) P5 = 0.0
      P6 = AMPL(6) * SIN(RAD)
      IF(P6 .GT. 0.) P6 = 0.0
C
C  CHECK IF FUNCTION VALUE EXCEEDS TRUNCATED VALUE
C
      IF(P1 .GT. TRUNC(1)) P1 = TRUNC(1)
      IF(P2 .GT. TRUNC(2)) P2 = TRUNC(2)
      IF(P3 .GT. TRUNC(3)) P3 = TRUNC(3)
      IF(ABS(P4) .GT. TRUNC(4)) P4 = -TRUNC(4)
      IF(ABS(P5) .GT. TRUNC(5)) P5 = -TRUNC(5)
      IF(ABS(P6) .GT. TRUNC(6)) P6 = -TRUNC(6)
C
C  SQUARE FUNCTION VALUES AND FORM  SUM
C
      SUM = SUM + (P1+P2+P3+P4+P5+P6)**2.
 1000 CONTINUE
C
C  CALCULATE AVERAGE OF SUM AND TAKE SQUARE ROOT
C
      AVET = SQRT(SUM/EN(NP))
      WRITE(6,1050) AVET
 1050 FORMAT(' AVERAGE VALUE = ', F10.0)
      END
```

APPENDIX C.--RMS FOR ALTERNATING CURRENT

```
C  THIS PROGRAM CALCULATES THE RMS FOR ALTERNATING CURRENT
C
C  AMPL     AMPLITUDE OF SIN FUNCTION
C    EN     NUMBER OF DATA POINTS THAT ARE USED TO AVERAGE
      DIMENSION AMPL(6),EN(6)
      DATA PI/3.14159265/
      DATA EN/181,301,361,361,361,361/
      DATA AMPL/6*0.0/
C
C  INPUT AMPLITUDE OF WAVES
C
      WRITE(6,500)
  500 FORMAT(' INPUT NUMBER OF WAVES')
      READ(5,/) NP
      DO 530 I=1,NP
      WRITE(6,510) I
  510 FORMAT(' INPUT AMPLITUDE OF WAVE NUMBER',I5)
      READ(5,/) AMPL(I)
  530 CONTINUE
C
C  CONVERT 120 DEGREES AND 240 DEGREES TO RADIANS
C
      R120 = 120. * PI/180.
      R240= 2*R120.
C
C  CALCULATE FUNCTION VALUE, SQUARE, AND SUM
C
C
C  SET CUMULATIVE SUM TO ZERO
C
      SUM = 0.0
      DO 1000 I=0,360,1
C
C  CONVERT I DEGREES TO RADIANS
C
      RAD = I * PI /180.
      P1 = AMPL(1)*SIN(RAD)
C
C  SET P1, P2, AND P3 TO ZERO IF NEGATIVE
C
      IF(P1 .LT. 0.) P1 = 0.0
      P2 = AMPL(2) * SIN(RAD-R120)
      IF(P2 .LT. 0.) P2 = 0.0
      P3 = AMPL(3) * SIN(RAD-R240)
      IF(P3 .LT. 0.) P3 = 0.0
      P4 = AMPL(4) * SIN(RAD-R240)
C
C  SET P4, P5, AND P6 TO ZERO IF POSITIVE
C
      IF(P4 .GT. 0.0) P4 = 0.0
```

```
           P5 = AMPL(5) * SIN(RAD-R120)
           IF(P5 .GT. 0.) P5 = 0.0
           P6 = AMPL(6) * SIN(RAD)
           IF(P6 .GT. 0.) P6 = 0.0
      C
      C  SQUARE FUNCTION VALUES AND FORM  SUM
      C
           SUM = SUM + (P1+P2+P3+P4+P5+P6)**2.
       1000 CONTINUE
      C
      C  CALCULATE AVERAGE OF SUM AND TAKE SQUARE ROOT
      C
           AVET = SQRT(SUM/EN(NP))
           WRITE(6,1050) AVET
       1050 FORMAT(' AVERAGE VALUE = ', F10.0)
           END
```

APPENDIX D.--PROGRAM TO CALCULATE MUTUAL RESISTANCE, ANODE TO CATHODE, USING RESISTANCE EQUATIONS FOR THE PARALLEL CONDUCTOR CASE IN TWO-LAYER EARTH

```
C      PI     CONSTANT(3.14.....)
C      L      CONDUCTOR LENGTH
C      W      PARALLEL ARRAY WIDTH
C      NA     NUMBER OF ANODE CONDUCTORS
C      I      SUBSCRIPT FOR ANODE CONDUCTORS
C      R      SUBSCRIPT FOR CATHODE CONDUCTORS
C      SA     SPACING BETWEEN ANODE CONDUCTORS
C             SA = W/(NA-1)
C      XI     (I-1)*SA
C      XRA    (R-1)*SA
C      ODA    DIAMETER OF ANODE CONDUCTORS
C      DA     DEPTH OF ANODE
C      NC     NUMBER OF CATHODE CONDUCTORS
C      J      SUBSCRIPT FOR CATHODE CONDUCTORS
C      SC     SPACING BETWEEN CATHODE CONDUCTORS
C             SC = W/(NC-1)
C      XJ     (J-1)*SC
C      XRC    (R-1)*SC
C      ODC    DIAMETER OF CATHODE CONDUCTORS
C      DC     DEPTH OF CATHODE
C      P1     AVERAGE RESISTIVITY OF POND
C      P2     AVERAGE RESISTIVITY OF EARTH OUTSIDE POND
C      K      (P2-P1)/(P2+P1) = REFLECTION FACTOR
C      NN      NUMBER OF IMAGES FOR SERIES CONVERGENCE
C      D       DEPTH OF TOP LAYER (AVERAGE DEPTH OF POND)
              REAL K,L
              INTEGER R
C
C             INPUT PARAMETERS
C
              WRITE(7,500)
          500 FORMAT(' INPUT CONDUCTOR LENGTH')
              READ(5,/) L
              WRITE(7,510)
          510 FORMAT(' INPUT PARALLEL ARRAY WIDTH')
              READ(5,/) W
              WRITE(7,520)
          520 FORMAT(' INPUT NUMBER OF ANODE CONDUCTORS')
              READ(5,/) NA
              WRITE(7,540)
          540 FORMAT(' INPUT DIAMETER OF ANODE CONDUCTORS')
              READ(5,/) ODA
              WRITE(7,560)
          560 FORMAT(' INPUT DEPTH OF ANODE')
              READ(5,/) DA
              WRITE(7,580)
          580 FORMAT(' INPUT NUMBER OF CATHODE CONDUCTORS')
              READ(5,/) NC
```

```
      WRITE(7,600)
  600 FORMAT(' INPUT DIAMETER OF CATHODE CONDUCTORS')
      READ(5,/) ODC
      WRITE(7,620)
  620 FORMAT(' INPUT DEPTH OF CATHODE')
      READ(5,/) DC
      WRITE(7,640)
  640 FORMAT(' INPUT AVERAGE RESISTIVITY OF POND')
      READ(5,/) P1
      WRITE(7,660)
  660 FORMAT(' INPUT AVERAGE RESISTIVITY OF EARTH OUTSIDE POND')
      READ(5,/) P2
      WRITE(7,680)
  680 FORMAT(' INPUT  VALUE FOR N')
      READ(5,/) NN
      WRITE(7,700)
  700 FORMAT(' INPUT DEPTH OF TOP LAYER (AVERAGE DEPTH OF POND)')
      READ(5,/) D
      PI = 3.141593
C
C  CALCULATE ANODE AND CATHODE SPACING
C
      SA = W/(NA-1)
      SC = W/(NC -1)
      K = (P2-P1)/(P2+P1)
C
C  CALCULATE ANODE RESISTANCE
C
      CALL RESIST(SA,NA,ODA,DA,D,L,NN,K,P1,RA)
C
C  PRINT ANODE RESISTANCE
C
      WRITE(7,800) RA
  800 FORMAT(' ANODE RESISTANCE = ', F10.7)
C
C  CALCULATE CATHODE RESISTANCE
C
      CALL RESIST(SC,NC,ODC,DC,D,L,NN,K,P1,RC)
C
C  PRINT CATHODE RESISTANCE
C
      WRITE(7,900) RC
  900 FORMAT(' CATHODE RESISTANCE = ', F10.7)
C
C  CALCULATE MUTUAL RESISTANCE - ANODE TO CATHODE FOR CATHODE NEAR
C  THE SURFACE
C
      T1 = P1/(PI*L*NA*NC)
      T5 = 0.0
      DO 4000 J=1,NC
      DO 4000 I=1,NA
      XI = (I-1)*SA
      XJ = (J-1)*SC
```

```
      T2=(L+SQRT((XJ-XI)**2.+L**2.+DA**2.))/SQRT((XJ-XI)**2.+DA**2.)
      T3=SQRT((XJ-XI)**2.+L**2.+DA**2.)/L
      T4=SQRT((XJ-XI)**2.+DA**2.)/L
      T5=T5+ALOG(T2)-T3+T4
 4000 CONTINUE
      T12=0.0
      DO 5000 J=1,NC
      DO 5000 I=1,NA
      DO 5000 N=1,NN
      XI=(I-1)*SA
      XJ=(J-1)*SC
      T6=(L+SQRT((XJ-XI)**2.+L**2.+(2.*N*D+DA)**2.))/
     1 SQRT((XJ-XI)**2.+(2.*N*D+DA)**2.)
      T7=(L+SQRT((XJ-XI)**2.+L**2.+(2.*N*D-DA)**2.))/
     1 SQRT((XJ-XI)**2.+(2.*N*D-DA)**2.)
      T8=SQRT((XJ-XI)**2.+L**2.+(2.*N*D+DA)**2.)/L
      T9=SQRT((XJ-XI)**2.+L**2.+(2.*N*D-DA)**2.)/L
      T10=SQRT((XJ-XI)**2.+(2.*N*D+DA)**2.)/L
      T11=SQRT((XJ-XI)**2.+(2.*N*D-DA)**2.)/L
      T12=T12+(K**N)*(ALOG(T6*T7)-T8-T9+T10+T11)
 5000 CONTINUE
      RM = T1 * (T5 + T12)
C
C  WRITE MUTUAL RESISTANCE
C
      WRITE(7,5500) RM
 5500 FORMAT(' MUTUAL RESISTANCE = ',F10.7)
      RAC = RA + RC -2*RM
      WRITE(7,5600) RAC
 5600 FORMAT(' ANODE TO CATHODE RESISTANCE =',F10.7)
      END
      SUBROUTINE RESIST(SA,NA,ODA,DA,D,L,NN,K,P1,RA)
C
C  SUBROUTINE TO CALCULATE ANODE OR CATHODE RESISTANCE
C
      WRITE(7,/) SA,NA,ODA,DA,D,L,NN,K,P1
      REAL K,L
      INTEGER R
      PI = 3.141592654
      T0=P1/(2.*PI*L*NA*NA)
      T8=0.0
      DO 2000 R=1,NA
      DO 2000 I=1,NA
      XRA = (R-1)*SA
      XI = (I-1) * SA
      T1 = XRA - XI - (ODA/2.)
      T2 = (L+SQRT(T1**2.+L**2.))/SQRT(T1**2.)
      T3 = (L+SQRT(T1**2.+L**2.+4.*DA**2.))/SQRT(T1**2.+4.*DA**2.)
      T4 = SQRT(T1**2.+L**2.)/L
      T5 = SQRT(T1**2.)/L
      T6 = SQRT(T1**2.+L**2.+4.*DA**2.)/L
      T7 = SQRT(T1**2.+4.*DA**2.)/L
      T8 = ALOG(T2*T3)-T4+T5-T6+T7+T8
```

```
 2000 CONTINUE
      T18 = 0.0
      DO 3000 R=1,NA
      DO 3000 I=1,NA
      DO 3000 N=1,NN
      XRA = (R-1)*SA
      XI = (I-1) * SA
      T9=(L+SQRT((XRA-XI)**2.+L**2.+4.*(N*D-DA)**2.))/
     1 SQRT((XRA-XI)**2.+4.*(N*D-DA)**2.)
      T10=((L+SQRT((XRA-XI)**2.+L**2.+4.*(N*D)**2.))/
     1 SQRT((XRA-XI)**2.+4.*(N*D)**2.))**2.
      T11=(L+SQRT((XRA-XI)**2.+L**2.+4.*(N*D+DA)**2.))/
     1 SQRT((XRA-XI)**2.+4.*(N*D+DA)**2.)
      T12=SQRT((XRA-XI)**2.+L**2.+4.*(N*D-DA)**2.)/L
      T13=SQRT((XRA-XI)**2.+4.*(N*D-DA)**2.)/L
      T14=(2.*SQRT((XRA-XI)**2.+L**2.+4.*(N*D)**2.))/L
      T15 = (2.*SQRT((XRA-XI)**2.+4.*(N*D)**2.))/L
      T16=SQRT((XRA-XI)**2.+L**2.+4.*(N*D+DA)**2.)/L
      T17=SQRT((XRA-XI)**2.+4.*(N*D+DA)**2.)/L
      T18 = (K**N)*(ALOG(T9*T10*T11)-T12+T13-T14+T15-T16+T17)+T18
 3000 CONTINUE
      RA = T0*(T8+T18)
 5000 CONTINUE
      RETURN
      END
```

APPENDIX E.--NOMENCLATURE

ac	alternating current
ASCR	aluminum, steel-core-reinforced
AWG	American wire gauge
d	density
dc	direct current
DSA	dimensionally stable anode
E_{AC}	alternating current voltage
E_{DC}	direct current voltage
I	current
I_a	average sinusoidal current
I_A	equivalent average current for continuous pulsing
ID	inside diameter
I_p	peak sinusoidal current
I_{RMS}	root mean square current
I^2R	electrical heating (current squared times resistance)
MCM	1,000 circular mils
OD	outside diameter
puR	per unit earth resistance
R	resistance
RMS	root mean square
RTV	commercial silicon adhesive made by General Electric
THW	type of electrical conductor that is rated for specific applications.

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