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TANK STUDIES OF THE RESISTIVITY HORIZONTAL PROFILING METHOD OF ELECTRICAL PROSPECTING

BY

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A

THESIS

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Approved by

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George B. Clark C. R. Christiansen

ABSTRACT

This research project was undertaken to perfect a technique whereby theoretical horizontal resistivity profiles could be reproduced in laboratory tank studies.

Several specimen materials were tried and finally an acceptable specimen material was found. It was found that carbon specimens suspended in salt water would give horizontal resistivity profiles that agree to a remarkable degree with the theoretically predicted curves.

The investigations showed that the depth of burial of the specimen has a marked influence on the position of the characteristic edge effects and on the magnitude of the apparent resistivity.

The studies also indicated that successful tank studies could be carried out using sand as the enclosing media, rather than a salt water media, but with a loss of some of the homogeneity.

PREFACE

The author wishes to express his sincere appreciation to Mr. R. A. Black, previously Associate Professor of Mining Engineering at this institution, and presently with the U.S.G.S., for his help in the selection of this thesis subject, and also for his help and guidance during the early stages of these investigations. Thanks are also due Dr. H. M. Zenor, for his guidance and constructive criticism during the latter part of these investigations.

He is also indebted to Dr. George B. Clark, Chairman of the Mining Department, for making available the equipment used and the purchase of sand used in the investigations, and also for the use of the machine shop. Thanks are due the personnel of the Mining Department machine shop for their help in preparation of specimens and repair of equipment.

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I. INTRODUCTION

Much of the interpretation of electrical resistivity surveys is carried out by comparing theoretical characteristic curves with those obtained in the field.

The horizontal profiling technique is well suited for many of the relatively shallow investigations carried out in mining problems, such as locating the lateral changes in resistivity that are often associated with ore bodies, sinks, and buried channels.

When the Lee partitioning and Wenner electrode configurations are employed the horizontal profiling technique involves keeping the electrode spacing constant and moving the entire configuration at given intervals along a line.

Unfortunately there is very little published data available on interpretation of horizontal resistivity profiles. There has been practically no mathematical analysis of this type problem because the mathematical treatment is extremely complicated and laborious for the most simple geologic structures and probably impossible for the more complicated structures. It is therefore obviously advantageous to be able to use tank studies to produce characteristic curves.

In the tank studies recorded in the literature, most of the investigators obtained results that deviated considerably from the theoretical. The results of tank studies conducted on this campus also deviated from the predicted curves. The need to perfect a better technique for conducting tank studies is therefore obvious.

The investigations were started by studying an aluminum specimen suspended in salt water. This specimen and the enclosing media had been used in earlier studies on this campus and found to give poor results.

After studies of this specimen were made and it had not been determined conclusively why poor results were obtained, a search for a better specimen material was made.

Carbon specimens were found to be very satisfactory and they gave horizontal resistivity profiles that agree with the theoretical. These profiles along with profiles showing the influence of depth of burial are presented in Section VI of this report.

The possibility of suspending the specimens in a sand media was also investigated and the advantages and disadvantages of this media as compared to a fluid media are discussed in Section VII.

Although most of the tests were made using models more conductive than the enclosing media, a few tests were made using specimens more resistive than the enclosing media, and the results of these investigations appear in Section VII.

II. GENERAL LITERATURE REVIEW

Probably the most extensive mathematical treatment dealing with horizontal profiling, that has been published, is that of Cook and Van Nostrand (1954). They have published a paper giving mathematical solutions for the characteristic curves to be expected for horizontal resistivity profiles over hemispherical sink and vertical dike structures. They also show a field curve for a sink structure that closely approaches the mathematically predicted curve. Details of some of their work are presented in Section IV of this report.

Tagg (1934) has also done some work on interpretation of horizontal resistivity data, principally with fault interfaces.

Swartz, (1931) in 1929 conducted model experiments in an open pit filled with sand and clay layered beds. His work was with vertical profiles and it yielded interesting results as to depth determination and electrode configurations. Among other things his work indicated that the Lee partitioning configuration gave more easily interpreted data than did the Wenner configuration.

In 1934, Hubbert (1934) presented a paper at the annual AIME conference in which he compared the results of field work over a known fault with a model study he made using a vertical piece of sheet metal in a tank of water. The same type anomaly was observed in both cases; the resistivity curve was in the shape of a W over the fault and over the sheet metal, and it had an extremely high peak at the center of the W. These results apparently did not agree with those reported by Low, Kelly, and Creagmile (1932). In the experiments recorded by these authors, a distinct drop was observed in the resistivity profiles when a conductive body was placed between the potential electrodes. It should be noted, however, that the conductive body in their experiments occupied a considerable portion of the volume between the electrodes, whereas in Hubbert's experiments the conductive sheet was extremely thin. In a discussion of Hubbert's paper Theodor Zuschlag stated that he had obtained results which checked with the foregoing. He found that a thick conductive sheet between the potential electrodes produced a drop in the resistivity curve, which became less pronounced as the sheet was made progressively thinner, and finally passed over a peak.

L. G. Howell, in a discussion of Hubbert's paper, stated that in tests made in wooden tub it was found that sheet metal with an uncleaned surface or grease film produced very high resistivity peaks over the sheet. A cleaned copper sheet showed a smoother rounded curve over the metal sheet.

Jakosky (1957, p. 513) stated that model experiments may produce considerable information that will be indicative of the results to be expected in field work. He also warned that the tank experiments usually do not yield the same curve characteristics obtained in the field. He indicated that this may be due to the absence of polarization and related phenomena at the interface of strata in the small scale tests.

Manhart (1937) conducted model studies at the Colorado School of Mines. The purpose of his studies was to provide a means of interpretating resistivity depth curves using models in a tank, and also to check by experiment, the theory of interpretation of resistivity curves which had been developed by Hummel (1932). These studies were with the vertical profiling technique.

Pritchett (1955) did some model studies but the results of his work seem to be inconclusive. He mentions that a surface made with the Wenner configuration over a model of a salt dome showed only a minor anomaly.

Model experiments were used by Sumi (1956) to check the results of theoretical and field curves of a horizontal resistivity profile across an inclined thin bed. He stated that there was good agreement between the results of the model runs and the theoretical and field curves.

The effect of tank wall material was investigated by Goudswaard (1937) and he found that by trial and error, the walls of the tank could be compensated to give a larger usable surface area for model experiments. He also found that the resistivity of the solution used had little influence on the amount of usable surface area available.

Kwentus (1960) obtained results from his model studies that greatly deviated from the mathematical curves. Although the curves obtained were somewhat similar in shape to the theoretical curves, they gave values that appear to be much too great over the center of conductive bodies, and the peaks on the curves were not at the expected distances from the model. He states that the departure from expected results may have been due to electrochemical reactions.

White (1957) conducted model studies using gelatin models. Although his work was in simulating borehole surveys using the wedge model method, his results appear to agree with theoretical results, but due to insufficient information it was not possible to determine how well his results duplicated theoretical results. The big drawback to gelatin models is the difficulty of handling, and the short usable life due to decay of the gelatin.

III. EQUIPMENT AND PROCEDURES

A. Equipment

1. Tank. The tank in which the model studies were conducted was made of concrete, and was the same tank used by Kwentus (1960) in his investigations. The walls of the tank were four inches thick and the bottom of the tank was six inches thick. The walls and bottom of the tank were reinforced with three-sixteenths inch wire mesh. Drain pipes, one inch in diameter, were located at the bottom of the tank at each of the four corners. They protruded through the ends of the tank and were parallel to the long axis of the tank. The tank was waterproofed with three coats of Pittsburgh Plate Glass Company masonry water repellent.

The tank was rectangular in cross-section and the inside dimensions of the tank were approximately three feet wide, six feet long, and two feet deep. The tank was supported on six, eight inch diameter steel pipe legs with one-eighth inch thick bearing plates welded on each end of the legs.

The support for the electrode holder was a one and one-half inch angle that spanned the tank parallel to the long axis. This angle could be moved along the edge of the tank so that profiles could be made along any desired line. The angle sat on two other angle supports fastened rigidly to the two short ends of the tank. Two yard sticks were clamped to the steel angle to serve as a position reference for the electrode configuration. The yard sticks were mounted so that they could be shifted to either side of center, and centered over the center of the specimen being studied. The positions recorded would then be distances to either side of the center of the specimen.

2. Electrodes. During most of the investigations ordinary pencils were employed as electrodes. Micro-projector electrodes were used in a few runs but their big disadvantage was that it was very difficult to get a sharp point on them, because of the hard porous core that breaks easily when they are sharpened. A sharp point was desired to serve as a point source.

In this respect the pencil electrodes were superior in that they were easily sharpened to a very sharp point. The top end of the pencils was bared so that good electrical contact could be made with the alligator clips from the connecting cable. The biggest disadvantage of the pencils was that the tops of the pencils would break off very easily where the alligator clips were connected. This problem was not important with the Micro-projector electrodes, but they were very prone to breaking if dropped or bumped very hard. All things considered the pencils proved to be the best electrodes.

This type electrode was used because the graphite or carbon will tend to reduce the amount of electrolysis. When metal electrodes are used the polarization is a much greater problem.

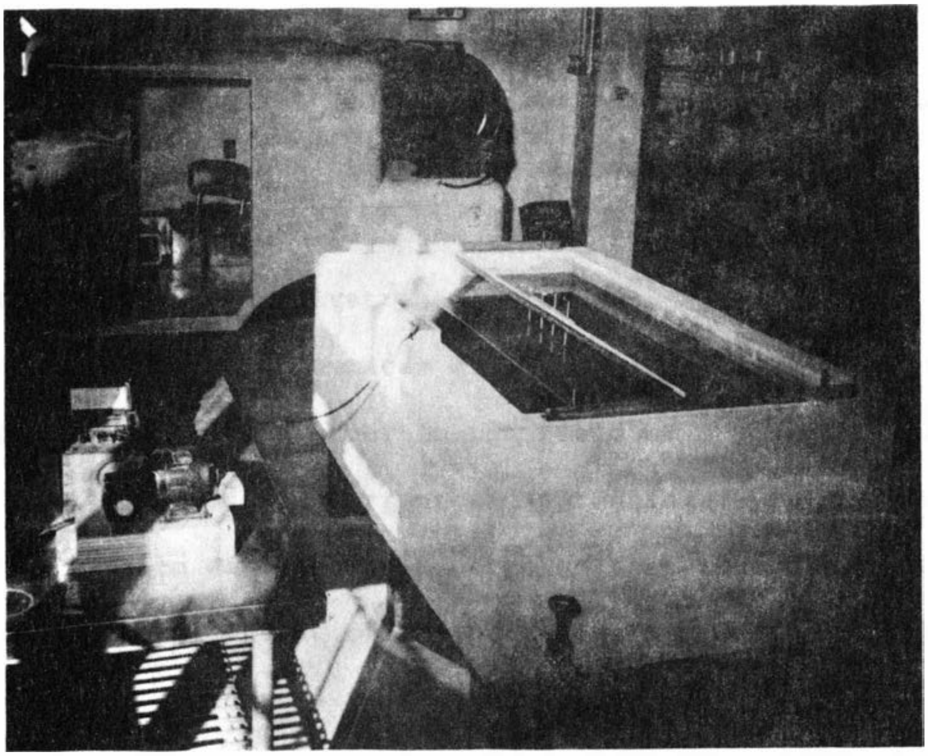
Nonpolarizing electrodes were necessary for the self potential surveys that were made. These nonpolarizing electrodes were made of glass tubing about six inches long and drawn down to a fine tip on one end. The tip end of the electrode was tamped full of cotton to serve as a porous media. The electrode was then filled with saturated copper sulfate solution and a copper wire was inserted from the larger end into the solution. This wire served as the electrical contact for the alligator clips from the connecting cables. Provided the copper sulfate solution is not contaminated, this type electrode is nonpolarizing.

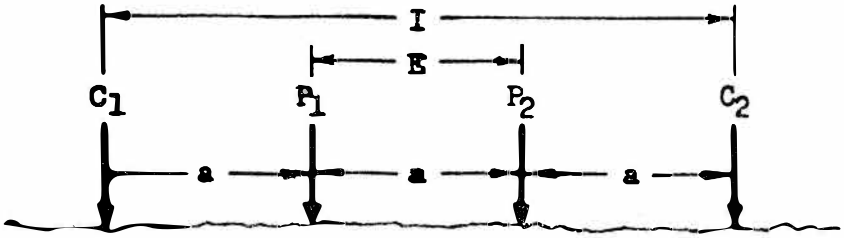
3. Electrode Holders. Wooden electrode holders were made with a slot that just allowed the holder to be placed straddling the horizontal portion of the angle support across the tank. The holders fitted back against the back side of the angle so that they were directly against the positioning scales. The center of the block was marked so that the position of the center of the electrode configuration could be read directly from the scale. These readings could be made directly to the nearest one-eighth inch and estimated to the nearest sixteenth inch if necessary.

The holders overhung the edge of the angle and the electrodes were held in place by vertical holes in the overhanging portion of the block. The holder was free to slide along the angle and thus readings could be taken at any desired position along the traverse.

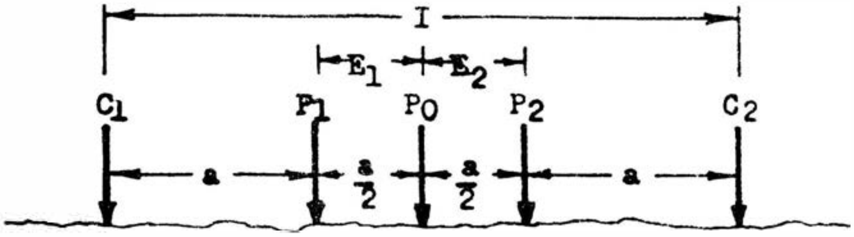
4. Megger Ground Tester. The instrument used in the investigations for measurement of resistivity was the Megger Ground Resistance Tester (No. 715688). The Megger supplies commutated direct current to the ground being tested. The instrument generates its own direct current and also commutates it. Commutated current is used to reduce or eliminate the effect of polarization, electrolysis, and stray currents. These factors would influence the apparent resistivity if direct current were used. The use of direct current also requires the use of nonpolarizing electrodes.

The current supplied by a self-contained direct current generator passes through the current coil of an ohmmeter, and then through a commutator attached to the generator shaft and is changed into commutated current of about fifty cycles per second. This current is then fed to the current electrodes, C_1 and C_2, of the electrode configuration. The





WENNER CONFIGURATION $\rho = 2\pi aE/I$



LEE PARTITIONING CONFIGURATION

$\rho_1 = 4\pi a\ E_1/I \qquad \rho_2 = 4\pi a\ E_2/I$

FIG. 1. TANK AND RESISTIVITY MEASURING APPARATUS SET UP FOR HORIZONTAL PROFILING AND SKETCHES OF THE ELECTRODE CONFIGURATIONS USED IN THE INVESTIGATIONS.

potential difference between two potential electrodes within the configuration, is then fed back through a second commutator, run synchronously with the first, which converts the current back into a unidirectional flow. This current is then fed back to the potential coil of the same ohmmeter that the current first passed through.

The two coils of the ohmmeter are mounted on the same shaft and work in opposition to each other in the field of a permanent magnet. The opposing torques of the current and potential coils automatically perform the division of volts by amperes so that the result is directly proportional to the quotient of the potential divided by the current. The scale is then calibrated to read volts divided by amperes, i.e., ohms, directly. If this value of resistance is then multiplied by the appropriate constant the apparent resistivity is the result. The proportionality constant depends on the geometry and distances of the electrode configuration (Jakosky, 1957, p. 542).

The Megger must be adjusted for each reading taken. This is accomplished by an adjustment that brings the total resistance of the potential circuit, including the resistance of the earth between the potential electrodes, to a predetermined value.

This particular instrument was designed to be hand cranked at about 135 rpm. The frequency of the commutated current is one-half the angular speed (in rpm) at which the instrument is cranked. The voltage across the open potential circuit is of the order of 50 volts and the current is less than 0.5 amp. For these investigations the hand crank was replaced by a 115 volt A.C., 1.8 amp., electric motor that turned the Megger at 86 rpm. This decrease to about two-thirds of the rated speed appears to be justified by the fact that no adverse effects were noted on the results obtained. Apparently the speed isn't too critical especially since the instrument is designed to be hand cranked.

5. Models and Enclosing Media. All of the models used in these investigations were hemispherical in shape. The three and one-half inch diameter aluminum hemisphere, and the three and one-half inch, and five inch diameter carbon hemispheres were all machined in the Mining Department machine shop.

One of the resistive specimens tested was one-half of a solid rubber ball, two and three-quarters of an inch in diameter. The other resistive specimens tested were three and five-eighths inches in diameter and were molded from hydrostone, using one-half of a hollow plastic ball for a mold. One of these hydrostone specimens was then coated with waterproof varnish.

During the investigations the specimens were suspended in an enclosing media that filled the test tank. Most of these investigations were made using salt water as the enclosing media. In this case and throughout the remainder of the report 'salt water' is used to mean a solution of water and sodium chloride. The salt was added to the water to lower the resistivity of the solution to a point where the Megger would operate. Ordinary hydrant water is too resistive for the Megger to operate.

Some of the latter investigations were conducted with the tank filled with sand. When the sand was used it was saturated with salt water and the salt water was filled to a level slightly higher than the sand so that good electrical contact could be made easily.

B. Procedures

1. Configurations. In practice two of the most commonly used electrode configurations are the Wenner and Lee partitioning configurations. The Wenner configuration is a four electrode configuration arranged in a straight line and the electrodes are separated by equal distances known as the 'a' spacing. The current electrodes, C_1 and C_2, are at the two extremes of the configuration and the potential electrodes, P_1 and P_2 are the two inner electrodes. The resistivity of a homogeneous media is then expressed as $\rho = 2\pi a\, E/I$, where 'a' is the electrode spacing, E the potential difference between P_1 and P_2 and I the current between C_1 and C_2. If the media is not homogeneous then this equation gives what is defined as the apparent resistivity.

The Lee partitioning configuration is similar to the Wenner configuration except that an additional potential electrode, P_0, is inserted midway between the potential electrodes, P_1 and P_2. The distance between the potential electrodes is 'a'/2, and the distance from the outer potential electrodes to the current electrodes is still 'a'. In this configuration two values of apparent resistivity are normally recorded. The two current electrodes are first used in conjunction with one of the outer potential electrodes and the center potential electrode, and the apparent resistivity between these electrodes recorded. A second reading is then taken using the two current electrodes in conjunction with the center and the other outer electrode to determine the apparent resistivity between these two potential electrodes.

Since these readings are taken separately it amounts to effectively using two, four electrode configurations in conjunction with each other; where three of the electrodes are common to both configurations. This configuration can give more information than the Wenner configuration and the resistivity in this case is given as $\rho_1 = 4\pi a\ E/I$, and $\rho_2 = 4\pi a\ E/I$, where ρ_1 and ρ_2 are the resistivities between the P_1P_o, and the P_2P_o electrodes respectively, if the media is homogeneous. For nonhomogeneous media these expressions give the apparent resistivity.

2. Vertical and Horizontal Profiling. In vertical resistivity profiling the center of the electrode configuration remains at a fixed point and the electrodes are expanded to different 'a' spacings along a straight line. These values for measurements for a particular location are usually plotted as apparent resistivity vs. the 'a' spacing and they are plotted on log-log graph paper.

In horizontal profiling the 'a' spacing of the configuration remains constant and the entire configuration is moved along the line of the electrodes with readings being made at appropriate intervals. In this case the apparent resistivity is generally plotted vs. the position of the configuration. When the Wenner configuration is used the position at which the apparent resisitivity is plotted is the geometric center of the configuration.

When the Lee partitioning configuration is used the 'offset plotting' technique is generally employed. In this case ρ_1 is plotted vs. the position of the midpoint of the line connecting P_oP_1, and ρ_2 is plotted vs. the position of the midpoint of the line connecting P_oP_2. It should be emphasized that for the Lee configuration the apparent resistivities are not plotted against the station at which they are determined, that is, the position of the center electrode P_o.

The Megger is made with four terminals to be used with a four electrode configuration. In order that the Megger could be used with the Lee configuration as well, the two potential electrode leads from the Megger were run to an external switch and from this switch were run three potential leads. The switch was arranged so that in one position it fed the P_0 and P_1 electrodes back to the Megger. In the other position the switch allowed the P_0 and P_2 electrodes to be fed back to the Megger. With this simple addition the Megger could then be used with the Lee configuration.

3. Model Runs. The actual horizontal profiles were conducted by sliding the electrode holder to the desired position and recording the ratio of E/I, in ohms as measured by the Megger. Readings were taken at close intervals, normally 'a'/2 or less between readings. It was not necessary to stop the Megger between readings provided the electrodes were not lifted out of the water; it was, however, necessary to adjust the Megger before each reading was taken.

The electrodes were normally at about one-eighth of an inch below the surface of the salt water. It was determined by several tests that slight variation in the depth of the electrodes made no noticeable change in the apparent resistivity. If the electrodes were just barely making contact or only poor contact it was observed that the Megger was unsteady and the readings not consistent. Where good electrical contact was made slight variations in depth made no measurable difference, provided the depth wasn't greater than about one-quarter of an inch.

For the studies where the models were suspended in solution, the models were suspended from the sides of the tank using fishing line. In the case of the rubber hemispherical specimen, it was lighter than water and had to be anchored to a small slab of rock placed in the bottom of the tank.

C. Testing of Tank

Although Kwentus (1960) had done some work in testing of the model tank to prove its linearity, this investigator did some additional work along this line. Of primary concern was whether consistent results could be obtained across the tank with only the solution in the tank and no specimen. In other words to what degree do the tank walls and bottom cause the apparent resistivity of the contained media to deviate from acting as an infinite media.

In horizontal profiles made with the Wenner configuration, Kwentus showed that the tank is linear across most of the tank up to very close to the tank walls. He checked this for a one, two, three, and four inch 'a' spacing. This investigator did further studies of this type using the Wenner configuration and the two inch electrode spacing.

The results of these studies are shown in Figure 2. The profile at the top of the page is a horizontal profile made down the center of the tank parallel to the long axis. It showed that the tank was linear out to where the P_o electrode was about ten inches from the end of the tank. In this case the electrode nearest the wall of the tank was about seven inches from the end of the tank before the end of the tank had any marked effect.

In similar profiles made parallel to the long dimension of the tank along profiles to either side of center, the results were consistently linear and of the same magnitude as those at the center, out to a distance of approximately twelve inches, from the center. In other words no change in the apparent resistivity was observed until the electrode configuration was about six inches from the tank walls and parallel to them. Curve b in Figure 2, represents values taken from each of the profiles at a given distance from the end of the tank in each case. These have been plotted as a profile across the tank, but it should be kept in mind that the electrode configuration was actually perpendicular to this profile at each of the recorded points.

On the basis of the foregoing it appears that the tank has a usable area of 52 by 24 inches. The tank wall doesn't appear to have any measurable affect on the apparent resistivity readings until at least one of the electrodes is within six or seven inches of the wall.

On the basis of Goudswaard's (1937) findings it would appear that the usable area would always be very near this amount. He stated that the resistivity of the solution used had little influence on the amount of usable area available.

Of lesser concern is the effect of the bottom of the tank on the tank of the apparent resistivity. Figure 3 represents the work done by Kwentus in this respect. He has shown that the bottom of the tank has little or no affect for electrode spacings up to four to six inches. This is considerably greater than the two inch electrode spacing used in most of the following investigations, it therefore appears that the use of a small electrode spacing of about two inches will not be appreciably effected by the bottom of the tank. Even if the bottom of the tank does give an affect for small electrode spacings, it has been shown that this effect is consistent across the tank and thus of no prime concern in the horizontal profiles. In tests conducted by this investigator similar results were obtained, and the vertical resistivity profile was approximately linear to about the four inch 'a' spacing.

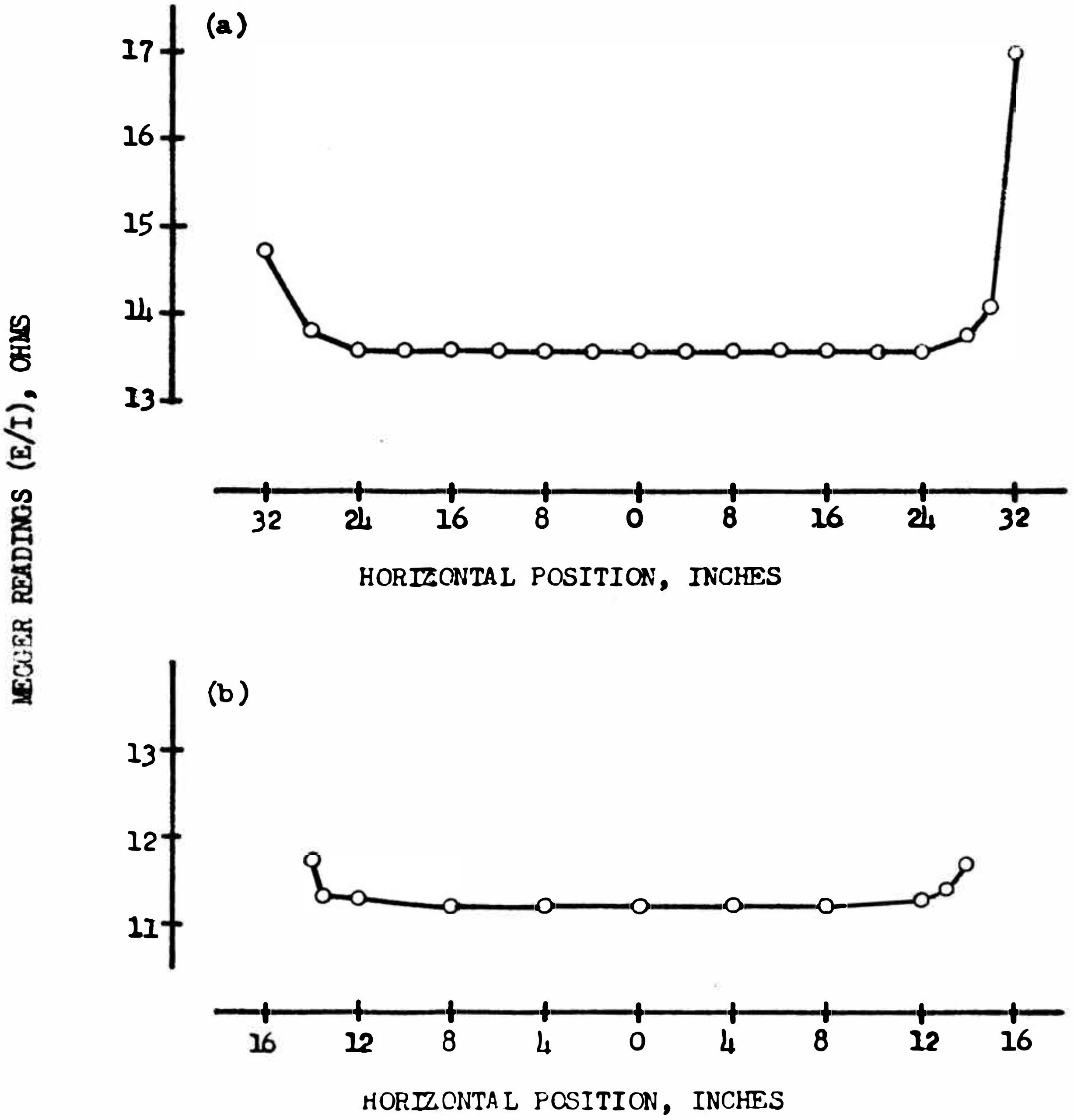


FIG. 2. HORIZONTAL RESISTIVITY TEST PROFILES (a) PARALLEL TO THE LONG AXIS OF THE TANK, (b) PERPENDICULAR TO THE LONG AXIS OF THE TANK. 'a' = 2 INCHES.

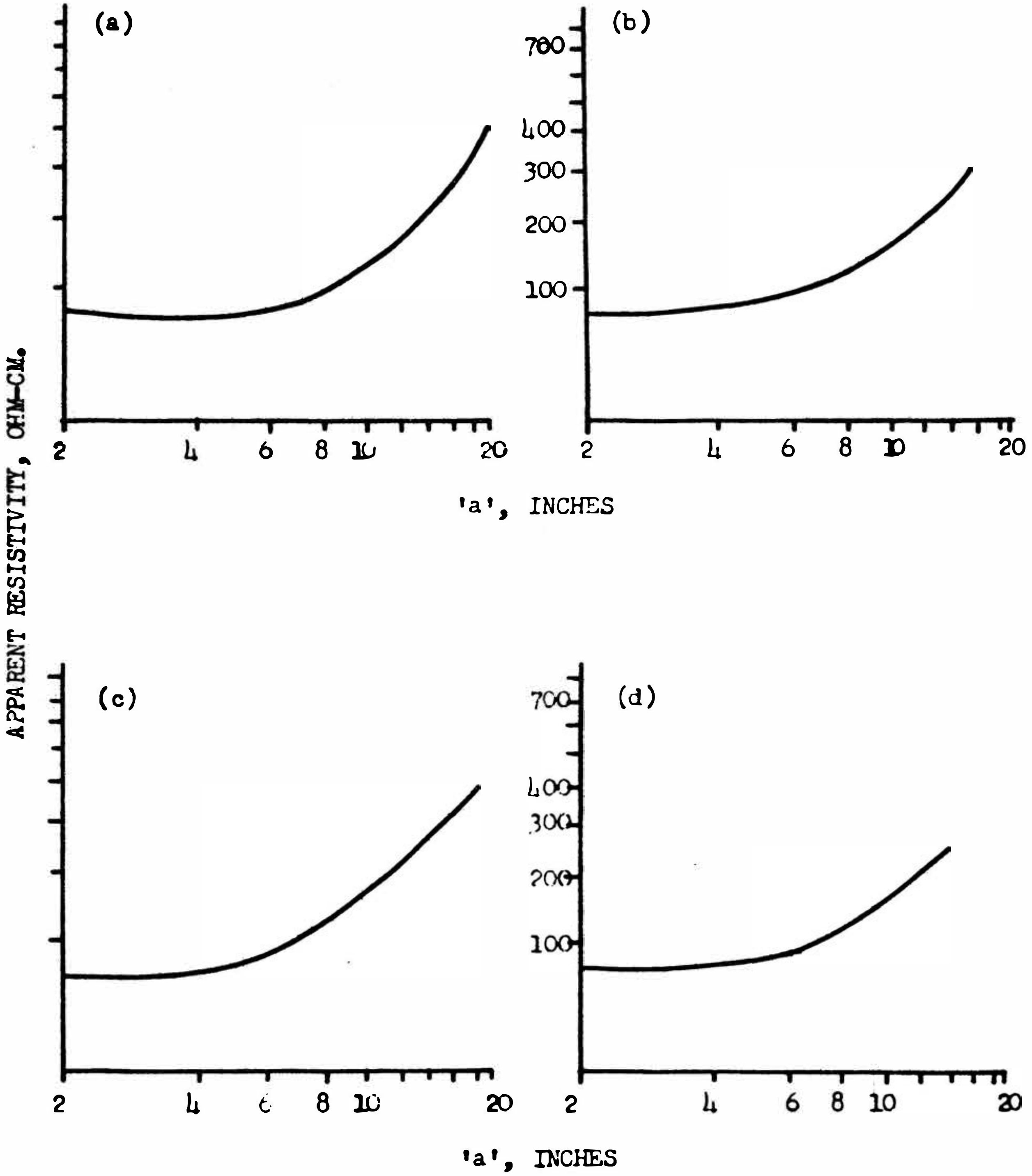


FIG. 3. VERTICAL PROFILES ON CENTER LINE OF THE TANK (a) AT THE CENTER, (b) FOUR INCHES FROM CENTER, (c) FOUR INCHES FROM CENTER ON OPPOSITE SIDE, (d) SIX INCHES FROM CENTER. (AFTER KWENTUS)

IV. DETAILED LITERATURE REVIEW OF THEORETICAL CURVES

A. Wenner Configuration

Before an attempt is made to analyze the data collected from model studies, the author feels that a study of the theoretical curves produced by Cook and Van Nostrand (1954) is in order. The primary object of this research has been to perfect a technique whereby model studies may be made to produce characteristic curves that approximate or duplicate the theoretical curves. All work has been done with hemispherical specimens, therefore the theoretical horizontal resistivity curves over the center of buried hemispherical conductors will be analyzed in detail.

Figure 4 is the theoretical horizontal resistivity profile over the center of a hemispherical sink, using the Wenner electrode configuration. The resistivity contrast (ratio of the resistivity of the hemisphere to the resistivity of the surrounding media) is assumed to be one to five and the diameter of the hemisphere is four times the electrode spacing ('a' spacing). The ordinate of the graph is a plot of the apparent resistivity divided by the actual resistivity of the enclosing media, while the abscissa is plotted as distance from the center of the hemisphere divided by the electrode 'a' spacing. This method of plotting is used so that the units are dimensionless and so that the graphs take on a more general nature.

It should be noted that in this particular case the value of the resistivity drops to an extremely low value over the hemisphere and that the maximum value at any of the peaks never exceeds the value of the resistivity of the surrounding media. Also note that at some distance from the hemisphere the apparent resistivity approaches that of the surrounding media. The peaks A, and B both fall at a distance of one-half 'a' outside the hemisphere, and the peaks C and D fall at a distance of one and one-half 'a' outside the hemisphere. Also note the characteristic curve at the bottom of the trough, over the hemisphere. Points E and F both fall at a distance of one-half 'a' inside the hemisphere, and points G and H fall at a distance of one and one-half 'a' inside the edges of the hemisphere.

Figure 5 represents the same type plot over the same type specimen with all conditions the same as in Figure 4, except that the diameter is now one and one-half the 'a' spacing. Note that the curve still takes the same general shape with a few changes. It is interesting to note that the values of the apparent resistivity have increased and that the maximum value of the apparent resistivity is now greater than the resistivity of the surrounding media. The extreme low or trough over the hemisphere still exists, but its shape over the hemisphere has been somewhat altered. The peaks E and F still fall in at a distance of one-half 'a' from the edge of the hemisphere but the peaks G and H no longer exist. They have been obscured with the use of the larger electrode spacing. If an electrode separation equal to the diameter was used, the points E and F would become coincident at the center of the hemisphere, and for larger electrode configurations they would disappear but the curve would continue to peak at a point directly over the center of the hemisphere. Theodor Zuschlag indicates that as the ratio of 'a' spacing to specimen diameter grows larger, the drop over the hemisphere will become progressively less pronounced and finally pass over into a peak.

Although the curve has undergone some change, the characteristic edge effects are still at a distance from the hemisphere that is only a function of the 'a' spacing. That is, the peaks A and B are still out at a distance of one-half 'a' from the edge of the hemisphere, and the peaks C and D are still at a distance of one and one-half 'a' outside the edge of the hemisphere. This appears to indicate that the positions of the characteristic edge effects are functions of the electrode spacing and independent of the ratio of diameter of the hemisphere to electrode spacing.

It is also logical to conclude that the distance to these characteristic peaks is independent of the resistivity or resistivity contrast when one sees that each of these characteristic peaks occurred when either a current or potential electrode just came in contact with the edge of the hemisphere, either entering or leaving it as the case may be.

B. Lee Configuration

In Figure 6, the same conditions exist that were true for Figure 4. The resistivity contrast is one to five and the diameter of the hemisphere is four times the 'a' spacing. In this case the Lee partitioning configuration, and the offset method of plotting have been used. The solid line represents the apparent resistivity ρ_1 divided by the regional resistivity and the dashed line represents the apparent resistivity ρ_2 divided by the regional resistivity Notice that as in the case of the Wenner configuration, the Lee configuration produces a curve of the same general shape with the large trough at the center of the hemisphere. In the case of the Lee configuration, there are two resistivity curves rather than one and these two curves give a mirror image about the center of the hemisphere except for the fact that they are interchanged.

The peaks A, A', B, and B' all lie outside the edge of the hemisphere at a distance of one-fourth 'a', and the peaks C and D lie out at a distance of one and three-fourths the 'a' spacing. The peaks C' and D' lie one and one-fourth 'a' from the edge of the hemisphere. The characteristic curve at the bottom of the trough is still present for the Lee configuration. The peaks E, E', F, and F' are at a distance of one-fourth 'a' inside the edge of the hemisphere. Peaks G and G' occur at a distance of one and one-quarter 'a', and peaks H and H' are at a distance of one and three-quarters 'a' from the edge of the hemisphere.

The Lee configuration has again been used in calculating the curves in Figure 7. The conditions are the same as in the first three cases except that the Lee configuration has been used and the diameter of the hemisphere has been taken as one and one-half times the 'a' spacing.

The effect of the larger electrode spacing has been to raise the apparent resistivity values and to eliminate the peaks G, G', H, and H'. The points E, E', F, and F' are still present and still fall at a distance of one-fourth 'a' inside the edge of the hemisphere. Peaks A, A', B, and B' again occur at a distance of one-fourth 'a' outside the edges of the hemisphere, peaks C and D at one and three-fourths 'a', and peaks C' and D' at a distance of one and one-fourth 'a' outside the edge of the hemisphere.

C. Comparison of Lee & Wenner Configurations

In the case of the Lee configuration as in the case of the Wenner configuration it appears that the edge effects are a function of the 'a' spacing only, except that the characteristic curve at the bottom of the trough becomes obscured as the electrode configuration is made larger as compared with the diameter. For the Lee configuration, as for the Wenner configuration, the peaks occur when the current or potential electrodes just come in contact with the edge of the hemisphere while entering or leaving it.

Cook and Van Nostrand (1954, p. 772) point out that although the maxima and minima that occur in the bottom of the resistivity trough are of academic interest, they are generally too small to be of practical assistance to the interpreter.

A comparison of Figures 4 and 6, which are for the same conditions except that the Wenner configuration is used in Figure 4 and the Lee configuration is used in Figure 6, will show that the magnitude of the features for the Wenner configuration is damped in comparison with the Lee configuration. Likewise a study of Figures 5 and 7 will verify this finding.

Cook and Van Nostrand (1954, p. 778) state that the additional resolving power of the Lee configuration over the Wenner configuration indicates that for the same number of stations taken along the same horizontal profile, the Lee method can give more detailed information than the Wenner method. They also state that in certain ambiguous cases, this additional information will lead the interpreter to recognize sink features on the Lee profiles that are not recognizable on the Wenner profiles. This conclusion seems to be in accord with other investigators including Swartz (1931).

According to Cook and Van Nostrand (1954, p 788), the Lee profiles are generally well worth the extra time, equipment, and personnel required to obtain them rather than the Wenner profiles They also indicate that for buried sink type problems, the horizontal profiles are generally more useful than vertical profiles. They warn however that it should not be concluded that the Lee horizontal profiles should be used to the complete exclusion of other techniques. In exploration each technique has its rightful place and the most effective resistivity survey is made by combining judiciously the various field techniques

D. Field Curves

Field curves were also run by Cook and Van Nostrand to check the theoretical curves. The surveys were made over a known sink with both the Wenner and Lee configurations, and the results were checked by drilling. The results of these surveys are shown in Figure 8.

Cook and Van Nostrand point out that when the usual irregularities of the field data are discounted, the correlation of the theoretical and the field curves is considered to be excellent.

In analyzing the field curves it must be kept in mind that they are the result of readings taken at some predetermined interval and are not continuous curves as are the theoretical curves.

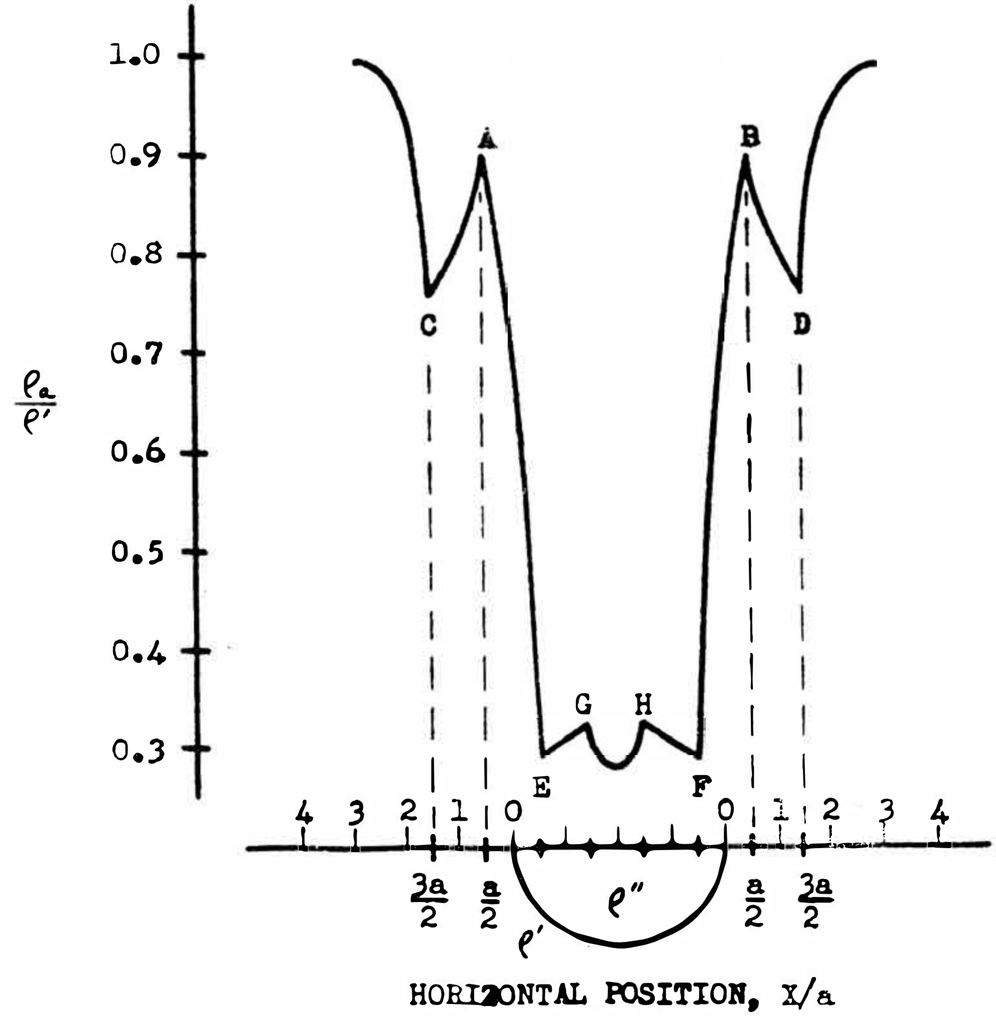


FIG. 4. THEORETICAL HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A HEMISPHERICAL SINK, WENNER CONFIGURATION. DIAMETER OF HEMISPHERE = 4 'a', DEPTH OF BURIAL = 0, ρ''/ρ' = 1/5. (AFTER COOK)

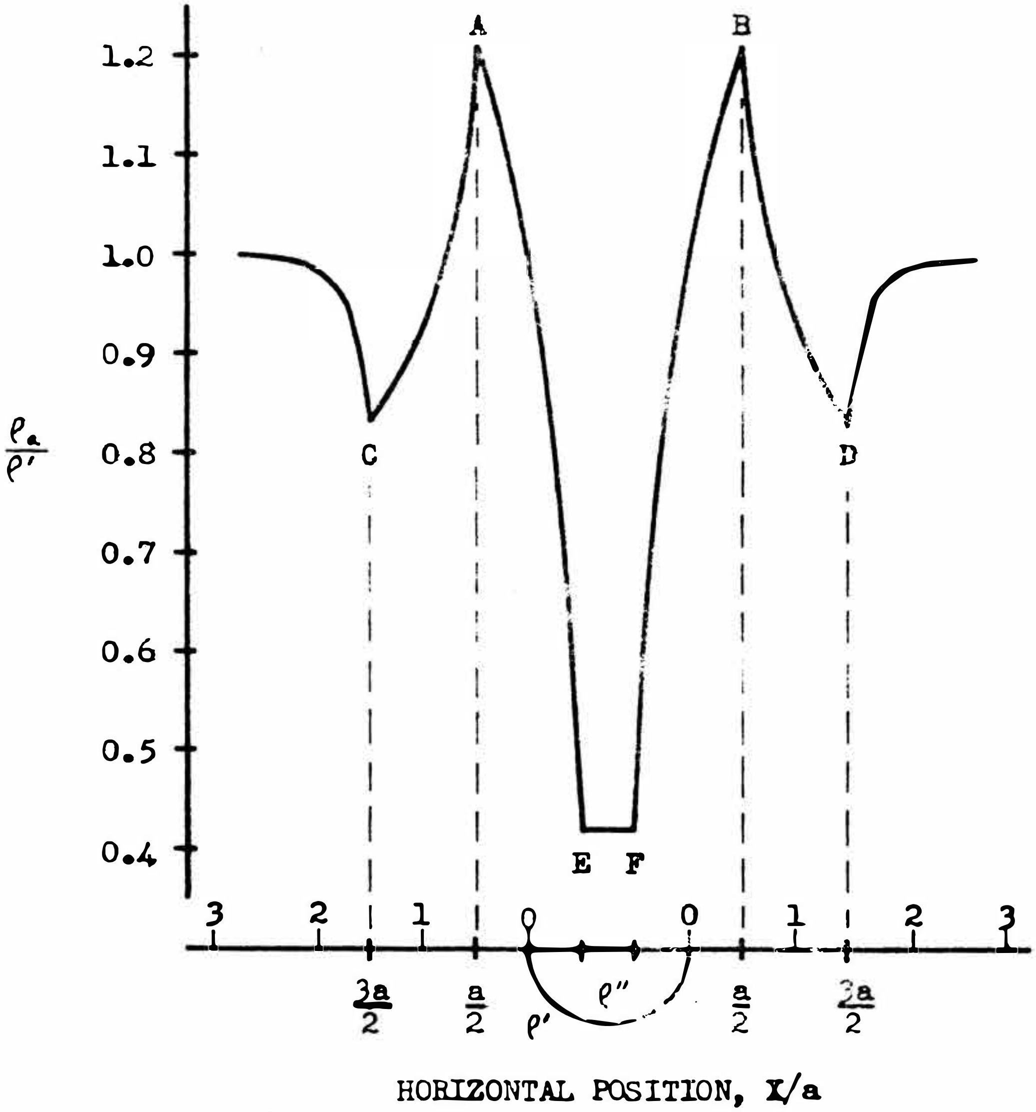


FIG. 5. THEORETICAL HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A HEMISPHERICAL SINK, WENNER CONFIGURATION. DIAMETER OF HEMISPHERE = 3/2 'a', DEPTH OF BURIAL = 0, $\rho''/\rho' = 1/5$. (AFTER COOK)

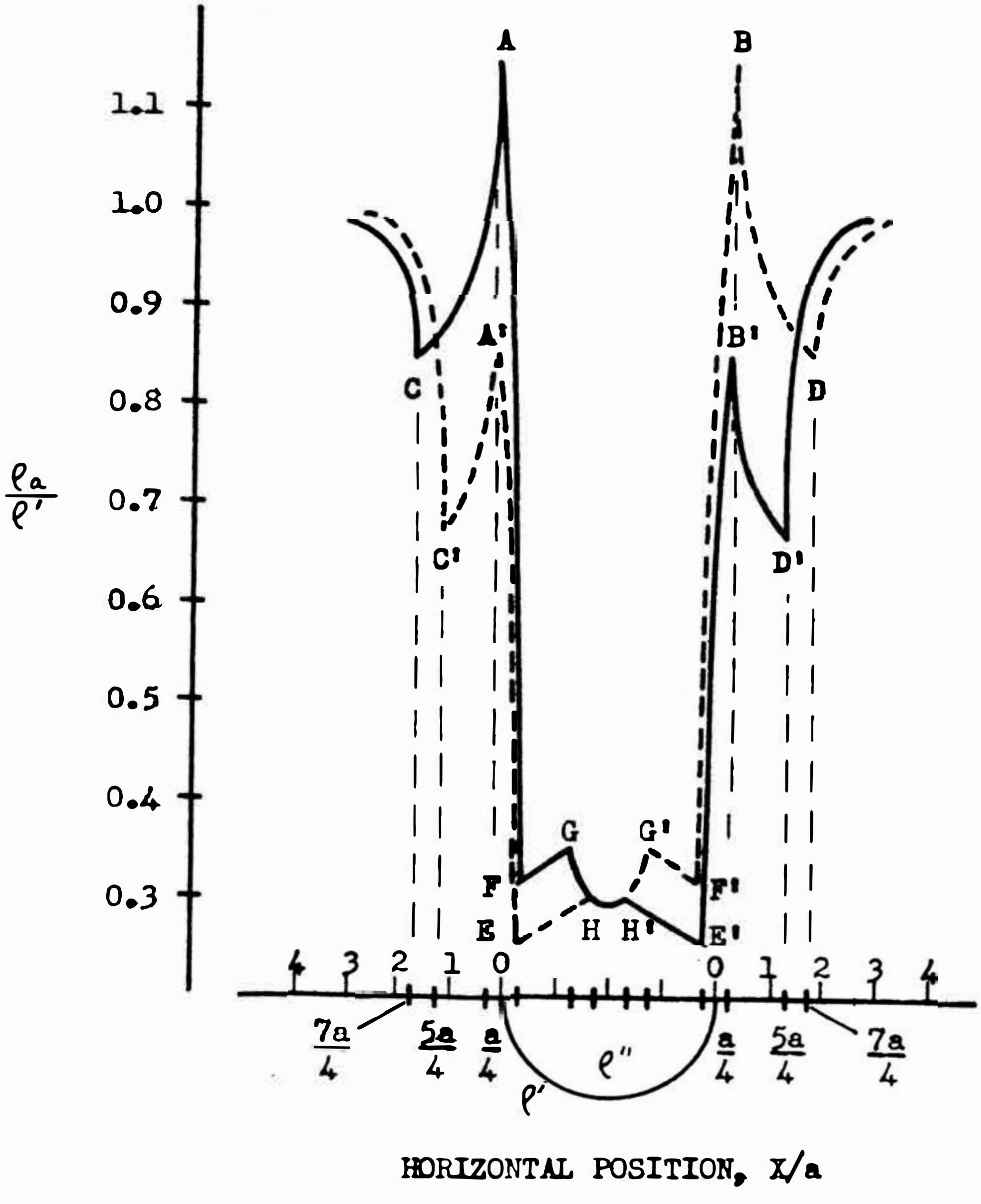


FIG. 6. THEORETICAL HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A HEMISPHERICAL SINK, LEE CONFIGURATION. DIAMETER OF HEMISPHERE = 4 'a', DEPTH OF BURIAL = 0, $\rho''/\rho' = 1/5$. (AFTER COOK)

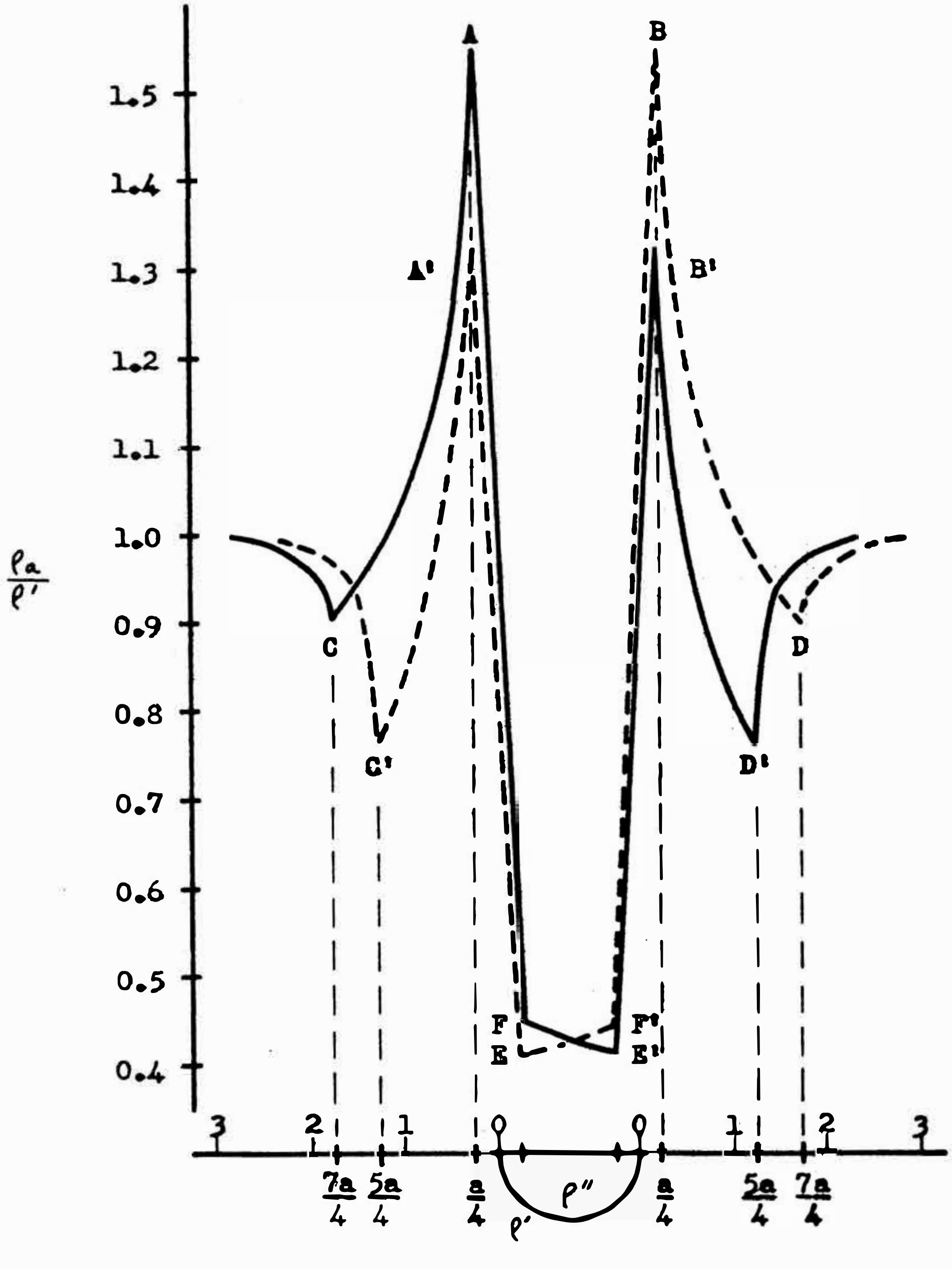


FIG. 7. THEORETICAL HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A HEMISPHERICAL SINK, LEE CONFIGURATION. DIAMETER OF HEMISPHERE = 3/2 'a', DEPTH OF BURIAL = 0, $\rho''/\rho' = 1/5$. (AFTER COOK)

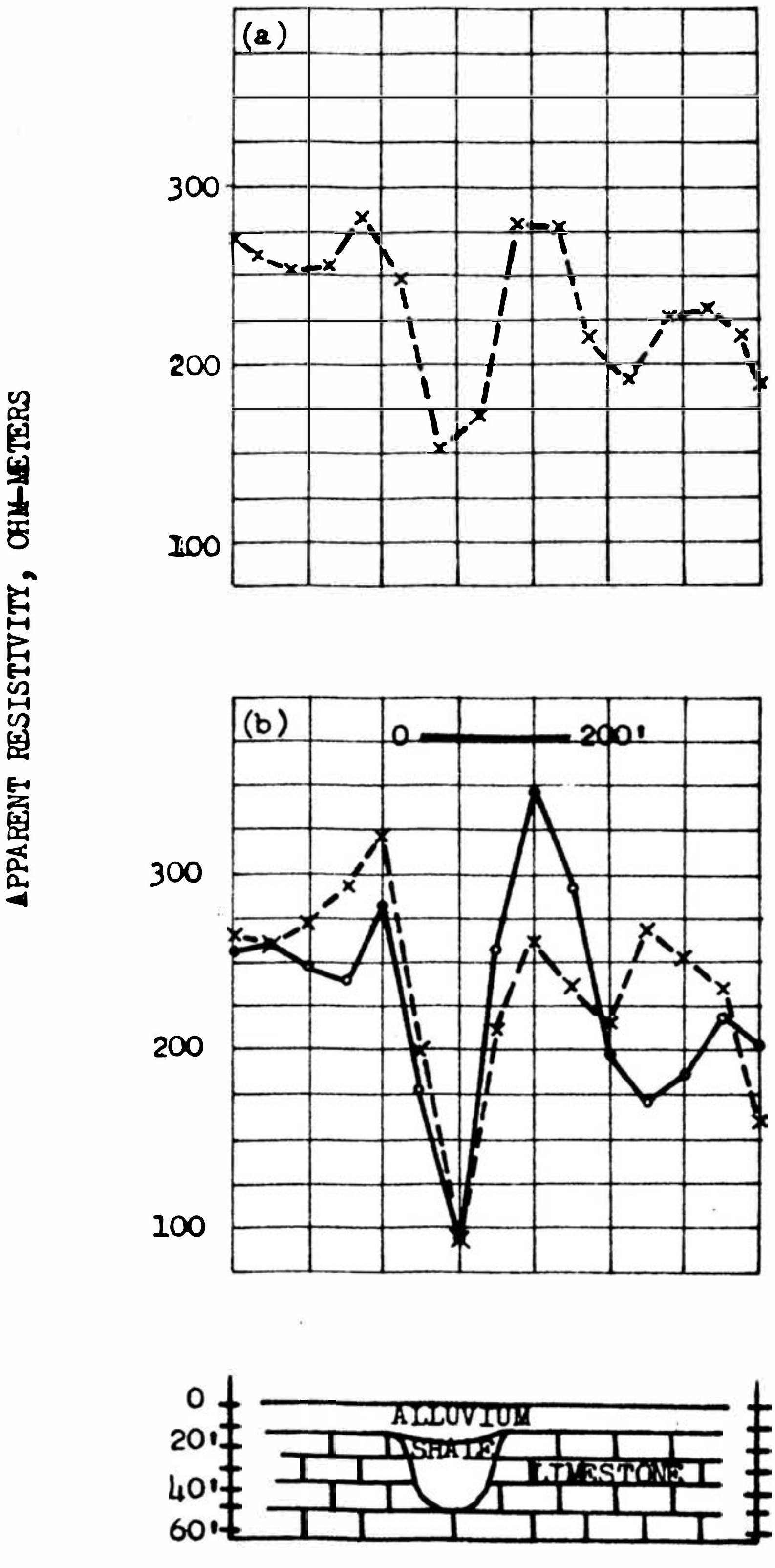


FIG. 8. FIELD CURVES OF HORIZONTAL RESISTIVITY SURVEYS OVER A KNOWN SINK (a) WENNER CONFIGURATION, (b) LEE CONFIGURATION. (AFTER COOK)

V. INFLUENCE OF ELECTROCHEMICAL ACTIVITY

A. Preliminary Investigations

Preliminary model studies were made using a three and one-half inch diameter hemispherical aluminum specimen suspended in salt (sodium chloride) water. This specimen was used first so that deviations from the theoretical, observed by Kwentus, could be checked and possibly explained. This specimen was also used first because it was available from the work done by Kwentus, and because it appeared to be as good a starting place as any. The results obtained by Kwentus (1960) over this specimen deviated considerably from the characteristic curves expected and predicted by Cook and Van Nostrand (1954) in their mathematical curves over buried hemispherical conductors.

This investigator felt that a more detailed study of the aluminum specimen might possibly lead to an explanation of the deviations observed. Kwentus stated that he thought the trouble might be due to electrochemical activity between the aluminum specimen and the salt water.

These investigations were made by placing the aluminum model near the center of the specimen tank, and just below the surface of the salt water that filled the tank to a depth of twenty inches. The specimen was placed at a small distance below the surface of the solution so that the electrodes would make good electrical contact while over the hemisphere; and so that the electrode configuration could be easily moved across the specimen.

In the conducted model studies the resistivity of the aluminum specimen was about 3×10^{-6} ohm-cm. and the resistivity of the surrounding media was about 350 ohm-cm. Although this is a tremendous resistivity contrast as compared to that used in calculating the theoretical curves prepared by

Cook and Van Nostrand, it is the opinion of this investigator that the characteristic peaks (edge effects) should still fall at the distances predicted by the theoretical curves. Recall that the positions of the characteristic peaks appeared to be only a function of the 'a' spacing and independent of either the resistivity, resistivity contrast, or the ratio of diameter to 'a' spacing.

The resistivity and resistivity contrast, according to theory, appear to affect only the magnitude of the resistivity curve. If the foregoing conclusions are true then the extremely high resistivity contrast should be advantageous in model studies in that it should cause the characteristic peaks to be amplified in magnitude and thus be easier and more accurately distinguished.

Although the Lee configuration has been shown by other investigators to give better detail and definition, it was decided to make runs over the specimen with both the Lee and Wenner configurations and to compare the results. Since the Megger Ground Tester is made to use a four electrode configuration, it had to be modified by the addition of an external switch which allowed the Lee configuration to be used. The switch permitted the selection of either P_oP_1 or P_oP_2 electrodes to be fed back to the Megger. Thus the Megger was set up to use the Lee configuration with absolutely no changes to the Megger tester itself. Since the Megger Ground Tester measures the ratio of E/I, the only change necessary when using the Lee rather than the Wenner configuration is that the Megger readings must now be multiplied by a different constant. This is explained in Section III.

Wenner and Lee profiles were run simultaneously over the hemispherical aluminum specimen which was buried one-half inch below the surface of the salt water solution. The results of the Wenner profile are shown in Figure 9 and the results of the Lee profile are shown in Figure 10. The resistivity curve produced by the Wenner configuration appears to be almost entirely unsatisfactory, as it is the type curve obtained by Kwentus. The outer edge effects are completely obscured and the two peaks A and B are higher than would probably be expected and they do not occur at the predicted distance from the edge of the hemisphere. On the theoretical curves, these peaks fall at a distance of one-half 'a' outside the hemisphere. The central low is also much higher than was expected. According to the theoretical curves, the resistivity should approach an extremely low value over the center since the resistivity of the aluminum is extremely low.

The Lee profile produced in Figure 10 shows more detail than the Wenner profile, as predicted by other investigators. There is some improvement in this curve over the Wenner curve in that the hemisphere has been brought down as expected and the two high peaks have been raised somewhat. All of the peaks on the edge effects are closer to the hemisphere than the theoretical curves seem to predict. On the basis of these investigations, it was decided to use only the Lee configuration for all ensuing investigations.

Since it was desired to try to reproduce a curve that duplicated or closely approximated the theoretical curve, it appeared that the Lee configuration would be better suited for this purpose since it gave the much needed detail and would probably allow the position of the characteristic peaks to be determined more accurately than would the Wenner configuration.

B. Study of Electrochemical Effect

After the Lee curve shown in Figure 10 was run it was decided to check out the possibility proposed by Kwentus, that the deviations from the theoretical were caused by electrochemical activity between the aluminum and the salt water. Ideally the Megger Ground Tester should eliminate any polarization effects and self-potential effects, because it uses a commutated D.C. current.

To check out this possibility, a self-potential survey was made over the aluminum body using nonpolarizing electrodes. Details of the electrodes used are given in Section III. One electrode was placed at a considerable distance from the specimen and the other electrode moved at given intervals along a profile over the center of the hemisphere. The potential of the moving electrode was recorded with respect to the stationary electrode and these values plotted at their respective positions along the traverse. These results are presented in Figure 11. Notice that the potential to either side of the hemisphere is approximately zero and there is a tremendous self-potential anomaly directly over the hemisphere. The rate of change in self-potential as we move onto the hemisphere is extremely rapid. It appeared to this investigator that this relatively large self-potential anomaly might possibly have an affect on the readings of the Megger especially since the rate of change was so abrupt at the edge of the hemisphere.

After the aluminum specimen had been used in several investigations, it was observed that the specimen was building up a white protective film on the surface which was originally clean and polished. The decision was then made to leave the aluminum specimen in the salt water for a period of time until it appeared that the electrochemical activity at the

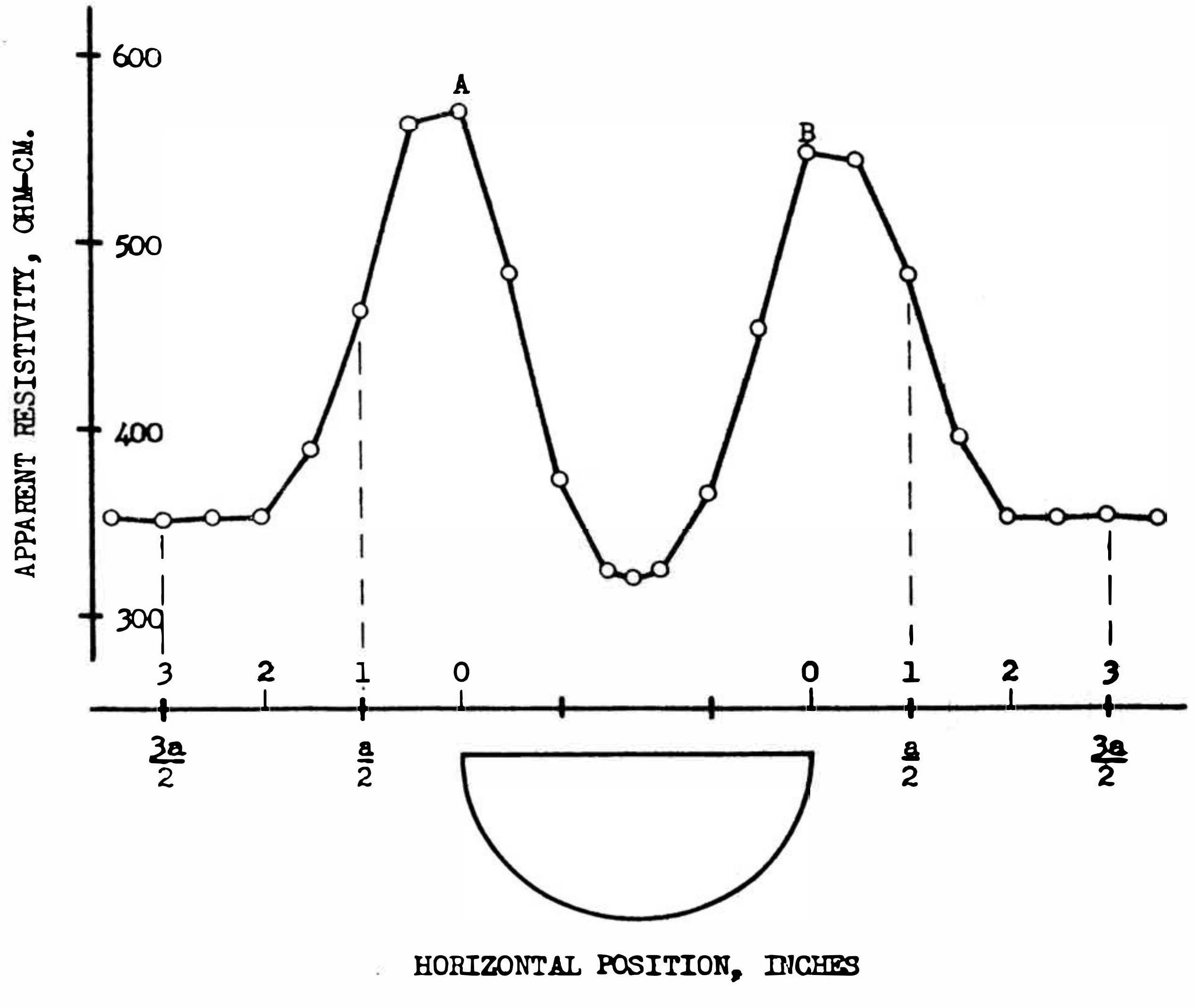


FIG. 9. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A THREE AND ONE-HALF INCH DIAMETER ALUMINUM HEMISPHERE, WENNER CONFIGURATION. 'a' = 2 INCHES, DEPTH OF BURIAL = 1/2 INCH.

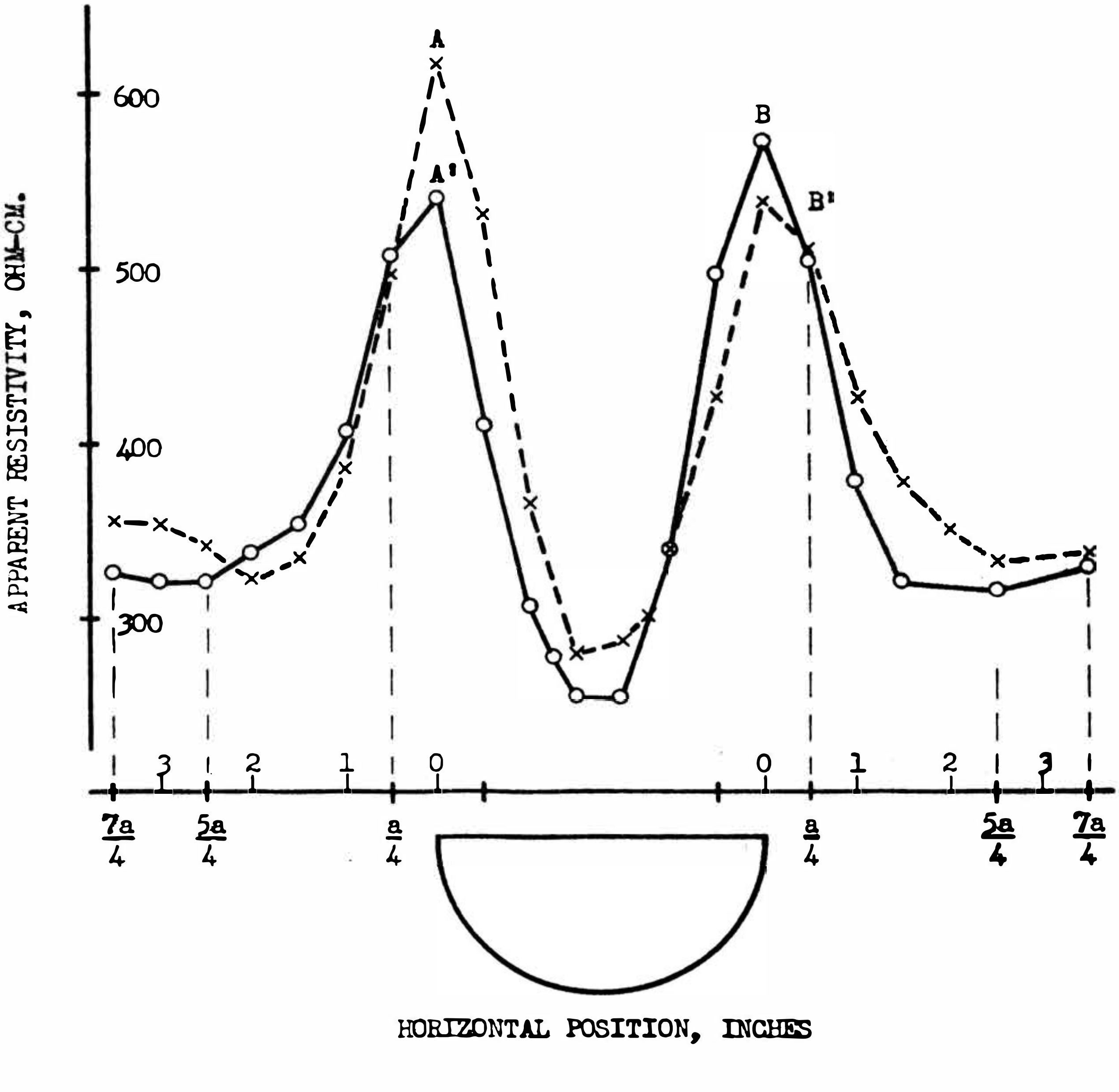


FIG. 10. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A THREE AND ONE-HALF INCH DIAMETER ALUMINUM HEMISPHERE, LEE CONFIGURATION. 'a' = 2 INCHES, DEPTH OF BURIAL = 1/2 INCH.

surface had diminished or ceased. It was hoped that the building up of this protective film on the surface of the specimen would eliminate most of the electrochemical activity and thus allow the investigator to determine what type effect, if any, the electrochemical activity had on the resistivity runs. Indications were that this was entirely due to surface phenomena.

After the aluminum hemisphere had been in the salt water for a considerable period of time, a second Lee profile was taken over the center of the hemisphere. In this case the specimen was placed five-sixteenths of an inch below the surface of the salt water. In the previous case the specimen was at a depth of one-half inch. The results of this survey are presented in Figure 12. The curve is shifted down considerably in comparison to the curve in Figure 10 and it approaches zero over the center of the hemisphere. Much of this shift in apparent resistivity may have been brought about by the fact that the specimen was placed nearer the surface in the latter run. The edge effects show up well in this profile but the characteristic peaks are not at the distances predicted by the theoretical curves.

The specimen was allowed to remain in the salt water for one more week and another Lee profile was made to see if there were any noticeable changes. This curve is presented in Figure 13 and it is for the same conditions, electrode spacing, and depth of burial as it was in Figure 12, except that the specimen had remained in the salt water for one more week. The peak positions appear to have remained at the same positions and the only noticeable change is the fact that the maximum value of the apparent resistivity has dropped down from slightly greater than seven hundred ohm-cm. to slightly greater than five hundred ohm-cm.

At this point a second self-potential survey was made over the hemisphere in the manner previously described. The conditions were the same as for the first self-potential survey except that the depth of burial was three-eighths of an inch rather than the one-half used in the previous self-potential survey. This data, presented on Figure 14, shows that the magnitude of the self-potential anomaly has been lowered somewhat and it is not quite as abrupt at the edge of the hemisphere. Although the decrease in self-potential doesn't appear to be too large, it was shown in another investigation that the self-potential anomaly drops off very rapidly with depth. Since this is the case, the second self-potential survey, which was made at a shallower depth than the first, might well represent a substantial reduction in the self-potential anomaly. The background self-potential level was probably due to electrode impurities.

The study of the effect of depth of burial on the self-potential anomaly was made and the results are presented in the appendix. The probe electrode was placed approximately one-quarter inch from the edge of the hemisphere and the depth of the hemisphere was then varied, and readings taken with increasing depth. The self-potential at the surface was observed to drop off very rapidly with a reading of 122 mv. at three-sixteenths of an inch depth, thirty eight mv. at one-half inch depth, and ten mv. at seven-eighths inch depth and below. The background potential between the two electrodes was observed to be about eight mv. This was due to impurities in the electrodes.

Another series of tests was conducted to see what effect, if any, induced potential would have on the Megger readings. In this test no specimen was used and the Wenner configuration was used since it would

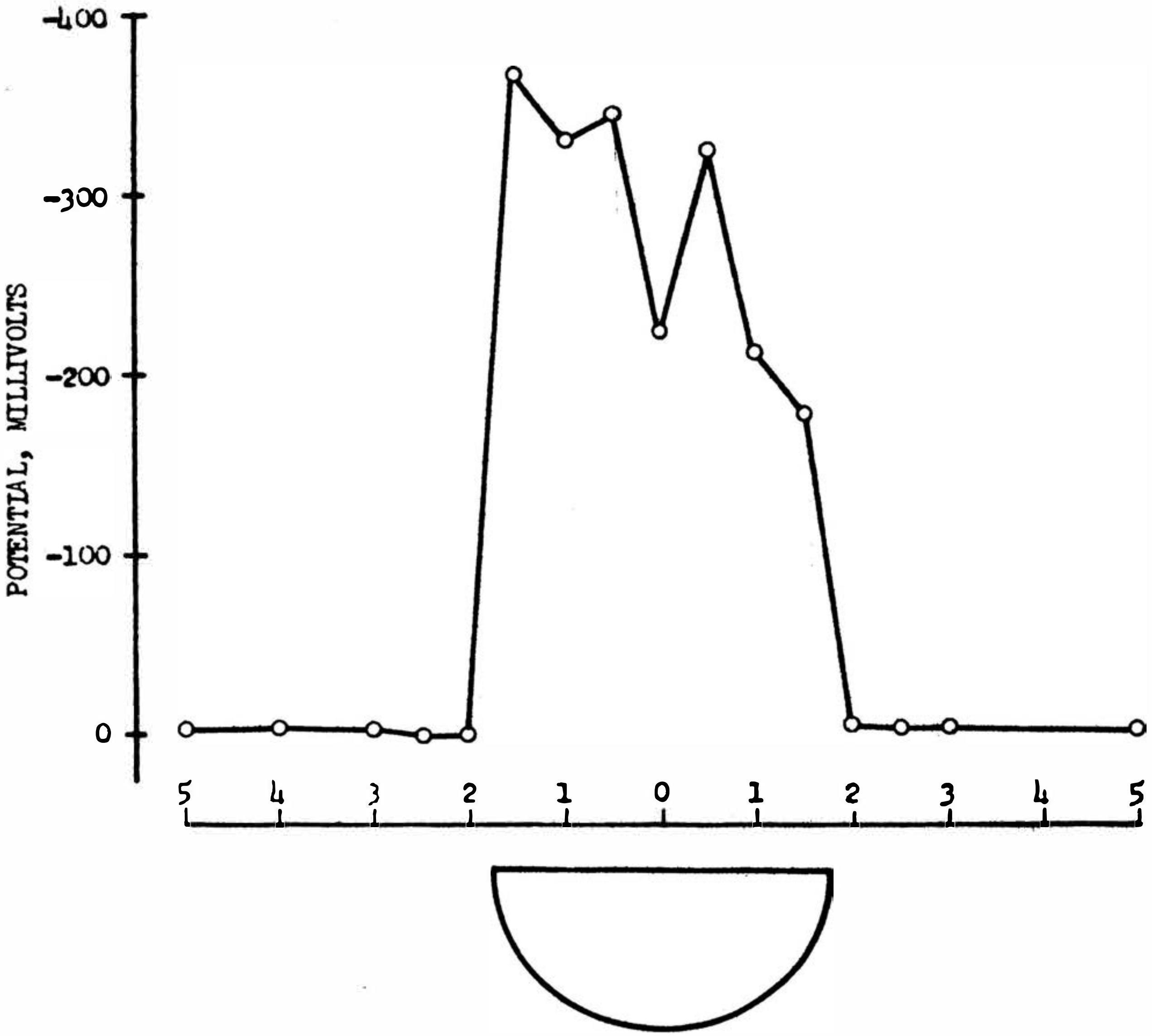


FIG. 11. SELF POTENTIAL SURVEY OVER THE CENTER OF A THREE AND ONE-HALF INCH DIAMETER ALUMINUM HEMISPHERE. DEPTH OF BURIAL = 1/2 INCH.

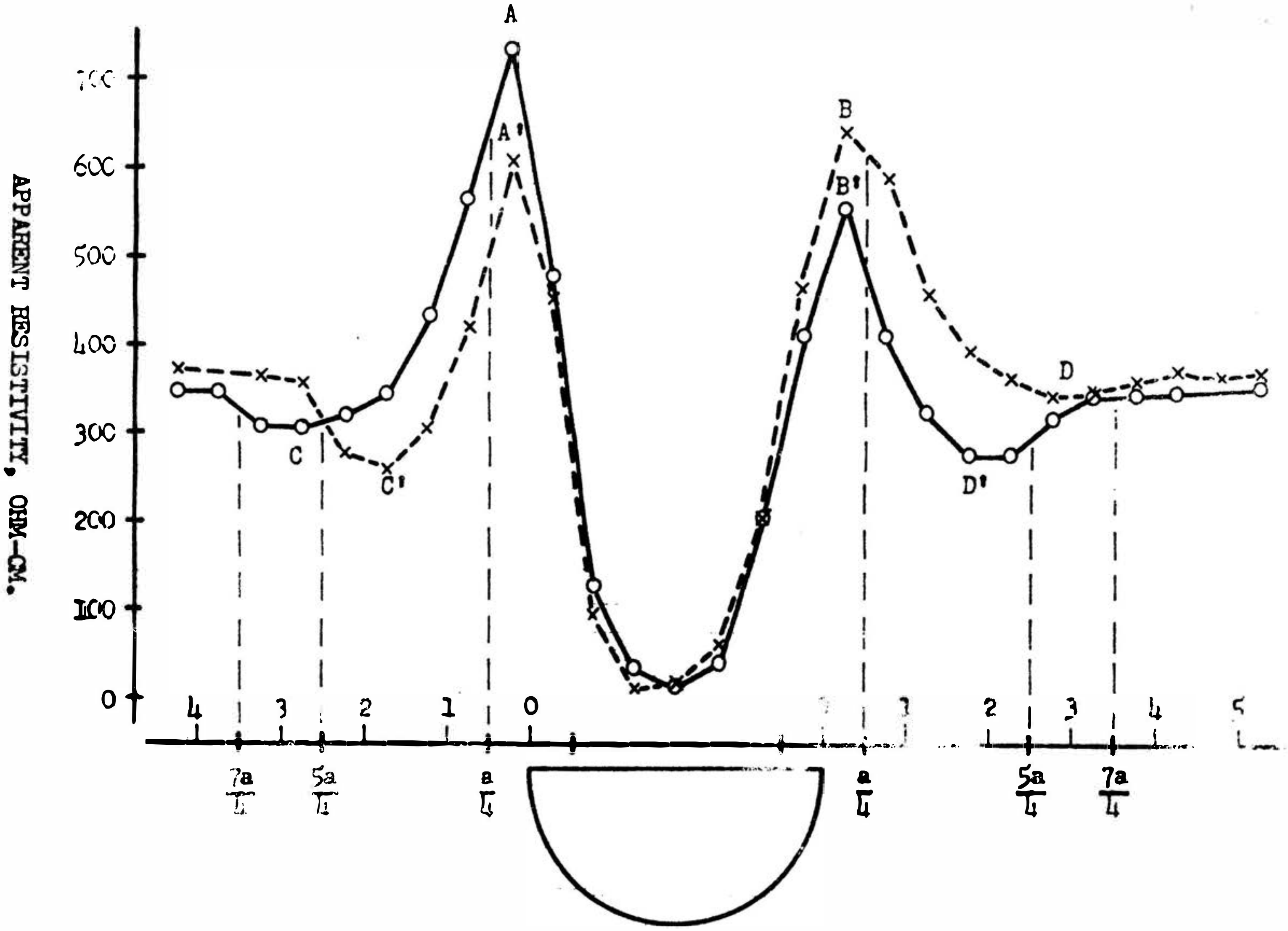


FIG. 12. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A THREE AND ONE-HALF INCH DIAMETER ALUMINUM HEMISPHERE, LEE CONFIGURATION. 'a' = 2 INCHES, DEPTH OF BURIAL = 5/16 INCH.

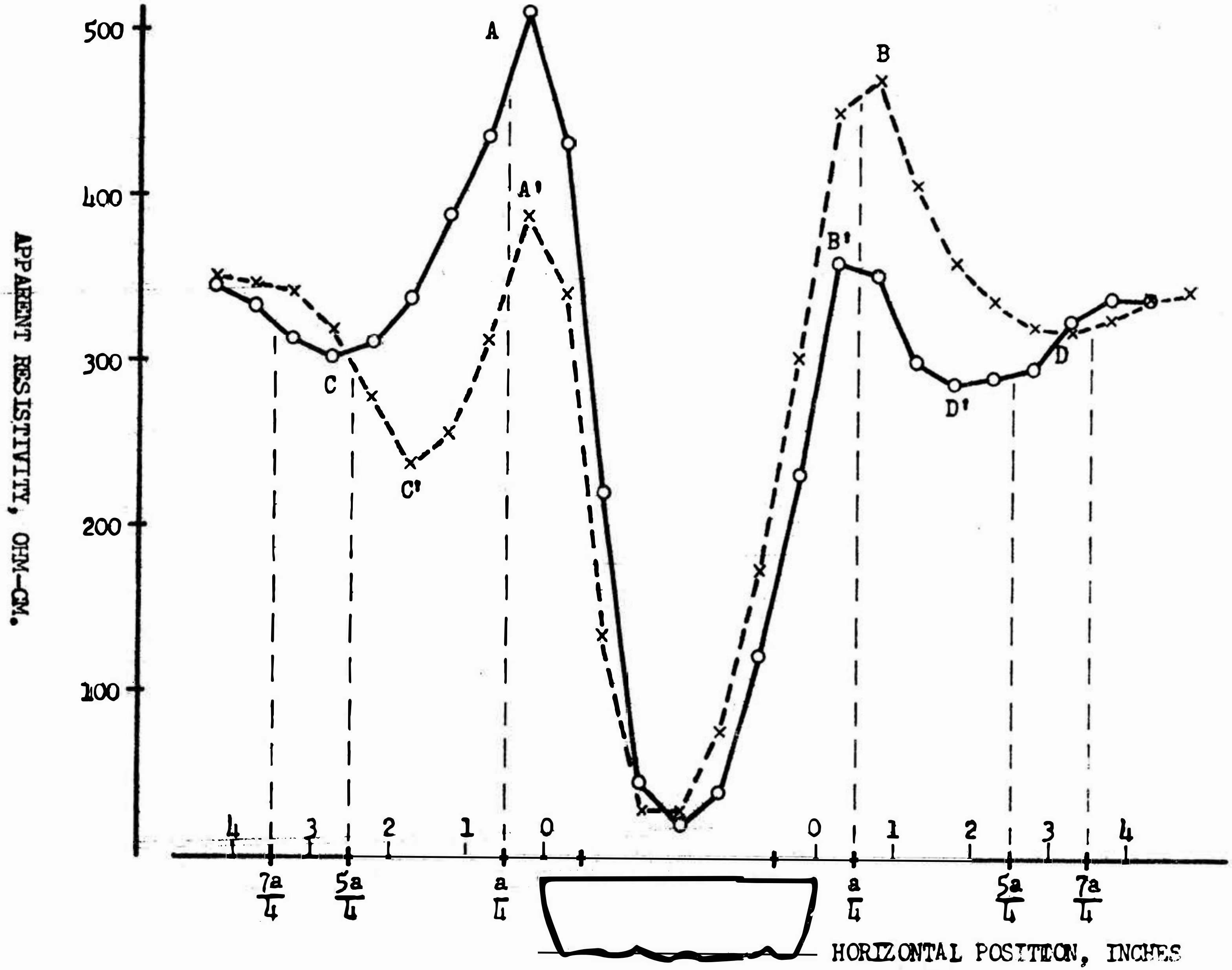


FIG. 13. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A THREE AND ONE-HALF INCH DIAMETER ALUMINUM HEMISPHERE, LEE CONFIGURATION. 'a' = 2 INCHES, DEPTH OF BURIAL = 5/16 INCH.

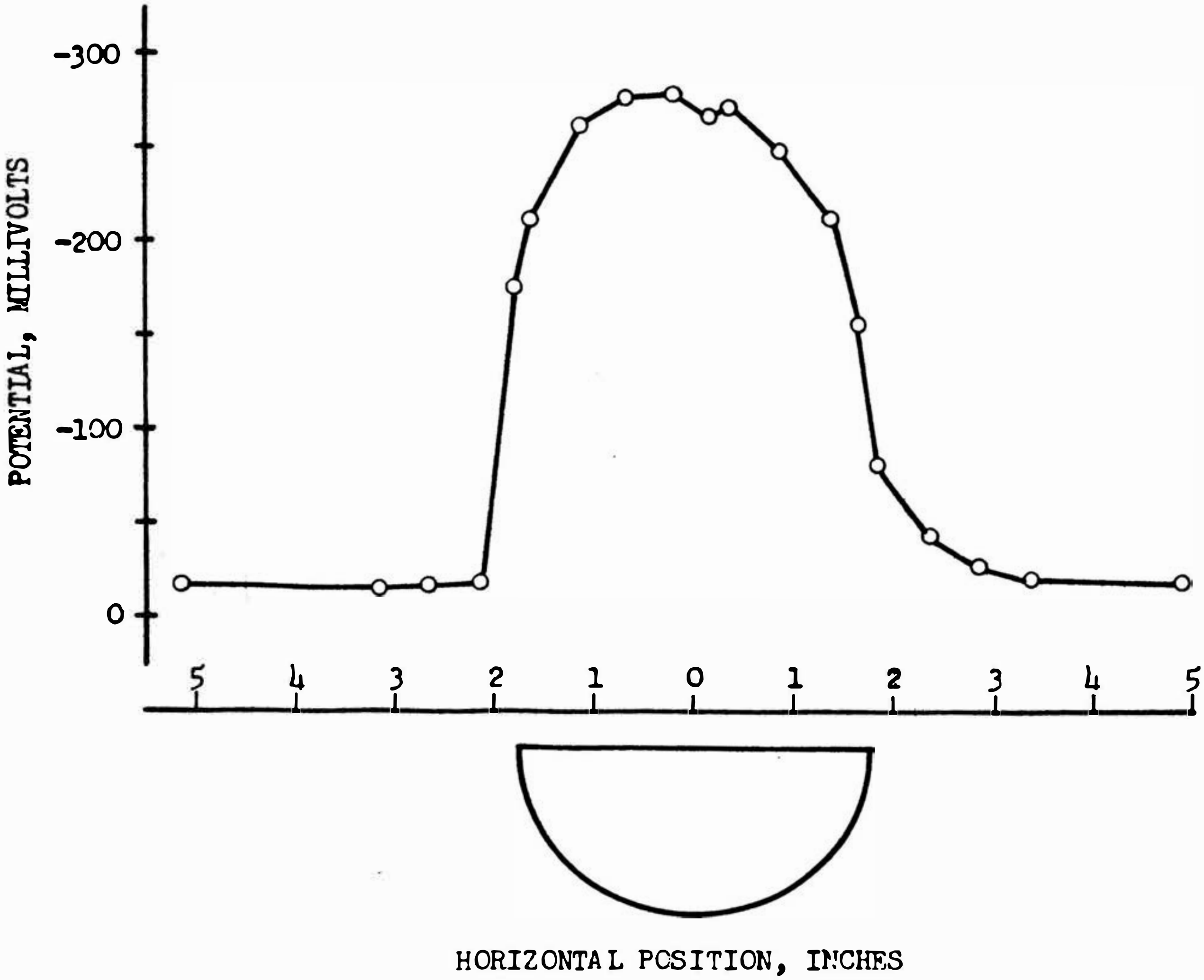


FIG. 14. SELF POTENTIAL SURVEY OVER THE CENTER OF A THREE AND ONE-HALF INCH DIAMETER ALUMINUM HEMISPHERE. DEPTH OF BURIAL = 3/8 INCH.

serve equally well in this experiment. The electrode configuration was placed at the center of the resistivity model tank and an external potential was applied between two different points in the tank. It was desired to see if this externally applied potential would in any way affect the magnitude of the apparent resistivity readings. First a reading was taken with no externally applied potential and then readings were taken while an external potential was being applied at different selected points in the tank. The only cases where the readings were affected was when one of the external potential electrodes was either coincident or very near one of the electrodes of the configuration. This seems to indicate that a relatively high potential gradient near the electrode configuration might well have an influence at least on the magnitude of the apparent resistivity readings. In other words, the high self-potential anomaly over the aluminum hemisphere might be great enough to change the magnitude of the readings. The data from this investigation is presented in the appendix.

A close analysis of the curves presented appears to indicate that there has been no noticeable change in the position of the characteristic peaks due to the lowering of the self-potential anomaly, and that probably the only effect of the lowering of the self-potential anomaly was to bring about a small shift downward in the resistivity curves. Most of the shift downward of the resistivity curves in Figures 12 and 13 as compared to Figure 10, was probably brought about by the fact that the specimen was placed nearer the surface in the later studies. This is especially true for the trough directly over the hemisphere.

Although the results are not conclusive, it appears that the only effect the self-potential anomaly has on the apparent resistivity curve is to shift the magnitude of the readings slightly.

It should be pointed out that during these early investigations the investigator was working under the assumption that depth of burial had little or no influence on the position of the characteristic peaks for small depths of burial. It was thought that the depth of burial affected primarily the magnitude of the apparent resistivity. Later studies showed this assumption to be incorrect.

VI. CONDUCTIVE MODELS IN SALT WATER

A. Producing Theoretical Type Curves

Although it appeared to this investigator that the only effect of the electrochemical activity on the apparent resistivity was to change the apparent resistivity slightly and give no shift in the position of the characteristic peaks, the decision was made to search for a better specimen material. A search was made for a conductive specimen material, which would give little or no electrochemical activity while in contact with the salt water solution.

The possibility of replacing the salt water with some other conductive media was considered, but this was unnecessary as an acceptable specimen material was soon found.

A three and one-half inch diameter hemisphere was made of electrode grade carbon, obtained from the Metallurgy Department. This specimen was then suspended in the salt water solution to a depth of one-quarter of an inch and a self-potential survey run over the center of the hemisphere. One electrode was placed at a considerable distance from the specimen and the other electrode was moved along the traverse and readings were taken at selected intervals. The self-potential level away from the hemisphere was about nine millivolts and this was due to impurities in the nonpolarizing electrodes. Notice in Figure 15 that the maximum self-potential reading over the hemisphere is 19.5 mv. or just 10.5 mv. above the background level caused by the electrodes. The aluminum hemisphere, at three-eighths of an inch depth, gave a maximum self-potential of about 275 mv. and at a depth of one-half inch originally gave a self-potential of almost 375 mv. When the

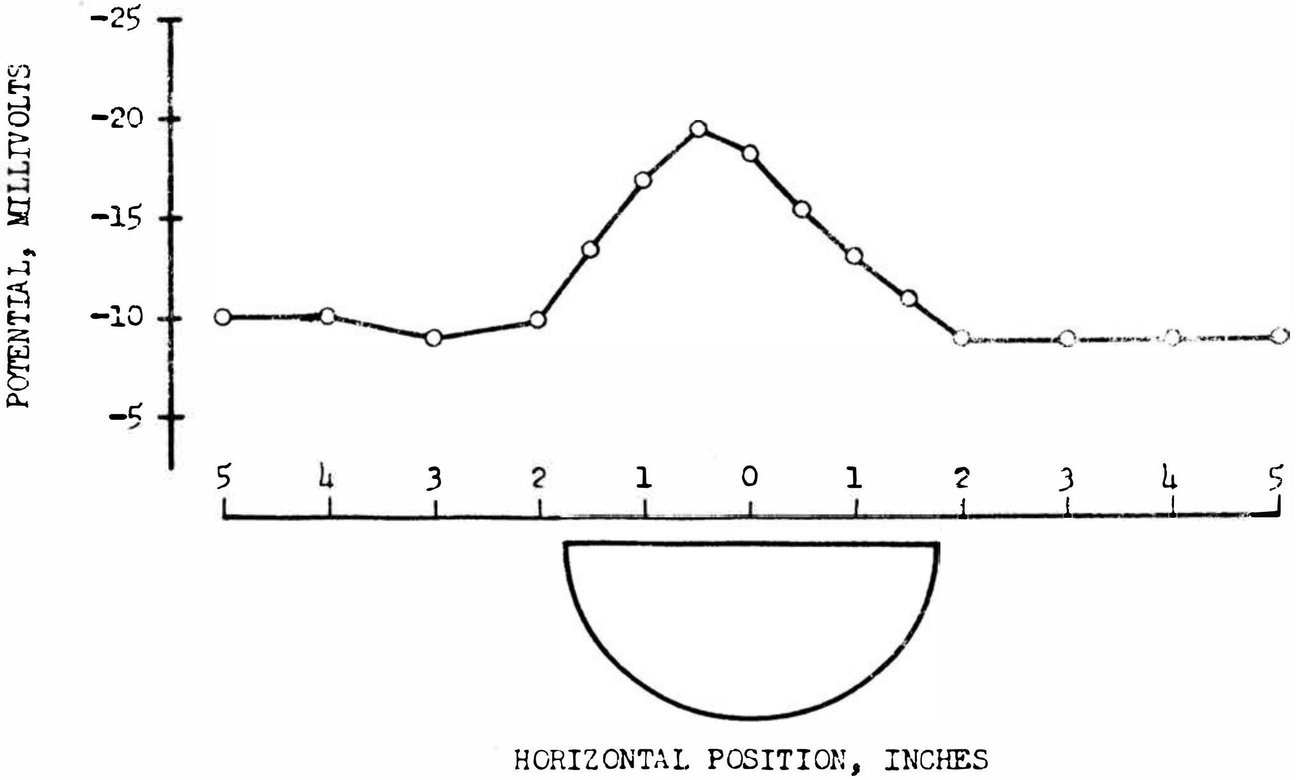


FIG. 15. SELF POTENTIAL SURVEY OVER THE CENTER OF A THREE AND ONE-HALF INCH DIAMETER CARBON HEMISPHERE, DEPTH OF BURIAL = 1/4 INCH.

self-potential anomaly for the carbon hemisphere is compared with the self-potential anomaly for the aluminum hemisphere it is obvious that it is negligible by comparison. This small self-potential measured over the carbon specimen was probably due to impurities in the carbon.

Since this carbon specimen had been determined to be satisfactory in respect to electrochemical activity, tests were continued with this specimen. Resistivity curves were made over the three and one-half inch diameter carbon hemisphere with it buried a small distance below the surface of the fluid as in previous investigations. The resistivity of the salt water was slightly greater than three hundred ohm-cm. and the resistivity of the carbon specimen was probably about 1400×10^{-6} ohm-cm. This is about the same values of resistivity used for tests with the aluminum hemisphere. The resistivity of the carbon is probably slightly greater than the resistivity of the aluminum but the resistivity of each is less than one ohm-cm., and in both cases the resistivity of the solution is about the same.

The resistivity survey in Figure 17 is over the carbon specimen at a depth of burial of two-tenths of an inch. There are no drastic differences between this curve and those obtained over the aluminum hemisphere. The values of resistivity in the trough over the hemisphere are slightly lower (approximately zero) and the bottom of this trough is flatter than for the aluminum specimen. The maximum apparent resistivity is also less but this is probably due to the fact that a slightly lower resistivity contrast now exists. The positions of the peaks appear to fall at approximately the same places as for the aluminum hemisphere. In both cases the peaks occurred nearer the edge of the specimen than expected. Notice in this case though, that the inner peaks A, A', B, B' are at the predicted positions.

In view of this run it was almost conclusive that the deviation of the peak positions was not a function of the electrochemical activity.

Resistivity profiles were also made over the three and one-half inch diameter carbon hemisphere with one and three inch 'a' spacings, in the hope that some simple relation between the electrode spacing and the deviation of the peak positions would appear. Examination of the curves in Figures 16, 17, and 18, gave no indication that such a simple relationship existed to explain the deviations in peak positions.

A five inch diameter carbon hemisphere was also made of the same carbon stock as the three and one-half inch diameter hemisphere, and resistivity profiles were made over this hemisphere with a two inch 'a' spacing to see if the amount of deviation would change with a change in specimen diameter. There was no apparent change in position of the peaks with this change in diameter.

After an examination of the collected data, the possibility was brought to mind that the position of the peaks in the edge effect might possibly be appreciably influenced by the depth of burial of the specimen.

If the depth of burial were an important factor in the position of the characteristic peaks, then it would be expected that the type curves predicted by Cook and Van Nostrand would hold only if the top of the buried hemisphere were level with the surface of the surrounding media. In order to check this possibility, the five inch carbon hemisphere was placed in the salt water with its top edge at the surface of the solution.

A resistivity profile was then made over this specimen and the result is shown in Figure 19. As the electrode configuration was moved over the specimen it was necessary to place each of the electrodes individually for each reading position. While the electrodes were over the hemisphere, they were in direct contact with the carbon specimen and care was necessary to insure good electrical contact. To aid in getting good electrical contact, the top of the hemisphere was kept wet with a thin film of water, even though the top edge of the hemisphere was level with or slightly above the level of the surrounding media.

Examination of this resistivity profile shows that the peaks all fall at the predicted positions, within the limits of the accuracy of the equipment employed. All of the outer edge effects fall at predicted distances and the two curves reach the minimum values at one-quarter 'a' inside the edge of the hemisphere as predicted by peaks E, E', F, and F' in the theoretical Lee profile shown in Section IV, Figures 6 and 7. The only characteristic effects that are not present on this profile are the peaks H, H', G, and G' shown on the theoretical curves. It was expected that these peaks would not show up because they were predicted to be extremely small and in this particular case they were undoubtedly obscured because the resistivity of the specimen was extremely small. The resistivity of the specimen was small enough that the Megger indicated zero resistivity over the center of the specimen. Care was taken in selecting the position of the readings so that all critical points along the traverse were read. The tabulated data for this curve is presented in the appendix.

In practically all respects the curves in Figure 19 approach the curves predicted by Cook and Van Nostrand to a remarkable degree. In order to assure that this curve was valid, profiles were made on two other occasions with similar results.

B. Variation With Depth

Once it had been definitely determined that depth of burial had a marked influence on the position of the characteristic edge peaks, a series of profiles for varying depth of burial were made. These curves exhibit fairly clearly, the effect of depth of burial on the apparent resistivity curves. Figures 20 thru 23 clearly show this effect of depth of burial. In each of these cases, the five inch carbon hemisphere was used and in each successive run, the depth was made deeper. The depth was not varied the same amount each time due to difficulty in accurately varying the depth of burial of the specimen.

Only the right half of the resistivity curves in this series is shown, since that is sufficient to show the effect of depth of burial. The other half of the curve would be similar with the two curves reversed as has been shown in the previous materials.

Notice that as the depth of burial increases, there is a marked movement in the position of the peaks D and D' nearer the specimen with increasing depth. The two inner peaks B and B' appear to be less affected by increasing depth, and they have moved farther away from the specimen with increasing depth.

It is interesting to note that these peaks B and B' remain at or very near their predicted position for shallow depth of burial and that they are affected to much less degree, than are the other peaks for the same depth of burial.

In restudying some of the earlier curves it will be seen that as in this series of runs, the inner peaks A, A', B, and B', were often at, or near, the predicted distances even with the small depth of burial and the other edge effects were always nearer the edge of the hemisphere than predicted by Cook and Van Nostrand's curves.

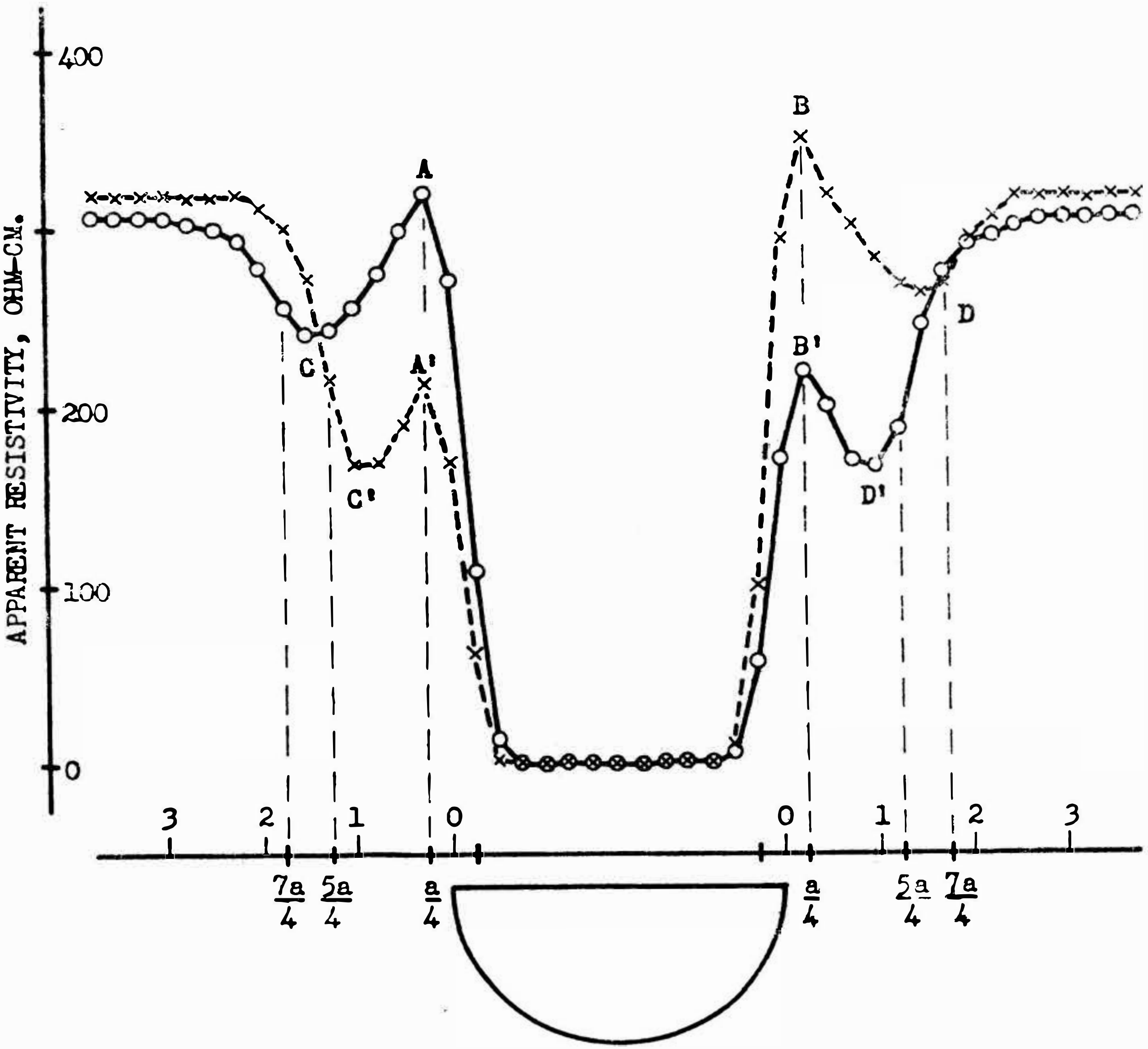


FIG. 16. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A THREE AND ONE-HALF INCH DIAMETER CARBON HEMISPHERE, LEE CONFIGURATION. 'a' = 1 INCH, DEPTH OF BURIAL = 3/8 INCH.

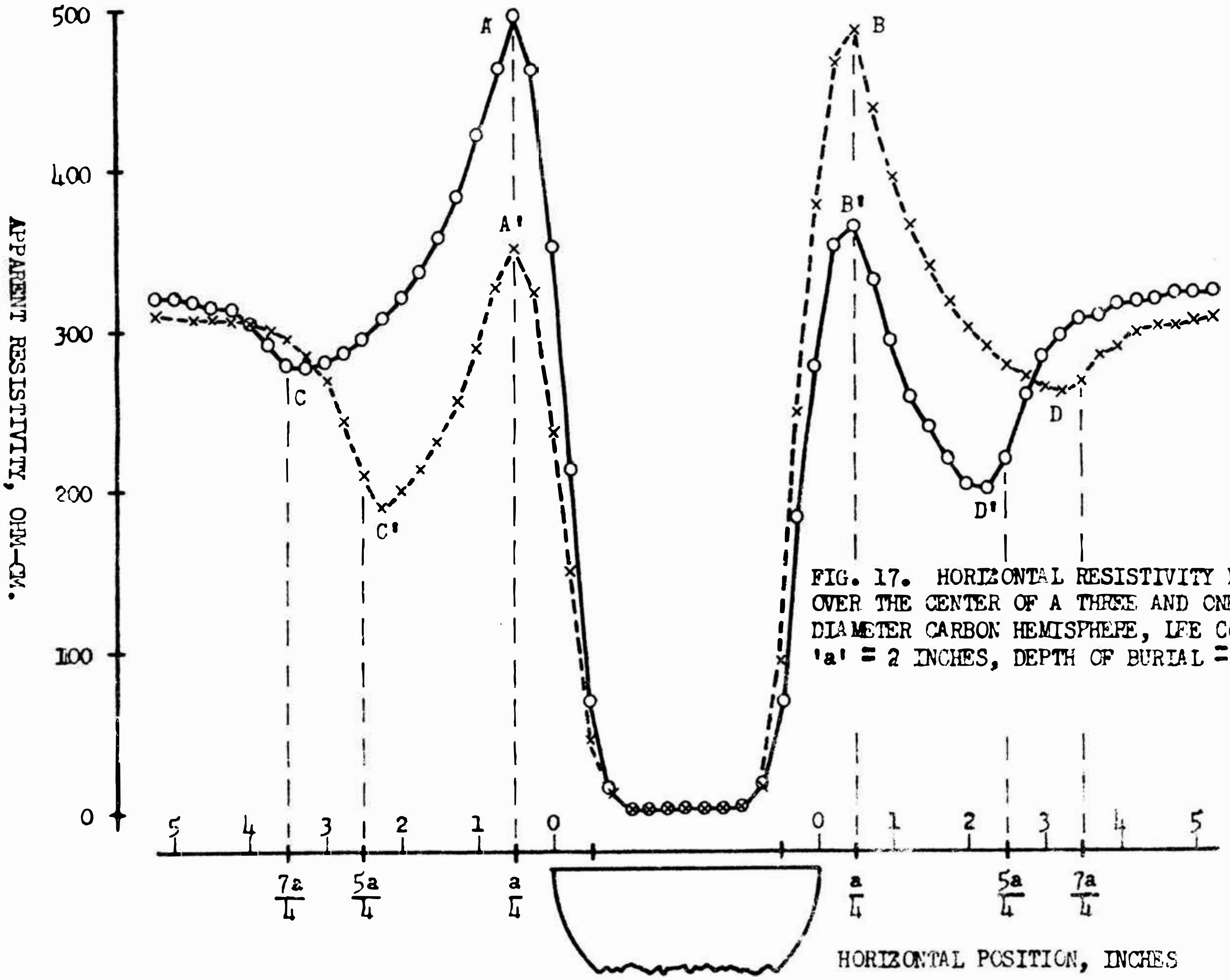


FIG. 17. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A THREE AND ONE-HALF INCH DIAMETER CARBON HEMISPHERE, LFE CONFIGURATION. 'a' = 2 INCHES, DEPTH OF BURIAL = 2/10 INCH.

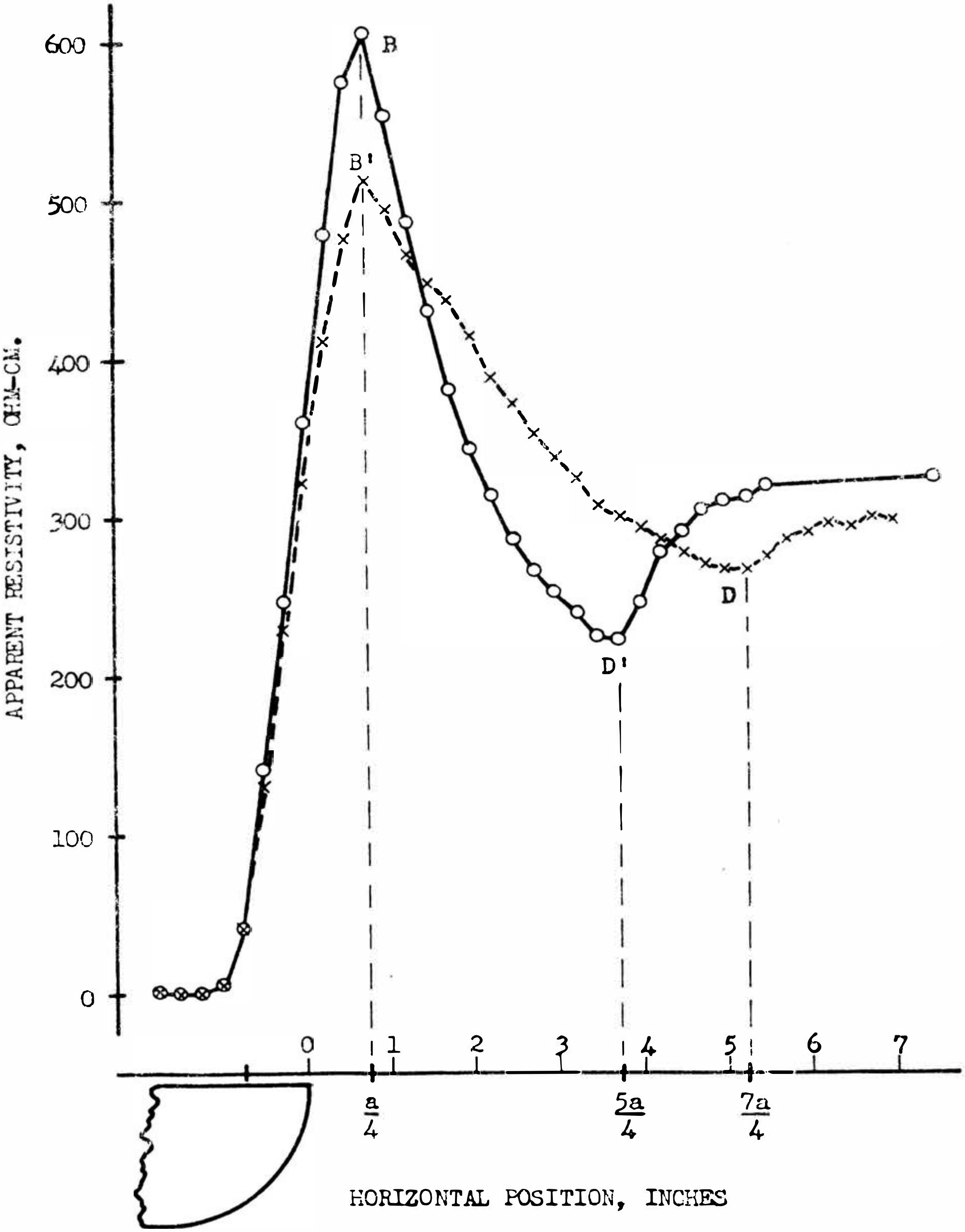


FIG. 18. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A THREE AND ONE-HALF INCH DIAMETER CARBON HEMISPHERE, LEE CONFIGURATION. 'a' = 3 INCHES, DEPTH OF BURIAL = 1/8 INCH.

The two curves in Figure 24 show the position of the peaks D and D' with respect to the edge of the hemisphere as a function of the depth of burial. No simple mathematical relationship was found to predict the manner in which these peak positions varied. It should be pointed out that at best these points are only approximate, due to the fact that accurate depth control was not available and as the depth increases it becomes increasingly difficult to tell exactly where the peaks of the curves occur.

The depth of burial has a marked affect on both the upper and lower values of the resistivity curve. At a depth of three-fourths the 'a' spacing, the edge effects have become almost completely obscured and the only prominent feature of the curve remaining is the trough over the center of the hemisphere.

It would be extremely interesting to see a theoretical explanation of the position of these peaks with depth of burial.

C. Aluminum Hemisphere at the Surface

Since it appeared that probably the only affect of electrochemical activity on the resistivity profile, is a possible small affect on the magnitude of the measured resistivity, it should then be possible to reproduce a resistivity curve using the aluminum specimen in which the peaks would fall at the expected distances.

The three and one-half inch diameter aluminum specimen used previously was placed at the surface of the resistivity model tank and a profile made over it with its top edge at the surface of the solution. As in the case of the carbon specimen, the electrodes had to be placed individually against the surface of the aluminum and the surface was kept wet to get good electrical contact.

The results of that run are shown in Figure 25. The peak positions are very close to the predicted positions; peak B' is at its predicted position and B is slightly inside its predicted position, D and D' are approximately at their predicted positions. The curve reaches the low values over the center of the hemisphere at points E' and F' and these points appear to be considerably in error. The one factor that might well explain the small deviations that still apear to occur, is the fact that it was very difficult to get good electrical contact with the pencil electrodes against the aluminum surface. Positioning of the electrodes and trying to get good electrical contact caused some disturbance of the specimen and therefore introduced some error in position of the electrodes with respect to the specimen. Electrode placement was not as serious in the case of the carbon specimen because the surface of the carbon isn't as hard and smooth as the aluminum, thus permitting easier electrical contact with less disturbance to the specimen.

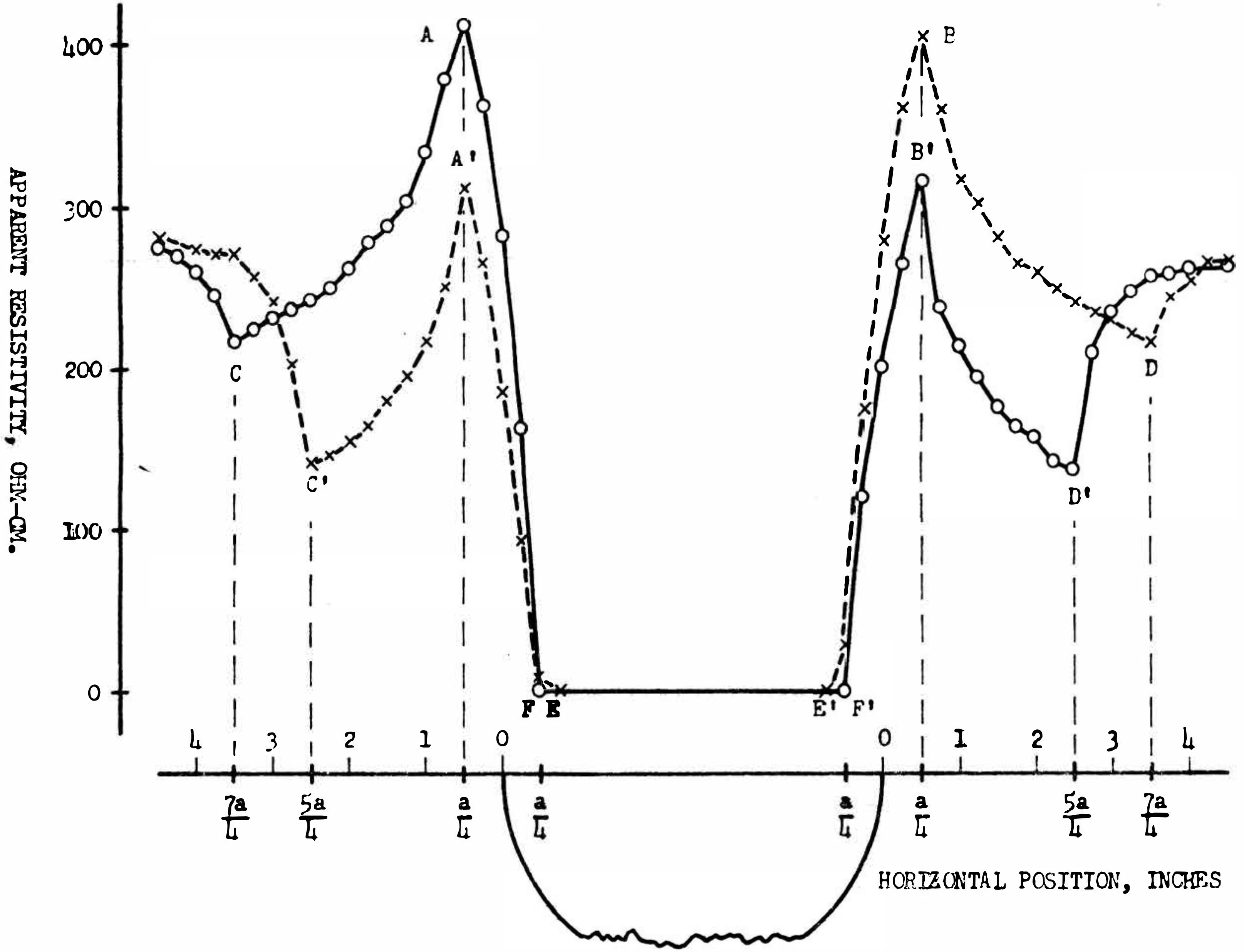


FIG. 19. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A FIVE INCH DIAMETER CARBON HEMISPHERE, LEE CONFIGURATION. 'a' = 2 INCHES, DEPTH OF BURIAL = 0.

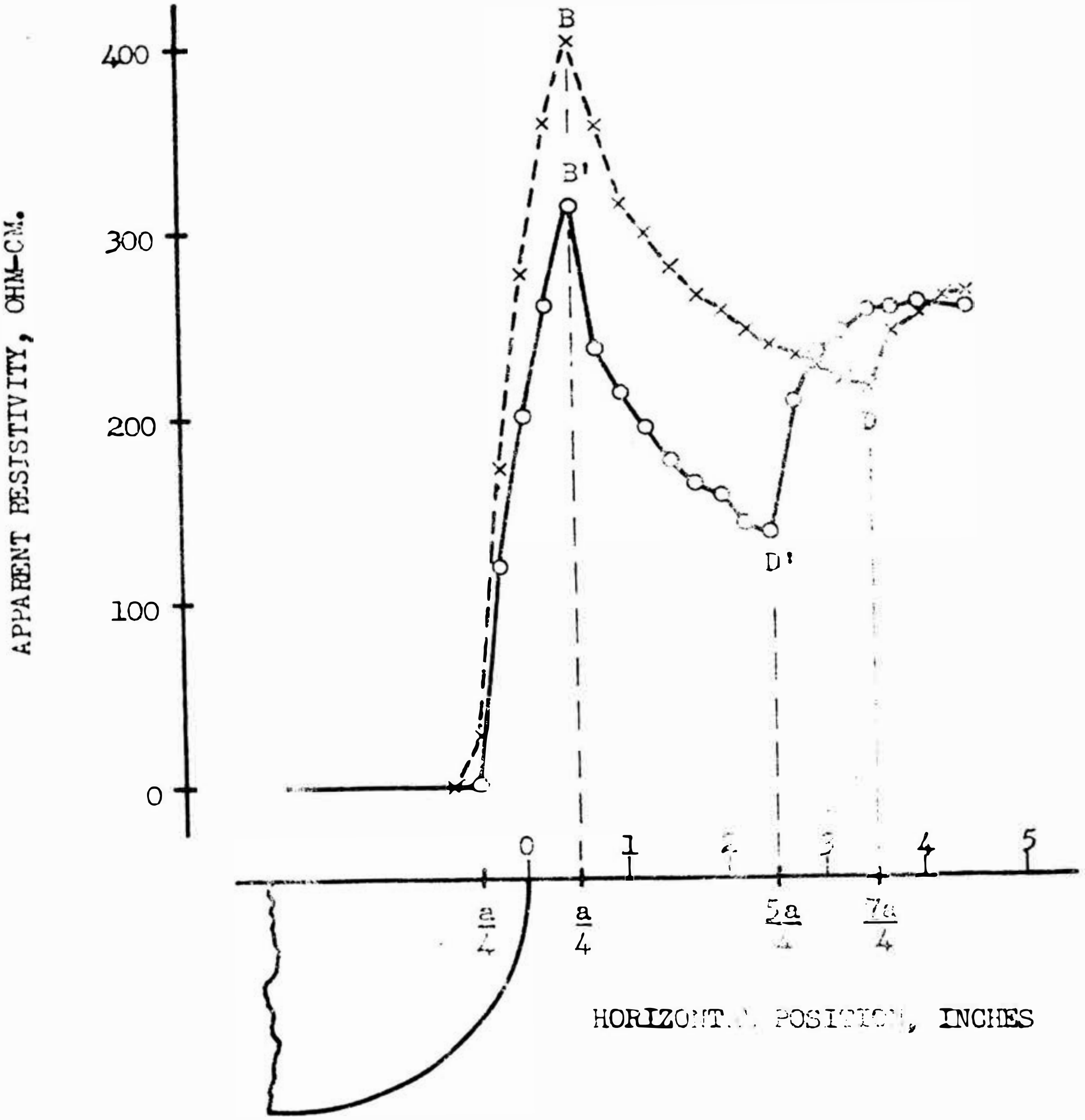


FIG. 20. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A FIVE INCH DIAMETER CARBON HEMISPHERE, LEE CONFIGURATION. "a" = 2 INCHES, DEPTH OF BURIAL = 0.

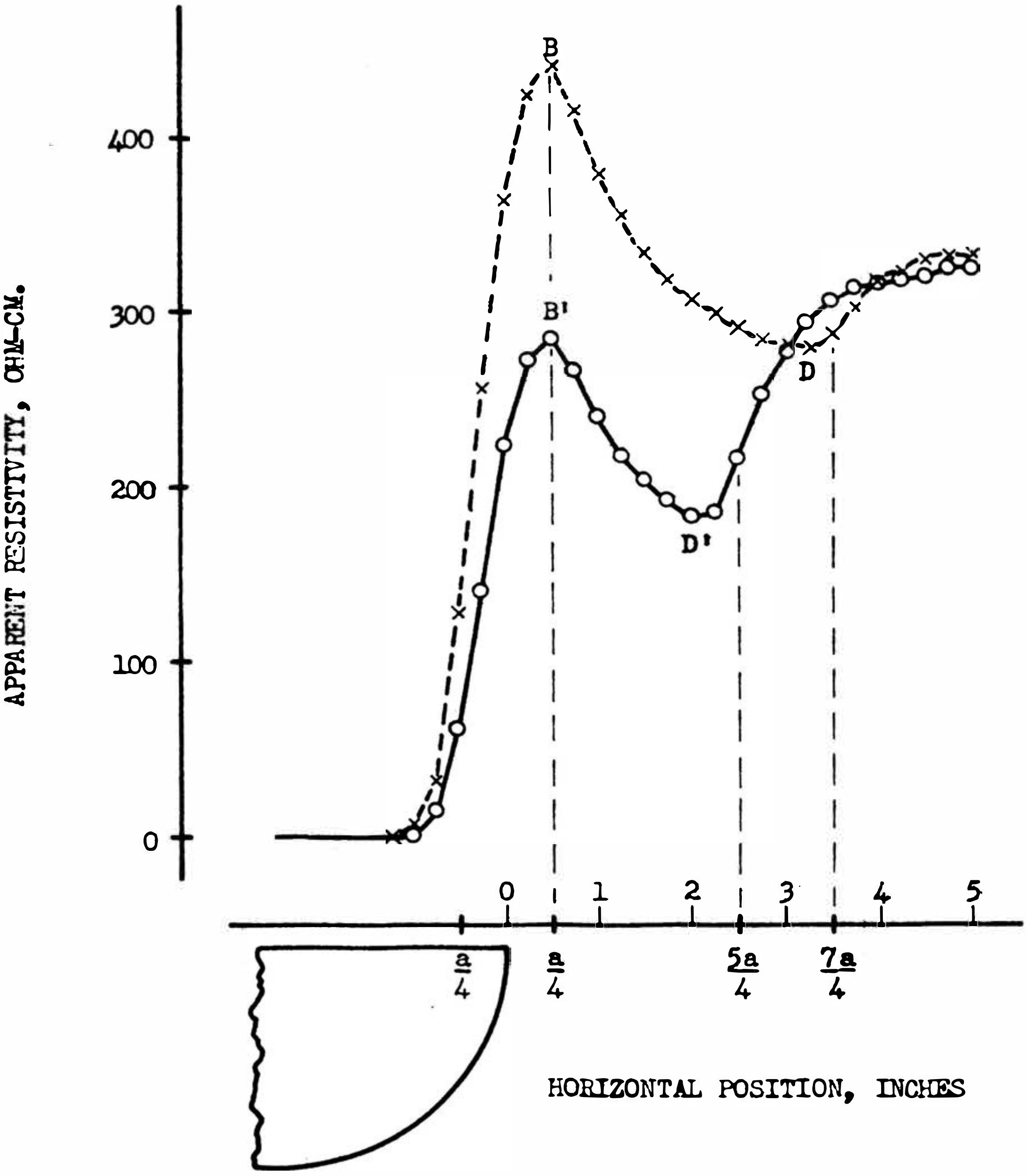


FIG. 21. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A FIVE INCH DIAMETER CARBON HEMISPHERE, LEE CONFIGURATION. 'a' = 2 INCHES, DEPTH OF BURIAL = 1/4 INCH.

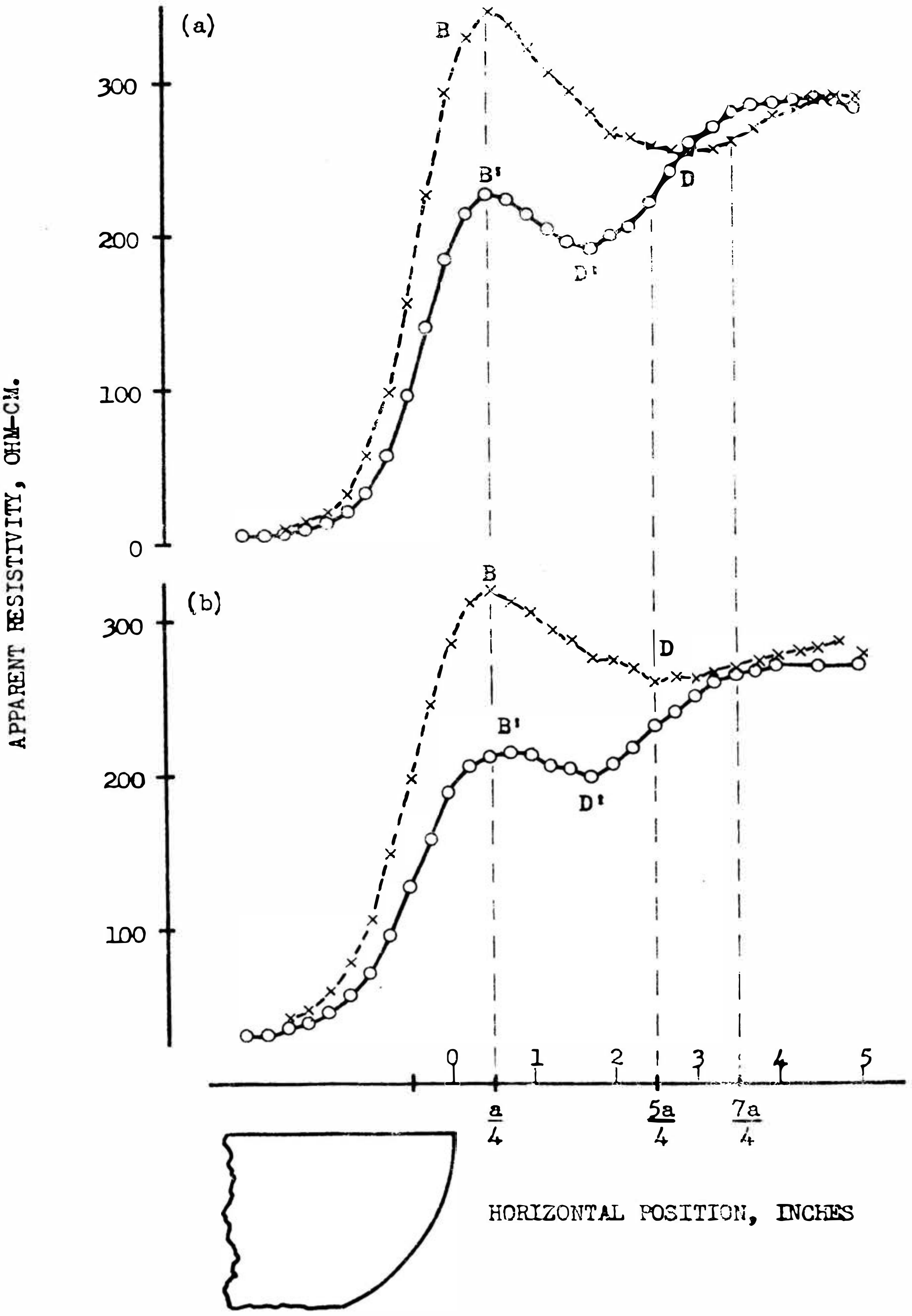


FIG. 22. HORIZONTAL RESISTIVITY PROFILES OVER THE CENTER OF A FIVE INCH DIAMETER CARBON HEMISPHERE, LEE CONFIGURATION. 'a' = 2 INCHES, DEPTH OF BURIAL IN (a) = 17/32 INCH, IN (b) = 11/16 INCH.

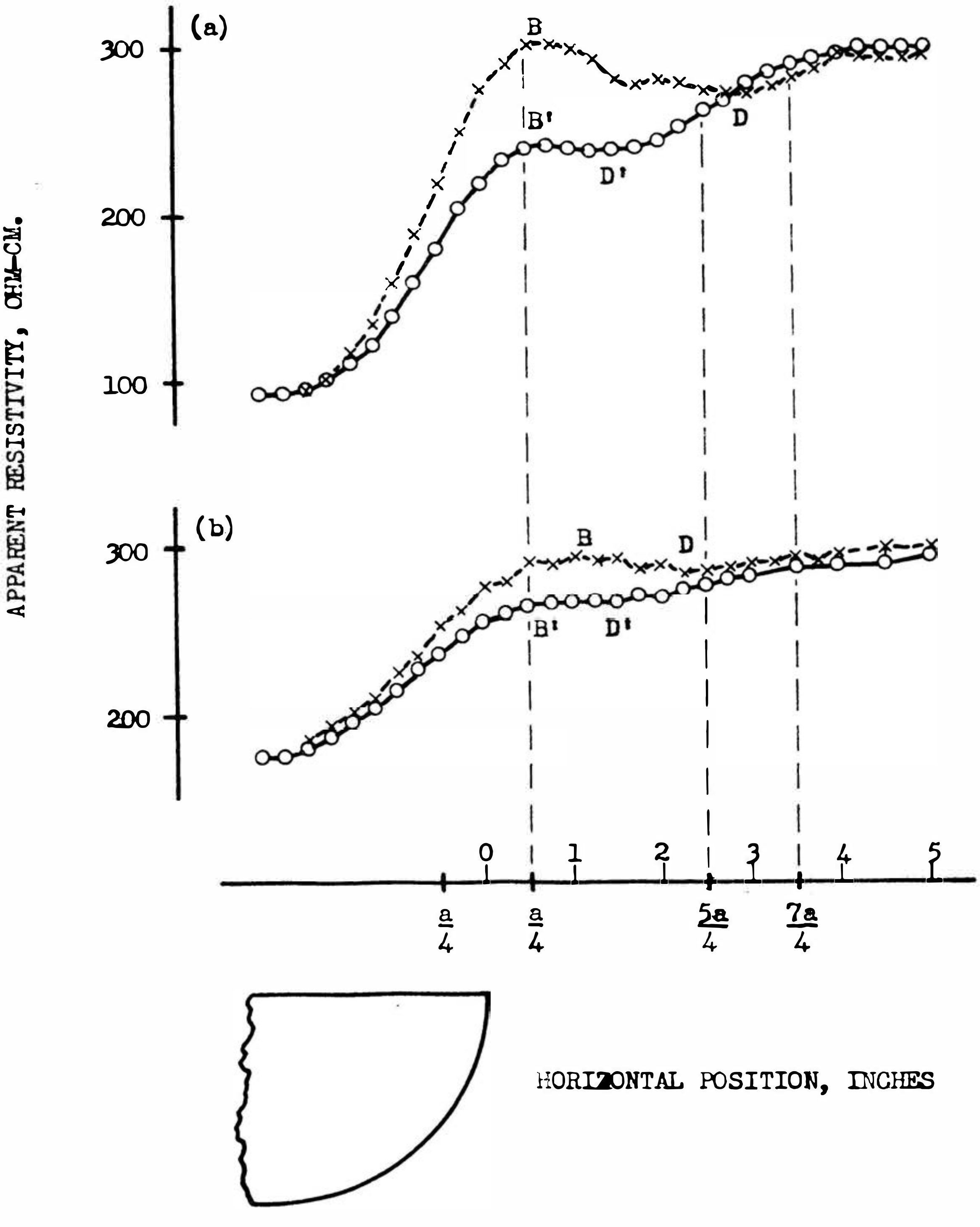


FIG. 23. HORIZONTAL RESISTIVITY PROFILES OVER THE CENTER OF A FIVE INCH DIAMETER CARBON HEMISPHERE, LEE CONFIGURATION. 'a' = 2 INCHES, DEPTH OF BURIAL IN (a) = 1-1/16 INCH, IN (b) = 1-1/2 INCH.

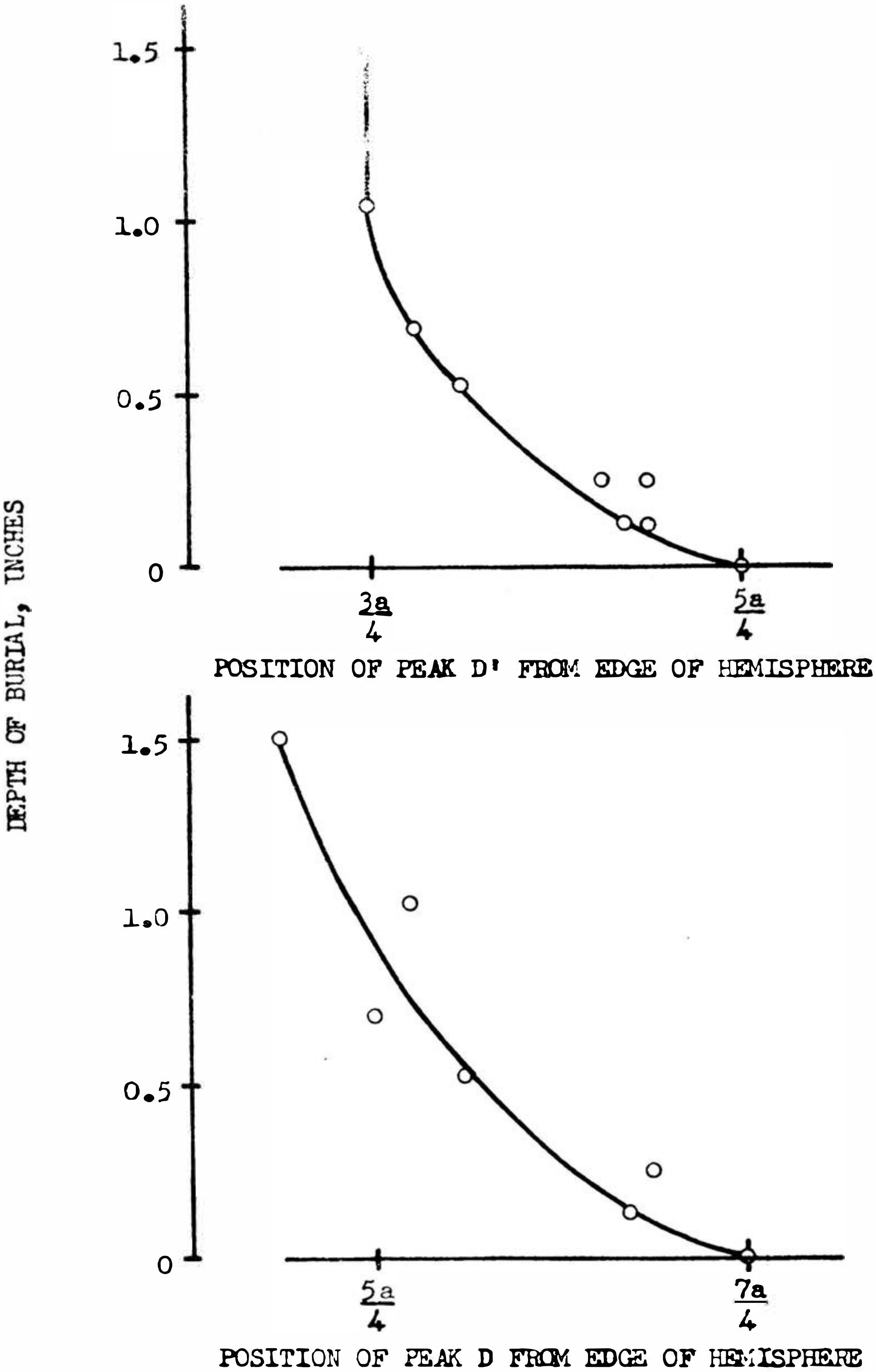


FIG. 24. POSITION OF PEAKS D' AND D FOR DIFFERENT DEPTHS OF BURIAL OF THE FIVE INCH DIAMETER CARBON HEMISPHERE. 'a' = 2 INCHES.

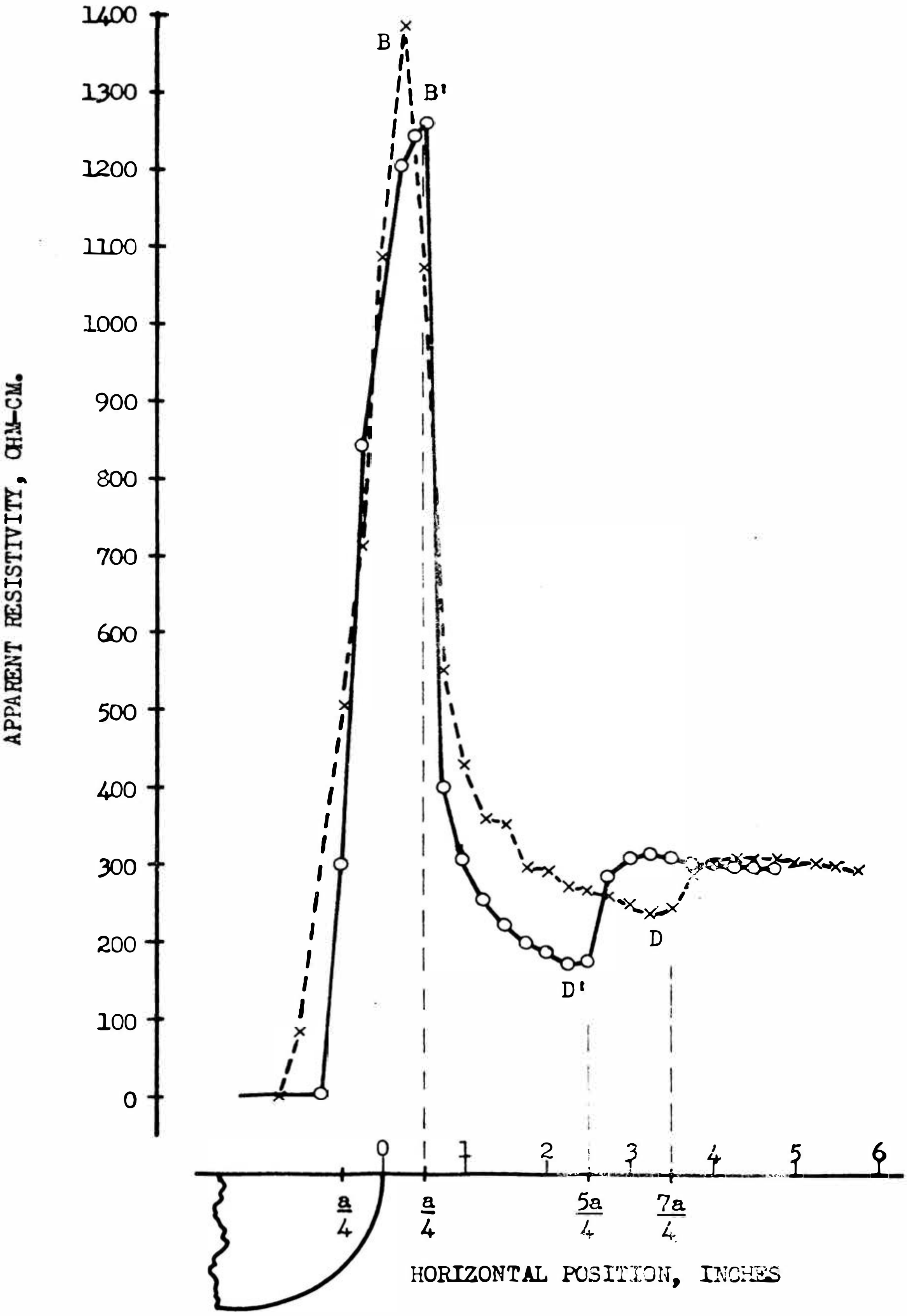


FIG. 25. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A THREE AND ONE-HALF INCH DIAMETER ALUMINUM HEMISPHERE. 'a' = 2 INCHES, DEPTH OF BURIAL = 0.

VII. CONDUCTIVE MODELS IN SAND

It has been shown in the previous sections that satisfactory results for horizontal resistivity profiles can be obtained by suspending models in a fluid conductive media. Although for some purposes this is fine and sufficient, for other purposes it is insufficient. If it were desired to reproduce two or more layers or beds in the model tank, it can be seen that this would be very difficult if not impossible using only fluid to represent the layers. Also the positioning of specimens in the fluid is a problem and accurate positioning is difficult, especially since one must be careful not to disturb the resistivity of the setup with the suspending vehicle.

One possible solution to this problem, and the one checked by this investigator, would be to use sand as a media in the tank. If the sand were then saturated with salt water and the salt water were filled to a level slightly higher than the sand, then this would more closely simulate the real case where the thin surface layer is underlain by a higher resistivity layer. If more layers were desired, then two or more different kinds of sand of different resistivity could be used or two or more sands of different size ranges so that the apparent resistivity would be different. As well as simulating more closely the actual case, the fluid layer at the surface with lower resistivity than the underlying media would give good electrical contact and make electrode positioning as easy as in the previous studies.

Kwentus tried using sand and encountered several difficulties. In his studies he used fine river sand, but at best there was a tremendous size range and much silt size particles were present. He added the sand to the salt water so that the concentration of salt water in the sand would be as uniform as possible. On his preliminary, or check runs, he obtained fairly linear results until he drained the tank and refilled it with salt water to change the concentration. After the tank had been drained, linear results were not obtained, not even after the upper six inches or so had been intimately mixed. Kwentus (1960, p. 51) states that this may have been due to migration of small conductive particles toward the drain end of the tank. Another possibility might be the concentration of salt toward the drain end of the tank.

In order to try to eliminate this problem, a fine graded and sized sand was used in the investigations. The specifications for this sand are given in the appendix. This sized and graded sand was much more nearly homogeneous and contained fewer impurities than did the sand used by Kwentus. It was found to give a slightly better linearity than did the sand used by Kwentus and it was easier to obtain this linearity. Also the nonlinearity present in this sand offered more gradual changes in resistivity than did that used by Kwentus.

Figure 26 is a resistivity curve over the five inch diameter hemisphere buried at a depth of seven thirty-seconds of an inch below the top of the fluid layer. The top of the specimen was flush with the top of the sand layer. The apparent resistivity of the media was about 1475 ohm-cm. Notice that the curve is of the type expected, with the peaks B and B' falling at the predicted distances and the peaks D and D' falling inside the predicted distances. This is what should be expected in light of previous findings.

Since the resistivity in the fore-mentioned run was extremely large in comparison with the other investigations, it was decided to add more salt to the solution and thus lower the resistivity to a value near that used in the previous studies. Salt was added by sprinkling it fairly uniformly over the surface and adding water in the same manner to replace water lost by evaporation. The tank was allowed to set for two days and a second run was then made. No other precautions were taken to assure a homogeneous media and an analysis of the results obtained indicated that no other precautions were apparently necessary. It should also be mentioned that no special precautions were taken in the placement of specimens in the sand. A small hole was scooped out in the sand and the specimen placed in the hole and the sand filled in around the specimen. The remaining sand was then distributed over the rest of the tank and the specimen was shifted until it was flush with the surface of the sand.

The results of this second resistivity profile are shown in Figure 27. The apparent resistivity of the media was about 325 ohm-cm. The profile was run first without the specimen in the tank and then with the specimen in place and both results are shown in Figure 27. Even though the background level of the resistivity of the media is not level it is fairly linear and the effect on the resistivity profile appears to be negligible, as the curve is of the type we would expect.

The foregoing seems to indicate that the sand can be used successfully provided that the resistivity contrast between the specimen and the enclosing media is large enough to make the nonlinearity of the tank small in comparison with the magnitude of the anomaly produced over the specimen.

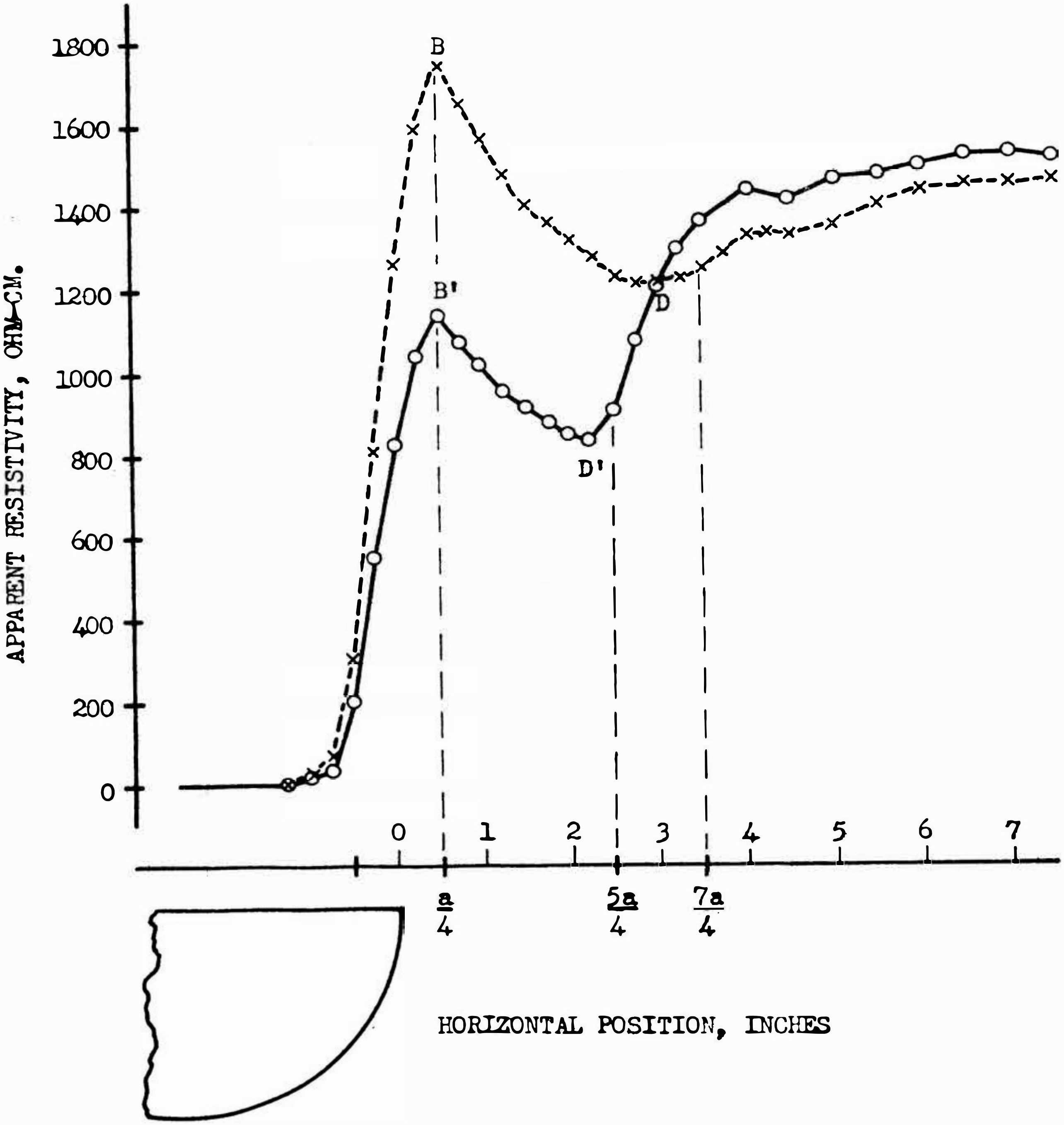


FIG. 26. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A FIVE INCH DIAMETER CARBON HEMISPHERE SUSPENDED IN A SAND MEDIA, LEE CONFIGURATION. 'a' = 2 INCHES, DEPTH OF BURIAL = 17/32 INCH.

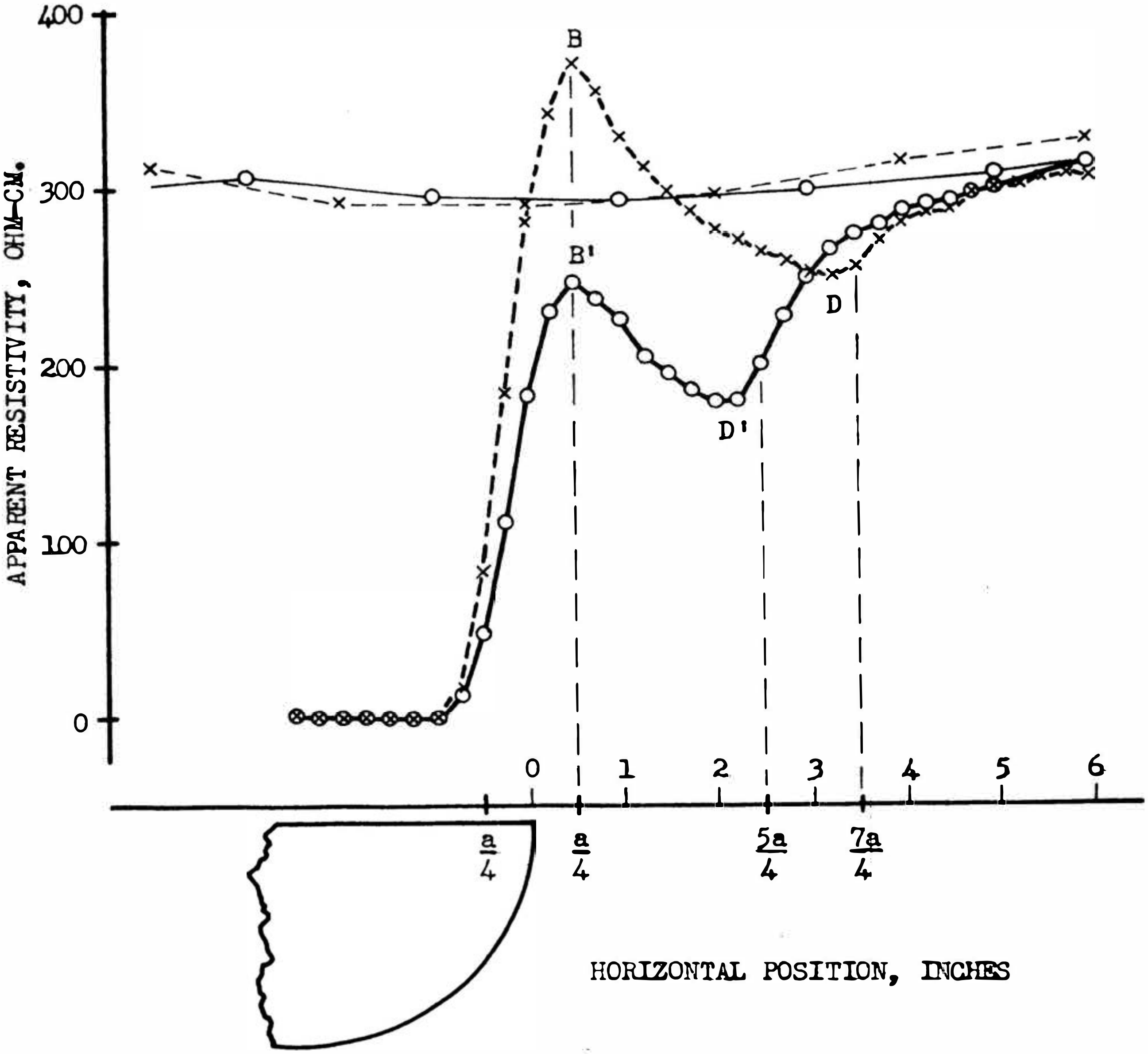


FIG. 27. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A FIVE INCH DIAMETER CARBON HEMISPHERE SUSPENDED IN A SAND MEDIA AND THE PROFILE OVER THE SAND WITH NO SPECIMEN, LEE CONFIGURATION. 'a' = 2 INCHES, DEPTH OF BURIAL = 3/16 INCH.

VIII. RESISTIVE MODELS IN SALT WATER

Horizontal resistivity profiles were also obtained over specimens that had a higher resistivity than the surrounding media. Very little work was done on these specimens, however, since there were no available theoretical curves for purposes of comparison. These curves have not been analyzed in any great detail and they are included for their academic interest only.

It might well be expected that if a hemispherical specimen were placed in a surrounding media of lower resistivity than the specimen, and the specimen were at the surface of the media in question, that the position of the characteristic peaks obtained by a horizontal resistivity profile across the body would be reversed to that of the case just studied where the resistivity of the specimen was less than the resistivity of the enclosing media. In other words, it might now be expected that the characteristic peaks would occur at distances of one-quarter 'a', one and one-quarter 'a', and one and three-quarters 'a' inside the edge of the hemisphere, rather than outside the hemisphere measured from the edge as in the previous case. It would also be expected that the two resistivity curves would cross at the center of the hemisphere.

The results of two of these profiles are shown in Figures 28 and 29. The first profile is over a three and five-eighths inch diameter hydrostone hemisphere with a varnished surface. Notice that the two resistivity curves cross at the center and diagnostic peaks occur at approximately the positions expected. Due to the small diameter, the edge effects due to one side of the specimen appear to be superimposed with edge effects from the other side to give less diagnostic peaks especially one-quarter 'a' inside the edges of the hemisphere. The expected characteristic peaks at one-quarter 'a' outside the edge of the hemisphere don't appear to have materialized, at least not to any appreciable degree, in the first curve shown.

It should be remembered that there are several factors that might well cause these peak positions to deviate from the predicted positions. For one thing, the curves are not continuous but represent discreet points on the resistivity curve and therefore don't necessarily fall at exactly the maximum and minimum points on the curves. On the basis of previous findings it might also be expected that the depth of burial has altered the position of the characteristic peaks.

Figure 29 is a resistivity profile for a two and three-quarter inch diameter rubber hemisphere, made by cutting a solid rubber ball in half. Notice that again the curves cross at the center as would be expected and the peaks are falling at approximately the predicted positions. In this case as in the previous case, the edge effects from one side appear to be superimposed with the edge effects from the opposite side, to give characteristic peaks between the two predicted points. This is illustrated just outside the edge of the hemisphere where the point one-quarter 'a' from one edge of the hemisphere and the point one and three-quarters 'a' from the other side of the hemisphere are very near one another and the peak falls halfway between these two points. This same thing is illustrated just inside the edges of the hemisphere where the point one-quarter 'a' from one side and one and one-quarter 'a' from the other side fall very near one another.

The results of these two studies seem to indicate that the characteristic peaks for bodies more resistive than the surrounding media probably fall at the distances predicted by the opposite case where the resistivity of the specimen was less than the resistivity of the surrounding media. Probably the only change would be that in this case the peaks would fall at the predicted distances inside the hemisphere as measured from the edge of the hemisphere rather than outside it.

These curves appear to indicate that usable results might well be obtained from resistive models. In any further investigations it might be well to study some models with a larger ratio of diameter to electrode spacing so that the edge effects from one side would not interfere with the edge effects from the opposite side of the specimen.

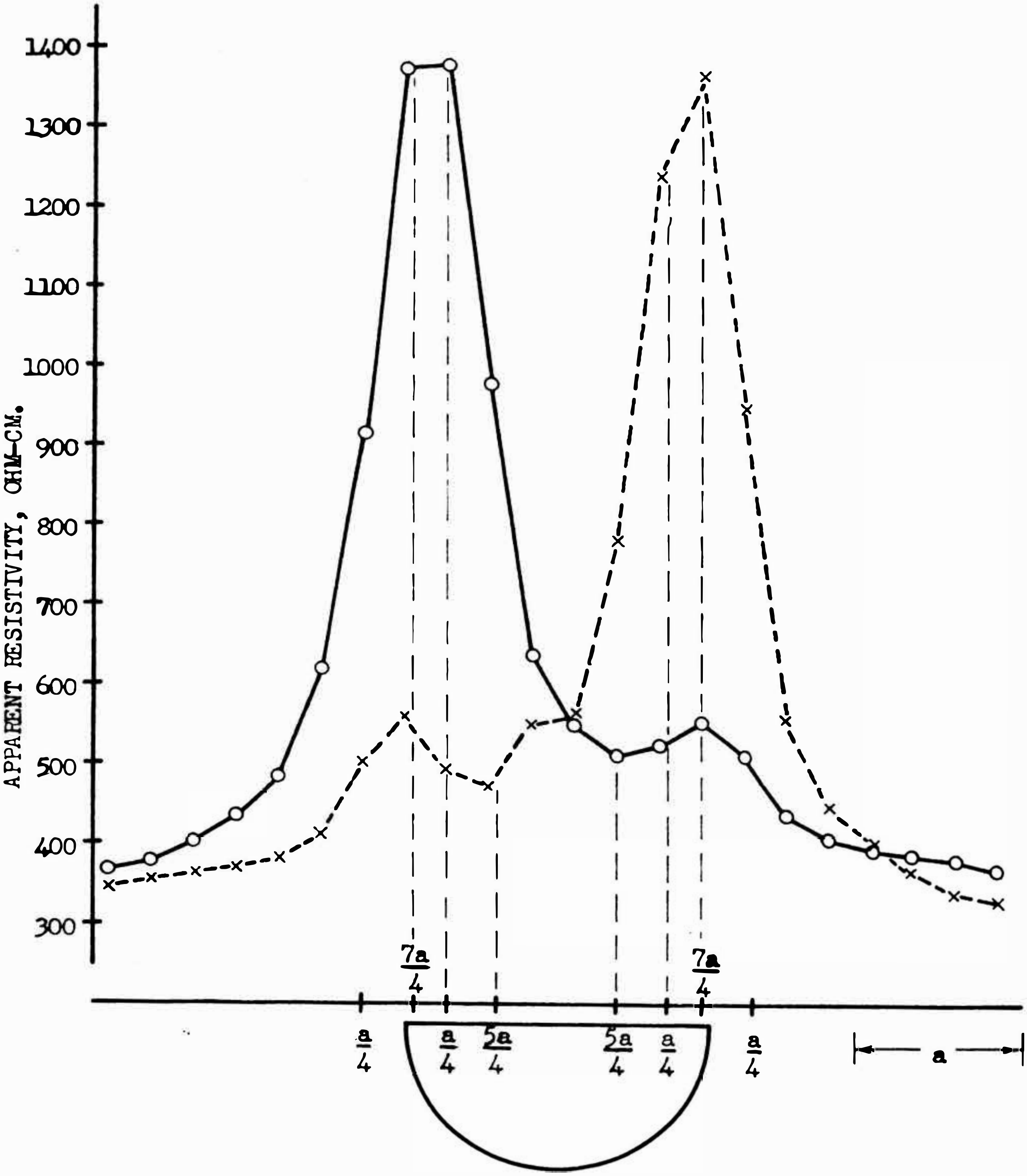


FIG. 28. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A THREE AND FIVE-EIGHTHS INCH DIAMETER HYDROSTONE HEMISPHERE, LEE CONFIGURATION. 'a' = 2 INCHES, DEPTH OF BURIAL = 1/4 INCH.

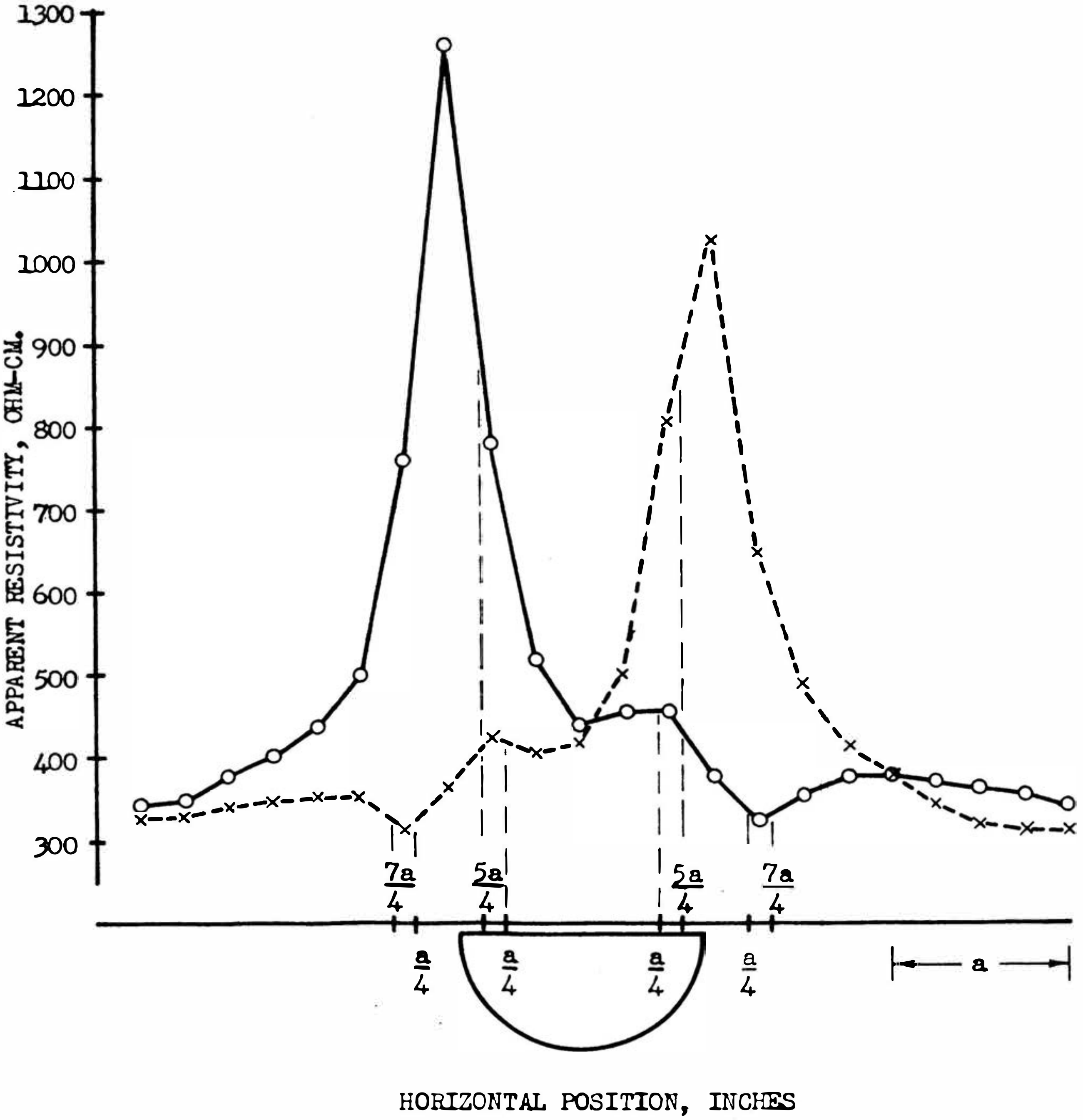


FIG. 29. HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A TWO AND THREE-QUARTER INCH DIAMETER RUBBER HEMISPHERE, LEE CONFIGURATION. 'a' = 2 INCHES, DEPTH OF BURIAL = 1/8 INCH.

IX. CONCLUSIONS

This investigation has brought about the following conclusions and observations:

A. Primary

1. Theoretical type horizontal resistivity profiles can be produced by the use of model studies. They were produced for a hemispherical conductor and there has been nothing found to indicate that theoretical type curves can not be obtained by model studies for other shapes of conductive specimens.

2. Depth of burial has a very definite influence on the position of the characteristic peaks, and this influence is felt most drastically on the two characteristic peaks at the greatest distance from the edge of the hemisphere, and felt to a lesser degree on the two major peaks nearest the outside edge of the hemisphere.

3. In addition to affecting the positions of the characteristic peaks, depth of burial also has a marked influence on the magnitude of the apparent resistivity. In the conducted studies the characteristic peaks were almost obscured at a depth equal to three-quarters the electrode spacing. At that depth the predominant feature was a gentle trough over the center of the hemisphere.

4. On the basis of all the findings it appears that the electrochemical activity of the aluminum specimen had little or had nothing to do with the position of the characteristic edge effects and that it probably had little to do with the magnitude of the apparent resistivity. The aluminum specimen is not a good specimen material but a good explanation for that fact was not found.

5. Successful model studies can be conducted in a media such as sand rather than in a fluid media, provided that the resistivity contrast is great enough to minimize the inhomogeneity of the media.

This type media gives the added advantages of easier and more accurate specimen placement, and the possibility of more than one layer but at the sacrifice of some of the accuracy due to the inhomogeneity of the sand.

6. Preliminary studies also indicate that successful model studies can be carried out with models more resistive that the enclosing media. The positions of the characteristic edge effects in this case appear to be located at the distances predicted for the conductive specimens except in this case they will be located over the specimen rather than outside the edges of the specimen as in the previous case.

B. Secondary

1. The positions of the characteristic peaks over a hemispherical conductor more conductive than the surrounding media are independent of the resistivity and the resistivity contrast.

2. The positions of the characteristic edge effects are independent of the ratio of the diameter to the electrode spacing except that the peaks over the hemisphere may be obscured for large electrode spacings.

3. The Lee partitioning configuration gives more detail than the Wenner configuration, as has been indicated by previous investigators.

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XI. APPENDICES

APPENDIX 1

INFLUENCE OF DEPTH OF BURIAL ON THE SELF POTENTIAL ANOMALY

Specimen--Aluminum hemisphere	Diameter--3½ inches
Profile position--Center of hemisphere	Electrodes--Non-polarizing

Stationary electrode located 26 inches north of the center of the specimen.

Position of Electrode 1	Position of Electrode 2	Potential Difference Between Electrodes 1 & 2	Depth of Burial
26 N	22 N	- 8 millivolts	
26 N	1 S	-122 mv.	3/16 inch
26 N	1 S	- 38 mv.	1/2 inch
26 N	1 S	- 10 mv.	7/8 inch
26 N	1 S	- 10 mv.	1-1/2 inch
26 N	1 S	- 10 mv.	2-7/16 inch

The electrodes were just making contact with the water during these investigations. The position 1 S was approximately 1/4 inch from the edge of the hemisphere.

APPENDIX 2

A STUDY OF THE EFFECT OF INDUCED POTENTIAL ON THE APPARENT RESISTIVITY

Configuration--Wenner Position of configuration--Center of tank

Specimen--None Electrode spacing--Two inches

P_1P_2 E/I ohms	Induced current flowing from E_1 to E_2	Position of E_1	Position of E_2
10.9	None		
10.9	50 ma.	16 N	16 S
10.9	-50 ma.	16 N	16 S
10.9	100 ma.	5 N	5 S
10.9	-100 ma.	5 N	5 S
10.4	100 ma.	5 N	0
10.8	-100 ma.	5 N	0
12.0	100 ma.	5 N	1 S
10.9	100 ma.	5 N	3 S, 6 W
10.9	-100 ma.	5 N	3 S, 6 W
10.9	100 ma.	3 N, 18 E	3 S, 6 W
10.3	50 ma.	2 N	0
10.4	-50 ma.	2 N	0

The electrode positions given are measured in inches north, south, east, or west of the center of the Wenner electrode configuration which was located at the center of the tank. The position 1 N is coincident with the P_1 electrode of the configuration and 1 S is coincident with the P_2 electrode of the configuration.

APPENDIX 3

HORIZONTAL RESISTIVITY PROFILE OVER THE CENTER OF A FIVE INCH DIAMETER CARBON HEMISPHERE

Configuration--Lee Profile Position--Center of Hemisphere

Specimen-- 5" Carbon Hemisphere Data Presented in--Figure 19

$a = 2$ inches, Depth of Burial = 0, $k = 63.84$

Date--October 26, 1960 Recorder--Hornsey

Tank conditions--20" Salt Water, Pencil Electrodes

0 at Center, Water over Hemisphere = 0

P_o Position	P_1P_o E_1/I	ρ_1 ohm-cm.	P_2P_o E_2/I	ρ_2 ohm-cm.
7.5 S	4.03	258	4.10	262
7.0 S	4.05	259	4.20	268
6.75S	4.01	256	4.20	268
6.5 S	3.98	254	4.15	265
6.25S	3.82	244	4.12	263
6.0 S	3.63	232	3.98	254
5.75S	3.21	205	3.85	246
5.5 S	2.10	134	3.35	214
5.25S	2.20	140	3.42	218
5.0 S	2.43	155	3.55	227
4.75S	2.53	162	3.63	232
4.5 S	2.73	174	3.71	237
4.25S	3.00	192	3.85	246
4.0 S	3.32	212	4.01	256
3.75S	3.70	236	4.12	263
3.5 S	4.90	313	4.39	280

APPENDIX 3 (Cont.)

P_o Position	P_1P_o E_1/I	ρ_1 ohm-cm.	P_2P_o E_2/I	ρ_2 ohm-cm.
3.25S	4.09	262	4.72	302
3.0 S	3.10	198	4.93	315
2.75S	1.83	117	5.60	358
2.5 S	0	0	6.33	404
2.25S	0	0	5.61	358
2.0 S	0	0	4.36	278
1.75S	0	0	2.71	173
1.5 S	0	0	0.42	27
1.25S	0	0	0	0
1.0 S	0	0	0	0
1.0 N	0	0	0	0
1.25N	0	0	0	0
1.5 N	0	0	0	0
1.75N	2.48	158	0	0
2.0 N	4.39	280	0	0
2.25N	5.62	359	0	0
2.5 N	6.42	410	0.08	5
2.75N	5.93	379	1.51	96
3.0 N	5.23	334	2.88	184
3.25N	4.72	302	4.16	266
3.5 N	4.49	287	4.88	312
3.75N	4.30	275	3.95	252

APPENDIX 3 (Cont.)

P_o Position	P_1P_o E_1/I	ρ_1 ohm-cm.	P_2P_o E_2/I	ρ_2 ohm-cm.
4.0 N	4.03	258	3.40	217
4.25N	3.88	248	3.05	195
4.5 N	3.77	241	2.82	180
4.75N	3.68	235	2.62	167
5.0 N	3.59	229	2.42	155
5.25N	3.48	222	2.30	147
5.5 N	3.39	216	2.19	140
5.75N	3.81	243	3.18	203
6.0 N	4.08	261	3.76	240
6.25N	4.19	268	4.02	257
6.5 N	4.28	274	4.19	268
6.75N	4.33	276	4.25	272
7.0 N	4.35	278	4.30	275
7.5 N	4.41	282	4.40	281

APPENDIX 4

SAND ANALYSIS

Chemical Analysis

Ottawa Silica Co. Sand

Silicon dioxide (SiO_2)	99.59 %
Iron oxide (Fe_2O_3)	0.026
Aluminum oxide (Al_2O_3)	0.08
Titanium dioxide (TiO_2)	0.014
Calcium oxide (CaO)	0.07
Magnesium oxide (MgO)	0.08
Loss on ignition	0.14

U.S. Screen Analysis

Washed & Dried Ottawa Sands

Banding Sand

AFA Grain Fineness - 88

On U.S.	# 50	3%
	70	30
	100	40
	140	20
	200	6
Passing	200	1

Purchased from: Midvale Mining & Mfg. Co.
5015 Manchester Avenue
St. Louis 10, Missouri
Phone: FRanklin 1-2442

XII. VITA

Edward Eugene Hornsey, son of Mr. and Mrs. Lewis E. Hornsey, was born on May 31, 1937, at Potosi, Missouri. He attended grade school and high school in the Potosi public schools and graduated from high school in May, 1955.

In September, 1955 he entered the Missouri School of Mines and Metallurgy, and received the degree of Bachelor of Science in Mining Engineering, in May, 1959.

During the school year 1959-60 he was employed as a graduate assistant in the Mining Department, while doing graduate work leading to the degree of Master of Science in Mining Engineering. He continued his graduate study during the school year 1960-61 while on appointment as Instructor in Mechanics in the Mechanics Department at the Missouri School of Mines and Metallurgy.

On November 26, 1959, the author was united in marriage to Joyce L. Albert of Ferdinand, Indiana.