A Method for Locating Abandoned Mines

By R. G. Burdick, L. E. Snyder, and W. F. Kimbrough
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#### UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

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ABSTRACT

The problems presented by old mine workings affect both present-day mining and land development. An automated method of locating these old mines from the surface using electrical resistivity techniques was developed earlier under a Bureau of Mines contract. Subsequent Bureau research has refined the techniques and expanded the area of study to a variety of geologic provinces.

During this research, six mining areas in the United States were investigated with the Bureau's automated resistivity method. This report describes the mining areas involved and the results of the resistivity investigations, which showed a high rate of success in detecting old mines. It also describes the field measurement techniques and data analysis procedures.

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2Mining engineer.
3Electronics technician.

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INTRODUCTION

Abandoned mines are a recurring problem for today's mining industry. In coal, metal, and nonmetal mining they pose a safety hazard if current workings intersect them; and if they are circumvented, large amounts of recoverable resources may be unnecessarily left in the ground.

The problem of delineating the boundaries of these old mines is multifaceted. In most cases, entry is precluded by flooding, caving, or extremely unsafe conditions below ground. In many cases the company that did the past mining has gone out of business, or the old mine maps were incomplete and/or inaccurate, or are missing. Particularly in the case of coal mining, using room and pillar methods, extraction was sometimes less than 50%. Therefore a drilling program is as likely to encounter coal as a void throughout an old mine area.

The resistivity method developed for detecting these old mines has been designed to allow rapid coverage of an area suspected to contain old workings and to delineate the boundaries of these workings where they exist; although it cannot reliably detect individual openings at all depths, it appears to detect boundaries of mined and unmined areas reliably. The method employed was originally developed by Bristow (1) to locate shallow caverns and passages in limestone karst topography. It has been modified by the Bureau to locate air-filled or water-filled voids in mining environments.

This report covers both the results of earlier contract research (2-3) and 2 yr of in-house research involving six mine sites in four States (Illinois, Wyoming, Colorado, and Kentucky). A total of 16 test lines were run at these sites, and corroborative drilling tests were made at 3 of the sites. The sites encompassed both shallow mines and mines that occurred near the theoretical detection limits.

DISCUSSION OF RESISTIVITY THEORY AS IT PERTAINS TO VOID DETECTION

A mine void in the earth (in an electrical context) may be thought of as a "system" composed of (1) rock and soil, (2) the interstitial free water contained in the soil or rock, and (3) the mine void itself, which may be either air or water filled. The rock materials themselves have very high resistivities (hundreds or thousands of ohm meters) and may be considered as mainly a matrix or framework for the contained free water. It is this water and its dissolved salts that allow conduction of the electrical current for our measurements. Air also has an extremely high resistance and may be considered as an insulator at the voltage levels used for the tests.

While the effect of large discrete voids is readily apparent, small cracks or voids, when occurring in extremely large numbers, may easily show the same overall effect. In a mining environment, these can be microfractures or delamination phenomena above the void which may migrate upward as subsidence phenomena. These cracks may be either air or water filled and will normally be interpreted as void areas.

Electrical resistivity measurements are performed by injecting an electric current into the ground and measuring the resultant voltage potentials generated by this current. Since the method's inception over 50 yr ago, many different electrode configurations have been used for a variety of purposes. The pole-dipole (Bristow) array is but one of the configurations used. The two other more commonly used arrays are the Wenner and the Schlumberger. For illustrative purposes the Wenner and Bristow arrays will be compared.

The Wenner method uses two current and two potential electrodes in a linear, symmetrical array (fig. 1). The current is injected between the two outer current electrodes, and the potential difference is measured between the inner

Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.
pair. As can be seen from the figure, the measurement volume is a function of the electrode separation. To make deeper measurements, the electrode spacings are increased, which results in a larger hemisphere being measured. Theoretically, this electrode expansion can be continued to make measurements to any depth. However, in practice, the volume of the hemisphere becomes so large that a mine void imposed within it would be undetectable.

The equation for calculating apparent resistivity \( \rho_a \) for the Wenner method is
\[
\rho_a = 2\pi a \frac{E}{I},
\]
where \( I \) = current injected between outer electrodes,
\( E \) = potential difference measured between inner electrodes,
and \( a \) = electrode separation distance (as shown in figure 1).

It has been found that the void detection capability of the method is limited by the ratio of the diameter of the void to the depth of overburden material. The ratio of either the Wenner or Schlumberger method is normally taken to be 1:4 or less (4).

The Bristow method uses one current electrode near the measurement site and another, the sink electrode, at effective infinity (five to 10 times the maximum depth of investigation). The two fixed-spaced potential electrodes are moved as a pair away from the current electrode in order to make deeper measurements (fig. 2). The measurement volume involved in this case is a hemispherical shell whose thickness is equal to the potential-pair separation and whose radius is equal to the current-potential electrode separation.

The equation for calculating apparent resistivity \( \rho_a \) for the Bristow method (pole-dipole) is
\[
\rho_a = \frac{2\pi}{\left( \frac{1}{r_1} - \frac{1}{r_2} \right)} \frac{E}{I},
\]
where \( I \) = current injected between current and sink electrodes,
\( E \) = voltage difference measured between potential electrodes,
\( r_1 \) = distance between current electrode and first potential electrode,
and \( r_2 \) = distance between current electrode and second potential electrode.

As is apparent, for a given depth, the volume of material being measured by this method is much smaller than for the Wenner, and the detection capability for a void is increased to a void-overburden ratio of 1:10, or under ideal conditions to 1:15 (5).

The term \( 2\pi \frac{E}{I} \) is the same for both equations 1 and 2. However, the geometry factors—"a" for the Wenner and \( \frac{1}{r_1} - \frac{1}{r_2} \) for the Bristow method.
for the Bristow—-are vastly different and become even more pronounced as the depth of investigation increases. As an example, for a 5-m depth, the volume measured by the Wenner is 262 m³ compared with 205 m³ for the Bristow, using a 2-m potential separation. In this case, the volume of the Bristow is 78% that of the Wenner. However, for a 50-m depth the Wenner volume is 261,792 m³ and the Bristow volume is 30,175 m³, or 11.5% that of the Wenner (fig. 3). From the above, it is obvious that the Bristow method is much more sensitive to the presence of voids than the other methods as the void represents a much larger percentage of its measurement volume.

However, even the Bristow method could theoretically detect a 2- by 2-m void at a maximum depth of only 20 to 30 m. From this it is inferred that some other phenomena are at least partly responsible for the deeper apparent voids that have been detected during this research. The concept of microfracturing above an opening in the earth appears to correspond with much of the field data acquired to date. The effect of subsidence features migrating or stoping upward from the void itself would also correspond with much of the data. One or both of these effects may be partly responsible for the fact that known voids are often shown higher in the section than their known depths. Still another possible reason for being able to detect voids at greater than theoretical detection depths might be that the electrical current distortions caused by multiple voids may be larger than those from a single void.

Which of the above phenomena is responsible for the ability to detect old mines is not known. It has been shown, however, that the deeper voids are detectable, although they generally are shown to be above the known or suspected depth of the void. This vertical transposition of the data seems to be a function of depth. That is, deep voids tend to show more vertical displacement than shallow voids.

In some cases the interpreted void is apparently skewed slightly toward the infinity electrode. In a short series of tests performed by Southwest Research Institute (SwRI), it was found that the potential field around the current electrode is not circular in plan view, but is rather of an elliptical or tear-drop shape with the long axis parallel to the current-sink electrode axis. This shows that the current-sink electrode separations, classically assumed to be effectively infinity, are not sufficient.

One technique that will detect skewness and allow for correction is to run the test line twice—with the sink electrode being placed equal distances from opposite ends of the line. This requires a double effort, but in some cases may be worth the extra work involved in that the skewness can be detected and removed.

DESCRIPTION OF AUTOMATED RESISTIVITY METHOD

In explanation of the Bristow method above, the original techniques were described—that is, the potential pair electrodes were moved incrementally away from the current electrode as deeper readings were taken. In effect this
results in a vertical resistivity profile of short lateral extent being developed. To cover a greater lateral area, the current electrode would then be moved ahead and the process repeated. While feasible, this process would require several days. Therefore, specialized equipment was developed for the Bureau by SwRI which allows much faster and more accurate data acquisition as well as digital data recording. This equipment, referred to as the automated resistivity system (ARS), is designed as a rugged, automatic system for performing Bristow-type surveys with a minimum of human intervention. The system is described in appendix C.

In operation, 1 to 64 current electrodes are implanted at the desired positions. These electrodes are then connected to individually addressable control modules, which are in turn connected to the current-address cable. This cable is controlled by the system and allows individual, sequential energization of the various electrodes. Therefore, by setting the pair of potential electrodes once and reading the resultant voltages as each current electrode is automatically energized, a large number of readings may be taken in only slightly more time than would be required for one reading in a manual mode. These readings are recorded on digital magnetic tape for later interpretation. The potential electrodes are then moved ahead one increment, and the process is repeated.

Using this technique, a test line 640 m long with current electrodes implanted every 10 m, sampled to a depth of 100 m in 2-m increments, can be completed in 1 working day using a field crew consisting of four or five persons. It has been found that two such lines may be run in 3 days. The extra day would be spent in laying cables, planting current electrodes, surveying, etc., in preparation for performing the tests themselves. A more complete description of the detailed field techniques and work assignments is given in appendix D.

DATA INTERPRETATION

A large amount of data is recovered on each test line, and a computer is required for their interpretation. To date, two separate interpretation methods have been used. The first, developed by SwRI (2), constructs a computer model and inserts a void at some discrete location within the section. It then compares the field data with this model and assigns a correlation number in the range of 0 to 1, depending on how well the field data correspond to the model. It then iteratively changes the location of the void in the model and compares its correlation with the data. Upon completion, a profile of the section is drawn based upon these correlation numbers. This results in contours where the higher numbers represent the higher probability of the void's location. The computer model may be used to look for both air-filled and water-filled voids. This method is referred to in this paper as the probability contour model.

The second method, used by the Bureau, simply calculates the resistivities of the field data and plots the information as a simple pseudosection beneath the current electrode positions. Based upon this profile section of resistivities, the interpreter makes decisions as to the location of voids. The second method uses much less computer time and allows the interpreter to interject personal knowledge of the area into the final interpretation. A description of these computer programs and their logic appears in appendix B.

DISCUSSION OF METHOD

The technique that has been described is a rapid, inexpensive method for investigating a large area in order to define the boundaries of old workings. However, it must be realized that phenomena other than old workings can cause some of the anomalies noted. Therefore, when interpreting the results, judgments must be
made as to what the anomalies shown by the data actually represent.

For example, at Sheridan, WY, the Monarch Mine was defined clearly by resistivity lows. These corresponded with the known edge of the old mine as well as with surface subsidence features. However, our drill tests at the nearby Acme Mine showed that one particular low anomaly drilled was caused by a wet silt pocket. In both cases the data were correct—there was an accumulation of moisture that caused a resistivity low. In one case it had collected in the silt, while in the other it had collected in the subsidence-caused loose material.

At the other extreme was the case at the Busick Mine, in Kentucky, where a known air-filled working was masked by an artificially created, perched water table located nearer to the surface. Surface water leaching through the spoil material and perching near the original ground surface created a highly conductive layer that tended to act as an electrical shunt and prevented a majority of the current from reaching the old workings below. While this was an isolated incident, it illustrates that judgment must be exercised in interpreting the data.

In general, the method may be used in most terrains. However, buried electrical conductors may adversely affect the results and should be avoided.

The current flow paths are assumed to approximate those shown in figure 2 when the data are calculated and displayed for interpretation. If a nonearth flow path exists between the current and sink electrodes or between the current and potential electrodes, the model and associated equations for apparent resistivity are not valid and the calculated values will be in error. For this reason, it is not advisable to perform resistivity tests where any metallic conductors, such as pipelines or fences, are present.

In coal mining, it must be considered that the old mines in this country were of the room and pillar type, and extraction, in some cases, was only about 50%. From this it can be inferred that 50% of the coal remains in these areas. In ordinary drilling tests, the drill may not encounter the old mine voids and so they will remain undetected. However, in the case of a resistivity survey of a mine area, the workings will probably be detectable. This is because resistivity is an areal technique, whereas drilling provides a single-point measurement.

Also, as pertains to drilling, it must be closely monitored and even subtle changes in the drilling noted. Loss of water or air, even for a short distance, should be logged. Softer, more easily drilled material at or above the old mine level should be noted. Unusual moisture conditions (in the case of pneumatic drilling), either within a hole or between adjacent holes, may be important in making the interpretation. Furthermore, to assure that complete observations are made, a trained observer should be at the drill throughout the drilling program, instead of having the driller make the observations. Drillers are trained to do the most rapid and efficient drilling in given situations, rather than as observers. Even the most conscientious driller may have stepped away to do minor maintenance work on the drill when some transient feature is encountered; thus it passes undetected. In other cases, the drillers' background does not show them the importance of what they see. For example, on one project it was noted by the driller that the hole did not encounter any evidence of mine workings. However, air blew out of a nearby hole, which had also bottomed at the old mine level. In many cases this would not have been entered in the driller's log. To the driller it was only a curiosity, while to a trained observer it could represent important evidence.

FIELD TEST RESULTS

The results below briefly summarize each of the six test sites investigated to date. Data analysis and other pertinent information on each site appear in appendix A.
CENTRAL CITY, KY--BUSICK MINE

Four test lines were run at this site by SwRI under a Bureau research contract. This was an active mine which contained abandoned, flooded sections, as well as air-filled workings. For three of the lines surveyed, resistivity high and lows were indicated in close proximity to known air-filled and water-filled mine workings. The anomalies were consistently shown shallower than the known depths of the mine. The fourth line was run across a large, flat strip mine spoil area which had been emplaced over an air-filled section of the mine. The natural ground beneath the spoil area was a heavy clay material. In this case there was no indication of the mine in the data; however, an almost solid layer of resistivity lows showed at about the interface between spoil and natural ground. It was theorized that surface water was percolating through the spoil and leaching out soluble minerals, thus forming a highly conductive layer perched on the old natural ground surface. This, in effect, shunted the electric current from penetrating deeper and prevented us from seeing the underlying resistivity highs from the mine workings.

MARSHALL, CO--U.S. GEOLOGICAL SURVEY TEST AREA

At this site the same physical line was run twice, with the current sink electrode at opposite ends of the line. In this manner it was possible to estimate the amount of skew the data would exhibit toward the sink electrode. The mine workings are 70 to 100 yr old.

The test line was laid out to cover both an abandoned mine and an equal area of unmined coal. It was later determined, however, that the supposedly unmined area had indeed been mined by another company. The original overburden thickness in the area ranged from 14 to 26 m. Based upon resistivity data, three holes were drilled. Two in high anomalies encountered voids, the third was in a low anomaly and encountered coal with free water at the base of the coal.

DANVILLE, IL--VJ-DAY MINE

This line was run in the same manner as the Marshall test with reversed current sink electrodes. The mine had been closed for 25 to 30 yr. Complete mine maps of the section were available, and surface control was excellent. However, during the field tests it was discovered that after the mine officially closed during the 1950's, several small groups of miners periodically mined for the next 6 to 7 yr. The depth to coal was approximately 45 m.

The data show persistent low anomalies at about the expected mine elevation, corresponding in a general way to the mined-out areas. An east-west set of main entries near the center of the line shows much wider anomalies than the entries themselves, and it is speculated that this might have been where the illegal mining took place.

SHERIDAN, WY--ACME MINE

This site was selected because it offered a deeper target, 65 to 75 m, and had good location control between the surface and the old mine workings. This test line was run in a reverse sink electrode configuration similar to that used in the Marshall and VJ-Day Mine tests. At this site the terrain was rolling, sage-covered, open land without habitation. For this reason the infinity electrode separation was extended to approximately 1,830 m without interference. There may be some lessening of data skewness on these tests, but it is not significant.

Most of the test area is underlain by sandstone at shallow depth. Near the center of the line many cracks and open fissures to 2.5 m or more in depth were observed. As other, shallower overburden sections of the same mine were showing spectacular massive subsidence, it was speculated that this broken sandstone might also be subsidence related. The test line was established to center it over the old mine boundary, as shown on the mine map, as the company presently operating in this area had indicated
there was some uncertainty as to the exact boundary. In addition, the line was positioned well south of a short series of "stub entries" shown on the mine map.

When trying to reconcile the data with the mine plan, it was learned that, while the working mine map was dated 1-3-38, the mine had continued operation until April 1941—a period of 27 months. It was not determined precisely where mining had taken place during this time, but it was somewhere in the vicinity of the test area. Corroborative drilling was attempted the next summer to verify the anomalies detected. At this time, active strip mining of the overlying coalbeds was in progress. In order not to interfere with the mining operations, drilling was accomplished in only one small area to the west of the mapped mine workings. On the basis of these holes it was determined that the low anomaly in this particular spot had probably been caused by a moist silt pocket. We were unable to drill any of the known mine area anomalies.

SHERIDAN, WY--MONARCH MINE

This site offered a shallower mine than the Acme (approximately 20 m) in the same geologic setting. The edge of a large panel had been precisely located during previous work by the Bureau and Office of Surface Mining on a mine fire at this location. The area near the test line showed extensive subsidence, and several craters and fissures were very close to the line.

The data show the edge of the mine quite clearly with a slight skew toward the infinity electrode. Several subsidence features seen on the surface also show in the data. It was not deemed safe to drill this site owing to the subsidence and rough surface topography.

SPARTA, IL--HOLIDAY MINE

This test site was used for two reasons. First, it offered a target 80 to 85 m deep, which is near the theoretical maximum depth of the ARS technique, and second, it was an area of extreme interest to a mining company planning underground development near the suspected limits of the old mine.

There was no mine-map control at this site. The mining company had performed some drilling in the area but had encountered a void in only one of four holes drilled.

Field tests were conducted during 1981 and 1982. During both field seasons rainy weather was encountered, which caused the surface materials to be moist for several days at a time. While this helped in making electrode contact with the soil, it may have caused some surface "shunting" of the current, similar to what happened on Line 4 at the Busick Mine in Kentucky. The 1981 tests consisted of a north-south line starting near the drill holes and progressing southward to what was assumed to be well beyond the old mine. A second line was started about midway along the first line and ran westward 700 m. It appeared that the old workings were visible in the data and extended farther than suspected by the mining company. For this reason, additional tests were performed in 1982. Line 2 was extended westward and line 1 southward. In addition, two more long north-south lines were run to the west of line 1. On the basis of these tests, an assumed "dangerous" perimeter was drawn around the old mine, and a zone where mining should only be approached cautiously was drawn to the south of the danger zone. While the old mine was not completely delineated at this site, enough information was obtained for the mining company to make a judgment as to the boundaries of the old workings.

SUMMARY AND DISCUSSION

The six mining areas investigated to date have ranged from shallow to deep in both wet and dry environments. While this number of mines cannot represent all possible conditions that might be encountered, it does offer a broad range of test conditions.
In general, the tests have been successful. In some cases the tests answered the question as to the location of the old mines but raised other questions that were not always satisfactorily answered. Examples of such questions follow: why the anomalies tend to be translated in the data toward the current sink electrode, why the anomalies tend to show higher in the section than the mine's known depth, and why only portions of the old mines seem to show, when a more general occurrence of anomalies would be expected.

Of 16 test lines run, only 1 failed to detect a known void. This was line 4 over the Busick Mine in Kentucky, where a low-resistivity layer between the spoil and the natural ground prevented current penetration. The other extreme, prediction of a void where none exists, has not occurred. However, the western end of the test line at the Acme Mine, supposedly unmined, showed anomalies similar to those of the mined portion. The one small area drilled showed that a wet silt pocket had probably caused this particular anomaly. Other causes remain unknown because it was impossible to drill other areas along the line.

As mentioned earlier in this report, a 2- by 2-m void should only be detectable under ideal conditions, assuming a 15:1 overburden-void ratio, to a maximum depth of 30 m. It has been noted in the data analyzed to date that anomalies deeper than 25 to 30 m are, in general, less well defined than shallower features. If microfracturing or a similar phenomenon is responsible for creating a larger target than the actual void, this loss of definition may be attributable to a "halo" effect of cracks around the void. While this is speculation, it would account for some of the features noted in the data from many of the test sites.

Of the 16 test lines, 15 (91%) tended to show mine voids near their known or suspected locations. However, at the present state of the technology, the human interpretation of the computer output is the most critical element in the system. Knowledge of the geology, lithology, and general characteristics of the mine involved such as depth, approximate location, and whether air or water filled is a prerequisite for accurate interpretation of the data. Where corroborative information is missing, ambiguous interpretations can occur. Therefore, all available project information such as drill-hole information, geologic or lithologic logs, mine maps, etc., should be used during data interpretation.

CONCLUSIONS

The automated resistivity method offers a rapid, inexpensive way to detect old mine workings and to delineate their boundaries if the workings are within 100 m of the surface. Individual features within these workings such as entries or small panels are difficult or impossible to define. Owing to the uncertainties of drilling, the method can locate old workings more easily and quickly than is possible with drilling programs. However, drilling tests or other corroboration should be attempted whenever possible.

Followup research is being conducted to increase the depth of detection to at least 200 to 300 m based on the concept of "focused resistivity," which promises to increase both the investigative depths and the resolution of targets related to old mines.

REFERENCES


APPENDIX A.--DATA ANALYSIS FROM FIELD TEST SITES

BUSICK MINE NEAR CENTRAL CITY, KY

Four test lines were run at this site by SwRI during the final phase of a research contract to develop the equipment. The mine was in production during the tests, and good underground to surface control was available. Mine depth averaged 50 to 70 m.

Some sections of the mine had been worked out and sealed. These sealed sections were being allowed to flood, but the actual extent and depth of the water were unknown in many places. The assumption was made that the down-dip areas were where the mine was completely flooded or where the water depths would most probably be the deepest and therefore should show as water-filled voids. The remainder of the mine was accessible and known to be air-filled.

Lines 1, 2, and 3 were run in a general north-south direction, perpendicular to the Main North entry. All three were started in an unmined area south of the South Graham Fault and extended across the entry into the room and pillar sections of the mine.

Line 4 was run in a southwest-northeast direction starting over a dry, mined-out area and extending onto unmined coal. This area was a leveled-out spoil pile from an adjacent strip mine and was easily accessible. It was later determined, however, that water had apparently leached through this unconsolidated spoil and was collecting as a perched layer on top of the original, tight clay, ground surface. This highly conductive layer at depth apparently acted as an electrical shunt and prevented a majority of the current from penetrating deeper into the old mine area. This prevented the mine from showing in the data, in effect rendering it invisible.

Line 1 was run along a shallow ridge top. The area along this line had been wooded at one time and cleared, but was apparently never cultivated. The ground surface appeared original and has not been reworked by mining activities. The line was 540 m long. It encountered the fault at about 150 m and the entry between 240 and 340 m. From 370 to 540 m, it crossed a flooded section of the mine, with the last 20 to 30 m over an unflooded section. There is excellent agreement between the data from this line and the known underground conditions. Figure A-1 shows a plot of resistivities from the computer analysis of this data.

Line 2 was 610 m long and was run as a tie-line to line 1 and in a more northwesterly direction. The line angled off of the ridge and through a marshy area before climbing again to higher ground on the northwest end. A large dense patch of brush at about the one-third point on the line was traversed by cutting a path with a machete. Through this area the current and data cables lay in close proximity to one another and in some cases actually touched. During data analysis it was found that this had apparently caused "cross feed" in the data cable and resulted in some degradation of the data beyond this point. The data clearly define the fault and other known features to about 200 m. Beyond this point the correlations are much less

![Figure A-1](image-url)
clear. Present field techniques tend to prevent cable proximity errors.

Line 3 was run to the east of line 1 in a wooded, brushy area. A dirt access road was used for cable layout, keeping the alignment as straight as possible. The line was 490 m long. The fault is shown at 130 and 200 m, while the entry and panel show as a large high extending from 270 to 460 m. The major high is just south of the entry at 270 m, but the entry cannot be resolved from the adjacent mined panel. A low between 340 and 380 m underlies a broad ravine which had apparently been draining water from the area shortly before the test was run. The surface materials were quite moist, and the moisture apparently extended to some depth.

Figure A-2 shows lines 1, 2, and 3 overlain on a plot of significant mine features. The anomalous lows are shown by open boxes; the highs are shown cross hatched. As may be seen, there is good agreement along line 1 with the fault, the air-filled (high) Main North, and the water- and air-filled portions of the mine. Line 2 shows good agreement with the fault zone, and in general with the water- and air-filled portions of the mine. However, near Main North an anomalous low shows above the mine level. Line 3 shows only marginal agreement with the subsurface features if drawn as originally surveyed (through dense timber and brush in rough terrain). However, if the low, corresponding to the Graham Fault on the other lines, is moved north approximately 30 m to coincide with the fault as shown by the mining company, the highs and lows correspond with the subsurface features much better than on the original plot. This possible misalignment of the data due to surveying is only speculation but could be the reason for the apparent lack of agreement between the subsurface and the data on this one line.

MARSHALL, CO, TEST SITE

This site was in an abandoned mining area where several mines operated from near 1900 until the 1920's. The mines are all closed and exhibiting various stages of collapse and surface subsidence. The mine depth along the test line ranged from 20 to 30 m. The 640-m test line was run in a northeast-southwest direction over what was thought at the time to be both mined and unmined coal. It was later determined that almost the entire line had been mined by one company or another. Owing to a lack of mine map control, a brief drilling program was undertaken to corroborate some of the anomalies shown by the data.

Three holes were drilled along the northeastern third of the line, where anomalous highs and lows had been interpreted as possible voids. Figure A-3 shows plotted data and drill-hole lithology for holes 1 and 3. Table A-1 shows the driller's logs for these holes. The two high areas drilled both encountered voids, while the low anomaly proved to be saturated, in-place coal with free water at the base. The drilling was done with compressed air rather than mud or water so that relative moisture changes could be noted as drilling progressed. Both the void at drill hole 1 and the series of smaller voids and rubble zones at drill hole 3 correlate with the resistivity profile interpretation data. Figure A-4 is a comparison of the northeast end of the line as shown by both the probability contour (fig. A-4A) and the resistivity pseudosection programs described earlier (fig. A-4B).
FIGURE A-3.—Correlation between drill log and resistivity contours for drill holes (DH) 1 and 3 at Marshall site.

VJ-DAY MINE, DANVILLE, IL

This mine had been abandoned for 25 to 30 yr. The surface terrain was flat, and the depth to coal was approximately 45 m. There was good surface-to-underground location control, but it was determined that several small groups of miners had continued to mine illegally at unknown locations within the mine for 6 or 7 yr after the mine's closure.

TABLE A-1. — Drill-hole (DH) logs for Marshall test site

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>Material and remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>DH1 at 228 m:</td>
<td></td>
</tr>
<tr>
<td>0-2.7......</td>
<td>Sandstone.</td>
</tr>
<tr>
<td>2.7-2.9....</td>
<td>Coal.</td>
</tr>
<tr>
<td>2.9-6.1....</td>
<td>Gray shale.</td>
</tr>
<tr>
<td>6.1-8.8....</td>
<td>Damp buff siltstone.</td>
</tr>
<tr>
<td>8.8-9.1....</td>
<td>Black shale.</td>
</tr>
<tr>
<td>9.1-14.6....</td>
<td>Sandstone and shale.</td>
</tr>
<tr>
<td>14.6-16.1...</td>
<td>Drill stem dropped 1.5 m, lost air.</td>
</tr>
<tr>
<td>16.1........</td>
<td>Total depth.</td>
</tr>
<tr>
<td>DH2 at 91 m:</td>
<td></td>
</tr>
<tr>
<td>0-4.0......</td>
<td>Sandstone and shale.</td>
</tr>
<tr>
<td>4.0-13.4...</td>
<td>Predominantly gray shale, thin damp zones below 9.0 m, still able to air-drill farther.</td>
</tr>
<tr>
<td>13.4-16.2...</td>
<td>Coal.</td>
</tr>
<tr>
<td>16.5-17.7...</td>
<td>Free water, wet shale, unable to air-drill farther.</td>
</tr>
<tr>
<td>17.7........</td>
<td>Total depth.</td>
</tr>
<tr>
<td>DH3 at 39 m:</td>
<td></td>
</tr>
<tr>
<td>0-4.0......</td>
<td>Sandstone and shale.</td>
</tr>
<tr>
<td>4.0-10.4....</td>
<td>Gray shale, 1 thin coal stringer.</td>
</tr>
<tr>
<td>10.4-11.3...</td>
<td>Damp zone near 10.7 m.</td>
</tr>
<tr>
<td>11.3-11.9...</td>
<td>Void, lost air.</td>
</tr>
<tr>
<td>12.2........</td>
<td>Heavy water flow.</td>
</tr>
<tr>
<td>13.1........</td>
<td>Small void.</td>
</tr>
<tr>
<td>14.0-15.2...</td>
<td>Rubble zone—material soft.</td>
</tr>
<tr>
<td>15.2-16.2...</td>
<td>Void, lost air, free water.</td>
</tr>
<tr>
<td>16.2........</td>
<td>Total depth.</td>
</tr>
</tbody>
</table>

The major problem in this area has been subsidence. Two large radio transmission towers are located near the site, and some concern about their stability exists owing to this subsidence. Because the area has been extensively leveled and farmed for several years, there was no visual evidence of subsidence along the test line. One line, 390 m long, was run in a south-north direction across areas shown as mined and unmined on the latest mine maps available.

There are several low anomalies along the line at the mine elevation that
correlate with the known workings in general location but not in areal extent. As it is unknown where the illegal mining took place, it is difficult to determine the validity of the data-workings correlations. The unmined zone near the southern end of the line corresponds well with a lack of these low anomalies, but is offset to the south by about 30 m. Figure A-5 shows the ARS analysis compared with mined and unmined areas as shown on the mine map.

The tests were run during a period of extremely wet weather. It had been abnormally wet for several weeks prior to the start of the tests, and the weather was wet and rainy during them. Several shallow, low anomalies are probably related to the deeply saturated condition of the ground.

**FIGURE A-4.**—Marshall site: A, Computer modeling output; B resistivity profile of same data.

**FIGURE A-5.**—Comparison of resistivity anomalies and mined-unmined areas at VJ-Day Mine.
ACME MINE NEAR SHERIDAN, WY

This site was over a mine that had been abandoned for over 40 yr. The mine was located at a depth of 65 to 75 m beneath almost horizontally bedded sedimentary rocks. One test line was run at this site in a general east-west direction. The line was 580 m long and ran along a ridge top through dense sagebrush and grass. The line was located to intersect both mined and unmined areas based upon the latest available mine map dated January 1, 1938. It was later determined, however, that mining had continued until April 1941 in this general area of the mine.

The mined area is defined by a series of low anomalies at depths of 15 to 30 m. From surface indications of incipient subsidence near the eastern end of the line—namely, wide, deep cracking in the sandstone caprock—it was assumed that the old workings were stopping toward the surface. This was also reinforced by the fact that the entire area seems prone to subsidence. The southern extent of this same mine, where the overburden thickness is shallower, shows extensive subsidence over an area many acres in extent.

Several similar anomalous lows show for approximately 270 m beyond the supposed west boundary of the old mine. These anomalies are unexplainable based upon the old mine map unless this area has also been mined. This possibility is strengthened by the presence of a "stub entry" shown extending westward and then south from the old mine about 225 m north of the line. These entries do not show as being sealed; thus, during the 27 months following the date of the map, mining could have taken place under the supposedly unmined portion of the line.

A drilling program was planned to corroborate some of the anomalous areas during the summer of 1982. However, owing to a change in the current mining company's plans, extensive strip-mining operations were underway in the area where the drilling was to be done, and only one small area of the line was accessible for drilling. No voids were encountered by the four holes drilled; however, a possible reason for one of the low anomalies was determined to be a wet silt pocket encountered where the normally occurring limestone had been eroded or channeled down to the underlying coalbed. Figure A-6 shows drill-hole locations with respect to the resistivity line and mine plat, while table A-2 shows drill logs of these holes.

MONARCH MINE NEAR SHERIDAN, WY

This test site is 3 or 4 miles southwest of the Acme site and offered a much shallower target in the same geologic setting as the Acme. The only information available at the time of the fieldwork was the depth to coal and the edges of a mine panel shown on a topographic map.

The location of the test line was controlled primarily by topographic constraints. The line started on the west near where an old reservoir had washed out and created deep erosion channels and ran eastward for 320 m to the vicinity of a barbed wire fence, which would have caused electrical interference had the line continued beyond. Its position was limited to the north by a steep hillside and to the south by numerous deep subsidence craters.

The data show a series of low anomalies starting at the edge of the mine panel and correlating with observable room subsidence near the center of the line and with cracking farther east where surface subsidence is not visible along...
TABLE A-2. - Drill-hole (DH) logs for Acme Mine site

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1.7....</td>
<td>Coal.</td>
</tr>
<tr>
<td>1.7-4.6...</td>
<td>Sandstone, shale, and limestone layers.</td>
</tr>
<tr>
<td>4.6-6.7...</td>
<td>Limestone.</td>
</tr>
<tr>
<td>6.7-14.3...</td>
<td>Sandstone and shale; 8.5- to 8.8-m coal stringer and damp shale.</td>
</tr>
<tr>
<td>14.3-15.5...</td>
<td>Limestone.</td>
</tr>
<tr>
<td>15.5-17.1...</td>
<td>Sandstone and shale.</td>
</tr>
<tr>
<td>17.1-21.6...</td>
<td>Coal.</td>
</tr>
<tr>
<td>21.6-23.5...</td>
<td>Sandstone and shale.</td>
</tr>
<tr>
<td>23.5-31.1...</td>
<td>Coal.</td>
</tr>
<tr>
<td>31.1-39.6...</td>
<td>Sandstone and shale.</td>
</tr>
<tr>
<td>39.6-43.3...</td>
<td>Hard limestone.</td>
</tr>
<tr>
<td>43.3-49.4...</td>
<td>Sandstone and shale.</td>
</tr>
<tr>
<td>49.4-56.1...</td>
<td>Coal.</td>
</tr>
<tr>
<td>56.7...</td>
<td>Total depth.</td>
</tr>
</tbody>
</table>

DH2, (near low anomaly):

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-4.0.....</td>
<td>Coal.</td>
</tr>
<tr>
<td>4.0-12.8...</td>
<td>Sandstone and shale.</td>
</tr>
<tr>
<td>12.8-14.3...</td>
<td>Coal.</td>
</tr>
<tr>
<td>14.3-18.6...</td>
<td>Sandstone and shale.</td>
</tr>
<tr>
<td>18.6-21.0...</td>
<td>Limestone.</td>
</tr>
<tr>
<td>21.0-23.5...</td>
<td>Coal.</td>
</tr>
<tr>
<td>23.5-25.0...</td>
<td>Limestone.</td>
</tr>
<tr>
<td>25.0-33.2...</td>
<td>Coal.</td>
</tr>
<tr>
<td>33.2-44.2...</td>
<td>Predominantly limestone with stone and shale partings.</td>
</tr>
<tr>
<td>44.2-51.5...</td>
<td>Hard limestone.</td>
</tr>
<tr>
<td>51.5-57.6...</td>
<td>Coal.</td>
</tr>
<tr>
<td>57.9...</td>
<td>Total depth.</td>
</tr>
</tbody>
</table>

DH3† (67 ft from DH2):

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1.5.....</td>
<td>Coal.</td>
</tr>
<tr>
<td>14.3-14.6...</td>
<td>Do.</td>
</tr>
<tr>
<td>21.0-22.6...</td>
<td>Do.</td>
</tr>
<tr>
<td>23.8-33.2...</td>
<td>Do.</td>
</tr>
<tr>
<td>33.2-50.9...</td>
<td>Hard limestone.</td>
</tr>
<tr>
<td>50.9-57.6...</td>
<td>Coal.</td>
</tr>
<tr>
<td>57.9...</td>
<td>Total depth.</td>
</tr>
</tbody>
</table>

DH4† (50 ft from DH3):

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1.8.....</td>
<td>Coal.</td>
</tr>
<tr>
<td>15.8-16.2...</td>
<td>Do.</td>
</tr>
<tr>
<td>22.3-25.0...</td>
<td>Do.</td>
</tr>
<tr>
<td>26.2-34.1...</td>
<td>Do.</td>
</tr>
<tr>
<td>39.6-48.2...</td>
<td>Moist silty material.</td>
</tr>
<tr>
<td>48.2-52.1...</td>
<td>No limestone (silt and shale to top of coal).</td>
</tr>
<tr>
<td>52.1-59.4...</td>
<td>Coal.</td>
</tr>
<tr>
<td>59.7...</td>
<td>Total depth.</td>
</tr>
</tbody>
</table>

†Abbreviated logs for drill holes 3 and 4 show only coalbeds and hard limestone marker bed above bottom coal.
the line. The anomalies plot much closer to the surface than the old workings would indicate, but considering the subsidence that has already breached the surface, this is very logical. Figure A-7 shows the relationship between data analysis and the known mine workings and surface features.

HOLIDAY MINE NEAR SPARTA, IL

This site represented the most difficult of all the research sites chosen. The workings are nearly 100 yr old, and any maps that might have existed were apparently destroyed by fire many years ago. This left only the approximate known location of the mine; its size was a matter of speculation. In addition, the depth to coal is about 85 m, which is near the limits of the ARS detection capabilities at this time. As future underground mining is proposed in this area, any judgments made regarding the mine's location were very important.

The mining company had conducted drilling tests previously during which they had encountered the mine with only one drill hole at a depth of 83 m. Using this located portion of the mine as a control, test lines were run to the east, west, and south in an attempt to locate the limits of the old mine. Initially, during the summer of 1981, two lines were run. Line 1 was east of the located void and ran in a north-south direction for 840 m. Line 2 started at the 410-m point on line 1 and ran west for 700 m. When these data were interpreted, it appeared that the old mine might have continued beyond the extent of these lines; therefore, the following year both lines were extended, and two additional north-south lines were run to the west of line 1.

Based upon interpretation of data from these four lines, a perimeter was drawn around the known mine location and several pronounced anomalies with recommendations that this area be avoided in future mining. In addition, based upon less pronounced anomalous areas, another zone was marked where mining should proceed cautiously with exploratory drill holes, etc., in advance of mining.

Figure A-8 is a fence diagram of the major anomalies from the four lines showing the "danger and caution" zones chosen from these anomalies.

The resistivity profile plot of line 3 is shown in figure A-9A; while figure A-9B shows a more simplified plot obtained by suppressing most of the apparently normal resistivity values. The resistivity values used for figure A-9A range from 0 to 116 Ω·m with 99% of the values below 70 Ω·m and 0.1% above 90 Ω·m. The data used for figure A-9B show only those values between 70 and 90 Ω·m.

It will be seen from figure A-9A that in addition to the strong anomalies between electrodes 11 and 23, a much larger zone consisting of a less pronounced anomaly extends from about electrode 4 to 28. As this larger anomaly tends to

![Figure A-7: Comparison of resistivity modeling anomalies and observed surface features at Monarch Mine.](image-url)
FIGURE A-8.—Fence diagram of resistivity anomalies at Holiday Mine showing modeling and resistivity contour anomalies. Dashed lines show interpretation of these data.

gradually blend with the surrounding resistivity values, only the more pronounced anomalies were used in the fence diagram. Therefore, the more widespread anomalies shown on the fence diagrams by the probability model plots are a function of the tight limits used for picking anomalies from the resistivity profile plots rather than a measure of the relative sensitivity of the two methods.

The mining company conducted drill-hole tests at two anomalous areas detected during the 1981 season without encountering any voids. However, the exact locations of these holes and the drill logs are not available and therefore cannot be appraised.
FIGURE A-9.—Resistivity contours from Holiday Mine. A, Line 3, using full range of resistivity values; B, same data, suppressing all but higher values to enhance high anomalies.
APPENDIX B.--DATA ANALYSIS PROCEDURES

As the data are taken in the field, they are recorded on magnetic tape cartridges. At the beginning of each reading cycle, header information is written onto the field tape indicating line ID number, current electrode spacing, current magnitude, starting and ending current electrodes, and potential electrode position; following the header are the earth voltage readings for that cycle. All of these data are written as ASCII characters using semicolons as delimiters. No gaps or control characters are written onto the tape by the system. The only breaks present are end-of-file gaps placed on the tape by the operator while collecting data.

Data analysis begins with transcription of the data from the field tapes to disk files on the computer system. After the data have been transferred, they are decoded so that the information is in a usable form. Once this decoding is completed, the actual computation process begins. In this process the apparent resistivity is calculated for each electrode position, and the data are written to another disk file for later use.

As the analysis begins, the data are copied from the tape cartridges to disk files; the data between the record gaps on the field tape comprise one disk file. After all of the data from a test line have been placed on disk, the individual files are combined into one large file, which is an image of the field tape but without record gaps.

As the data are taken in the field, errors in procedure sometimes occur. When this happens, an abort button is pressed that adds additional characters to the record, showing that the data are wrong. To get the data into a usable form, the field tape image disk file must first be analyzed so that the good readings are grouped together and the bad readings discarded. This is done with a program that detects each header block and decodes it, deciding how many potential readings are associated with the particular header block. The program then reads the data, counting the number of readings and comparing the actual number of readings encountered with the number of expected readings. If too few or too many potential readings are encountered, the data are discarded and the program begins looking for the next header. All of the usable data are written to another disk file for later use.

After being decoded, the data are still multiplexed so that a series of potential readings are not associated with a particular current electrode. The next step in the processing is to read the data from the disk file, demultiplex them, and calculate the apparent resistivities under each current electrode position. Because the potential readings are taken in 2-m increments, the apparent resistivity is calculated at 2-m increments below the current electrodes, with the total depth being determined by the current electrode-potential electrode separation used when the data were taken. After the calculations have been made, the data are written to still another disk file, which is used for later analysis procedures.

The analysis procedures developed by the contractor who built the automated resistivity system differ from those developed by the Bureau. Although the contractor calculated the resistivity values, these values were normalized during the analysis. The normalized theoretical resistivity values calculated from a model of a tunnel were compared to the field values, and a goodness of fit or correlation number between the model and the field data was obtained. The fit was then plotted as either contours or gray shades showing equal levels of goodness of fit. This was done for both anomalously high and low resistivity values.

The Bureau-developed procedure uses the calculated resistivity values as the basis for a contoured or gray-scale plot and leaves the detection of anomalous zones to the eye of the interpreter. It has been found that plots or maps of resistivity are often of greater value than goodness of fit maps. When relying on goodness of fit plots for detecting workings, a great deal depends on the accuracy of the model used to generate the plots. The models currently in use are
based on a 2- by 2-m tunnel placed in a homogeneous medium, which is not always a good representation of a coal mine; plots of resistivity values seem to present a truer view of subsurface conditions. During this research, when comparing resistivity maps to the goodness of fit plots, a good correlation is shown; but more detail are available in the resistivity maps.

Once the resistivity values have been calculated, the next step is to calculate the mean, standard deviation, and range of the resistivity values and to plot a histogram of these data. Generally, the data have a large range; there are usually a small number of very high resistivity values, but the majority of the data are fairly well grouped. Examination of the computer-generated statistics and the histogram aids in picking the bounds to be used in contouring. Contoured output is produced on the line printer and is plotted to a scale of 1 inch equals 20 m. This scale gives true length-to-depth ratios, using the number of lines and number of characters per inch characteristic of most line printers. The contour plotting program will generate up to 19 contour intervals. The usefulness of contour maps depend on how well the intervals are chosen. If a contour interval is too large, smaller but possibly significant details will be obscured; if it is too small, undue significance will be given to noise in the data. Sometimes it is necessary to make more than one map so that the range of resistivity values is adequately covered. This procedure is done rapidly on a computer, and little additional time is required to do several contour analyses in order to get the best map for interpretation.

Other analysis techniques were tried in an attempt to improve data interpretation. Trend surface and residual analyses were applied in an effort to improve the detection of anomalies. Surfaces up to the fifth degree and their residuals were calculated. After examining several data sets, it was determined that the use of this technique did not significantly enhance the ability to detect anomalies. In performing the analysis it was determined that smoothing the data by using a moving-average technique improved the resistivity maps while not significantly affecting the data. Smoothing was performed by calculating a three-point moving average of the resistivity values below each current electrode position. Gradient mapping techniques were also investigated. It was hoped that gradient mapping would enhance the edge of mined areas because the change in resistivity should be greatest at the boundary between mined and unmined areas. However, the gradients were not steep enough to give usable results.
APPENDIX C.—DESCRIPTION OF THE AUTOMATED RESISTIVITY SYSTEM

EQUIPMENT AND MODIFICATIONS

As mentioned previously, the specially developed equipment for this method is essential to acquiring large amounts of data in a short time. The following descriptions apply to both the original equipment and a new modification developed by the Bureau.

Figure C-1 is a simplified block diagram of the automatic resistivity system (ARS) showing the major basic units of the overall system. The ARS system control unit is the nerve center of the system, and from here the base station operator directs what data to take and how these data are to be taken. The system control unit sends signals to the constant current transmitter when it is time to transmit, and then directs constant current to the proper current control module under direction of the address generator subsystem of the system control unit. The current is injected into the ground at different sequential locations by means of the current cable through equally spaced current electrodes (stainless steel stakes). A potential difference between two potential electrodes normally spaced 2 m apart is obtained by the ground potential preamplifier which is carried along the test line by the remote operator. These data are an analog signal which is conditioned and sent to the system control unit via the communication cable. The analog signal is then converted into digital information for the modified digital recorder, where it is permanently recorded on magnetic tape for later use.

The following is a list of the main units of the ARS and their main functions:

```
Generator
115 Vac
400 Hz

System control unit

Digital recorder
Constant-current transmitter

Ground potential preamplifier

Potential electrodes

Current electrode

Current control modules

Current cable

Ground

Communications cable
```

FIGURE C-1.—Block diagram of ARS showing use of the communications cable for data and voice transmission.
1. The constant-current transmitter injects a precisely known and regulated electric current into the ground through the current electrodes.

2. The system control unit serves as the ARS nerve center, providing most of the system's timing, addressing, analog to digital conversions, formatting data for tape recording, and communications between base and remote station. It also provides fault detection for many different operations and contains power supplies for the system control unit, current modules, and ground potential preamplifier.

3. The ground potential preamplifier provides amplification and filtering for ground potential signal, and provides calibration circuitry and communications between remote and base stations.

4. The current control module directs current into the ground at the proper electrode when its preset binary address agrees with the transmitted address sent from the system control unit. Each module can be preset to any of 64 possible addresses.

5. The digital recorder records data and system information on tape for permanent record. The record contains the following information:
   - Data ID.
   - Current probe separation.
   - Current level used.
   - Potential electrode location.
   - Start scan (first current electrode energized).
   - Stop scan (last current electrode energized).
   - Data (potential readings associated with each current electrode).

6. The AC generator provides 115-V ac, 400-Hz power to system.

7. The AC regulator regulates 115-V ac, 400-Hz unregulated power and supplies this power where needed.

AUTOMATIC RESISTIVITY SYSTEM TELEMETRY

The ARS was initially designed to be used with a communication cable and a current cable, both of which had to be physically connected to the system control unit and other associated devices. After many tests it became apparent that a different configuration would be advantageous to operators and field operations; thus some system modifications needed to be developed. This led to the development of the present telemetry system modification, which has replaced the communication cable.

Operation has been improved so that it is no longer necessary for the remote operator to pull the communication cable along as he or she moves, nor is the operator required to make and break cable connections every 100 m. The problem of deploying the communication cable in adverse terrain has also been eliminated.

Data received at the base station may contain errors when both communication and current cables are used, because of inductive coupling between cables when they are not adequately separated from each other. This problem has been eliminated by the use of the telemetry system.

What has been done with the telemetry system is to replace the communications cable with a radio link (fig. C-2). This meant the addition of new units to send and to receive the data via air waves. The first of these units, the remote telemetry backpack unit, replaces the ground potential preamplifier unit and receives the analog signal from the potential stakes. This analog signal is converted to a digital signal and transmitted to the base station telemetry receiver at the frequency 408.49375 MHz. At the base station the signal is received, converted back to an analog signal by the base station telemetry receiver, and fed to the system control unit, which sees this signal just as if it had come over the original communication cable.

This system has been designed in such a way that, in case of a telemetry malfunction, the system can be reconfigured as a cable system and operation can be continued. Changeover from telemetry to cable or vice versa takes approximately 30 min in a field situation.

The second modification was that new communication between base and remote operators takes place by transceivers at a frequency of 418.050 MHz. The data signal and communication signal (voice) is done by means of a multiplexing system
so that there is no crosstalk between the two signals, which might cause data degradation.

"CURRENT CONTROL MODULE" ANALYZER

The current control module analyzer shown schematically (fig. C-3) is an accessory device developed after approximately 2 yr of field research indicated the need for a means to check the individual current control modules for proper operation. The analyzer is designed to check for short circuits in the relay section of the current control module, and to check the binary address setting of the current control module to verify that the current control module is only addressed to a single binary number.

The relay short-open-close test is performed by use of a simple continuity checking circuit, using an LED to indicate whether the relay is shorted, closed, or open.

The address check is performed by a binary counter starting at decimal 0 (binary 000000) and counting up to decimal 63 (binary 111111). As the count proceeds from 0 to 63, there will be a number to which the current control module is addressed; this number, when the same as the count, will cause a digital comparator circuit to close the relay of the module. When this relay is closed, a 5-V signal is applied to the analyzer, inhibiting the counter. A reset switch is available so that the count can be continued to verify that the module is addressed to one and only one binary code.

For the operator, the following indicators are available on the front panel of this unit: binary readout, digital readout, short-open-close.
Inhibit pulse from control module

FIGURE C-3.—Block diagram of analyzer for detecting misaddressed or faulty current control modules.
APPENDIX D.--FIELD TECHNIQUES FOR THE AUTOMATED RESISTIVITY SYSTEM METHOD

The equipment, as described in appendix C, consists of a system controller-receiver-recorder and a constant-current transmitter located at the base station and a voltage measurement-transmitter device which is moved along the line as data are taken.

The efficient use of this equipment allows many thousands of data to be acquired in a working day by a small crew. For example, a line 640 m long, sampled with 2-m resolution to a depth of 40 m, will result in 11,200 individual data being taken. As the depth of investigation increases, the number of data also increases. A 640-m line has become the norm for determining the distance that can be investigated in a working day.

PERSONNEL AND DUTIES

The number of persons on a field crew is four or five. One site was investigated in 1981 using a three-person crew, but this proved to be too slow and inefficient for normal use. Duties are divided among crew members as follows:

Crew chief—primary system operator.—Supervises layout of test line and reads equipment for test.

Assistant chief—secondary system operator.—In charge of surveying and electrode, cable, and control module emplacement.

Second assistant—instructor.—Assists in setup.—Initially performs potential cable hookups for taking measurements. Instructs laborers in this technique so that crew may rotate during the day.

Laborers (one or two).—Assist in surveying and cable layout. During the day they normally rotate every hour between using the potential-measuring device and emplacing potential electrodes ahead of the measurement point.

COMMENTS

1. Either the crew chief or one of the assistants should be qualified to do minimal electronic troubleshooting at the board-replacement level, as loose integrated circuit cards or broken wires have been an infrequent but persistent cause of problems in the past related to transporting the equipment between various sites.

2. As a rule, the equipment can be readied for use in less than 1 h. Surveying, electrode emplacement, and cable layout usually require about 2 h.

3. On several occasions only the crew chief and assistant have been available for fieldwork, and the remainder of the crew have been untrained personnel. On such occasions extra time is required initially to train the others to perform the setup and data acquisition, but after 1 day the crew can usually perform at normal speed.

PROCEDURE

Initially, after determining the location of the test line, all of the current electrodes are emplaced at exact horizontal distances (normally either 10 or 20 m apart), and their elevations are determined by running survey levels. Upon completion of this task, or concurrently with it, the current cables are deployed and the current control modules are hooked up between the cable and the electrodes in sequential positions. Either the crew chief or one of the assistants will then closely check all module positioning and hookups before proceeding with the tests.

Next, potential electrodes are emplaced for approximately the first 100 m of the test line. One man can accomplish both the measurements and the emplacement by means of a premeasured, nonconducting, elastically tightened rope devised to extend between current electrodes. The safety of the person doing this job is ensured by an elastic loop which may be placed upon or removed from a current stake without touching it while tests are in progress. As measurements proceed along the line, one man removes the potential electrodes no longer needed and places them ahead of the measurement point.

Once the tests commence, only three persons are actively engaged in the work:
the system operator, the lineman hooking up to potential electrodes, and the person removing and emplacing potential electrodes beyond the measurement point. The remaining two are available to rotate jobs with the other three or to perform other minor tasks around the base station. The choice of a crew of five results in some inactivity during the day for the two backups, while a crew of four sometimes requires brief shutdowns if conditions become too hectic for the single backup person.

A 640-m line with current electrodes at 10 m and sampled in 2-m increments requires about 8 h to complete. Longer lines, up to 1,120 m in length, with 20 m between current electrodes and again sampled in 2-m increments, have been completed in 10 to 11 h. This results in 2-m vertical resolution, but only 20-m horizontal resolution, which is sufficient in some cases.