REPORT OF INVESTIGATIONS

APPLICABILITY OF RADIO TO EMERGENCY MINE COMMUNICATIONS

PROGRESS REPORT - SEPTEMBER 1946 TO NOVEMBER 1947

BY

E. W. Felegy AND E. J. Coggeshall
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UNITED STATES DEPARTMENT OF THE INTERIOR - BUREAU OF MINES

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INTRODUCTION

Since 1920, the Bureau of Mines and other agencies have conducted numerous investigations of methods of communication for use in mines in times of disaster or emergency. The results of these investigations have been reported in various publications (3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16).

In November 1944, the Bureau of Mines resumed the study of emergency underground communications. Until March 1946, the program was directed toward reexamining methods of underground communication that indicated possibilities of success. Since April 1946, the principal interest of this investigation has been in methods of application of radio to communication in mines, low-frequency radio seeming to offer the most promise as a successful method of emergency mine communication.

Results achieved in reexamining other methods and in the investigation of the application of low-frequency radio between November 1944 and September 1946 were reported previously in a publication entitled "Some Studies on Emergency Mine Communications" (2).

SCOPE OF INVESTIGATION

This report includes the results obtained between September 1946 and November 1947 in the investigation of low-frequency radio as a means of communication underground. It includes the results of tests conducted at the Experimental mine of the Bureau of Mines, at two commercial bituminous-coal mines and three anthracite mines in Pennsylvania, and at a salt mine and an iron mine in New York.

Oral two-way radio communication was tested at these mines between underground and surface through the ground strata alone; between different points within the mines and between the underground and surface utilizing the aid of trolley wires, air and water pipes, and other metallic installations; and between the hoisting engineer and moving or stationary man cars and cages in various shafts and slopes.

The six principal objects of these tests were:

1. To determine if an optimum single frequency or band of frequencies could be defined for each of the different methods of communication and if that frequency or band of frequencies were identical for all mines or different for each mine.

2. To determine the method of connection for the transmitter and receiver to achieve the best results for each of the conditions encountered.

3. To determine the maximum distance through which radio communication could be achieved solely through the ground, without depending upon wire or other metallic circuits between the points of transmission and reception.

\[4/\] Numbers in parentheses refer to items in the bibliography at the end of this report.
4. To determine the effect on communication through the ground of different types and different numbers of strata between the points of transmission and reception.

5. To determine the effect on communication through the ground and on communication through the open areas in a mine where wire and other metallic circuits are present between the points of transmission and reception.

6. To determine the applicability of radio to communication between the hoisting engineer and man-cars, both at rest and in motion in slopes and shafts.

The investigation is being continued in coal, metal, and nonmetallic mines in both the eastern and western mining districts of the United States.

ACKNOWLEDGMENTS

The investigation is being conducted under the direction of D. Harrington, chief, Health and Safety Division; and S. H. Ash, chief, Safety Branch, Bureau of Mines, Washington, D. C. The authors are indebted particularly to S. H. Ash for his constant interest in the progress of the investigation, his continued efforts in guiding the investigative program, and his invaluable assistance in reviewing the periodic progress reports of the investigation and the manuscript of this publication.

The authors express their appreciation to numerous officials of the Pittsburgh Consolidation Coal Co., Pittsburgh, Pa.; the Glen Alden Coal Co., Wilkes-Barre, Pa.; the Hudson Coal Co., Scranton, Pa.; the Philadelphia & Reading Coal & Iron Co., Pottsville, Pa.; the International Salt Co., Inc., Retsof, New York; and the Republic Steel Corp., Fort Henry Division, Fort Henry, N. Y., for their wholehearted courtesy and cooperation in making possible experiments at the mines of their companies.

The authors acknowledge their indebtedness to engineers of Farmers Engineering & Manufacturing Co., Pittsburgh, Pa., and Union Switch & Signal Co., Swissvale, Pa., for their aid in overcoming technical difficulties encountered in this investigation. The helpful suggestions of E. J. Gleim, supervising engineer, Electrical-Mechanical Section, Bureau of Mines, in reviewing this report, and the assistance given in performing field tests by other Bureau of Mines personnel at the Pittsburgh, Pa., Wilkes-Barre, Pa., and Albany, N. Y., stations of the Bureau of Mines, are sincerely appreciated.

DESCRIPTION OF EXPERIMENTAL EQUIPMENT

The term "AC transmitter" and "AC receiver" are employed in this report to define the transmitter and receiver that can be operated only by a 110- to 120-volt alternating-current source of power. A 110- to 120-volt alternating-current source of power is available on the surface at most mines but seldom at all underground points at which it is desired to make tests. When the required source of power is available underground, the AC transmitter and receiver are utilized underground in some tests, but generally their use is restricted to surface stations.
The terms "underground transmitter" and "underground receiver" are employed in this report to define the transmitter and receiver operated by a 6-volt battery and a vibrator power pack, and thus are independent of any external power source. When tests are being conducted, the underground transmitter and receiver always are set up at underground stations.

A single transmitter and a single receiver had been used in previous tests, and that equipment is described in a previous report (2). To expedite the progress of this investigation, an additional transmitter and receiver were built before the tests described in this report were begun.

Detailed tests of signal strengths received by the method most commonly employed in this investigation - that is, by connecting both terminals of the receiver to metal rods driven into the ground - indicated that certain modifications in the design of the original AC receiver were necessary. An additional stage was constructed in the receiver to act as a "buffer stage" between the primary winding of the receiver antenna coil and the ground-rod connections, and the frequency range of the receiver was expanded.

The improved AC receiver has, as its first stage, a triode tube with 1-million ohm grid-leak resistance, across which the receiver terminals are connected. The plate circuit of the triode tube energizes the primary winding of the receiver antenna coil. Beyond that stage, the AC receiver is a generally conventional 6-tube, amplitude-modulated superheterodyne, operating from any available 110- to 120-volt alternating-current power source.

A 175-kilocycle intermediate frequency is employed after one radio-frequency amplification stage. A direct-current 0-30 microammeter is inserted in the cathode of the second detector to read intensity of rectified current and thereby afford a means of comparing received signal strengths. In addition, the secondary winding of the antenna coil is shunted by a potentiometer with fixed taps connected to the control grid of the radio-frequency stage to provide controlled and calibrated attenuation of the received signal strength. The frequency range of the receiver is 30 to 220 kilocycles, in two overlapping bands of 30 to 100 kilocycles and 85 to 220 kilocycles. Noise limiters are not provided, and no separate noise suppressors or special filtering circuits are employed. Automatic volume control is not used.

The underground receiver and transmitter are constructed as two sections of one transceiver unit and operate from a 6-volt battery and a vibrator power pack. The receiver is a conventional 6-tube amplitude-modulated superheterodyne, employing one radio-frequency amplification stage and 175-kilocycle intermediate frequency. The receiver terminals are connected directly to the primary winding of the antenna coil. The receiver can be tuned continuously over a single band of frequencies from 80 to 175 kilocycles. Audio volume control is provided, but radio-frequency gain control is not provided.

To limit the size, weight, and complexity of the underground receiver and thereby attain maximum portability and to limit the current drain from the battery used as a power source and thereby prolong the time during which tests can be made with a single battery, the underground receiver is designed for maximum simplicity, and no provisions are made to measure signal strengths received underground with this unit.
The underground transmitter is essentially a two-stage amplitude-modulated transmitter. The first stage employs a triode tube in a Hartley oscillator circuit that oscillates at prefixed frequencies controlled by selecting suitable fixed capacities connected across the oscillator coil. The power tube of the transmitter is excited by the oscillator. The final output tube of the receiver section, employed in reception to drive the loudspeaker, is employed in transmission for plate modulation of the power tube of the transmitter. A single-button carbon microphone affords voice modulation through a third winding provided for that specific purpose on the audio transformer of the receiver section in the underground unit.

The underground transmitter covers a frequency range of 33 to 220 kilocycles in two overlapping bands at fixed frequencies of 33, 40, 49, 58, 70, 80, 89, and 100 kilocycles on the lower band and 89, 109, 132, 161, 188, and 220 kilocycles on the higher band.

An 8-step tapped output coil provides matching of transmitter output impedance into load impedance under field conditions. In the laboratory, maximum transmitter output was measured at approximately 4 watts; under field conditions the power output rarely exceeded 3 watts and in most instances was less than 2 watts.

The AC transmitter is an adaptation of the RCA-815 ultrahigh-frequency transmitter with circuit components changed to obtain the desired low frequencies. Basic circuits and a description of the transmitter construction are given in detail in the 1942 RCA Guide for Transmitting Tubes.

The AC-transmitter power supply operates from a 110- to 120-volt alternating current power source. Maximum power output of the transmitter under field conditions was measured at 40 watts or less. A 5-step tapped output coil provides matching of transmitter output impedance into load impedance.

The AC transmitter employs two fixed frequencies, 110 and 150 kilocycles. The entire range of frequencies provided in the underground transmitter is not provided in the AC transmitter because the underground receiver is not used to obtain test measurements (see p. 5). Received signal strengths are measured only on the AC receiver, and the AC transmitter and underground receiver are used only to complete two-way communication between the test stations.

Standard vacuum-tube voltmeters and thermocouple radio-frequency ammeters are used to obtain voltage and current measurements for test data.

The AC and underground transmitters and receivers are shown in figures 1 and 2.

GENERAL PROCEDURE

Radio communication in mines, as accomplished in this investigation, can be classified in three categories: Communication solely through the ground strata; wired or carrier-current communication over the power distribution system; and inductive communication utilizing (without direct connection) the telephone, signal, and power wires, and other metallic equipment.
Figure 1. - AC receiver (top bank), transmitter (middle bank), and power supply (lower bank). Receiver loud-speaker rests on voltmeter at right of picture.

Figure 2. - Underground transmitter-receiver (center). Receiver loud-speaker rests on vibrator unit at left of picture; standard 6-volt storage battery is shown behind the transmitter-receiver.
Transmitter and receiver terminal connections differ with the system of communication tested and also depend to some extent upon whether the transmitter and receiver are stationed at some point underground or on the surface.

The "underground" transmitter and receiver are independent of any external source of power because they operate from a vibrator power pack that requires only a 6-volt battery and can be set up at any point at which it is desired to make tests. These units are used underground almost without exception and are always referred to as the underground transmitter and underground receiver. A standard 6-volt automobile battery is used with the power pack to insure sufficient capacity to conduct tests for an entire day or longer without recharging the battery.

**Test Procedure**

General procedure for test purposes is to transmit from underground to surface. Transmitter antenna current and voltage are measured underground, and received signal strength is measured on the surface receiver. A constant transmitter antenna current is maintained at every frequency in each test. Where 110- to 120-volt alternating-current source of power is available underground, the AC transmitter and receiver are utilized underground to conduct tests of communication wholly within the mine.

When communication solely through the ground is sought, the underground transmitter and receiver terminal connections are made in a number of ways: To two metal rods or pegs driven into the top, rib, or bottom ore, coal, or rock; to one metal rod driven in the same manner and to the rail or trolley wire; to two points on the rails, 90 feet or more apart; or to the trolley wire and to the rail. At the same time, the AC transmitter and receiver terminals invariably are connected to two metal rods driven into the earth, 100 feet or more apart.

When tests are conducted on wired, or carrier-current, communication or inductive communication over the power-distribution system, the underground transmitter and receiver terminals are connected to the trolley wire and to the rail, to two points on the rails 90 feet or more apart, or in a few instances to mine telephone wires and to the rail. The AC transmitter and receiver terminal connections are similar to those of the underground transmitter and receiver, but not necessarily identical; for example, in some tests where the terminals of the underground units are connected to the trolley wire and the rail, the terminals of the AC units are connected to two points on the rails.

For communication tests between a cage or man-car and the hoisting engineer, the underground transmitter and receiver are mounted on the man-car or cage. The terminals are connected in most instances to the hoisting rope and to the metal frame of the cage of man-car, but in a few tests a loop antenna of 5 turns or less has been used both for transmitting and receiving on the cage.

For conducting communication tests in shafts or slopes, the AC transmitter and receiver are stationed in the engine room or at the collar of the shaft,
and terminal connections are made to two rail points, to a rail and a ground point, to two ground points, or to the signal system normally employed in shaft signaling.

**Calibration Procedure**

Direct measurement of the absolute values of test results are not made in the field because of the unavailability of suitable measuring instruments. The final evaluation of field data obtained by the meters used in this investigation is completed by laboratory calibration of the test equipment.

For all tests, signal strengths of the unmodulated carrier frequencies received on the surface are measured as needle deflections on the microammeter in the second detector circuit of the receiver and recorded together with the carrier frequency and all dial and control settings on the receiver.

In the laboratory the unmodulated carrier frequencies used in testing are reproduced by a signal generator and fed through a calibrating unit to the receiver terminals. The calibrating unit is a voltage divider network that provides a 1,000-to-1 or 390-to-1 step-down of the signal generator voltage. The dial and control settings and the deflection of the meter on the receiver are duplicated, and the voltage delivered by the signal generator is measured at the terminals of the generator. The signal voltage at the terminals of the receiver for each field-test reading is computed without difficulty.

In each of the tables in this report the signal voltages measured in the tests are reported as "units of received signal strength." The "units of received signal strength" are the product of the signal strength in microvolts (as measured in the tests) times "k", an arbitrary factor. The received signal strength ranges from less than 100 microvolts in some tests to several hundred thousand microvolts in other tests. The arbitrary factor "k" for each test is selected to reduce signal strengths measured in different tests to a similar magnitude for all tests and thereby permit all curves to be drawn to the same scale and enable easier comparison of the different curves. The value of "k" for each test is shown at the top of the column of "units of received signal strength" in each table.

The signal generator and the calibration unit are well-shielded and the signal generator and the receiver are well-separated to guard against possible errors in calibration caused by receiver pick-up of radiated energy.

The receiver does not have a flat response, and the calibration procedure automatically compensates for receiver response deviations.

**TESTS AT THE EXPERIMENTAL MINE**

Results of initial radio communication tests at the Experimental mine of the Bureau of Mines at Brucetown, Pa. (2) had been inconsistent, and the trend of frequency-response curves between 33 and 120 kilocycles had not been in close agreement with the trend to be expected from indications of previous frequency-response tests at audio frequencies.
When the frequency range of the AC receiver was extended to 220 kilocyles, additional tests were conducted at the original test stations at the Experimental mine.

In the original receiver and initially in the modified receiver, the untuned primary winding of the antenna coil was connected to the receiver terminals, and the terminals connected directly to the metal rods employed as receiving points in the ground. Analysis of results of numerous tests under controlled field conditions at the Experimental mine indicated that direct connection of the very low impedance, represented by the untuned primary of the antenna coil at low frequencies, to the relatively high impedance between the metal rods driven into the ground, was affecting the signal voltages between the two rods and introducing errors in signal strength readings on the receiver.

For this reason the receiver was modified to provide a very high impedance at the terminals by the inserting before the antenna coil, the triode buffer stage, with a million-ohm grid resistance, which is placed across the input terminals of the receiver.

Tests were made of communication through ground strata between the observatory on the surface and the sump at B butt, a slant distance of 500 feet. At the sump, transmitter and receiver terminal connections were made to roof and rail. The terminals of the AC transmitter and receiver, set up in the observatory, were connected to the rail and to the permanent ground rod provided behind a switchboard in the observatory.

The geologic section in the vicinity of the sump is indicated by the following borehole log:

<table>
<thead>
<tr>
<th>Depth - feet</th>
<th>Formation</th>
<th>Thickness, feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
<td>Surface soil and clay</td>
<td>30</td>
</tr>
<tr>
<td>30-40</td>
<td>Shale and black shale</td>
<td>10</td>
</tr>
<tr>
<td>40-42</td>
<td>Coal</td>
<td>2</td>
</tr>
<tr>
<td>42-54</td>
<td>Shale</td>
<td>12</td>
</tr>
<tr>
<td>54-58</td>
<td>Limestone</td>
<td>4</td>
</tr>
<tr>
<td>58-60</td>
<td>Soft shale</td>
<td>2</td>
</tr>
<tr>
<td>60-69</td>
<td>Hard gray shale or fire clay</td>
<td>9</td>
</tr>
<tr>
<td>69-84</td>
<td>Sandstone</td>
<td>15</td>
</tr>
<tr>
<td>84-91</td>
<td>Black shale</td>
<td>7</td>
</tr>
<tr>
<td>91-109</td>
<td>Shale and coal</td>
<td>18</td>
</tr>
</tbody>
</table>

Additional tests were made between the observatory and the transmitter station at No. 2 room west, 550 entry, a distance of approximately 900 feet. The presence of recording wires and other metallic equipment near the transmitter station provide additional paths for the signals to travel, so that communication between No. 2 room west, 550 entry, and the observatory is not achieved through the ground strata alone. In the observatory, the receiver and transmitter terminals were connected to the rail and to the permanent ground rod, or to the rail and to a ground rod on the hillside almost directly above the B-butt transmitter station underground. At the underground station the terminals were connected to a point in the roof and to a point in the ground.
The transmitting and receiving stations, the type of terminal connections available, and the distances between stations are described in detail in the earlier report (2).

In Table 1 are listed data of representative tests of communication between the observatory and the B-butt sump and between the observatory and the station at No. 2 room west, 550 entry. Figures 3 and 5 show the frequency-response curves obtained from these tests. The real values shown in all tables and on all frequency-response curves in this report as units of received signal strength, are the calculated comparative intensities of received signals at each frequency and are not the absolute signal voltages measured in the tests.

### Table 1. Frequency-response tests - Experimental mine

<table>
<thead>
<tr>
<th>Frequency, kilocycles</th>
<th>Transmitter at B-butt sump</th>
<th>Transmitter at No. 2 room west, 550 entry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_1' = 0.7$</td>
<td>$k_1' = 0.05$</td>
</tr>
<tr>
<td>33</td>
<td>561</td>
<td>491</td>
</tr>
<tr>
<td>40</td>
<td>700</td>
<td>563</td>
</tr>
<tr>
<td>49</td>
<td>672</td>
<td>425</td>
</tr>
<tr>
<td>58</td>
<td>546</td>
<td>355</td>
</tr>
<tr>
<td>70</td>
<td>350</td>
<td>525</td>
</tr>
<tr>
<td>80</td>
<td>154</td>
<td>728</td>
</tr>
<tr>
<td>89</td>
<td>39</td>
<td>689</td>
</tr>
<tr>
<td>100</td>
<td>14</td>
<td>613</td>
</tr>
<tr>
<td>109</td>
<td>49</td>
<td>575</td>
</tr>
<tr>
<td>132</td>
<td>84</td>
<td>350</td>
</tr>
<tr>
<td>161</td>
<td>28</td>
<td>429</td>
</tr>
<tr>
<td>188</td>
<td>83</td>
<td>325</td>
</tr>
<tr>
<td>220</td>
<td>49</td>
<td>145</td>
</tr>
</tbody>
</table>

$\frac{1}{k}$ is an arbitrary factor for each test (see p. 8).

The best frequency for communication through the ground at the Experimental mine was between 40 and 50 kilocycles; this is shown by the peak in the frequency-response curve in Figure 3. An audio-frequency response curve of frequencies between 1 and 50 kilocycles, obtained in previous tests at the Experimental mine, is shown in Figure 4, and the test data are listed in Table 2. Comparison of Figure 3 with Figure 4 shows that the indicated best frequency of transmission for ground conduction at the Experimental mine was almost identical in two separate tests using different equipment for each test.

The indicated best frequency of transmission in the range of 40 to 50 kilocycles in this particular instance is not entirely in agreement with the best frequencies found by theoretical calculations or with the actual results of tests at the Mammoth Cave in Kentucky, as reported by Eve, Keys, Lee, and Joyce (4, 6, 14). Attenuation formulas applied by Eve (4) to underground reception indicated that signal attenuation should decrease with decreasing frequency. Eve, Keys, and Lee (6), observed that reception of 20- to
Figure 3. - Frequency-response curve, Experimental mine, B-butt sump.
Figure 4. - Audio-frequency-response curve, Experimental mine, B-butt sump.
Figure 5. - Frequency-response curves, Experimental mine, 550 entry, No. 2 room west.
30-kilocycle frequencies was much louder than reception of 40- to 100-kilocycle frequencies, which indicated that the 20- to 30-kilocycle frequencies passed through this limestone with considerably less attenuation; however, they suggested that this condition well might bear further investigation. It is shown later in this report that the results of additional tests in the current investigation are in agreement with the above-mentioned theory and results.

<table>
<thead>
<tr>
<th>TABLE 2. - Audio-frequency response tests - Experimental mine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency, kilocycles</td>
</tr>
<tr>
<td>-----------------------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>25</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>35</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>45</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>Curve</td>
</tr>
</tbody>
</table>

\(\frac{1}{k}\) = an arbitrary factor for each test (see p. 8).

Curves A and B (fig. 5) show that for tests between the station at No. 2 room west, 550 entry, and the observatory, the best frequencies of transmission are in the range of 80 to 100 kilocycles. This result is in close agreement with the results of initial tests at these two stations that showed the best frequencies to be in the range of 70 to 90 kilocycles.

It is interesting to observe that on curve A, where the major peak in response occurs at a frequency of 80 kilocycles, a minor secondary peak occurs at one-half that frequency, or 40 kilocycles; and on curve B, where the major peak in response occurs at approximately 90 kilocycles, a minor secondary peak occurs at one-half that frequency, or approximately 45 kilocycles.

The occurrence of one or more secondary peaks was observed again in frequency-response curves of tests conducted in other mines and is described in this report.

At the Experimental mine the transmitter output current was held constant at 100 milliamperes in each test. The power output of the transmitter in tests at the B-butt sump was 1.7 watts, and in tests at the station at No. 2 room west, 550 entry, it was 1.9 watts.
TEST AT COMMERCIAL BITUMINOUS-COAL MINES

Pittsburgh Consolidation Coal Co., Montour No. 10 Mine

Tests of radio communication underground, using the original equipment, had been conducted at the Montour No. 10 mine of the Pittsburgh Consolidation Coal Co. at Library, Allegheny County, Pa. Tests at the same stations in that mine were repeated, and some additional tests were made, using the modified equipment.

Coal is mined in the Pittsburgh bed at Montour No. 10 mine. The mine extends more than 5 miles from two drift entries. The South Side Shaft, approximately 2-1/2 miles from the entry, and the Murdock shaft, further inby, are used only for ventilation; however, they can be used as auxiliary escape-ways. A geologic section at Montour No. 10 mine is not given, because it was proved to the satisfaction of the investigators that all radio communication achieved at this mine was effected primarily over wire and other metallic circuits and not through the ground strata.

Table 3 lists the data, and figure 6 shows the frequency-response curve for a representative carrier-current communication test at Montour No. 10 mine. The underground station was at the fire-boss shanty along Seven Mains haulageway, and the surface station was at the first-aid station at Lick Run entry, 2-1/2 miles from the underground station. Transmitter and receiver terminals were connected to the trolley wire and to the rail at both surface and underground stations.

TABLE 3. - Frequency-response test - Montour No. 10 mine, carrier-current communication

<table>
<thead>
<tr>
<th>Frequency, kilocycles</th>
<th>Units of received signal strength, microvolts times kJ</th>
<th>k / = 0.003</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>199</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>129</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>214</td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>367</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>413</td>
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</tr>
<tr>
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<tr>
<td>89</td>
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<td>736</td>
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<tr>
<td>109</td>
<td>416</td>
<td></td>
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<tr>
<td>132</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td>161</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>188</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Curve</td>
<td>Fig. 6</td>
<td></td>
</tr>
</tbody>
</table>

1/ k = arbitrary factor for each test (see p. 8).

The frequency-response curve shown in figure 6 peaks between 90 and 100 kilocycles. At 60 kilocycles and at 110 kilocycles, the received-signal strength decreased to 50 percent of maximum and continued to decrease at
Figure 6. - Frequency-response curve, Montour No. 10 mine, carrier-current communication.
Figure 7. - Frequency-response curves, Montour No. 10 mine, inductive communication.
frequencies below 60 and above 110 kilocycles. At transmission frequencies of 161, 188, and 220 kilocycles, the intensity of the received signals was too low to be measured. Although the peak in the curve occurs between 90 and 100 kilocycles, communication was satisfactory over the broader band of frequencies between 70 and 110 kilocycles.

In the initial tests conducted at Montour No. 10 mine, the frequency-response curves showed the peak frequency to lie somewhere between 80 and 95 kilocycles in different tests, so that the results of the two series of tests are in very close agreement. It has been observed that, in different tests at any given mine, the optimum frequency may shift over a range of 15 to 20 kilocycles between the highest and lowest frequency peaks obtained in carrier-current communication. It appears that, by analyzing the results of several tests, a single frequency that would assure satisfactory continuous communication over the power-distribution system could be selected near the middle of the range of optimum frequencies.

In inductive radio communication over the power-distribution system at Montour No. 10 mine, a different condition was observed. Inductive communication was achieved at Montour No. 10 mine when either the transmitter or the receiver terminals or both the transmitter and receiver terminals were connected to two rail points, to the rail and to a ground point, or to the roof and to a rail or ground point, rather than directly to the trolley wire and to the rail. When this method of communication was tested, the peak in the frequency-response curves of different tests occurred at several widely varying frequencies, and in some instances the intensity of received signals was nearly equal at two different frequencies in the same test. Frequency-response curves containing the points corresponding to such intensities are shown in figure 7, and the data for the tests are listed in table 4. Tests A and B were conducted on two different days. For both tests the terminals of the transmitter were connected to the trolley wire and to the rail at the fire-boss shanty in Seven Mains, 2-1/2 miles inby the Lick-Run entry. The receiver station was at Lick Run entry for both tests; the terminals of the receiver were connected to the rail and to a ground point for test A, and to two rail points for test B.

For the same power output, radio communication over the mine power-distribution system was obtained through greater distances when carrier-current communication was conducted than was possible when inductive communication was conducted. Radio communication was established between stations 5 miles apart at Montour No. 10 mine by the carrier-current system, utilizing a transmitter antenna current of 200 milliamperes with a maximum transmitter power output of 2.5 watts. It was not possible to establish communication between the same two stations by any inductive system tested with the experimental equipment. When an inductive system of reception is employed - that is, when the receiver terminals are not connected to the trolley wire - reception is much quieter, and for that reason inductive reception was employed in many tests in this investigation.
TABLE 4. - Frequency-response tests - Mountour No. 10 mine, inductive communication

<table>
<thead>
<tr>
<th>Frequency, kilocycles</th>
<th>Test A</th>
<th>Test B</th>
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<tr>
<td></td>
<td>$k_1/ = 0.077$</td>
<td>$k_1/ = 0.04$</td>
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<td>33</td>
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<td>188</td>
<td>63</td>
<td>464</td>
</tr>
<tr>
<td>220</td>
<td>-</td>
<td>292</td>
</tr>
</tbody>
</table>

Curve A, fig. 7 | B, fig. 7

$k_1/ = \text{an arbitrary factor for each test (see p. 8).}$

The results of a majority of the tests of radio communication over the power-distribution system at the Montour No. 10 mine indicate that the best frequency for radio communication at that mine is 80 kilocycles or higher. However, it must be noted that, in a few tests the trend of the curve of signal strengths received tended to increase at 33 kilocycles and that, in one test, the signal strength at 33 kilocycles was higher than at any other frequency, although the accompanying noise interference was severe and made reception unsatisfactory. It is possible that, under particular conditions at some mines, the best frequencies for power-system communication may be in the band of frequencies below 33 kilocycles. If, in addition to other considerations, a favorable signal : noise ratio can be obtained at those frequencies.

Because of experimental results obtained early in this investigation, two commercial companies are manufacturing radios to provide communication over the power system in mines, primarily for dispatching purposes. Installations of this type in mines of the Hanna Coal Co. at Neffs, Ohio, and the Lake Superior Mining Co. at Superior, W. Va., are reported in the coal-mining literature (1, 17). The possibility that different frequencies may be desirable for carrier-current and inductive communication under special conditions at some mines is more appropriately a problem of research for the radio-manufacturing companies and consequently has not been examined extensively in this investigation.

Several tests were attempted to communicate through the ground alone at Montour No. 10 mine. Frequency-response curves obtained in these tests definitely showed that communication was being achieved over metallic circuits rather than through the ground. Because of the lack of 110- to 120-volt alternating current, which is necessary to operate the AC receiver and
transmitter, it was not possible to establish surface and underground stations at points where communication could be accomplished through the ground without the aid of metallic circuits, and no further tests of communication through the ground alone were attempted at this mine.

Several tests were made in which loop antennas (rather than ground, rail, roof, or trolley-wire connections) were utilized for transmitting and receiving purposes along the haulageways. Communication was accomplished with the loop antennas, and noise levels accompanying the signal abated considerably. At the same time the signal intensity was reduced to such a marked degree that it was apparent that satisfactory emergency radio communication could not be achieved underground with loop antennas, without utilizing excessive power, and no further tests were made with loop antennas.

In the tests conducted at Montour No. 10 mine, the maximum power output of the transmitter exceeded 2.5 watts in only one test, in which the power output was 3.3 watts. In the majority of tests the power output of the transmitter was 2 watts or less for communication between stations ranging 300 feet to 5 miles apart.

A power station is maintained on the surface at the South Side shaft, 260 feet vertically above the main haulageway underground. A 20-microfarad capacitor between the positive and negative lines on the surface is a permanent part of the mine power system for protection against lightning. The 20-microfarad capacitor offers an effective resistance of 0.25 ohm or less to alternating currents of the low radio frequencies (33 to 220 kilocycles) employed in this investigation. It was considered that the capacitor at this point might represent a short circuit between trolley wire and rail to radio-frequency currents, a condition analogous to that presented if the trolley wire were to fall across the rails after a fire or explosion.

An underground transmitter station was established at a point 1,250 feet inbye the power station. The transmitter terminals were connected to the trolley wire and to the rail, and the surface receiver terminals were connected to the trolley wire and to the rail at the first-aid station, Lick Run entry. A frequency-response test was made. The received signal strengths showed no appreciable decrease below those received from the fire-boss shanty, outbye the power station and 1,600 feet closer to the receiver. The frequency-response curve was almost identical to that obtained in a test at the fire-boss shanty and shown in figure 6. However, from this test no prediction could be made as to whether or not a direct short circuit of the trolley-wire system would have as little effect upon the transmission of signals, because in this particular instance, the effective shorting point represented by the capacitor was 260 feet from the main path of signal transmission.

**Pittsburgh Consolidation Coal Co., Renton No. 3 Mine**

A few tests were conducted at the Renton No. 3 mine of the Pittsburgh Consolidation Coal Co. at Renton, Allegheny County, Pa.

The mine is opened in the Upper Freeport coal bed by two double-compartment shafts and one three-compartment shaft. A geologic section at this mine
is not given. The mine workings extend a maximum of 2-1/2 miles from the shaft, near which the surface receiver station was established. The shaft is 500 feet deep. Suitable surface test stations were unavailable because of the lack of the power source necessary to operate the surface receiver; consequently, no tests of communication through the ground strata were conducted.

The 260-volt direct-current power supply at Renton No. 3 mine is obtained from two 300-kilowatt mercury-arc rectifiers installed underground. The installation is of interest in this investigation because of the effect of mercury-arc rectifiers on radio reception.

The lamp house, near the head of the shaft used to hoist men and material, contains transformers to supply 440-, 220-, and 110-volt alternating-current power.

When the AC receiver was set up in the lamp house and the underground transmitter was set up in the dispatcher's office near the foot of the shaft, almost directly beneath the lamp house, communication between those points was very poor, regardless of the type of terminal connections on the surface or underground. The mercury-arc rectifiers created objectionable noise interference, but the primary cause of poor reception was the very low signal intensity received. The measured output voltage of the AC transmitter was abnormally low. Because the AC transmitter and receiver were immediately alongside the transformers and other electric machinery in the lamp house, it must be assumed that both transmitted and received signals were absorbed by that electric equipment.

The AC transmitter and receiver were installed in the underground motor barn near the foot of the shaft, and the underground transmitter and receiver were set up at different stations along the haulage roads. By connecting the transmitter terminals to the trolley wire and to the rail and connecting the receiver terminals to two rail points, communication was accomplished easily throughout the entire mine, a maximum distance of 2-1/2 miles. Signals were received when the receiver was connected to the trolley wire and to the rail, but the noise interference caused by the mercury-arc rectifiers was severe. When the receiver terminals were connected to two rail points, the noise interference was reduced to a much greater degree than the reduction in signal intensity, and much better reception was obtained.

Frequency-response curves drawn from test data show peaks at 132 kilocycles in all tests except one in which the peak shifted to a higher frequency. In several tests the presence of minor peaks at other related frequencies was indicated, but the secondary peaks were not as pronounced as in the frequency-response curves of carrier-current and inductive communication tests at Montour No. 10 mine and at the Experimental mine.

TESTS AT ANTHRACITE MINES

Glen Alden Coal Co., Truesdale Colliery

Truesdale colliery of the Glen Alden Coal Co. at Nanticoke, Luzerne County, Pa., comprises three separate sections, known as the Truesdale, the
No. 20 Tunnel, and the Sugar Notch sections. Communications tests were confined to the Truesdale section, in that portion opened from the No. 1 slope.

The Truesdale section is opened from the surface by No. 1 and No. 6 slopes and by No. 1 and No. 2 shafts, with additional inside slopes utilized to facilitate mining at the lower levels. In this section, 17 anthracite beds are present, of which 14 are being mined on dips ranging 0° to 90°. The highest altitude is +724 feet at the collar of No. 1 shaft; the altitude of the lowest level at which anthracite is now mined consistently is -500 feet, although old workings not abandoned entirely lie at an altitude below -800 feet. The mining area is vast and covers horizontal distances of well over 3 miles at some points, and an extensive haulage system is maintained.

No. 1 slope is driven across the dip of the Mills vein on an average dip of 17° from a surface altitude of +660 feet to a bottom altitude of +259 feet, where it leaves the Mills vein, cuts through rock, and intersects the George vein. Two levels are mined from No. 1 slope. Originally, No. 1 slope was continuous in the Mills vein to a depth of altitude -500 feet. The continuity now is broken at the manhole at No. 3 East at an altitude of +360 feet, where the present No. 1 slope turns left and continues as described above. The lower portion of the original slope, now termed the "coal slope," is equipped with a separate hoist, at altitude +340 feet. There is no direct connection between the two portions of the slope.

No. 1 slope is equipped with 36-inch-gage single track of 65-pound rails. There are no power or telephone circuits in the slope, but signal wires extend the entire length of the slope.

In the section of the mine in which tests were conducted, the mouth of No. 28 tunnel opens in the George vein near the foot of the present No. 1 slope. No. 28 tunnel cuts through six separate anthracite beds on both the dip and rise limbs of a synclinal basin and intersects Road 952 in the No. 4 vein at altitude +300 feet. Road 952 continues along the strike of No. 4 vein until a turn-out swings the road around a fault section and back into the No. 4 vein, where it continues as Road 1054 along the strike of the bed to a point near the property line.

The relative positions of the underground and surface stations, as given in the following descriptions, are defined in terms of the vertical distance between the two points and the travel distance between them. The vertical distance in each instance is the correct difference in altitude between the two stations. The second distance given in each instance is that distance measured on the mine maps along the most direct route of travel between the two points. It cannot be defined correctly as either a horizontal or a slope distance, because in almost every instance it consists of both the distances along one or more slopes and the meandering distances of the traverse along water-level gangways and through tunnels across the dip of the beds.

The first surface receiver and transmitter station was established at the head shanty of No. 1 slope, 600 feet from the slope mouth. Transmitter and receiver terminals were connected to two points on the rail 90 feet (or three rail lengths) apart.
Communication was established immediately from the mouth of the slope, the first station selected for the underground units, when the terminals of the underground units were connected across 90 feet of rail.

Station 2 was established at the manhole at No. 3 East, 350 feet below and 2,100 feet from the surface station at the head shanty. The surface receiver was maintained as initially set up and terminal connections underground again were made to two rail points. Two-way communication was satisfactory; a frequency-response test indicated maximum received signal strength in the frequency range between 109 and 161 kilocycles, and a single-frequency peak at 109 kilocycles. Signal strength was low at 40 kilocycles and not measurable at 40 and 33 kilocycles, and noise intensity was high at these low frequencies.

Station 3 was established in the George vein at the mouth of No. 28 tunnel, just off the foot of No. 1 slope, 450 feet below and 3,800 feet from the head shanty, with several curves and acute angle turns in the traverse between the two points. No. 28 tunnel is the main underground haulageway at this point. Trolley wire is present above the track, and telephone wires parallel the track at this point. The terminals were connected to two rail points at station 3, and two-way communication with the surface station was established immediately. A frequency-response test showed maximum signal strength received in the band of frequencies around 161 kilocycles, the peak response occurring just above 161 kilocycles. Signals were completely indistinguishable at 33 kilocycles, and the noise intensity was high at the frequencies below 70 kilocycles. The spread of the most satisfactory frequencies was wider than in the tests at station 2, and the peak section of the frequency-response curve was shifted toward the higher frequencies, but the change is not significant. It is interesting to note in figure 8 that at station 3 a very definite secondary peak in the response curve occurred at 80 kilocycles, one-half the maximum single frequency peak near 161 kilocycles, a condition similar to that observed at the Experimental mine; also that a third peak was indicated at 40 kilocycles, one-half the frequency of the secondary peak.

Station 4 was established at the mouth of No. 44 tunnel, No. 6 East, in the Mills vein off the coal slope. Station 4 was 740 feet below and 4,300 feet from the surface station. When the terminals were connected to two rail points at both the surface and the underground stations, signals received on the surface were intelligible but weak. When the terminals of the underground transmitter were connected to the trolley wire and to the rail, signals received on the surface were appreciably stronger. Strongest signals were received on the surface when one receiver terminal was connected to the rail and the second terminal was connected to the metal siding of the head shanty. Best reception was obtained underground when both the surface transmitter and underground receiver terminals were connected to two rail points. Signal intensity received underground was highest when the underground receiver terminals were connected to the trolley wire and to the rail, but the accompanying noise intensity was so much higher that the net result was less satisfactory.

A frequency-response test at station 4 was made only over the upper band of frequencies between 109 and 220 kilocycles; the peak response occurred between 161 and 188 kilocycles.
Other terminal connections for the surface receiver and transmitter were tried by using ground rods, guy wires, standpipes, other rails, and the nearest trolley wires, 200 feet away, but the best results were obtained when the receiver terminals were connected to the rail and to the head shanty, and the transmitter terminals were connected to two rail points.

Telephone wires between underground and surface are installed in the manway adjacent to No. 1 slope. The wires closely parallel the slope tracks from the slope portal to the head shanty, at which point a telephone is installed. This condition probably is primarily responsible for the fact that best reception was obtained on the surface when one receiver terminal was connected to the head shanty.

Station 5 was established at the junction of Roads 1081 and 1082 in the Mills vein, off the foot of the coal slope, 1,185 feet vertically below and 5,600 feet from the surface station. Two-way communication was established between these two stations without difficulty. Results of tests at station 5 were similar to those obtained at station 4, and no formal frequency-response test was made.

Station 5A was established in No. 28 tunnel at a point 100 feet inby the junction of Roads 851 and 852 in the George vein. At this point the trolley wire is sectionalized by a permanent insulating strip, and the power on the trolley wires on opposite ends of the insulator is supplied from two different and independent circuits. The power lines between the mine workings and the surface are installed in a borehole situated several hundred feet from Road 852.

At station 5A it was observed that when the transmitter terminals were connected to the trolley wire and to the rail, outby the insulating strip in the trolley wire, reception on the surface was excellent, but when the transmitter terminals were connected to the trolley wire and to the rail at a selected place inby the insulating strip, reception on the surface was poor. Signals received underground were weak but intelligible when the receiver terminals were connected to the trolley wire and to the rail outby the above-mentioned insulating strip; underground reception was loud but extremely noisy. When the receiver terminals were connected to the trolley wire and to the rail inby the insulating strip, no signals were received underground. The results of numerous tests indicated that most of the signals coming to or transmitted from the above-mentioned point inby the insulating strip apparently were traveling up the borehole to the power station. The adverse effect of power installations electrically close to a transmitting or receiving point had been noted previously at Renton No. 3 mine. It was observed further that a capacitor connected across the insulating strip in the trolley wire immediately overcame the apparent effect of the borehole power lines and permitted satisfactory transmission and reception on either side of the insulating strip.

Station 5A was 1,000 feet inby the nearest telephone lines. Nevertheless, when the terminals of the surface transmitter were connected to one side of the telephone line at the head shanty and to the slope rail, instead of to two rail points, the intensity of signals received underground increased tremendously. Similarly, when the telephone-rail connections were used for the
terminals of the surface receiver, the signals received on the surface were intensified greatly when underground transmissions were made with the transmitter terminals connected either to two rail points or to the trolley wire and to the rail. Intensity of signals received on the surface was not increased further by connecting both terminals of the receiver to the telephone wires, nor was the intensity of signals received underground increased further by connecting both terminals of the surface transmitter to the telephone wires.

Station 6 was established on Road 952 in the No. 4 vein at the intersection with the tunnel connecting through to Road 1041. Station 6 was 390 feet vertically below and 9,000 feet from the surface station, and 5,000 feet inby the nearest telephone lines. The terminals of the surface transmitter and receiver were connected to the telephone wire and to the slope rail. Two-way communication was established immediately, when signals were received and transmitted underground with the terminals connected either to two rail points or to the trolley wire and to the rail. No frequency-response tests were made at station 6.

Station 7 was established along Road 1054 in the No. 4 vein, 5,200 feet inby station 6 and within 500 feet of the most distant areas in the Truesdale section. Station 7 was 360 feet vertically below and more than 14,000 feet from the surface station, and more than 10,000 feet inby the telephone lines at the mouth of No. 28 tunnel.

The terminals of the surface receiver and transmitter were connected to the telephone wire and to the slope rail at the head shanty. Two-way communication was established without difficulty when the terminals of the underground transmitter at station 7 were connected either to two rail points or to the trolley wire and to the rail. Signals were received underground with either type of receiver terminal connections. Although the signals received underground were stronger when the terminals were connected to the trolley wire and to the rail, the accompanying noise level was much higher than when the terminals were connected to two rail points; that is, most satisfactory reception was obtained underground when the terminals of the receiver were connected to two rail points, the same condition noted in previous tests.

A frequency-response test at station 7 showed a rather sharp maximum peak on the response curve at 161 kilocycles and another very definite secondary peak at one-half that frequency, or 80 kilocycles.

A series of special tests was conducted at Truesdale colliery. The underground units were reestablished in the George vein near the mouth of No. 28 tunnel, a few feet from station 3, described previously. A surface station was established at the electrical shop, within 200 feet of the head shanty at No. 1 slope, and an attempt was made to establish communication between the underground and surface stations by utilizing as a metallic circuit the compressed-air lines between the two points.

The air-compressor units are between the electrical shop and underground station 3. Approximately 200 feet of the compressed-air line underground consists of sections of 8-inch flanged pipe formerly used for pumping water. The flanged joints are gasketed with electrical insulating material. The remainder of the air line consists of screw-joint pipe.
The terminals of the underground transmitter and receiver were connected to two points 100 feet apart on the air line, and the terminals of the surface units were connected in a similar manner across a 100-foot length of the air line. No signals were received on the surface. Signals transmitted from the surface and received underground were intermittent, weak, and unsatisfactory.

The terminals of both the underground and the surface units then were connected to the trolley wire and to the air line. Two-way communication was possible but unsatisfactory. When the terminals of the underground transmitter were connected across a 100-foot length of air line and the terminals of the surface receiver were connected to the trolley wire and to the air line, received signals again were unsatisfactory.

A wire jumper was connected across the section containing the flanged joints in the air line, and the surface transmitter and receiver were moved to the No. 1 slope fan house, essentially the same distance from underground station 3 as before. The terminals of the surface receiver were connected to the main valve of the air line at the side of the fan house and to the air line at a point 100 feet down the manway that opens at the fan house. When the terminals of the underground transmitter were connected across 100 feet of air line, two-way communication between station 3 and the surface station in the fan house was established satisfactorily.

Frequency-response tests showed a peak in response at 161 kilocycles and a secondary peak between 80 and 89 kilocycles. At 49, 40, and 33 kilocycles, received signal strengths were not measurable, and the noise interference was severe. At 220 kilocycles an abnormally high signal intensity was noted, entirely out of line with the trend of the response curve. The frequency-response curve, except for the abnormal deviation at 220 kilocycles, was similar to those obtained at other stations in gangways and tunnels where trolley wire and telephone lines were present. Trolley wire and telephone lines parallel the air line along the portion at which the underground units were connected, and telephone wires and power lines are present in the manway. The characteristic frequency-response curve indicates that the wire circuits probably acted as the major portion of an inductive system of communication and that the function of the air line was negligible in carrying the signals between the two stations (station 3 and fan-house station).

No. 1 slope head shanty again was used as the surface station, and station 8 was established underground along Road 983 in the No. 4 vein, 600 feet inby No. 343 tunnel. This section of Road 983 is abandoned. The trolley wire is in place but is dead-ended 1,000 feet inby station 8. Station 8 was 600 feet below and 8,500 feet from the surface station and 4,500 feet from the nearest telephone lines.

The terminals of the underground transmitter and receiver were connected to the trolley wire and to the rail, and the terminals of the surface units were connected to the telephone line and to the slope rail. Excellent two-way communication was established immediately.

A capacitor was connected as an alternating-current short circuit between the trolley wire and the rail at a point between the underground and surface
stations, 100 feet from the underground transmitter. Over the entire frequency range of 33 to 220 kilocycles, the signal strengths received on the surface were 20 to 50 percent of the signal strengths received without the short circuit from trolley wire to rail but provided satisfactory communication. A frequency-response test yielded results entirely dissimilar to those obtained in previous or later tests and were so erratic that the significance of the results is not known.

When the short circuit was placed 100 feet inby instead of 100 feet outby the underground transmitter, signal strengths received on the surface were decreased further. Reception underground was satisfactory when the trolley wire was shorted to the rail on either side of the underground receiver but was weaker than reception without the short circuit.

A trolley-wire sectionalizing switch is installed between the underground and surface stations at a point 300 feet from underground station 8. When the switch was opened, no signals were received at either the surface or the underground station with or without a short circuit between trolley wire and rail on either side of the underground unit. When a capacitor was connected across the open switch, normal communication was reestablished.

In an attempt to bridge the open switch without using a capacitor, a 100-foot length of rubber-covered wire was employed under five conditions:

1. Wire lying along track, midpoint of wire under switch, both ends free.

2. Wire lying along track, midpoint of wire under switch, end under energized trolley wire free, end under deenergized trolley wire connected to rail.

3. Wire lying along track, midpoint of wire under switch, both ends connected to rail.

4. One end of wire connected to deenergized trolley wire, midpoint of wire under switch, opposite end of wire connected to rail under energized trolley wire.

5. One end of wire connected to deenergized trolley wire, midpoint of wire under switch, opposite end of wire free.

Because of the physical conditions (fallen rock and coal, broken track, heaved bottom, standing water pools, and very poor roof) in the abandoned section of the road at station 8, the underground units could not be set up at any point within sight of the mine electrician manipulating the bridging wire at the switch. Water flowing in the drainage ditch alongside the road and a hammering in the water line extending along this section made so much noise that oral communication with the electrician was impossible. Therefore, the tests under the five conditions listed above and under a sixth condition with the trolley-wire switch closed necessarily were conducted on a time schedule. The electrician synchronized his watch with the watches of the investigators before taking his station at the switch and then at prearranged time.
intervals arranged the bridging wire to conform with each of the above-mentioned conditions.

After the tests were completed and communication with the surface reestablished through the closed switch, it appeared that all the above-mentioned conditions failed to permit communication with the switch open, and no further attempts were made to bridge the open switch. However, later comparison of notes indicated that condition 1 had been successful in bridging the open switch and that condition 2 probably had been successful, the initial indication of negative results arising from confusion about the time schedule.

After the indication of probable success had been discovered, no opportunities to repeat the tests at the same mine or at other mines were presented; therefore, the results are inconclusive. In previous tests to establish communication through the ground (p. 14) at Montour No. 10 mine, the terminals of the underground transmitter had been connected to the roof and to the rail or to the trolley wire and to the rail, inby an open trolley-wire sectionalizing switch. Results of the tests proved that communication had been achieved over wire circuits instead of through the ground, despite the open switch. The fact that in these tests the open switch had been bridged in some manner not controlled by or known to the investigators indicates the possibility that some satisfactory method or means may be devised to permit radio communication in mines over a mechanically disrupted power system. Further research into this phase of the investigation is necessary to prove or disprove that possibility.

A section of the trolley wire near station 8 at Tuesdale colliery was broken and removed from the hangers and dropped across the ground and the track at different points between station 8 and the surface station. No success was achieved in communicating between the surface and underground under any of these conditions.

A unique condition was observed in one instance during the course of the tests at station 8. In all previous tests, when the terminals of the underground transmitter and receiver were connected to the trolley wire and to the rail, communication between the underground and surface stations was achieved with ease, except at those times when a sectionalizing switch was opened in the trolley wire between the underground and surface stations. In a single test at station 8, when the terminals of the underground units were connected to the trolley wire and to the rail and when to the best of the investigators’ knowledge all trolley-wire switches were closed, communication could not be established between the surface and underground stations.

The first attempts at communication in this test were made at 11 a.m., when practically all work in the mine ceases as the miners eat lunch. Transmissions were continued, and about 11:15 a.m., when the miners resumed work, both underground and surface stations began to receive signals, at first faintly and then with increased intensity. About 5 minutes after the first weak signals were received, communication again was normal. This condition seems to indicate that when the trolley wire is energized but current is not drawn by locomotives and other mine machinery, radio communication over the direct-current power-distribution system is affected seriously. It also gives
rise to the inference that when a power-distribution system is deenergized, radio communication over that system may be an entirely different problem from communication over an energized system.

This condition never was observed again in any of the succeeding tests, and on the basis of one test the failure to communicate cannot be credited definitely to the lack of current flow in the trolley wire. Other abnormal conditions, not known at the time, may have caused the failure of communication.

The surface transmitter was operating on a carrier frequency of 80 kilocycles and the underground transmitter on a carrier frequency of 110 kilocycles during the time when no signals were received. The surface and underground receivers were tuned to receive the assigned frequency of the opposite transmitters, and until communication was reestablished, the transmission frequencies could not be changed. Therefore, the entire frequency band could not be tested under this condition, and it was not possible to determine whether communication would have been successful at another frequency, as, for example, the low frequencies that give the best results in communication through the ground.

An excellent opportunity to conduct a few elementary tests in shaft communication was presented at the Askem shaft, in a different section of Tuesdale colliery.

The Askam shaft is a two-compartment shaft over 2,000 feet deep. When the tests were made, water was standing in the shaft a few hundred feet above the bottom, and the cage was lowered to a maximum depth of 1,500 feet below the surface. Telephone lines are present in the shaft; but the mine telephones assigned to those lines are inoperative, and there is no direct telephonic communication between the shaft landings and the hoisting engineer. A bell-pull system of signaling is employed.

The surface transmitter and receiver were set up at the shaft collar, and the transmitter and receiver terminals were connected to the head frame at the collar and at a point 75 feet above the top landing. The underground transmitter and receiver were placed on the floor of the cage, and the terminals were connected to the metal frame of the cage and to the hoisting rope at a point 75 feet above the bonnet of the cage.

When the cage was in motion, constant two-way communication between the cage and the surface was maintained with no difficulty. The motion of the cage either ascending or descending at a normal rate of speed did not interfere with signal reception; and two-way communication was as clear, positive, and regular when the cage was in motion at any point in the shaft as it was when the cage was stationary. The intensity of received signals actually increased as the cage descended, and frequency-response tests from 1,500 feet below the surface indicated a single extremely high peak response at 161 kilocycles. No secondary peak occurred at any frequency, but communication was clear and understandable at all frequencies, and noise interference was negligible.
Figure 8. - Frequency-response curve, Truesdale colliery, station 3.
Figure 9. - Frequency-response curve, Truesdale colliery, Askam shaft.
The phenomena of increasing signal strength as the cage descended and the singularly high peak response at 161 kilocycles at a depth of 1,500 feet may be explained by consideration of standing waves. The physical dimensions of the shaft, together with the circuit characteristics of the wires in the shaft, may have presented the requisite conditions to produce standing waves of voltage and current according to the accepted conception of standing waves in transmission lines. If this were the case, maximum signal strength might be expected to occur at one-quarter and three-quarter wave-length distances between the transmitter and receiver, and minimum signal strength to occur at one-half and unit wave-length distances, with the received signal strengths increasing and decreasing sinusoidally between those points. The theoretical one-quarter wave length of a 161-kilocycle frequency is calculated to be 1,528 feet, from the formula,

\[
\text{Wave length (meters)} = \frac{300,000,000}{\text{frequency (cycles)}},
\]

and the actual physical one-quarter wave length may be identical to the distance of approximately 1,500 feet between transmitter and receiver.

A surface station was established in the engine room, 200 feet from the head frame at the shaft. The receiver and transmitter terminals were connected to a grounded pipe inside the building and to a cyclone fence surrounding a gasoline pump at a point 50 feet toward the shaft. The installation on the cage was not changed.

Signals received in the engine room were weaker than those received at the shaft collar, but communication between the cage and the hoisting engineer was clear and satisfactory when the cage was either stationary or in motion at any point in the shaft. A frequency-response test from the stationary cage when 1,500 feet below the surface yielded results similar to those obtained in the first test. The response curve again showed a single peak at 161 kilocycles, but the peak was broader and very much less exaggerated than in the curve obtained from the test at the shaft collar. Noise accompanying the received signals was more intense in the engine room than at the shaft collar, but it did not interfere to any appreciable extent with satisfactory communication. Reception in the cage again was very quiet. The power output of the transmitter in all shaft tests was between 1 and 2 watts.

The data obtained at station 3, typical of the results obtained in many of the tests at Truesdale colliery, and the data obtained in communication tests at the collar of the shaft, are listed in table 5. Figures 8 and 9 are the frequency-response curves obtained from the data in table 5.

Several significant points were observed in the tests at Truesdale colliery. The material assistance given to signal transmission by telephone lines beginning several thousand feet away from the point of transmission is of extreme interest. The continuity of wire circuits in a mine more often than not is disrupted by a mine fire or explosion. If the results obtained in tests at Truesdale colliery can be accepted as criteria, those portions of wire circuits that remain intact after a mine fire or explosion may assist appreciably in making radio communication possible between the surface and underground or between different underground sections of the mine.
TABLE 5. - Frequency-response tests - Truesdale colliery, station 3 and Askam shaft

<table>
<thead>
<tr>
<th>Frequency, kilocycles</th>
<th>Units of received signal strength, microvolts times $k^1$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Station 3</td>
</tr>
<tr>
<td></td>
<td>$k^1 = 0.04$</td>
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<tr>
<td>33</td>
<td>-</td>
</tr>
<tr>
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<tr>
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<td>220</td>
<td>476</td>
</tr>
<tr>
<td>Curve</td>
<td>Fig. 8</td>
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</table>

$1^1 k$ = an arbitrary factor for each test (see p. 8).

A short circuit between the underground and surface stations did not destroy communication at Truesdale colliery. This fact was noted previously in a test at Montour No. 10 mine and offers at least an indication that trolley wire dropped across the track, but not broken by a fire or explosion, may permit radio communication over the power system between the mine and the surface.

Open switches in the trolley wire interfered seriously with communication, but the tests show a distinct possibility that breaks in the trolley wire may be bridged by the presence of short lengths of other wires extending only limited distances on each side of the break.

In tests conducted the previous year at Montour No. 10 mine, it was not possible to achieve communication between the surface and an underground station in a wet section of the mine, although only a short distance separated the two stations. Fritsch (8), when experimenting with radio waves underground in Germany, had reported the same loss of signal due to a local wet condition.

At Truesdale colliery, the majority of the underground stations were established at wet sections in the mine. An appreciable volume of water was flowing in drainage ditches along the haulage roads, and at the most distant point, station 7, water was flowing freely from the loading chutes. In some instances one rail connection was submerged completely in water. Communication never appeared to be hindered by water in this mine, which may indicate that the deterrent effect of water in mines on radio communication will prove to be the exception rather than the rule.
The results obtained in shaft communication were highly satisfactory. The equipment was not designed for such application and only two tests were made. Radio communication in shafts should be improved appreciably by further detailed tests of equipment designed specifically for that purpose.

Philadelphia & Reading Coal & Iron Co., Reliance and Alaska Collieries

A series of tests in emergency mine communication was made at the Reliance colliery of the Philadelphia & Reading Coal & Iron Co. at Mt. Carmel, Northumberland County, Pa. Anthracite is mined in 10 beds - the Diamond, Orchard, Primrose, Holmes, Four Foot, Mammoth, Skidmore, Seven Foot, Buck Mountain, and Lykens Valley. The dip of the beds ranges 50° to 55°. The main opening is a two-compartment shaft through which coal, men, and materials are hoisted. A tender slope is provided to take in timber and to hoist mine cars for repair, and a number of other openings are utilized for ventilating purposes and as escapeways.

Tests at Reliance colliery were confined almost exclusively to communication through the earth between five points on the surface and four points underground. Figures 10 and 11 are section maps at Reliance colliery showing the relative positions and the intervening distances between the underground and surface stations established for ground-communication tests.

Station 1 underground was established in 29 gangway, at No. 6 breast, fourth lift, West Lykens Valley vein. Station 1 on the surface was 579 feet directly above underground station 1. The strata intervening between this station and the surface consist of beds of sandstone, conglomerate, slate, clay, and a thin layer of top soil. The combined thicknesses of the different rocks, as determined from a borehole in that vicinity, are 400 feet of sandstone, 150 feet of conglomerate, and 30 feet of slate, clay, and surface soil. At this point, no anthracite beds lie between the Lykens Valley vein and the surface.

The terminals of the surface receiver and the transmitter were connected to two iron rods driven into the ground 150 feet apart. The terminals of the underground transmitter and the receiver were connected to two iron rods driven 1 foot into the rib near the roof, 100 feet apart. Roof, rib, and bottom were wet, and considerable water was flowing down the breast. Two-way communication was established immediately. A frequency-response test was made by following the standard procedure of maintaining a constant transmitter current output at all frequencies tested. The power output of the transmitter remained essentially constant between 1.8 and 1.9 watts at all frequencies. The test showed maximum signal intensity received at 80 kilocycles. The signal intensity decreased steadily as the frequency increased above 80 kilocycles, and it decreased at frequencies below 80 kilocycles, except that at 33 kilocycles the signal intensity received again increased to almost that received at 80 kilocycles.

A second frequency-response test was made by maintaining the same terminal connections both on the surface and underground. Transmitter output power remained constant at slightly less than 1 watt at all frequencies. Test results in this instance showed maximum signal strength received at 33 kilocycles, the
lowest frequency obtainable with the test equipment, and a steady decrease in signal strength received as the frequency increased.

The terminals of the underground units at station 1 were connected to two points 90 feet apart on the rail in 29 gangway. No changes were made at the surface station. Transmitting over the entire frequency range at a constant current output, the power output increased from 0.7 watt at 33 kilocycles to 2.4 watts at 161 kilocycles. However, the frequency-response curve obtained was almost identical to that obtained from results of the test when both terminals were connected to rib points; maximum signal strength was received at 33 kilocycles, and the intensity of received signals decreased steadily as the frequency increased. At 188 and 220 kilocycles, the received signals were too weak to measure.

Tests were made by changing the compass direction of the lines connecting (1) the terminals of the surface receiver to the ground rods and (2) the terminals of the underground transmitter to rib rods by extending the lines along the gangway or up and down the breast. The surface terrain is irregular; the exact relative direction of the surface and underground lines could not be determined without an instrument survey, and the rods had to be driven to different depths to obtain a good contact, but it was determined approximately that maximum signal strength was received when the lines on the surface paralleled those underground.

The spacing between rods underground was changed, and it was found that increasing the distance to more than 100 feet between rods did not increase the signal strength received on the surface, but when the distance between the rods underground was decreased to 50 feet, the intensity of signals received on the surface decreased to less than half of the signal intensity received when the underground rods were 100 feet or more apart.

Surface station 1A was established at the fan house of the Lykens Valley bed. The underground station was not changed. Surface station 1A was 513 feet vertically and 390 feet horizontally from underground station 1, a straight-line distance of 645 feet. The Buck Mountain bed, which is 2 feet thick, several beds only a few inches thick, and rock strata described previously lie between the two stations. The terminals of the surface transmitter and receiver again were connected to two iron rods driven into the ground 150 feet apart, the only method of connection available.

Tests in which the compass direction of the surface and underground lines were changed successively were repeated at station 1A. Again, it was shown approximately that maximum signal strength was received on the surface when the underground and surface lines were parallel.

Additional tests in which the surface rods were driven to successive depths of 1, 2, and 3 feet showed that the signal strength received increased slightly as the receiving rods were driven to greater depths.

The terminals of the underground units were connected to rib, rail, roof, and ground points in combinations of rib-to-rib, roof-to-rib, rib-to-rail, rail-to-rail, roof-to-roof, roof-to-rail, and ground-to-ground. Extra lengths
of wire were connected to the end of an abandoned trolley wire in 29 gangway, thereby effectively extending the trolley wire to the test station. The terminals of the underground transmitter and receiver also were connected to the trolley wire and to the rail, and to two points on the trolley wire. In addition, tests were made when the terminals were connected to a 100-foot length of uninsulated copper wire completely buried in the mud, and when the terminals were connected to grounded and ungrounded loop antennas.

Two-way communication was achieved in every test regardless of the type of terminal connections used underground. The different types of terminal connections underground had no effect upon the frequency-response curves obtained; maximum signal strength on the surface always was received at the lowest frequencies, and the signal strength always decreased as the frequency increased. Intensity of signals received in different tests, however, changed with the type of terminal connections used underground. The best results usually were obtained when the underground terminals were connected to the trolley wire and to the rail, but the intensity of signals received on the surface was almost as great in one instance of rail-to-rail terminal connections and in one instance of rib-to-rib terminal connections as in the tests when the terminals were connected to the trolley wire and to the rail.

A series of tests was conducted between underground station 1A and surface station 1A to determine the effect of transmission into the trolley wire under different conditions on communication through the ground.

The first sectionalizing switch is 250 feet from the end of the trolley wire near station 1A and a second sectionalizing switch is one-half mile from the same end. The terminals of the underground transmitter were connected to the trolley wire and to the rail. The first switch was closed and the second switch opened, so that one-half mile of trolley wire was connected to the transmitter terminal. Signal strength readings were taken on the surface. When the first switch was opened, so that only 250 feet of trolley wire was connected to the transmitter terminal, signal strengths received on the surface were reduced to not less than 75 percent of the original real values. The sectionalizing switch 250 feet from station 1A was left open in subsequent tests.

Both terminals of the transmitter then were connected to the trolley wire. Signal strengths received on the surface increased only slightly as the distance between connections was increased from 100 to 250 feet, but signal strengths received decreased very rapidly when the spacing between connections was reduced below 100 feet.

The transmitter terminals again were connected to the trolley wire and to the rail, and the hangers were disconnected from the trolley wire one by one until one-half the original number of hangers remained connected. Signal strength received on the surface remained constant.

An additional 50-foot length of wire was extended from the end of the trolley wire. The transmitter terminals were connected to the end of the extension wire and to the rail, and signal-strength readings were taken on the
surface. Beginning at the sectionalizing switch, portions of the trolley wire were disconnected successively from the hangers and permitted to fall to the ground and be buried in the mud and water. Signal strengths received on the surface remained essentially constant until the length of wire remaining suspended decreased below 200 feet; the signal strengths received then decreased to (1) 80 percent of the initial signal strength when 175 feet of wire remained suspended, (2) 70 percent when 100 feet remained suspended, and (3) 60 percent when 50 feet remained suspended.

Station 1B was established on the surface in the engine room of the tender slope situated near the surface shops, and the underground units were retained at station 1. Station 1B was 406 feet vertically and 1,100 feet horizontally from underground station 1, a straight-line distance of 1,170 feet.

The terminals of the underground transmitter and receiver were connected to two metal rods in the roof; and the terminals of the surface receiver and transmitter were connected to two iron rods driven into the ground 150 feet apart, as at the other surface stations. Results of tests under these conditions yielded a frequency-response curve that showed that (1) the maximum signal intensity was received at the lowest frequency, (2) a rapid decrease in signal intensity occurred as the frequency increased to 70 kilocycles, (3) a minor peak in response occurred between 90 and 100 kilocycles, and (4) a very low signal intensity was received at 109 kilocycles. At frequencies above 109 kilocycles, the signal was too weak to be measured. A telephone in the engine room is connected to telephones inside the mine, but no telephone was present underground within 2,000 feet of the two roof connections for the underground transmitter. Nevertheless, when the receiver terminals were connected directly to the telephone lines, additional tests proved that signals transmitted underground were induced in the telephone system in some manner and the telephone lines were aiding communication between the two stations.

The frequency-response curve seemingly verified this fact in that the curve appeared to be a combination of the two different curves obtained in communication solely through the ground and in communication utilizing metallic circuits. No further tests were made at this station.

Underground station 2 was established in the Lykens Valley plane at the 8th lift east. A slush bank covered the point on the surface vertically above the underground station, so surface station 2 was established at a point on the surface on a line with the Lykens Valley plane, 952 feet vertically and 445 feet horizontally from underground station 2. The straight-line traverse of 1,050 feet between the two stations passed through rock strata similar in character to that at station 1, but the thin, unmined Buck Mountain bed and the mined Skidmore bed lie between the two stations at this point.

The area surrounding underground station 2 has been mined out, and no wires, rails, or other metallic conductors of any kind are present. The terminals of the underground units were connected to two rods 150 feet apart driven 1 foot into the dry bottom. The terminals of the surface units again were connected to the two iron rods driven into the ground 150 feet apart.

Two-way communication was established without difficulty. The intensity of signals received on the surface was low and almost at the limit of
sensitivity of the receiver, but it was high enough to conduct frequency-
response tests. Results of the tests showed that maximum signal strength
was received at the lowest frequency (33 kilocycles) and that the signal
strength received decreased as the frequency increased. At 188 and 220 kilo-
cycles, the signal strengths were too low to be measured.

The underground units were maintained at station 2, and the surface
units were returned to station 1A at the Lykens Valley bed fan house. Surface
station 1A is 1,154 feet vertically and 1,685 feet horizontally from under-
ground station 2, a straight-line distance of 2,040 feet. The rock strata
described before lie between the two stations, and no coal beds are known to
be intersected by a straight-line traverse between the two stations.

The terminals of the underground units again were connected to two rods
driven into the dry bottom 150 feet apart, and the terminals of the surface
units were connected to two iron rods driven into the ground 150 feet apart.
Transmitter output current underground was held constant at 90 milliamperes,
the maximum value that could be obtained consistently at all frequencies;
under this condition the power output of the transmitter was constant at 2
watts. Identifiable signals were received on the surface at 49, 58, 70, and
100 kilocycles, but the signals were too weak to be measured. Messages were
understandable only at 70 kilocycles. At 33 and 40 kilocycles, the noise
level was too great to permit absolute identification of signals.

Underground station 3 was established at 9-1/2 lift on the extension of
the Lykens Valley plane, and surface station 3 was established 1,007 feet ver-
tically above the underground station. Six mined-out anthracite beds and the
thin, unmined Buck Mountain bed lie between the two stations at this point in
addition to the normal rock strata. The terminals of the surface receiver and
transmitter again were connected to two ground rods. Underground, after all
other methods of connection had failed to permit communication, the transmis-
ter terminals finally were connected to an air line and to a 500-foot length
of old telephone wire not connected to any mine installation on either end.

Noise interference on the surface was intense. The noise appeared to be
similar to that caused by mine power rectifiers in previous tests at other
mines. Occasionally a motor whine was heard in the surface receiver, identi-
cal to the noise produced by underground motors undertaking a sudden load.
Noise interference probably was due principally to the presence of a 66-kilo-
volt power line that formed a semicircle around the surface receiver at a
distance of 200 feet.

Intermittent contact was established between surface and underground
stations. The only frequency used underground was 70 kilocycles, and the
frequency used on the surface was 110 kilocycles. When signals from the un-
derground station were received on the surface, signals also were received
underground from the surface station, and when reception failed at either
station it failed at both stations. When reception was obtained, messages
from the underground station were intelligible on the surface, but voice per-
ception underground generally was unintelligible except for vowel sounds.

The underground units were moved 365 feet up the Lykens Valley plane to
the 9th lift, at which point the terminals were connected to the trolley wire
and to the rail in the 9th lift gangway. The distance between the surface and underground stations was as before, and the path of the signals also remained essentially the same. Signal reception on the surface was clear and distinct at the first contact, but signals were not received underground. A frequency-response test was attempted; but, except at 70 and 80 kilocycles, either the noise interference was too high or the signal strength was too low to obtain significant results. Because of lack of communication between the underground and surface stations, no additional tests were made at station 3.

Company officials were interested in whether radio communication might be used by fire bosses to report immediately any dangerous conditions found in their inspections. Accordingly, AC units were set up in the 7th lift pump room, and the underground units were set up in the 7th lift on the south dip of the East Mammoth bed at No. 13 chute on 124 gangway. At this point, the most distant fire-boss station on the 7th level, the communication units were approximately 1-1/2 miles apart. The terminals of both transmitters and receivers were connected to the trolley wire and to the rail, and two-way communication was accomplished over the entire frequency range with no difficulty. The frequency-response curve showed a peak, or maximum signal strength received, at 80 kilocycles.

The AC receiver and transmitter next were set up at a surface station near the head frame of the shaft, and the terminals were connected to the trolley wire and to the rail on the feeder lines between the power station and the borehole through which the direct-current power is taken into the mine. Although maximum power output underground was less than 1 watt, signal intensity received on the surface was so high that the frequency-response curve was distorted because the received signals could not be attenuated sufficiently to obtain correct signal strength measurements. When a trolley-wire sectionalizing switch 750 feet from the underground station was opened, signals were received underground, but reception was impossible on the surface.

The AC units were returned to the 7th lift pump room and the underground units were moved to the 9th lift east, Lykens Valley "spoon" gangway, the most distant fire-boss station on that level and about 2-1/2 miles from the 7th lift pump room. When the terminals were connected to the trolley wire and to the rail at both stations, two-way communication was established quickly, but the received noise level was high. A frequency-response test over a part of the frequency range indicated a peak on the response curve at 161 kilocycles. When the receiver terminals were connected to two rail points, reception was quieter and more satisfactory, although the measured signal strengths were not as high.

When the receiver terminals were connected to the trolley wire and to the rail, it was observed that reception continued when a trolley-wire sectionalizing switch near the receiver was opened, and in fact, less noise interference was received than with that switch closed. However, when a sectionalizing switch near the transmitter was opened, signals could not be detected at the receiver station.

Another point of interest to company officials was the effect of an impounded body of mine water upon radio communication through the ground. Study
of the maps of various mines of the company showed only one pool of water, at Reliance colliery, at which it was possible to approach the desired test conditions.

A station for the underground transmitter and receiver was selected at the bottom of the 8th lift slope in the Mammoth vein. The AC transmitter and receiver were set up alongside a water dam on the 9th lift at the curve to the West Buck Mountain gangway. Theoretically, signals between the two stations had to travel both through the strata and through the water impounded behind the dam.

Different methods of connecting the terminals were tried at both stations, including rail-to-rail, rail-to-ground, ground-to-ground, rib-to-ground, rib-to-rib, and rib-to-rail. Two-way communication generally was satisfactory, using any method for connecting the transmitter and receiver terminals, although noise interference from trolley locomotives was high. The best signals were received when the receiver terminals were connected to two ground points and the transmitter terminals to two rail points. A frequency-response test showed greatest signal strength received at the lowest frequencies, apparently indicating that communication was effected through the ground.

The test, however, was inconclusive. The distance through water was only a small portion of the total distance between the two stations. Despite the frequency-response curve obtained, it is possible that either the signals traveled entirely through the strata around the water pool between the two stations or were aided materially by wire-installations at and between both stations, some possibility existing that communication was achieved entirely by means of wire circuits instead of through the ground. Additional tests must be conducted under more rigidly defined conditions to show the effect of a body of water on transmission of signals in low-frequency radio communication through the ground.

No. 4 inside slope in Alaska colliery, adjoining the Reliance colliery, of the Philadelphia & Reading Coal & Iron Co., was selected for a test of radio communication between the hoisting engineer and a moving man car in the slope.

The AC receiver and transmitter were set up in the engine room of the slope and, for the initial contact, the terminals were connected to two rail points 90 feet apart. It was found that better reception was obtained when one terminal was connected to the frame of the hoist and one terminal to the slope rail, and these connections were used in conducting the tests. The underground transmitter and receiver were set up in a man-car; the terminals were connected to the hoisting rope at the coupling to the car and to the rope 100 feet above the car.

No. 4 slope is 2,000 feet long, and both telephone and signal wires are installed throughout its entire length. Constant communication was maintained between the man car and the engine room as the man car was lowered to the foot of the slope. The accompanying noise level was appreciable when the man-car was in motion but this did not prevent the constant exchange of messages. A
frequency-response test at the foot of the slope showed a maximum response at 132 kilocycles. The peak of the response curve is broad and shows that between 70 and 200 kilocycles the intensity of signals received does not decrease to less than 70 percent of maximum.

A five-turn wire loop was constructed around the body of the man-car and not grounded at any point. The terminals of the units on the man-car were connected to the loop, and another frequency-response test was made. The curve obtained from the test showed a sharp response peak at 188 kilocycles and a secondary peak between 100 and 109 kilocycles. The band of frequencies, at which the response was at least 70 percent of maximum, was narrowed to the range between 161 and 220 kilocycles. Signals received in the engine room were weaker and more unstable than when the transmitter terminals were connected to the hoisting rope, but communication was satisfactory. Constant communication between the man-car and the engine room was maintained by using the loop when the man-car was in motion at normal speed.

Figures 12, 13, and 14 show typical frequency-response curves obtained in tests of low-frequency radio communication through the ground at Reliance colliery. Figure 15 shows the frequency-response curve obtained in a slope communication test. The data from which the curves were drawn are given in table 6.

**TABLE 6. - Frequency-response tests - Reliance and Alaska collieries**

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<thead>
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<th>Frequency, kilocycles</th>
<th>Units of received signal strength, microvolts times kl/</th>
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<td>345</td>
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<td>400</td>
<td>658</td>
</tr>
<tr>
<td>132</td>
<td></td>
<td>245</td>
<td>247</td>
<td>224</td>
<td>744</td>
</tr>
<tr>
<td>161</td>
<td></td>
<td>227</td>
<td>82</td>
<td>264</td>
<td>658</td>
</tr>
<tr>
<td>188</td>
<td></td>
<td>-</td>
<td>-</td>
<td>82</td>
<td>630</td>
</tr>
<tr>
<td>220</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>457</td>
</tr>
<tr>
<td>Curve</td>
<td></td>
<td>Fig. 12</td>
<td>Fig. 13</td>
<td>Fig. 14</td>
<td>Fig. 15</td>
</tr>
</tbody>
</table>

\(1/ k = \text{arbitrary factor for each test (see p. 8).}\)

A summary of the results obtained in the many tests conducted at Reliance colliery shows several points of extreme interest to the development of an emergency system of mine communication utilizing radio. The results of the
Figure 12. - Frequency-response curve, Reliance colliery, underground station 1, surface station 1.
Figure 13. - Frequency-response curve, Reliance colliery, underground station 1, surface station 1A.
Figure 14. - Frequency-response curve, Reliance colliery, underground station 2, surface station 2.
Figure 15. - Frequency-response curve, Alaska colliery, slope communication.
tests definitely proved that radio communication through the ground is feasible. Two-way radio communication was achieved in many tests at different stations where no wire or other metallic circuits existed between the underground and surface stations. Communication was established where no anthracite beds were present in the strata between the underground and surface stations, where thin, solid anthracite beds were present between the underground and surface stations, and where a number of mined-out anthracite beds were present between the two stations. Satisfactory communication with the test equipment was achieved through the ground for distances up to 1,050 feet, and intermittent communication through distances up to 2,040 feet. The distance through which communication is possible through the above-mentioned strata probably can be increased by improvements in the radio equipment.

Test results show that the lowest frequencies are attenuated the least but that the accompanying noise level increases at the lower frequencies. With the equipment used in this investigation, optimum results were obtained at frequencies between 60 and 80 kilocycles because of the most favorable signal-to-noise ratios at those frequencies. Modification of the radio sets to operate at a single fixed frequency instead of over the wide range of frequencies required in the test equipment, may make it possible to utilize (1) a frequency of 33 kilocycles or lower and (2) special noise filtering or suppression circuits and thus achieve maximum distances through the ground.

Another important point demonstrated in the tests at Reliance colliery is the fact that a terminal of the underground transmitter and receiver may be connected to the trolley wire to achieve radio communication through the ground. Daily radio communication over the trolley-wire system, a phase of normal mine operation now practiced at a number of bituminous-coal mines, also is accomplished by connecting a radio terminal to the trolley wire. Thus, the same method employed to connect the underground radio to achieve normal communication over the trolley-wire system can be employed in times of emergency to achieve communication through the ground.

The tests indicate that as long as 100 feet of the trolley wire remains suspended near the point of transmission and reception underground, radio communication can be accomplished over the trolley-wire system if the continuity of the circuit is not disrupted, even though the trolley wire is short-circuited to the rail at numerous points. Furthermore, if the continuity of the trolley wire is broken, other wires extending only a short distance on both sides of the break may bridge that gap and permit radio communication over the power system.

The tests also indicate that, in establishing radio communication through the ground strata, a suspended length of trolley wire as short as 100 feet is long enough to permit use of that trolley wire as a point of connection for terminals of the underground transmitter and receiver.

Use of the trolley wire as a point of connection for radios underground is convenient but is not essential in achieving communication through the ground. Communication through the ground can be established by connecting the terminals of the underground radio to the rails, to pipes, or to metal rods driven into the roof, rib, or bottom.
At Reliance colliery, as at Truesdale colliery, extreme wetness either in sections of the mine at which stations were established or in the strata between underground and surface stations, did not interfere in any instance with radio communication.

Tests of communication between the engineer and a man-car in an underground slope showed that constant two-way radio communication was entirely practical in that slope, but slope communication was slightly more difficult to obtain than shaft communication because of greater noise interference.

The Hudson Coal Co., Loree Colliery

The last tests in this investigation in the anthracite region were conducted at the Loree colliery of the Hudson Coal Co. at Larksville, Luzerne County, Pa. The mine is opened by seven shafts: Loree shafts 1 to 5, inclusive, and Boston shafts 1 and 2. Boston No. 1 shaft is not in use. Anthracite is mined in 10 beds - the Hillman, Stanton, Five Foot, Cooper, Bennet, Twin, Top Ross, Bottom Ross, Top Red Ash, and Bottom Red Ash. The dip of the beds ranges from 0° to 30°, and the average dip is 15°. A typical section shows the beds range 3 to 14 feet in thickness. Three additional beds (Snake Island, Abbott, and Lance) overlie the Hillman, but they are mined out. The maximum depth reached at Loree colliery is 900 feet.

Officials of the company were interested, among other things, in establishing radio communication over the trolley-wire system from the colliery office on the surface to all sections of the mine. Despite the fact that in tests at other mines radio communication was established over trolley-wire systems with ease, at Loree colliery it proved difficult to achieve two-way radio communication between the surface and underground in this manner.

The direct-current power-distribution system at Loree colliery is complex. The mine is old; operations were suspended in 1931, and the mine remained idle until 1943, when production was resumed. At that time, new electrical machinery was difficult to obtain, and old machinery that had been standing idle in the mine for 12 years was recovered and put into service wherever possible. Power for the haulage system is taken into the mine through Loree Nos. 2, 3, and 5 shafts, and through Boston No. 2 shaft. Each of the four motor-generator sets has different operating characteristics so that no two of the sets can be tied together, and each operates as an independent power system. The alternating-current power system underground also is split and consists of both 60-cycle and 25-cycle power, which is utilized to operate old pumps and motors that have been reclaimed and put into service.

A generalized sketch of the lay-out of the underground power-distribution system at Loree colliery, not drawn to scale, is shown in figure 16, in which the trolley-wire and feeder lines are represented by the solid lines. Underground test stations are designated by the points marked "X". The points marked "S" designate the surface test stations, the station at the colliery office having been connected by 370 feet of cable to the direct-current feeder lines extending over the surface. Conventional capacitor symbols are shown at underground points where two independent direct-current power distribution systems were connected with capacitors for radio communication test purposes.
Figure 16. - Loree colliery underground power distribution.
Communication between surface and underground by utilizing any individual power-distribution system was a simple matter. However, when communication was attempted over two or more of the systems, noise levels increased to intensities higher than ever encountered before, and it was difficult to obtain satisfactory results. In other mines it had been found that the presence of telephone wires for merely a short portion of the distance between the transmitter and the receiver offered definite assistance in propagation of transmitted signals, even though no direct connections were made between the radio and telephone systems. At Loree colliery the telephone system is sectionalized in a manner similar to the sectionalization of the direct-current power-distribution system, and no appreciable help was obtained from the presence of the telephone wires when signaling across more than one section of the power system.

Numerous tests were made, both with the experimental equipment and with commercial mine-dispatching radio units, and signal strengths were traced throughout the mine. These tests showed that complete communication coverage of the mine from the colliery office could be accomplished by connecting one microphone and one receiver at the colliery office to two radio units established at points marked "S" on figure 16, so that not more than two power sections need be covered directly by one radio system. Frequency-response curves drawn from test data showed maximum signal response at 100 kilocycles, a secondary minor peak in response between 60 and 70 kilocycles, and a still lower tertiary peak in response at 33 kilocycles. The occurrence of minor peaks in response at lower frequencies than the optimum frequency has been observed before at the Experimental mine, at Renton No. 3 mine, and at Tressesdale colliery. At Loree colliery, one frequency-response test between the surface office and a point in one of the uppermost levels near No. 2 shaft indicated maximum signal response at the lowest test frequencies; however, at 100 kilocycles a peak having slightly lower intensity than the maximum signal intensity received at 33 kilocycles appeared in the response curve. A similar condition of high response at low frequencies has been noted previously in a few isolated tests over the trolley-wire system at Montour No. 10 mine, but the significance of this fact has not been determined.

Shaft communication tests similar to those previously described were conducted between the engine room and the cage in Loree No. 4 shaft. No. 4 shaft, which is 366 feet deep, has two compartments. The usual bell-pull system of signaling, mine-telephone lines, and air lines are installed throughout the length of the shaft. Constant communication was maintained between the cage and the engine room with no difficulty during several tests made while the cage was in motion at both slow and normal speeds. A frequency-response test at the foot of the shaft showed the best frequency to be between 161 and 188 kilocycles, the usual result obtained in shaft tests at other mines.

Two audio-frequency communication units were tested in the shaft, but the results were negative. The audio-frequency units failed to provide communication between the engine room and any point in the shaft.

Radio communication solely through the strata between underground and surface points also was successful to some degree at Loree colliery.
An underground station was selected in the Bottom Red Ash bed, 3 west, 2 plane, at altitude +370 feet. The surface station was near the strippings at altitude +800 feet and 200 feet east of the underground station. The straight-line traverse between the two stations was 475 feet. The Top Red Ash, the Top and Bottom Ross, the Bennet, Cooper, and Five Foot beds, all robbed, and the solid Twin bed, lie between the surface and underground stations, the intervening strata consisting predominantly of sandstone and sand slate in beds of varying thicknesses, as shown in the following geologic column:

<table>
<thead>
<tr>
<th>Formation</th>
<th>Thickness of strata, feet</th>
<th>Accumulative depth, feet</th>
<th>Bed condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface material</td>
<td>65</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Sandslate</td>
<td>18</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>Five Foot bed</td>
<td>5</td>
<td>87</td>
<td>Robbed.</td>
</tr>
<tr>
<td>Sandslate</td>
<td>5</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td>55</td>
<td>147</td>
<td></td>
</tr>
<tr>
<td>Cooper bed</td>
<td>11</td>
<td>158</td>
<td>Robbed.</td>
</tr>
<tr>
<td>Slate divider</td>
<td>1</td>
<td>159</td>
<td></td>
</tr>
<tr>
<td>Bennet bed</td>
<td>11</td>
<td>170</td>
<td>Robbed.</td>
</tr>
<tr>
<td>Sandstone</td>
<td>48</td>
<td>218</td>
<td></td>
</tr>
<tr>
<td>Twin bed</td>
<td>2</td>
<td>220</td>
<td>Unmined.</td>
</tr>
<tr>
<td>Sandstone</td>
<td>64</td>
<td>284</td>
<td></td>
</tr>
<tr>
<td>Top Ross bed</td>
<td>4</td>
<td>288</td>
<td>Robbed.</td>
</tr>
<tr>
<td>Sandstone</td>
<td>34</td>
<td>322</td>
<td></td>
</tr>
<tr>
<td>Bottom Ross bed</td>
<td>3</td>
<td>325</td>
<td>Robbed.</td>
</tr>
<tr>
<td>Sandstone</td>
<td>34</td>
<td>359</td>
<td></td>
</tr>
<tr>
<td>Top Red Ash bed</td>
<td>11</td>
<td>370</td>
<td>Robbed.</td>
</tr>
<tr>
<td>Sandstone</td>
<td>46</td>
<td>416</td>
<td></td>
</tr>
<tr>
<td>Bottom Red Ash bed</td>
<td>14</td>
<td>430</td>
<td>First mined.</td>
</tr>
</tbody>
</table>

The terminals of the underground transmitter and receiver were connected in several combinations to the roof, rib, bottom, and rail, and the terminals of the surface receiver and transmitter were connected in the usual manner to two ground rods 150 feet apart. Noise intensity in the surface receiver was high and the signals received were intelligible only intermittently because of the noise interference. Signals transmitted from the surface could not be understood underground and the intensity of received signals could not be ascertained definitely, again because of the high noise level in the receiver at the underground station.

A second underground station was established in the Top Ross vein, 3 west, 4 slope, 28 plane, and a new surface station was established at the blacksmith shop, 343 feet vertically and 200 feet horizontally from the underground station, a straight-line distance of 395 feet. At this point the solid unmined Twin bed and the robbed Bennet, Cooper, and Five Foot beds, together with intervening beds of sandstone and sand slate, lie between the surface and underground stations. The geologic column shows:
Figure 17. - Frequency-response curve, Loree colliery.
<table>
<thead>
<tr>
<th>Formation</th>
<th>Thickness of strata, feet</th>
<th>Accumulative depth, feet</th>
<th>Bed condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface material</td>
<td>60</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td>15</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Five Foot bed</td>
<td>5</td>
<td>80</td>
<td>Robbed</td>
</tr>
<tr>
<td>Sandstone</td>
<td>5</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td>25</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Cooper bed</td>
<td>10</td>
<td>120</td>
<td>Robbed</td>
</tr>
<tr>
<td>Sandstone</td>
<td>43</td>
<td>163</td>
<td></td>
</tr>
<tr>
<td>Bennet bed</td>
<td>13</td>
<td>176</td>
<td>Robbed</td>
</tr>
<tr>
<td>Sandstone</td>
<td>113</td>
<td>289</td>
<td></td>
</tr>
<tr>
<td>Twin bed</td>
<td>1</td>
<td>290</td>
<td>Unmined</td>
</tr>
<tr>
<td>Sandstone</td>
<td>48</td>
<td>338</td>
<td></td>
</tr>
<tr>
<td>Top Ross bed</td>
<td>5</td>
<td>343</td>
<td>First mined</td>
</tr>
<tr>
<td>Sandstone</td>
<td>41</td>
<td>384</td>
<td></td>
</tr>
<tr>
<td>Bottom Ross bed</td>
<td>3</td>
<td>387</td>
<td>First mined</td>
</tr>
<tr>
<td>Sandstone</td>
<td>11</td>
<td>398</td>
<td></td>
</tr>
<tr>
<td>Top Red Ash bed</td>
<td>10</td>
<td>408</td>
<td>First mined</td>
</tr>
<tr>
<td>Sandstone</td>
<td>28</td>
<td>436</td>
<td></td>
</tr>
<tr>
<td>Bottom Red Ash bed</td>
<td>14</td>
<td>450</td>
<td>First mined</td>
</tr>
</tbody>
</table>

Signals transmitted from the surface at this station were received underground when the terminals of the underground units were connected to two roof points, to the roof and to the rail, or to the trolley wire and to the rail, but reception was noisy at most times. During those intervals when noise intensity abated, the signals received underground were loud and clear.

Reception on the surface was entirely satisfactory when the terminals were connected to two ground rods in the normal manner. Two frequency-response tests were conducted at these stations, one when the terminals of the underground transmitter were connected to the rail and to a metal rod in the bottom, and one when the terminals were connected to the trolley wire and to the rail. The frequency-response curves obtained in tests of communication through the ground at Reliance colliery; the intensity of the received signals was highest at the lowest frequencies and decreased as the frequency increased, and the optimum frequency was noted to be between 60 and 80 kilocycles because of the most advantageous signal: noise ratio at those frequencies. Transmitter output current was held constant at each frequency, and the transmitter output power varied from 1.7 watts at 33 kilocycles to 2.9 watts at 161 kilocycles.

The data for this test are listed in table 7, and the frequency-response curve is shown in figure 17.

Previous commitments to conduct tests at another mine prevented performance of additional tests to improve the results obtained in radio communication through the ground at Loree colliery.
### TABLE 7. - Frequency-response test - Loree colliery

<table>
<thead>
<tr>
<th>Frequency, kilocycles</th>
<th>Units of received signal strength, microvolts times k/</th>
<th>k/ = 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>585</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>515</td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>425</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>365</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>245</td>
<td></td>
</tr>
<tr>
<td>89</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>225</td>
<td></td>
</tr>
<tr>
<td>109</td>
<td>165</td>
<td></td>
</tr>
<tr>
<td>132</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>161</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>188</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Curve Fig. 17

1/ k = an arbitrary factor for each test (see p. 8).

### TESTS AT A SALT MINE

International Salt Company, Inc., Retsof Mine

A few tests of low-frequency radio communication for emergency underground use were made at the Retsof mine of the International Salt Company, Inc., at Retsof, Livingston County, N. Y.

All production at the Retsof mine is from a single salt bed at a vertical distance of 1,100 feet below the shaft collar. The workings are extensive and are opened by several shafts, only one of which is used currently to transport salt, materials, and men. The shaft has three compartments - two skipways used only to hoist salt, and one for other services. A single stainless-steel wire is exposed in the shaft and used in a bell-pull system of signaling for shaft repair work. Normal shaft signaling is by telephone communication from the shaft landing to the engineer. The telephone wires and the power lines in the shaft are encased in fiber ducts and buried in the concrete that lines the shaft completely from the collar to the bottom.

The strata overlying the producing salt bed consist predominantly of beds of limestone and shale, although occasional beds of gypsum and dolomite, interspersed with thin beds of salt, also occur in the geologic column. The geologic section at the Retsof mine is not shown in this report.

The results of several tests conducted in an attempt to establish radio communication through the ground were entirely negative. Approximately 1,200 feet of overburden is present at points where underground and surface stations could be established with absolute assurance that no "sneak" metallic circuits existed between the two stations. In the method of mining at Retsof, a layer of salt is left in place on the roof and on the bottom; the strata contiguous...
to the salt bed also contain some salt. Numerous tests by the authors in
different localities demonstrated conclusively that the success of radio
communication through the ground depends upon the ability to obtain ample
current from the transmitter. Dry salt is an excellent insulator; conse-
quently, the transmitter delivered only a slight current when the terminals
were connected to metal rods in the roof, rib, or bottom underground.

When the terminals of the underground units were connected to two rail
points or to the trolley wire and the rail, communication should have been
achieved through the ground to some extent, but not necessarily through 1,200
feet of the salt-bearing strata. Because salt is mined on only one level at
the Retsof mine, it was not possible to establish stations where less than
1,200 feet of overburden exists between underground and surface stations.
Therefore, the depth of overburden through which radio communication might
be accomplished could not be determined.

Trolley locomotives are employed for underground haulage, but the
trolley-wire feeders or circuits for power return are not exposed on the
surface. Moreover, 110- to 120-volt alternating-current power required to
operate the AC equipment was not available underground; consequently, no
tests of radio communication over the direct-current power system could be
conducted at the Retsof mine.

It was, however, an extremely simple matter to establish two-way radio
communication between the cage and the hoisting engineer. The terminals of
the underground transmitter and receiver, mounted on the cage, were connected
to the cage frame and to the hoisting rope at a point 45 feet above the bon-
net of the cage. The terminals of the AC units, set up in the engine room
alongside the engineer, were connected to a ground point and to the shaft wire
or to a metal contact on the headframe. Constant two-way communication was
maintained when the cage was in motion at any point in the shaft. A fre-
quency-response test from near the bottom of the shaft showed a peak response
at a frequency somewhat higher than 132 kilocycles and a secondary peak re-
sponse at 70 kilocycles. Signals received from the bottom landing of the
shaft were very noisy, not because of electrical or static interference, but
because of the noise created by the crusher, the rotary dumps, and other nor-
mal operations; these noises were transmitted through the microphone in the
same manner as voice. However, from all points 30 feet or more above the
shaft bottom, communication was very clear, strong, and quiet. Physical
noise interference through the microphone at the shaft bottom might be over-
come easily in a permanent working installation by providing a booth for the
transmitter similar to the booth now provided for the telephone, or by the
use of a less sensitive microphone or a differential microphone without an
enclosing booth.

TESTS AT A METAL MINE

Republic Steel Corp., Harmony Mine

Tests of emergency underground communications were conducted at the
Harmony mine, Port Henry district, Republic Steel Corp., at Mineville, Essex
County, N. Y. Production at the Harmony mine is from a magnetite-ore deposit.

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The country rock associated with the ore deposit consists of granitic gneiss with mica or biotite schists, hornblende gneiss, biotite gneiss, gabbro, and some crystalline limestone. The overburden in the vicinity in which the tests were conducted averages 100 feet in thickness and consists of glacial till composed of sand, boulders, and clay. The area is geologically complex, and a typical geologic column was available at the mine.

Two separate producing areas, the Harmony and the underlying Old Bed workings, are connected underground by crosscuts. The Old Bed section is opened by the Joker, Bonanza, and Clonan shafts; the Harmony mine is opened by the A and B vertical shafts and the Don B inclined shaft. The A and B shafts are used only for ventilation, and the Don B shaft is used for production. Communication tests were conducted in the Harmony mine in and around the vicinity of the Don B shaft.

A surface station was selected in the mining engineer's office at altitude +1,140, and the terminals of the surface units were connected to two metal rods driven into the ground 120 feet apart. An underground station was selected at a convenient point just off the Don B shaft at altitude +570, a straight-line distance of 800 feet from the surface station. The terminals of the underground units were connected to metal rods in two roof points, two ground points, or a roof and a ground point situated in or near the ore body. Communication could be established in one direction only - from the surface to underground. Weak but clear and distinct signals were received underground by using any of the different types of connections, but signals from the underground transmitter could not be identified in the surface receiver.

At the above-mentioned surface and underground stations, a direct-current potential was applied to the metal rods in conjunction with the radio-frequency potential applied in transmission to ascertain whether communication might be improved in this manner. The direct-current voltage applied was greater than the peak radio-frequency voltage applied between the two metal rods, and the resultant direct current flowing between the two metal rods was greater than the peak value of radio-frequency current flowing between the same two points. Superimposing the radio-frequency voltages upon the direct-current potential between the rods did not improve communication, and signals again were received underground but could not be identified on the surface.

Underground reception was exceptionally noise-free in all tests, and although received signals were weak, they were understandable at all times because of the marked absence of noise interference. The noise level in the surface receiver at all times was appreciable. Inability to identify signals on the surface does not prove the absence of signal voltages on the surface, because signal intensities as low as those received underground could have been present at the terminals of the surface receiver and have been obscured by the accompanying noise.

Station 2 was established with both units set up underground. The AC units were set up near the electrician's shop on the -680 level, the underground units near No. 7 contract on the -850 level, almost straight down the pitch from the surface units. Both stations were approximately 400 feet west of the Don B shaft and were separated by a straight-line distance of 525 feet. One or both terminal connections on each level was made in the ore body.
The terminals of the units on the -680 level were connected to two points 125 feet apart in the ore along the rib of the drift. The terminals of the units on the -850 level were connected to the rail and to a point in the ore along the rib of the drift. A frequency-response test produced a curve different from any curve obtained previously in this investigation; the intensity of received signals remained essentially constant between 33 and 109 kilocycles, showing a flat response in that range of frequencies, and the curve fell off at frequencies above 109 kilocycles as the intensity of received signals decreased with increase in frequency to 132, 161, 188, and 220 kilocycles.

On the -680 level, 50 feet of 440-volt line paralleled the lead between one terminal of the units and its point of connection to the rib, and the track, water and air pipes, a 110-volt line, and telephone wires extended parallel to the leads to both rib-point connections. On the -850 level, a 440-volt line extended along the drift in which the units were set up. The 440-volt lines on both levels extended east to points near the shaft where the lines were connected to transformers tapped off the 3,300-volt power line in the shaft.

The units on the -680 level were moved to a point 150 feet west of station 2, and the terminals were connected to a point in the ore in the rib of the drift and to a rail point 100 feet away. Only the track and the 110-volt line supplying power to the units were present at this station, but the other wire and metallic circuits were 150 feet or less from the transmitter and receiver. The units on the -850 level were moved farther west from the shaft to a point 50 feet beyond No. 15 contract and 250 feet beyond the end of the 440-volt line, so that the track was the only metallic circuit present in the immediate vicinity of the transmitter and receiver. The underground units at this point were separated by a straight-line distance of 575 feet from the surface units on the -680 level. The terminals of the underground units were connected to a point in the ore in the roof, and to the rail. The type of terminal connections was changed when the new stations were established because it was not possible to drive rods into the ore body or rock, and connections at each station were made to available metallic objects, such as pipes for platform supports and survey spads remaining in place from mining development.

A frequency-response test at these two stations showed a flat response curve between 58 and 132 kilocycles. The curve dropped off at both the low and high ends of the frequency band as the intensity of signals received decreased at frequencies below 59 kilocycles and at frequencies above 132 kilocycles.

The AC units on -680 level were moved 1,500 feet farther west of the shaft to a point 200 feet beyond the last contract and near the end of the drift. The underground units on -850 level were moved a few hundred feet farther west of the shaft to a point 125 feet beyond No. 19 contract and within sight of the end of the drift. The AC and underground units were separated by a straight-line distance of 915 feet between these points. Track was present on both levels, and the end of the 440-volt line was 400 feet east of the point at which the equipment was set up on the -850 level. On the -680 level, the 110-volt line supplying power to the equipment extended 150 feet to a transformer, from which point the 440-volt line continued east to the shaft.
The terminals of the surface units on -680 level were connected to two rail points 150 feet apart. The terminals of the underground units on -850 level were connected to the roof and to the rib. The drift at this site is not in the ore body, and both points of connection were in hornblende gneiss.

The signals received in a frequency-response test were weak. Because of the instability of the receiver at extremely sensitive settings of the controls, signal strengths at frequencies below 49 kilocycles and above 132 kilocycles could not be measured satisfactorily, and the readings at 109 and 132 kilocycles were erratic. The response curve obtained between 49 and 132 kilocycles again was essentially flat, as the intensity of received signals remained practically constant over this range of frequencies.

The terminal connections of the units on the -850 level were maintained roof-to-rib in hornblende gneiss, the only connections available at that point, and the terminal connections of the receiver on the -680 level were changed to one rail point and to a point in the ore body along the rib of the drift. Using these connections in a frequency-response test, readings were obtained between 40 and 161 kilocycles, and the intensity of received signals was higher than the intensity received when the receiver terminals were connected to two rail points. The response curve was flat between 49 and 109 kilocycles but received-signal intensity decreased at frequencies below 49 kilocycles and above 109 kilocycles. A direct-current potential, applied simultaneously with the radio-frequency potentials, between the roof and rib connections of the transmitter on -850 level, again did not affect the intensity of signals received on -680 level.

The AC receiver and transmitter were moved to a station situated 1,700 feet west of the shaft, at the last split in the drift on the -550 level. The terminals of the units were connected to two points in the ore body along the rib of the drift, the only connection points available. The underground transmitter and receiver were set up on the +26 level at a station 50 feet east of diamond-drill holes 439 and 440, 2,000 feet west of the shaft. The underground transmitter and receiver at this point were at a straight-line distance of 1,200 feet from the AC units on the -550 level. The ore body was continuous between the levels. The area on +26 level is abandoned; no wires were near the point at which the equipment was set up, and only a few discontinuous sections of track remained in place.

The terminals of the units on +26 level were connected to two roof points, to a roof and a ground point, and to the roof and to a section of rail. Best results were obtained when the terminals were connected to the two roof points, both of which were in the ore body. In a frequency-response test conducted under these conditions, receiver instability at extremely sensitive control settings again made it impossible to secure significant signal strength measurements at 168 and 220 kilocycles, but stable and satisfactory signal strength readings were obtained at all frequencies between 33 and 161 kilocycles. The curve obtained from the test showed the same results that had been noted in tests at Reliance and Loree collieries, where communication was achieved solely through the ground. Maximum signal intensity was received at the lowest frequency, 33 kilocycles, and as the frequency increased the received-signal intensity decreased. The transmitter-output-power range was 0.6 watt at 33 kilocycles to 2.1 watts at 161 kilocycles.
Figure 18. - Frequency-response curves, Harmony mine.
Curves A and B (fig. 18) show the two types of frequency-response curves obtained at the Harmony mine. The data from which the curves are drawn are listed in table 8.

| Frequency, kilocycles | Units of received-signal strength, microvolts times $k_l$ | | | |
|-----------------------|-----------------------------------------------------------|---|---|
| From -850 level to -680 level | $k_l = 6.0$ | From +26 level to -550 level | $k_l = 2.0$ |
| 33 | 348 | 742 |
| 40 | 216 | 654 |
| 49 | 468 | 554 |
| 58 | 600 | 436 |
| 70 | 600 | 326 |
| 80 | 582 | 298 |
| 89 | 618 | 256 |
| 100 | 600 | 226 |
| 109 | 600 | 216 |
| 132 | 600 | 160 |
| 161 | 480 | 140 |
| 183 | 240 | - |
| 220 | 232 | - |

Curve A, fig. 18 B, fig. 18

$k_l = k$ is an arbitrary factor for each test (see p. 8).

Reception underground at all points in the Harmony mine was extremely quiet. The received-noise level was so low that when the receiver was operating at its most sensitive settings, only a negligible deflection of the needle was noted on the meter when no signal was being received. Thus, it was possible to measure signal voltages as low as a few microvolts. In many instances in previous tests when the control settings were such that the receiver was comparatively insensitive, needle deflections were large, and at times the needle was driven off scale by received-noise levels alone when no signals were being transmitted and received. These facts raise the question whether, in many other tests, inability to measure signals received was really proof of the absence of signal voltages at the terminals of the receiver, or whether the signal voltages of low intensity received were present but were obscured and overridden by the greater noise levels received. This remains essentially an academic question until such time as circuits or other means, not known at present, are devised whereby undesirable noises received may be eliminated entirely. Under the present conditions, the only justifiable procedure is to report no reception when signals cannot be measured, irrespective of the possibility that signal potentials may not be absent entirely but may be present at such low levels as to be obscured by an unfavorable signal : noise ratio.

It can be accepted that communication was achieved through the strata alone in the test conducted when the underground transmitter was set up on +26 level, because the ore body was continuous between the transmitter station and the receiver station on -550 level and because the transmitter was separated
far enough from any metallic circuits to preclude the possibility of aid by wire circuits to propagation of signals. The frequency-response curve (curve B, fig. 18) is identical to the frequency-response curves obtained in other tests where it was known that communication had been effected through the strata alone. The frequency-response curves obtained from tests at other stations in the Harmony mine that show a flat response over most of the frequency range and fall off at one or both ends of the frequency band are new and entirely different from all other curves obtained to date. In each of the tests that yielded a flat response curve, the possibility exists that some energy from the transmitter might have been transferred inductively to metal circuits that existed between points in proximity to both the transmitter and receiver. Because of the long and devious path of such circuits and particularly because of the several power transformers through which the signals had to pass in following power circuits between transmitter and receiver, the aid offered by such circuits should be small, but nevertheless would affect the results obtained in the frequency-response tests. Whether this condition is partly or totally responsible for the flat response curves, unique in this investigation, was not demonstrated.

Tests on communication between the hoisting engineer and the cage were conducted in the Don B inclined shaft. The shaft is approximately 10 by 20 feet in cross section, although the area is much larger at some points in the shaft. A double track of 110-pound rails, 64-inch gage, separated by 32 inches between the inside rails, is laid throughout the entire shaft length. Fifty-two or more pairs of signal wires in a rubber sheath and 52 or more pairs of telephone wires in a lead sheath extend from the bottom of the shaft to the hoist. In addition, water lines, air line, and 3,300-volt power circuits are installed in the shaft. The wires are visible along the east side of the shaft, except at those intervals where they pass behind solid rock pillars and are obscured completely from the shaft proper.

The surface receiver and transmitter station was established in the hoist room, and the terminals of the units were connected to a pair of unused signal wires extending from the hoist to the -1,035 ore pocket.

The underground transmitter and receiver were mounted on the cage, or man car. The cage is metal and has a 50-man seating capacity. The terminals of the transmitter and receiver were connected to a multiple-turn loop arranged around the open top of the cage, and a test of communication was made when the cage was in motion in the shaft. It was found that at those points in the shaft where the wires were visible along the side of the shaft, two-way communication between the moving cage and the hoist was satisfactory, but at those points in the shaft where the wires disappeared behind rock pillars, communication ceased. After several tests with the loop yielded the same unsatisfactory results, the system was considered to be undependable, and the use of the loop was discontinued in further tests.

The terminals of the transmitter and receiver mounted on the cage then were connected to the body of the cage and to a point on the hoisting rope 75 feet above the cage. Using this system of terminal connections, two-way communication between the cage and the hoist was possible at all points in the shaft when the cage was either stationary or in motion.
Frequency-response tests were conducted from the stationary cage at the -1,185 level, 4,915 feet from the hoist, and from the -550 level, 3,868 feet from the hoist. Results of the tests from the -1,185 level showed a double peak in the frequency-response curve; maximum signal intensity occurred at 49 kilocycles, and a secondary peak in the intensity of signal received occurred at 100 kilocycles. The frequency-response curve obtained in tests at the -550 level showed a single peak in the response curve at 100 kilocycles. Additional tests when the cage was in motion showed the 100-kilocycle frequency to be the most satisfactory frequency for communication throughout the entire length of the shaft. Noise accompanying the reception of desired signals, as in other tests of communication in slopes, was more intense than the noise received in communication in vertical shafts, but it did not prohibit satisfactory interchange of messages from all points in the shaft.

The tests at the Harmony mine concluded the field work of the investigation in that portion covered in this report of applications of radio to emergency mine communication.

COMPARISON OF TESTS ON RADIO COMMUNICATION IN MINES IN THE UNITED STATES AND WITH TESTS ON RADIO COMMUNICATION IN GOLD MINES ON THE WITWATERSRAND, SOUTH AFRICA

In an interesting summary of tests on radio communication in gold mines on the Witwatersrand, conducted by the Telecommunications Research Laboratory, South-African Council for Scientific and Industrial Research, Wadley (18) reports results that agree in general scope but vary in several important details with the results obtained in the investigation by the Bureau of Mines. The South African tests were conducted under different conditions from those in the United States, but they are the only other tests of recent date reported on radio communication through the ground.

Underground communication in South Africa was accomplished entirely through quartzite by use of line aerials not connected to the rock underground or to the rock or ground on the surface. An interrupted continuous wave method of Morse-code signals was used to convey intelligence, rather than voice-modulation of a carrier frequency, as in the investigation by the Bureau of Mines.

Underground communication in the United States generally was accomplished through several different strata of sedimentary rocks, bituminous-coal beds, metamorphic rocks, and anthracite beds. In tests conducted at a magnetite mine in the United States, the rock formations were igneous or metamorphic in character, but the geologic structure at that mine was complex. Ungrounded line aerials used in a few tests yielded essentially the same results obtained in the majority of tests conducted when the antenna lines were connected to the ground or to the rock strata. Test readings were taken on unmodulated carrier frequencies, but the significance of the results of the investigation are based on voice-modulated carrier frequencies because of the far greater value of voice communication to the mining industry.

Using frequencies between 10 kilocycles and 5 megacycles, the South African investigation proved that least attenuation of signal in passage
through the earth occurs at the lowest frequencies and that as the frequency increases the degree of attenuation also increases, a point with which the Bureau of Mines investigators concur. However, because of the length of the aerial used - 500 feet in the actual conduct of the tests - Waddy cites the practicable range of frequencies as between 100 and 300 kilocycles and states further that reduction of aerial length to 200 feet - the optimum practicable length - favors the use of 300 kilocycles for earth communication. The tests in which a 500-foot aerial was used showed maximum working distances of 5,000 to 6,000 feet through quartzite for frequencies between 100 and 300 kilocycles and a power output of 10 watts, the nominal working range to be considered as 4,000 feet through the same type of rock if a 200-foot, instead of a 500-foot, aerial is used, and if the same power output is maintained.

In the investigation conducted by the Bureau of Mines over a band of frequencies between 33 and 220 kilocycles, the maximum signal was obtained at the lowest frequency - 33 kilocycles - in almost every test of communication through the ground, thus verifying both the calculated and measured test results of Eve, Keys, and Lee, referred to on page 10 of this report. In the tests at the coal mines (bituminous and anthracite), the optimum frequency was indicated to be in the range of frequencies between 60 and 80 kilocycles, because of the most advantageous signal:noise ratios at those frequencies. In the series of tests at an iron mine, maximum signal strength was received at 33 kilocycles in a test in which it was known definitely that communication was achieved solely through the ore body and rock, and because of the absence of noise interference, that frequency was also the optimum frequency for communication. In other tests at the iron mine in which it could not be proved conclusively that communication was solely through rock strata, but may have been aided by wire circuits, an optimum band of frequencies was indicated between 50 and 100 kilocycles. Thus, in an overwhelming majority of the tests conducted, the optimum frequency for communication through the ground, as determined in this investigation, was indicated to be 80 kilocycles or less, and in no instance was the optimum frequency determined to be in the high end of the frequency band.

In the tests conducted in this investigation, the length of the antenna lines, grounded on both ends, was in the range of 100 to 150 feet, a condition which, according to the findings of the South African investigator, should favor the use of higher frequencies. In a few tests in which connections were made to the trolley wire, which then represented an aerial in the same sense as the aerial used in the tests in South Africa, the frequency-response curve obtained did not differ in any respect but again showed maximum signal received at the lowest frequencies and, because of the most advantageous signal:noise ratios, optimum frequencies of from 60 to 80 kilocycles.

Satisfactory two-way voice communication was obtained through distances up to 1,050 feet in bituminous-coal and anthracite mines in the United States and unsatisfactory but identifiable intermittent communication through distances up to 2,040 feet. At the iron mine, two-way voice communication was accomplished satisfactorily through 1,200 feet, the maximum distance attempted. These distances can be increased by the use of improved equipment, but they are not incompatible as they stand with the working distance of 4,000 feet cited in the mines of South Africa.
According to Wadley (18), the distance of 4,000 feet achieved by the use of 10 watts output power would be reduced at least 700 feet by reducing the output power to 2 watts, a somewhat greater value than the average power used in the tests in the United States. In addition, a further loss in range of 1,500 feet would be experienced by using voice modulation instead of the telegraphic system employed to obtain the nominal 4,000-foot range. This 2,200-foot loss in working range thus reduces the nominal range, as cited by Wadley, to a maximum of 1,800 feet through quartzite only, under similar conditions of power output and voice modulation. According to Wadley, although laboratory measurements on Jeppetown shale showed an attenuation similar to that experienced in quartzite, laboratory measurements on Kimberly shale showed an attenuation about twice that of quartzite, so that with a transmission path wholly through that shale, the maximum range obtainable would be halved. Thus, the range of 1,800 feet under conditions similar to those encountered in the United States might be reduced to 900 feet for communication through a single type of rock. Either figure arrived at from Wadley's investigations should be reduced further and, perhaps, to a large degree, by consideration of the heightened attenuation of signals when passing from one type of rock to another, as from shale to sandstone, a transfer that must be accomplished several times in passing through the multiple sedimentary strata found in those areas in the United States in which the tests were conducted. However, ignoring the additional attenuation caused by the multiple strata condition, and applying only those modifying factors cited by Wadley, the working ranges indicated by both investigations are roughly comparable, and the principal disparity lies in the frequency of 300 kilocycles cited by Wadley as against a maximum frequency of 80 kilocycles indicated in the investigation by the Bureau of Mines.

The report of the South African investigation states that the presence of water does not affect the results unduly, provided that the water is confined to the mine workings and does not extend far into the rock itself and suggests that an excessively wet transmitting and receiving site should be avoided where possible. The findings of the investigation by the Bureau of Mines are similar. Although in tests in anthracite mines, extremely wet transmitting and receiving sites were used without apparent detriment to communication, earlier tests in a bituminous-coal mine failed in a wet section of the mine, and the avoidance of an excessively wet transmitting and receiving site, where possible, is a reasonable precaution.

The South African report states:

The presence of rails, pipes, etc., does not appear to assist or impede the transmission to any extent. They do, however, distort the field in their vicinity giving rise to polarization effects and rapid local variations of field strength, depending on their configuration. The actual transmission of the radio energy takes place through the rock considerably far removed from the mine workings, even in a long, straight tunnel.

The results obtained in the Bureau of Mines investigation are diametrically opposed to these conclusions. It was proved definitely and repeatedly that the presence of rails, pipes, and other metallic materials in the mine aided tremendously in the transmission of signals. Communication in long gangways and
haulageways where rails, pipes, and wires were present was accomplished through distances as great as 5 miles, without connecting either the transmitter or the receiver directly to any of the metallic circuits. That the transmission of radio energy in a long tunnel should take place through the rock considerably far removed from the mine workings, as postulated in the South African report, to the complete exclusion of inductive and perhaps direct transfer to energy to the propagation path offered by installations of rails, pipes, and other metallic circuits, is not conceivable theoretically and was disproved in practice in every test made. Furthermore, the effect of portions of pipe, track, and other metallic materials, not continuous from transmitting to receiving points but offering only intermittent and indirect interconnection paths, was evident in numerous tests by the increase in signal strengths received, the greatly extended range of communication, and the radical change in the frequency-response curves obtained.

SUMMARY

1. Applications of low-frequency radio to emergency communication in mines between underground points, between underground and surface points, and in shafts and slopes were investigated at the Experimental mine of the Bureau of Mines, at two commercial bituminous-coal mines and three anthracite mines in Pennsylvania, and at a salt mine and an iron mine in New York.

2. Radio communication in mines as accomplished in this investigation can be classified in three categories: Communication through the ground; wired, or carrier-current, communication over the power distribution system; and inductive communication utilizing, without direct connection, the telephone, signal, and power wires, and other metallic materials in the mine.

3. Testing equipment used in earlier experiments, reported in a previous publication (2), was modified and improved to obtain more accurate results.

4. Tests of oral communication, provided by amplitude modulation of a carrier frequency, were conducted over the range of frequencies between 33 and 220 kilocycles.

5. The power output of the transmitter in field tests rarely exceeded 3 watts and in most instances was less than 2 watts.

6. At the Experimental mine of the Bureau of Mines, the best frequency for communication through the ground was indicated to be in the band of frequencies between 40 and 50 kilocycles, and the best frequency for inductive communication utilizing wire circuits without direct connection to those circuits was indicated to be in the band of frequencies between 80 and 100 kilocycles.

7. At Montour No. 10 mine, Pittsburgh Consolidation Coal Co., the best frequency for carrier-current communication over the power-distribution system through distances up to 5 miles was indicated to be in the band of frequencies between 90 and 100 kilocycles, and satisfactory communication was achieved over the broader band of frequencies between 70 and 110 kilocycles.

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8. At Montour No. 10 mine, the results of a majority of the tests indicated that the best frequency for inductive radio communication is 80 kilocycles or higher. However, it was noted in a few tests that the trend of the frequency-response curve of signal strengths received tends to increase at 33 kilocycles and that in one test the signal strength received at 33 kilocycles was higher than the signal strength received at any other frequency, although the accompanying noise interference was severe and made reception unsatisfactory. Therefore it is possible that, under particular conditions at some mines, the best frequency for radio communication, directly or indirectly utilizing wire and other metallic materials, may be in the band of frequencies below 33 kilocycles if, in addition to other considerations, a favorable signal: noise ratio can be obtained at those frequencies.

9. Because of experimental results obtained early in this investigation, two commercial companies are manufacturing radios to provide communication over the power distribution system in mines, primarily for dispatching purposes. Research into the possibility that different frequencies may be desirable for carrier-current and inductive communication under special conditions at some mines is more appropriately a problem of research for those radio-manufacturing companies, and that possibility has not been examined extensively in this investigation.

10. Experiments at Montour No. 10 mine, in which loop antennas were used for transmitting and receiving purposes, showed that, without excessive power requirements, satisfactory emergency radio communication cannot be achieved underground by the use of loop antennas.

11. A simulated short circuit between the trolley wire and the track at Montour No. 10 mine did not prevent radio communication over the power-distribution system from inby the point of the short circuit to the surface.

12. At Renton No. 3 mine, Pittsburgh Consolidation Coal Co., mercury-arc rectifiers underground did not prevent the maintenance of satisfactory two-way radio communication over the power distribution system. Communication was established through a distance of 2-1/2 miles, and the results of frequency-response tests indicated that the best frequency for communication was approximately 130 kilocycles.

13. At Renton No. 3 mine, tests indicated that transformers and other electric machinery close to a transmission or reception point absorb radio signals and interfere with satisfactory communication.

14. At Truesdale colliery, Glen Alden Coal Co., the best frequencies for carrier-current and inductive communication were shown to be in the band of frequencies between 132 and 188 kilocycles.

15. Tests at Truesdale colliery proved that telephone lines beginning several thousand feet from the point of transmission aid materially in radio communication in mines; this indicates that short sections of wire conductors or other metallic materials remaining intact after a mine fire or explosion may make radio communication possible between the surface and underground or between different underground sections of a mine.
16. Successful communication at Truesdale colliery over a power distribution system short-circuited to alternating currents verified similar results obtained at Montour No. 10 mine and indicated that trolley wire dropped across the track, but not broken by a fire or explosion, may permit radio communication over the power distribution system between the underground workings and the surface.

17. Open switches in the trolley wire interfered seriously with communication at Truesdale colliery, but tests showed a distinct possibility that breaks in the trolley wire may be bridged by the presence of short lengths of other wires extending only limited distances on each side of the break, thus permitting communication even though the continuity of the power distribution system is disrupted.

18. Failure to achieve communication over the power-distribution system at Truesdale colliery under a unique condition of little or no current being drawn from an energized system indicated that radio communication over a de-energized power-distribution system may present a different problem than radio communication over a normal energized system, particularly with respect to the optimum band of frequencies to be employed. This possibility should be examined more closely in future investigations.

19. Constant and highly satisfactory radio communication was established without difficulty between the hoisting engineer and a moving cage in Askam shaft at Truesdale colliery. The maximum depth at which tests were made was 1,500 feet.

20. Communication solely through the ground was attempted at Montour No. 10 mine but was not achieved at that mine, at Renton N. 3 mine, or at Truesdale colliery, because suitable surface stations were not available for conducting tests.

21. Radio communication solely through the ground was proved definitely feasible in many tests at Reliance colliery, Philadelphia & Reading Coal & Iron Co. Communication was established where no anthracite beds were present in the strata between the underground and surface stations, where unmined anthracite beds were present in the strata between the underground and surface stations, and where a number of mined-out anthracite beds were present between the two stations.

22. Satisfactory two-way communication through the ground was achieved through distances up to 1,050 feet, and intermittent communication was established through distances up to 2,040 feet. The distance through which communication is possible probably can be increased by improvements in radio equipment.

23. The lowest frequencies were attenuated the least in communication through the ground at Reliance colliery, but the accompanying noise interference increased at the lower frequencies. Optimum results were obtained in the investigation at Reliance colliery at frequencies between 60 and 80 kilocycles, because of the most favorable signal:noise ratios at those frequencies.
24. On the surface, the terminals of the transmitter and receiver were connected to two metal rods driven into the ground. Underground, the transmitter and receiver terminals were connected to ground, roof, rib, rail, air or water pipes, and trolley wires, in all possible combinations, and communication was achieved in every instance.

25. A piece of trolley wire as short as 100 feet is sufficiently long (when suspended) to permit use of that wire as a terminal connection to achieve radio communication through the ground. The 100-foot length of wire may be open at one or both ends or may be part of a continuous circuit. A suspended 100-foot length of trolley wire also is sufficient to permit radio communication over the power-distribution system, provided, however, that the continuity of the circuit is not disrupted, although the trolley wire may be in contact with the rail at numerous points.

26. Because the trolley wire now is being used for a terminal connection in the use of radios for dispatching purposes in mines to provide communication over the power distribution system, it is a definite advantage that terminal connections need not be changed but also may be made to the trolley wire to achieve emergency communication through the ground.

28. At Reliance and Tuesdale collieries, extreme wetness either in sections of the mine at which communication stations were established or in the strata between underground and surface stations did not interfere in any instance with radio communication through the ground or with radio communication utilizing the aid of wire and other metallic materials. In previous tests at Montour No. 10 mine, however, it was not possible to achieve communication over any appreciable distance when the transmitter was set up in a very wet section of the mine.

29. The results of a number of tests on communication through the ground at Reliance colliery indicated that maximum signal strength is received on the surface when the antenna lines from the terminals of the underground units to the ground, roof, rib, or other points of connection are parallel to the corresponding lines on the surface. However, although signals received were weaker, communication was possible when the underground and surface lines were in any position relative to each other, including a right-angle, or perpendicular, position.

30. Tests of communication between the hoisting engineer and a man-car in an underground slope, which is 2,000 feet long, at Alaska colliery showed that constant two-way radio communication was entirely practicable when the car was stationary or in motion. However, communication on the slope was slightly more difficult to maintain than communication in a vertical shaft because of the greater noise interference.

31. Results of a test on communication through the ground to determine the effect of a pool of water impounded between the transmitting and receiving stations indicated that communication was not destroyed, but the results were not conclusive.

32. At Loree colliery, the Hudson Coal Co., it was proved possible to establish radio communication over the power-distribution system at that mine.
from the office on the surface to all sections of the underground workings. Frequency-response tests showed the optimum frequency to be approximately 100 kilocycles.

33. Curves drawn from some frequency-response tests at Loree colliery, Truesdale colliery, Renton No. 3 mine, Montour No. 10 mine, and the Experimental mine showed that, in addition to the highest peak response determined, a secondary peak occurred at approximately one-half the frequency of the primary peak, and in a few instances a third minor peak at one-half the frequency of the secondary peak. The exact significance of these results and of an occasional indication of maximum signal strength received at the lowest frequency in carrier-current or inductive communication has not been determined.

34. Excellent radio communication between the hoisting engineer and a moving cage in Loree No. 4 shaft was accomplished with no difficulty. The shaft is 366 feet deep.

35. Two audio-frequency communication units were tested in Loree No. 4 shaft but failed to provide communication between the engine room and any point in the shaft.

36. Communication through the ground was achieved at Loree colliery through almost 400 feet of overburden that included several anthracite beds in unmined, first-mined, and robbed condition. Maximum signal strength was received at the lowest frequency, but again the optimum frequencies were in the band between 60 and 80 kilocycles because of the most advantageous signal-to-noise ratios at those frequencies.

37. Tests on communication through the ground at the Retsof mine, International Salt Co., Inc., were unsuccessful. Inability to obtain more than a slight current output from the transmitter into the salt and salt-bearing formations made it impossible to achieve communication through 1,100 feet or more of overburden. Test sites could not be established at points with less than 1,100 feet of cover, and it was not possible to determine through what thickness of strata communication might be possible.

38. Communication between the hoisting engineer and the moving cage in the Retsof mine shaft was highly successful and was established with no difficulty. The shaft is 1,100 feet deep.

39. At the Harmony mine, Republic Steel Corp., communication was established through 1,200 feet of magnetite ore with no aid from wire or other metallic materials in the mine. Maximum signal strength was received at the lowest frequency (33 kilocycles), which in this instance was also the optimum frequency. The extremely low level of noise interference underground at all frequencies provided the most favorable signal-to-noise ratio at the frequency that yielded the maximum signal intensity. At both transmitting and receiving stations, the terminals of the radios were connected to metal rods driven into the ore body.
40. Communication was achieved in the Harmony mine between other underground points spaced at different distances, but it could not be proved definitely that communication was achieved without some aid from power-distribution circuits in the mine. A unique frequency-response curve, essentially flat over most of the frequency band but dropping off at both the high and low ends of the band, was obtained in the tests where it could not be proved that communication was solely through the ground.

41. Test results at Harmony mine indicated that the signals find their way into and follow the ore body (magnetite). Although communication was achieved when the transmitter terminals were connected to points in the strata considerably far removed from the ore body, it was not possible to achieve communication through the strata unless the receiver terminals were connected to points in proximity to or actually in the ore body.

42. Several tests were conducted at the Harmony mine to determine if communication through the ground could be improved by the application of DC potentials in conjunction with the AC potentials to the points of connection in the strata. The added DC potentials made no ascertainable difference in the results.

43. Constant two-way communication between the hoisting engineer and a moving car in the Don B inclined shaft at the Harmony mine was accomplished satisfactorily. The maximum shaft length through which communication was attempted was 4,915 feet.

44. The results of tests on underground communication by radio in gold mines on the Witwatersrand, South Africa, agree in general scope but vary in several important details from the results obtained in this investigation.

45. Investigation by the Bureau of Mines of the applicability of radio to emergency mine communication is being extended to mines in the western United States and also is being continued in mines in the eastern United States.

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