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TROLLEY CARRIER PHONE MINE COMMUNICATIONS

ADAPTIVE VOLUME CONTROL AND USE OF A DEDICATED WIRE OR A LOW IMPEDANCE LINE FOR IMPROVED CARRIER PHONE COMMUNICATIONS IN MINES

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16. Abstract (Limit: 200 words)

This report presents the results of a program that was initiated to study, implement, and test the operation of an adaptive volume control circuit for the loudspeaker of a mine trolley carrier phone. The design goal was for the control to sense the ambient noise conditions and to operate the communications equipment such that the sound output would be loud under noisy conditions, and quieter under quiet conditions, thereby resulting in an understandable and non-startling volume level under all normal operations conditions.

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FOREWORD

This report was prepared by Arthur D. Little, Inc., Cambridge, Massachusetts, under USBM Contract No. J0377098. The contract was initiated under the Coal Mine Health and Safety Program. It was administered under the technical direction of the Pittsburgh Mining and Safety Research Center with Mr. Harry Dobroski acting as the technical project officer. Mr. Joseph Gilchrist was the contract administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this contract during the period September 1977 to January 1979. This report was submitted by the authors in February 1979.

No inventions or patents were developed, and no applications for inventions or patents are pending.

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I. EXECUTIVE SUMMARY

A. PHASE I - ADAPTIVE SPEAKER VOLUME CONTROL FOR MINE CARRIER PHONES

1. Objective

When in motion, mine rail haulage vehicles generate high ambient acoustic noise levels. For dispatching purposes these vehicles require communication. Thus, when the noise level on the vehicle is high, the volume level from the trolley wire carrier phone loudspeaker should be correspondingly high, so that the message can be heard and understood. Conversely, when the vehicle is stopped, it can be both annoying and startling when a full volume loudspeaker starts to issue a message under quiet ambient noise conditions.

This program was initiated to study, implement, and test the operation of an adaptive volume control circuit for the loudspeaker of a mine trolley carrier phone. The design goal was for this control to sense the ambient noise condition, and operate the communications equipment such that the sound output would be loud under noisy conditions, and quieter under quiet conditions, thereby resulting in an understandable and nonstartling volume level under all normal operating conditions.

2. Findings

A number of approaches were considered for deriving the signals to operate the adaptive volume control circuitry and for obtaining the power to run it. For space considerations, the trolley carrier phones for mine vehicles are packaged in a number of separate units. In addition, generally only the loudspeaker and microphone unit are present at the vehicle operator's location. The other units, where useful signals and power supplies are available to operate an adaptive volume control, are generally installed on the vehicle remote from the operator's location. Therefore, it was decided to build the adaptive volume control so that it could be placed within, and operate from, the loudspeaker enclosure, without the need for access to any of the remote signals or power available in the transceiver unit.

The prototype control device (powered by its own battery power supply) developed for feasibility demonstration purposes was built and installed in the loudspeaker enclosure of a Gulton Femco trolley carrier phone. This unit was tested on a jeep vehicle in a coal mine, and found to have the expected desirable characteristics of adaptive volume control. One minor defect in its operation was discovered during the in-mine testing, namely, an occasional transition to a "loud" volume condition due to acoustic feedback within the unit itself. This defect is readily amenable to cure with minimum modification to the existing circuit approach.

3. Recommendations

It is recommended that a second prototype volume control be built based on the circuit principles established in the first prototype. The new design goals to be met are:

- Eliminate the minor defect discovered during in-mine testing.
- Reduce the power supply requirements of the unit so that the self-contained battery life will be extended, or preferably, find a convenient way to power the unit from the carrier phone itself.
- Package the unit so that it is easily installable in all presently operational mine carrier phones.

B. PHASE II - DEDICATED WIRE EXPERIMENT FOR MINE CARRIER PHONE SYSTEMS

1. Objective

Trolley carrier phone systems used in electric rail haulage coal mines often suffer from poor communications between carrier phones. This poor communication performance is largely due to the many bridging loads found across the trolley wire/rail transmission line. A recent theoretical treatment made by Arthur D. Little, Inc., under Bureau Contract H0346045, Task Order No. 2, Task I, shows that the use of an auxiliary wire, called the dedicated wire, strung along the wide side of the rail haulageway should overcome the problems of poor transmission caused by such bridging loads. The objective of this project was to perform an in-mine experimental test to demonstrate the utility of the dedicated wire approach for overcoming poor carrier phone signal transmission on the trolley wire/rail line, and to provide guidelines on the installation and use of such dedicated wires.

2. The Experiment

Consolidation Coal's Montour No. 4 coal mine in southwestern Pennsylvania provided cooperation for the performance of the experimental tests. Measurements were made under mine-operating conditions during an early visit to the mine to determine carrier phone system performance in the absence of the dedicated wire, the dominant bridging loads across the trolley wire/rail line, and the specific areas of the mine having trolley carrier phone communication problems that could be alleviated by the dedicated wire. These measurements concentrated on developing a signal level map of the trolley wire/rail voltage, along nearly four miles of the mine rail haulageway, produced by the remotely activated dispatcher's transceiver connected to the pager phone line at a central location in the mine. The pager phone line was already being used by the mine as an imperfect dedicated wire together with carrier signal couplers to the trolley wire. Plans were also worked out with mine operating staff concerning methods and procedures for installing the dedicated wire and performing the measurements.

About one month later during the coal strike, the signal level map for the mine's normal carrier phone system configuration was repeated just prior to installing the dedicated wire, to determine the effects on system performance of the mine's nonoperating condition. Then about 20,000 feet of dedicated wire were installed, using spads and J-hooks to support the wire, on the wide side of the rail haulageway. The run started at the position of the dispatcher's remote carrier phone transceiver and continued to a position where signal reception was poor, about 18,000 feet from the dispatcher's unit. The dedicated wire was terminated to the rail through a 200 ohm resistor at this end. A branch was added to this main dedicated wire by means of a signal splitter, and run to a second region nearby having poor signal reception. This branch wire was similarly terminated to the rail through a 200 ohm resistor.

After installation, a signal level map was measured with the dispatcher's remote transceiver now connected directly to the dedicated wire/rail line. The current in the dedicated wire was also measured at points along its run to determine the attenuation along the wire and compare results with theory.

3. Findings

The main findings are summarized below:

- The dedicated wire improved the dispatcher's signal levels along the trolley wire/rail line by as much as 20 dB. Improvement was most significant in areas having weak reception in the absence of the dedicated wire.
- The measured attenuation rate along the dedicated wire/rail was less than 1 dB per kilometer.
- A strong signal can be placed on the dedicated wire/rail line, and can be distributed with low loss throughout wide regions of a mine via this wire.
- Signals on the dedicated wire/rail line can be split and distributed down branches of the dedicated wire/rail line. Dedicated wire/rail lines can be terminated to minimize the generation of standing wave nulls.
- The spacing of the dedicated wire from the rib or roof does not appear to be critical.
- The velocity of signal propagation on the dedicated wire/rail line appears to be about 65% that of the free space value.
- The dedicated wire allows the carrier phone signal on the trolley wire/rail line to remain strong throughout the mine, without the use of hard wired signal couplers between the dedicated wire and the trolley wire.

4. Recommendations

The dedicated wire approach is strongly recommended as a valid and practical method for improving trolley carrier phone system performance in coal mines. Furthermore, we recommend that the dedicated wire application guidelines presented in this report be followed to ensure a systematic and effective installation and to obtain the best possible system performance.

The success of this project suggests the following work would be beneficial for providing further practical information concerning the flexibility and utility of this dedicated wire technique.

- Measure the improvement in performance at the Montour No. 4 mine under operating mine conditions to see how it compares with that found under the nonoperating mine condition.
- Provide a more stringent and comprehensive test of the theory by performing in-mine measurements over significantly longer lengths of rail haulageway and with carrier phone units connected directly across only the trolley wire/rail line.
- Examine methods for optimizing the performance and simplifying the installation of the dedicated wires.

C. PHASE III - LOW IMPEDANCE LINE EXPERIMENT FOR MINE CARRIER PHONE SYSTEMS

1. Objective

A second means for overcoming the signal loss caused by the many mismatched bridging loads found across trolley wire/rail transmission lines in mines is the low impedance line technique. This technique was also studied theoretically and experimentally by Arthur D. Little, Inc., under Bureau Contract H0346045, Task Order No. 2, Task I, and shown to have promise as a means of reducing the signal attenuation caused by such bridging loads. The load mismatches, and thus the signal attenuation, can be reduced by resonating the individual loads at the carrier frequency to increase the magnitudes of the bridging load impedances, or by loading the line with periodically spaced shunt capacitors to lower the characteristic impedance of the line. The objective of this work was to perform an in-mine experiment to demonstrate the effectiveness and practicality of the low impedance line technique in an operating coal mine environment.

2. The Experiment

Consolidation Coal's McElroy coal mine located in Moundsville, West Virginia, cooperated in the performance of the experimental tests. We made an early visit to the mine to determine the mine electrical haulage system layout, the dominant bridging loads across the trolley wire/rail line, and the most suitable locations to perform experiments along both a controlled de-energized section of trolley wire/rail and an operational section of main haulageway. We also worked out plans with the mine electrical personnel concerning methods and procedures for installing the shunt capacitors and for performing the experiments with their assistance.

The experiments on a de-energized section of trolley wire/rail transmission line were made during the second visit. The 300 volt DC power was disconnected from an unloaded 1200 foot section of trolley wire/rail line in a remote area. Measurements of line inductance, capacitance, characteristic impedance, and propagation phase velocity were made, in addition to measurement of signal strength behavior in the presence of two low impedance resistive shunt loads, under both normal and low impedance line conditions. Attempts to obtain valid measurements of signal strength versus distance along an operational section of haulageway were thwarted by equipment failures during this second visit. These measurements were carried out during a third visit along a 3900 foot stretch of operational main haulageway having two 500 kW power rectifier shunt loads under normal and low-Z line conditions. During each series of tests, the low-Z line configuration was created by installing 0.04 μF shunt capacitors spaced about 200 feet apart along each test section.

3. Findings

The experiments show that a mine trolley wire/rail line behaves as a transmission line having a characteristic impedance value of approximately 200 ohms. The actual value is close to 250 ohms in the absence of a feeder cable, but closer to 170 ohms when a feeder cable is present.

The tests along the short de-energized section of trolley wire/rail line having no feeder cable demonstrated that the line characteristic impedance (and propagation phase velocity) could be reduced approximately as predicted by periodically shunt loading the line with discrete capacitors. Reductions by factors of 6.6 and 7.8 were achieved for the characteristic impedance and phase velocity respectively. The results of the line parameter measurements performed along this section of haulageway are summarized as follows:

De-energized Trolley Wire/Rail Line Parameters

	Normal Line	Low-Z Line	
L	37 μH/100 ft.	37 μH/100 ft.	
C	630 pF/100 ft.	.026 μF/100 ft.	
Z_o	243 - 268 ohms	38 - 40 ohms	Ranges for various methods of measurement
v_p/c	66.6 - 76.4%	9.6 - 10.4%	Ranges for various methods of measurement

c is the free space propagation velocity. Finally, significant predicted signal losses caused by shunt bridging loads on normal trolley wire/rail lines were verified experimentally, as were the marked reductions in signal loss predicted under low-Z line conditions.

The normal and low-Z line signal strength comparison tests along the section of operational trolley wire/rail line with a feeder cable demonstrated significant improvements in signal strength over most of the run under low-Z line conditions. However, the results were not as favorable or as conclusive as those on the de-energized controlled section of line, especially over that half of the run farthest from the transmitter where unanticipated propagation anomolies led to a deviation from the expected signal versus distance behavior and less than expected overall improvements in signal strength. In addition, the following observations were made. Significant predicted losses in signal strength caused by rectifier loads under normal line conditions were verified experimentally. Voltage drops of about 8 dB were measured at rectifiers not equipped with rf bridging capacitors across the trolley wire DC deadblocks and were found to be in general agreement with approximate theoretical estimates. Finally, phase velocities of 50% and 14% of the free space velocity were derived from the signal strength versus distance curves for the normal and low-Z lines, respectively; giving a reduction factor of 3.6 as compared with the factor of 7.8 for the unenergized section.

4. Recommendations

Of the two major methods examined for improving carrier signal transmission along mine trolley wire/rail lines, we recommend the use of the dedicated wire method over the low-Z line method as the most effective and practical way to upgrade trolley carrier phone communications in U. S. coal mines. This recommendation is based primarily on the favorable performance and experience in mines to date with the dedicated wire, and on the more involved installation and maintenance procedures associated with the low-Z line. A secondary consideration is the presence of some unresolved questions regarding lower than anticipated performance of the low-Z line along a section of operational main haulageway.

In spite of some of its relative shortcomings, the low-Z line can be an effective method, and we recommend its use to reduce mismatch losses and improve signal transmission in localized or extended mine applications where other methods may not be appropriate. In such cases, we also recommend that more permanent, practical and safe capacitor installations than those used during these reported experiments be devised. A method that incorporates the capacitors into the trolley wire hanger insulator appears to have particular merit.

II. PHASE I - ADAPTIVE SPEAKER VOLUME CONTROL FOR MINE CARRIER PHONES

A. BACKGROUND

The acoustic noise levels in a mine vary very widely from extremely high sound pressure levels in the vicinity of operating machinery to very quiet conditions when machinery is stopped or absent. These noise levels pose a particular problem when trying to communicate to personnel on rail haulage vehicles used in the mine. Such vehicles can themselves generate extremely high noise levels in excess of 105 dBA when underway.

Communication to such vehicles is normally accomplished by means of trolley carrier phones which transmit radio frequency carrier signals to and from the vehicles over the trolley wire/rail transmission line. Depending upon whether the vehicle is moving or not, the volume setting on the loudspeaker of the carrier phone must be set either to combat the extremely high ambient noise level when the vehicle is moving, or to a more acceptable moderate level allowed when the vehicle is stationary. This produces a dilemma. Namely, when the vehicle is moving and generating a considerable ambient noise level, the volume control on the trolleyphone must be turned up to the full volume; then when the vehicle is stopped, and the ambient noise is very low, the volume control setting on the trolleyphone should be turned down to produce a more comfortable sound level for communicating. This change in volume setting is highly desirable to avoid the so-called loudspeaker "barking" effect which causes considerable discomfort when a transmission is received in a quiet environment when the volume control is left at its full setting.

The constant adjustments to the volume control on the trolleyphone necessitated by the variable acoustic environment in a mine haulage vehicle can lead either to missed messages, if the vehicle is moving and the volume control is set to a quiet condition, or to annoyance of the personnel in the vehicle if the vehicle is stationary and the trolleyphone "barks" (at its full volume level setting). Economical and reliable electronic components are now available to implement a loudspeaker control that adjusts the speaker volume in accordance with the background acoustic noise level. Therefore, the purpose of the task discussed in this Phase I chapter is the development of a circuit approach that is reliable in terms of always providing the correct loudspeaker volume regardless of: the acoustic background noise, the loudspeaker generated sound, or the vehicle operator's voice transmissions over the carrier phone microphone.

B. DESIGN REQUIREMENTS

1. The Acoustic Environment

When a mine vehicle is moving along a mine rail haulageway, the ambient noise acoustic level is of the order of 100 - 105 dBA. This necessitates a sound output from the loudspeaker in excess of such levels in order for communications to be possible. The use of earphones is generally unacceptable due to the rough nature of the mine environment and the inconvenience to the operator. However, when the vehicle stops, the acoustic environment is very quiet, the greatest noise generally being generated by people's voices, when the vehicle is not in the vicinity of other operating machinery.

Thus, an adaptive volume control has been designed whereby in a high-noise environment, such as when the vehicle is moving, the output of the carrier phone loudspeaker is at maximum volume setting; but when the vehicle is in a stationary condition and there is no loud machinery operating in the vicinity, then the loudspeaker output is at a low volume setting which is adjustable by the operator. An additional requirement is that the adaptive volume control should not be affected either by the reception of incoming messages, the sending of messages by the operator, or other conversation in the vicinity of the carrier phone. (It should be noted that, when the carrier phone is operated in a quiet environment, then the volume control will be more or less set to that level associated with normal conversational requirements. This level in general is not greater than 90 dBA.)

Thus, the mine carrier phone exists in two essentially contrasting acoustic environments. The first is when the vehicle on which the trolleyphone is installed is moving or in the vicinity of other operating mining equipment, where the acoustic environment is extremely loud. The other is in a quiet environment, when machinery is stopped or the vehicle is stopped. This latter condition is more or less a normal conversational environment. The function of the adaptive volume control is to differentiate between these two acoustic environments, and arrange that the output of the carrier phone loudspeaker be at a maximum volume under high noise conditions, and at a comfortable volume, controllable by the vehicle operator, when the carrier phone is operating under acoustically quiet conditions.

2. Initial Approach

In order to implement such an adaptive volume control, the initial approach suggested using the microphone that is already part of the trolley carrier phone as the device to monitor the background acoustic noise. The microphone press-to-talk switch would be used to tell the circuit that the operator is using the microphone for transmission. To determine when the receiver is supplying audio power to the speakers, a squelch signal would be used. When one of these two events occurred, a stored level of background acoustic noise would be used to maintain the speaker volume control setting. Storage time would be made compatible with the longest normal transmission. The storage level would be updated at a rapid rate except during the time period identified by the squelch signal or the press-to-talk signal.

Once detailed designs were considered, this initial approach was abandoned since the packaging of the currently available mine carrier phones is such that the transceiver unit of the equipment, where squelch signals are available, is separate from the loudspeaker/

microphone unit. In general, for space saving reasons the loudspeaker/microphone unit is packaged separately from the transceiver and battery charger unit, depending on which manufacturer's carrier phone is under consideration.

A common factor to all of the available carrier phones, however, is that the transceiver unit provides to the loudspeaker unit full volume at all times for received sound messages, and volume control is accomplished in the loudspeaker unit by absorbing some of the audio frequency energy provided by the transceiver unit to the loudspeaker. Therefore, a more practical and reasonable design approach was conceived, namely, one that controlled the loudspeaker volume by a circuit residing in the loudspeaker unit itself. Such an approach would avoid requiring access to the squelch control, which is only available in the transceiver unit, and thereby avoid a change in the cabling between the loudspeaker unit and the transceiver unit.

The initial design approach also considered the use of the carrier phone microphone as the local acoustic noise sensing unit. This approach requires energization by the microphone key for normal operation, and also consumes power from the trolleyphone battery in the vehicle. This microphone is generally also a noise cancelling type of microphone which, of course, would yield some indication of background noise conditions, however not so clearly as would a conventional microphone. As a result of these negative factors, the use of the local microphone part of the carrier phone for measuring background acoustic noise was abandoned.

3. Alternate Approaches

In an attempt to utilize sensors that are most readily available for measuring the background noise, we examined using the loudspeaker horn itself as a background noise level sensor. It was hoped that the use of such existing equipment would simplify the design. Laboratory tests were made to show that the existing loudspeaker horn would produce between 100 and 200 mV of signal at the loudspeaker electrical input in an acoustic environment consisting of white noise at a level of about 105 dBA. Unfortunately this approach was not easily usable, since the output of the loudspeaker coil depended not only upon the acoustic noise level incident on the speaker, but also upon the volume level setting, and the impedance of the amplifier driving the loudspeaker. Thus, it was finally concluded that a more simple approach using a separate local microphone, independent of either the operator's microphone or the speaker, would be the simplest and most economical.

A further idea was pursued during the initial design study period of this task. This idea was to use the power supply available in the trolleyphone transceiver unit to operate the adaptive volume control. Unfortunately, for reasons stated previously, the adaptive volume control electronics are best situated in the loudspeaker unit itself, as opposed to in the transceiver unit. When such a constraint is adopted, the only power supply available is that which comes to the loudspeaker assembly from the transceiver unit. This power is available through the microphone cable, and powers the microphone when the transmit key is pressed. This power supply could be used to charge NiCad batteries associated with the speaker control circuits when the operator's microphone key is not depressed, which is most of the time. Such an approach is a possibility and should be considered in future designs of adaptive speaker control units. However, it was decided that the additional circuit complexity of such an approach over that obtainable by using a separate battery power supply was not warranted for the prototype unit being developed on this task to demonstrate concept feasibility.

4. The Chosen Approach

As a result of the previous investigations the approach chosen for this demonstration unit to show feasibility of the adaptive volume control follows:

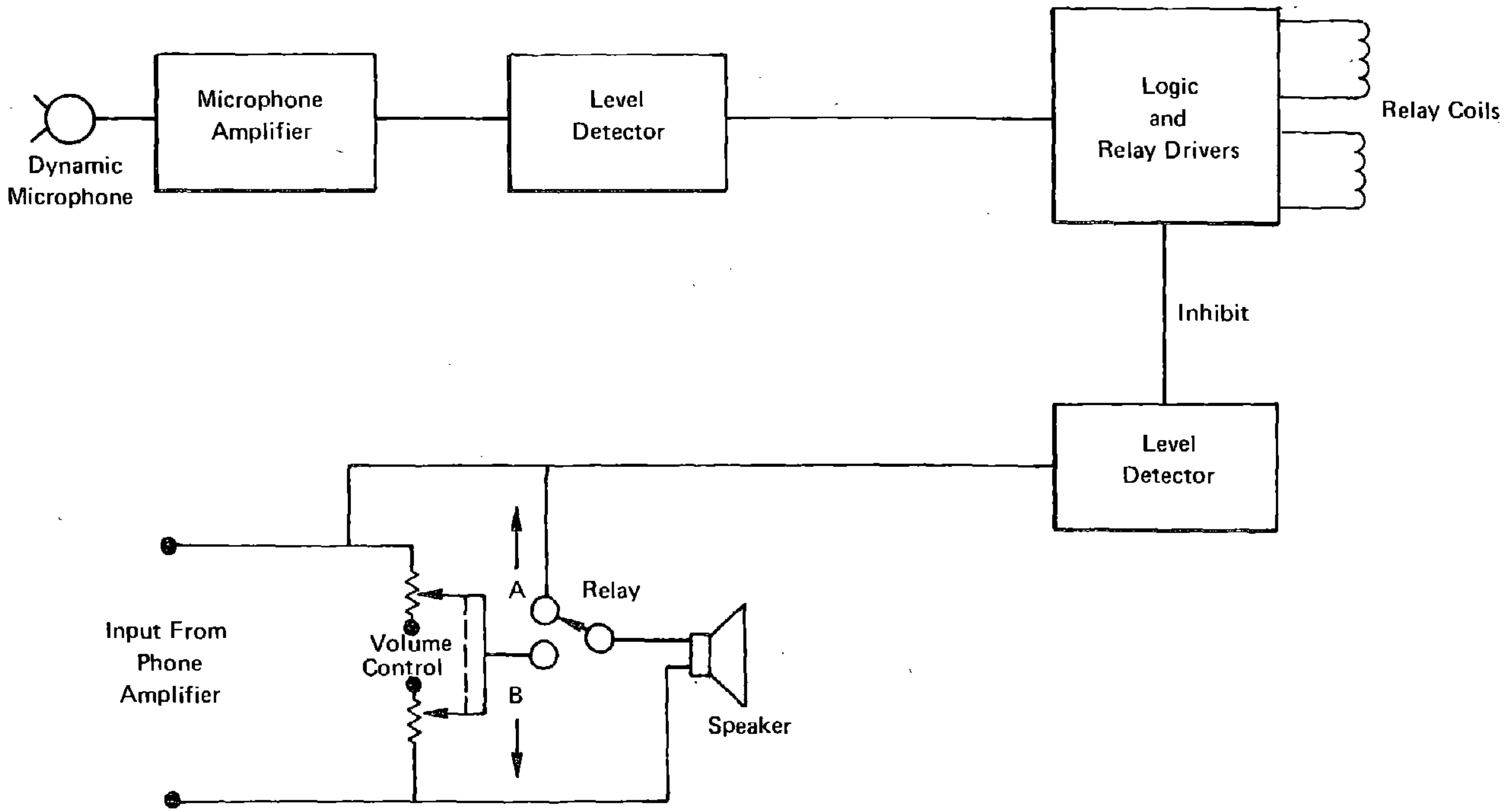
- The adaptive volume control should be capable of being fitted into the loudspeaker unit of any currently available commercial mine trolleyphone.
- It should be self-powered.
- The unit should have its own microphone (inexpensive dynamic type) to measure the ambient acoustic background noise level.
- The sensing of the ambient acoustic background level must not be affected by trolleyphone operations. Namely, when the operator is speaking over the microphone or the unit is receiving a message from the dispatcher, the volume setting should not change.

C. CIRCUIT IMPLEMENTATION

1. Block Diagram Overview

The overall operation of the adaptive speaker volume control circuit can be determined by referring to the block diagram in Figure 1. The circuit requires two inputs. One input is from a small dynamic microphone placed in the loudspeaker unit, and the other input is from the transceiver unit audio amplifier used to drive the loudspeaker. The output of the separate dynamic microphone is amplified so that the signal is large enough to be measured by a level detector circuit, which is set to a threshold level that is used to switch the loudspeaker input level from soft to loud. Thus, under low noise conditions, when the vehicle is not moving and the ambient acoustic noise level is low, a relay in the loudspeaker unit connects the loudspeaker to the normal volume control, in its normal way, such that the volume setting can be manually adjusted to a comfortable level by the vehicle operator (position B).

When the vehicle starts to move, the ambient noise level will increase; thus, the output from the microphone amplifier will increase to the preset level that the level detector will determine to be a



Note: A — Loud Setting
B — Quiet Setting

FIGURE 1 BLOCK DIAGRAM OF ADAPTIVE VOLUME CONTROL loud ambient noise condition. Above this threshold level the output of the level detector will operate relay driver circuits that energize the appropriate relay coil to switch the loudspeaker from its soft normal setting to the full volume setting, which presents the full output from the trolleyphone audio amplifier to the loudspeaker (position A).

In order that the system not oscillate when an incoming message is being received, an additional circuit logic function is required. This is to prevent the adaptive control circuit from latching up or changing state (into the full volume setting) on sounds produced by the carrier phone loudspeaker when receiving incoming messages. Laboratory tests showed insufficient isolation between the noise measuring microphone and the acoustic output from the loudspeaker, thereby causing this latchup at certain quiet-condition volume settings. Therefore, it was decided to use a level detector on the output of the trolleyphone audio amplifier to the loudspeaker. This level detector inhibits the relay drivers from changing the relay setting during reception of incoming messages, thereby solving the latchup problem. This also requires a delay time constant before the circuit becomes operative in order to prevent echoes from interfering with the desired performance.

It has also been demonstrated by laboratory tests that latchup or change in state does not occur when a message is being transmitted by the operator in a quiet environment. Namely, the acoustic sound level of the operator speaking into the microphone is not sufficiently high to make the adaptive volume control go into its loud condition.

2. Detailed Circuit Description

The circuit is shown in more detail in the circuit schematic diagram of Figure 2. The microphone amplifier is an LM308, which operates successfully off a 6-volt power supply. Six volts was chosen so that subsequent circuit developments may derive the power for the adaptive speaker volume control through the microphone circuit from the trolleyphone battery. The output of the LM308 preamplifier is

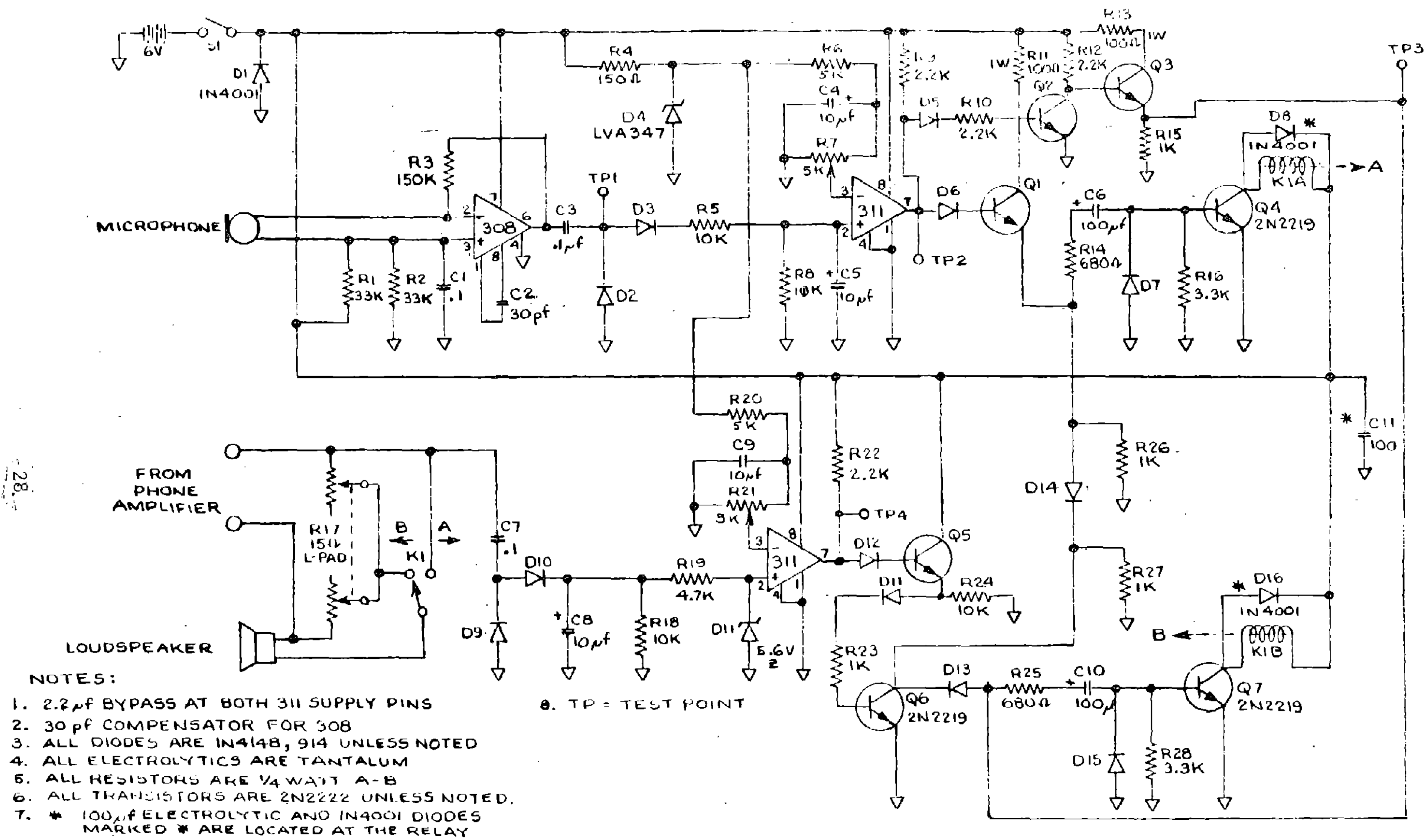


FIGURE 2 SCHEMATIC OF ADAPTIVE VOLUME CONTROL

AC coupled to a rectifier which produces a DC level proportional to the sound level incident on the microphone. This DC level is compared by an LM311 comparator with a preset DC level to determine the threshold at which switching from the loud noise condition to the quiet condition will take place. A similar level detector circuit arrangement is connected to the full voltage of the trolleyphone audio amplifier to determine whether a message is being received, so as to provide the necessary inhibit signal for the relay driver.

The common emitter outputs of the 3115 are used to drive emitter followers to keep total quiescent current (and thus power drain) down to about 20 mA. The low impedance emitter follower outputs provide adequate drive to the relay circuitry.

The relay shown in this circuit is a very small latching (flip flop) relay with two coils, one coil to set the relay in one position and the other coil to set the relay in the other position. Thus, two driving circuits are required. The reasons for the choice of a latching relay were: to minimize the quiescent current taken by the adaptive volume control circuit when not actually switching from one volume setting to another and to eliminate the need for an additional flip flop.

The adaptive speaker volume control circuit was constructed and packaged into the loudspeaker enclosure of a Gulton Femco mine carrier phone as shown in Figures 3 and 4. Figures 5 and 6 provide close-up views of the two sides of the adaptive volume control circuit.

D. TESTING

1. Laboratory Test

The adaptive speaker volume control circuit was set up in the laboratory for test. It was tested in a Femco mine carrier phone. The incoming carrier frequency signal to the carrier phone was simulated by a signal generator operating at 100 kHz and modulated with ±3 kHz frequency deviation at a single sinusoidal frequency in the 500 - 2000 Hz audio band. The mine ambient acoustic noise was simulated

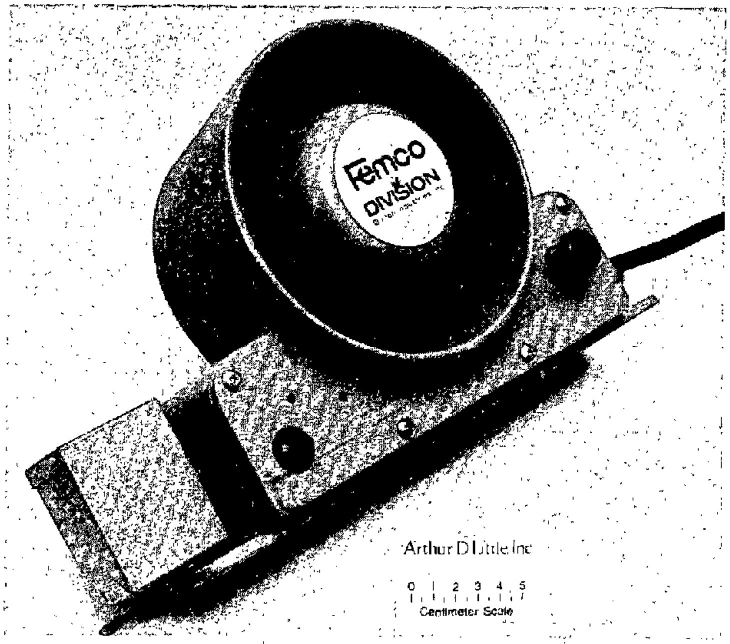


FIGURE 3 TROLLEY CARRIER PHONE SPEAKER ASSEMBLY INCORPORATING A PROTOTYPE ADAPTIVE VOLUME CONTROL

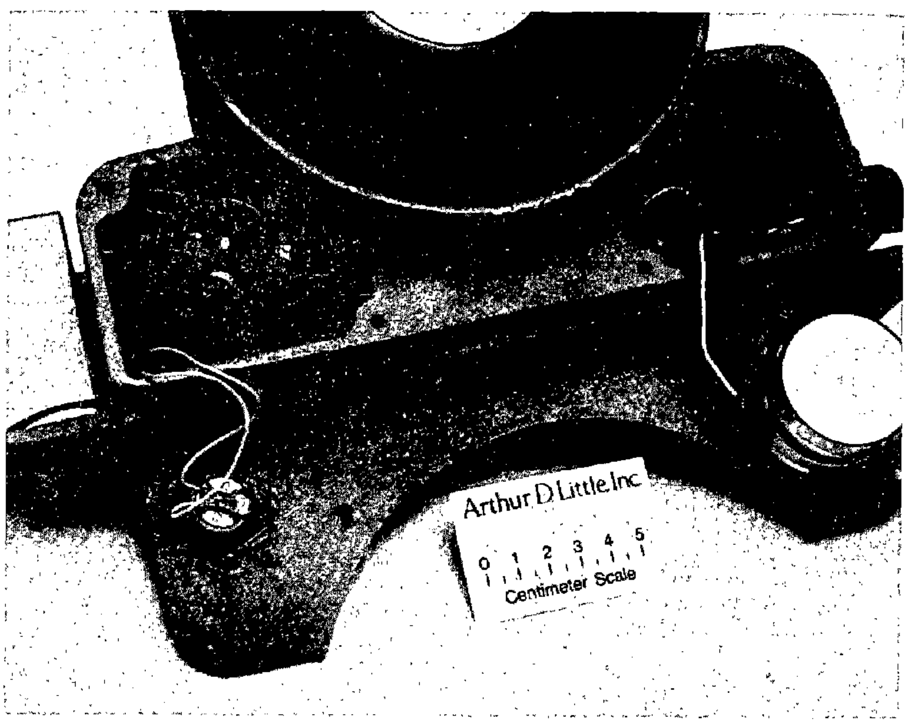


FIGURE 4 PROTOTYPE ELECTRONIC MODULE MOUNTED IN THE TROLLEY CARRIER PHONE SPEAKER ASSEMBLY

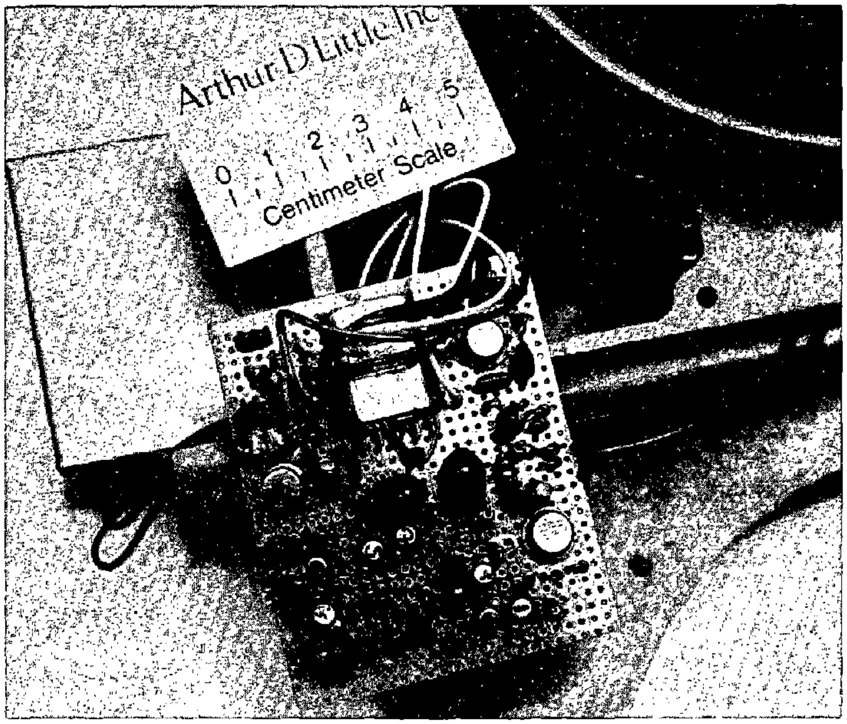


FIGURE 5 COMPONENT SIDE OF THE PROTOTYPE ADAPTIVE VOLUME CONTROL CIRCUIT

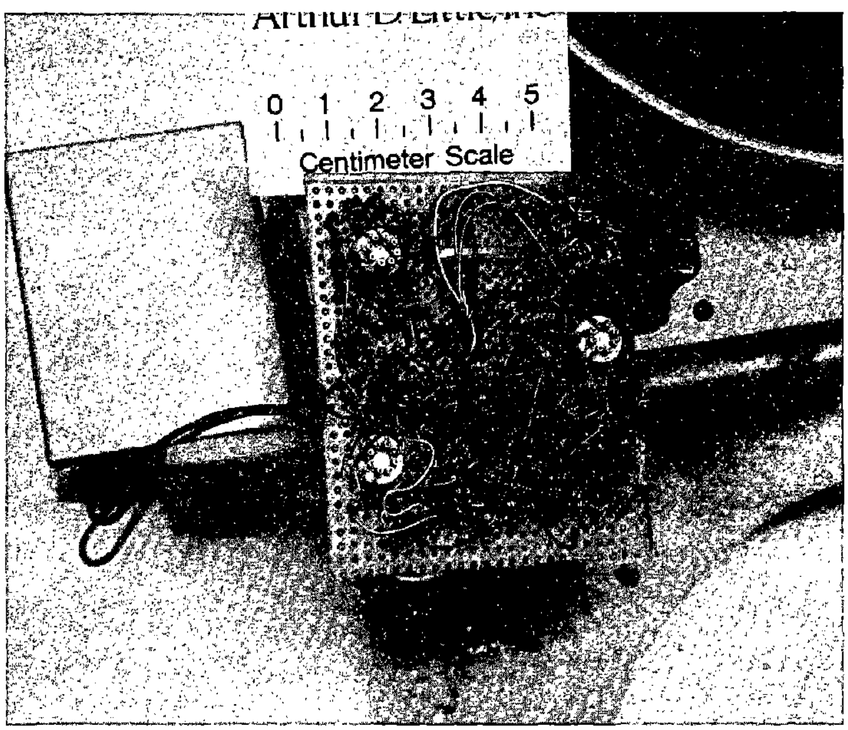


FIGURE 6 CIRCUIT SIDE OF THE PROTOTYPE ADAPTIVE VOLUME CONTROL CIRCUIT

by a loudspeaker horn driven from a 50 watt amplifier by a white noise source. The level of sound produced by this generator could, of course, be varied (up to 120 dBA), and was measured with a sound pressure level meter to check the calibration of the threshold adjustment which was set at 100 dBA. Laboratory tests showed that the system worked satisfactorily.

2. In-Mine Test

The adaptive speaker volume control was tested in a jeep rail haulage vehicle in the U. S. Steel Robena mine south of Pittsburgh on March 2, 1978. The ambient acoustic noise level when the jeep was moving was measured, and found to be quite close to or in excess of the laboratory test value of 100 dBA. The Gulton Femco carrier phones used in the Robena mine were not connector-compatible, as had been hoped, with our modifed Femco equipment. This necessitated some on-site wiring modifications, which were made before commencing the tests.

Testing was conducted over a one hour period. The testing consisted of starting and stopping the jeep while maintaining communication with the underground dispatcher. The adaptive volume control device was required to change its volume level on numerous occasions as the ambient noise level in the jeep fluctuated with starting and stopping. In general the device functioned well, and almost completely satisfied all goals of the feasibility demonstration of adaptive speaker volume control.

However, this particular implementation suffered from a minor operational problem in the mine. On occasion, the device would switch into the "talk loudly" mode during periods of relative quiet. This is believed to be due to marginal time-amplitude discrimination in the circuitry, which is easily adjustable to eliminate this problem entirely. It may be possible to achieve this fix simply by changing the value of one capacitor.

E. CONCLUSIONS

The prototype adaptive speaker volume control constructed and tested under this program has proved to be feasible for in-mine operation. Observers of the test in the mine reported that its operating characteristics were most desirable, except for the minor problem mentioned in Section D, which may easily be cured by simple circuit alterations.

The principles of operation of the circuit are easily applicable to any of the currently operational mine carrier phones. The circuitry may be added by the manufacturer of the carrier phone at the time of manufacture. Alternatively, after suitable packaging studies have been completed, the circuitry may be retrofitted to existing units.

F. RECOMMENDATIONS

The device functions well. However, the occasional switching into the "high level" mode during in-mine testing indicates that the time-amplitude discrimination method used in the prototype should be modified to prohibit any chance of false mode switching. In addition, the number of emitter follower transistors could be reduced by utilizing a comparator with low quiescent current when its output is low, e.g., a non common-emitter output.

Now that the feasibility and desirability of adaptive speaker volume control has been established, a second prototype should be constructed and tested. This prototype should have as a design goal, either a total power consumption current drain of under 10 mA, which will increase battery life substantially, or the more desirable one of deriving its power from the host carrier phone, thereby making it independent of a separate battery power supply.

Since the circuitry may be retrofitted to existing carrier phones in use, as well as being incorporated in the manufacture of new units, a packaging study should also be carried out to encourage and simplify the implementation of this desirable feature in mine carrier phones.

III. PHASE II - DEDICATED WIRE EXPERIMENT FOR MINE CARRIER PHONE SYSTEMS

A. BACKGROUND

Trolley carrier phones are used for dispatching haulage vehicles in almost all electric rail haulage coal mines. These carrier phones use the trolley wire/rail as the transmission path for the carrier signal. Experience has shown that this path is often a poor one for signal transmission due to a number of factors, the principal one being the many bridging loads normally found across this trolley wire/rail DC power feeder line. These include: mine motors (vehicles), pumps, lights, heaters, rectifiers, insulators, and the carrier phones themselves. Add to this the fact that branches occur on the line and line terminations are not present, and it is remarkable that the carrier phones work as well as they do.

Under contract H0346045,[5] we developed a theory on how a "dedicated wire" would improve the transmission of carrier signals on such lines. The concept behind the dedicated wire is to provide a parallel low-loss transmission line comprised of the rails and a single conductor strung in the haulageway. The natural coupling of this wire to the trolley wire/rail line provides signal coupling. The results of the theory show that an extremely lossy trolley wire/rail can be markedly improved by the use of such a dedicated wire. This is particularly true for dispatcher-to-vehicle and vehicle-to-dispatcher communications, because the dispatcher can connect his carrier phone directly to the low-loss dedicated wire. The theory shows that trolley wire/rail lines for which the attenuation rates are as high as 20 dB/km can be converted to lines which exhibit only 1 or 2 dB per km by the use of a single parallel dedicated wire in the haualageway.

The theory is based on representing the trolley wire/rail as a lossy transmission line. An actual trolley wire/rail is a poor transmission line because of the many discrete bridging loads as noted above. The theory treats the trolley wire/rail as a line characterized by uniform, continuously distributed, shunt and series loss, while the dedicated wire/rail is treated as a low loss line having only continuously distributed series loss. For most examples treated by the theory, a loss of 1 dB per kilometer was used for this dedicated wire/rail line in the absence of the trolley wire/rail line.[1,5]

Two examples of findings are shown for the conditions illustrated in Figure 7 where we assume the following dimensions in meters:

$d_1 = 5$, $d_2 = 2.5$, $h = 0.3$, $a = 0.015$, $b = 0.0015$, $c = 0.1$,

$x_a = 0.5$, $y_a = 2.2$, $x_c = 1.25$, $y_c = 0$.

The "dedicated" wire is placed at $x = 2.2$, $y = 2.2$ for calculations of signal strength versus z. One example is shown in Figure 8, where it is assumed that the transmitter is connected to the dedicated wire. The dedicated wire voltage and the trolley wire voltage are plotted. All voltages are measured with respect to the rail, which serves as a common ground. For comparison, the trolley wire voltage for transmission on the trolley wire in the absence of the dedicated wire is also shown. The companion plot, Figure 9, illustrates the theoretical currents under the same conditions.

The theory shows that a low loss line comprised of a dedicated wire and a rail can significantly extend the communication range on the trolley wire/rail system.

B. PURPOSE

The purpose of this program was to demonstrate the use of a dedicated wire in an actual coal mine and obtain corresponding data. It was also to demonstrate how signal splits and line terminations could be applied to the dedicated wire. Lastly, it was to provide recommendations on how to install and use such dedicated wires.

C. EXPERIMENTAL PROGRAM

1. General

Several problems were faced in the design of the experiment:

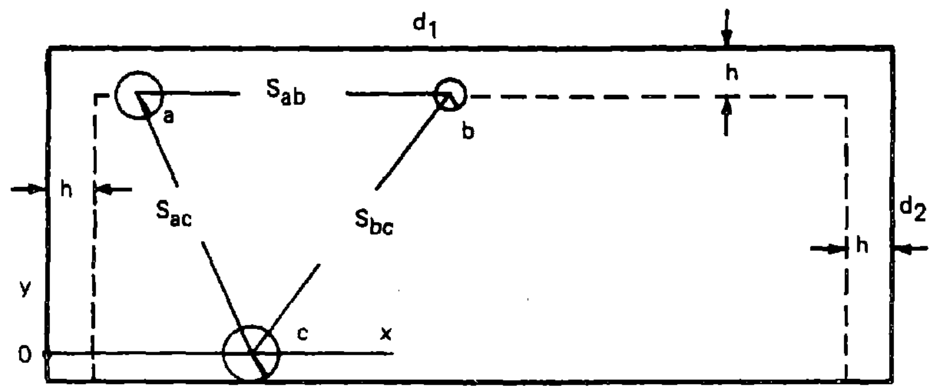
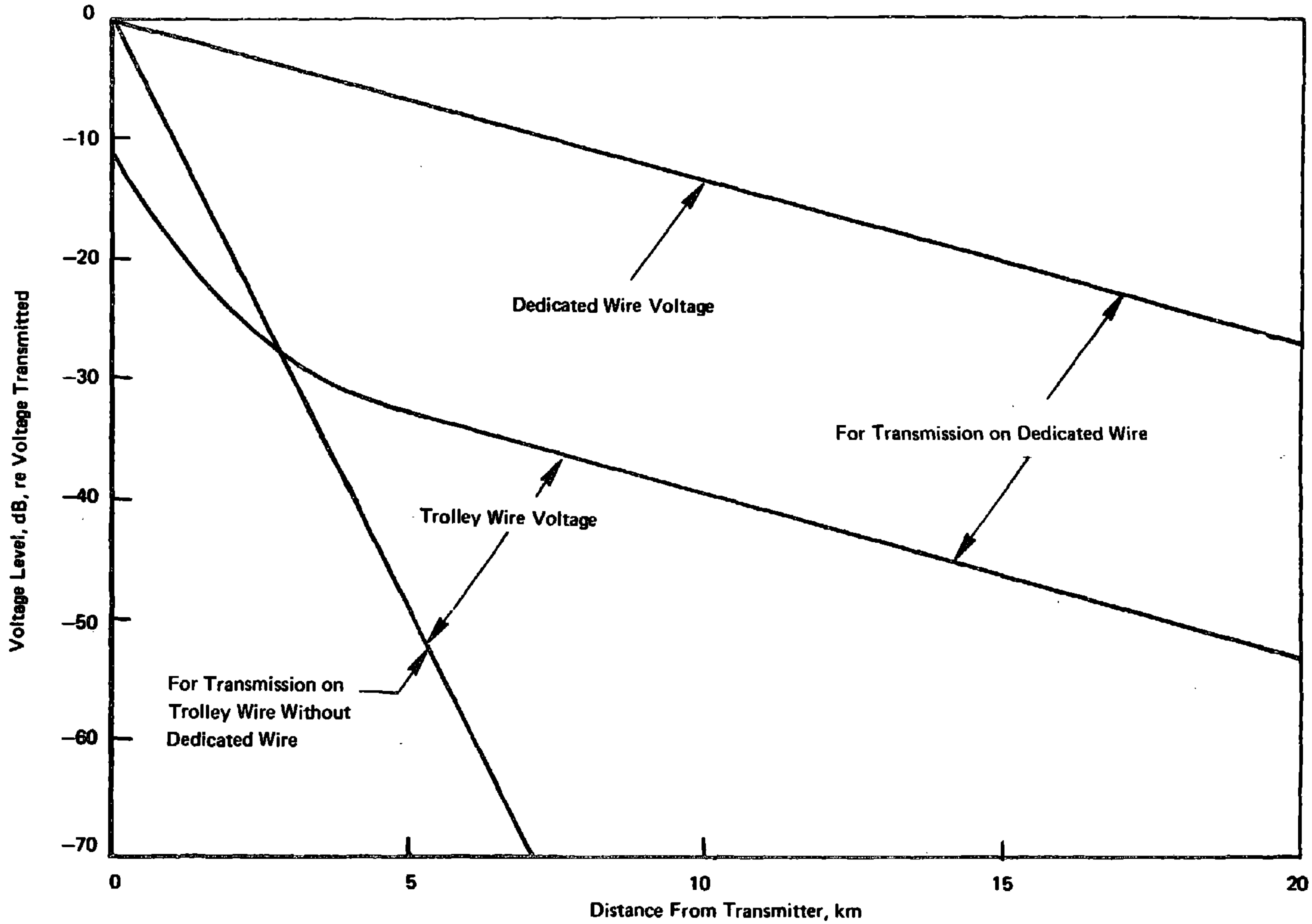
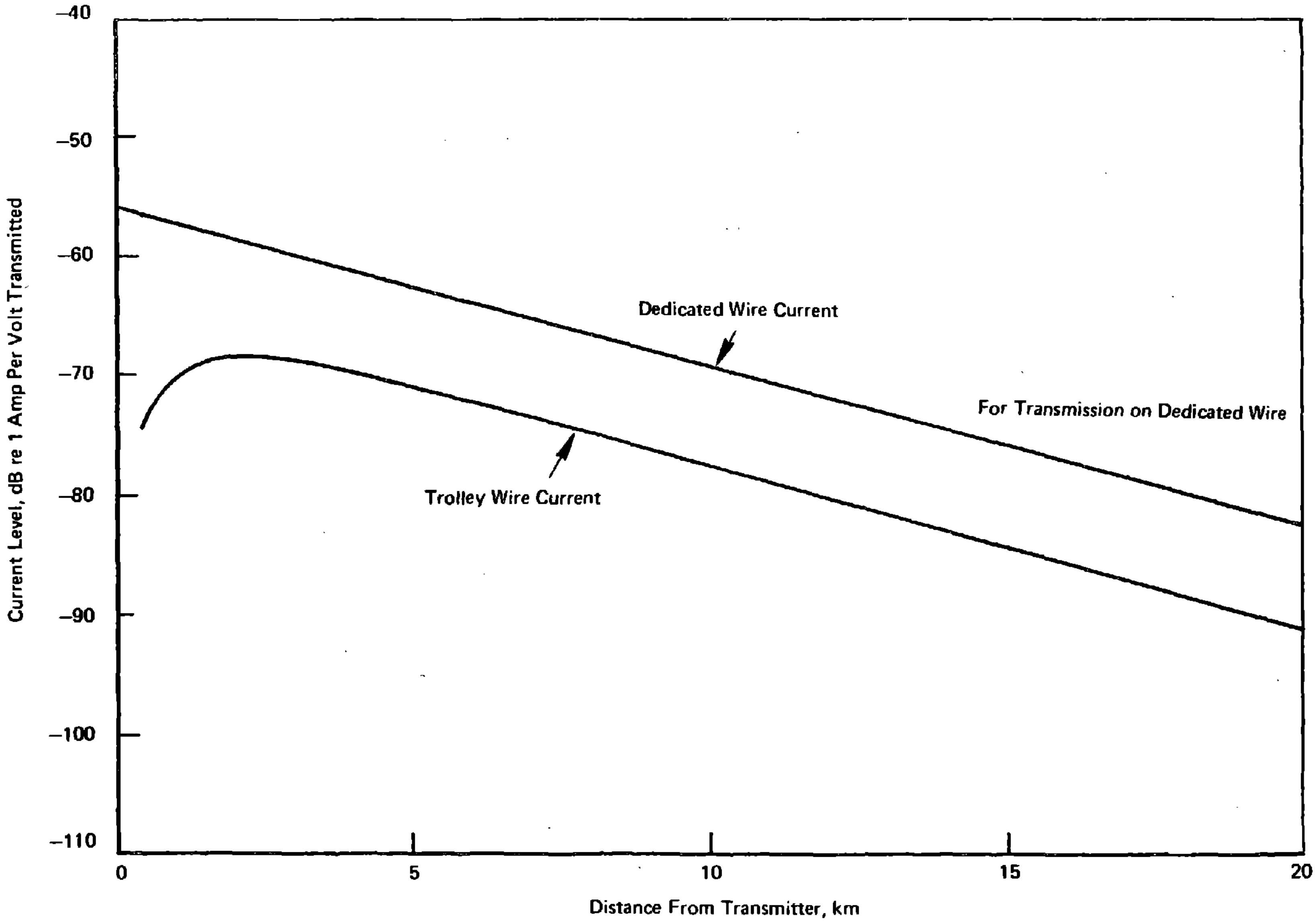


FIGURE 7 CROSS SECTION OF TUNNEL, OF DIMENSIONS $d_1 \times d_2$, SHOWING THE TROLLEY WIRE, DEDICATED WIRE, AND RAIL, OF RESPECTIVE RADII a, b, c, SEPARATED BY DISTANCES S_{ab}, S_{bc}, S_{ac}.



Note: For Attenuation Rates of α_T = 10 dB/km For The Trolley Wire/Rail Line in the Absence of the Dedicated Wire/Rail Line, and α_D = 1 dB/km For The Dedicated Wire/Rail Line in The Absence of The Trolley Wire/Rail Line.

FIGURE 8 THEORETICAL VOLTAGE LEVELS VERSUS DISTANCE



Note: For Attenuation Rates of α_T = 10 dB/km For The Trolley Wire/Rail Line in the Absence of the Dedicated Wire/Rail Line, and α_D = 1 dB/km For The Dedicated Wire/Rail Line in The Absence of The Trolley Wire/Rail Line

FIGURE 9 THEORETICAL CURRENT LEVELS VERSUS DISTANCE

- finding a cooperative mine
- assuring that the mine had communication problems amenable to solution by application of the dedicated wire
- working out the logistics of installing several miles of wire

Mr. Harry Dushac of the Lee Engineering Division of Consolidation Coal Company played a key role in the favorable resolution of these problems. He identified a mine, Consol's Montour No. 4, experiencing such communication difficulties, and he obtained their cooperation. In addition, the impending strike offered a unique opportunity to handle the wire installation with minimum interference to normal mining operations.

2. The Montour No. 4 Mine

The Montour No. 4 Mine is a large Consolidation Coal Company mine located in southwestern Pennsylvania in the Pittsburgh coal seam. Nominal mine depth is 250 feet. Figure 10 is a scale map showing the mine's electrical system along the section of haulageway selected for the experiment. We have marked a number of locations along the DC electric rail haulage system. These numbers identify the location of particular loads across the trolley wire/rail and positions where measurements were taken. Table I lists these locations and loads together with their distances from the mine dispatcher's carrier-phone installation.

Figure 11 is an approximate sketch of the layout and disposition of cables and other conductors in the main haulageway where the measurements were made. The track consists of 60 pound rails with 46" center-to-center separation, the trolley wire is attached to and supported by 1000 MCM feeder cable on the near side of the haulageway, while the rails are intermittently bonded to a 500 MCM feeder cable used as a ground strapping. The pager phone line is located on the far side of the haulageway. Two 7200 volt AC cables were also hung on the trolley wire side of the haulageway, together with two water lines located on the floor (bottom). As a general rule the number and location of AC cables in the haulageway varied along its length as did the water pipes. Typically these changes occurred in the vicinity of active sections

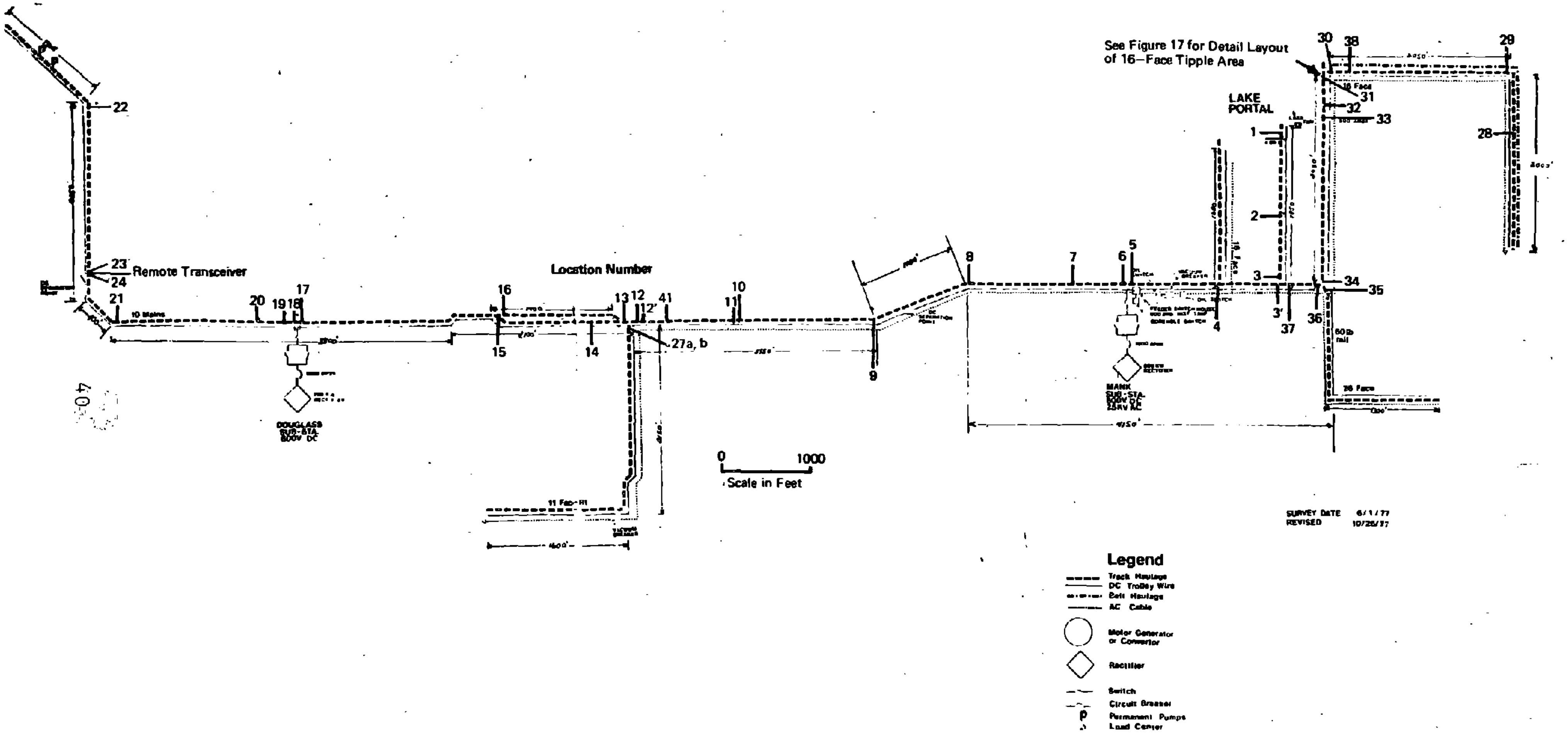


FIGURE 10 MONTOUR 4 ELECTRICAL MAP

TABLE I

TABULATION OF DISTANCE TO KEY LOCATIONS FROM REMOTE CARRIER PHONE TRANSCEIVER SERVING THE LAKE PORTAL SIDE OF THE MONTOUR NO. 4 COAL MINE

(Use in Conjunction with Annoted Mine Electrical Map--Figure 10)

Location No. or Piece of Equipment	Main Line Haulageway Distance(ft) From Remote Transceiver	Distance off Main Haulage Track: Location	Distance off Main Haulage Track: Feet	
Location 22	-1,850			
Pump No. 19	-1,400	Pump Setback	20(?)	Toward Hahn/Hill Portals
Pump Near Mont. No. 1	-300	Pump Setback	20	
Location 23	-25			
Remote Transceiver	0	Transceiver Setback	20	
Location 24	+5			
Location 21	+700			Toward 16-Face
Location 20	2,280			
Location 19	2,570			
Location 18	2,720			
Douglas Substation Rectifier 750 kW	2,740	Rectifier Setback	355	
Location 17	2,760			
Location 15 - At Runaround Intersect	5,000	Location 16 - In Runaround	40	
Location 14	6,150			
Location 13 - Just beyond Run-around & before 11-Face	6,520			

TABLE I (Continued)

Location No. or Piece of Equipment	Main Line Haulageway Distance(ft) From Remote Transceiver	Distance off Main Haulage Track					
		Location	Feet	Location	Feet	Location	Feet
Location 12 - 11-Face Intersection	6,660	Location 27a, 11-Face Curve	80	11-Face extends 3700 ft.(right) beyond Location 27a, b - Usually have 2-DC shuttle buggies and personnel heater			
Location 12' - MSA Signal Coupler Bet. T-Line & P-Line	6,750						
Location 41 - Between Pumps 16 and 17	7,000						
Location 11	7,900						
Location 10	7,940						
Pump 15	7,960	Pump Setback	20				
Location 9	9,410						
DC Switch (closed)	9,800						
Location 8	10,400						
Location 7	11,550						
Pumps 13 & 14	11,560	Pump Setback	20				
Location 6	12,270						
Mank Substation Rectifier 500 kW	12,340	Rectifier Setback	265				
Location 5	12,400						
Location 4	13,100						
15-Face Intersection	13,110	15-Face extends 1600 ft.(left)beyond intersection Usually have 2-DC shuttle buggies and personnel heater					
Lake Portal Intersection	13,900	Location 3 (left)	70	Location 2	850	Location 1 (Three light circuits nipped off trolley wire at Location 1)	1,800

TABLE I (Continued)

Location No. or Piece of Equipment	Main Line Haulageway Distance(ft) From Remote Transceiver	Distance off Main Haulage Track: Location	Feet	Location	Feet	Location	Feet
MSA Signal Coupler Bet. T-Line & P-Line	14,000						
Location 37	14,020						
Location 36 - Intersection of Main Line with 16 & 26	14,390	Location 35 - 26-Face Curve	50	26-Face Extends 2400 ft.(right)beyond Location 35 - Usually have 2-DC shuttle buggies and personnel heater			
Location 34 - Continuation of Mains into 16-Face	14,450						
Location 33 - At Tipple Inter-section with 16-Face Track	16,340	Car Push, Pumps 10 & 11, lights & heater down this tipple spur (See Figure 17 for detail layout)					
		Location 42 On Tipple Track (Position of Dedicated Wire Splitter)	150	Location 39 Middle of 1st Bend on Loop-Around Leading to Empties Track	600	Location 40 Loop-Around Empties Track, 26-Face Side of 1st Bend Inter-section	900
		Location 43 Loop-Around Empties Track, Tipple Side of 1st Bend Inter-section	900	Location 44 Tipple End of Loop-Around Empties Track (Location of Dedicated Wire Tipple Branch Termination)	1400		
Location 32	16,450						
Location 31 - At Short Spur Intersection	16,750						
Location 30	16,850						

TABLE I (Continued)

Location No. or Piece of Equipment	Main Line Haulageway Distance(ft) From Remote Transceiver	Distance off Main Haulage Track: Location	Distance off Main Haulage Track: Feet
Location 38 - At 16-Face, 1-Butt	17,200	New panel to be developed next on the 16-face section (Location of dedicated wire 16-face termination)	
Location 29 - At Short Spur Intersect	18,860		
Location 28	19,650		
16-Face Trolley Phone Connected to Phone Line And Rail	19,660	Track extends 1200 ft. beyond location 28 -- Usually have 2-DC shuttle buggies and personnel heater.	
Pump No. 9	19,680		

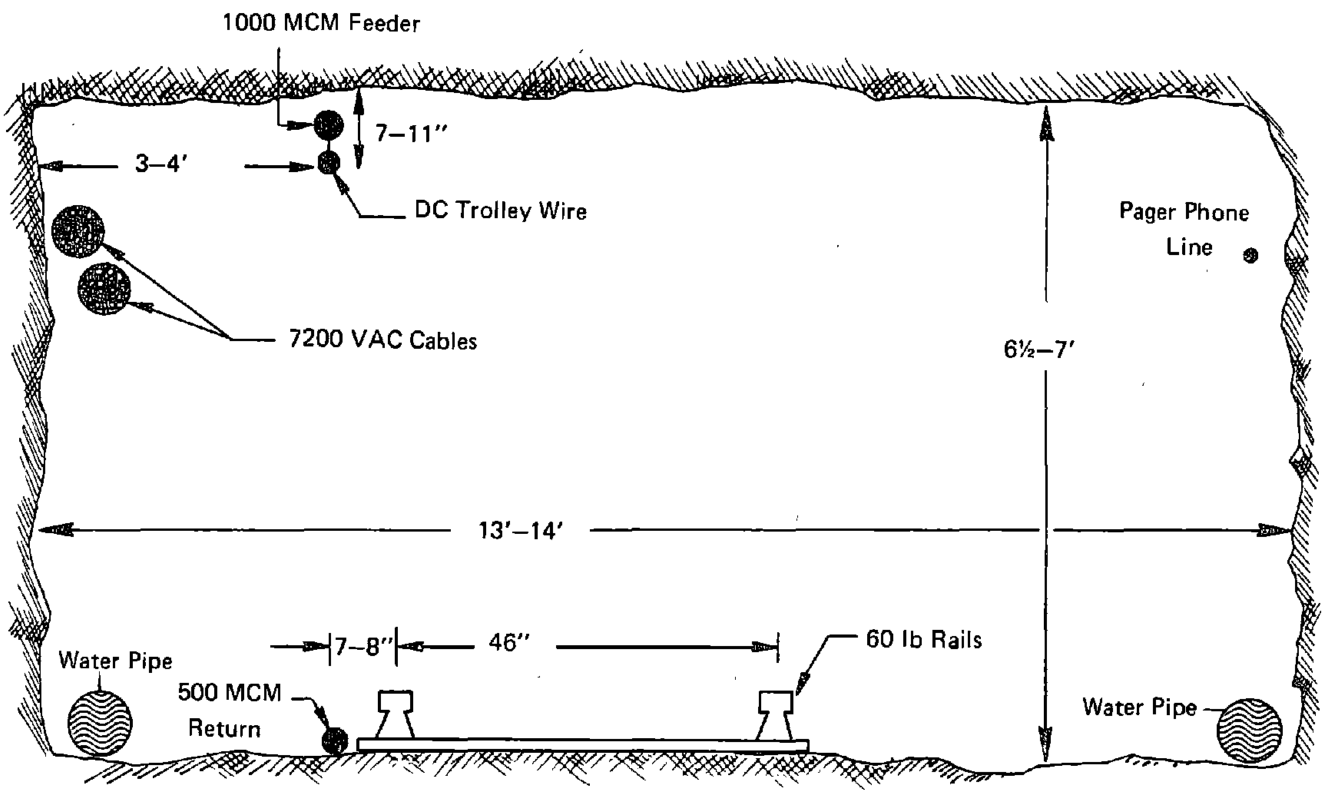


FIGURE 11 APPROXIMATE CROSS-SECTION OF HAULAGEWAY LAYOUT (ALL DIMENSIONS NOMINAL, SIGNIFICANT VARIATIONS IN DIMENSIONS AND DISPOSITION OF CONDUCTORS OCCUR WITH DISTANCE)

located off the main haulageway and in the vicinity of pump stations and rectifier stations. An attempt was made during the measurements to note changes of the presence and disposition of these conductors at each measurement location.

The Mank substation consists of a 600 volt DC 500 kW rectifier and a 7.5 kV AC substation, protected by an 1800 amp breaker. The Mank substation, as all the substations for the mine, is located on the surface, feeding power down a bore hole to the rail haulage system. The approximate setback of the Mank substation bore hole from the track is about 25 feet, and the depth of the bore hole is 240 feet, making the total setback of about 265 feet. The substations are located in a building directly above the bore holes. The Douglas substation consists of a 600 volt DC, 750 kW rectifier protected by an 1800 amp circuit breaker as in the case of the Mank substation. As in the case of the Mank substation, the Douglas substation is located on the surface. The bore hole setback from the trolley wire rail is approximately 25 feet, and the depth of the overburden through which the bore hole passes is 330 feet, making for a total setback of approximately 355 feet. The following is a listing of the overburden depths at each of the substation locations:

Mank	240 feet
Douglas	330 feet
Hickman	190 feet
Hopper	210 feet
Nantiker	210 feet
Hahn	317 feet
Big Bottom	850 feet (slope entry length)
Lake Shaft (Portal only)	133 feet (no substation)

The insulators used along the trolley wire are mainly single ones and spaced on the order of 20 feet apart. The off-track mining equipment in this part of the mine generally consisted of two DC operated shuttle buggies nipped off the end of the track on each section. No fan circuits were encountered across the DC trolley wire. Other typical shunt loads were pumps, lights, and personnel heaters.

3. The Mine Trolley Carrier Phone System

The mine dispatcher uses a remote transceiver to provide coverage to vehicles thoughout the mine's extensive rail haulage network. This remote transceiver is located at position 24 shown on the annotated mine map. The transceiver's output is connected between the rail and the mine pager phone line. This connection means that the mine is already using a form of low grade dedicated wire. The communication network is further augmented by the use of two signal couplers connecting the RF signals on the pager phone line to the trolley wire at positions 37 and 12'. However, in regions far from the remote transceiver, where signals on the phone line have been reduced by mismatches and branches, trolley wire communication performance deteriorates signficantly; for example, in the 16-face section of the mine. In one particular region of the 16-face area, near positions 39, 40, 42, and 43, vehicle operators have extreme difficulty communicating with the dispatcher.

Thus, in spite of the fact that this mine was already using a low-grade type of dedicated wire, the decision was made to proceed with the dedicated wire experiment at this mine. We concluded that the experiment could, indeed, still demonstrate the utility of the dedicated wire, albeit primarily at one extreme of the mine rail haulage line. It could also demonstrate the feasibility of signal splits, and it could permit signal attenuation on the dedicated wire to be measured. Furthermore, the mine's cooperative nature and desire for a solution to its real communication problem, our commitment to and preparations for working with this mine, and the uncertainties and mixed opportunities presented by the strike situation, all tended to favor such a decision.

4. Loads Across the Trolley Wire/Rail

Table II lists and characterizes at 88 kHz the major operating electrical loads across the trolley wire/rail in the haulageway

TABLE II

SIMPLIFIED CHARACTERIZATION OF MAJOR ELECTRICAL SHUNT LOADS ACROSS TROLLEY WIRE/RAIL LINE FOR APPROXIMATE THEORETICAL SIGNAL CALCULATIONS

[For Nonoperational (on-strike) Mine Conditions[1] During Dedicated Wire Experiment]

			Impedance Estimate @ 88 kHz		
Electrical Load	Distance from Remote Transceiver at Location 24	Location No.	Intrinsic	Setback Inductive Reactance X_L	Resultant Including Setback X_L
Douglas 750 kW DC Power Rectifier Substation	2,740 ft.	18	0	j45Ω[2]	j45Ω
2-30 hp Pumps (#13 and 14)	11,550 ft.	7	83Ω[3] Each	j33Ω Each	42 + j17Ω Net Parallel
Mank 500 kW DC Power Rectifier Substation	12,340 ft.	6	0	j35Ω	j35Ω
Change in Line Characteristic Impedance Z_o Beyond Tipple Spur Intersection	16,340 ft.	33	170Ω with 1000 MCM feeder present before 33 250Ω without feeder beyond 33		
Effective Resistive Load for Tipple Area Equipment[4] (Approx. Twice Minimum Resistance)	16,750 ft.[4]	31	67Ω	Neglected	67Ω
Single Trolley Carrier Phone Load (MSA)[5]	18,860 ft.	29	200Ω	0	200Ω
1-15 hp Pump (#9) in Parallel with Single Trolley Phone Load[5]	19,680 ft.	28	167[3]//200Ω	Neglected	91Ω

Notes: See Table II (Continued)

TABLE II (Continued)

(1) Under nonoperational mine conditions, the number and distribution of electrical shunt loads are significantly reduced, thereby simplifying the theoretical analysis somewhat. However, the loads that were present are not only some of the most significant but also are a representative sample of commonly found loads in mines. Under operational conditions, the added loads will further deteriorate performance.

(2) The inductive reactance introduced by the setback distance of the load from the trolley wire/rail line was estimated using a two-wire line model for the connecting link, taking into account setback length and the size and separation of the conductors.

(3) Using extrapolations of horsepower/resistance behavior found by D. Paice of Westinghouse. See reference 9.

(4) The tipple area has a large number of heavy shunt loads, such as a 26 hp pump, a 25 hp car pusher, 2.5 kW personnel heater, light bulbs, and a vehicular trolley phone. Since the exact locations and activity of these loads and the associated tipple area track routing were not known at the time of the theoretical calculations, a resistive load equal to about twice the minimum expected resistance of about 33Ω was used and placed across the 16-face trolley wire/rail at location 31. The signal behavior with this load value and location, although not exact, is considered quite representative.

(5) Simulating a MSA Vehicular Carrier Phone (200Ω) in the Standby/Receive Mode in a stationary vehicle having its lights and heater off. Such a vehicle with its lights and heater on, can present a load of about only 40Ω across the trolley wire/rail line.

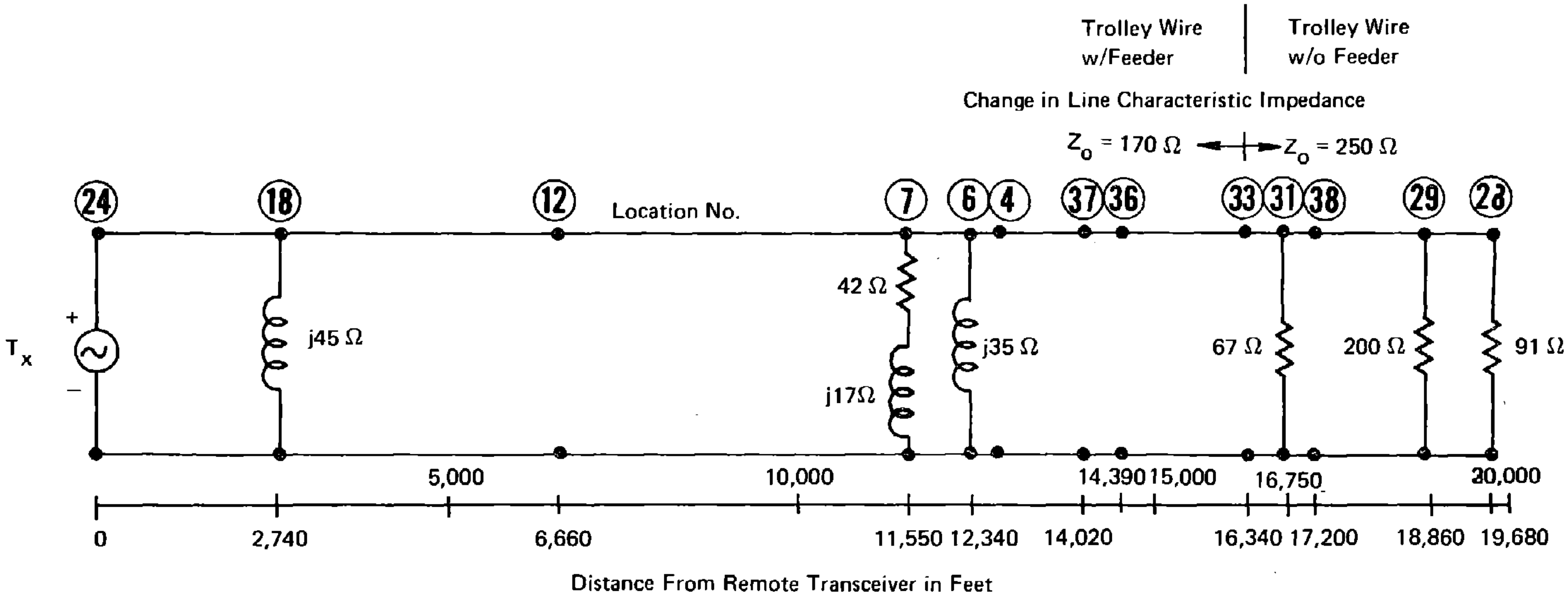
during the period of the dedicated wire experiment. Figure 12 is a companion electrical model representing these loads and associated sections of the trolley wire/rail transmission line.

5. Early Measurements

The data for Table II were obtained during a mine visit in November 1977. At that time measurements were made to characterize the electrical behavior of the installed trolley carrier phone system during normal mine operating conditions. The plot of Figure 13 shows the measured trolley wire/rail voltage signal strength versus distance from the remote transceiver installed at position 24 shown on the mine map. The levels were obtained from a jeep equipped with a Sierra Model 303A tuned volt meter. Although this signal level shows quite good behavior along part of the mine haulageway, the signal level deteriorates to marginally useful values at areas near stations 28 and 38. This behavior offers particular problems to a fixed carrier phone installed at the tipple and to vehicles operating on the tipple loop around track.

6. Design of the Dedicated Wire Installation

During this first visit to the mine, discussions were held with mine foreman, Robert Burgh, and his staff on how and when the installation might be made. The impending strike identified mid-December as a likely favorable time for the installation and the experiment. Based on the measurements and discussions with Montour No. 4 mine staff during the first mine visit, the following details of the experimental dedicated wire installation were defined and agreed upon. The route for the dedicated wire would extend from the remote transceiver (position 24) to an area near number 1 butt (Location 38) in the 16-face area. A branch circuit would be installed somewhere along the route. The dedicated wire would be run along the roof or rib using spads and J-hooks to support it. Number 12 insulated, stranded copper wire would be used for the dedicated wire. The necessary materials were ordered—spads, J-hooks, and wire, and subsequently delivered to Lee Engineering and thence to Consol's Montour No. 4 mine.



Notes: Free Space Wavelength, λ_o = 11,160 Ft at 88 kHz

Effective Wavelength on Trolley Wire/Rail Line, λ_e = 7,500 Ft @ 88 kHz, as Determined From in-Mine Measurements. Therefore λ_e Must be Used for Theoretical Signal Strength Calculations

FIGURE 12 SIMPLIFIED ELECTRICAL MODEL OF THE TROLLEY WIRE/RAIL TRANSMISSION LINE AND ITS SHUNT LOADS AT 88 kHz

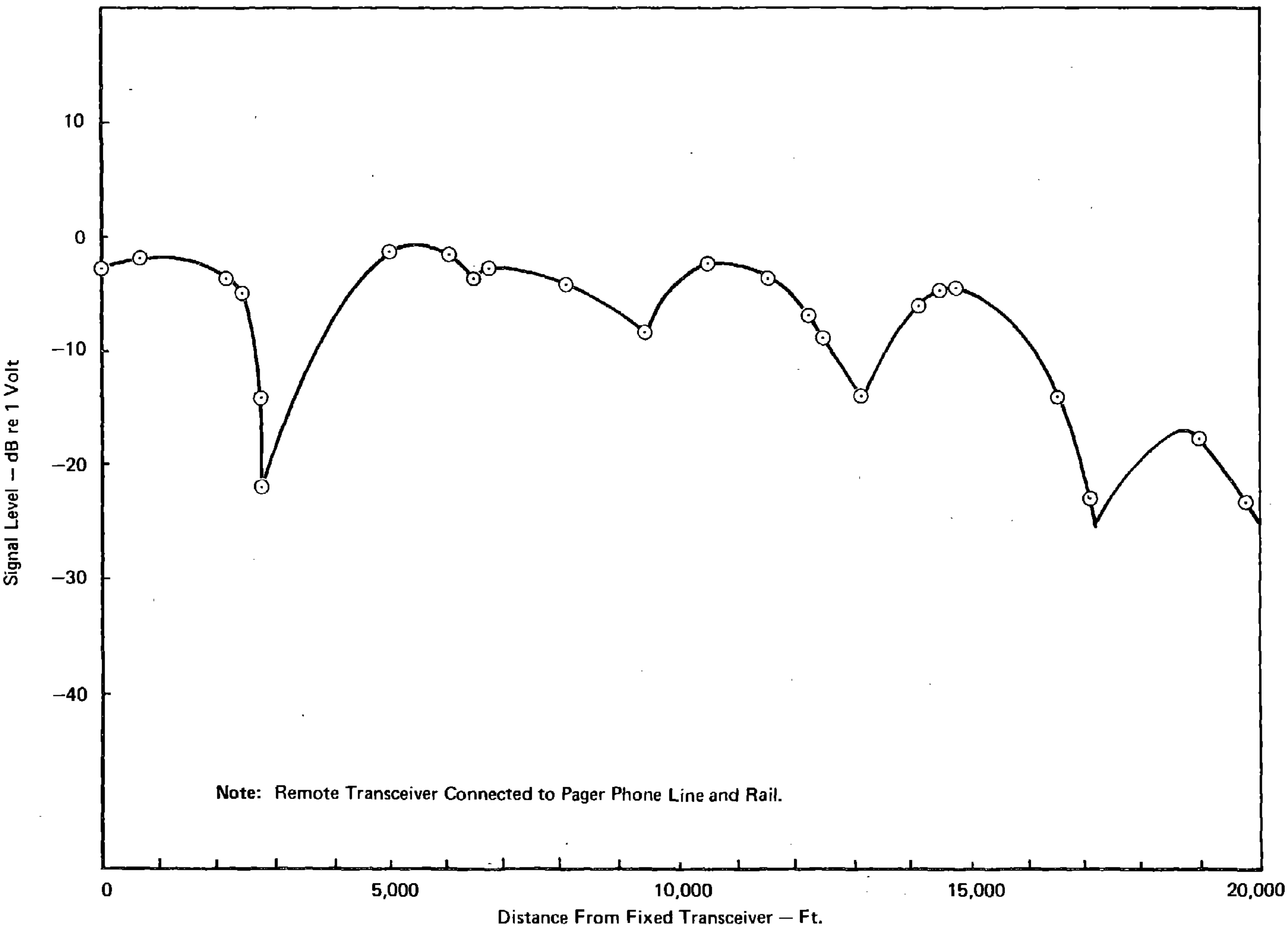


FIGURE 13 TROLLEY WIRE VOLTAGE – MINE OPERATING –

7. Measurements in December

The final measurements were made in December 1977, both with and without the dedicated wire. Measurements of the trolley wire voltage were repeated in the absence of the dedicated wire, because the November measurements applied for an operating mine while those in December were for a nonoperating mine during the strike period. While the repeat measurements were being made, the Montour No. 4 Mine staff was preparing to install the dedicated wire by putting the spads and J-hooks in place. Measurements were made with and without the signal coupler (Z-box) connections to the trolley wire, both before and after the dedicated wire was installed. Measurements were also attempted with the remote transceiver connected directly across the trolley wire/rail line. However, these had to be abandoned when we were unable to maintain communications with the dispatcher beyond only about 2700 feet from the remote transceiver,i.e., in the vicinity of the Douglas power rectifier substation.

Figure 14 illustrates the trolley wire voltage signal level found for the original trolley wire system installation with signal couplers connected at locations 12'and 37. These couplers connect the trolley wire to the pager phone line. In comparison to the November measurements, the signal level was found to be as much as 5 dB higher in some places, and in others the level was about the same. To assess the effects of the couplers, a second plot, Figure 15, shows the signal level variation with the couplers removed. A lumpier signal plot results, which also exhibits some signal enhancement. However, this enhancement occurs at the wrong part of the rail haulage network; namely, where signal strengths are already strong. The results of the measurements made in the presence of the dedicated wire are presented in the Findings section.

D. DEDICATED WIRE INSTALLATION

The installation of the dedicated wire was done by the Montour No. 4 mine staff. The wire was supported along its length by J-hooks

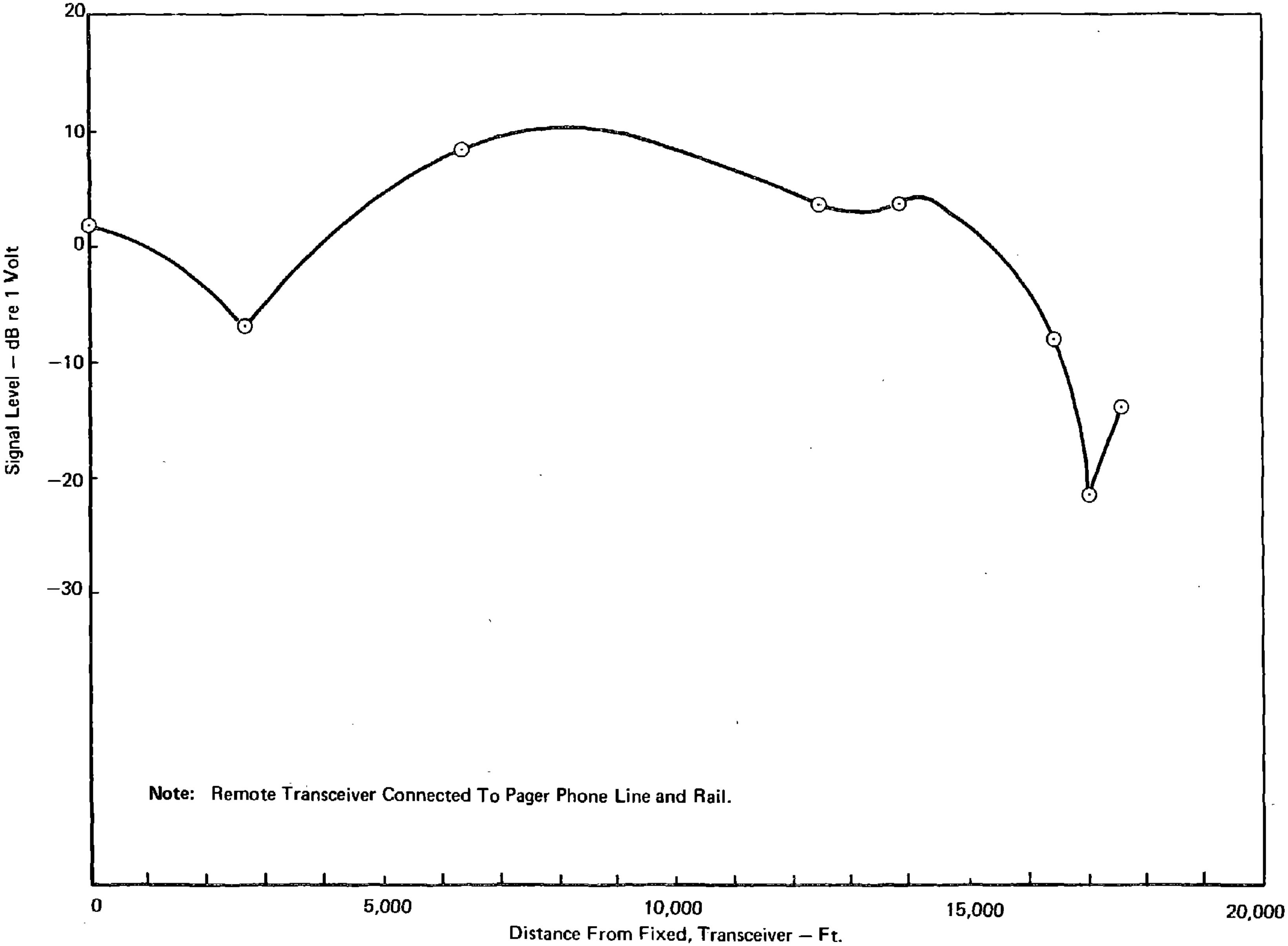


FIGURE 14 TROLLEY WIRE VOLTAGE – MINE NOT OPERATING – SIGNAL COUPLERS IN

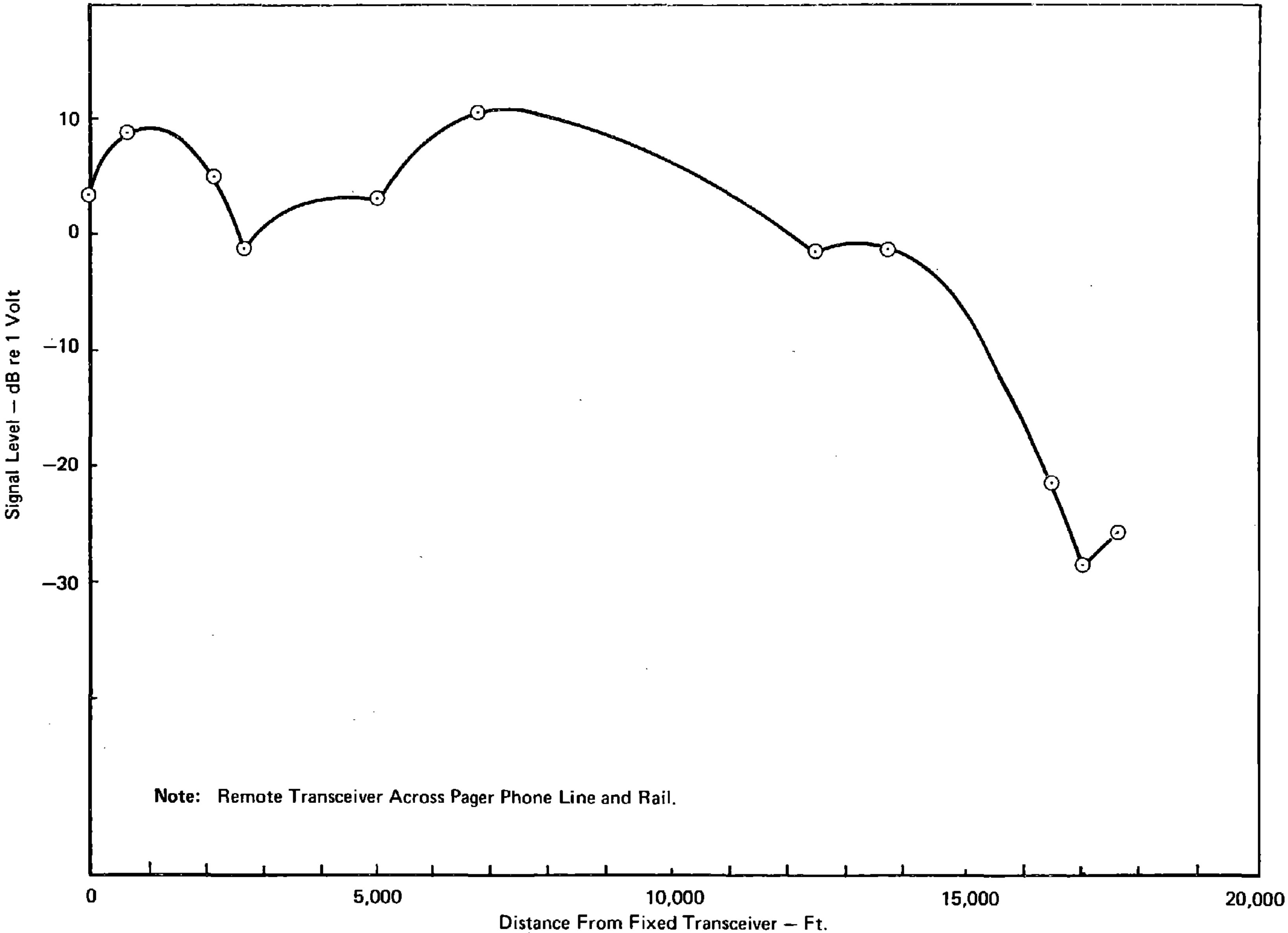
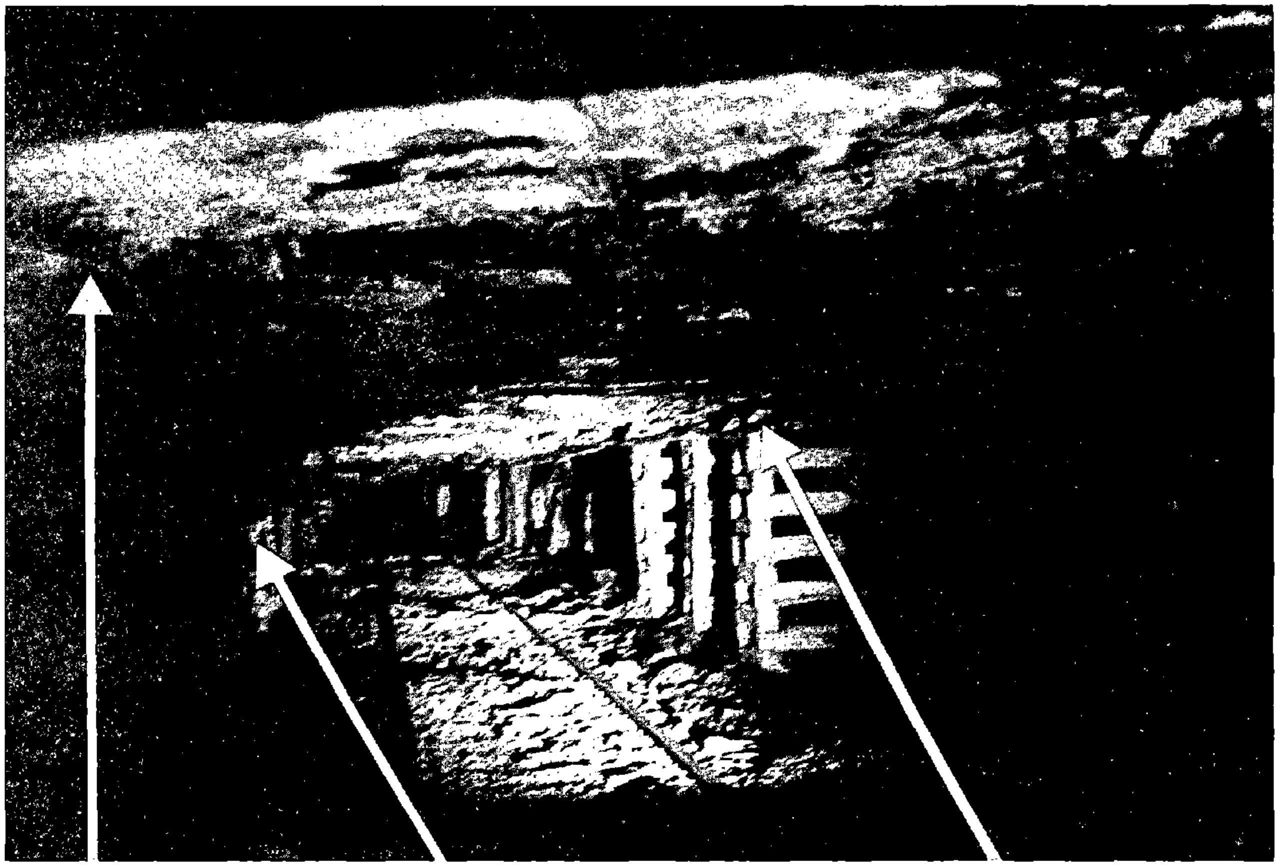


FIGURE 15 TROLLEY WIRE VOLTAGE – MINE NOT OPERATING – SIGNAL COUPLERS REMOVED

attached to spads. The spads were driven into the rib, roof, or roof support timbers on the wide side of the haulageway. The routing was along the numbered sections of haulageway shown in Figure 10, generally in the vicinity of the pager phone line, although separated from it by an average distance of about 1 - 1-1/2 feet. Figure 16 is a photo of a section of the Montour No. 4 main haulageway showing the rails, the trolley wire and feeder in the upper right corner, the pager phone line on the left side, and the dedicated wire in the upper left corner. Figure 17 shows in greater detail the routing of the dedicated wire in the 16-face area where the signal split and terminations were installed.

The dedicated wire was deployed after the spads and J-hooks were installed over the selected run and after the "before" signal measurements were completed. Number 12 insulated stranded copper wire was used. It was fed off a reel (2,500 ft. length) on a spindle mounted on a jeep. At rail haulage intersections where the dedicated wire had to cross over the trolley wire, the dedicated wire was passed through a section of protective hose before installation over the trolley wire. At intervals slack was created and hung in cross cuts, to permit easy repair in the event of damage to the wire. Connections between sections of the wire were made using wire nut splices that were then wrapped in electric tape.

Twenty watt, 20 ohm terminating resistors were installed at the two ends of the line, positions number 38 and 44. Clamps were applied to a section of the rail near each termination and the resistors were attached to a convenient support nearby. The dedicated wire was connected to one end of each resistor using wire nuts, and the other end was connected in the same fashion to a wire running to the rail connection. Temporary resistor terminations were later replaced with the more permanent terminations placed in suitable housings as shown in Figure 18. A signal splitter was similarly installed by joining the ends of three sections of the dedicated wire through three 50 ohm resistors to a resistor common at the signal split point as shown in Figure 19.



Dedicated Wire

Pager Phone Line

Trolley Wire and Feeder

FIGURE 16 HAULAGEWAY AT MONTOUR NO. 4 MINE

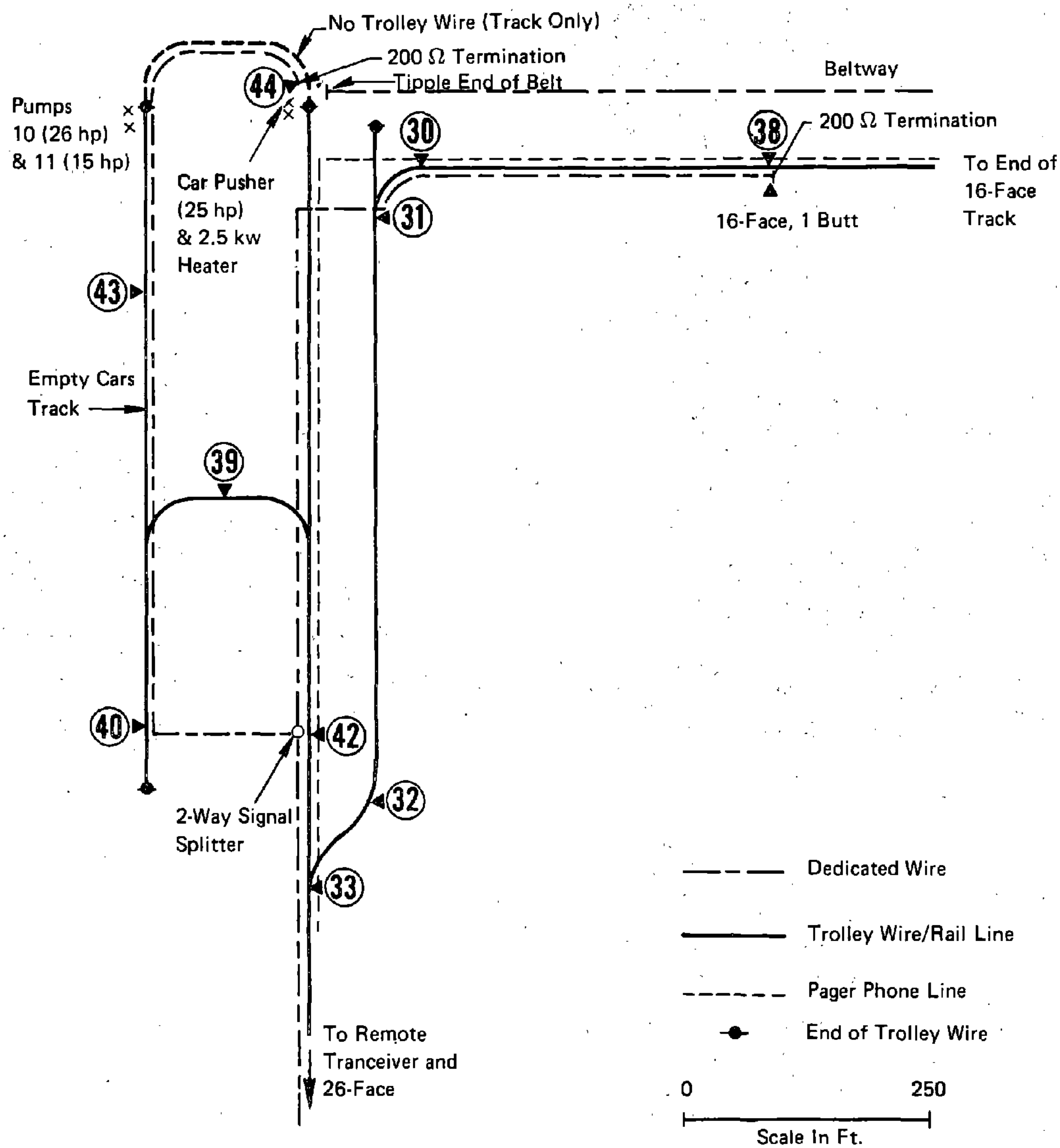


FIGURE 17 DETAIL ROUTING OF TROLLEY WIRE/RAIL LINE AND DEDICATED WIRE SIGNAL SPLIT AND TERMINATION INSTALLATIONS IN THE 16-FACE TIPPLE LOOP-AROUND

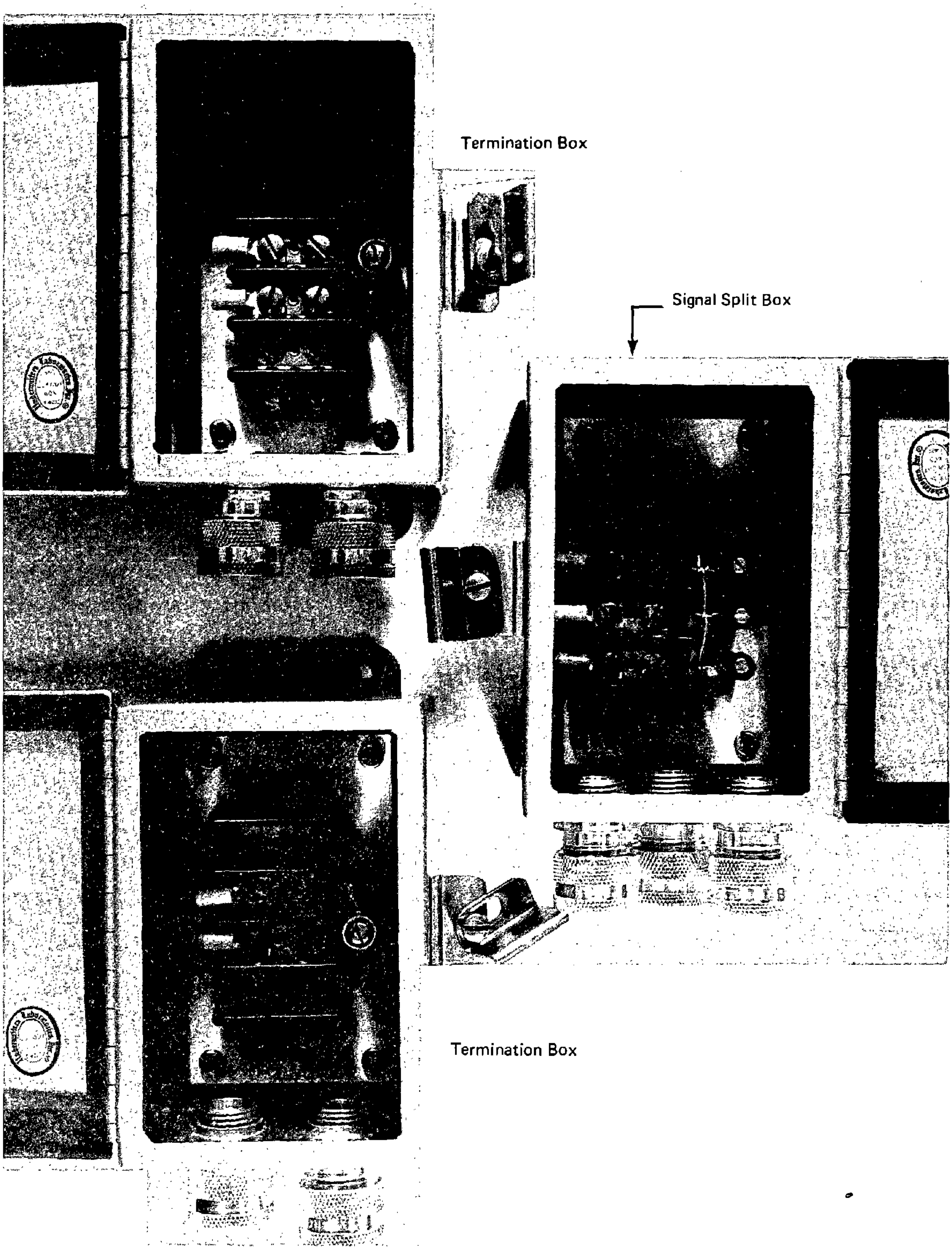


FIGURE 18 TERMINATION AND SIGNAL SPLITTING BOXES

At the dispatcher's remote carrier phone transceiver, the other end of the dedicated wire was connected to the transceiver output terminal, the internal selector link was set for high impedance, and the transceiver output filter tuning was adjusted for maximum output to the dedicated wire. With this adjustment, a carrier phone transceiver output of approximately 40 volts RMS was achieved. The dedicated wire current was .15 amperes RMS, thus yielding an impedance of 265 ohms. Thus, input power to the dedicated wire/rail line was approximately 6 watts.

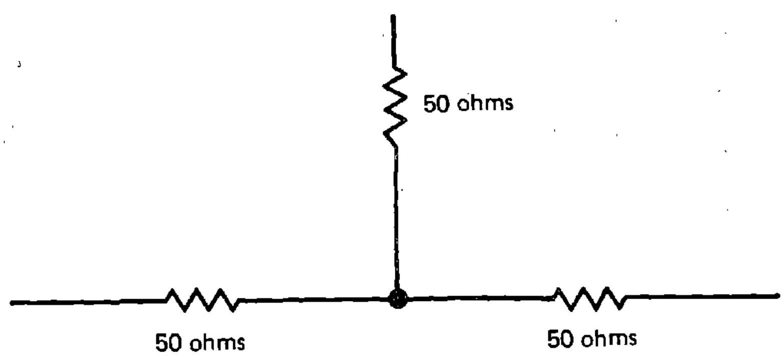


FIGURE 19 SIGNAL SPLIT SCHEMATIC

E. FINDINGS

1. Standing Waves

For the geometry of the installed dedicated wire/rail, it was estimated that the characteristic impedance would fall within the range 150 - 300 ohms. We chose a characteristic impedance of 200 ohms for the purpose of terminating the dedicated wire/rail line, and for making the resistive signal splitter. The mismatches resulting from such signal splits and terminations were expected to be small. The data of Figure 20, which plots the dedicated wire current versus distance, can be analyzed for standing waves, and an estimate of the standing wave ratio (SWR) and wavelength made. Based on this approach three estimates of wavelength yield individual values of 7,300, 6,900, and 7,400 feet, averaging 7,200 feet. The free space wavelength at 88 kHz is 11,160 feet, so the actual wavelength measured on the line is about 65% of the free space value. This value compares favorably to a value of 67% estimated from November measurements made on the trolley wire/rail line at Montour No. 4, and to a value of 64% found in Consol's Renton mine on a trolley wire/rail line. The standing wave ratio is also estimated from the plot and yields a value of 1.58, indicating only a modest mismatch by the terminating resistors.

2. Current Behavior at the Signal Split

Currents were measured at the signal splitter. The current on the remote transceiver side was measured at 60 milliamperes, with the two output currents being 28 and 34 milliamperes. Thus, a fairly even split of current was achieved.

3. Dedicated Wire Current Attenuation

The presence of small standing waves makes the estimate of line attenuation somewhat difficult. To provide an estimate, the straight line drawn on Figure 20 is used. The attenuation shown for this line is

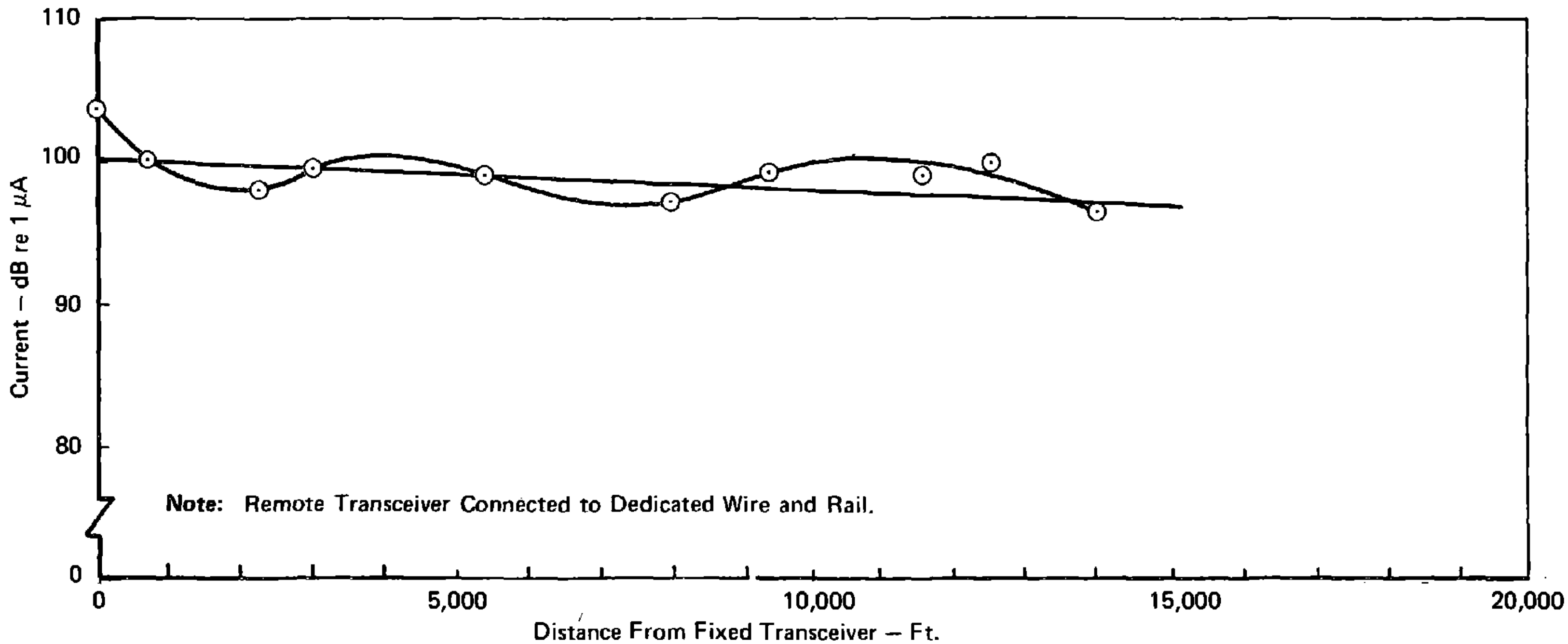


FIGURE 20 DEDICATED WIRE CURRENT VS. DISTANCE

100.5 - 97.2 dB or 3.3 dB over a distance of 15,200 feet (4.63 kilometers), thus yielding a value of .71 dB per kilometer. In comparison, the work of Hill and Wait[1] shows the following theoretical attenuation per kilometer.

TABLE III: ATTENUATION VERSUS CONDUCTIVITY

Conductivity (MHos/Meter)	Attenuation (dB/km)
10^{-1}	.9
10^{-2}	.65
10^{-3}	.54

These values of attenuation are for a wire installed in a coal mine tunnel having a return current path via rails. It can be seen that the observed value of about .7 dB/km falls within the range of attenuation rates that are predicted by Hill and Wait. When we compare these results to those for our theory of the dedicated wire where an attenuation rate of 1 dB per kilometer on the dedicated wire/rail line becomes translated to approximately 1.4 dB per kilometer when in the presence of a loaded trolley wire as shown in Figure 8, we see that the measured value for the Montour No. 4 installation also appears reasonable.

4. Current Coupling

The coupling occurring between the dedicated wire rail and the pager phone line/rail (common mode) acting as a psuedo trolley wire/rail line, showed relative values ranging from 4 to 10 dB as shown in Figure 21; the current in the pager phone line being 4 to 10 dB less than the current in the driven dedicated wire. Our dedicated wire analyses documented in the Task Order No. 2, Task I, Final Report, "Improvements for Mine Carrier Phone Systems," Contract H0346045, showed an expected value of about 8 dB for coupling between the dedicated wire and a similarly disposed trolley wire/rail. Therefore, one could conclude that the pager phone/rail line should behave in much the same way as a trolley wire/rail line would in the presence of a dedicated wire. Thus, the coupling values found appear reasonable.

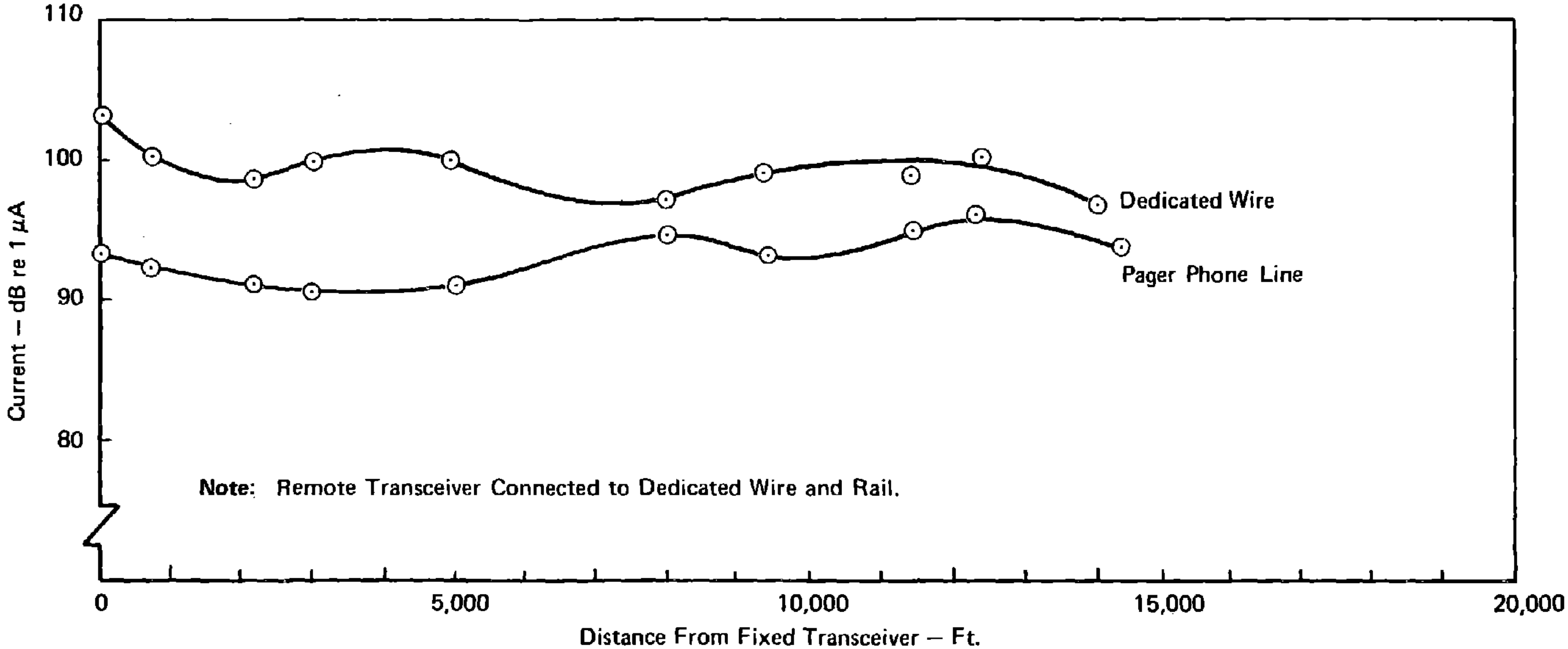


FIGURE 21 CURRENT COUPLING TO PAGER PHONE LINE

5. Signal Enhancement Results

Figure 22 is a good way to view the overall results of the dedicated wire experiment. This plot shows the trolley wire/rail voltage for two conditions of operation. The lower voltage plot is for a trolley wire/rail line condition similar to the one originally found at the mine, except that the two signal couplers were removed for this set of measurements. At about the 17,000 ft. distance the signal level has fallen to low values. Reference to Table I, the mine map of Figure 10, and Figure 17 in particular, reveals several branches to the trolley wire/rail in this region. This branching, together with the shunt loads across the trolley wire/rail line on these branches, play a key role in weakening the signal level in that area. In this area, the dedicated wire also has been branched. The upper plot shows the signal voltage level on the trolley wire/rail line after the dedicated wire was installed. It is noticed that the signal levels are higher and less variable in the presence of the dedicated wire. Furthermore, the areas of low signal level show considerable improvement when the dedicated wire is used. For comparison, the plot also shows the dedicated wire current.

One particular region of the mine known to have poor dispatcher-to-vehicle carrier phone communication was the 16-face loop around track in the tipple area. This area is shown in Figure 17. Locomotive operators work in this region when returning and positioning empty coal cars for reloading, and it is desirable from operational and safety standpoints that good communication be available to these locomotive operators. Measurements were made at two places, 39 and 40, in this area for the carrier phone communication system in its original configuration, both with and without signal couplers. A branch of the dedicated wire was routed through this area as shown in Figure 17. This branch was terminated with a 200 ohm, 20 watt resistor at the position (#44) of the DC operated car push used to advance the loaded cars. Measurements were made, both with and without signal couplers, in the presence of the dedicated wire installation. A summary of the measurements is presented in Table IV.

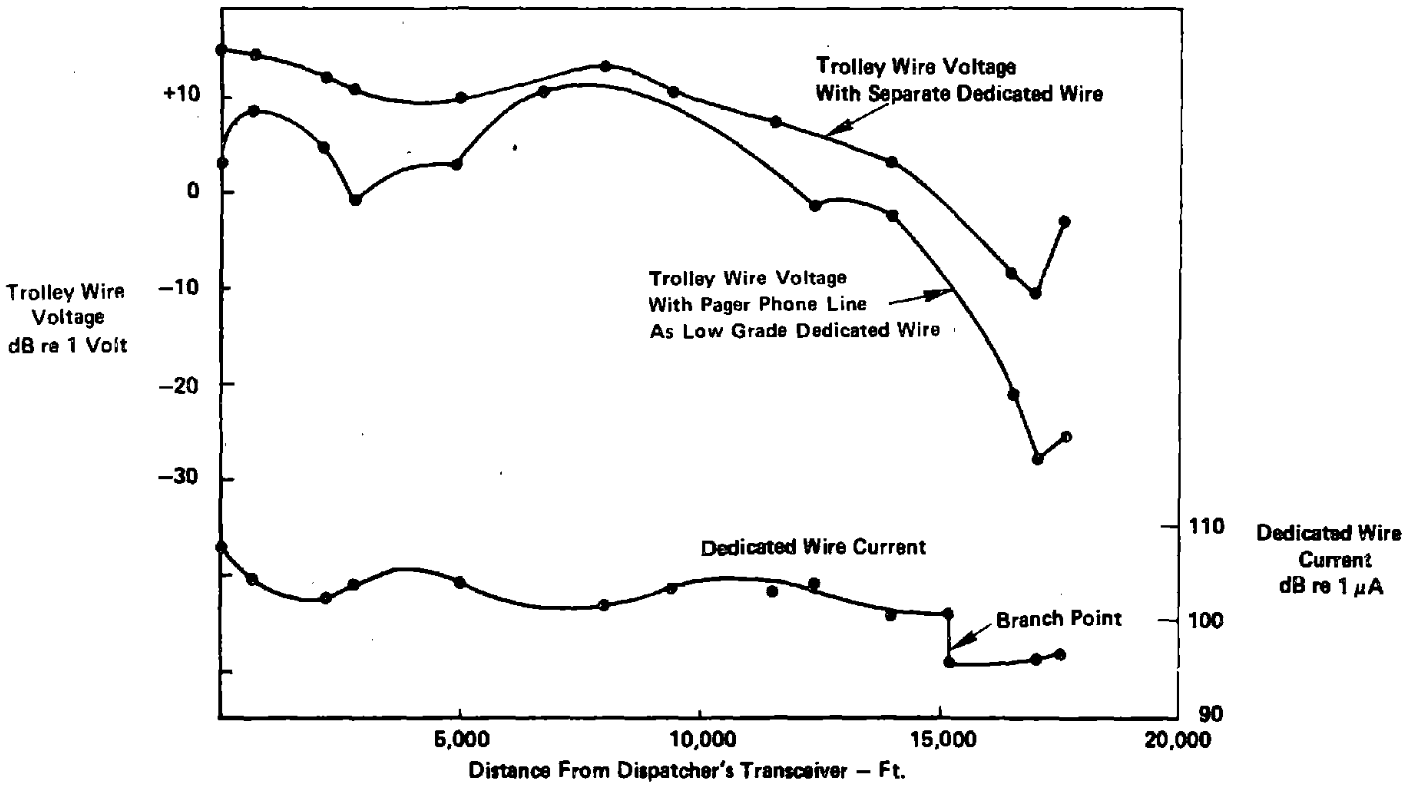


FIGURE 22 SIGNAL LEVELS VS. DISTANCE

TABLE IV

TROLLEY WIRE/RAIL VOLTAGE ON 16-FACE TIPPLE LOOP AROUND TRACK

Position Number	For Original Configuration Couplers In	For Original Configuration Couplers Out	For Dedicated Wire Installation Couplers In	For Dedicated Wire Installation Couplers Out
39	.085	.045	.44	.60
40	.180	.050	.50	.50
42	-	-	.46	.35
43	-	-	.43	.93

These tabulated values show that original configuration signal levels of around .050 volts were increased by about a factor of 10 to 1 to about .5 volts by the use of the dedicated wire. With the dedicated wire installation it was also found that signal couplers are not required, and, in fact, they can actually lead to poorer performance in some places. However, the presence of signal couplers does help in the absence of the dedicated wire.

6. Theoretical Estimate of Unaided Trolley Wire/Rail Signal Behavior

For comparison with experimental results Figure 23 shows a theoretical signal voltage versus distance plot for a carrier phone transmitter connected directly across a trolley wire/rail line unaided by the presence of couplers or auxiliary lines. This plot was derived by Smith chart analysis of the simplified electrical model of the Montour No. 4 trolley wire/rail transmission line system shown in Figure 12, which represents the known principal shunt loads likely to affect communication performance at the time of the mid-December nonoperational mine tests. The plot represents the ideal open circuit voltage seen across the line. In practice, the voltage seen by the vehicle will be less, due to the loading effects of the carrier phone and the vehicle electrical system.

The signal fall-off rate is seen to be significant, namely about 9 dB/km average over the 19,680 feet run. It would of course be worse if the power rectifier substations were not set back so far from the

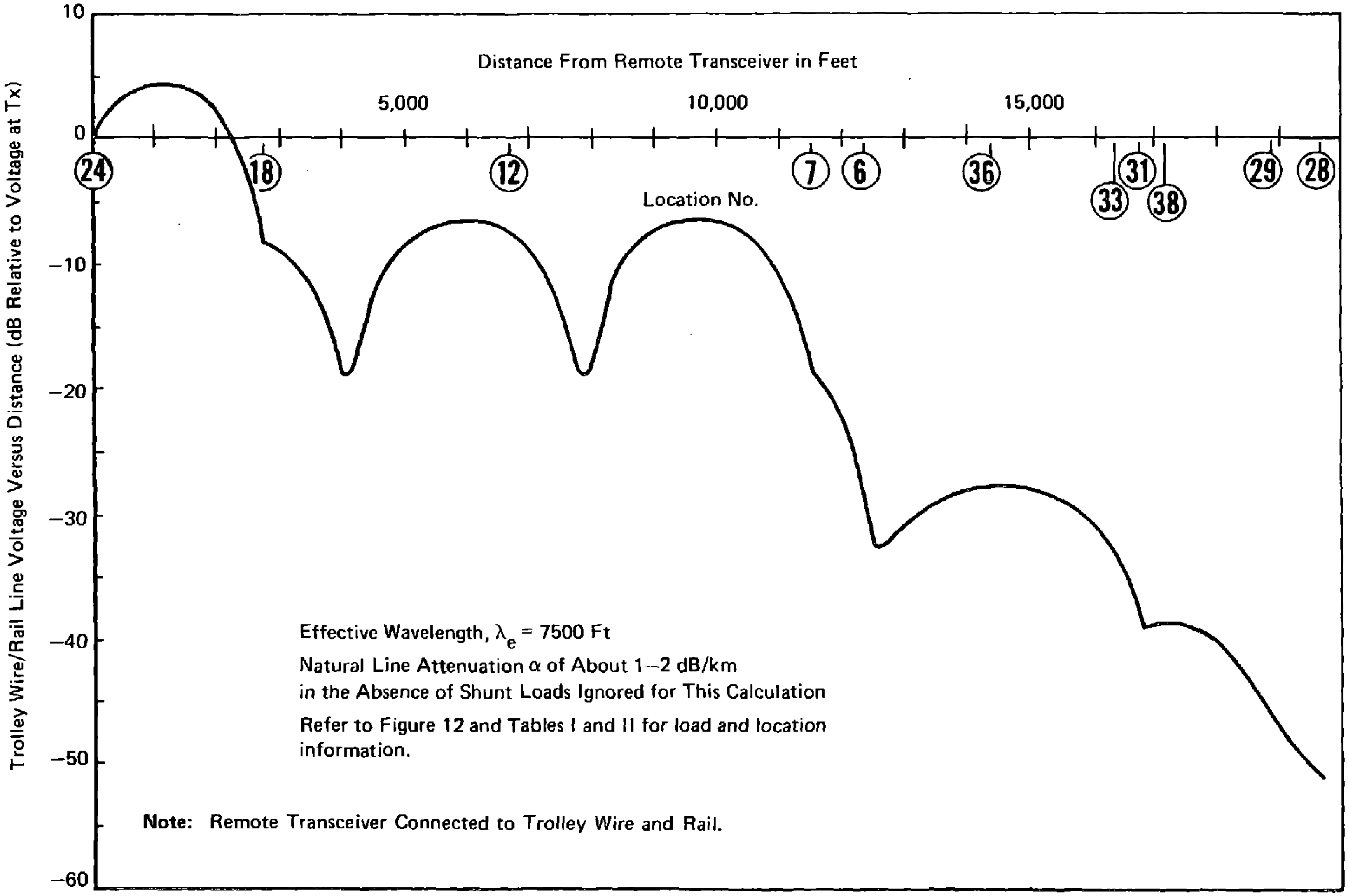


FIGURE 23 VOLTAGE ACROSS TROLLEY WIRE/RAIL LINE VS. DISTANCE – THEORETICAL CURVE

trolley wire/rail line, i.e., on the surface. Adding to this average rate the 1-2 dB/km natural attenuation rate in the absence of shunt loads gives an α of about 10 dB/km, which is equal to that for the theoretical case shown in Figure 8. This behavior points to this mine's need for some type of auxiliary line assistance to obtain workable carrier phone communication along many parts of the rail haulage route.

F. EQUIPMENT DESCRIPTION

Details of how the dedicated wire was installed have been presented. Here we describe the equipment used to make the measurements. The trolley wire/rail voltage was measured with a Sierra model 303A portable tuned voltmeter. The bandwidth setting was 3.1 kHz and the bridging impedance was 600 ohms. During the measurements, this meter was connected to the low voltage side of the blocking capacitor of an MSA 1601 carrier phone transceiver mounted in a mine jeep vehicle. This transceiver was equipped with its battery pack to ensure maximum transmitter output from the vehicle unit. Currents in the dedicated wire and pager phone line were measured using a Singer model 91550-1 current probe* having a transfer impedance of 1.65 ohms at 88 kHz together with a Singer NM12AT portable, tunable field strength meter. The bandwidth setting was on Broad and the function switch was set to Noise. The configuration of equipment installed and used on the jeep for the dedicated wire experiment voltage and current measurements is shown in Figure 24. The fixed location remote carrier phone transceiver used to drive either the dedicated wire or pager phone line is also an MSA model 1601 carrier phone. This unit is DC-powered from the trolley wire/rail line through a fuse and capacitor connection.

A number of measurements using a nonclamp-on, specially-designed, current probe were made, but are not reported on here due to a question regarding the integrity of the data taken with this probe on some particular runs. The questionable performance of this probe is thought to have been caused by a faulty BNC cable connector.

*This probe is not suitable for measuring current flowing in the trolley wire, primarily from a safety standpoint. A specially-designed probe like the one described in reference 5 should be used for trolley wire current measurements.

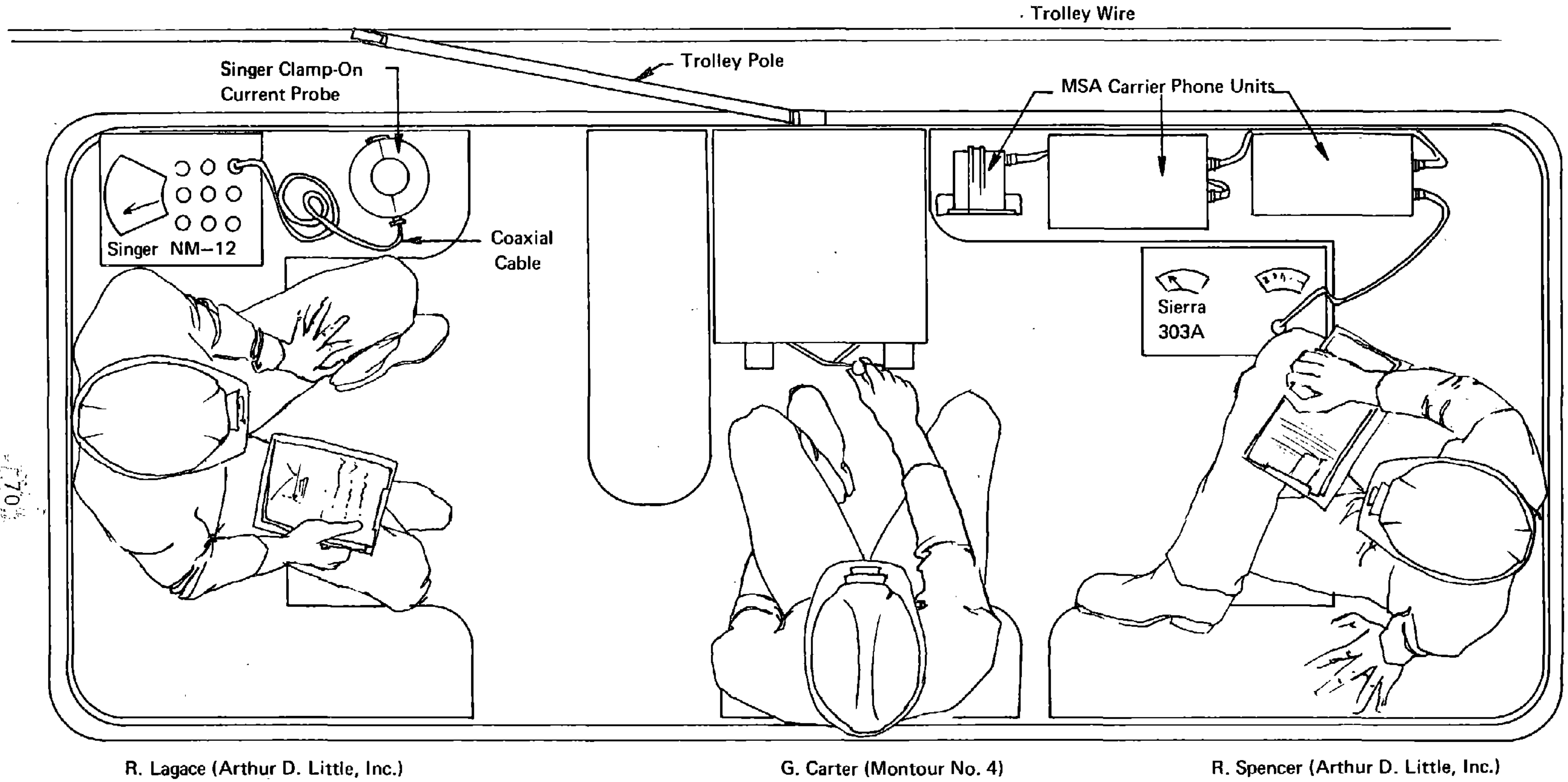


FIGURE 24 PLAN VIEW OF JEEP HAULAGE VEHICLE SHOWING APPROXIMATE DISPOSITION OF EQUIPMENT & PERSONNEL DURING DEDICATED WIRE EXPERIMENT MEASUREMENTS

G. GUIDELINES FOR APPLICATION OF THE DEDICATED WIRE

The following are guidelines for use of mine communication personnel considering the addition of a dedicated wire to improve the performance of their trolley wire carrier phone communication systems.

1. Determination of Need and Applicability

If the dispatcher has continuing problems reaching vehicle transceivers, and if it is known that these problems are not related to transceiver maladjustments or deficiencies, then the problem is most likely being caused by excessive signal attenuation along the trolley wire/rail transmission line. Consideration should then be given to using a dedicated wire, in addition to other possible solutions described in previous reports,[5,8] to overcome the communication problem.

2. Determination of the Layout for a Dedicated Wire

A mine map should be used to determine the layout for the dedicated wire. The regions of the mine where poor dispatcher signal strength occurs should be identified. If available, a tuned voltmeter such as the Sierra 303A can be used to good advantage to obtain quantitative data. These areas will typically, but not always, be regions far from the dispatcher's transceiver location. A route for the wire should be marked on the map. This route map should include branch points and places for terminating the ends of the dedicated wire. These ends should be located 500 - 1,000 feet beyond the regions of weak signal strength, if possible.

3. Installation

Spads and J-hooks provide one way to support the wire. Other means may be used if appropriate. These supports should be installed on the rib, the roof, or roof support members at spacings of 10 - 20 feet, depending on mine roof and rib conditions, and must be on the wide side of the haulageway. It is preferable to keep the wire a foot or more from the pager phone line or other prominent conductors in the mine haulageway.

8

Wires should be Number 12 gauge or larger, and have 600 volt or greater insulation. Stranded wire is recommended. Copperweld wire is a good choice having increased strength, although conventional stranded copper wire can also be used. Where the wire must pass over trolley wires, they must be protected with approved hose tubing, and treated like a pager phone line that must overpass a trolley wire.

The method for unreeling the wire can be any one convenient for the mine operator. Dispensing the wire from a jeep mounted reel spindle is one way. Splices should be made using wire nuts and should be wrapped with a protective layer of electrical tape. If appropriate, slack length of wire for simplifying repair work can be built into the installation, by making occasional short runs of wire down and back unused cross cuts. The wire in these slack areas should be supported much the same as in the main haulageway.

Resistive terminations should be made at the ends of the dedicated wire. The ground connection should be made by welding a fitting to the rail and attaching a ground wire to it. Mechanical protection should be applied to the wire, for instance, by burying the wire along its run to the termination box location. Boxes such as shown in Figure 18 are recommended. The ground wire should be connected to one screw terminal on the terminal strip, and the dedicated wire to the other. The resistor should be 200 ohms in value and have a power rating of 10 watts or more. The schematic for the connection is as shown in Figure 25. Where branching of the dedicated wire is required, the signal splitter schematic in Figure 26 applies. A typical branching splitter box is shown in Figure 18. The ends of the three sections of dedicated wire to be connected should be attached to the terminal strip. Three 68 ohm resistors of at least 10 watt power rating should be connected within the box as shown in Figure 26.

4. Check-Out of Dedicated Wire

When the installation has been completed and a visual inspection has been made, a simple test should be made from the location of the dis-

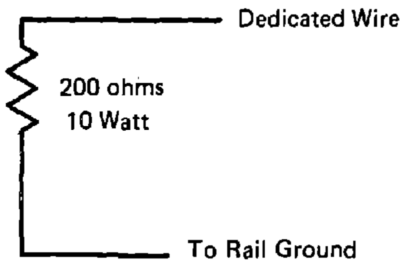


FIGURE 25 SCHEMATIC FOR TERMINATION

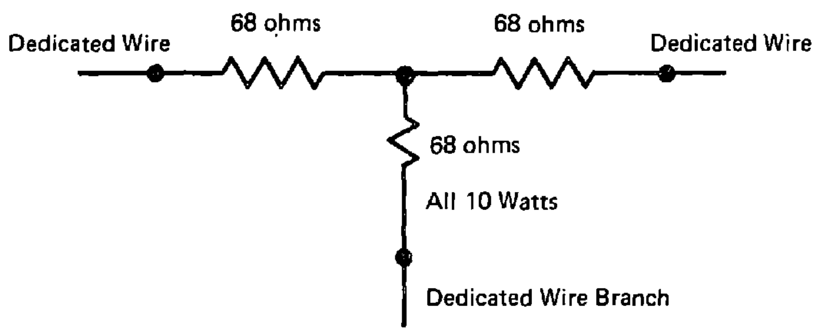


FIGURE 26 SCHEMATIC FOR SIGNAL SPLIT

patcher's transceiver. Here a ground should be made available, preferably welded to the rail, so that two wires are available for connection to the carrier phone transceiver. A continuity check should be made before making the connections to the transceiver. If there are no opens or shorts in the dedicated wire, the resistance between the dedicated wire and the rail should be approximately 200 ohms. A d-c voltage of a few volts will probably be found between the rail and the dedicated wire due to currents flowing in the rails. A multimeter may be used to measure this voltage and then switched to the current scale to measure current. The ratio of voltage to current should be about 200 ohms for an installation without opens or shorts. If no measurable voltage is found, the multimeter can be used in the resistance mode to directly measure the resistance. A resistance near 200 ohms should be found. If a very high value is found, say larger than 400 ohms, an error probably exists in the dedicated wire installation, and it should be found and corrected. Similarly, a value substantially below 200 ohms requires an examination of the wiring for errors.

If the resistance is found to be within the above allowable range, the transceiver can be connected to the two wires using the transceiver manufacturer's instructions. The transceiver should be connected for a high impedance load. Retuning of the output, if required, should be done as per the manufacturer's instruction book.

When connection and adjustment have been made, the level of carrier frequency signal put on the line should be measured. The multimeter can be used in the AC voltage range to do this. At least 20 volts RMS should be found when the transceiver is keyed on. The signal levels at the splits and terminations should also be checked. Table V shows some approximate voltage level criteria for validating the goodness of the installation.

TABLE V

EXPECTED VOLTAGE SIGNAL LEVELS BETWEEN DEDICATED WIRE AND RAIL VERSUS DISTANCE FROM FIXED LOCATION TRANSCEIVER

Distance - Feet	Percent of Applied Signal Expected
5,000	80%
10,000	60%
15,000	50%
20,000	40%
25,000	30%
30,000	25%
35,000	20%
40,000	16%
45,000	13%
50,000	10%

These percentages are for a dedicated wire alone,* without branches. If a signal branching splitter is used, one can expect that one half of the incoming signal level will appear on each of the outgoing wires at the signal splitter. One half of the incoming power is also lost in the dividing resistors. Beyond the splitter one can proceed along the dedicated wire using the above signal level reductions, but referenced to the signal level at the output side of the splitter whose location can be used as the new zero feet position. The integrity of the dedicated wire can be assessed in this way.

H. CONCLUSIONS

The principle of enhancement of trolley wire/rail line signals through the use of a dedicated wire has been proven in an actual coal mine. The dedicated wire permits a dispatcher's carrier phone signal to be carried to extended ranges of a mine with low loss by means of the natural coupling between the dedicated wire/rail and trolley wire/

*Assuming a nominal 1 dB/km signal attenuation rate.

rail lines. In particular, the dedicated wire in-mine experiment also demonstrated that:

1. A strong signal can be placed on the dedicated wire/rail line and can be distributed with low loss throughout wide regions of a mine on this wire.

2. Signals on such a dedicated wire/rail line can be split and hence distributed down branches of the dedicated wire and trolley wire/rail lines.

3. Dedicated wire/rail lines can be terminated to minimize the generation of standing wave nulls.

4. The dedicated wire need not be spaced more than a few inches from the roof or rib in order to preserve signal integrity on the line.

5. The velocity of signal propagation on the dedicated wire and trolley wire/rail lines appears to be about 65% that of free space.

6. The dedicated wire allows the carrier phone signal on the trolley wire/rail line to remain strong in most regions of the mine.

It should be noted that the original mode of carrier phone system operation in the Montour No. 4 mine was one in which the pager phone line was used in common mode as a sort of low-grade dedicated wire. During our experiments, we overlayed a much cleaner dedicated wire over the original system comprised of the low-grade dedicated wire and the trolley wire/rail line. For this reason direct comparison to the theory developed in our previous report was not appropriate. However, it is shown that the enhanced results expected from the theory were achieved for the test program at the Montour No. 4 mine.

I. RECOMMENDATIONS

The dedicated wire approach is strongly recommended as a valid and practical method for improving trolley carrier phone system performance in coal mines. Furthermore, we recommend that the dedicated wire application guidelines presented in this report be followed to ensure a systematic and effective installation and to obtain the best possible system performance.

The successful demonstration of the dedicated wire technique for improving performance also points to the following areas where further work would be beneficial.

1. The performance of the present dedicated wire installation should be measured under mine operating conditions to see how it compares with the performance attained in the nonoperating mine condition.

2. A practical method of driving the dedicated wire/rail line with the full 25 watt capability of standard mine carrier phones should be devised. A simple transformer may prove suitable for this purpose.

3. In-mine tests could be made to determine if simpler terminations than are presently used could be employed. For instance, by terminating the ends of the wire to roof bolts, problems associated with making an adequate connection to the rail, and protecting it over a period of time, could be avoided.

4. A more stringent and comprehensive test of the theory could be obtained through additional in-mine measurements over a significantly longer length of rail haulageway, together with tests between vehicles and between vehicles and the dispatcher connected directly across the trolley wire/rail line.

5. The performance of the presently installed dedicated wire could also be examined over a range of frequencies to determine if an optimum frequency exists from the viewpoint of signal

coupling and noise. Similarly, this dedicated wire could also be tested to determine the attenuation rate as a function of frequency, and compare it to the results of theoretical predictions.

These work areas are aimed at obtaining further practical information concerning the flexibility and utility of the dedicated wire technique for improving the performance of mine trolley wire carrier phone communication systems.

J. REFERENCES

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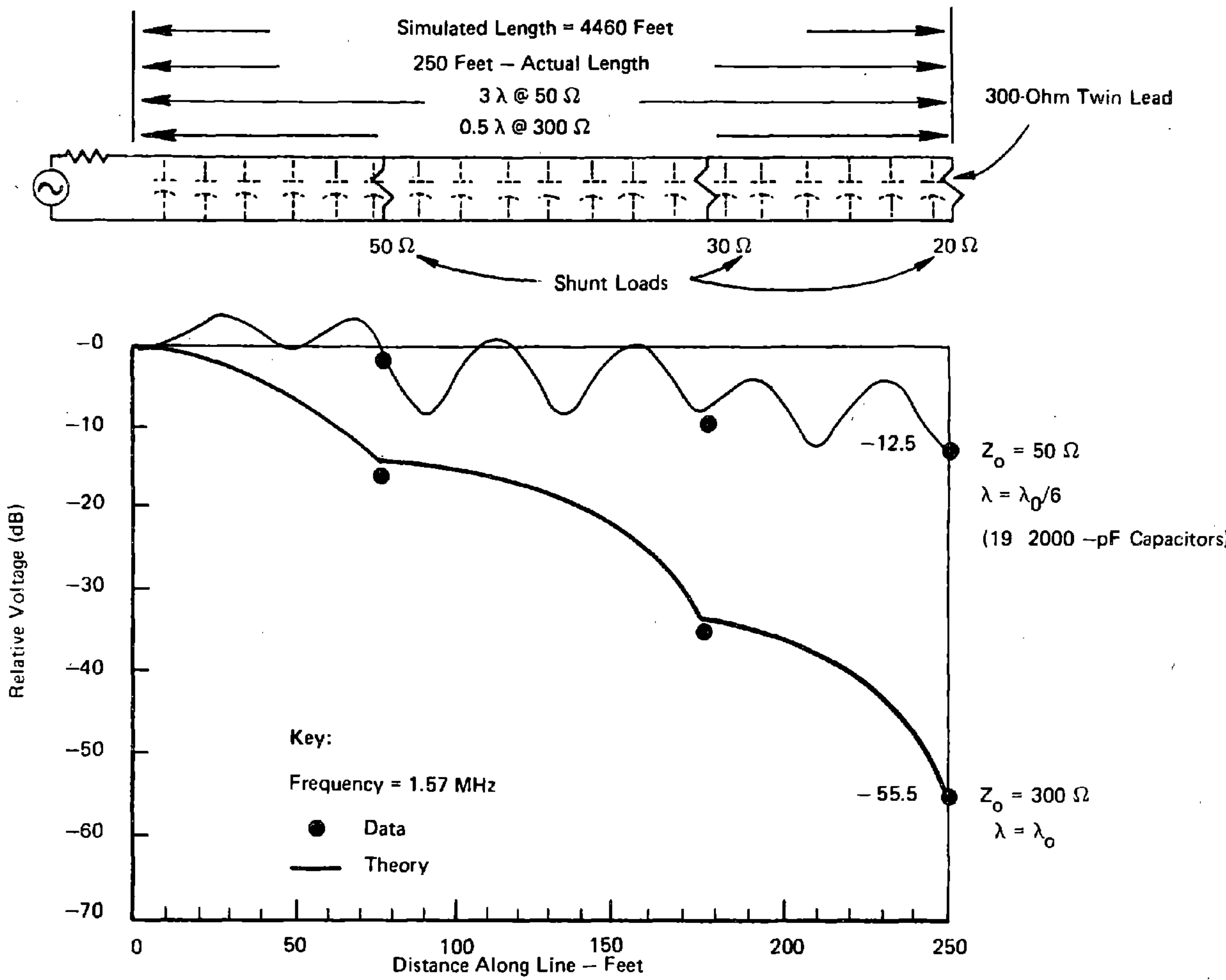
IV. PHASE III - LOW IMPEDANCE LINE EXPERIMENT FOR MINE CARRIER PHONE SYSTEMS

A. BACKGROUND

This chapter treats the low impedance (low-Z) line method for improving the signal attenuation characteristics of the heavily shunt loaded trolley wire/rail transmission line used by trolley carrier phone systems in many coal mines. The trolley wire/rail line is usually bridged by many loads such as very low impedance rectifiers, as well as vehicle motors, pumps, heaters, and lights that introduce a very significant shunt loss to carrier phone signals. The signal loss introduced by a single bridging load is related to the impedance of the bridging load compared to the characteristic impedance of the transmission line. This loss can be reduced either by increasing the impedance of the bridging load at the operating frequency or by reducing the characteristic impedance of the transmission line. The low impedance line method examined in this chapter is one that reduces the characteristic impedance of the line by periodically loading the line with discrete shunt capacitors which increase the apparent capacitance per unit length of the line.

Figure 27 from a previous Arthur D. Little, Inc., report[1] illustrates the performance improvements predicted by theory and verified by laboratory experiments with a twin-lead transmission line. Adding capacitors across the line lowered the characteristic impedance from 300 ohms to 50 ohms, and thus reduced the loss dramatically from 55.5 dB to only 12.5 dB, an improvement of 43 dB. The promise offered by these results prompted this task to perform in-mine demonstration experiments to determine whether the predicted improvements in performance could be achieved in practice on a trolley wire/rail line in an operating coal mine.



Source: Reference 1.

FIGURE 27 THEORY AND LABORATORY EXPERIMENTAL RESULTS FOR APPLICATION OF LOW-IMPEDANCE TECHNIQUE

B. OBJECTIVES

The objective of the demonstration experiments is to evaluate the ability of the low impedance line technique to reduce the signal attenuation rate on a trolley wire/rail transmission line. To accomplish this and to obtain a fuller understanding of the behavior of the low impedance trolley wire/rail the following sub-objectives were established:

- Characterize the normal trolley wire/rail line by determining its inductance per unit length, capacitance per unit length, and its characteristic impedance.

- Determine the optimum value and spacing of the discrete shunt capacitors used to decrease the line characteristic impedance.

- Characterize the low impedance trolley wire/rail line by determining its inductance per unit length, capacitance per unit length, and its characteristic impedance.

- Measure the voltage signal level versus distance away from a transmitter on a section of trolley wire/rail line under complete control of the experimenters under both normal and low impedance conditions. This section should be disconnected from mine power and loaded down with known, low power, resistive shunt loads to provide an unambiguous set of conditions for this test.

- Measure the voltage signal level versus distance away from a transmitter along an operating section of main haulageway having several deleterious shunt loads, and being of sufficient length, to demonstrate performance under both normal and low impedance conditions.

C. EXPERIMENTAL PROGRAM

1. General

The program for demonstrating the low impedance technique followed these steps:

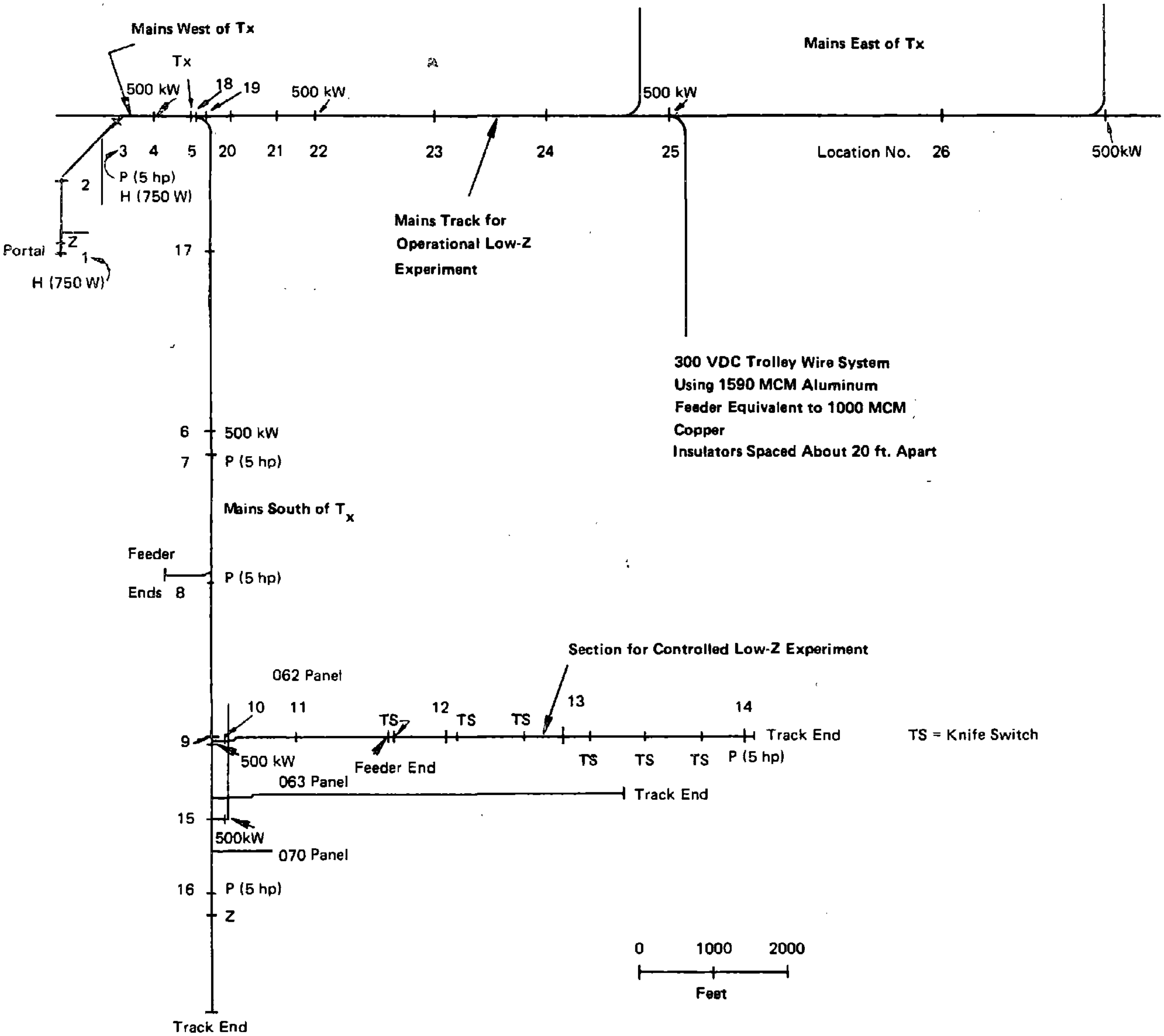
- Find a cooperative coal mine and visit it to obtain physical, electrical, and operational information and data for planning the locations, methods and schedules for the in-mine tests and for estimating system performance under normal and low-Z conditions.
- Calculate expected signal strength behavior versus distance based on theory and the data gathered from the informational visit to the mine.
- Develop a test plan outlining the procedures, techniques, and equipment needs for conducting the in-mine experiments.
- Obtain, prepare, test and deliver to the mine the materials and equipment required to perform the demonstration tests.
- Conduct the planned experiments in the mine together with mine electrical personnel.
- Analyze the data, compare experimental results for normal and low-Z conditions, and with theoretical predictions, and attempt to resolve any major discrepancies.
- Prepare a final report documenting the work, findings and conclusions.

2. McElroy Mine

The McElroy Mine, a Consolidation Coal Company mine, is a moderate sized mine located in the panhandle of West Virginia in Moundsville, south of Wheeling, West Virginia. The seam is the Pittsburgh seam. The mine operates three shifts. Figure 28 is a scale map showing part of the mine's electrical system and indicating the regions in which experiments were performed. Key electrical items are marked and numbered on this map, together with other locations along the rail haulage network. Figures 29 and 30 are sketches of the layout and disposition of electrical cables and other conductors in the haulageways in two regions of the mine where the experiments were conducted. The electrical layout in the cross section of the 062 panel section haulageway in Figure 29 is quite simple; no feeder is present above the trolley wire and the only other conductor in the haulageway besides the rails is a single pair phone line. In contrast, the main East-West haulageway cross section in Figure 30 has considerably more features, including the AC power cable indicated, the use of feeders for the trolley wire, the multi-pair telephone cable, as well as the pager phone line, and both plastic and aluminum water pipes. Trolley wire insulators are spaced approximately 20 feet apart in these haulageways. Table VI identifies the key electrical items and other locations of concern to this program along the haulageway network of this mine.

3. Mine Trolley Carrier Phone System

The mine uses MSA Model 1601 carrier phones on the vehicles. The system operates at a carrier frequency of 100 kHz. The dispatcher is located on the surface and uses a remote operated underground phone placed just east of position number 18 on the partial map of the mine's rail haulage network shown in Figure 28. One terminal of the carrier phone is connected common-mode to one pair of a twenty-five pair telephone cable while the other terminal is connected to the rail bond. This twenty-five pair cable runs along the east/west main haulageway, while a twelve-pair cable branches off down the north/south main haulageway.



Note:
- Remote Carrier Phone Transceiver Connected to Rail and One Pair (Common Mode) in a 25 or 12 Pair Telephone Cable Running on the Wide Side of Haulageway and Acting as a Dedicated Wire
- 25 Pair Cable Runs in East-West Mains
- 12 Pair Cable Runs in South Mains
- 1 Pair Only Runs into 062 Panel Section — Not the Pair to Which Carrier Signal is Impressed On
- Pager Phone Line Runs Only in the Mains, Not into the Sections
- Carrier Phones — MSA Model 1601 (100 kHz)
- Z—MSA Carrier Signal Coupler, Phone Line to Trolley Wire

FIGURE 28 RAIL HAULAGE MAP – McELROY MINE (Sections Examined in Preparation for Low-Z Line Experiment)

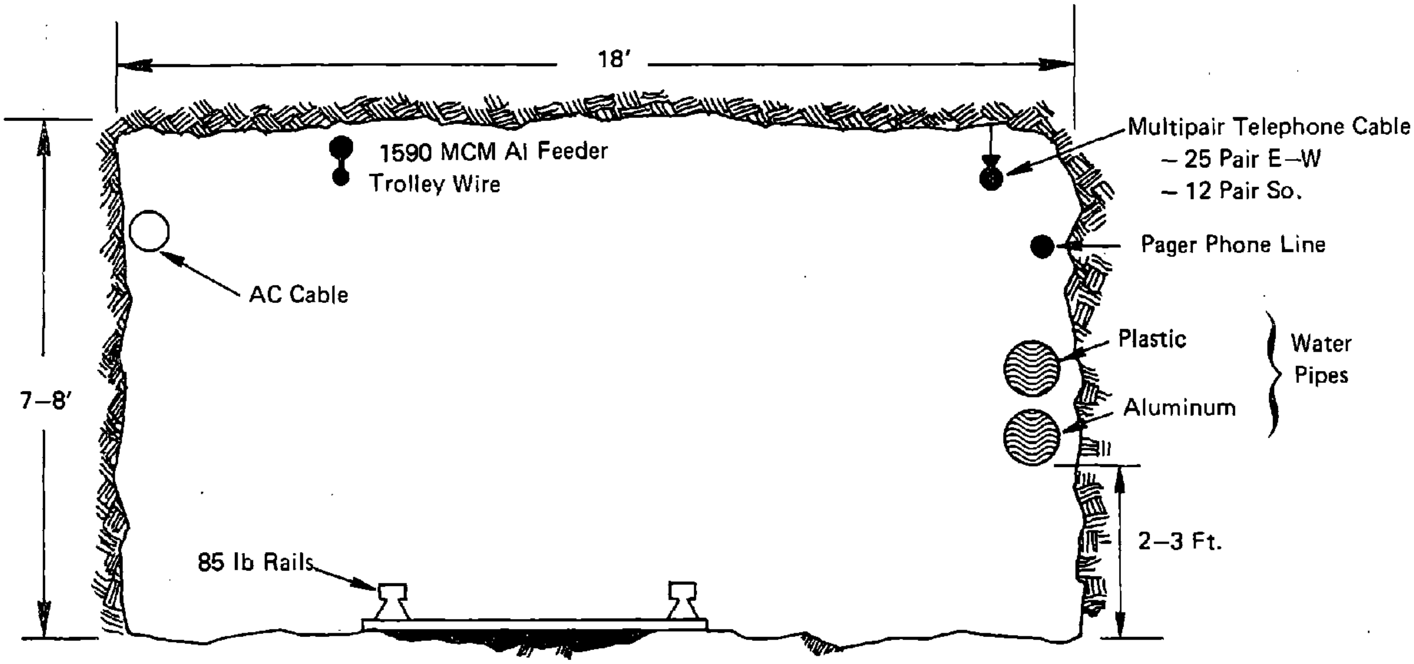


FIGURE 29 TYPICAL CROSS-SECTION – MAIN HAULAGEWAY

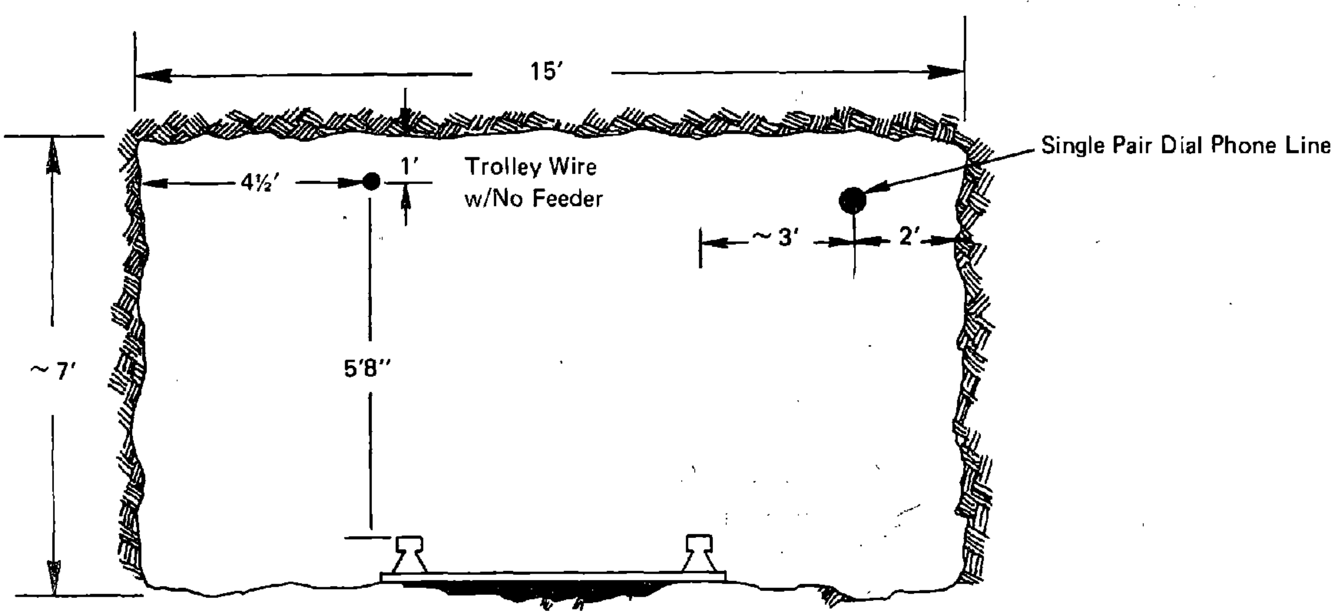


FIGURE 30 TYPICAL CROSS-SECTION – 062 SECTION HAULAGEWAY

TABLE VI

TABULATION OF DISTANCES AT KEY LOCATIONS FROM REMOTE CARRIER PHONE TRANSCEIVER

(Use in Conjunction with Annotated Reduced Scale Mine Haulage Map [Figure 28])

MSA 1601 - 100 kHz System

Location No. or Piece of Equipment	Distance (ft.) from Remote Transceiver	Notes
Run Towards Portal-West of Transceiver		
Remote Transceiver - Connected to a Telephone Pair & Rail	0	Using telephone pair as a dedicated wire
Location 4, 500 kW Rectifier	500	Setback approximately 50 ft., for mains track
Portal Track Intersection	975	
Location 3, 750 W Heater and 5 hp Pump	1,050	Bridging capacitor missing
Location 2	1,625	No MCM feeder
MSA Signal Coupler	2,400	
Location 1	2,550	
750 W Heater	2,575	
Run Down Mains-East of Transceiver		
Remote Transceiver	0	
Location 18 - Intersection with South Mains	50	
Location 19	200	
Location 20	550	

TABLE VI (Continued)

Location No. or Piece of Equipment	Distance (ft.) from Remote Transceiver	Notes
Location 21	1,175	
Location 22, 500 kW Rectifier	1,700	Setback approximately 65 ft., for mains track
Location 23	3,325	
Location 24	4,825	
Location 25, 500 kW Rectifier	6,525	For mains & sections
Location 26	10,250	Manda sealer machine on track 1 cross cut away
500 kW Rectifier	12,450	
Run Down Mains - South of Transceiver and onto 062 Panel		
Remote Transceiver	0	
Location 18 - Intersection with South Mains	50	
Location 5	125	
Location 17 - New 500 kW Rectifier - Not Connected Yet	1,850	For mains track
Location 6 - 500 kW Rectifier	4,225	Setback approximately 50 ft., for mains track
Location 7 - 5 hp Pump	4,500	
Location 8 - 5 hp Pump	6,225	
Location 9 - Intersection with 062 Panel Loop Around	8,250	

TABLE VI (Continued)

Location No. or Piece of Equipment	Distance (ft.) from Remote Transceiver	Notes
500 kW Rectifier	8,350	For mains track
Location 15	9,400	500 kW rectifier located about 150 feet away on loop around - serves 2-sections and may not be connected to mains track
Location 16 - 5 hp Pump	10,400	Pump working, no rf choke, empties beyond location 16 prevent further travel. Feeder ends about 50 feet beyond.
MSA Coupler (Disconnected)	10,675	
Section DC Shuttle Car	12,000	
Run onto 062 Panel		
Location 10 on Loop Around	8,350	
Loop Around Intersection	8,450	
Section Track Intersection	8,500	
Location 11	9,400	At tag 7 + 20
End of Feeder	10,650	
Location 12	11,400	At tag 27 + 86
Location 13	13,075	At tag 44 + 57
Location 14 - 5 hp Pump	15,500	At tag 68 + 29 approx. 1 cross cut from end

Thus as in the Montour No. 4 mine, the trolley carrier phone system in this mine is operated with the dispatcher's phone connected to an "unoptimized dedicated wire" instead of to the trolley wire itself.

4. Planning Visit to Mine

When the McElroy Mine agreed to our conducting the low-Z line experiments at their mine, we made a planning visit to the mine. The purpose of this visit was twofold. The first was to acquaint the mine electrical staff with our detailed requirements and to determine with them the best ways to meet these requirements. The second was to obtain information and data descriptive of the mine trolley wire/rail haulage system and its electrical loads so that the desired experiments could be carefully planned and efficiently performed. Therefore, we travelled the rail haulage system to examine the sections of haulageway proposed for the experiments and to make some initial measurements of trolley wire carrier voltage levels. Mr. James Marsh, the mine electrical engineer, made several very worthwhile suggestions about the means for connecting the required capacitors to the trolley wire and to the rail. Mr. William Stees, of Consolidation Coal Company's Eastern Region Moundsville Operations office, assisted us in making these initial underground observations and measurements and helped us obtain the cooperation of the McElroy Mine. The information summarized in Table VI was obtained on this visit.

5. Design of the Low-Z Line - Choice of Capacitor Size and Spacing

To design a low-Z line, one requires two basic inputs:

- The desired value of line characteristic impedance Z, and
- The desired spacing of discrete shunt capacitors.

The target value for Z should preferably be one which yields the least signal attenuation with distance along the loaded transmission line. This is achieved by optimizing the trade-off between line shunt losses and series losses.(1) In the present case, we assume a nominal characteristic impedance of 200 ohms, a series loss of 0.5 dB per kilometer and a shunt loss of 10 dB per kilometer, values which are typical for loaded trolley wire/rail lines.(1) Optimization according to the procedure described in reference 1, results in a target value of lowered characteristic impedance of 45 ohms. For the practical installation in the McElroy Mine, a target value of 40 ohms was chosen, a 5 to 1 reduction in characteristic impedance.

This target value Z can be achieved by increasing the capacitance per unit length of the line by a factor of 25 using either a large number of closely spaced small value capacitors or a smaller number of more widely spaced capacitors of larger value. To simplify the in-mine installation, we chose to use as wide a spacing as practically possible that would not only provide the desired performance, but also allow the installation, measurement, and removal operations to be performed within a single work shift. (It was judged inadvisable to leave the temporary capacitor installations along an active main haulageway unattended for long periods of time.) For a permanent installation, the choice of capacitor size and spacing would also lean towards using the largest practical capacitor values and spacing consistent with acceptable performance.

Based on an expected value of C = 10 picofarads per foot for the trolley wire/rail line distributed capacitance and a desired span of 200 feet between capacitors, the 25 to 1 increase in effective line capacitors having a value C_s = 25 x (10 x 200) - 0.05 mircofarads. Therefore, we chose to use a commercially available one thousand volt rated .04 microfarad ceramic capacitor for the demonstration experiments.

The capacitor spacing of two hundred feet was based on the desire to keep the spacing as large as possible while still ensuring that the chosen operating frequency of 80 kHz remained well below the frequency of the first null (cut-off frequency) in the amplitude response of the lump loaded transmission line. The cutoff frequency f_o for such a loaded line is:

$$f_o = \frac{1}{2\pi\sqrt{LC_s}}$$

where L is the total inductance of the line between lumped capacitors C_s. Based on an expected value of L = .35 microhenrys per foot for the line distributed inductance, the total inductance between capacitors spaced 200 feet apart is 70 microhenrys. Therefore, shunt capacitors C_s = 0.04 microfarads give a cutoff frequency f_o = 190 kHz, a value well above the experimental operating frequency of 80 kHz. A doubling of the spacing and size of the capacitors would have reduced the cut-off frequency to 95 kHz, a value too close to the operating frequency of 80 kHz.

6. Installation Method for Shunt Capacitors

A safe and practical way for making a temporary installation of discrete shunt capacitors every 200 feet along de-energized and fully energized sections of haulageway had to be devised. This was accomplished through consultation with electrical personnel at the McElroy Mine during the planning visit to the mine. Figure 31 illustrates in a schematic sense the method chosen for making the required connections to the live trolley wire and to the rail. Figure 32 shows the parts used.

The capacitors were installed with #12 stranded copper insulated wire. Burndy connectors were used for attaching one piece of #12 wire to the rail bond straps for the rail connections. The corresponding connections of #12 wire to the trolley wire were made with light-duty, current taps, clamped onto the trolley wire. A short piece of #12 wire was used to connect one terminal of the capacitor to the trolley wire, and a long piece of wire was used for the rail connection. This provided an additional safety precaution by making sure that only a limited portion of the #12 connecting wire was at the trolley wire voltage; most of it being at the rail potential. The #12 wire was buried for protection under a few inches of floor material near the rail connectors, and then run over to and up the rib or a roof support member, passed through a J-hook support, and then run back to the trolley wire. The #12 wire would also act as a fast-acting fuse to remove any shorted part of the wire from the circuit should any

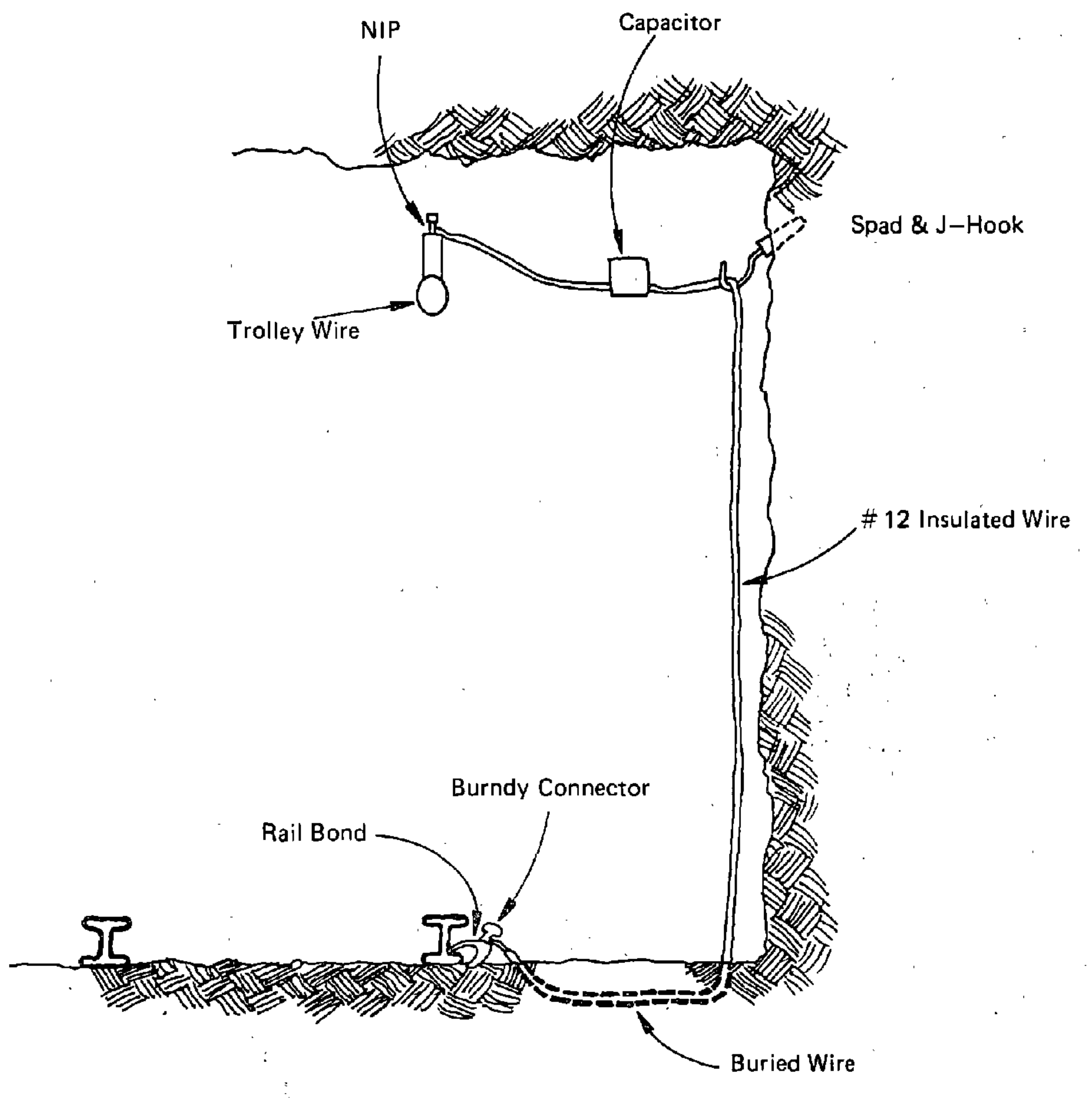


FIGURE 31 SCHEMATIC OF CAPACITOR INSTALLATION

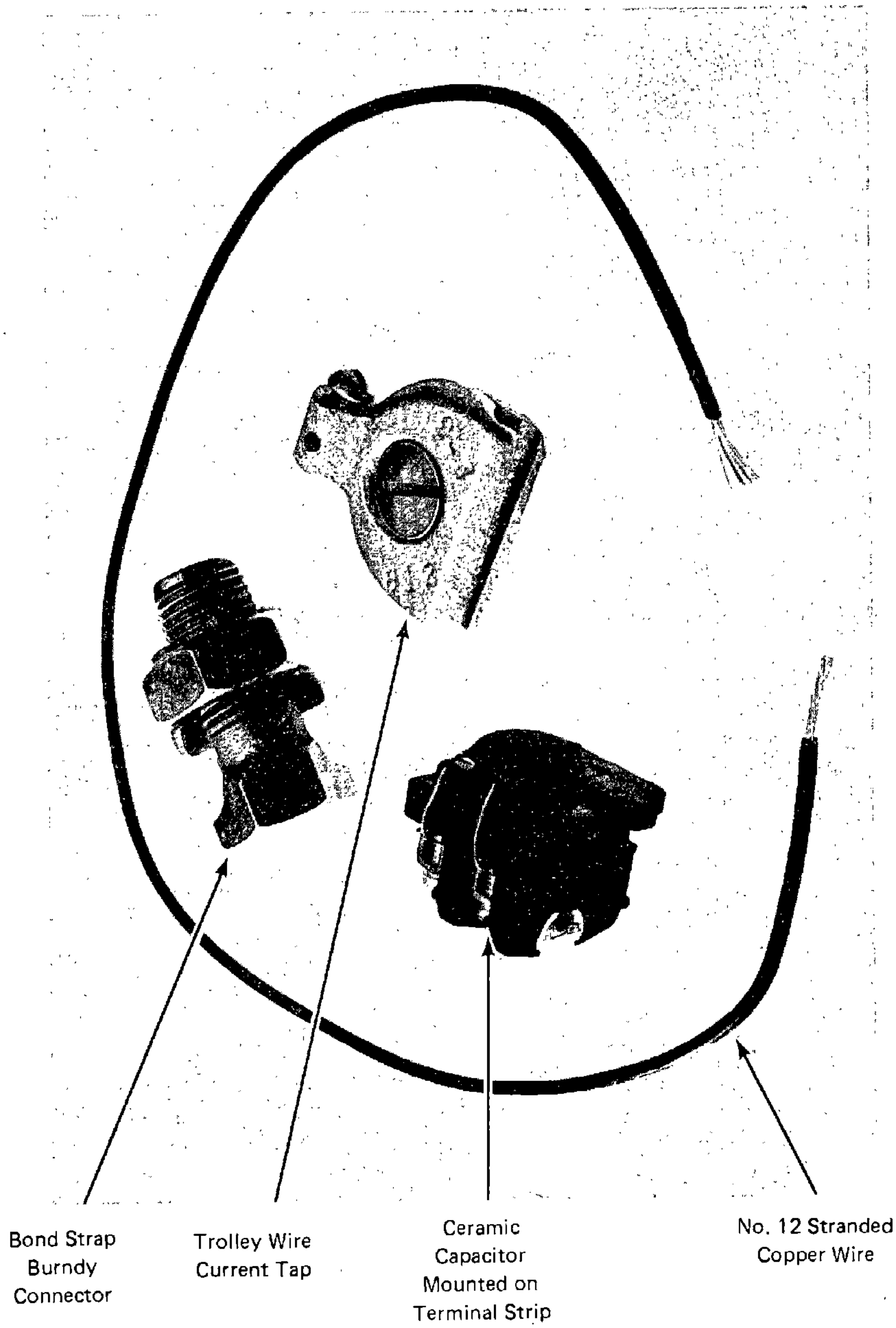


FIGURE 32 INSTALLATION PARTS

accident occur. We used 1000 volt ceramic capacitors mounted on terminal strips for easy connection to the #12 wire.

This method is applicable only for very temporary installations* such as the ones used during the demonstration experiments which lasted for periods of only two or three hours. At the end of each period the wires and capacitors were removed, but the Burndy connectors and the current taps were left attached.

7. Planned In-Mine Tests

During the time between the mid-June planning visit and the scheduled mine tests in mid-July, equipment was ordered which included the capacitors, interconnecting wire, current taps and Burndy connectors. These pieces of equipment were delivered to the McElroy Mine for use during the July test period. A test plan was prepared describing each of the planned measurements, and the required tools and measuring equipment for the trip were assembled.

Two types of tests were planned. One type was aimed at measuring the characteristic parameters of mine trolley wire/rail transmission lines such as the line capacitance and inductance per unit length, the line characteristic impedance, and the line phase velocity of signal propagation, under both normal and low-Z line conditions. The second type was aimed at measuring the amount by which the signal attenuation rate along loaded trolley wire/rail lines could be reduced by adding periodically spaced shunt capacitors to create a low-Z line condition.

The characteristic parameter measurements were performed on a relatively short (approximately 1200 feet long) section of de-energized trolley wire/rail line under nearly complete control of the measurement team. The signal voltage level versus distance measurements were performed in two parts of the mine, on the relatively short, de-energized section of the line which was artificially shunt loaded with two known resistive loads, and on an approximately 3900 foot stretch of fully operational main haulageway with a normal complement of shunt loads, including two 500 kW power rectifiers. The signal level measurements

*Some alternatives for permanent installations are discussed in Appendix D.

were A-B tests, under normal and low-Z line conditions, to provide direct experimental measures of improvement which could also be compared with theoretical predictions. The test plans for these two types of in-mine tests are described in more detail in Appendix A.

8. July Measurements

a. Tests on Short De-energized Section

The measurements performed on the first day of the July test period proceeded very smoothly and were completed without difficulty during the normal day work shift of the mine. They included measurements, as described in Appendix A, of the normal and low-Z line characteristic parameters and A-B signal level versus distance tests on the short de-energized section of trolley wire/rail line in the 062 panel of the mine indicated in Figure 28. During the planning visit to the mine, we picked out a section of trolley wire/rail line at the end of this panel, together with locations for attaching the shunt capacitors to produce a low-Z line. Figure 33, taken from a mine map of the McElroy mine, shows this chosen section. The symbols TS1 and TS2 represent locations of the knife switches where the trolley wire can be disconnected from the mine DC power supply.

The tests were performed on the trolley wire/rail line extending to the right of TS2. After opening knife switch TS2 and assuring ourselves that the power was removed from this section of line, R. Spencer and R. Lagace of Arthur D. Little, Inc., and mine electrician, D. Cory, proceeded to walk the 1200 foot length of the test section and install the current taps on the trolley wire, the Burndy connectors to the rail bonds, and the capacitors and resistors, with the #12 wire leads attached only to the rail bond connectors. Connections of the capacitor and/or resistor leads to the trolley wire current taps were made only when required by the specific tasks described in Appendix A. The attachment locations and the attached items, running from the starting point to the right of knife switch TS2, are listed below.

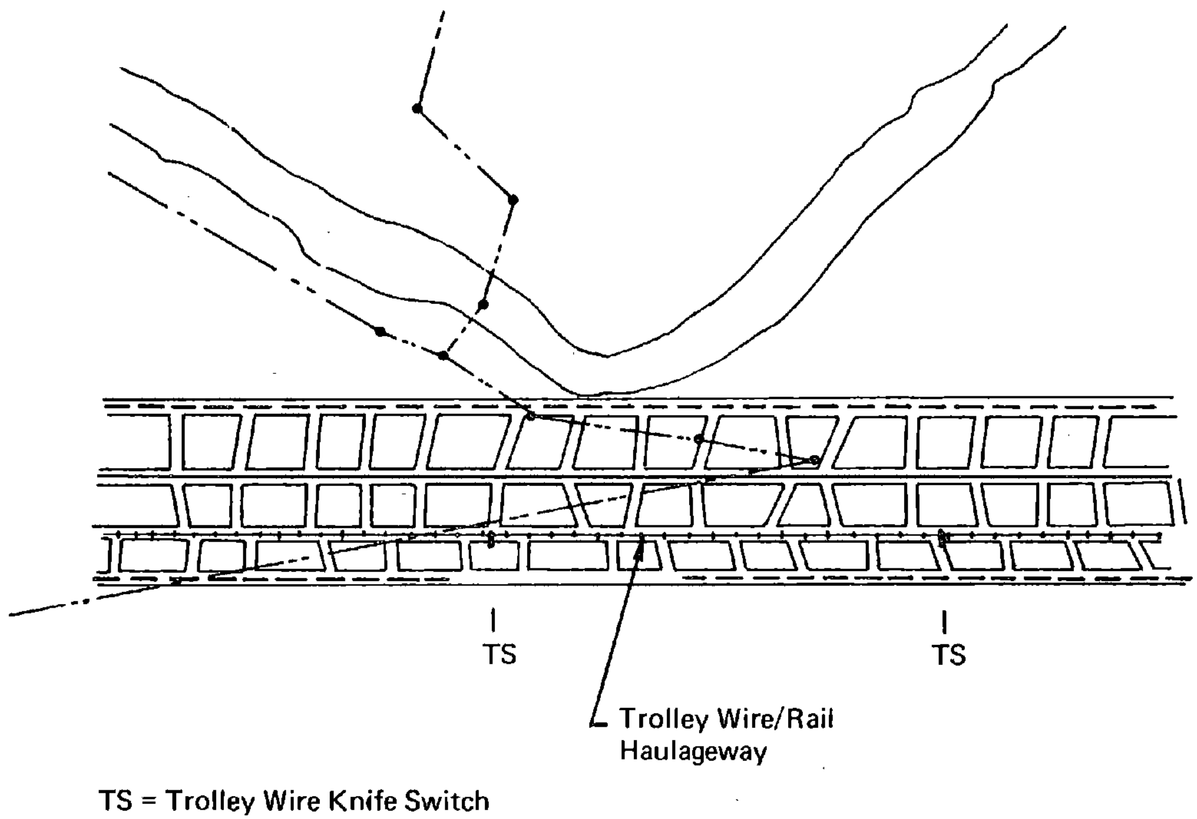


FIGURE 33 MINE MAP SHOWING DE-ENERGIZED LINE TEST LOCATION AT END OF 062 PANEL SECTION

TABLE VII

LOCATION OF ITEMS ATTACHED TO DE-ENERGIZED SECTION OF TROLLEY WIRE/RAIL LINE

Distance	Attachable Items (See Appendix A)
0	Transmit oscillator, GR impedance bridge, voltmeter
100 ft.	Capacitor (.04 μF)
300 "	"
497 "	"
700 "	"
765 "	Resistor (10 Ω)
900 "	Capacitor (.04 μF)
1080 "	"
1210 "	Capacitor (.04 μF) in parallel with resistor (10 Ω) at end of line

All scheduled tests were performed under normal line conditions first. The capacitor leads were then attached to the trolley wire current taps, and the tests repeated under low-Z line conditions. The requirement that measurements at one end of the line be coordinated with circuit terminations at the other end 1210 feet away was made possible by the use of UHF frequency MX Motorola walkie-talkies. These walkie-talkies allowed the tests to proceed quite smoothly, thereby avoiding the major difficulties that would have occurred without them. Because there was no rail traffic on this de-energized section of the trolley wire/rail line during these measurements, we did not have to take extreme care in dressing the wires connecting the capacitors to the trolley wire and rail. The results of these tests are presented in Section D.

b. Tests on Operational Main Haulageway

The A-B signal level versus distance measurements planned for the second day along a 7500 foot stretch of the East/West main haulageway under operational conditions did not proceed without delay and difficulty and were not successfully completed. As a result of higher priority mine maintenance tasks, mine electrical staff were not able to install the trolley wire current taps, rail bond connectors, and capacitor lead attachments to the rail bond connectors, spaced about 200 feet apart during the midnight shift as planned. Faced with having to fit the installation and measurement tasks into the available day shift time, we chose to reduce the test section of haulageway from the planned 7500 feet to about 3300 feet, and to install the attachments and connections ourselves with the aid of mine electrician D. Cory.

A total of 16 capacitors were installed approximately 200 feet apart over a 3300 foot stretch of trolley wire/rail line running East from a point about 125 feet West of the 500 kW rectifier nearest the portal track, as indicated on the annotated sections of the trolley line electrical map shown in Figure 34. Because of the complexity and time required for the low-Z installation, we decided to install the capacitors and perform the low-Z line signal level measurements before those for the normal line conditions. The installation was completed in 2-1/2 hours.

The method of installation involved carrying the equipment and installation parts on-foot along the haulageway, stopping at the identified locations on the map of Figure 34 near alternate cross cuts. The numbers refer to measurement points and the circled dots indicate capacitor locations. The rail bond nearest each of these locations was chosen as the attachment point. The installation was made at this point according to the method described in Section C6. During the installation period, frequent retreats to protected areas were required to allow the passage of rail haulage traffic. A line-operated 80 kHz CW transmit oscillator was attached across the trolley wire/rail line about 50 feet West of the 500 kw rectifier power center near the portal track. The oscillator was powered from an AC outlet on the rectifier power center.

A Rycom tuned voltmeter mounted on a jeep was used to make the signal level measurements as shown in Appendix A. One lead was connected to the low voltage side of the isolating capacitor of the jeep's

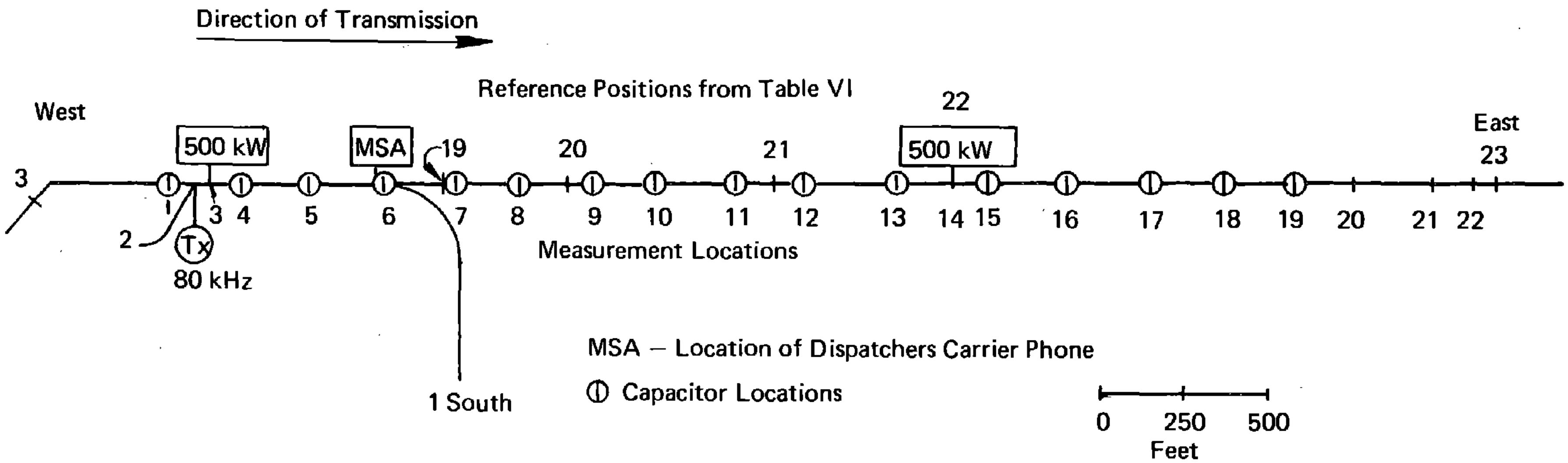


FIGURE 34 MEASUREMENT CONFIGURATION AND CAPACITOR LOCATIONS ALONG OPERATIONAL SECTION OF EAST-WEST MAIN HAULAGEWAY FOR *INITIAL* TESTS IN *JULY* – McELROY MINE

MSA 1601 trolley carrier phone and the other to jeep ground. We proceeded to make voltage measurements at the transmitter, each capacitor location, and each rectifier along the haulageway run. At the end of this run, the Rycom began to malfunction, as a result of what we now believe was a high energy voltage transient. Recognizing that the equipment was not in fully operational condition and that time was running out, we nevertheless proceeded to perform a quick set of voltage measurements along the line for the normal line conditions with all the capacitors disconnected. This was accomplished with great dispatch within the 10-minute lull between changes in shift crews, after which we left the mine. The capacitors were disconnected by simply cutting loose the #12 wire leads at the current taps and Burndy connectors with wire cutters.

Rather than attempt any further measurements with equipment that was malfunctioning in a way that was not understood at the time, we decided to suspend further measurements so that we could repair the equipment, examine the reliable de-energized section results we had obtained, and make arrangements for another visit to redo the measurements on the operational haulageway.

9. August Measurements on the Operational Main Haulageway

After reviewing the results of the incomplete main haulageway measurements taken on the previous mine visit, we decided to add two more capacitors to the eastern end of the test section and to also place the transmitter at this end, thereby reversing the direction of transmission. This transmitter location provides a more favorable disposition of transmitter and major rectifier loads for the experimental signal comparisons. It also places the transmitter in a location where it and the signal it generates will be less disturbed by mine traffic than was the case at the original transmitter location. In addition, we decided to use a battery operated signal transmitter, thereby obviating the need to locate the transmitter near a rectifier where 115 volt power was available. This procedure allowed us to use the same points of attachment to the trolley wire/rail line for the capacitors as before, since the current taps and bond connectors had been left in place.

R. Spencer and R. Lagace of Arthur D. Little, Inc., returned for a single day of measurements in late August to find the mine temporarily short of electrical staff, which prevented the taking of measurements on the day shift as planned. Fortunately we were able to perform the tests during the midnight shift when D. Cory, the highly competent electrician who worked with us during the previous measurements, was able to join us.

During this shift we first walked the test region, relocated the attachment points, reinstalled the capacitors, added two additional attachments and capacitors to the east end of the run, and installed the battery operated CW 80 kHz transmitter approximately 125 feet east of the last capacitor. The frequency of 80 kHz was chosen because it is far enough below the 100 kHz trolley carrier phone frequency used at McElroy to avoid interference with mine carrier phone communications. The installation is shown on the annotated section of the mine trolley line electrical map in Figure 35. As before, the numbers refer to measurement locations and the circled dots indicate capacitor locations. The 18 capacitors were installed as described in the previous section over a distance of 3740 feet with an average spacing of 208 feet, compared to the target spacing of 200 feet. The actual distribution of intercapacitor spacings in feet is listed in Table VIII for convenient reference. The installation was again completed in 2-1/2 hours.

When the installation was completed, we travelled the test stretch of haulageway with a jeep and measured the signal level at the transmitter, at each capacitor, and at both sides of each rectifier. We initially used the Rycom tuned voltmeter for these measurements connected to the jeep carrier phone as stated in the previous section. Unfortunately, this instrument was damaged again by a high energy voltage transient generated near a rectifier. Therefore, the measurements were repeated using a Sierra tuned voltmeter that we brought along as

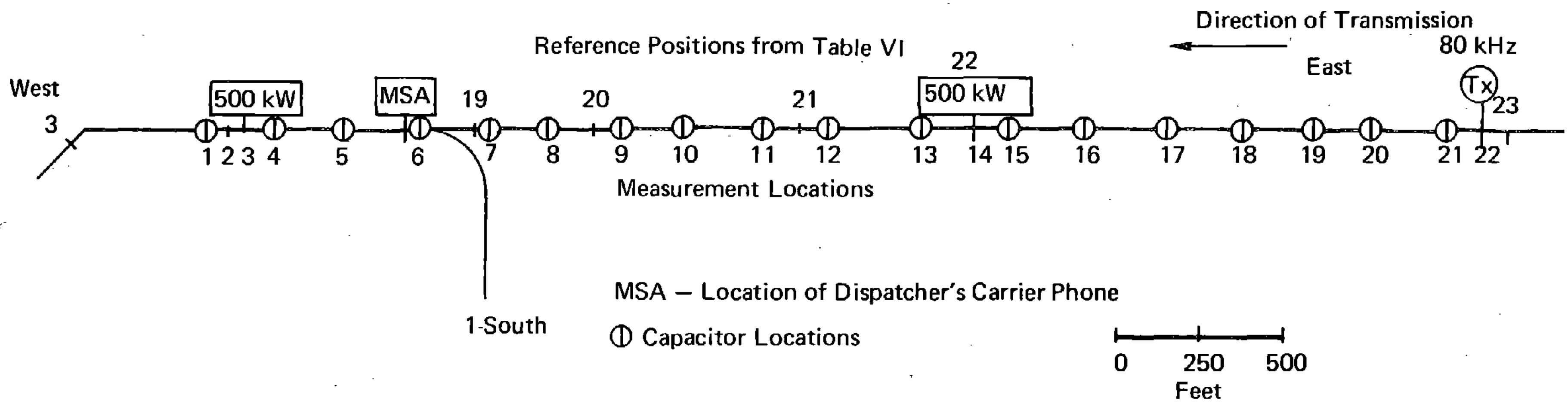


FIGURE 35 MEASUREMENT AND CAPACITOR LOCATIONS ALONG OPERATIONAL SECTION OF EAST-WEST MAIN HAULAGEWAY FOR *FINAL* TESTS IN *AUGUST* – McELROY MINE

TABLE VIII

APPROXIMATE INTERCAPACITOR SPACING IN FEET ALONG MAIN HAULAGEWAY

Capacitor ID	Spacing
1 - 2	200
2 - 3	200
3 - 4	240
4 - 5	220
5 - 6	180
6 - 7	220
7 - 8	190
8 - 9	250
9 - 10	200
10 - 11	270
11 - 12	260
12 - 13	230
13 - 14	250
14 - 15	210
15 - 16	200
16 - 17	180
17 - 18	240

Average capacitor spacing = 208 feet.

Note: The capacitor identification numbers refer to the numerical order in which the capacitors are installed running from West to East in Figure 35. They do not refer to the measurement location numbers.

a spare. We used extra care to prevent further damage by transients during these and subsequent measurements by disconnecting the voltmeter from the system except when the jeep was stationary and we were ready to take a measurement. (This operation prevented damage by transients generated by the jeep.) Upon completion of the low-Z line signal level measurements, all capacitors were cut free, and the signal levels were remeasured in the same manner for the normal line condition, thereby completing the A-B signal level tests on the operational main haulageway line approximately one hour before the end of the shift. The results of these tests are presented in Section D.

D. FINDINGS--DE-ENERGIZED SECTION

This part presents the results of the measurements of transmission line parameters and signal strength behavior under normal line and low-Z line conditions. These measurements were taken with portable equipment, as described in Section C.8.a and Appendix A along a 1210 foot section of trolley wire/rail haulageway in the 062 panel of the mine shown in Figures 28 and 33. A typical cross section of this haulageway is shown in Figure 29.

1. Line Inductance, Capacitance, and Characteristic Impedance (A-C Bridge Method)

Using the 1000 Hz A-C bridge method described in Sections II 1, 2, and 7 of Appendix A, the total inductance L_T and capacitance C_T of the 1210 foot length of trolley wire/rail line were measured under normal and low-Z line conditions.

a. Normal Line

For the normal line conditions, we obtained

C_T = 7600 pF (for end of line open circuited)
L_T = 450 μH (for end of line short circuited)

These reduce to the unit length values of

C = 630 pF/100 ft.
L = 37 μH/100 ft.,

from which the characteristic impedance can be calculated, namely,

$$Z_o = \sqrt{\frac{L}{C}} = 243 \text{ ohms.}$$

b. Low-Z Line

For the low-Z line condition, created by the addition of discrete .04 μF capacitors, only the total capacitance was remeasured. The inductance was not altered. We obtained

C_T = 0.315 μF (for end of line open circuited),

giving the unit length values of

C = 0.026 μF/100 ft.

L = 37 μH/100 ft.

This value of C results in the new calculated value of characteristic impedance

$$Z_o = \sqrt{\frac{L}{C}} = 37.8 \text{ ohms,}$$

producing a 6.4 to 1 reduction in Z_o.

2. Line Characteristic Impedance (Termination Matching Method)

Using the method described in Sections II 3 and 8 of Appendix A, and in Figure 36, the characteristic impedance was measured directly by finding the value of resistance termination that created a matched line condition. This condition was determined by plotting at two frequencies the input voltage as a function of termination resistance over a range in the vicinity of the expected value of characteristic impedance. For the expected values of less than about 300 ohms, the setup of Figure 36 provides the desired high impedance drive. Since the input voltage is frequency independent under matched conditions, the intersection point of the two plotted curves defines the value of the line characteristic impedance.

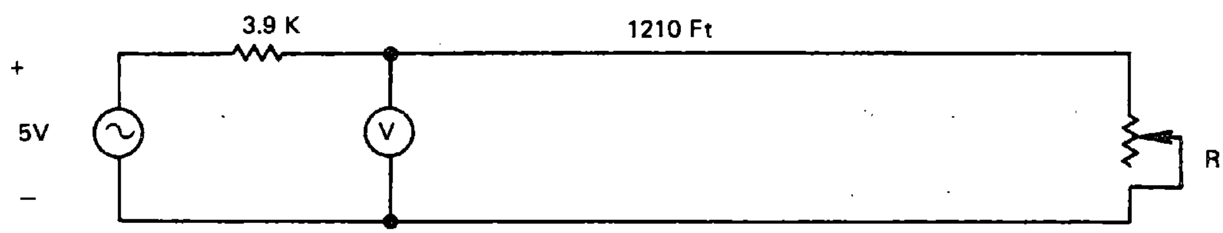


FIGURE 36 TEST SETUP FOR DETERMINING MATCHING RESISTANCE

a. Normal Line

Figure 37 is a plot of the data taken at 10 and 100 kHz for the normal line configuration. The intersection of the two curves defines a matching resistance of

Z_o = 268 ohms.

b. Low-Z Line

Figure 38 is a plot of the corresponding data taken at the scaled down frequencies of 2 and 12 kHz for the low-Z line configuration. The intersection of the two curves defines a matching resistance of

Z_o = 39.5 ohms,

resulting in a 6.8 to 1 reduction in Z_o.

3. Line Phase Velocity of Propagation (1/8 Wavelength Method)

The λ/8 method for measuring line velocity of propagation is described in Sections II 4 and 9 of Appendix A, Appendix B, and Figure 39. The setup in Figure 39 behaves as a current source driving the line for the values of the line impedance expected. The λ/8 condition is defined as the lowest frequency for which the line input impedances (and input voltage in Figure 39) for both open circuit and short circuit terminations are equal. Therefore, the λ/8 frequency is determined by the intersection of the open and short circuit input voltage versus frequency curves.

a. Normal Line

The λ/8 intersection of the two curves plotted in Figure 40 occurs at a frequency of 80 kHz. Comparing the line wavelength of 9680 feet (8 x 1210 feet) with the corresponding free space wavelength of 12,276 feet at 80 kHz, we get a line velocity equal to 78.9% of the free space velocity.

b. Low-Z Line

The λ/8 intersection of the two curves plotted in Figure 41 occurs at a frequency of 9.7 kHz for the low-Z line. Comparing the line wavelength of 9680 feet (8 x 1210 feet) with the corresponding free space

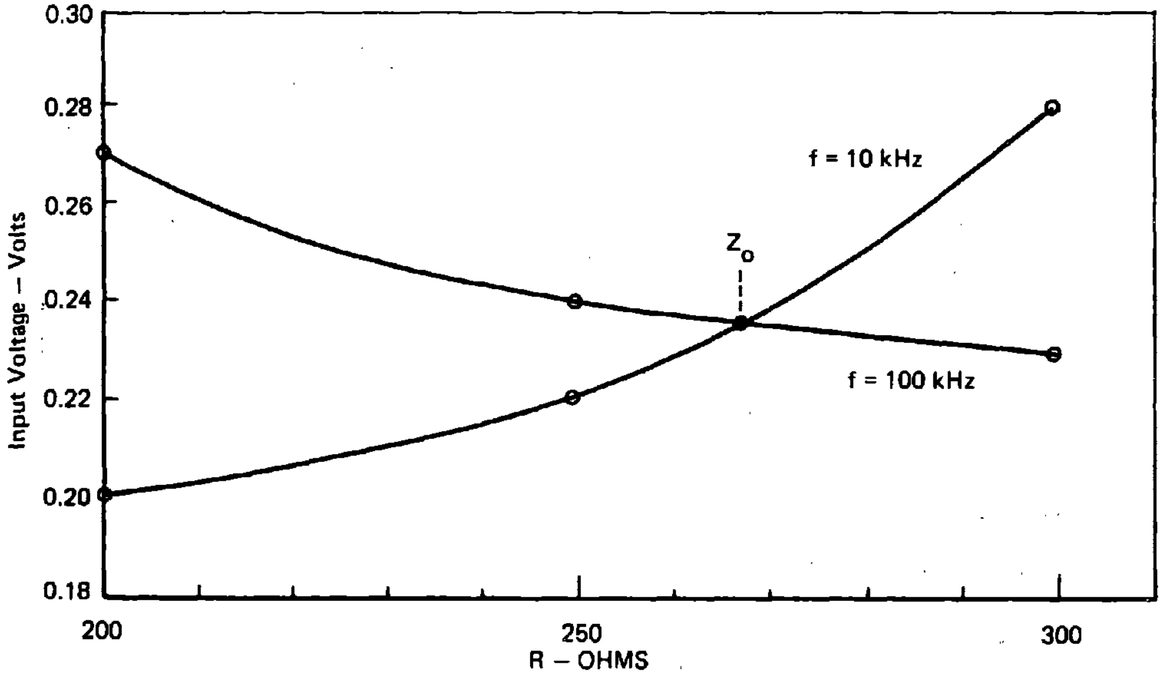


FIGURE 37 PLOT FOR DETERMINATION OF MATCHING RESISTANCE (NORMAL LINE)

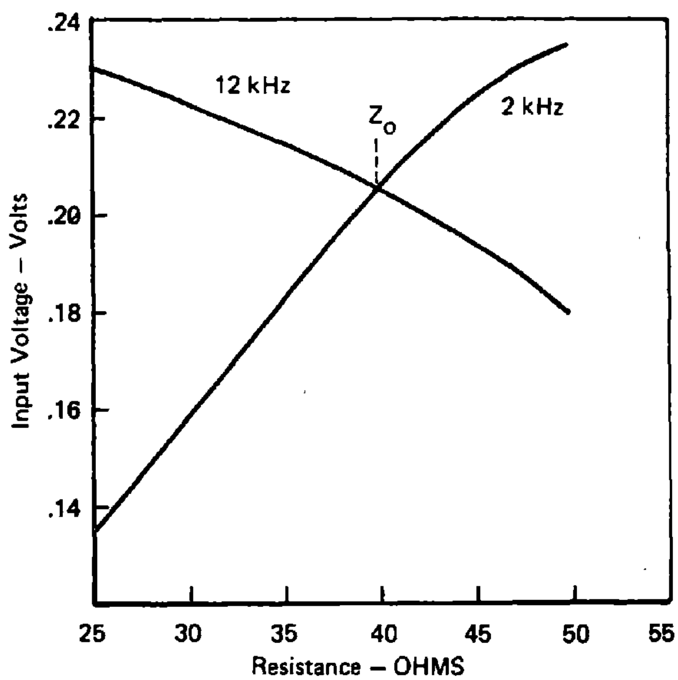


FIGURE 38 PLOT FOR DETERMINATION OF MATCHING RESISTANCE (LOW-Z LINE)

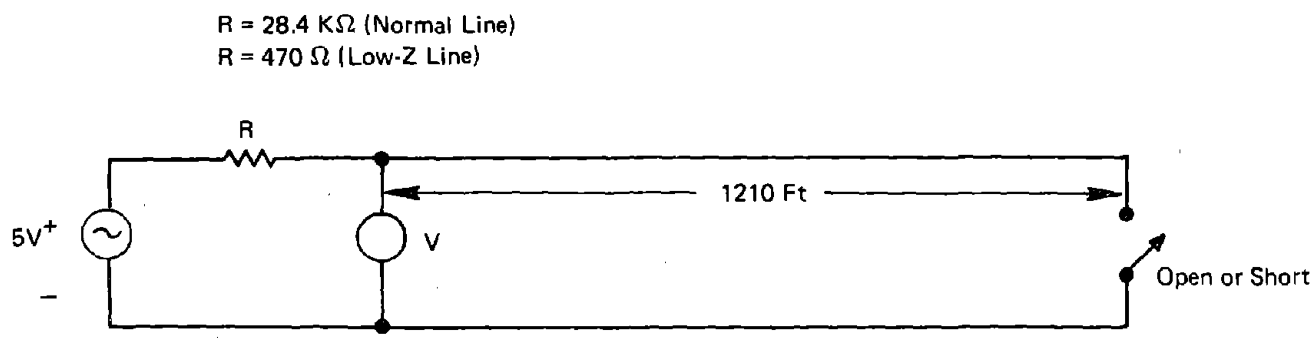


FIGURE 39 TEST SETUP FOR DETERMINING VELOCITY OF PROPAGATION BY 1/8 WAVELENGTH METHOD

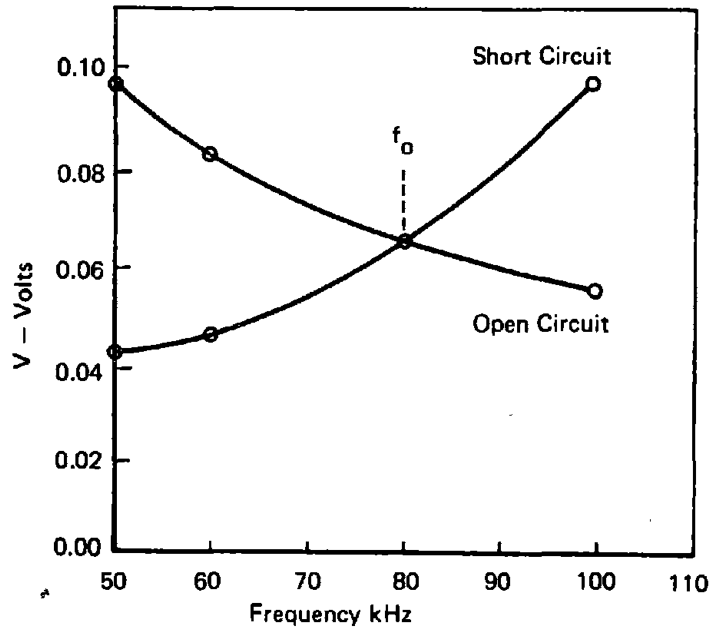


FIGURE 40 RESULTS OF 1/8 WAVELENGTH TEST (NORMAL LINE)

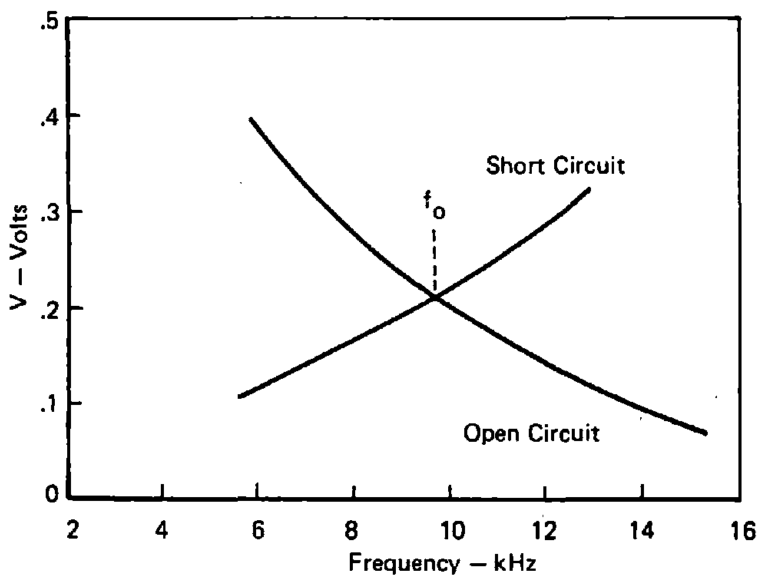


FIGURE 41 RESULTS OF 1/8 WAVELENGTH TEST (LOW-Z LINE)

wavelength of 101,200 feet at 9.7 kHz, we get a low-Z line velocity equal to 9.6% of the free space velocity. This represents an 8.2 to 1 reduction in the normal line velocity of propagation.

4. Line Phase Velocity of Propagation (Resonance Method)

The resonance method for measuring line velocity of propagation is described in Sections II 5 and 10 of Appendix A. The test setup of Figure 39 was applied. For the normal line configuration the $\lambda/2$ resonance condition for an open circuit termination was created, whereas for the low-Z line, the $\lambda/4$ resonance condition for a short circuit was produced. As the frequency is increased, the line input impedance will pass through a maximum when the above $\lambda/2$ and $\lambda/4$ conditions occur. The short circuit setup gives a less ambiguous result for the low-Z line configuration.

a. Normal Line

For the normal line configuration, the $\lambda/2$ impedance maximum occurred at 310 kHz, giving a line wavelength of 2420 feet (2 x 1210 feet). Comparing this wavelength to the free space wavelength of 3168 feet at 310 kHz, we get a line velocity equal to 76.4% of the free space velocity.

b. Low-Z Line

For the low-Z line configuration, the $\lambda/4$ impedance maximum occurred at 20.8 kHz, giving a line wavelength of 4840 feet (4 x 1210 feet). Comparing this to the free space wavelength of 47,200 feet at 20.8 kHz, we get a line velocity equal to 10.3% of the free space velocity. This represents a 7.4 to 1 reduction in the normal line velocity of propagation.

5. Line Phase Velocity of Propagation (A-C Bridge Results)

The line velocity can also be computed by substituting the unit length values of L and C into the expression $v_p = 1/\sqrt{LC}$.

a. Normal Line

Using the measured values of L and C from the A-C bridge measurements, we find the computed value of v_p to be 66.6% of the free space velocity c.

b. Low-Z Line

Using the corresponding values for the low-Z line configuration, we find v_p to be 10.4% of c. We do not yet understand why this method produces a v_p/c estimate consistent with those of the other methods for the low-Z line configuration, but not for the normal line configuration.

6. Summary of Line Parameters

Table IX presents a summary of the line parameter values determined by the different methods along a 1210 foot stretch of trolley wire/rail having no feeder cable attached to the trolley wire. Note that increasing the line capacitance by a factor of 41 decreases Z_o by an average factor of 6.6 (in agreement with the expected value of $\sqrt{41}$ = 6.4), but decreases v_p/c by an unexpectedly higher average factor of 7.8. The reason for this v_p/c behavior is not apparent.

TABLE IX

SUMMARY OF MEASURED LINE PARAMETERS

Normal Line

L(μH/100 ft.)	C(pF/100 ft.)	Z_o(ohms)	v_p/c(%)
37	630	243	66.6
		268	78.9
			76.4

Low-Z Line

L(μH/100 ft.)	C(μF/100 ft.)*	Z_o(ohms)	v_p/c(%)
37	.026	37.8	10.4
		39.5	9.6
			10.3

*Using 0.04 μF capacitors and an average separation of 185 feet.

For convenient reference we have included below the corresponding values measured in another mine[1] along a stretch of main haulageway having a feeder cable.

Normal Line (with feeder, Renton mine)

L(μH/100 ft.)	C(pF/100 ft.)	Z_o(ohms)	v_p/c(%)
35 ±10%	900 ±20	200 ±30	64

7. Signal Strength Versus Distance Comparisons for Normal and Low-Z Lines

The signal level versus distance A-B measurements were performed along the de-energized section as described in Section C.8.a above and in Sections II 6 and 11 of Appendix A. These measurements demonstrate the improvements obtainable with the low-Z line technique in an actual mine environment under known and controllable shunt load conditions. The results of these tests are tabulated in Table X. They are also plotted in Figure 42 together with calculated theoretical values, all normalized with respect to the line input voltage. The theoretical signal strength values were derived using the experimentally determined representative values of $Z_o = 250\ \Omega$ and $v_p = .76c$ for the normal line, and $Z_o = 40\ \Omega$ and $v_p = .097c$ for the low-Z line. The plots indicate the substantial decrease in signal attenuation rate achieved with the low-Z line, and the close agreement between measured and theoretical results. These in-mine results also support earlier laboratory and theoretical findings presented in Figure 27.

The above comparison has been made on the basis of equal input voltages. A comparison based on equal input powers would have to provide a correction factor that takes into account the real part of the line input impedances at the transmitter location for the two line conditions.

TABLE X

SIGNAL STRENGTH COMPARISON MEASUREMENTS ALONG DE-ENERGIZED SECTION UNDER NORMAL AND LOW-Z CONDITIONS

Station No.	Item	Distance from Source	Normal Line Voltage without .040 μF Capacitors	Low-Z Line Voltage with .040 μF Capacitors
0	Voltage Source	0 ft.	1.35 volts	0.285 volts
1	Capacitor	100	1.30	0.225
2	Capacitor	300	0.83	0.340
3	Capacitor	497	0.55	0.440
4	Capacitor	700	0.17	0.160
4'	10Ω Resistor	765	0.092	0.086
5	Capacitor	900	0.075	0.145
6	Capacitor	1080	0.041	0.120
7	Capacitor and 10Ω Resistor	1210	0.012	0.035

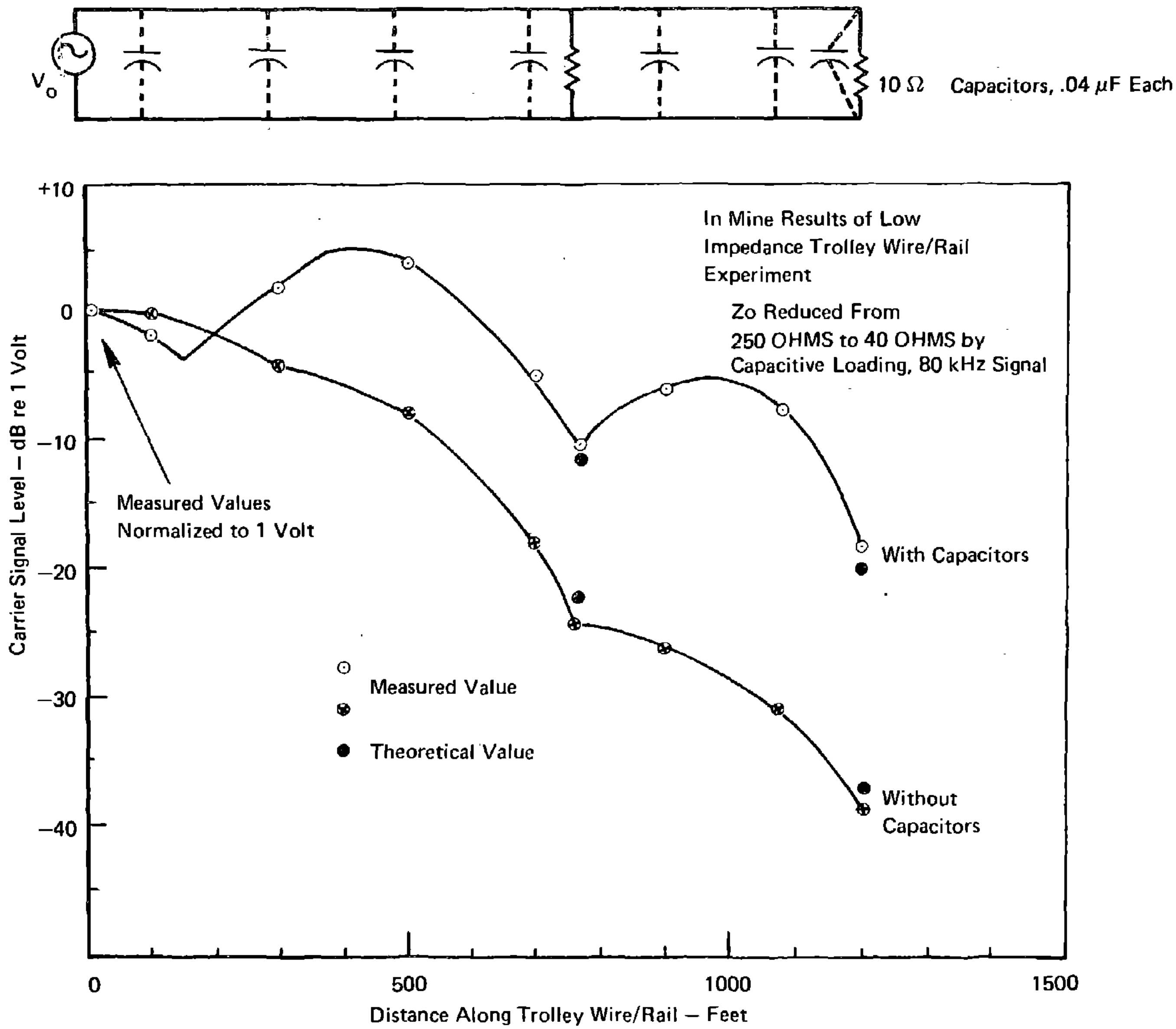


FIGURE 42 VOLTAGE VERSUS DISTANCE – DE-ENERGIZED SECTION

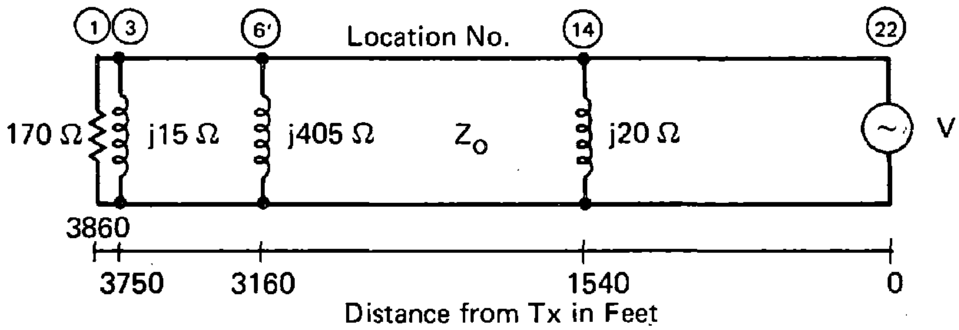
E. FINDINGS--OPERATIONAL SECTION

This part presents the results of the A-B signal strength measurements taken under normal line and low-Z line conditions along a 3900 foot stretch of operational East-West main haulageway containing two major shunt loads, namely two 500 kW DC power rectifiers. The measurements were taken with jeep mounted portable equipment as described in Section C.9 of Appendix A. The stretch of main haulageway is shown in Figures 28, 34, and 35, while Figure 30 depicts a typical cross section view of the haulageway. Figure 35, in particular, depicts all the capacitor locations and measurement stations for the final test configuration along the operational section of haulageway. Note that the signal generator has been placed at the eastern end of the chosen section of the trolley wire/rail line. This facilitated the measurements and provided a more predictable and representative set of test conditions than was the case during the abortive initial set of measurements performed with the signal generator placed at the western end of the test run.

1. Electrical Characterization of Test Section

The test section of haulageway was characterized electrically twice, first based on preliminary information and engineering assumptions and judgments prior to the first set of measurements, and second based on the incomplete results of the first measurements, together with the results of the second set of measurements and refined engineering judgments.

The simplified electrical model for the section of main haulageway used for the second and complete set of signal strength measurements is shown in Figure 43. The diagram is drawn with the signal generator on the right to allow ready identification with the mine map and experiment geometry. Table XI presents corresponding tabulations of the estimated impedances of the major electrical loads across the trolley wire/rail line together with the line parameters for this section of haulageway.



Note: Use in Conjunction with Table XI.

FIGURE 43 SIMPLIFIED ELECTRICAL MODEL FOR TEST SECTION OF OPERATIONAL HAULAGEWAY AT 80 kHz

TABLE XI

MAJOR ELECTRICAL SHUNT LOADS AND LINE PARAMETERS ALONG TEST SECTION OF OPERATIONAL HAULAGEWAY FOR AN 80 kHz OPERATING FREQUENCY

A. ESTIMATED LOAD IMPEDANCES

Electrical Load	Distance from Transmitter at Location 22	Location Number	Impedance Estimate at 80 kHz
1-No. 500 kW power rectifier w/65 ft. setback	1540 ft.	14	$j20\Omega$ (1)
Transformed impedance of 1-So. 500 kW power rectifier w/50 ft. setback	3160 ft.	6'	$j405\Omega$ (2)
Portal 500 kW power rectifier w/50 ft. setback	3750 ft.	3	$j15\Omega$ (1)

B. ESTIMATED LINE PARAMETERS (3)

	Z_o	v_p/c	λ_{line}
Normal line	170	50%	6200 ft.
Low-Z line	48	14%	1750 ft.

Notes: (1) Including inductive reactance introduced by the setback distance of the rectifier from the trolley wire/rail line. A rectifier intrinsic impedance of 0 ohms was assumed, connected to a two-wire transmission line consisting of 1,000,000 CM feeder cables separated by 6 ft. running the length of the setback distance, and having an inductance per unit length of 0.61 μH/ft.

(2) The transformed impedance of the 1-South 500 kW rectifier as viewed at the intersection of the 1-South mains with the East-West mains.

(3) Normal line Z_o based on theoretical calculations, rest of parameters based on analysis of signal strength data taken during tests. In particular, analysis of wavelength differences shows a λ and Z_o reduction ratio of 3.5 to 1.

2. Signal Strength Versus Distance Comparisons for Normal and Low-Z Lines

a. Experimental Results

The results of the A-B signal strength measurements taken along the operational section of haulageway are shown in Figure 44. As in Figure 42, the values are all normalized with respect to the input voltage at the transmitter. Examination of Figure 44 reveals the expected low-Z line signal behavior relative to that of the normal line, together with some surprises. As expected, the signal displays the standing wave behavior at a significantly reduced effective wavelength and a lower rate of overall signal attenuation over most of the run. The surprises include: a lower than expected phase velocity (50% of c) for the normal line condition; jump discontinuities in the line voltage at each of the two rectifier loads; significant changes in the sizes of these jumps at the two rectifiers, an equal overall decrease in voltage at the end of the run for both normal and low-Z lines; and a more "linear" than expected decrease in voltage between locations 10 and 3 from 2420 to 3750 feet from the transmitter.

The normal line phase velocity, determined by estimating the quarter wavelength distance from the voltage behavior between the transmitter and the first rectifier, was found to be approximately .50c instead of the value of .76c found along the short de-energized section in the 062 panel. In the absence of additional data, we hypothesize that this reduction in phase velocity may be caused by higher than anticipated insulator rf capacitance to the roof.

Comparison of the normal and low-Z line wavelength estimated from the corresponding curves of Figure 44 reveals a 3.5 to 1 reduction in phase velocity. We made no characteristic impedance measurements along this section. So we have assumed the same 3.5 to 1 reduction in the characteristic impedance, Z_0, together with a normal line Z_0 of 170 ohms, the same value we assumed to calculate the theoretical signal strength behavior along a similar main haulageway in the Montour No. 4 mine.

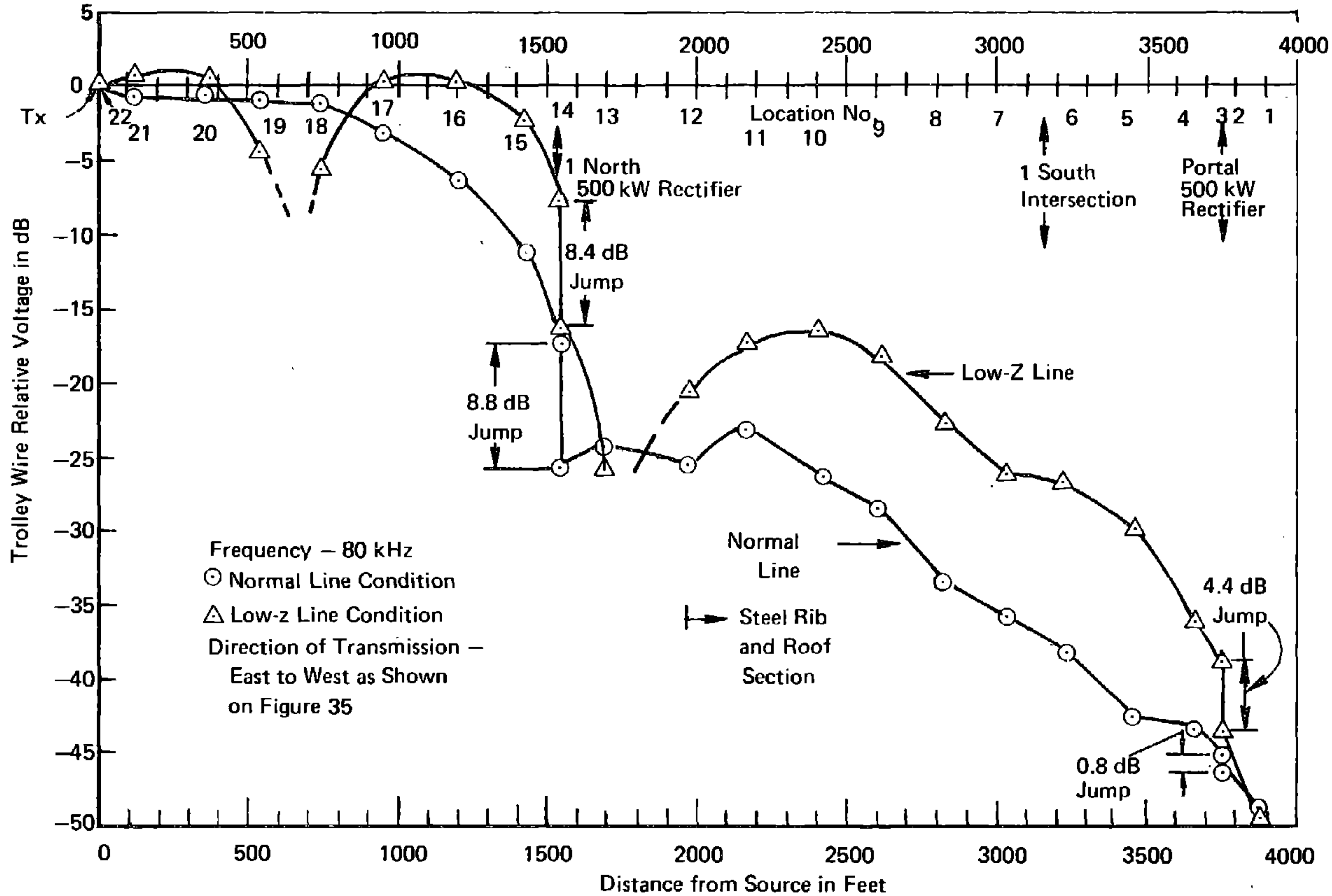


FIGURE 44 **EXPERIMENTAL SIGNAL STRENGTH VERSUS DISTANCE BEHAVIOR ALONG AN OPERATIONAL MAIN HAULAGEWAY TROLLEY LINE UNDER NORMAL AND LOW-Z LINE CONDITIONS**

After reviewing the experimental conditions at the rectifiers, we generated the hypothesis that the unexpected voltage jumps occurred because rf bridging capacitors were not connected across the deadblock breaks in the trolley wire between the two points where the feeder cables from the rectifier are connected to the trolley wire and its feeder. Approximate theoretical calculations, which are detailed in Appendix C, show that the inductive mutual coupling between the three-wire configuration of the rectifier setback feeder and ground cables can indeed result in a jump drop in voltage of about the 8 dB experienced at the 1 North rectifier at location 14.

Without the opportunity to revisit the mine, we do not have a satisfactory explanation for the smaller voltage drops suffered at the portal rectifier at location 3. However, the reason may be related to the fact that beyond approximately location 12 to the end of the run, the ribs and roof of the haulageway are reinforced with continuous steel sections. This steel roofing and siding tends to increase the line capacitance and decrease the characteristic impedance of the line, and may also act as an "effective rf short circuit impedance" across the two setback feeders to the rectifier. The change in the nature of the trolley wire/rail transmission line environment introduced by the steelwork may also be the cause of the more linear than expected signal behavior in this region, and for the equalization of the overall voltage drop for both normal and low-Z lines. It may also be related to some unaccounted for load condition on the 1-South haulageway that connects to the East-West haulageway between locations 6 and 7 along this same stretch of track. These issues remain unresolved.

b. Theoretical Estimates

For comparison with the experimental results of Figure 44, theoretical calculations of signal strength behavior were performed for normal and low-Z line conditions and plotted in Figure 45. These plots were derived by Smith chart analysis of the simplified electrical model having the circuit and transmission line parameters of Figure 43 and Table XI, and have been plotted with all values normalized with respect to the input voltage at the transmitter as in Figure 44. The

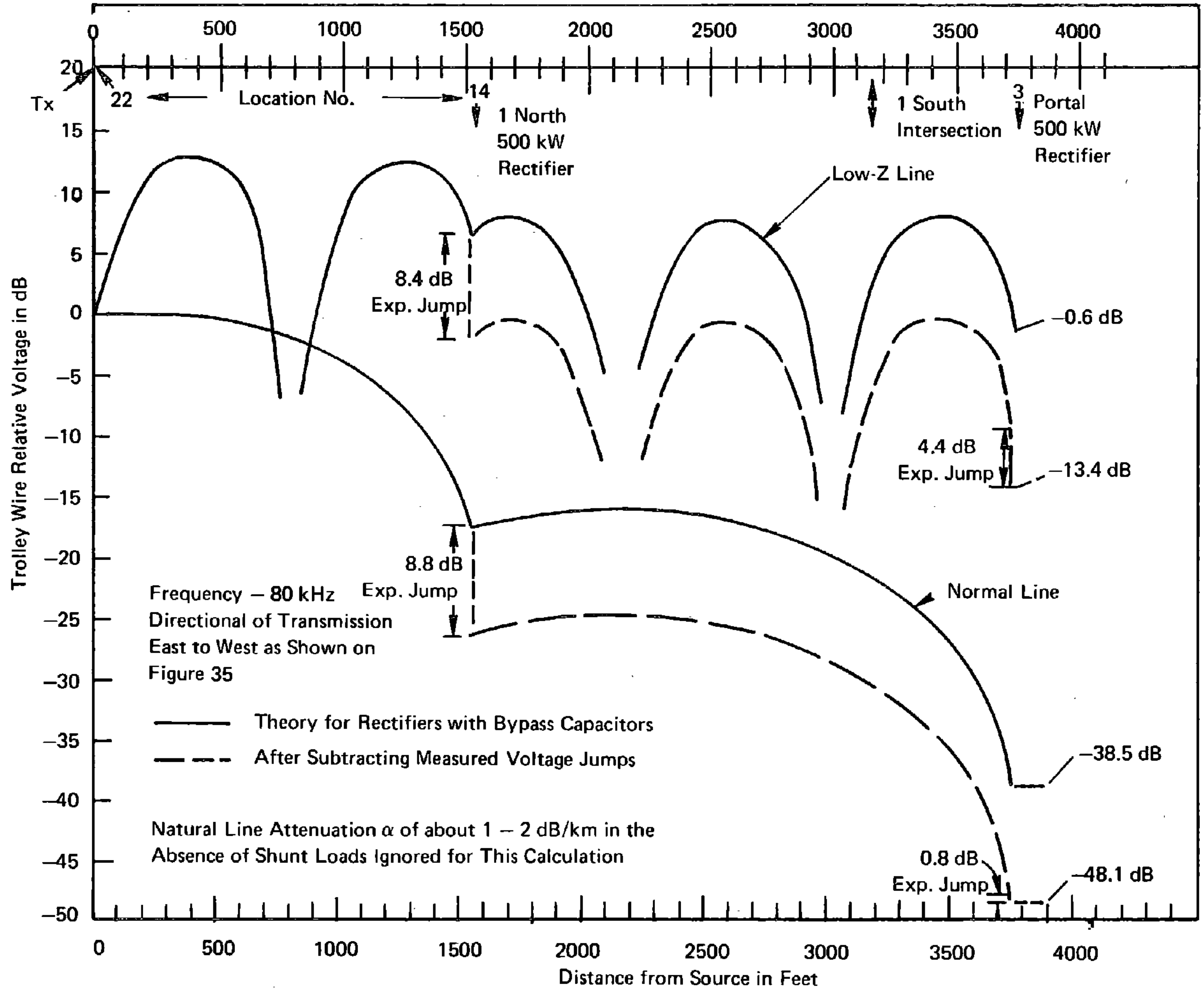


FIGURE 45 THEORETICAL SIGNAL STRENGTH VERSUS DISTANCE BEHAVIOR ALONG AN OPERATIONAL MAIN HAULAGEWAY TROLLEY LINE UNDER NORMAL LOW-Z LINE CONDITIONS

theoretical curves have also been plotted in modified form, indicated by dashed portions, to illustrate the effects of the experimental values of the voltage jumps at each of the rectifiers unequipped with dead-block bridging capacitors. The plots represent the ideal open circuit voltage seen across the line. In practice, the voltage seen by the vehicle will be less, due to the loading effects of the carrier phone and the vehicle electrical system.

Examination of the curves of Figure 45, and comparison with the experimental ones of Figure 44, reveals the following:

- Unaided signal transmission along normal trolley wire/rail lines suffers prohibitively high attenuation in the presence of typical rectifier shunt loads. Furthermore, the general overall shapes and total line losses for both experimental and theoretical results are in reasonable agreement, with the exception of the more linear than expected signal decrease in the steelwork section beyond about 2000 feet that includes the intersection with the 1-South haulageway, as previously mentioned.
- The experimental results over much of the run confirmed the predicted significant reductions in signal loss and changes in the shape of the signal versus distance behavior for the low-Z line configuration. The lower than predicted signal level improvement over the first 2000 feet of the test run is due mainly to a slight underestimate of the wavelength on the low-Z line from the data. Such an underestimate places the location of the transmitter, and thus the voltage reference, closer to a minimum in the voltage standing wave pattern (low impedance point) calculated from theory than to a maximum (high impedance point) indicated by the data. Beyond 2000 feet, the unexpected linear decrease in measured signal level and the sharp drop in level experienced at the end of the run is still unexplained, as stated above.
- Additional measurements will be required to clear up the unexpected behavior beyond 2000 feet, but as a practical

matter such measurements may not be warranted at this time. Such measurements, if performed, should include the direct measurement of characteristic impedance and phase velocity.

F. CONCLUSIONS

The experiments conducted in the McElroy coal mine to demonstrate the low-Z line technique confirm that normal trolley/wire rail lines have a characteristic impedance of approximately 200 ohms. The value is close to 250 ohms in the absence of a feeder cable, but closer to 170 ohms when a feeder cable is present. The experiments also show that the effective characteristic impedance and propagation phase velocity of a trolley wire/rail line at mine carrier phone operating frequencies can be lowered by shunt capacitive loading. Capacitive loading with 0.04 μF ceramic 1000 volt capacitors spaced an average 200 feet apart was judged the most favorable for the test environment. Lowering of the characteristic impedance was shown to reduce the mismatch presented by shunt loads normally found in mines, and therefore the signal losses caused by such loads. These results are based primarily on measurements made on a 1210 foot long unenergized section of trolley wire/rail, namely, one disconnected from its DC power source.

The experiments on an unenergized section of trolley wire/rail were supplemented by a set of signal strength versus distance measurements on an operational section of trolley wire/rail along a main haulageway in active service, for both normal and low-Z line configurations. The conditions of these measurements were less controlled than those on the unenergized section, and the results were not as conclusive as those on the de-energized section. Unexpected behavior was introduced by the absence of bridging capacitors across the trolley wire deadblocks at each rectifier location, and by about a 2000 foot stretch of steel encased haulageway that also intersected with a second main haulageway not under the control of the experiment team. The absence of bridging capacitors causes step drops in voltage that appear to be relatively unaffected by reductions in line impedance, while the steel encased sections appear to alter the propagation characteristics of the line somewhat. In spite of these factors, measured signal levels along most of the line in its low-Z configuration were indeed appreciably higher than those along the line in its normal configuration. The lack of experiment control over the section of operational trolley wire/rail beyond the test section and down the intersecting haulageway may also have contributed to some of the unanticipated abnormal signal behavior.

G. RECOMMENDATIONS

Whereas the unenergized section of trolley wire/rail line showed results that correspond very well with theoretical predictions for the low-Z line, the results on the energized operational section were not as favorable. We do not believe that the effort required to determine the precise causes of this unexpected behavior on the operational section is warranted. Rather, we believe that emphasis should be placed on the alternative method for improving signal transmission examined during Phase II, namely, the "dedicated wire," which has other inherent advantages not realizable by the low-Z method. Two major advantages are: the "dedicated wire" allows exact control of signal splitting where it is desired (not possible with the low-Z technique), and the "dedicated wire" can be installed and maintained more easily than the many capacitors required for the low-Z line. These considerations and the performance experience to date for both methods override an important potential advantage of the low-Z line method; namely, that failure of individual capacitors should produce only incremental deterioration in performance as opposed to the major deterioration caused by a break in the dedicated wire.

Therefore, we recommend that the dedicated wire method be favored as the most effective and practical way to upgrade trolley carrier phone signal performance and range in U. S. coal mines. Secondly, we recommend that the low-Z line technique be considered a less practical, and possibly less effective, signal improvement method that may be better suited to solving some particular localized mismatch problems. For example, the reduced characteristic impedance and phase velocity may make it quite useful as an impedance transformer over short troublesome sections of track. In such cases, we also recommend that more permanent, practical and safe capacitor installations than those used during these reported experiments be devised. A method that incorporates the capacitors into the trolley wire hanger insulator appears to have particular merit.

H. REFERENCES

1. Spencer, R.H., Emslie, A.G., Lagace, R.L., et al, "Improvements for Mine Carrier Phone Systems," Arthur D. Little, Inc., Final Report, Task I, Task Order No. 2, Bureau of Mines Contract H0346045, April 1977, NTIS No. PB273292AS.

APPENDIX A

TEST PLAN - LOW IMPEDANCE TROLLEY WIRE DEMONSTRATION EXPERIMENTS

I. INTRODUCTION

Theory and laboratory experiments have confirmed the expectation that periodic loading of the trolley wire/rail with capacitors reduces the characteristic impedance and the mismatch of bridging loads, and therefore reduces the signal loss for trolley carrier phone signals. The tests outlined in this plan are directed toward demonstrating the capabilities of this low-impedance technique in an actual coal mine.

Two levels of in-mine test are planned: first, those related to determining fundamental characteristics of the transmission line formed by the trolley wire/rail, and second those that demonstrate the signal transmission behavior of the low impedance line along both controlled and uncontrolled sections of haulageway.

II. TESTS ALONG DE-ENERGIZED TROLLEY WIRE/RAIL IN 062 PANEL SECTION

The first tests will be done on a de-energized section of trolley wire/rail with all normal bridging loads removed. These tests are as follows:

1. Measure line capacitance using configuration in Figure A1 with end of line open circuited.

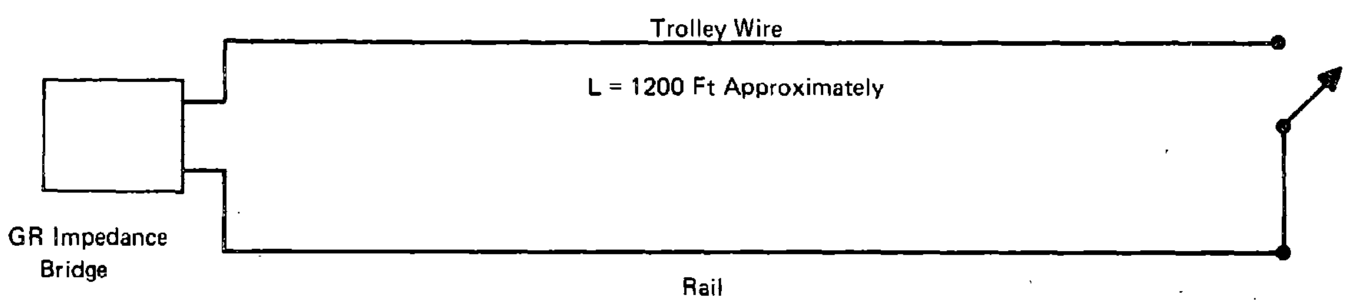


FIGURE A1 CONFIGURATION FOR MEASUREMENT OF LINE CAPACITANCE AND INDUCTANCE

2. Measure line inductance using configuration in Figure A1 with end of line short circuited.

3. Measure line characteristic impedance by determining the value of terminating resistance that matches the line as shown in Figure A2.

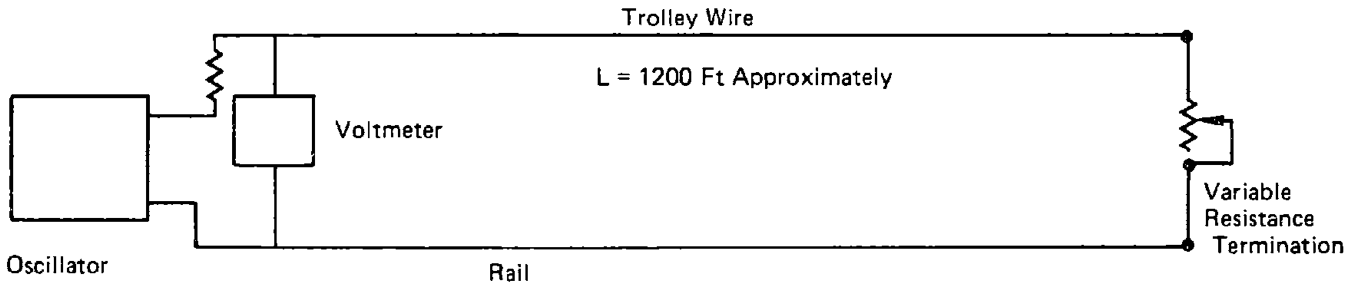


FIGURE A2 **CONFIGURATION FOR MEASUREMENT OF LINE CHARACTERISTIC IMPEDANCE**

4. Measure phase velocity of signal propagation along line by determining the frequency for which the line is 1/8 wavelength long from open and short circuit measurements as indicated in Figure A3 and in Appendix B.

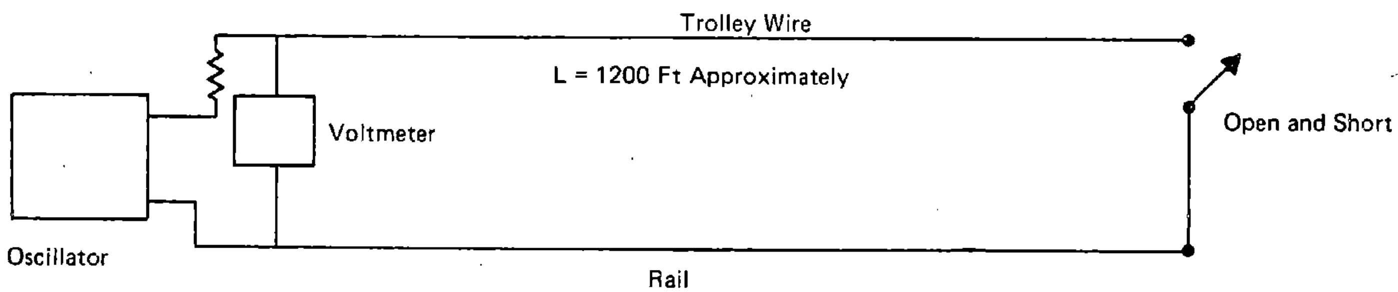


FIGURE A3 **CONFIGURATION FOR MEASUREMENT OF LINE PHASE VELOCITY**

5. Measure phase velocity of signal propagation along line by determining 1/2 wavelength resonant frequency (at impedance maximum) of line for configuration in Figure A3 with end of line open circuited.

6. Measure signal voltage levels along line with artificial resistive loads placed across the line. Measure at least the 3 voltages indicated in Figure A4.

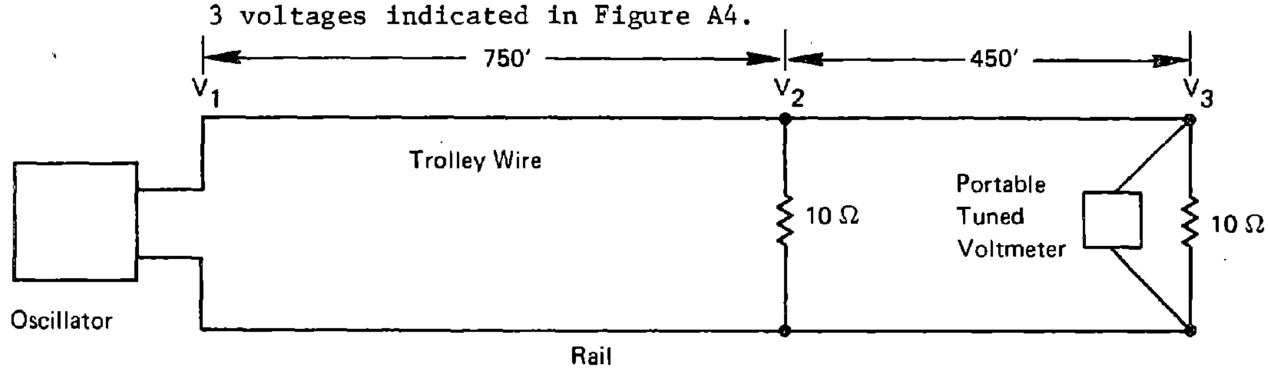


FIGURE A4 CONFIGURATION FOR SIGNAL LOSS MEASUREMENT FOR NORMAL LINE

7. Measure total line capacitance of low-Z line configuration after adding capacitors at 200 foot intervals as shown in Figure A5.

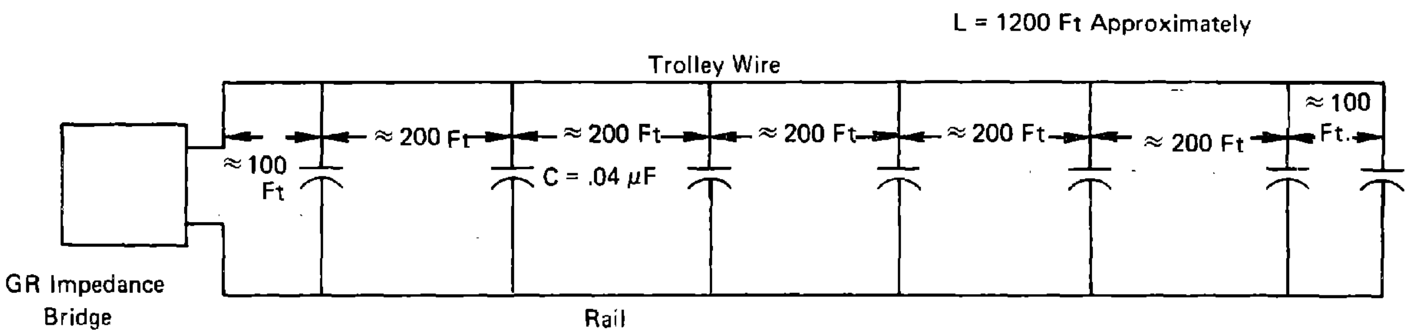


FIGURE A5 LOW-Z LINE CONFIGURATION FOR MEASUREMENT OF LINE CAPACITANCE

8. Measure low-Z line characteristic impedance by determining the value of terminating resistance that matches the line as shown in Figure A6.

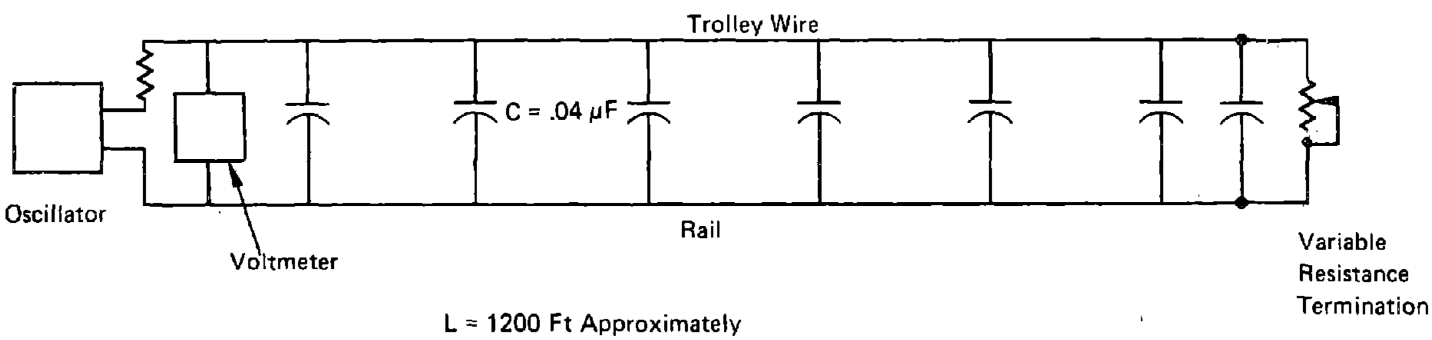


FIGURE A6 LOW-Z CONFIGURATION FOR MEASUREMENT OF LINE CHARACTERISTIC IMPEDANCE

9. Measure phase velocity of signal propagation along line by 1/8 wavelength open and short circuit measurements as indicated in Figure A7 and in Appendix B.

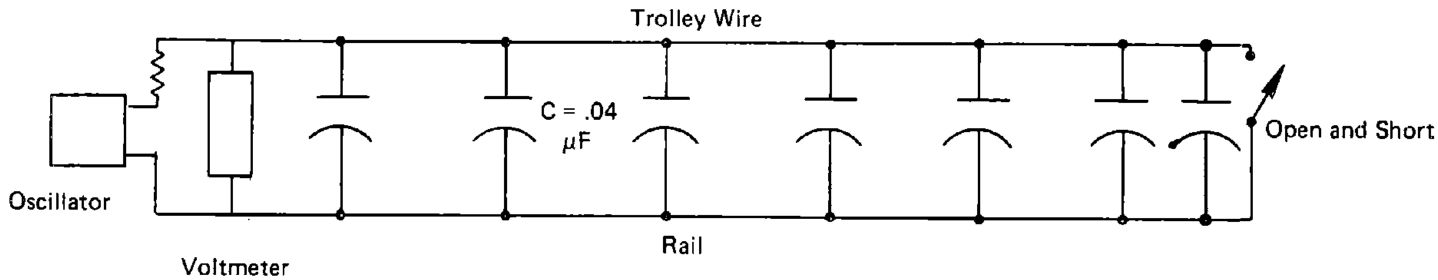


FIGURE A7 LOW-Z CONFIGURATION FOR MEASUREMENT OF LINE PHASE VELOCITY

10. Measure phase velocity of signal propagation along line by 1/2 wavelength resonance method for low-Z line configuration in Figure A7 with end of the line open circuited.

11. Measure signal voltage level along low-Z line with artificial resistive loads re-installed across the line as in Figure A4. Measure at least the 3 voltages indicated in Figure A8.

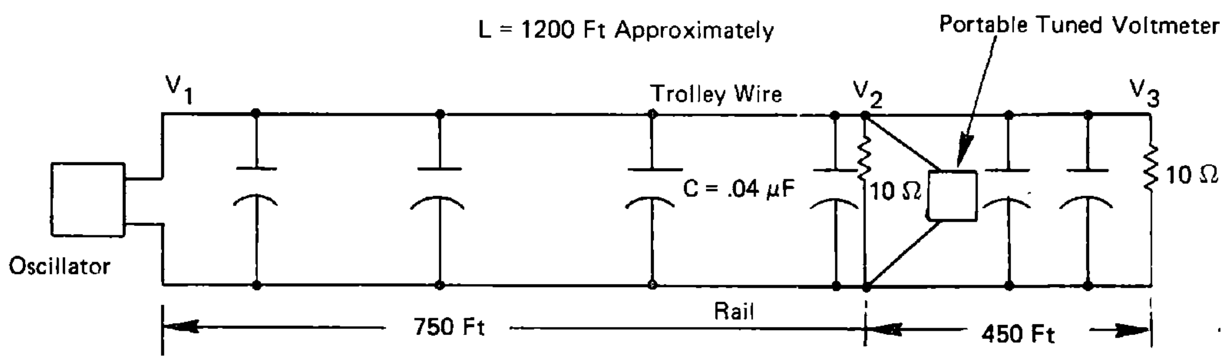


FIGURE A8 CONFIGURATION FOR SIGNAL LOSS MEASUREMENT FOR LOW-Z LINE

III. TESTS ALONG OPERATIONAL TROLLEY WIRE/RAIL IN EAST/WEST MAIN HAULAGEWAY

The second set of tests will be done along a stretch of an energized, active section of trolley wire/rail having a normal complement of bridging loads, and in particular two 500 kW power rectifiers.

1. Measure signal voltage level versus distance along a run of about 7500 feet of the selected section of East/West mains haulageway as indicated in Figure A9 (reduced to 3300 feet and 3900 feet during actual tests as described in Section C).

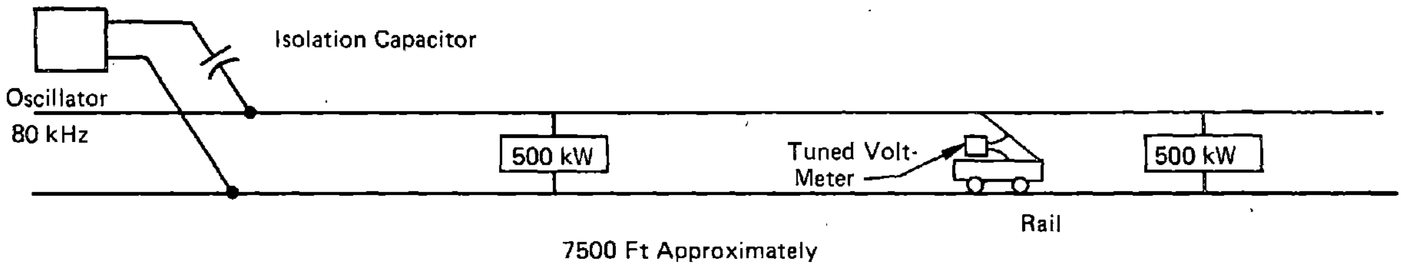
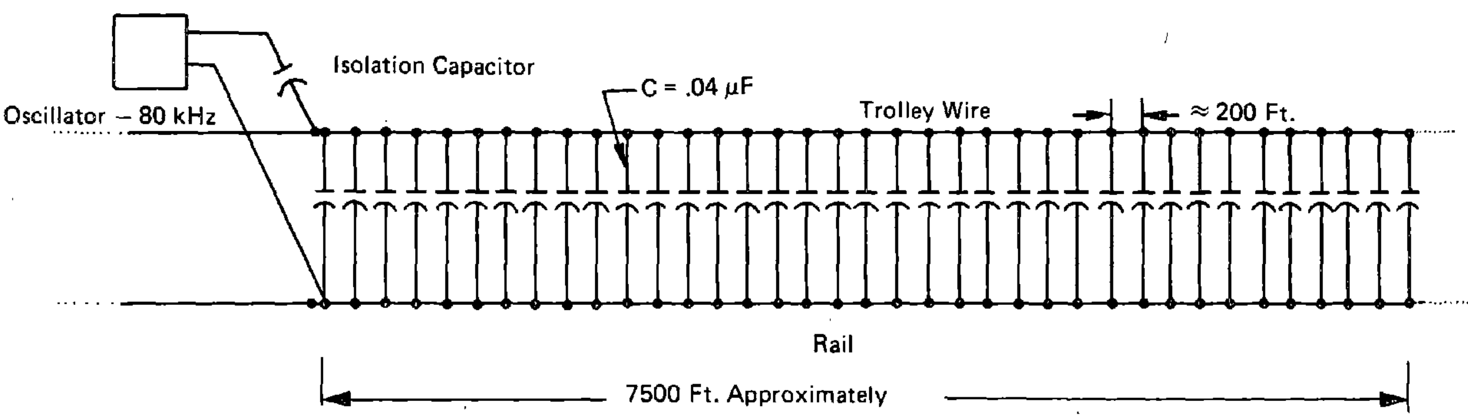


FIGURE A9 CONFIGURATION FOR MEASUREMENT OF SIGNAL VOLTAGE LEVEL ALONG ENERGIZED ACTIVE SECTION OF MAIN HAULAGEWAY

2. Measure the signal voltage level versus distance along the same 7500 foot run of haulageway depicted in Figure A9 after shunt loading capacitors have been installed at 200 foot intervals over the entire 7500 foot run to create a low-Z line configuration as shown in Figure A10 (reduced to 3300 feet and 3900 feet during actual tests as described in Section C).



Shunt Loads and Mobile Measurement Method Same as in Figure A9.

FIGURE A10 LOW-Z LINE CONFIGURATION FOR MEASUREMENT OF SIGNAL VOLTAGE LEVEL ALONG ENERGIZED ACTIVE SECTION OF MAIN HAULAGEWAY

IV. SCHEDULE FOR MEASUREMENTS

It is expected that each set of tests will take one shift. This relatively short time is predicated on careful preparation and work done in the mine in advance of the tests. The key ingredient to achieve such expeditious tests is the means chosen for attaching the loading capacitors to the trolley wire/rail. Screw on "current taps" will be used to connect to the trolley wire. Connection to the rails will be made at the rail bonds with screw type Burndy cable clamps. #12 stranded wire will be used to make the interconnections. Capacitors mounted on terminal strips will be used to complete the circuit. Spads and J-hooks will be used to dress the wires in a safe configuration. The installation of the capacitor attachments to the trolley wire and rail bonds along the main haulageway can be completed before the test period. Only the last connection (to the current taps) need be made on the day of the energized main haulageway tests.

V. EQUIPMENT, TOOLS AND SUPPLIES

The following is a list of equipment, tools and supplies for the tests.

1. Equipment

   Battery powered oscillator
   Battery powered voltmeter
   GR impedance bridge (battery powered)
   Line powered oscillator
   Tuned voltmeter
   Walkie talkies (Motorola MX Series UHF units)

2. Tools

   Screw drivers
   Crescent wrench
   Wire stripper
   Diagonal cutters

3. Supplies

   #12 insulated stranded wire
   Current taps

Cable clamps (Burndy connectors)

Clip leads

Set of resistors and a potentiometer for loading and terminating the line

.04 μF capacitors connected to terminal strips

Tape

Decoupling capacitors

Extension cord

Spads

J-hooks

APPENDIX B

THE $\lambda/8$ METHOD FOR MEASURING LINE VELOCITY OF PROPAGATION

A convenient method for determining the velocity of propagation along a known, fixed length of transmission line is based on open and short circuit measurements over a range of frequencies. It can be shown that the input impedance of a transmission line terminated by either a short or an open circuit has a magnitude equal to the line characteristic impedance when the operating frequency is such that the line is 1/8 wavelength long. Therefore, we designed a simple measuring technique based on this fact, one which requires that only the frequency be accurately known.

The technique uses an oscillator, a series resistor and a voltmeter as shown in Figure B1. The line input voltage is measured as a function of frequency for both a short circuit and open circuit line termination. The lowest frequency at which the two input voltages are equal in magnitude is the frequency at which the line is 1/8 wavelength long. This can be determined by direct observation or by finding the intersection frequency of the two voltage versus frequency plots. This frequency, together with the length of the line, allows the phase velocity to be computed using $\lambda f = v_p$. The beauty of the method is based on the fact that only the frequency of voltage equality and the length of the line are required. One does not need to know the oscillator voltage, the resistance value or the absolute value of input voltage. Furthermore, the voltmeter can be nonlinear and can also have a frequency dependent response. Therefore, it is an ideal method to use for taking measurements in the hostile mine environment.

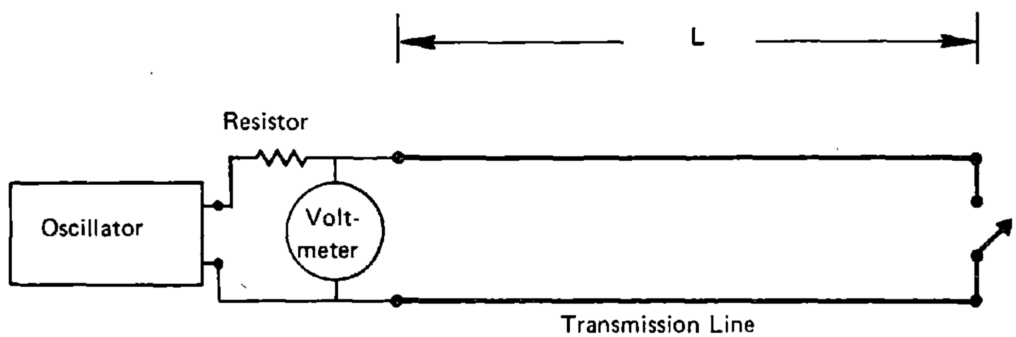


FIGURE B1 SET UP FOR OPEN CIRCUIT/SHORT CIRCUIT MEASUREMENTS

APPENDIX C

EXPLANATION OF VOLTAGE JUMPS FOUND AT RECTIFIERS

Figure C1-a illustrates the approximate physical layout of a power rectifier and its feeder cables relative to the trolley wire/rail at the McElroy mine. Rectifiers are typically set back about 25 to 100 feet from the trolley wire/rail. When the deadblocks in the trolley wire between rectifier feeder connection points are not bridged by capacitors, electrical continuity for the DC, and presumably for the trolley carrier phone rf signals, is lost. However, the feeder and ground cable geometry is such that, as shown in Figure C1-b, inductive coupling between the left and right cable circuits, provides a loosely coupled transformer action for the transfer of carrier phone rf signals past the deadblock. A simple approximate method for estimating the resulting voltage step-down ratio is presented below.

To good approximation, the rectifier can be represented by a short circuit, and the feeder/ground cable circuit represented by purely inductive self and mutual reactances. Thus, the configuration of Figure C1-b can be treated as a two terminal pair network, the behavior of which can be described by the conventional equations:

$$V_1 = Z_{11}I_1 + Z_{12}I_2 \tag{C1}$$

$$V_2 = Z_{21}I_1 + Z_{22}I_2 \tag{C2}$$

where

$$Z_{11} = \left.\frac{V_1}{I_1}\right|_{I_2=0} = j\omega L_{11} \tag{C3}$$

$$Z_{22} = \left.\frac{V_2}{I_2}\right|_{I_1=0} = j\omega L_{22} \tag{C4}$$

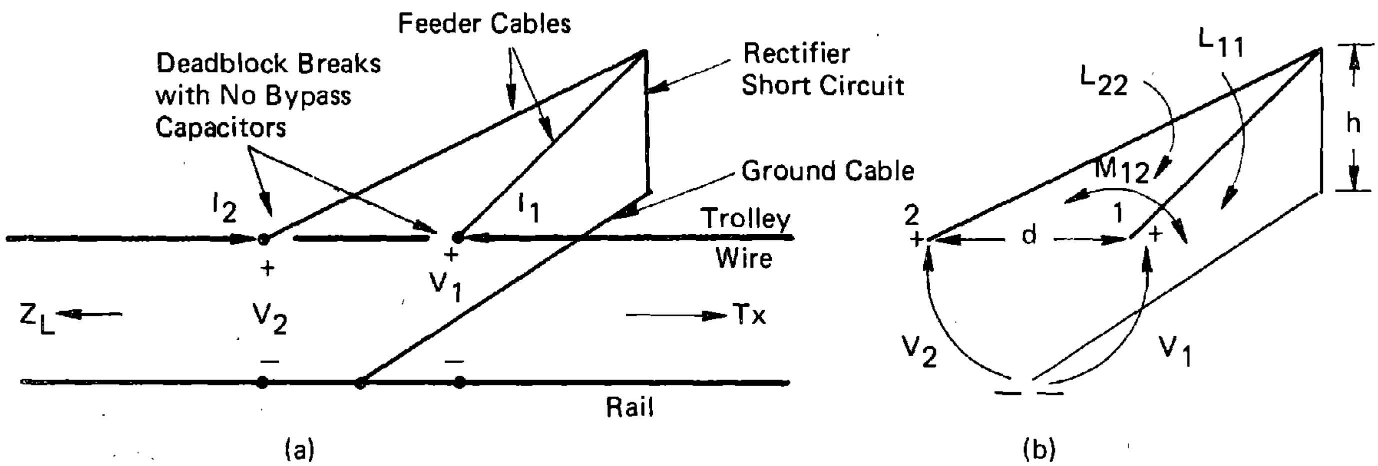


FIGURE C1 POWER RECTIFIER SETBACK LAYOUT (a) AND INDUCTIVE COUPLING NOMENCLATURE FOR FEEDER CABLE CIRCUITS (b)

$$Z_{12} = \quad_{21} = \frac{V_2}{I_1}\bigg|_{I_2=0} = j\omega M_{12} \tag{C5}$$

The objective is to estimate the value of the voltage V_2 after the rectifier in terms of the voltage V_1 on the transmitter side of the rectifier. The voltage V_2 is defined as

$$V_2 = Z_L I_2 \tag{C6}$$

where Z_L is the line impedance seen to the left of the rectifier connection terminals 2-2.

Substituting for Z_{11}, Z_{22}, Z_{12} and V_2 into Eq (C1) and (C2) we get

$$V_1 = j\omega L_{11} I_1 + j\omega M_{12} I_2 \tag{C7}$$

$$0 = j\omega M_{12} I_1 + (Z_L + j\omega L_{22}) I_2 \tag{C8}$$

Solving for I_2 and then substituting the result into Eq (C6) gives the voltage V_2 in terms of V_1

$$V_2 = \frac{-j\omega M_{12} Z_L V_1}{\left[\omega^2\left(L_1 L_2 - M_{12}^2\right) - j\omega L_{11} Z_L\right]} \tag{C9}$$

which can be rewritten in the more convenient form

$$V_2 = \left(\frac{M_{12}}{L_{11}}\right) Z_L V_1 \Bigg/ \left[j\omega L_{22}\left(1 - \frac{M_{12}^2}{L_{11}L_{22}}\right) + Z_L\right] . \tag{C10}$$

When Z_L is large compared to the self and mutual impedances of the rectifier feeder circuits, as can be expected in most mine trolley wire/rail applications, Eq (C10) reduces to the simple form

$$V_2 \simeq \left(\frac{M_{12}}{L_{11}}\right) V_1 = C_{12} V_1 \tag{C11}$$

where C_{12} is the voltage transfer ratio. Thus, if the two feeder circuits are only loosely coupled so that the mutual inductance M_{12} is small compared to the self inductance L_{11}, a significant voltage drop or jump can occur between terminals 1-1 and 2-2 when no rf bypass capacitors are present across the deadblocks in the trolley wire.

To estimate the magnitudes of the self and mutual impedances and of this voltage drop, we approximated the triangular feeder setback geometry of Figure C1 by a parallel conductor geometry similar to that used to describe the behavior of the trolley wire/rail and dedicated wire configuration in reference 1. Figure C2 depicts plan views of the triangular setback geometry and its parallel conductor approximation. A separation between conductors a and b equal to one-half the maximum separation d of the rectifier feeders was chosen for this calculation.

From reference 1, the self and mutual inductances per unit length for the parallel conductor geometry are given by

$$\ell_{11} = \frac{\mu_o}{2\pi} \ln\left(\frac{S_{ac}^2}{ac}\right) \tag{C12}$$

$$\ell_{22} = \frac{\mu_o}{2\pi} \ln\left(\frac{S_{bc}^2}{bc}\right) \tag{C13}$$

$$m_{12} = \frac{\mu_o}{2\pi} \ln\left(\frac{S_{bc} S_{ac}}{C\, S_{ab}}\right) \tag{C14}$$

where the S's are the separations between conductor centers and a, b, c are the conductor radii. Therefore, the voltage transfer ratio C_{12} of Eq (C11) reduces to

$$C_{12} = \frac{M_{12}}{L_{11}} \simeq \frac{m_{12} D}{\ell_{11} D} = \frac{m_{12}}{\ell_{11}} \tag{C15}$$

For the case of interest, $S_{ab} = d/2$, $S_{bc} = S_{ac} = [h^2 + (d/4)^2]^{1/2}$, $h = 2m$, $d = 8m$, $D = 16m$, $c = b = a = 0.04m$. Substituting these values into (C12), (C14) and (C15), we get $\ell_{11} = 1.7\ \mu H/m$, $m_{12} = 0.78\ \mu H/m$, and $C_{12} = 0.46$, which is equal to a -6.8 dB voltage jump. This value is in reasonable agreement with the values of 8.4 and 8.8 dB measured at the 1-North rectifier, considering the nature of the approximation

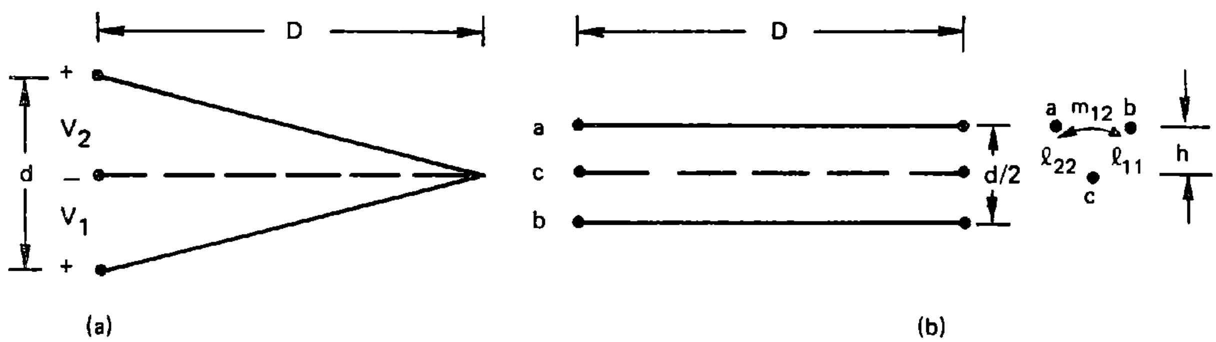


FIGURE C2 VIEWS OF RECTIFIER FEEDER GEOMETRY (a) AND PARALLEL CONDUCTOR APPROXIMATION (b)

by parallel conductors and the trial choice of separation distance equal to d/2. The distance d/2 is just the average separation distance for the triangular geometry. It can be shown that a more exact treatment of the triangular setback geometry, involving more complicated integration, produces similar results.

APPENDIX D

ALTERNATIVES FOR PERMANENT INSTALLATIONS

The low-Z line design described in this report is based on using the maximum practical spacing between loading capacitors for temporary installations. For permanent installations in operating mines, other factors have to be considered, namely a more permanent, practical and safe method of installing the capacitors would be required. One possible approach in this regard is to make the loading capacitors integral parts of the insulators used on the trolley wire hangers.

The insulated hangers are spaced about 20 to 25 feet apart in most mines. Therefore, to lower the line characteristic impedance by the same amount as in the experiment, every eighth or tenth insulator could be replaced by a special one bearing a capacitor value of equal to the 0.04 μF used in the low-Z line experiment. Alternatively, all insulators could be equipped with about one tenth of this capacitance, namely 0.004 μF.

The ground return path could be provided by either a wired connection from the hanger to the rail via the rib of the tunnel, or by using the naturally present spreading resistance of the hanger's attachment post into the roof. The importance of spreading resistance is made apparent if we compare the reactance of the capacitor to the spreading resistance of the attachment post. The reactance at 100 kHz for a 0.004 μF capacitor is about 400 ohms. If we could assume a nominal spreading resistance of 50 ohms, we might expect reasonable performance. Since the resistance appears in series with the capacitive reactance, the important factor is the amount of equivalent shunt resistance. The parallel equivalent resistance will be approximately 3200 ohms. However, this shunt resistance occurs approximately every 20 feet, giving a shunt resistance per 1000 feet of about 64 ohms. Using the simplified low-loss expression for line attenuation rate that can be applied for such a resistance value, we find that the added loss due to the shunt resistive loading is 2.7 dB per 1000 feet, a moderately high but not unreasonable value with which to contend. The magnitude of the added loss depends on the value of loading capacitance, and hence would be different for different reduction ratios of characteristic impedance.

In practice, the naturally occurring spreading resistance is more likely to be in the vicinity of 100 to 200 ohms, which will further reduce performance to unacceptable levels. This applies even more so for the case of 0.04 μF capacitors spaced about 200 feet apart. Therefore, for most installations it will be necessary to run a ground return wire from the hanger to the rail to avoid the serious added loss due to the spreading resistance. The use of such a wire does introduce an inconvenience factor, but it should not represent a serious problem for it will be at ground potential, and it can be installed simply by stapling it to the roof and rib and burying it to a shallow depth in the floor material. Lastly, to keep the installation and maintenance activities within reasonable bounds, a mine installation having higher-value capacitors spaced about 200 feet apart will be more practical than one with lower-value capacitors placed in each insulator.