TECHNICAL SERVICES FOR MINE COMMUNICATIONS RESEARCH

IMPROVEMENTS FOR MINE CARRIER PHONE SYSTEMS

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UNITED STATES
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16. Abstract

The purpose of this program was threefold:

(1) to identify the symptoms of poor or inadequate performance of trolley carrier phone systems;

(2) to assess the root causes of performance difficulties and classify them on the basis of equipment, coupling, or transmission;

(3) to propose, analyze, test, evaluate and verify means of overcoming performance difficulties.

Based on interviews and discussions with knowledgeable persons, laboratory experiments, and in-mine measurements, it was determined that the major impediment to good carrier phone system performance is the extreme signal attenuation found on the trolley wire/rail largely due to the many bridging loads.

Three means are identified to help overcome the performance difficulties: the low impedance trolley wire, a metho of improving performance by capacitively loading the transmission line; the dedicated wire, a low-loss means of extending trolley signal coverage; the use of isolators to remove the offending bridging loads at the carrier frequency. Other subjects treated in the report are design reviews of hardware, guidelines for the use of information in the report, recommendations, and a description of a probe for measuring trolley wire current.

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FOREWORD

This report was prepared by Arthur D. Little, Inc., Cambridge, Massachusetts under USBM Contract No. HO346045. 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. Howard E. Parkinson acting as the technical project officer, and with technical assistance from Mr. Harry Dobroski. Mr. Michael W. College 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 June 1975 to April 1977. This report was submitted by the authors in April 1976.

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

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EXECUTIVE SUMMARY

A. PURPOSE AND SCOPE

The purpose of this study was threefold:

- To identify symptoms of poor or inadequate performance of trolley carrier phone systems used in electric rail haulage coal mines;
- To assess the root causes of the performance difficulties and classify them on the basis of equipment, coupling, or transmission problems; and
- To propose, analyze, test, evaluate and verify means of overcoming the performance difficulties.

B. APPROACH

The approach started with interviews and discussions with mine operators, mine communication equipment suppliers, and Bureau of Mines (BuMines) personnel held to assess the present status of trolley carrier phone communication systems and to develop a listing of system performance difficulties. This step was followed by in-mine tests to ascertain certain fundamental properties of the carrier transmission medium, the trolley wire/rail located in a tunnel in a layered conducting medium. The performance difficulties were then related to the specific root causes, and concepts that gave promise of potential for overcoming these performance difficulties were developed.

The concepts were then typically treated by theory to ascertain how great the potential of the concept was. These concepts were then treated by one or more of the following:

- computer simulation,
- laboratory experiments, and
- in-mine testing.

C. PRESENT STATUS OF TROLLEY CARRIER PHONE SYSTEMS

1. General

The trolley carrier phones serve as the basis of one of the backbone electric rail haulage coal mine communication systems used in most mines of this type today. Despite quite serious problems with equipment, equipment maintenance, and transmission medium properties, these carrier phones provide the vital communication link necessary for dispatcher control in such coal mines. It is overall rather remarkable that, despite these obstacles, most trolley carrier phone systems of this type provide adequate performance.

2. Equipment

Trolley carrier phone transceivers are relatively unsophisticated equipments, typically operating at carrier frequencies of 88 or 100 kHz and using narrow-band frequency modulation (FM). The equipment typically are rated at 25 watts, providing 25 volts into a 25-ohm resistive load. Most mines use a few fixed-location trolley carrier phones and a large number of mobile trolley carrier phones on locomotives, jeeps, and, in some instances, on portal buses.

3. Environment

The operating environment for trolley carrier phones is quite severe. The mobile units are subjected to constant vibration and shock, and suffer the extremes of temperature variation from season to season. They also operate in 100% relative humidity (RH) environments during much of the warm season. Not only do they have to operate in the 100% RH region, but they are frequently exposed to acid vapors often found in mines, and to dust and dirt. The mere presence of electronic equipment in conjunction with the heavy equipment commonly found in mines places it in a hazardous environment by itself. The electrical environment in which the carrier phones must operate is quite severe. For example, the trolley wire is known to have voltage extremes running as high as 12,000 volts for a few milliseconds, and to be subjected to the ever-present AC ripple generated by the rectifiers and the variations of nominal values that are measured in terms of +30%, -40%.

4. Maintenance

Maintenance problems relate to two particularly vital portions of the carrier phone system: the transceiver equipment itself and the transmission medium. Equipment maintenance is frequently performed with an absolute minimum of service equipment. In fact, some mines have hundreds of carrier phone sets that are maintained with no more measurement equipment than a multimeter. In some mines, vendors are contracted to repair carrier phone transceivers; these vendors are either the original suppliers or a service organization.

5. Transmission Line

The transmission line that interconnects the carrier sets represents the major difficulty in obtaining and maintaining good carrier phone performance. It is not the fundamental character of the transmission line (comprised of a trolley wire/rail) that imposes this problem. Rather, it is the many bridging loads necessarily placed across the trolley wire and the branches imposed on the trolley wire/rail by rail haulage requirements that make the transmission medium the most difficult factor in maintaining good carrier phone communications. The attenuation rate for a typical trolley wire/rail in a tunnel in a conductive medium is approximately 1 dB/km.* A typical trolley carrier phone can accommodate a 70-dB transmission loss, that is, a loss from 25V rms to 8 mV rms. For such a condition it can be seen that a 70-km communication range can be expected, or 40 miles of coverage. However, the bridging loads interfere with achieving anywhere near such a communication range. These bridging loads, which eat into the allowable transmission loss at an extremely rapid rate, are comprised of such items as:

- personnel heaters
- rectifiers
- pumps
- mine motors
- lightning arrestors
- signal and illumination lights
- locomotive and jeep light bulbs
- carrier phones
- vehicles
- insulators
- bore hole shorts

These bridging loads range in impedance from a few ohms to as much as 1000 ohms. The amount of insertion loss that can be expected from such bridging loads is shown in Table S-1.

The very large insertion losses imposed by certain of these loads has compelled mine operators to attempt to raise the impedance of certain of the offending loads at the carrier frequency to obtain better carrier signal transmission. In some instances, very large air core inductors, using as much as 100 pounds of copper, have been made to isolate the otherwise very low impedance presented to the trolley wire/rail by a rectifier. Smaller inductors have frequently been used, sometimes in conjunction with parallel tuning, to isolate such items as pumps from presenting low impedance to the trolley wire/rail.

The performance of trolley carrier phone systems is further degraded by the presence of certain sources of noise on the trolley wire/rail. Worst offenders among these are the many rectifiers which produce very high order harmonics of the fundamental frequency extending

*See Chapter III.

TABLE S-1

CHARACTERISTICS OF BRIDGING LOADS

Bridging Load		Estimated Impedance at 100 kHz (ohms)	Insertion Loss* (dB)	Loss in Voltage
Rectifier with minimum setback		2	34.1	51 to 1
Rectifier with 50-foot setback†		9†	21.6	12 to 1
Rectifier with 100-foot setback†		19	15.9	6 to 1
Carrier phone with 20-Ω receiver		20 Ω	15.6	6 to 1
Carrier phone with 100-Ω receiver		100 Ω	6.0	2 to 1
Jeep or portal bus motor		500 Ω	1.6	1.2 to 1
44-ton locomotive motor		60 Ω	8.5	2.7 to 1
Vehicle with two 150-W, 32-V headlights isolated resistively**	300-V system	60	8.5	2.6 to 1
	600-V system	120	5.3	1.8 to 1
Illumination lights (assumed to be 200-W load)	300-V system	450	1.7	1.22 to 1
	600-V system	1800	0.5	1.06 to 1
Single insulator		200,000	0.0043	1.0005 to 1
1 mile of insulators with 12-foot spacings (440 insulators)		—	1.90	1.2 to 1
1000-W personnel heater	300-V system	90 Ω	6.5	2.1 to 1
	600-V system	360 Ω	2.1	1.3 to 1
5000-W personnel heater	300-V system	18 Ω	16.3	6.6 to 1
	600-V system	72 Ω	7.6	2.4 to 1

Notes to Table S-1

*This insertion loss is that calculated for an otherwise unencumbered trolley wire/rail having a 200-Ω characteristic impedance, using the formula

$$L = 20 \log_{10} \frac{2R + Z_o}{2R}$$

where R is bridging load resistance.

For a trolley wire/rail having a large number of loads, load interaction will cause the total net transmission loss, in most practical cases, to be less than the sum of these tabulated losses due to load interaction.

**At the trolley wire carrier frequency the bridging impedance of a locomotive or vehicle appears to be dominated by the headlights. Motors have impedances at carrier frequencies that are somewhat larger than these values and therefore the load imposed by the lights only is considered. Newer vehicles with DC-to-DC converters that supply the light circuits may have appreciably less effect.

†The bridging impedance of a setback rectifier is higher in value than one with minimum setback due to the feed wire inductance. These figures assume a feed wire inductance of 0.3 μH/ft and a frequency of 100 kHz. The values of Z will be somewhat less, but not significantly for 88-kHz operation.

into the carrier range, the arcing noise produced by the moving mine motors, and the noise generated by fixed DC motors. These sources combine to produce noise levels typically in the order of a few millivolts on the trolley wire/rail within the band used by trolley carrier phones.

There is evidence of seasonal effects on the performance of trolley carrier phone systems; the good season being the dry season, which is typically the fall and winter months, and the bad season being the spring and summer months. The dampness present in mines in the spring and summer months and the relative dryness present in the fall and winter months are apparently the causes, respectively, of the "bad" and "good" seasons.

6. Aided Transmission

The extreme seriousness of the many bridging loads across the trolley wire/rail mentioned in the Section C.5 has often made it impossible for carrier communications to be achieved over distances of more than a few miles. The mine operators, with the assistance of the equipment manufacturers resorted to the use of aided transmission, which is typically effected by coupling the trolley carrier signals from the trolley wire to the mine pager phone line, using it in a common mode as a single conductor to extend the communication range of the trolley carrier phone systems. Alternatively, some mine operators have made use of auxiliary wires strung for the sole purpose of providing aided transmission. This line is free of the branches and other impediments to good propagation that occur on the pager phone line. Such use also eliminates the presence of trolley wire/rail audioband noise that might otherwise be coupled to the telephone lines.

7. Performance Difficulties

The performance difficulties experienced with carrier phone systems are dominated by the excess transmission loss between a pair of carrier phone sets. Such a loss is, in turn, dominated by the large number of bridging loads across the trolley wire/rail which, in the absence of these bridging loads, would provide a very good transmission medium for trolley carrier signals. Minor problems are presented by certain equipment shortcomings. However, major improvements in trolley carrier phone systems can only come about by treating the transmission medium as the first-order cause of carrier phone system difficulties.

D. HARDWARE CHARACTERISTICS

1. General

Our search for improvement opportunities included an examination of the hardware implementation of trolley carrier phones currently provided by three manufacturers: Femco, MSA, and Pyott-Boone. We examined the implementation of the transceivers of these three manufacturers to determine their suitability for the tasks for which they are used and for opportunities for improvement. In addition, we examined the possible applicability of a new carrier phone designed for hoist communication applications, with a view to determining how well it would meet trolley carrier phone needs.

2. Findings

Our hardware review suggests that there are several areas where discrete hardware improvements that would enhance carrier phone system performance could be made. These are noted in summary form below:

- greater use of functional, state-of-the-art, integrated circuits to decrease component count and production costs and, simultaneously, to increase reliability;
- addition of a noise blanker to improve the immunity to transient noise interference;
- reduction of perceived audio distortion by the use of more linear frequency modulators and by preventing clipping of speech waveforms in both the transmitter and receiver;
- addition of a speech compressor to the transmitter audio circuits to reduce the peak to average ratio of the speech waveform; such a compressor could improve the received signal to noise ratio by 6 to 10 dB;
- control of the frequency response of the circuits to optimize speech intelligibility for typical operator voices;
- addition of circuits that would automatically set the receiver output audio level as a function of ambient acoustic noise;
- substitution of efficient power conditioning circuits to eliminate the several hundred watts of heat dissipated by resistive voltage droppers and thereby alleviating packaging problems;
- repackaging the unit so that all circuits are included in the loudspeaker housing;
- possible elimination of the changeover relay by use of electronic switching; and
- addition of tone-controlled squelch to overcome the squelch problems caused by the variable noise environment.

In our examination of the HCS 102 hoist phone (Collins Radio), we addressed such questions as:

- Can this hoist phone be used as a trolley phone, with or without modification?
- Is the specification to which the HCS 102 is designed a reasonable one for trolley phones? Is the HCS 102 a cost-effective design?

- Should the HCS 102 form the basis of a "industry standard" trolley carrier phone?

Our examination of the characteristics of this phone resulted in the following conclusions:

- The hoist phone has too low a power output for use as a trolley carrier phone, but this could be corrected by modest engineering changes.
- The hoist phone circuits are much more complex than present trolley phone circuits, in part due to severe specifications on frequency stability and selectivity.
- The hoist phone does not provide for operation from 300- or 600-V DC supplies and modifications would therefore be needed.

E. THE TRANSMISSION MEDIUM

1. Introduction

Early in the program it became evident that one of the greatest impediments to the successful use of trolley carrier phones in mines is the set of problems associated with the trolley wire/rail used as the transmission medium. In this regard, our program encompassed four aspects:

a. determination of the theoretical attenuation rates for a typical trolley wire/rail unencumbered by the many bridging loads across it;

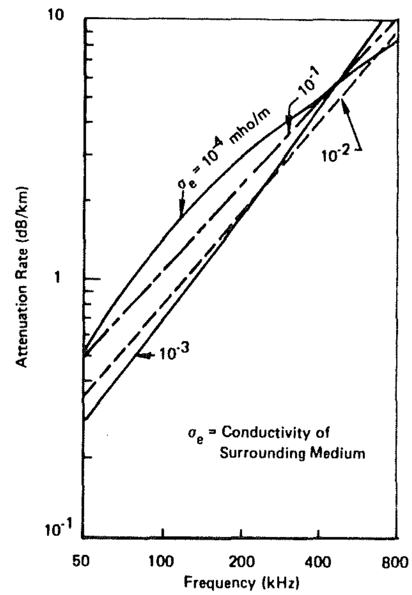
b. performance of in-mine measurements on actual trolley wire/rail systems to support the theory;

c. an assessment of the effects of the many bridging loads across the trolley wire/rail, once the factors about the characteristics of the trolley wire/rail were known; and

d. provision of an organized method of treating bridging loads across such transmission lines to facilitate computations.

2. The Unencumbered Trolley Wire/Rail

Through a cooperative arrangement and under an already existing contract, Dr. James Wait and Dr. David Hill of the Institute of Telecommunication Sciences (ITS) agreed to develop the theoretical attenuation rate for a model trolley wire/rail surrounded by a conducting medium formulated by ADL. The key findings of their theoretical analysis are presented in Figure S-1. The figure shows that the attenuation rate is less than 1 dB/km for the frequency range of interest, 88 to 100 kHz, and for expected rock conductivities of the surrounding medium ranging between 10^{-3} and 10^{-1} mho/m. These figures apply for a 20-cm separation of the trolley wire from the conducting medium.



Source: Wait, J.R., and Hill, D.A., *Radio Frequency Transmission Via a Trolley Wire in a Tunnel with a Rail Return*, IEEE Trans. on Antennas and Propagation, March 1977.

FIGURE S–1 ATTENUATION RATE FOR UNENCUMBERED TROLLEY WIRE/RAIL (σ_e = CONDUCTIVITY OF SURROUNDING MEDIUM; TROLLEY WIRE DIAMETER = 1.5 cm; AND SPACING FROM WALL = 20 cm)

The significant conclusion from this study of the theoretical attenuation rate is that the trolley wire/rail can be viewed as a low-loss transmission line for carrier signal propagation, if it is unencumbered by bridging loads.

3. In-Mine Measurements

With the results of the theoretical study in hand, it was deemed advisable to verify the attenuation rate expectation, and thus in-mine measurements were made for this and other purposes. As a result of these in-mine measurements, we feel that the following characteristics appropriately describe the trolley wire/rail as a transmission line. These measurements were obtained in the Renton coal mine and we feel that they are typical of mines having approximately the same geometry. The characteristics follow:

- Characteristic impedance: 200 ± 30 ohms;
- Attenuation rate for unencumbered trolley wire/rail: 1.6 dB/km;
- Inductance per unit length: 0.35 ± 10% μH/ft;
- Capacitance per unit length: 9 ± 2 pF/ft; and
- Velocity of propagation: 0.64 that of the velocity of propagation in free space.

These measurements support the concept that the trolley wire/rail by itself is a relatively low-loss medium for the propagation of trolley carrier signals.

4. Bridging Loads

Almost anything that either supplies the trolley wire/rail with electric power or obtains electric power from the trolley wire/rail acts to inhibit the propagation of carrier signals on a trolley wire/rail. A first-order estimate of the degree to which such bridging loads impede the propagation of carrier signals can be developed by the use of the insertion loss equation. This equation represents the ratio by which the voltage on an otherwise matched transmission line changes at the point of load application when a bridging load is attached. The ratio can be expressed as:

$$L = \frac{2R + Z_o}{2R}$$

where Z_o is a characteristic impedance of the transmission lines (for most coal mine applications, 200 ohms may be used without introducing a significant error); and R is the bridging impedance in ohms at the carrier frequency. A simple way of determining whether bridging loads will interfere with carrier signal propagation is to examine each of the loads, estimate its resistance at the carrier frequency, and compute the loss introduced by that load. The multiplication of all such loss factors then gives a measure of signal loss that can be expected when such bridging loads are interposed between a pair of carrier phones. A more convenient way of expressing the loss is to use the decibel rating for the loss which is simply $20 \log_{10} L$.

A conservative value of total loss that can be accommodated in a carrier phone system is approximately 70 dB, that is, a signal change from 25 V transmitted to 8 mV at reception. Table S-1 presents approximate values for typical bridging impedances and the corresponding dB of insertion loss, together with the ratio by which the line voltage is decreased in the presence of these loads.

5. Computational Techniques

In the previous section, the concept of insertion loss was used to make the first-order estimate of the degradation of carrier signals produced by bridging loads. However, this was only an approximation. For exact solutions, transmission line equations, or alternatively, the representation of the problem on Smith charts, may be used. This approach is particularly useful in determining, for example, how a tuned impedance across the trolley wire/rail reflects itself at various distances from its point of attachment.

F. THE LOW-IMPEDANCE LINE

The equation for insertion loss and the representative value used for transmission line Z_0, together with the values of bridging impedances found on the transmission line comprised of the trolley wire/rail, clearly show the seriousness of losses introduced by these bridging loads. It is evident that raising the carrier frequency impedance of the loads can reduce the loss. Similarly, lowering the characteristic impedance of the trolley wire/rail can decrease the loss.

The natural characteristic impedance of the trolley wire/rail is determined largely by the size and spacing of the conductors comprising the trolley wire/rail, that is, the trolley wire as one conductor and the rails as the other. Closer spacing and larger sized conductors will reduce the characteristic impedance. Clearly, pursuing either of these approaches is difficult. However, the line can be periodically loaded with fixed-value capacitors to artificially lower the characteristic impedance. The characteristic impedance can be expressed as

$$Z_0 = \sqrt{\frac{L}{C}}$$

where L is the inductance of the line per unit of length and C is the capacitance of the line per unit length. The natural inductance and capacitance are determined basically by the geometric relations of the conductors. The natural capacitance can be augmented by fixed-value capacitors connected between the trolley wire and the rail at appropriate spacings, thereby increasing the effective capacitance per unit length and lowering the characteristic impedance.

An example of the performance improvement that can be expected is shown in Figure S-2 which depicts theoretical and measured results for such treatment of a transmission line. Frequency and distances for the experiment were scaled. A marked reduction of signal loss is illustrated in this example where three bridging loads originally caused a carrier signal loss of 55 dB. This loss was reduced to 12 dB by the application of capacitors of practical values spaced at not inconvenient distances. This improvement of 43 dB in signal level illustrates the promise that the lowering of line impedance offers as a means of improving signal propagation.

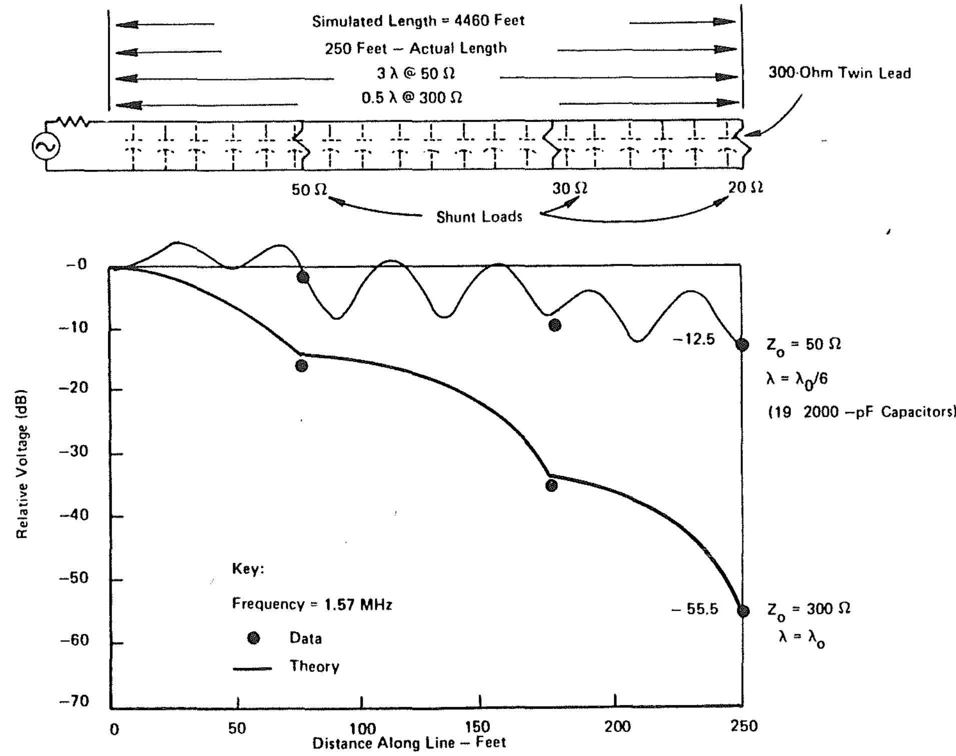


FIGURE S–2 THEORY AND EXPERIMENTAL RESULTS FOR APPLICATION OF LOW-IMPEDANCE TECHNIQUE

G. THE DEDICATED WIRE

As previously discussed, low bridging impedance values may seriously degrade signal propagation on a trolley wire/rail. Lowering the characteristic impedance of the trolley wire/rail, or raising the impedance of the offending loads, will both serve to improve signal propagation. Another means of improving signal propagation is to provide an alternate path of low loss. The theory of signal propagation on a pair of conductors in a tunnel with a conductive medium surrounding them shows that the natural attenuation rate is quite low. For this reason, one can certainly expect that a transmission line comprised of a signal conductor insulated from, but attached to, the roof or rib of a coal tunnel, together with the rails as a return path, would act as a low-loss line for the transmission of carrier signals. Moreover, any such line installed in a tunnel that has a trolley wire is fairly well coupled to the trolley wire. Thus, signals impressed on one appear on the other.

Theory, together with a computer model of such a system, reveals the performance that can be expected. An example of the results obtained in this manner is shown in Figure S-3. This figure shows the signal level as a function of distance on both the trolley wire/rail and the dedicated wire/rail for transmission on both the trolley wire/rail and on the dedicated wire/rail. The example is that of a trolley wire/rail that shows a loss of 20 dB/km, a rather

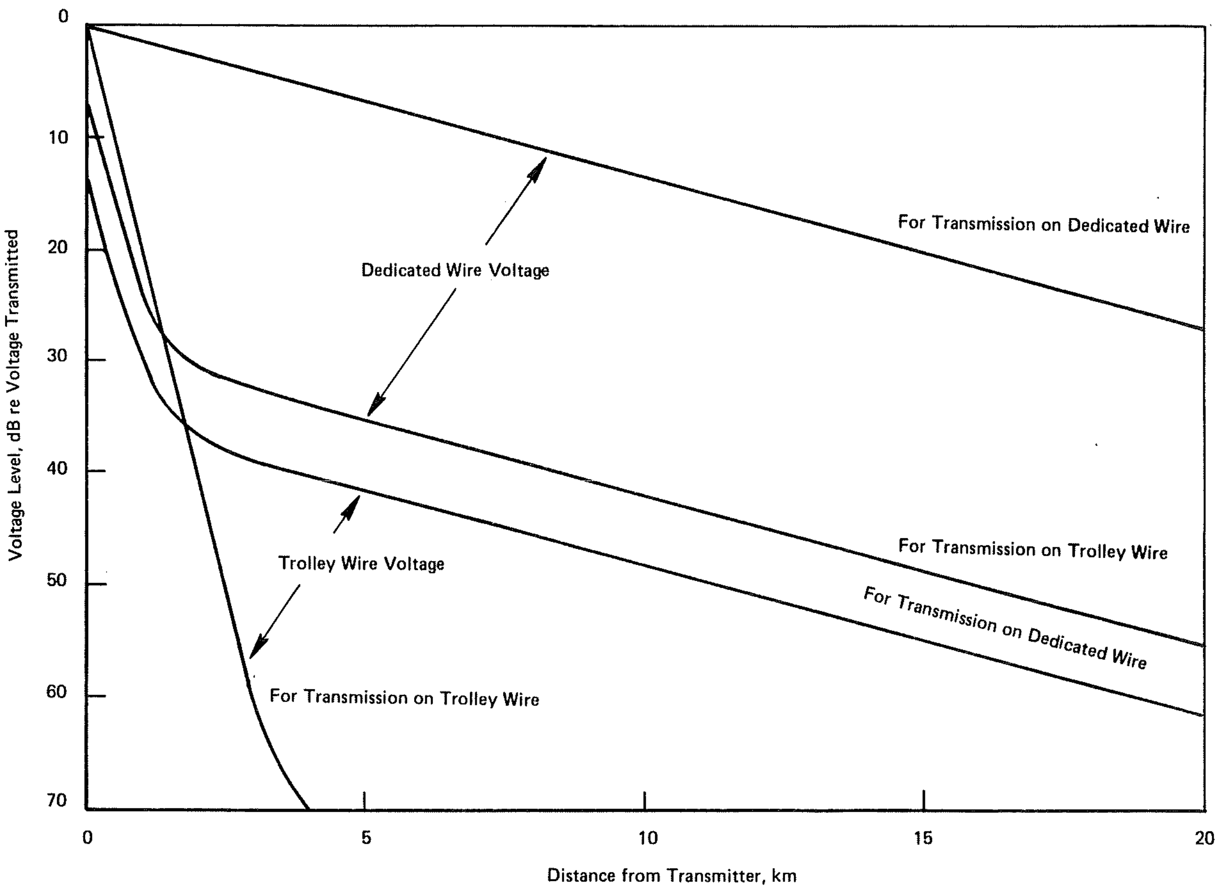


FIGURE S–3 VOLTAGE LEVELS VERSUS DISTANCE
α_T = 20 dB/km
α_D = 1.0 dB/km

extreme level of loss, due to the many bridging loads across the trolley wire/rail. In fact, the way that the signal would decrease as a function of distance for transmission on the trolley wire/rail in the absence of the "dedicated" wire is pretty much the way that the signal behaves for the first few kilometers, namely, the steeply sloping part of the curve at the left hand end. The plot illustrates that a dedicated wire not directly connected to the trolley wire/rail provides enough coupling to markedly increase propagation over that obtained directly on the trolley wire/rail. The preferred way of implementing such a system is to connect the dispatcher's transmitter between the dedicated wire and the rail. Thus, the dispatcher's signal will propagate along the dedicated wire with low loss and will reach all regions of the mine to which the dedicated wire extends. The presence of this signal on the dedicated wire means that a proportionate but lower level of signal exists also on the trolley wire/rail.

H. ISOLATORS

The seriousness of bridging loads impeding propagation carrier signals has been firmly established. Impedance isolators may be used to partially relieve the deleterious effects of such loads. This alleviation is achieved typically by adding a series element to the offending load. This element has very low DC resistance so that the necessary DC path between the load and the trolley wire/rail is maintained, but it presents a high impedance at the carrier frequency. The typical element is a series inductance, either by itself or tuned. The degree to which such impedance isolators can improve signal level is illustrated in Figure S-4. This figure shows the improvement possible for various bridging loads, assuming that the bridging load is placed across an otherwise matched transmission line with a characteristic impedance of 200 ohms.

Other techniques include tuning the feed wire inductance of rectifiers with setbacks of more than 50 feet, and making use of the trolley wire/rail inductance to tune a rectifier that is not set back far enough that the feed wire inductance can be used for this purpose.

I. GUIDELINES

Findings of the program apply to four interested parties: (1) users of carrier phones in present mines; (2) planners of new mines; (3) equipment suppliers and manufacturers, and (4) Bureau of Mines personnel. Guidelines for using the results of this program by these concerned parties are presented below.

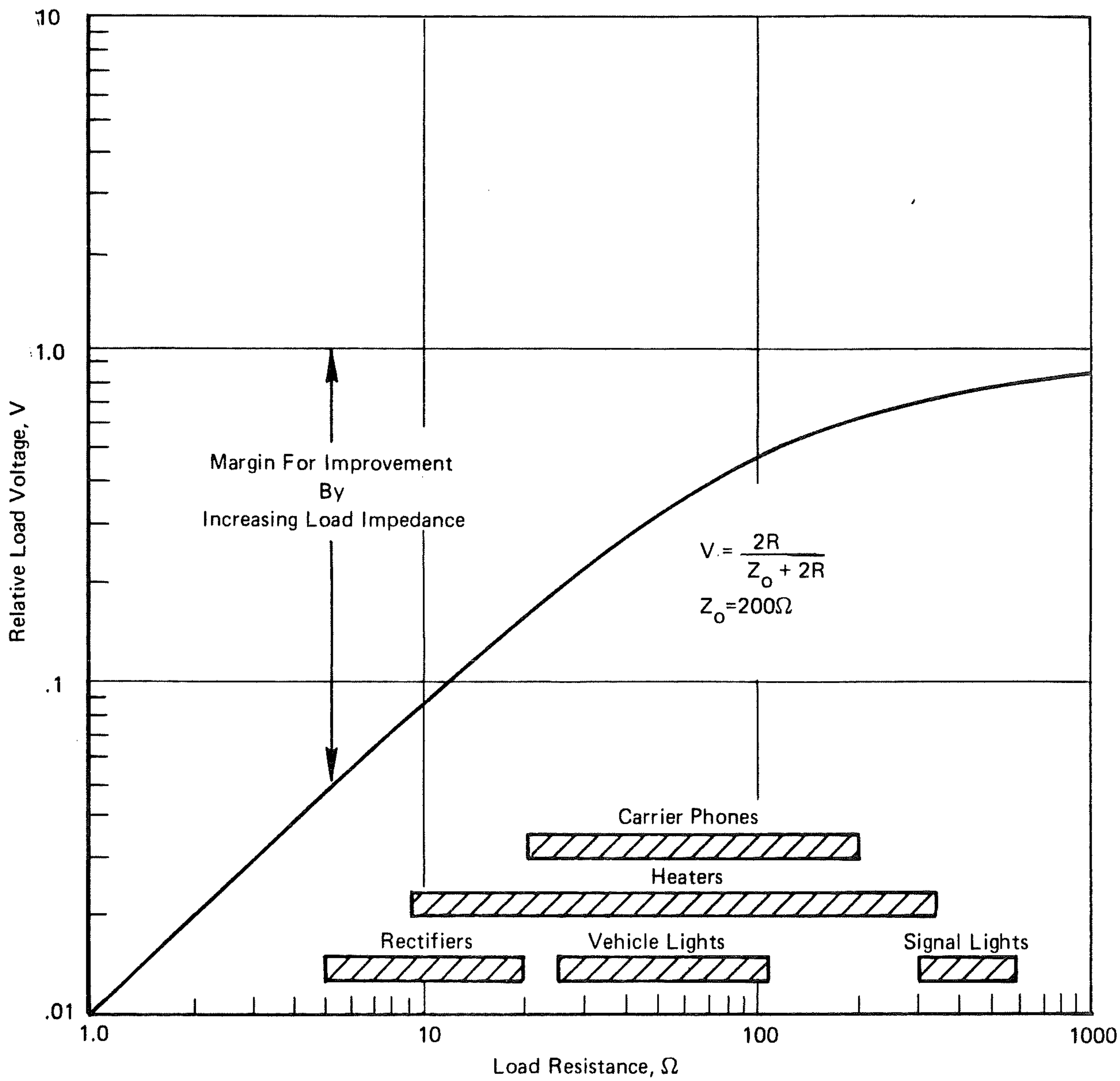


FIGURE S–4 LOAD VOLTAGE AS A FUNCTION OF LOAD RESISTANCE

1. Users of Carrier Phones in Present Mines

Where trolley carrier phone systems show performance shortcomings, the guidelines encourage and describe:

- mapping of carrier phone signal and noise strength on the trolley wire/rail and auxiliary conductors to determine the status of the carrier phone system;
- identification of bridging loads that interfere with carrier signal propagation and means of isolating such loads;
- use of an auxiliary wire to improve signal propagation; and
- use of a centralized remote transceiver in certain circumstances.

2. Planners of New Mines

Guidance is given to the planners of new mines so that carrier phone systems can operate under favorable circumstances. The guidelines suggest:

- operating as many as possible of the auxiliary loads from mine AC power rather than from trolley wire/rail;
- planning on the installation of a dedicated wire to aid carrier propagation;
- selection of carrier phones showing a high standby impedance;
- selection of vehicles with high carrier frequency impedance;
- planning for a setback of at least 50 feet for rectifiers;
- seeking rectifiers with internal impedance isolation; and
- planning for the installation of impedance isolators for other necessary auxiliary loads.

3. Equipment Suppliers and Manufacturers

Manufacturers can provide equipment that will improve carrier phone performance. In particular, the following suggestions are made:

- transceiver equipment – improve performance by adding: tone-controlled squelch, adaptive loudness, linear modulators, high standby impedance, DC to DC converters, volume compression, tailored audio frequency response, and control of out-of-band emissions;
- auxiliary equipment – encouragement is given to develop: compact, low-cost tuned voltmeters, packaged isolators for various bridging loads, high-impedance vehicles (at carrier frequency), and integrated rectifier isolators.

4. Bureau of Mines Personnel

Encourage the development of the above by manufacturers and sponsor the following: a confirmation of the deciated wire expectations, a demonstration of the low-impedance line, an integrated package for carrier phone transceivers, a loop receive/trolley wire transmit carrier phone set, a complete new design of carrier phones, and alternator-powered carrier phone set, and a task force to solve user problems.

J. AN INSTRUMENT TO AID IN DIAGNOSTICS

During the course of the program, a "slipover" probe was developed to make possible the measurement of trolley wire carrier frequency currents safely in the presence of the trolley wire DC voltage. The instrument used is an insulated body which holds a small, shielded pickup coil that is held at a fixed distance from the trolley wire and intercepts the magnetic field surrounding the trolley wire. The voltage generated in the coil is a measure of the current of the trolley wire. The Singer NM-12 AT-tuned voltmeter is used to measure the coil voltage. The unit has been used in a coal mine to determine trolley wire current.

I. PRESENT STATUS OF TROLLEY CARRIER PHONE SYSTEMS

A. INTRODUCTION

At the present time there are two backbone coal mine communication systems in general use: the pager phone and the trolley wire carrier phone. Both of these systems are in general day-to-day use in coal mining operations and are essential to the safe conduct of mining operations. In our work we conducted a number of interviews with carrier phone manufacturers, users, and representatives of the Bureau of Mines to identify the root causes of problems experienced in implementing reliable carrier communication systems in coal mines. This section combines the results of the interviews and the knowledge gained from them.

The first installation of a trolley wire carrier phone system was made by Femco in the Monhegan Mine in Welch, West Virginia, in the summer of 1946. The system was comprised initially of a single dispatcher's station and a single motor equipped with the carrier equipment. It is of interest to note that this initial carrier phone was packaged in a quarter-inch-thick, steel-plate case for installation on the motor. This Femco installation was followed within a very few months by a similar installation made by MSA. Thus was started the use of mine carrier phones for dispatch-control purposes. The industry rapidly accepted the use of such carrier phone equipment, and Femco and MSA have remained among the key manufacturers of carrier phones for coal mines. The initial versions used vacuum tubes. These were superseded with solid-state equipment in the late '50's and early '60's.

The carrier phones operate in a wide variety of mine topographical layouts – mines ranging from as small as a few miles in dimensions to many miles in dimensions and encompassing many miles of trolley wire/rail, including switches, crossovers, and sidings in the usual configurations found in rail haulage systems. They operate in a wide variety of mine sizes and layouts, with various kinds of equipment, moisture contents of mines, acid contents in the moisture, branches on the rail lines, and standing-wave problems presented thereby. They also operate in the face of an ever-changing mine layout as the mining progresses. It is also apparent that there is no such thing as a representative mine for analyzing trolley wire communication systems. Each mine is distinctly different.

B. EQUIPMENT CONSIDERATIONS

The principles upon which the carrier transceivers are fabricated are relatively straightforward. A narrow-band FM form of modulation is used. The typical total bandwidth is about 8,000 Hz for the mine equipment with this mode of operation. The equipments are typically comprised of nominal 25-watt transmitters with internal impedances of 25 ohms, so that the 25 watts is delivered to a 25-ohm resistive load. Some of the equipments provide for a higher impedance output level of up to 500 ohms. Receivers are typically simple TRF types, although newer models are coming out with phase-lock receiver circuitry. The receivers use one or another form of squelch control to prevent continuous noise from the speaker in the absence of a validly received carrier signal. The transceivers operate typically at an 88-kHz or 100-kHz center frequency. The lack of control of the transmission skirts and receiver selectivity is such that the 88-kHz phones will typically interfere with the 100-kHz phones and vice versa.

C. ENVIRONMENT

The carrier phones operate in a relatively tough environment. In particular, the vehicle-mounted units are subjected to considerable amounts of vibration and shock. The worst axis for the vibration and shock is believed to be the horizontal axis, that is, the axis in the direction of the motion of the vehicle. This occurs because of couplings, stops, and unloading processes. Some of the carrier sets use vibration isolators to decouple the vehicle vibrations to some degree from the circuit elements themselves. The vibrational problems have been reduced somewhat by adopting solid-state circuits to replace the vacuum-tube circuits. Despite this, there is some feeling that vibration can induce changes to such things as transformers which are slug-tuned. In addition to the vibration environment, there is a substantial exposure to moisture and rock dust. Some of the carrier phone sets are gasketed, but none of them is hermetically sealed.

Several kinds of physical damage have been found on equipments subjected to the mine environment. Radio frequency coils are frequently found out of adjustment because of the continuous vibrations to which they are subjected. Interconnections, boards, supports, and screw terminals are also subjected to malfunction due to the vibration. It is to be noted that electronic heat-generating equipment is useful in the mine environment in that it keeps the electronics dry. Moisture and corrosion are both problems in the mine environment and green, corroded copper has been found in some equipments. It is possible that if the circuit boards were conformally coated with polyurethane, such problems would be alleviated. The dripping that occurs in mines sometimes causes problems if the communication equipment happens to be under such a drip. Other forms of mechanical damage occur because of poor installation and handling, and the ever-present vibration on vehicle installations. Microphones and cables have presented a continuing problem. It is apparent that speakers, such as those used in carrier phones, have not presented much of a problem because they are always protected by a cast housing. It was noted by one organization that services mine electronic equipment that such communication equipment represents the "oddball" in the mining environment, particularly when compared to 50-ton locomotives, with coal-mining equipment, shuttle cars, and portal buses. Thus, there is a natural mismatch between the mine staff and communication equipment.

The electrical environment to which the carrier phones are exposed is extremely severe. 12,000-volt peak pulses of 2 msec have been found on the trolley wire, and a number of failures can be traced to equipment that is not tolerant of this and the other voltage variations that occur on the DC trolley wire. The extreme variation of nominal mine power was illustrated when a nominal 115-volt line exhibited 140 volts and caused equipment failure until it was recognized that this wide a range of voltage had to be accommodated.

Connectors have continued to be a problem due to corrosion and oxidation, and it has even been suggested that terminal strips might be used to solve some of the continuing problems experienced with connectors.

Good electrical grounds continue to represent a problem for mine communication equipment. It has been reported that the only kind of ground that maintains integrity in the face of the mine environment is a solidly welded one.

D. MAINTENANCE

1. Maintenance Problems

A number of maintenance problems occur with carrier equipment. For example, the carrier phones are fused, and the fuses age and open without being actually overloaded; in addition, microphones frequently get broken and the microphone cables are damaged because of rough usage. There are sometimes problems in keeping the transmitters on frequency.

One of the problems related to overall system operation appears to be the presence of dead spots, namely, places where communication between the dispatcher and a mine locomotive is not possible. In many mines, the locations of these dead spots change as the mine advances. The dead-spot problem is usually handled by using the pager phone line as an auxiliary transmission line to carry signals around the dead spots, or to reinforce signals in dead-spot regions.

Microphones on mine vehicles are exposed to an extremely rough environment, which, along with misuse of equipment, often leaves them in a damaged condition. In one instance it was reported that the vehicle operator, during his lunch hour, cracked hickory nuts by hitting them with a microphone. In another instance, a trolley phone repeatedly blew fuses, because the operator was inserting a wire coat hanger through the ventilation holes of the case.

It has also been frequently found that, just after initial installation, a carrier phone system produces fine performance, but, as time goes on, degradation takes place. 'It has been noted that, as mines got larger, using bigger motors, longer haulageways, and more equipment powered from the trolley wire, problems increased. It was also noted that the accumulation of a large number of relatively small amounts of deterioration in the carrier phone system can eventually lead to an inoperative system. The trolley phone systems usually do not receive attention until they become inoperative.

The maintenance of a good carrier communication system requires the maintenance of a good mine electrical system. Maintenance is required both on the pager telephone lines (which, as noted above, are frequently used to carry signals around dead spots) and on the trolley wire itself, including its insulators and the rail bonds. Big mines usually do a better job of maintenance on everything, and captive mines are generally better than the non-captive mines in their maintenance performance. Small mines usually have major maintenance problems.

Other factors leading to deterioration of carrier phone performance are related to corrosion in the mine atmosphere. The moisture in a mine usually has traces of acid in it, which can create problems in electronic equipment. Connectors are prone to failure because of oxides and acid water. It has been found impractical, in some instances, to use printed-circuit card edge connectors because of corrosion problems, and high-quality connectors had to be used instead.

2. Maintenance and Service Equipment

The manufacturers of carrier phone equipment usually recommend at least four items of equipment: a counter, such as an HP-5221B; an AC voltmeter, such as the HP-4278; an oscillator, such as the HP-204B; and a selectively tuned voltmeter, such as a Sierra 127C. In actual practice, such equipment is usually not available to the mine's maintenance people. Most mine maintenance people manage to maintain and service the carrier phone equipment using nothing more than a Simpson or Triplett multimeter. In one mine the tuning of as many as 300 carrier sets is done using no more than a multimeter by zero-beating the subject carrier phone to the dispatcher's transmitter. In this way the dispatcher's set is the frequency standard and all sets are tuned to match the frequency of the dispatcher.

3. Maintenance Resources

While the mine maintenance people manage to do a remarkable job with a minimum of internal resources (including component replacement on cards), should they be unable to restore equipment to functional operating conditions, they usually have at least two outside resources to call upon: the original supplier of the equipment and contract repair services.

4. Mapping of the Carrier Voltages

One of the key means employed by skilled communications personnel in assessing the condition of a carrier phone system is to map the signal strength as a function of position within the mine, the drive source being the dispatcher's transmitter. In general, two types of signal distribution are found in mines: (1) a gradual deterioration of signal level as a function of distance from the dispatcher, and (2) the frequent discovery of dead spots, these being related to standing-wave phenomena on the carrier systems. The use of such a signal map of the mine has been found useful in identifying the deterioration of carrier phone systems with time, corrosion, mining expansion, or poor maintenance.

5. Installation Work

The manufacturers of carrier phone equipment sometimes install the equipment and sometimes merely provide the equipment for installation by the mine personnel. The larger mines usually can undertake the installation themselves; the smaller mines frequently rely on the manufacturer's staff or representatives to do the installation for them.

6. Training of Mine Personnel

The level of training of mine personnel could stand to be improved. In particular, simple aids for training, similar to Army training literature, would be extremely useful. The impetus for this suggestion appears to be that many things that a surface electrician would do naturally are not always done in the mining environment. In particular, strains on cables, bending radii for cables, location of electronics equipment near heat sources, and pinching of cables seem to indicate that some of the basic procedures recognized on the surface are not always recognized in the mining environment.

7. Test Sets

One of the carrier phone manufacturers provides a very simple test set for verifying the performance of various parts of its carrier system. Most users do not choose to obtain these test sets with their systems. Such a test set could be extremely useful for rapid assessment of carrier phone set performance.

E. THE TROLLEY WIRE AS A TRANSMISSION LINE

1. The Unencumbered Line

Early in the program we tried to identify what kind of attenuation factor is associated with a bare, unencumbered trolley wire/rail located in a typical coal mine tunnel. There seemed to be almost no data on this property of trolley wire/rails, except for a figure of about 2 dB per mile at 88 kHz.* Through the cooperation of Dr. Sacks of the Bureau of Mines, Drs. David Hill and James Wait of ITS conducted a theoretical investigation of the unencumbered attenuation that would be expected in trolley wire/rail communication. Figure I-1 shows the results they obtained; viz., that the unencumbered trolley wire/rail represents a low-loss transmission line and should provide for communications over very long ranges with the 25-watt levels of typical trolley carrier phones and typical receiver sensitivities of several millivolts for such phones.

It is thus apparent that the observed difficulty in obtaining long-range coverage on trolley wire carrier phones is associated largely with the parasitic loads imposed across the trolley wire/rail by a number of items in the coal mine, together with the presence of branches on the trolley wire system.

2. Bridging Impedances

There are many sources of bridging impedances across the trolley wire/rail in coal mines. The items listed below represent the kinds of bridging impedances confronted in such coal mines, and that impede carrier frequency transmission.

a. Heaters

The personnel heaters often used in the coal mines may have resistances as low as 5 ohms, and act like a 5-ohm resistance at the carrier frequencies of 88 and 100 kHz.

b. Rectifiers

The number and type of rectifiers and their setback from the trolley wire markedly influence the propagation of carrier frequencies on the trolley wire. The solid-state rectifiers commonly employed in coal mines appear to act as impedances of the order of 1 ohm across the trolley wire/rail and, as such, serve as a major impediment to the propagation of carrier signals on the trolley wire/rail.

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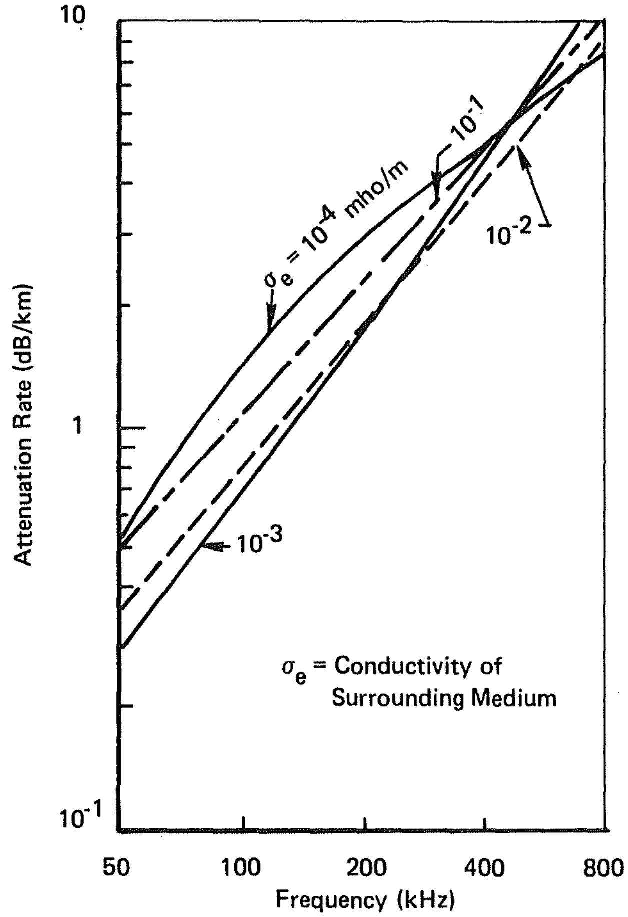
*Lagace, R., et al, Survey of Electromagnetic and Seismic Noise Related to Mine Rescue Communications, Vol. I, Arthur D. Little, Inc., Final Report, Bureau of Mines, Contract HO122026, January 1974.



Source: Wait, J.R., and Hill, D.A., *Radio Frequency Transmission Via a Trolley Wire in a Tunnel with a Rail Return,* IEEE Trans. on Antennas and Propagation, March 1977.

FIGURE I–1 ATTENUATION RATE FOR UNENCUMBERED TROLLEY WIRE/RAIL (σ_e = CONDUCTIVITY OF SURROUNDING MEDIUM; TROLLEY WIRE DIAMETER = 1.5 cm; AND SPACING FROM WALL = 20 cm)

c. Pumps

Many mines employ DC-operated pumps. These are typically rated at a few horsepower, and represent another source of bridging impedance likely to interfere with the propagation of carrier frequency signals on the trolley wire/rail.

d. Motors

A 50-ton Jeffrey locomotive contains four motors, each having the following characteristics: armature resistance, 0.014 ohm; series field resistance, 0.0083 ohm; and motor inductance, 0.08 millihenry under load. Motor inductance equals 2.4 millihenrys at one-sixth load. The inductive reactance for four parallel motors at a carrier frequency of 88 kHz is thus approximately 100 ohms. Measurements such as those made by Mr. Derek Paice* show a somewhat lower value of measured impedance. This may be accounted for by the fact that the motor windings are relatively close to ground surfaces and thus represent a capacitive bypassing of the motor inductance. These motor impedances, then, also act as a further impediment to the propagation of carrier signals on the trolley wire/rail. Furthermore, they are continually moving about the mine, presenting a moving, relatively low-impedance load, thus resulting in variable carrier signal propagation effects.

e. Locomotive and Jeep Light Bulbs

The light bulbs used on locomotives and jeeps at carrier frequencies behave as resistive elements. A locomotive or jeep using two 150-watt, 32-volt headlights with dropping resistors presents the trolley wire with a 30-ohm load on a 300-volt system or 60 ohms on a 600-volt system. These loads represent a loss to carrier frequency propagation on a trolley wire carrier system.

f. Carrier Phones

The carrier phones themselves present a bridging impedance to the trolley wire/rail transmission line even in the receive mode. Depending on model and manufacturer, the commonly used carrier phones present a bridging impedance ranging from 20 to 100 ohms.

g. Vehicles

From d, e, and f above, it is apparent that the net bridging impedance presented by a vehicle is due to three parallel impedances: net motor impedance, the light circuit impedance, and the carrier phone impedance. As an example we use 100 ohms for the motor, 30 ohms for the lights, and 20 ohms for the carrier phones, thus yielding a net impedance of about 11 ohms. This value of bridging impedance presents a severe load on the transmission line.

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*Paice, D., Development of an 88-kHz Active Impedance Multiplier, Phase III, Task A Report, U.S. Bureau of Mines Contract HO122058.

h. Lightning Arrestors

Any system in which the trolley wire emerges from the ground requires that a lightning arrestor be placed on the system. These lightning arrestors are typically comprised of a capacitor in parallel with a spark gap. This added bridging impedance may have either beneficial or deleterious effects on the propagation of carrier signals.

i. Signal and Illumination Lights

Frequently light bulbs are strung across the trolley wire/rail to provide lighting or signaling. In any particular mine the total number of such light bulbs can be a major contributor to the loss of carrier power in the system.

j. Insulators

The insulators used at quite frequent intervals to support the trolley wire to the roof of the mine can, in some instances, represent a substantial loss to carrier frequency signals. This is because they are not intended for operation in the carrier frequency region and the dielectric can typically exhibit a substantial loss factor at the carrier frequencies. The very large number of such insulators aggravates the problem. We have measured the characteristics of typical trolley wire insulators and have found that such insulators over a mile of trolley wire/rail could represent 100 ohms of carrier frequency load. In addition, these trolley wire insulators may become covered with rock dust and dirt and, during the moist season, may represent an even higher degree of loss to carrier frequency signals than our laboratory experiments indicate. Experiments at PMSRC have failed to show added loss due to dust and moisture.

k. Bore Hole Shorts

Where the power leads have been brought down bore holes for powering the trolley wire, the large diameter associated with the leads inside the relatively small diameter conduit can represent a low capacitive shunt reactance to carrier signals. Hence, a further impediment to propagation of carrier signals could result.

3. Isolation of Low-Impedance Loads

Historically, two means have been used to try to increase the level of bridging impedance presented by the rectifiers to the trolley wire/rail. In the first of these techniques, a series choke is used. It is usually made up of several turns of feeder cable in a coil having a diameter of several feet, together with the addition of strengthening members to keep the coil from responding to the forces caused by large currents. These coils can be made to represent on the order of 10 or so ohms at the carrier frequency and, further, may be tuned to resonate at the carrier frequency, thus raising the level of impedance to the order of hundreds of ohms. Approximately 100 pounds of feeder wire are typically used in forming such inductors. A further feature of this method of isolating the rectifier from the carrier frequency signals on the trolley wire is that it also reduces the amount of inband carrier frequency noise generated by the rectifier reaching the trolley wire. In many instances, such tuning is only resorted to at rectifiers, and only when no auxiliary line is available to carry signals past such low-impedance loads.

The second method of treating the rectifier is to tune the rectifier feed-wire leads. This method is successful in instances where the rectifier is set back a distance of more than 50 feet from the trolley wire. In this instance the fact that the feed wire represents on the order of 0.25 to 0.5 μH/ft yields working impedances on the order of 10 or so ohms. Again these may be tuned with a capacitor to raise the impedance level to the order of a hundred ohms, thus markedly reducing the rectifier loading at the carrier frequency.

In comparison to the practices for utility carriers who frequently revert to utility-type traps, the mine-operators act under much stronger cost influences, and are alleged not to be able to afford such traps in their operations. Some mine operators, in fact, have been reluctant to accept the cost of the feed-wire inductors discussed above.

4. Other Impediments to Carrier Propagation

a. Dead Blocks

Where the mine power system is divided through the use of dead blocks, it is necessary to provide an easy path for the propagation of carrier frequency signals through these dead blocks. Capacitors of 600- to 1000-V rating with values between 0.5 and 10 μF are frequently used for this purpose.

b. Rail Bonds

Poorly maintained rail bonds produce arcing noise which contributes to noise on the trolley wire. The key to keeping rail bonds from representing problems to the carrier system is good maintenance of the bonds. In most mines, the main haulageway is properly maintained because it has to be to allow efficient operation of the mine locomotives. Thus, on the main haulageway, this carrier communications problem is usually minimal.

5. Noise Sources

Three classes of noise sources that generate noise on the trolley wire are typically found. Each is described below.

a. DC Supply Noise

Historically, three classes of supplies for trolley wires have been used: rotary machines, mercury-vapor rectifiers, and solid-state rectifiers. The present trend leans toward the use of solid-state rectifiers, although many mines maintain the original class of equipment. The mercury-vapor rectifiers used in the past could frequently misfire, creating a particular class of repetitive noise of high level in the carrier band. Solid-state rectifiers certainly produce less noise than a misfiring mercury-vapor rectifier. It is uncertain whether the solid-state rectifiers produce more or less noise than the rotary machines. One person felt that the noise from the solid-state rectifiers depended on whether a six-phase, half-wave rectification was used in preference to a three-phase, full-wave. He felt that the three-phase, full-wave produced more noise than the six-phase, half-wave rectifier, although the voltage waveform placed on the trolley wire would seem to have the same shape in either case.

b. Mine Motors

Mine motors, both on moving equipment and in fixed locations, such as pump sites, produce arc-generated noise. In one instance a 3-hp pump was placing 100 millivolts of in-band noise on the trolley wire. In that particular instance, the problem was cured by inserting a parallel LC filter in series with the motor.

c. Arc and Spark Noise

Moving vehicles on the trolley wire/rail create arcs and sparks and these contribute to the noise placed on the trolley wire/rail system.

6. Seasonal Effects

Carrier phone system users agree that carrier phone system performance is affected by seasonal variations. During the period from fall to spring when the inside of the mine is relatively dry, communications are good. During the rest of the year when water and dampness levels increase in the mine, communication deteriorates. The decrease in performance is believed to be caused by wet or damp rock dust on trolley wire insulators and on parts of the pager phone lines used as the auxiliary carrier line in many mines.

7. Impedance Levels

Mine operators and equipment suppliers generally agree that if one measures the impedance presented at most places between the trolley and wire and the rail from a parallel entry point, a value typically between 10 and 30 ohms is found. At the carrier frequencies, this value is considerably lower than one would compute for an unencumbered trolley wire/rail transmission line where the characteristic impedance is between 200 and 300 ohms, and hence the parallel entry impedance should be between 100 and 150 ohms. Thus, there is evidence that the many bridging impedances on the trolley wire/rail contribute substantially to a lowering of the nominal impedance presented by the trolley wire/rail.

From the previous discussion, it can be asserted that if the measurements were made near almost any mine vehicle, one could expect to find impedances near the above values, based on the impedance of the vehicle alone.

8. Anomalous Behavior

Two anomalous behavior problems have been reported. The first concerns two vehicles very close to one another, one of which is able – and the other unable – to maintain communication with the dispatcher. This is because of the very sharp threshold effect present in FM receivers, which could be responsible for one set working while the other one did not, due to only slight changes in signal level below the threshold over the distance of vehicle separation. A vehicle being only a few feet closer to a rectifier, for instance, could make the difference between good communication and no communication.

The other problem concerns two locomotives parked very close to one another which are unable to communicate because of the high signal levels blocking the front end of early models of certain low-frequency carrier sets. This problem does not exist today, however, for systems using new carrier phones.

9. Unaided Propagation

Some mine operators and suppliers have reported that it is highly unlikely that a useful trolley carrier communication system could be contrived using present techniques without the aid of an auxiliary carrier wire in any but the very smallest of mines.

F. AIDED TRANSMISSION

1. General

During the 30 years over which trolley carrier phone systems have been used in coal mines for dispatching purposes, a wide body of treatments has developed for overcoming deficiencies in transmission of carrier signals on the trolley wire/rail. As noted in the previous sections, resort has sometimes been made to tuning out the exceptionally low impedance of rectifiers across the line as a means of aiding the transmission of carrier signals. More important perhaps has been the adoption of the use of an auxiliary carrier wire. The idea behind the use of such a wire is that, if the dispatcher is directly connected to an auxiliary wire of this type which is generally free of the extremely low-impedance loads that are found on the trolley wire, then it can be expected that integrity of signal transmission on this wire can be obtained to the far reaches of, and over branches within, a mine. This auxiliary wire is usually coupled through impedance couplers to the trolley wire at appropriate points. In this way, difficult transmission situations have been overcome. In general, one of two kinds of wires is used for this purpose: (1) the pager phone line, used in common mode as a single wire; and (2) a dedicated single-purpose wire used only to aid the transmission of carrier signals throughout the mine. It is recognized that there will be a loss suffered by the signal from a mine motor transmitter on its trolley wire, and coupling to the auxiliary wire. However, once the signal has appeared on the auxiliary wire, it is fully expected that it will reach back to the dispatcher without a high degree of attenuation. Below are noted some of the experiences and comments we obtained in examining this aspect of trolley carrier systems.

2. Use of the Telephone Line

Coupling to the pager telephone lines to aid carrier transmission is usually done by driving the pager phone line in common mode through a pair of capacitors so that the audio frequencies on the phone line are not shorted out by the coupling means. Although the original coupling to the phone line is made in common mode, it is not at all unusual to find that a few hundred feet from the coupling point the common mode has become almost totally differential mode, thereby putting large signal levels across the telephone line. There are sometimes problems when the length of a branch on the phone line is $\lambda/4$ at the carrier frequency, thereby transforming the natural open-circuit termination of the common mode telephone line into a short circuit at the branch point. This in turn confronts the line with the same sort of problems that the trolley wire/rail faces, that is, low-impedance bridging loads. An example of the transfer of common mode signal to differential mode was one where, at the point of coupling, a 100-volt peak-to-peak carrier signal was applied to each phone line. At a fair distance from the coupling point, one line had gone to 300 volts peak-to-peak and the other to 100 volts peak-to-peak, both with respect to ground, thereby applying at least 200 volts of differential mode 88 kHz signal to the telephone circuits.

An opinion was expressed by a service organization that signal couplers could actually be considered as hazardous devices, in that they could connect the trolley wire DC voltage to the phone line. Since the phone line extends into working sections, this could represent a potential hazard. This hazard was further emphasized by the fact that if the ground wire is lost on the coupler, the system could directly apply the 300 or 600 volts to an output terminal of the coupling device.

In addition to this problem, the fact that the couplers connect the trolley wire to the phone wire could, in some instances, place much of the low-frequency, rectifier-generated trolley line noise directly onto the phone lines. Then, if the phone lines were not perfectly matched, this audio band noise could appear in the phone system.

The pager lines are used for this purpose because they generally are found in the same haulageways as the trolley wire/rail is found, and hence are an available means of aiding the transmission of carrier signals. This does not mean that its use is not confronted with problems, as discussed above.

3. Use of a Dedicated Wire

It was the universal opinion of the manufacturers of carrier phone equipment and their representatives that, everything else being equal, they would much prefer to deal with a dedicated wire, that is, a wire whose sole purpose was to improve the transmission of carrier signals, instead of using the telephone pair for this purpose. The telephone pair presents problems, as illustrated above. The use of a dedicated wire gives a considerable degree of freedom in ideally matching this line to the needs of extending carrier transmission. Several examples of the use of a dedicated wire are found in mines today. In the U.S. Steel Robena mine complex there are approximately 4.5 miles of dedicated line used to extend the dispatcher's communication capability. This #10 wire, which is run along the wide side of the entryway, is insulated with neoprene and spaced 12 inches from the rib and roof. This dedicated wire is connected to the dispatcher's transceiver directly, and is coupled to the trolley wire/rail at the far end of the wire. An alternative to this is used in Consolidation Coal's Robinson Run mine, where the dedicated wire is spaced much closer to the trolley wire than in Robena.

There appear to be a substantial number of advantages to the use of a dedicated wire that does not use signal couplers. In particular, such an arrangement would permit the matching of the characteristic impedance of the dedicated wire at the transmitter and at a far-end termination. It could also provide for signal splitting at branches. However, it would appear that the use of the pager phone lines or dedicated carrier wire may be confronted with one particularly interesting feature, in that it is highly unlikely that the velocity of propagation on the trolley wire/rail would be the same as that on the dedicated wire or the pager phone line. It could then be anticipated that, in a mine with an extensive trolley wire network, nulls would occur between signals generated directly from propagation on the trolley wire at one velocity and propagation on the auxiliary carrier wire at another velocity. This would be particularly true if signal couplers were used. It would seem that the use of the closely coupled, non-hardwired-connected, dedicated wire should receive serious consideration since it appears to be the most general and useful way of overcoming the problems of obtaining good transmission of carrier signals in coal mines. The possibilities of this use are treated in Section V.

G. PRESENT STATUS

The present status of carrier phone systems in coal mines is one in which they are a backbone mine communication system. They are not without their problems; in some instances continuing difficulties occur, requiring almost constant attention. The problems of dead spots in the mines and dead spots that move as the mine advances continue to plague operations. The maintenance is done by people generally with a minimum of equipment. In view of the minimal equipment, the mine personnel, in general, do a remarkable job in keeping the systems on the air. Perhaps the greatest lack that these maintenance people have is that of an easy means of mapping the signal levels within an operating mine. The only answers they typically get are the "go," "no go," "the receiver works," or "the receiver doesn't work." They have no indication of the manner in which the signal levels change throughout the mines. The major equipment faults appear to be the continued breakage of microphones and the microphone cables. It seems that the use of a dedicated wire, loosely coupled to the trolley wire, would be the best means of providing a known and controllable transmission path for carrier signals.

H. POSSIBLE IMPROVEMENTS

1. Improved Transceivers

It has been noted that some newer carrier phone equipment has improved sensitivity, in some instances going to 300 microvolts. The use of newer, advanced circuitry, including phase-lock loops, better discriminators, and better squelch circuits, all point to means of improving carrier system performance, particularly in locations where both the signal and the noise have decreased. At these locations the older sets with poor sensitivities will quit operating, although the signal-to-noise ratio may be adequate for operation of sets with improved sensitivity.

2. Use of Other Frequencies

There does not seem to be much opportunity to improve carrier communication systems by altering the operating frequency. If one goes to lower frequencies, the contribution of rectifier noise increases dramatically. At the same time, the inductive impedances of motors tend to fall, making it an even worse situation for propagation along the line. There is little expectation that going to higher frequencies would improve things markedly either. Although some of the bridging impedances would increase in value, the losses which cause signal attenuation on the line are expected to increase if frequencies are increased. The situation is further aggravated by the fact that the requirement for compatibility among communication equipment means that it would be difficult to move away from the highly accepted 88- to 100-kHz frequencies.

There have been reports of attempts to use the South African 325-kHz radio equipment on certain trolley wires with reasonable performance. However, details on the actual results obtained were not available.

3. Low-Impedance Line

In Chapter IV we treat the advantages that might be found by artificially creating a low-impedance line and thereby reducing the effects of bridging impedances. The utility of this approach in an actual mine operation is yet to be demonstrated.

4. Integrated Locomotive Carrier Communication Systems

One manufacturer is considering whether it might not make sense to deliver locomotives with the carrier phone built in, thereby avoiding difficult installation problems met every time that installation is required aboard a locomotive. This integrated system might give a higher degree of physical integrity to the carrier phone on a locomotive.

5. Inductive Coupling

A number of manufacturers and key persons at the Bureau of Mines have expressed an interest in using an inductively coupled carrier phone where direct electrical contact with the trolley wire might not be necessary. A difficulty with this approach may be that the loss faced both "going into" the trolley wire and "coming out" of the trolley wire might be too large. However, a hybrid approach of transmitting on the trolley wire and receiving on an inductively coupled loop could have considerable advantages in certain mines. It would seem worthwhile to conduct experiments to verify this hybrid approach which could make use of some of the advantages of the inductive coupling.

6. Termination of Lines

If dedicated lines are used to control the transmission of carrier signals in mines, these lines should be terminated in their characteristic impedances and, where branches occur, signal-dividing circuits should be used so that standing waves would not develop. An additional advantage enjoyed with the dedicated line is the ability to provide this matching and signal dividing at low voltage.

7. Approval Problems

Some of the manufacturers pointed out the difficulty of introducing new carrier communication systems at the present time. In particular, equipment standards and approval standards for equipment manufactured today are different from those that applied for early models. This fact makes it difficult in some instances to introduce new equipment and, therefore, the older equipment continues to be used and new designs are not being introduced. A way should be found to overcome this real or perceived obstacle.

8. Active Impedance Multipliers

Work has been done by Derek Paice under contract to the Bureau,* using active impedance multipliers to raise the level of bridging loads, such as jeep motors and locomotive motors, so that their bridging impedances are raised to higher values. Such an approach is probably a costly way of improving transmission on the trolley wire/rail.

I. ACKNOWLEDGMENT

This section is based partly on a number of interviews with representatives of the Bureau of Mines, Bureau of Mines' contractors, manufacturers, manufacturers' representatives, and users. In all cases, the persons contacted were extremely helpful and cooperative. We wish to thank the following for their valued assistance:

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Henry Kolesar, Renton Mine
William Simpson, Renton Mine
Paul Mohr, Mathies Mine
Dr. James Wait, Dept. of Commerce, ITS
Dr. David Hill, Dept. of Commerce, ITS

*U.S. Bureau of Mines Contract HO122058.

II. HARDWARE CHARACTERISTICS

A. TROLLEY PHONES

1. Introduction

In Chapter I, we noted the early development of trolley carrier phones and their rapid acceptance as one of the backbone coal mine communication systems. Over the years advancement in state-of-the-art design improvements has been limited by several factors, including the long period of decline in coal production, the limited market for carrier phones, and equipment approval problems. In view of the many problems associated with obtaining and maintaining good performance of trolley carrier phones (as discussed in Chapter I), we conducted a design review of the current models of carrier phones available from three manufacturers to identify possible improvements that could be made to their performance. The review is not a criticism of the designers or manufacturers. Overall when one considers the difficulties presented in obtaining usable transmission of carrier signals on the trolley wire/rail and the adverse conditions to which the carrier phone equipment is exposed, trolley phones have generally provided remarkably useful service.

2. Summary

In this study, we reviewed the circuit diagrams of three commercially available mine trolley phones to assess whether:

(1) their designs were basically sound, and

(2) circuit changes could be made to improve their respective performances.

The two older designs (MSA, Femco) understandably make almost no use of integrated circuits and contain many RF and audio transformers (which are expensive, unreliable, and physically large). The third unit (Pyott-Boone) is of recent design, using several sophisticated integrated circuits and very few inductive components.

Possibilities for improvement in hardware which apply to all three units include:

- Using more state-of-the-art functional integrated circuits;
- Adding a noise blanker to improve immunity to transient noise interference; this would permit increasing receiver sensitivity to help overcome problems with "dead spots" in mines;
- Reducing perceived audio distortion by using more linear frequency modulators, and by preventing clipping of speech waveforms in the transmitter and receiver;

- Adding a speech compressor to the transmitter audio circuits to reduce the peak-to-average ratio of the speech waveform; this would improve the received signal-to-noise ratio by 6-10 dB;
- Controlling the frequency response of the circuits to optimize speech intelligibility;
- Adding circuits to automatically set the receiver output level as a function of ambient noise;
- Substituting efficient power-conditioning circuits (similar to the Femco unit) to eliminate the several hundred watts of heat dissipated by the resistive voltage droppers and the corresponding packaging problems;
- Repackaging the unit so that all circuits are included in the loudspeaker housing;
- Possibly eliminating the change-over relay by use of electronic switching; and
- Adding a tone-controlled squelch capability to overcome the variable noise environment.

Whether these suggestions could be implemented on a retrofit basis is doubtful. Most would represent a substantial effort by a skilled technician, and would cause non-technical problems such as voiding of manufacturers' warranties. A preferable approach might be to design a new "U.S. standard" trolley phone, for which a documentation package could be made available to qualified manufacturers.

3. Design Review

a. Generalized Carrier Phone

Figure II-1 is a general block diagram applicable to all the trolley phones we examined. The units are FM transceivers which operate on carrier frequencies near 100 kHz.

The transmitters consist of a frequency-modulated oscillator running at the carrier frequency. Tuned power amplifiers are used to raise the output level to about 25 watts. The output is coupled to the trolley wire through a coupling circuit which provides DC isolation and harmonic filtering. Carbon microphones are used for ruggedness, and their signals are amplified before being applied to the transmitter modulator.

The receivers are of the TRF type; that is, no frequency conversion is used. Amplifier stages are tuned to the carrier frequency and are designed to limit above a certain signal level. This provides a high degree of rejection to AM signals and impulse noise. The amplifier chain is followed by an FM demodulator, the output of which is amplified to a level suitable for driving a loudspeaker. The loudspeaker is the horn type used in public address systems, rather than the cone type used in sound reproduction equipment. This type loudspeaker gives higher acoustic efficiency at the expense of greater amplitude distortion and reduced

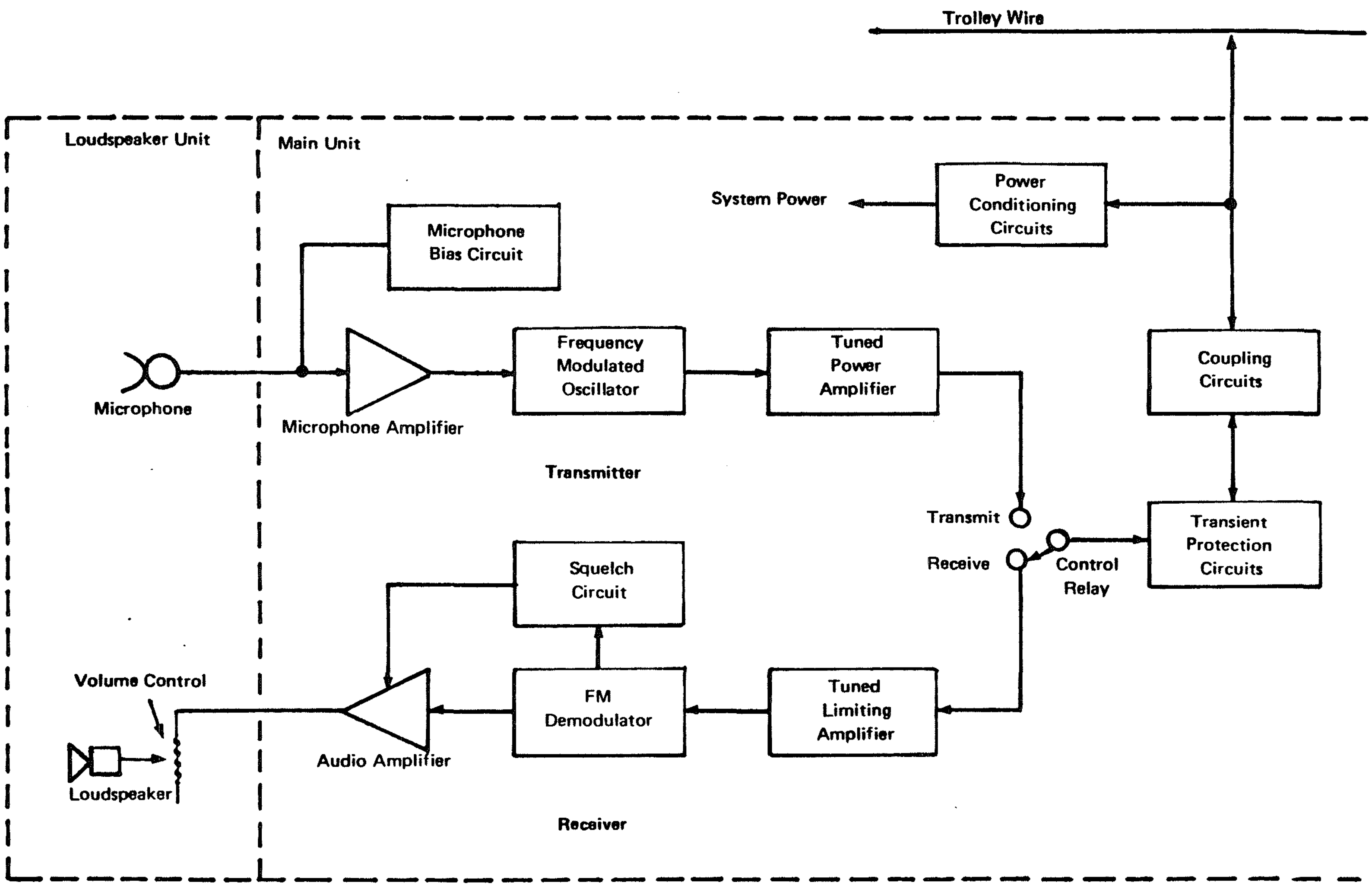


FIGURE II–1 GENERAL BLOCK DIAGRAM FOR TROLLEY-PHONES and less flat frequency response. The receivers include squelch circuits which disable the audio amplifier in the absence of an incoming signal.

Power-conditioning circuits provide transient protection for the transceiver, and convert the 200- to 600-V DC input to the required +12V. The conversion is effected by resistive voltage droppers (which dissipate much heat), or by switching inverters using power transistors (which are complex, expensive, and less reliable).

The basic transmit-receive control function is provided by a relay which is operated by switch contacts on the microphone.

b. The MSA 1601 System

The schematic of the MSA 1601 system is shown in Figure II-2. It is clearly an old design, using many inductive components and no integrated circuits at all. Although this does not prevent it from providing the necessary performance, it can no longer be regarded as a cost-effective design in terms of parts cost and assembly/test labor costs. The frequency-modulated oscillator is relatively crude, and will induce both AM as well as FM on the carrier. It will also act in a non-linear fashion, with resulting audio distortion.

The receiver consists of three tuned RF amplifiers, followed by a diode discriminator for FM demodulation. The audio amplifier is a transformer-coupled, push-pull design with an uncompensated bias circuit in the output stage. The output transformer provides a 500-Ω output for line-driving applications which would not be available from a direct-coupled output stage, but a 500-Ω output is not required on any vehicular installations.

The squelch circuit is the type which monitors the high-fequency noise level of the demodulator output. In the absence of an incoming carrier, the demodulator output is wideband noise. This passes through the squelch amplifier and disables the receiver audio stage. In the presence of an incoming carrier, the wideband noise level drops, and the demodulator output is a speech waveform. This waveform contains very little high-frequency energy, so the squelch circuit is deactivated and the audio stages are turned on.

The MSA power conditioning circuits are shown in Figure II-3. A 12-volt lead-acid battery is the primary power source. When the unit is connected to the high-voltage trolley wire, the battery is continuously charged through a series bank of three high-power resistors. These have values of 96 ohms each and therefore dissipate approximately 300 watts in a 300-volt system. This power level could cause thermal problems unless properly treated.

The coupling between the transceiver and the trolley wire is provided by a series-tuned circuit resonating at the carrier frequency. This circuit partially suppresses harmonics from the transmitter and provides isolation from the DC trolley supply.

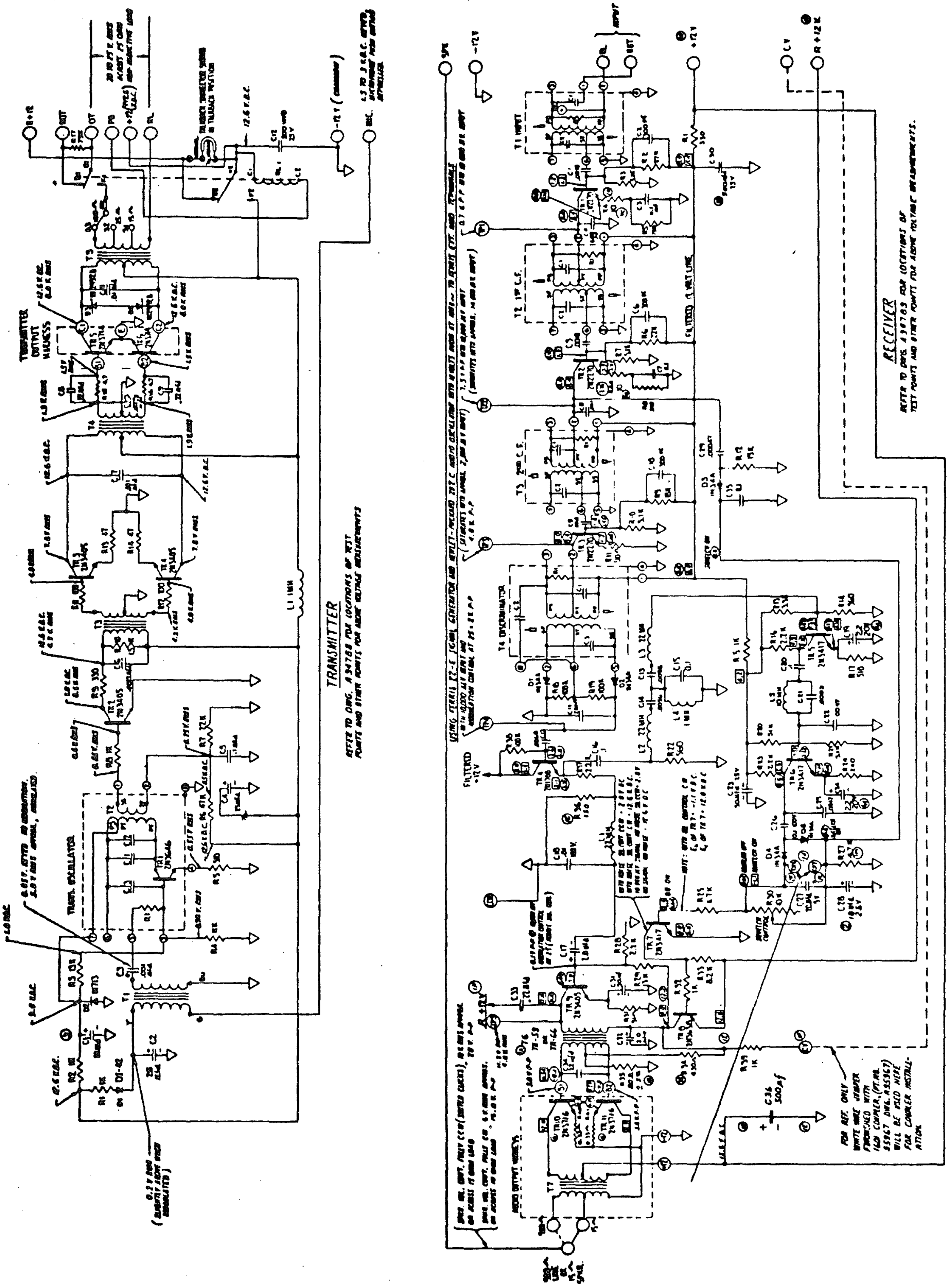


FIGURE II–2 TRANSMITTER AND RECEIVER SECTIONS OF MSA UNIT

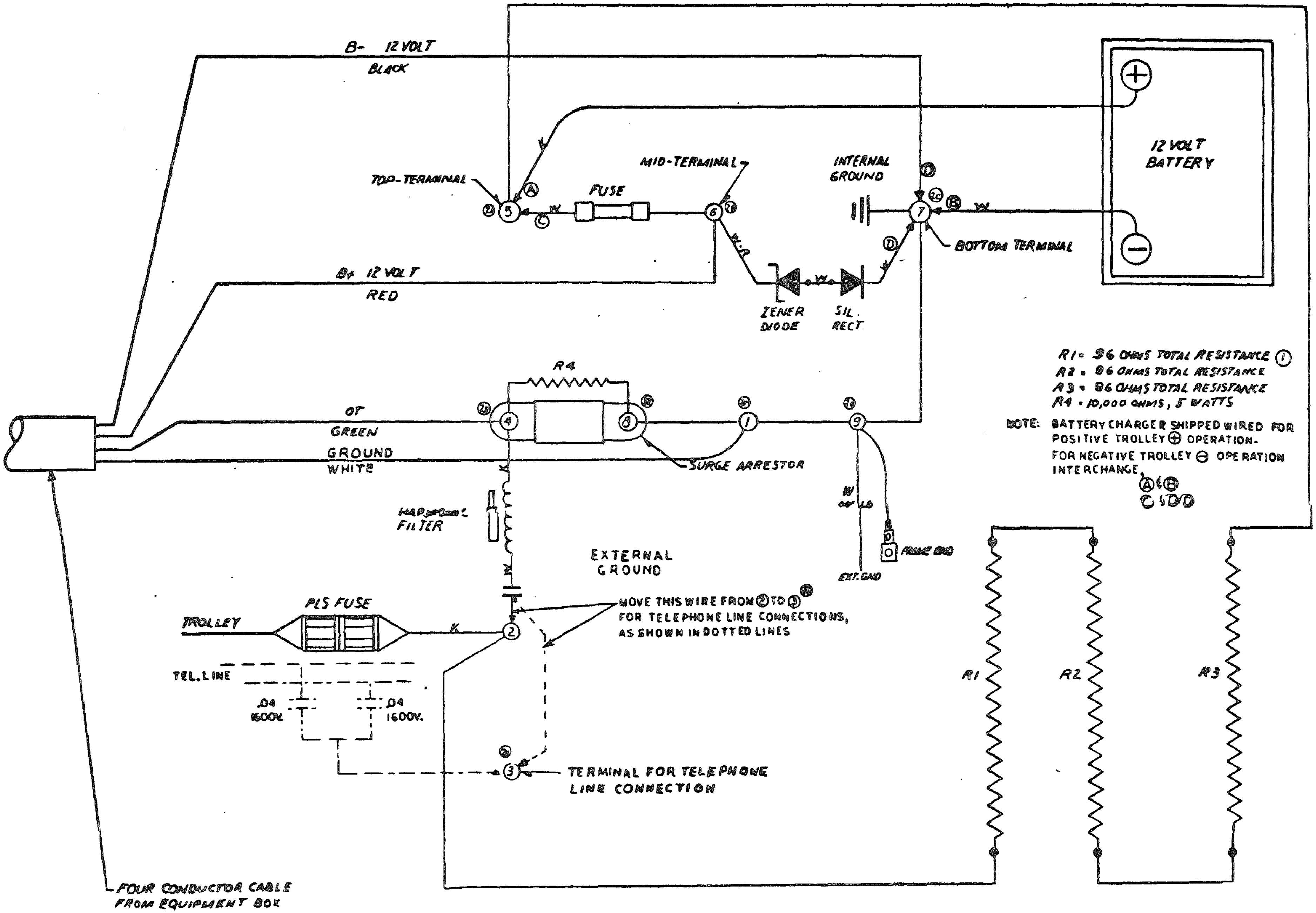


FIGURE II–3 POWER CONDITIONING CIRCUITS OF MSA UNIT

c. Femco Model 731901

The Femco unit (Model 731901) is similar to the MSA unit (above), except for the following:

- Three integrated circuits are used, although each is a relatively simple gain stage;
- The transmitter coupler includes a three-section, low-pass filter for improved harmonic rejection;
- The bias circuit in the receiver output stage is temperature-compensated;
- The receiver squelch circuit operates on received signal level rather than on wideband noise at the demodulator output; and
- The power-conditioning circuit is a transistorized switching inverter followed by a series regulator; this approach is more complex, but is thermally efficient.

Complete schematics are given in Figures II-4 and II-5.

d. Pyott-Boone "Trolley-Comm"

The Pyott-Boone "trolley-comm" unit is of very recent design. It includes several complex linear integrated circuits, which reduce the number of inductive components and makes the unit easier to align. On the other hand, the transceiver circuits are still burdened with many unnecessary discrete components.

The transmitter (Figure II-6) is simple, but could still benefit from circuit minimization. The frequency-modulated oscillator is an IC voltage-controlled oscillator, the control input of which is connected directly to the microphone circuit. The remainder of the unit is an amplifier chain, which includes a conventional push-pull output stage.

The receiver (Figure II-7) uses an IC gain stage (IC1), followed by a phase-lock loop chip (IC3) as FM demodulator. No tuned circuits are used at all. IC4 is an amplifier circuit with AGC and squelch facilities, which processes the demodulator output before it passes to the audio output chip (IC5). This chip has a lower output power capability than the transformer-coupled stages in other units, because of the use of a 12-volt supply. It provides 1.5 watts into an 8-ohm load which should be adequate.

Squelch operation depends on a tone decoder chip (IC2) which is used to detect the presence of a carrier within the receiver passband. In the absence of a carrier, IC4 is muted by IC2.

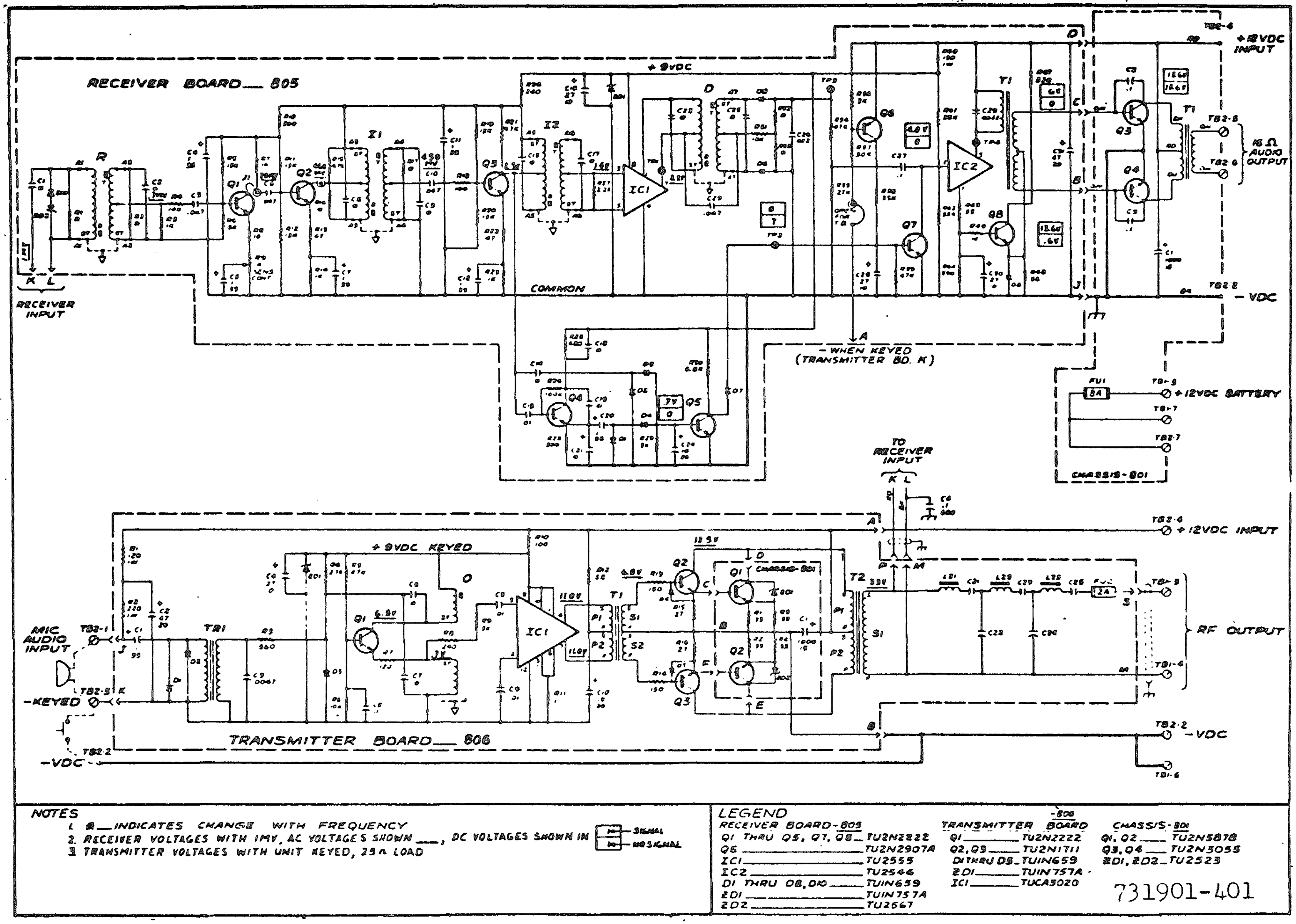


FIGURE II–4 TRANSMITTER AND RECEIVER CIRCUITS OF FEMCO UNIT

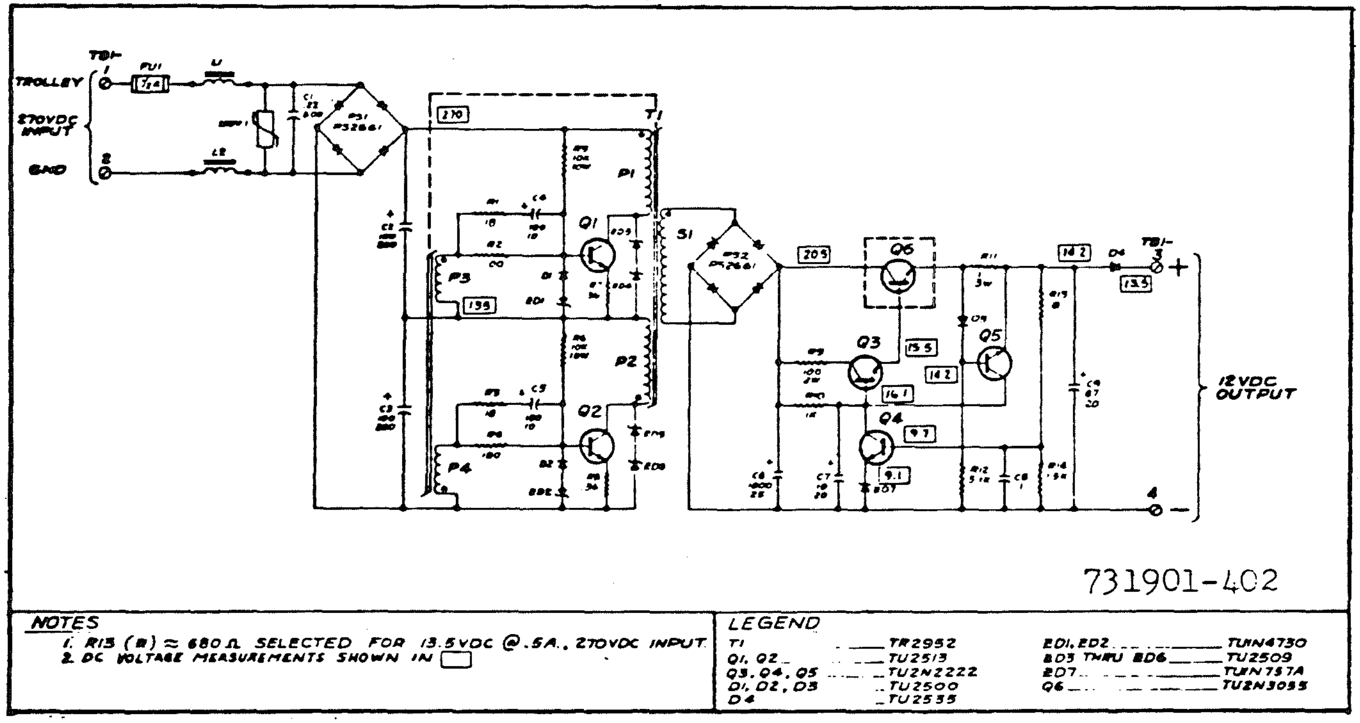


FIGURE II–5 POWER CONDITIONING CIRCUIT FOR FEMCO UNIT

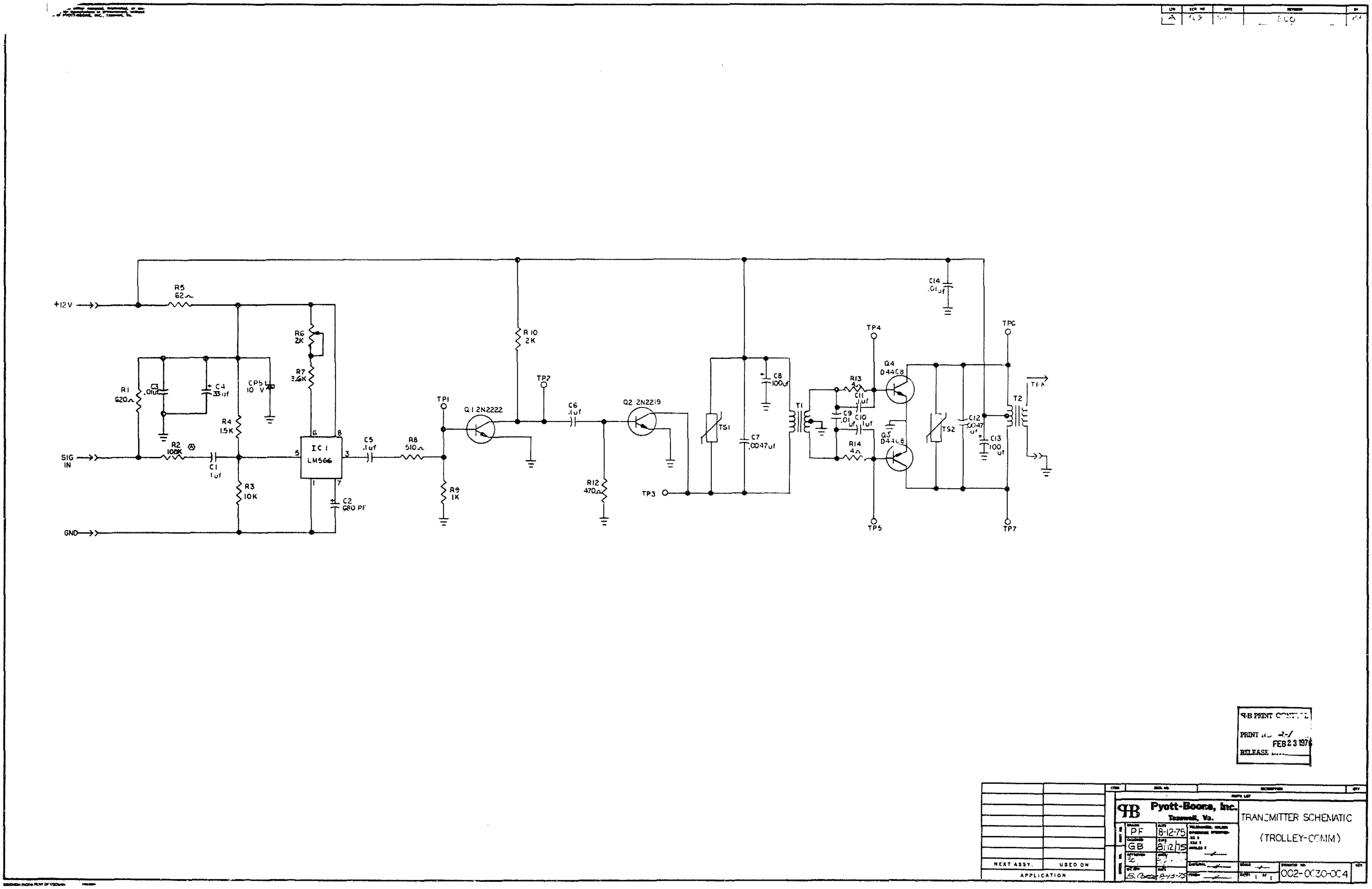


FIGURE II–6 TRANSMITTER SECTION OF THE PYOTT-BOONE "TROLLEY-COMM"

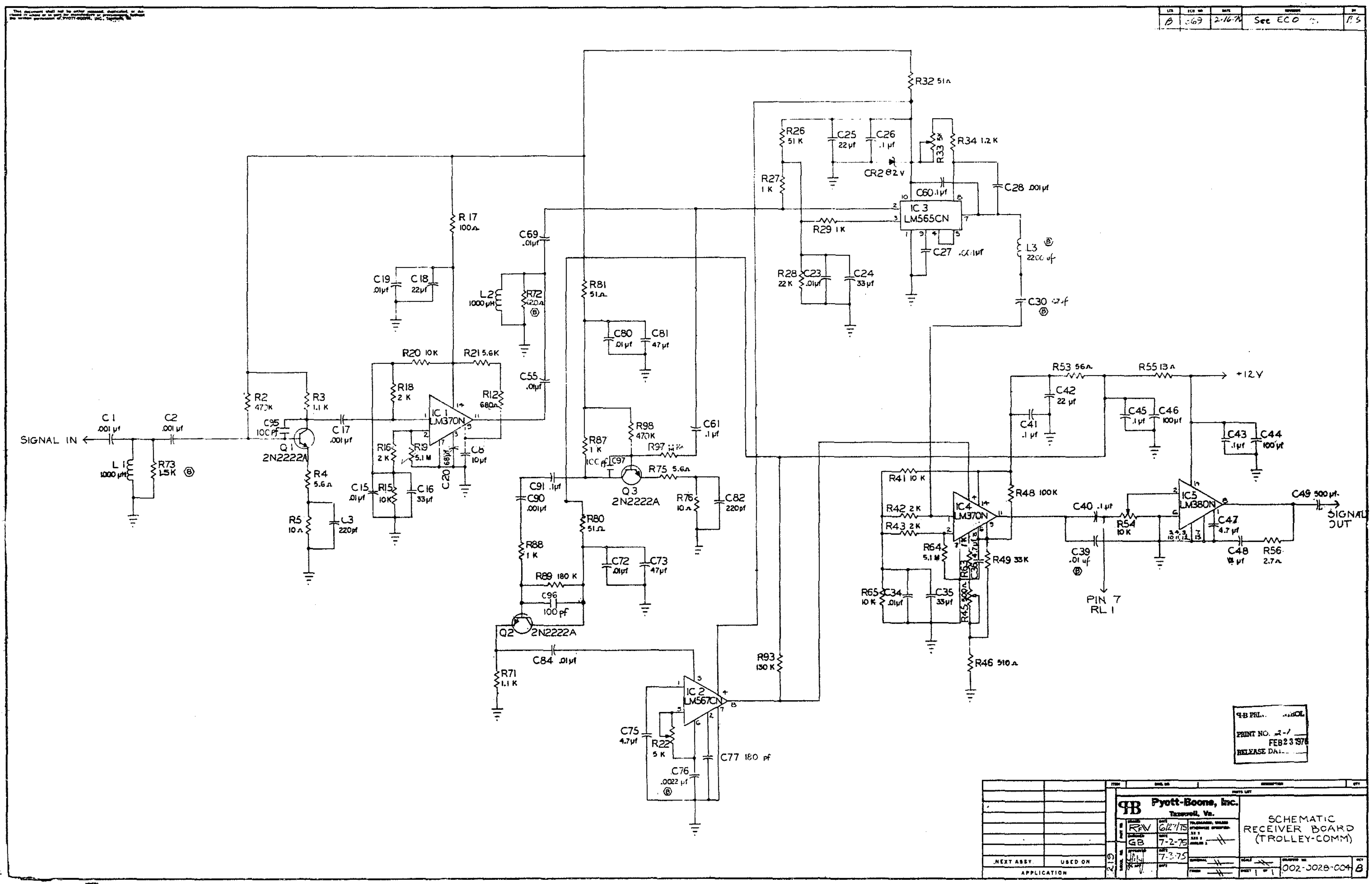


FIGURE II–7 RECEIVER SECTION OF THE PYOTT-BOONE "TROLLEY-COMM"

e. Design Review Conclusions

Table II-1 lists some parameters of the three trolley phones reviewed. The differences between new and old designs are obvious: IC technology has permitted a reduction in parts count (especially in inductive components) and a simplification of alignment procedures.

The trolley phone market is insufficient to justify frequent redesign of equipment, or even thorough cost reduction programs. It is therefore understandable that two of the designs are technically obsolescent, and that the most recent design does not take the best advantage of available components and new circuit design techniques.

TABLE II-1

SOME CHARACTERISTICS OF TROLLEY CARRIER PHONE EQUIPMENT GENERALLY INDICATIVE OF AGE OF DESIGN

	MSA 1601	Femco*	Pyott-Boone
No. of integrated circuits	0	3	6
No. of discrete transistors	17	15	7
No. of inductive components	17	13	5
No. of production adjustments	9	9	3
Power conditioning	Resistive divider	Switching converter	Resistive divider

*Excluding power converter circuit.

4. Suggestions for Improvements

The following suggestions for improvement resulted from three activities:

- Studying how techniques used in other communications systems might be applied to mine trolley phones;
- Devising paper solutions to the problems known to be experienced by trolley phone users today; and
- Applying cost reduction techniques usually associated with high-volume production of electronic products.

a. Use of State-of-the-Art Integrated Circuits

The Pyott-Boone unit has demonstrated that most of the basic functions of an FM transceiver can be implemented with integrated circuits (IC's). However, many types of functional IC's for communications equipment are available, and they could enhance performance considerably (as described in some of the specific suggestions below). In addition, general-purpose

IC's (such as operational amplifiers) are now very inexpensive, and they could be used to reduce parts count in areas where special-purpose IC's are not suitable. [A good example of this is the circuitry around Q2 and Q3 in the Pyott-Boone receiver section.] The following is a partial list of the types of IC's which might be useful.

Operational amplifiers,
Wideband video amplifiers,
Complete IF strip/multi-mode detector chips,
Phase-lock loops and tone decoders,
Voltage-controlled oscillators,
Microphone amplifiers with fast-attack, hang AGC,
Audio power amplifiers,
Series regulators for power supplies,
Switching transistor arrays, and
Timers.

Most of these IC's are available at prices ranging from $0.50 to $3.00, depending on chip complexity and quantity ordered.

b. Improved Performance in the Presence of Transient Noise

The trolley phone environment is inherently noisy, especially since each receiver is attached to a high-power electrical machine which is powered by a sliding shoe on a high-voltage wire. Under these conditions, one would expect a level of transient noise interference that would degrade the system's signal-to-noise ratio. This problem is common in mobile radio installations and in HF radio communications.

Each noise transient consists of a very short-lived, high-energy burst. Each pulse might be only 100 μsec long, which is short compared to the period of the speech waveform with which it is competing. However, several mechanisms exist which could expand the pulse duration by as much as a factor of 1000, thereby reducing signal intelligibility. In the case of mine trolley phones, probable pulse-stretching mechanisms include:

- Ringing induced in loudspeaker resonances in response to a high-energy transient;
- Acoustic echoes in the mine tunnel in response to a wideband transient;
- Overload phenomena in RF and/or AF stages in the receiver; and
- Psycho-acoustic overload phenomena in the auditory system of the user.

In the absence of hard data, it is not possible to predict how communications efficiency would be affected by transient noise. However, circuits known as noise blankers have been used effectively to solve the problem in other applications. The function of a noise blanker is to detect high-energy noise transients before they have been "stretched" and to momentarily mute the receiver so that each pulse is replaced by 100 μsec or so of blanking (which is imperceptible).

One outcome of the use of noise blankers should be improvement in the effective receiver sensitivity. This, in turn, might help to alleviate the problem of "dead spots" in trolley phone systems to which communication is impossible.

c. Reducing Audio Distortion

The mine trolley phones have many sources of audio distortion which affect speech intelligibility. Some of these are almost unavoidable – such as the carbon microphone and the horn loudspeaker – but others can be treated in circuit design.

Low-order distortion (especially second-order) has relatively little effect on speech intelligibility, but high-order distortion (such as that produced by sharp waveform clipping) can make a communications link unusable. Fortunately, the unavoidable sources of distortion are predominantly low order and can be ignored. The following avoidable distortion sources should be treated:

- Two of the designs reviewed use non-linear means for generating a frequency-modulated carrier in the transmitter. This poor behavior can be corrected without cost penalty by using current technology;
- Means should be provided to prevent speech clipping in the microphone amplifier or in the frequency modulator when a user shouts loudly into a microphone held at close quarters (apparently normal practice). This possibility is discussed under Speech Compression (below); and
- Clipping should be avoided in the demodulator and audio amplifier stages of the receiver by the use of automatic gain control techniques or by increasing the dynamic range of these circuits.

d. Speech Compression

Speech waveforms are characterized by a high peak-to-average power ratio. In a communications system, such as the carrier phone, which is peak-power-limited (peak-deviation-limited in the case of FM), the average signal-to-noise ratio will therefore be well below the available peak signal-to-noise ratio.

The average signal-to-noise ratio can be improved by 6 to 10 dB by the use of speech-compression techniques, although the higher figures are only attainable by either severe clipping (with resultant high-order distortion) or by complex and expensive circuits (converting the speech signal to high-frequency double-sideband, clipping the RF waveform, filtering to remove intermodulation distortion, and then converting back to baseband audio). A circuit using a combination of moderate peak clipping and fast-acting automatic gain control could be economically implemented to give a useful improvement in the average signal-to-noise ratio.

Speech compression techniques are widely used in single-sideband (SSB) communications equipment. In the trolley phone application, they would improve effective receiver sensitivity and could further help to alleviate the problems of "dead spots."

e. Controlling Frequency Response

Frequency components below 300 Hz or above 3000 Hz add little to speech intelligibility. The male voice has its energy concentrated at low frequencies. It is therefore advantageous to limit the audio bandwidth of a communications link to include only those frequencies of interest. [This has been universally adopted by the telephone companies and all users of voice radio communications.] In mine communications, bandwidth limiting may also reduce interference from acoustic echoes in tunnels caused by low-frequency components of speech.

There are many points in a mine trolley phone circuit which are amenable to simple bandwidth control. However, the effort should be concentrated in the microphone amplifier of the transmitter (before any speech compression) and in the audio stages of the receiver (before any AGC).

f. Automatic Adjustment of Receiver Output as a Function of Ambient Acoustic Noise Level

A difficulty with using the trolley phones is that the volume control needs frequent adjustment to compensate for large changes in the ambient acoustic noise level. It may be possible to add circuits to the receiver which adjust the audio gain automatically, using the existing microphone to monitor the local noise level. This technique is complicated by the acoustic feedback from the loudspeaker to the microphone, but it should nevertheless be a practical solution to the problem.

Figure II-8 shows one approach to the problem. In normal operation (transmitter and receiver both inactive), the acoustic noise detected by the microphone is used to control the gain of the receiver output stage. The control signal passes through a sample/hold circuit, so that if the microphone signal becomes invalid, the hold circuit can be used to "remember" the ambient acoustic noise level. This occurs any time the receiver squelch circuit detects

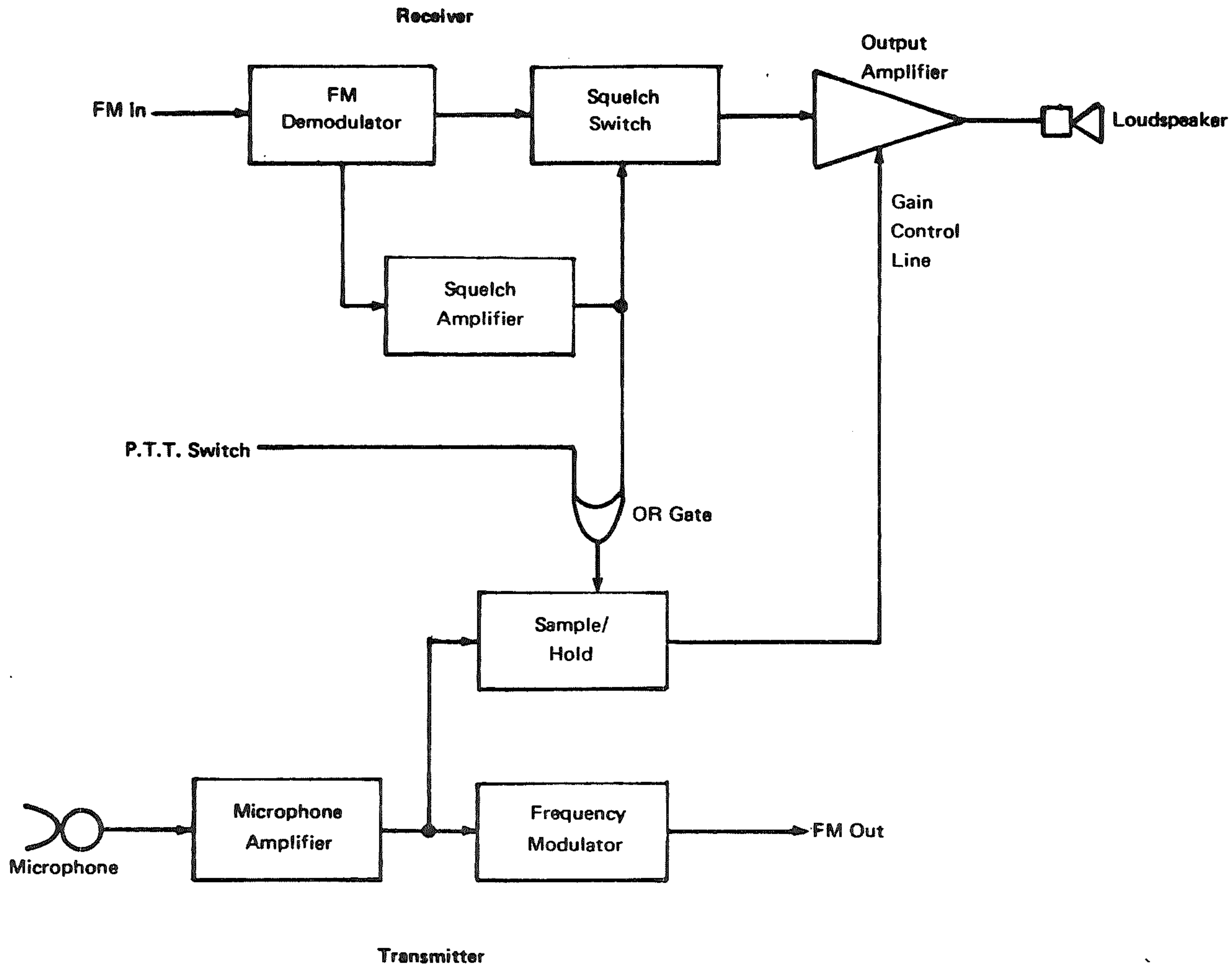


FIGURE II–8 BLOCK DIAGRAM OF APPROACH TO AUTOMATICALLY VARY THE RECEIVER OUTPUT LEVEL AS A FUNCTION OF AMBIENT ACOUSTIC NOISE LEVEL an incoming carrier, or any time the press-to-talk (PTT) switch is operated. A typical OR-gate is used to combine these two functions for switching the sample/hold circuit.

g. Efficient Power Conditioning Circuits

The use of high-power resistors to drop the trolley-wire voltage to 12 volts is very simple, but produces several hundred watts of heat. The Femco unit demonstrated that transistorized switching inverters can solve the problem of thermal efficiency at the expense of circuit complexity, but other approaches should be considered. A simple series switching regulator could be used, although the design may not conveniently provide for operation from positive and negative supplies. The Femco unit includes a transformer, which gives DC isolation, and thus avoids the problem.

h. Repackaging to Reduce Manufacturing Cost

If an efficient trolley phone design could be evolved using IC's where appropriate, it should be quite feasible to mount all the components in the loudspeaker housing. This would eliminate one or two other housings, and most of the connectors and cabling. The only components which would have to be outside the loudspeaker housing would be the line fuse and the microphone. The cost savings achieved by such a redesign would be substantial. Reliability and maintainability would also be enhanced. An example of such packaging is shown in Figure II-9.

i. Replacement of the Change-over Relay by Switching Transistors

The change-over relay controls certain power-switching functions, and switches the "antenna" between the transmitter and receiver. Switching transistors and an electronic transmit/receiver (T/R) switch could replace the relay for a further cost saving.

j. Reduction of Out-of-Band Emissions

As the amount of communications equipment used in mines increases, so will the pressure to reduce mutual interference between different systems. Control of spurious emissions from transmitters will therefore have to be improved over current practice.

In trolley phone equipment, examples of spurious emissions are harmonics of the carrier frequency and excessive signal bandwidth. Most existing trolley phones include at least a simple harmonic filter, but there is much room for improvement. The design of transmitter output filters is complicated by the variability of the load, but computer-aided design techniques might be used in the optimization process.

Signal bandwidth is controlled by ensuring that the microphone amplifier and FM modulator are properly designed. For example, the signal bandwidth of a FM-modulated carrier

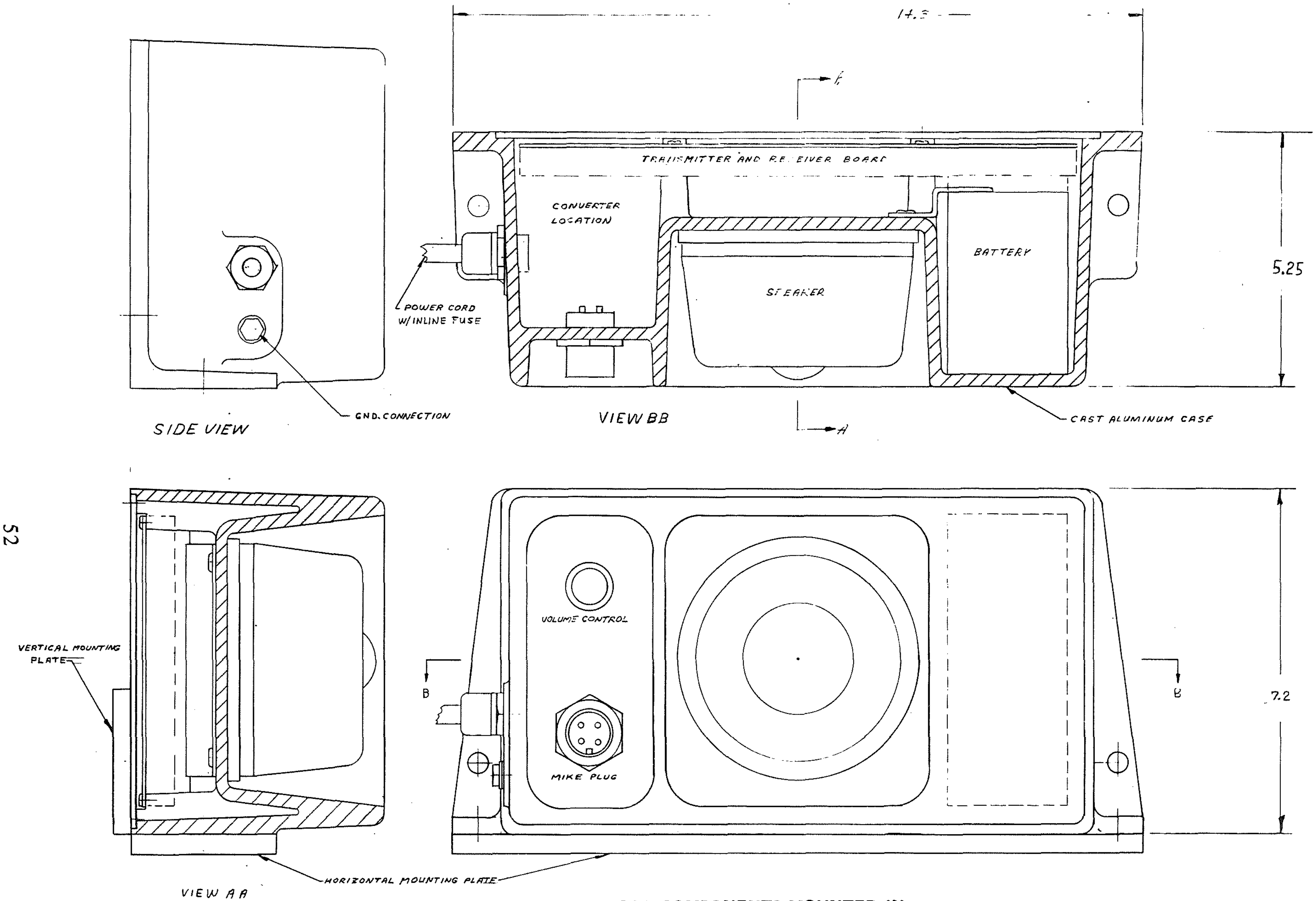


FIGURE II–9 REPACKAGED COMPONENTS MOUNTED IN HANDSPEAKER HOUSING

is unaffected by the non-linearity of transmitter power amplifiers (which may operate in Class C). However, a poor-quality frequency modulator will also amplitude modulate the carrier. When such a signal passes through a non-linear power amplifier, intermodulation distortion causes the signal sidebands to broaden.

k. Tone-Controlled Squelch

Tone-controlled and tone-coded squelch circuits have been used for years in commercial communication equipment. The highly variable noise conditions encountered by trolley carrier phones make them a good candidate for application of tone-controlled squelch. Less breaking of squelch and more certain message reception should be obtained in this way.

B. APPLICABILITY OF A HOIST PHONE

1. Summary

The HCS-102 hoist phone was developed by the Collins Radio Group of Rockwell International in response to the Bureau of Mines' need for a reliable inductive radio hoist phone for deep-shaft metal mines. The unit was designed to meet a detailed specification more stringent than is normal for mine communications equipment, primarily because of concerns about crowding the RF spectrum underground.

The question of whether it could also serve as a state-of-the-art trolley carrier phone has been raised. In this chapter, we address such questions as:

- Could the HCS-102 hoist-phone be used as a trolley carrier phone, with or without modifications?
- Is the specification to which the HCS-102 was designed reasonable for both trolley carrier phones and hoist phones?
- Is the HCS-102 a cost-effective design, and has it taken advantage of recent advances in solid-state technology?
- Should the HCS-102 form the basis of an "industry-standard" trolley carrier phone?

We have compared the HCS-102 with existing trolley carrier phone equipment, studied its specifications, and reviewed its circuit design, and we have reached the following conclusions:

- The hoist phone has too low a power output to be used as a trolley carrier phone, but this could be corrected by modest engineering changes;

- The hoist phone circuits are much more complex than known trolley carrier phone circuits, due in part to the severe specifications on frequency stability and selectivity; its manufacturing cost will be relatively high as a result;
- The hoist phone failed to meet some requirements of the Bureau of Mines and/or Collins specification by large margins; in particular, transmitter harmonic output rejection was only 37 dB, rather than 60 dB; spurious outputs in the vicinity of 100 kHz were rejected by 37 dB rather than 80 dB; and receiver audio output power was 2 watts instead of 5 watts;
- The hoist phone has no dynamic range specification, and since its receiver sensitivity is 300 times higher than a typical trolley carrier phone, overload phenomena may occur when transmitters and receivers are in close proximity (in a trolley carrier phone application); and
- The hoist phone does not provide for operation from 300- or 600-volt supplies; modifications are needed to permit charging the 12-volt lead-acid battery through a resistive dropper (as in the MSA trolley carrier phone), through a switching converter (as in the Femco trolley carrier phone), or by other means.

2. Equipment Specifications

Table II-2 compares some critical specifications for the Collins hoist phone and a typical trolley carrier phone (Femco Model 731901). The important differences between the units are described below.

a. Transmitter Power Output

Trolley carrier phones have output power ratings of about 25 watts, since the noise level at the receiver and the signal path loss are both frequently high. The hoist phone uses a 0.5-watt transmitter and a sensitive receiver, and therefore would not be suitable as a trolley phone without modification. In principle, a power output stage could be added to the hoist phone transmitter, although its implementation might not be straightforward because of packaging constraints or other details.

b. Transmitter Frequency Stability

The Femco unit has a ±0.5% specification for frequency stability over temperature, whereas the Collins hoist phone specification is ±0.25%. This has apparently forced the design away from a simple LC oscillator to a pair of frequency-modulated crystal oscillators whose frequencies are subtracted to obtain the desired carrier frequency. As a result, the Collins oscillator contains almost as many parts as the whole Pyott-Boone trolley phone.

TABLE II-2

COMPARISON OF CRITICAL PARAMETERS OF THE COLLINS HOIST PHONE AND THE FEMCO TROLLEY CARRIER PHONE

Parameter	Femco Spec.	Collins HCS-102: Bureau of Mines Spec.	Collins HCS-102: Collins Spec
General			
Size (in.)	14 x 11 x 6	12 x 12 x 4	–
Temp. range (°C)	-40 to +60	-30 to +50	–
Freq. range (kHz)	61 – 190	30 – 200	–
Transmitter			
Output power (W)	25	–	0.5
Freq. stability (%)	± 0.5	± 0.25	± 0.25
Freq. deviation (kHz)	± 3	± 3	± 3
Harmonic rejection (dB)	-20	-60	-37*
Spurious outputs (dB)	–	-60**	-50*
Receiver			
Sensitivity for 20 dB quieting (μV)	3,000 (300 optional)	10	10
Dynamic range (dB)	80	–	–
Bandwidth (kHz)	± 4 at -3 dB	⩾ ± 5 at -6 dB	± 7 at -6 dB*
Selectivity (kHz)	± 10 at -30 dB	± 20 at -60 dB	± 20 at -60 dB
Audio output (W)	6W into 16Ω	5W into 8Ω	2W into 8Ω*

*Based on Bureau of Mines test data.
**-80 dB required at 88 and 100 kHz.

It is questionable, therefore, whether the Collins circuit represents a good compromise between performance and economy of design for a trolley carrier phone.

The Pyott-Boone transmitter uses a voltage-controlled oscillator which has RC components determining the carrier frequency. This circuit probably has a stability of a few percent over temperature, which leads to the question: Is the Collins design an overkill for trolley carrier phone use?

c. Harmonic Rejection

The Femco unit has a harmonic rejection specification of 20 dB, whereas the Bureau of Mines specification for the hoist phone is 60 dB. Collins achieved only 37 dB in practice, so none of the equipment under review even approaches the 60-dB requirement. The requirement can be met by adding a multisection LC filter to the transmitter output, but this would lead to significant cost increases.

d. Spurious Output Rejection

Spurious transmitter outputs can be created by circuits such as mixers, where high-order sums or products fall inside the pass-band of subsequent amplifier stages. In the Femco trolley carrier phone, the transmitter circuits all operate at the carrier frequency, and spurious outputs are unlikely to occur. In the Collins unit, a mixer is used to obtain the carrier frequency from the difference of two oscillator frequencies. However, the separation of the mixer input and output frequencies is so great that spurious responses should not be a problem. This is confirmed by the output spectrum of the unit, plotted by the Bureau of Mines, which shows no spurious outputs above the –60 dB level, except one of –49 dB at half the carrier frequency. The cause of this spurious output is not obvious.

The Bureau of Mines specification calls for a –80 dB spurious output rejection of any unwanted outputs at 88 and 100 kHz. This is best achieved by traps tuned to these frequencies, but it will only be necessary if a harmonic of the carrier falls close to one of them. The Collins unit does not include such a trap, so the second harmonic of its 52-kHz carrier (–38 dB) falls within the passband of any other mine systems using a 100-kHz carrier.

e. Receiver Sensitivity

The Collins hoist-phone receiver is much more sensitive than the Femco trolley-carrier phone (10 μV versus 3000 μV for 30 dB quieting). The additional sensitivity would be helpful in providing coverage in localized "dead spots" around a mine, provided the noise level at the "dead spot" was sufficiently low.

f. Receiver Dynamic Range

High receiver sensitivity is not itself disadvantageous. However, receivers are capable of handling signals only over a limited dynamic range: typically 60-100 dB, but occasionally as high as 140 dB. The Femco trolley carrier phone sepecification cites a 80-dB dynamic range; from 3 mV to 30 V. The Collins hoist phone has no dynamic range specification, but an 80-dB range would correspond to 10 μV to 100 mV. Above this level, one might expect the Collins receiver to show overload symptoms such as excessive distortion, sensitivity to out-of-band signals, or blanking (desensitization). Since a nearby trolley carrier phone transmitter is capable of supplying signals well in excess of 100 mV, a potential problem exists. However, it is readily corrected by adding an attenuator to the receiver input circuit to lower its sensitivity.

g. Receiver Selectivity

The ability of the receivers to reject adjacent channel interference is a function of the skirt selectivity of the signal filters. The Collins hoist phone uses an electromechanical filter* to provide 60 dB of attenuation at ± 20 kHz from the carrier, whereas the Femco trolley phone uses conventionally tuned circuits to achieve 30 dB at ± 10 kHz. Although these figures are not directly comparable, the Collins circuit probably offers better selectivity. Unfortunately, it does so at the expense of greater circuit complexity: since the electromechanical filter is fixed-tuned, the receiver must be a superheterodyne rather than TRF type.

The high degree of selectivity provided by electromechanical filters is only necessary if adjacent channel interference is created by other mine communication systems. A comprise will have to be made between equipment complexity and future mine communications requirements.

3. Hoist Phone Modifications Needed for Trolley Phone Operation

Before the Collins hoist phone can be used effectively as a trolley carrier phone, at least the following changes will be required:

- Increase transmitter power output from 0.5 to about 25 watts;
- Ensure that the receiver dynamic range is compatible with trolley phone signal levels; this will probably necessitate reducing the receiver gain;** and
- Add power conditioning circuits for recharging the hoist phone battery from the trolley wire (or provide other means for recharging).

* Manufactured by Collins.

** In a trolley carrier phone system where incoming signals are received on a loop antenna, the levels may be lower and compatible with the existing hoist phone receiver circuits.

Once these changes are made, the hoist phone should offer equal or better performance than existing trolley carrier phone equipment.

4. Suitability of Bureau of Mines Hoist Phone Specification for Trolley Carrier Phones

The Bureau of Mines specification for the hoist phone could be used as a basis for a trolley carrier phone specification, but some changes of both substance and detail will be needed for trolley carrier phone applications. For example:

- Some specifications may be unnecessarily tight, such as those for frequency stability, rejection of spurious outputs, operating temperature range, audio response, receiver sensitivity, and receiver selectivity; a slight relaxation of these specifications could have a substantial impact on equipment costs;
- Some specifications need rewording to apply properly to trolley phones; for example, frequent reference is made to signal couplers which do not exist in trolley phones; and
- Some additional specifications might be needed; for example, the receiver dynamic range is not specified.

In view of these comments, extensive rewriting will be required.

5. Cost-effectiveness of the Hoist Phone Design for Trolley Carrier Phone Applications

The HCS-102 hoist phone is much more complex than existing trolley carrier phones, even though it makes use of many integrated circuits. This is due in part to the severity of the specifications, but in many areas fewer components could have been used in the circuit design; e.g., in the receiver audio output stage. The Pyott-Boone trolley phone uses one integrated circuit (IC) and four discrete components for this function. On the other hand, the Collins unit uses one IC and 34 discrete components.

As discussed earlier, the hoist phone specifications led to the use of a superheterodyne receiver and a mixer-based frequency modulator. These two factors at least double the complexity of the unit relative to existing trolley phone designs. The 10-μV sensitivity requirement meant additional gain stages were needed in the design.

6. The Hoist Phone as the Basis for an "Industry Standard" Trolley Carrier Phone

The hoist phone should only form the basis of an "industry standard" trolley carrier phone if it offers substantial improvements over existing equipment. One of the intentions of the

Bureau of Mines specification for the hoist phone was to define equipment which could continue to be useful after an expansion of mine communication systems leading to spectrum crowding underground. This led to the stability, selectivity, and spurious response figures discussed above, and it was expected that the Collins unit would excel in these areas. In reality, its stability and selectivity are only slightly better than the Femco trolley phone (although much better than the Pyott-Boone unit), and its spurious outputs fail to meet specification by a large margin.

Another consideration is that several functional improvements to trolley phones have been contemplated (as discussed in Chapter II). The Collins hoist phone naturally does not include these.

In view of the substantial modifications required by the hoist phone and its specification before it becomes useful in trolley carrier phone markets, the unit would appear to be poorly qualified as an "industry standard" trolley carrier phone.

III. TRANSMISSION MEDIUM

A. TRANSMISSION MEDIUM I – THE UNENCUMBERED TROLLEY WIRE/RAIL

Any assessment of what can be done to improve trolley carrier phone systems has to focus on the transmission medium, which is, the trolley wire/rail. It becomes clear that there are several aspects to understanding the medium, the most important of which are:

- Characteristics of the trolley wire/rail itself as an RF transmission line;
- Characteristics of the bridging loads across the trolley wire/rail and the way they degrade signal transmission; and
- The branches and terminations on the trolley wire/rail and the way they influence signal propagation.

There has been a dearth of information on how an unencumbered trolley wire/rail behaves as an RF transmission line. Discussions with Dr. H. K. Sacks of the Bureau and Dr. James Wait of the Institute of Telecommunication Sciences suggested that ADL formulate a concise statement of the problem and that Dr. Wait address the solution of this problem. Of particular concern was the attenuation rate that the trolley wire/rail inside a tunnel in a conducting medium could be expected to show for the various combinations of frequency, conductor sizes, separation from the rib and roof, and conductivity of the surrounding medium. Results of this theoretical study are shown in the several figures that follow. Figure III-1 shows a representation of the trolley wire/rail. This representation is based on the concept that the bonded rails can be represented as a ground plane and the solution to the problem can be represented as shown in Figure III-1. Results for this model are shown in Figure III-2. From these figures it can be seen that the worst-case attenuation rate to be expected at 100 kHz is less than 0.8 dB/km.

A second model representing the transmission line was also investigated, as shown in Figure III-3. For this model the rails are represented by a single circular conductor buried near the boundary of the tunnel. Figure III-4 shows the expected attenuation rate for this model. These rates are somewhat higher than for the previous model, but still show an attenuation rate of less than 1.2 dB/km in the worst case.

The theory thus indicates that the unencumbered trolley wire/rail represents a low-loss transmission line for carrier frequency signals used in coal mines. For example, if we use an attenuation rate of 1 dB/km and assume that the carrier phone sets can accommodate a 70-dB transmission loss (25 V to 8 mV), then a 70-km (40 miles) communication range could be expected.

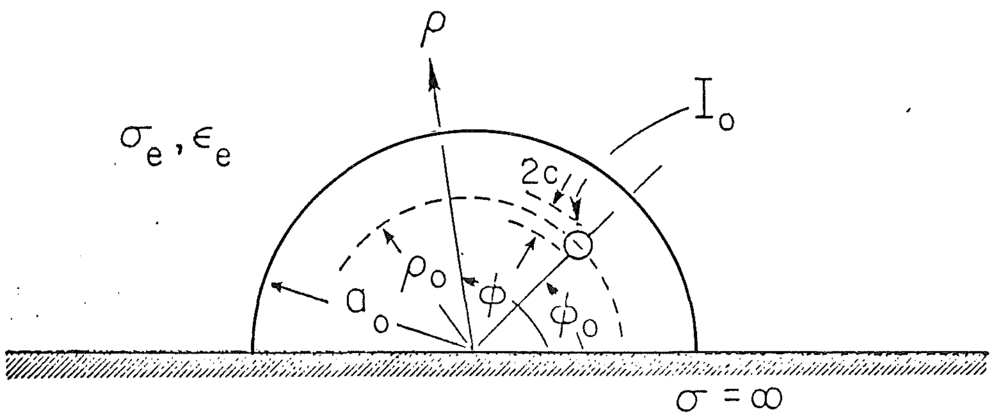
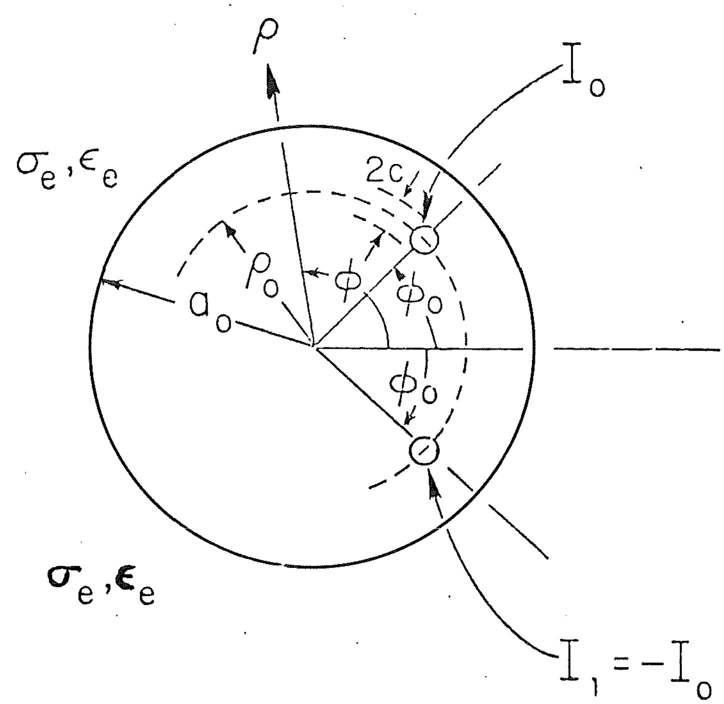
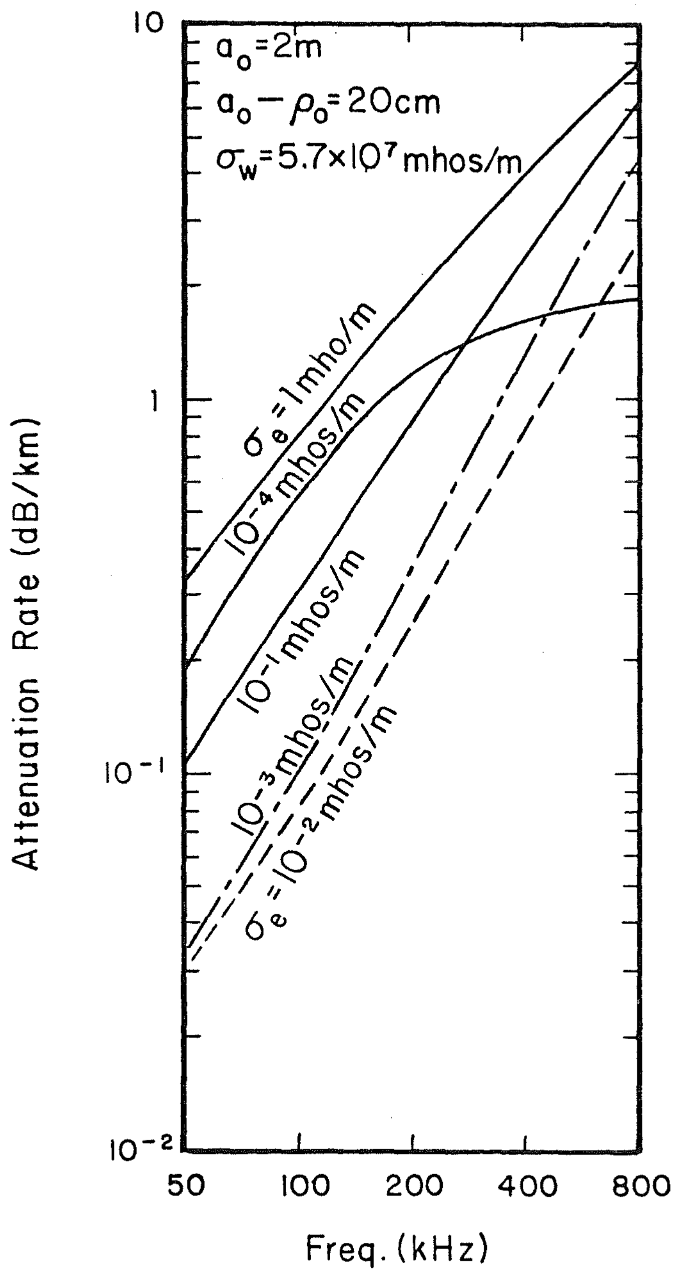


FIGURE III–1a AN AXIAL CONDUCTOR OR TROLLEY WIRE LOCATED IN A SEMI-CIRCULAR TUNNEL



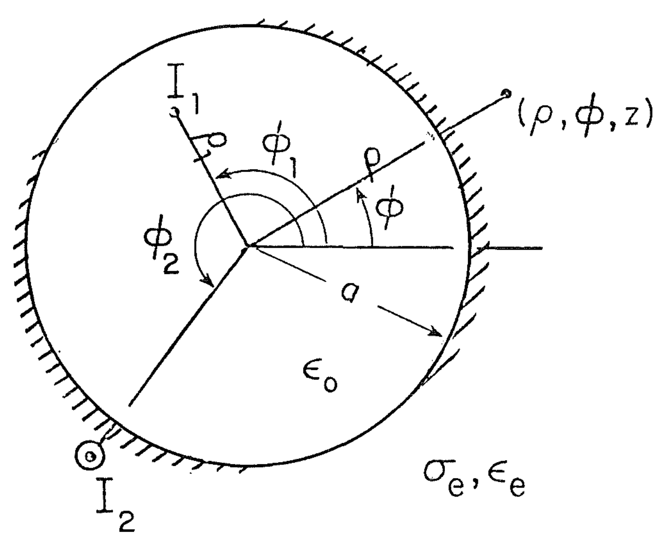
Source: Hill & Wait.

FIGURE III–1b THE EQUIVALENT TWIN-WIRE LINE IN A CIRCULAR TUNNEL



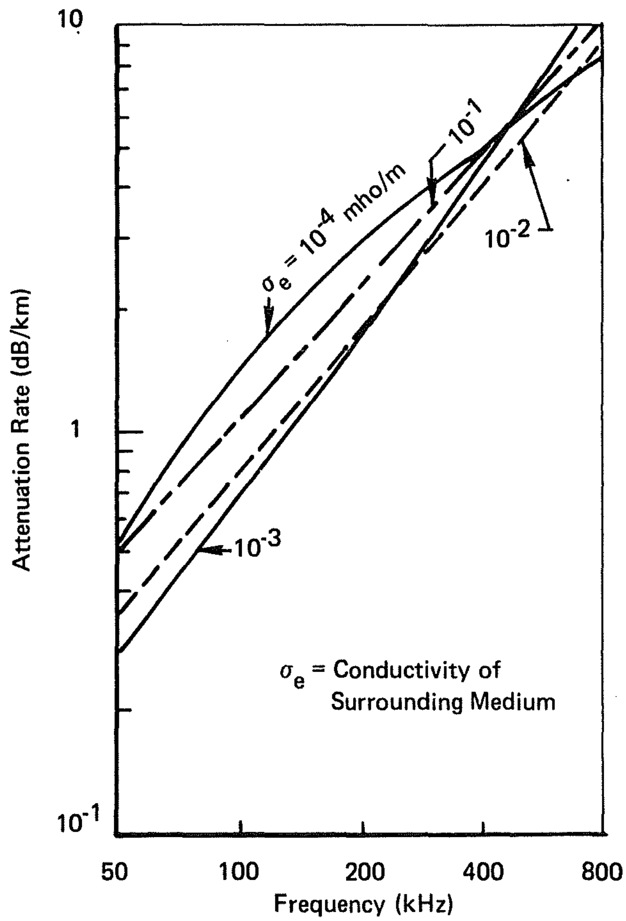
Source: Hill & Wait.

FIGURE III–2 THE DEPENDENCE OF THE ATTENUATION RATE ON THE ROCK CONDUCTIVITY σ_e FOR THE RANGE FROM 10^{-4} TO 1 MHOS/M



Source: Wait & Hill.

FIGURE III–3 CIRCULAR TUNNEL WITH A TROLLEY WIRE AT (ρ, ϕ, z) CARRYING CURRENT I_1 AND A BURIED RAIL OR EARTH CONDUCTOR AT (ρ_2, ϕ_2, z) CARRYING A CURRENT I_2



Source: Wait & Hill.

FIGURE III–4 ATTENUATION RATE OF THE DOMINANT MODE FOR THE MODEL SHOWN IN FIGURE III-3

B. TRANSMISSION MEDIUM II – MINE MEASUREMENTS OF TRANSMISSION LINE PROPERTIES

1. Introduction

The results of the theory for expected attenuation rates of carrier signals on a trolley wire/rail required verification by in-mine tests. With the cooperation of Consolidation Coal's Renton mine and the Bureau of Mines, measurements were made in the Renton mine to confirm the theoretical findings made by Wait and Hill and to conduct other tests regarding signal propagation on trolley wires including the determination of the characteristic impedance and per unit length values of capacitance and inductance.

2. The Test Section

A number of measurements were made on an isolated section of trolley wire/rail at Consolidation Coal's Renton mine on April 3, 1976. Participants in these measurements included Harry Dobroski and William Shiffbauer of PMSRC, Bureau of Mines; John Conti, radio man at Renton mine; Henry Kolesar, underground electrical engineer for Renton; and Richard Spencer of Arthur D. Little, Inc. A typical cross-section of the region where tests were made is illustrated in Figure III-5. Figure III-6 is a representation of the Renton mine showing the region in which the tests were made.

A section of trolley wire 580 feet long, indicated in Figure III-6, was used for the tests. This section was de-energized by opening two power switches. A walk along the trolley wire route was made to ascertain that there were no auxiliary loads on the line. A nip connection for supplying power to a small pump was removed from the trolley wire. Two incandescent light bulbs were also removed. The trolley wire is thus believed to have been completely free of auxiliary loads during the tests.

A number of different measurements were made to determine the fundamental electrical parameters of the transmission line formed by the trolley wire and rail and used for carrier signal transmissions of the mine carrier phone system. The measurements and results obtained are treated in the sequence in which they were performed, as described below.

3. Time Delay Reflectometer Measurements

The arrangement of Figure III-7 was used to make time delay reflectometer (TDR) measurements on the line. With the far end opened, no response was seen using the impulse mode of operation. Using the step mode, a cathode ray oscilloscope response, as noted in Figure III-8a occurred. The inferred length of line using the first arrival of the echo was 505 feet. Similar results were obtained for a short on the far end. Observations of the cathode

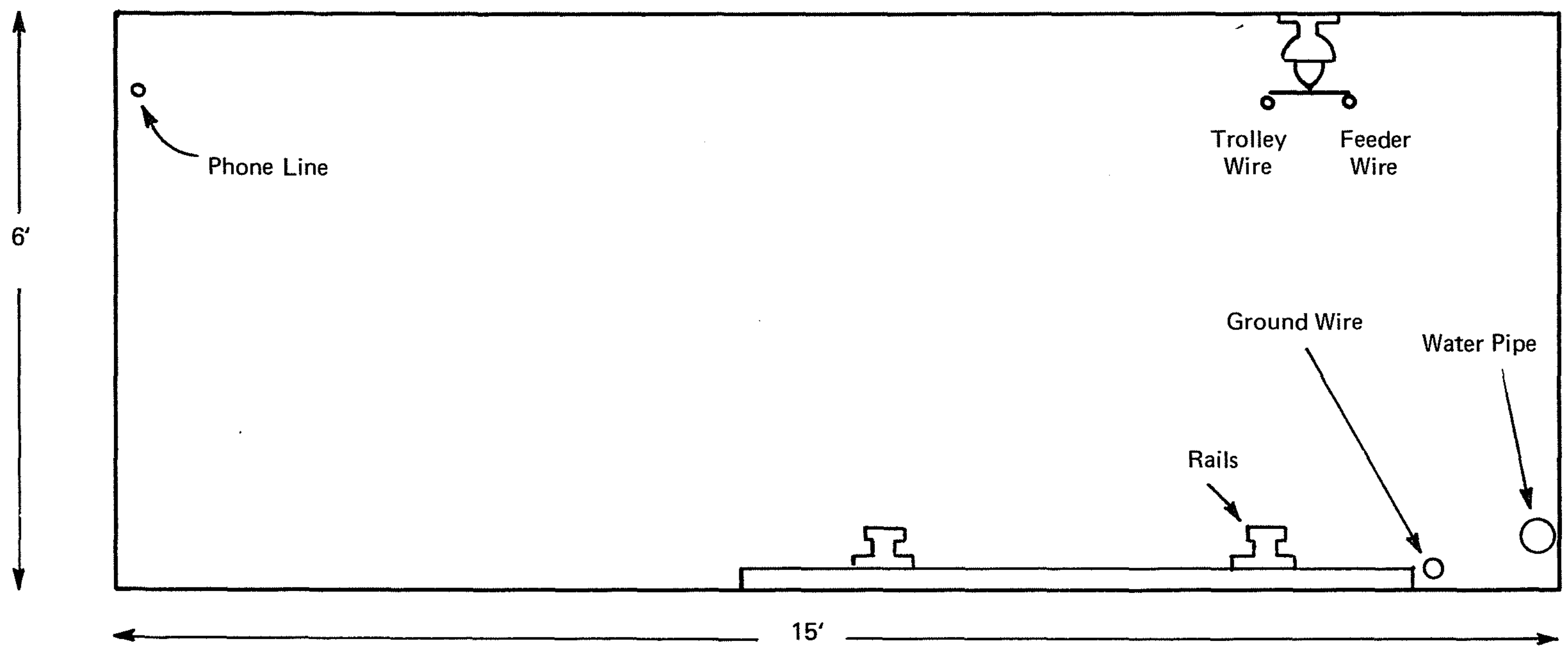


FIGURE III–5 TYPICAL HAULAGEWAY CROSS SECTION

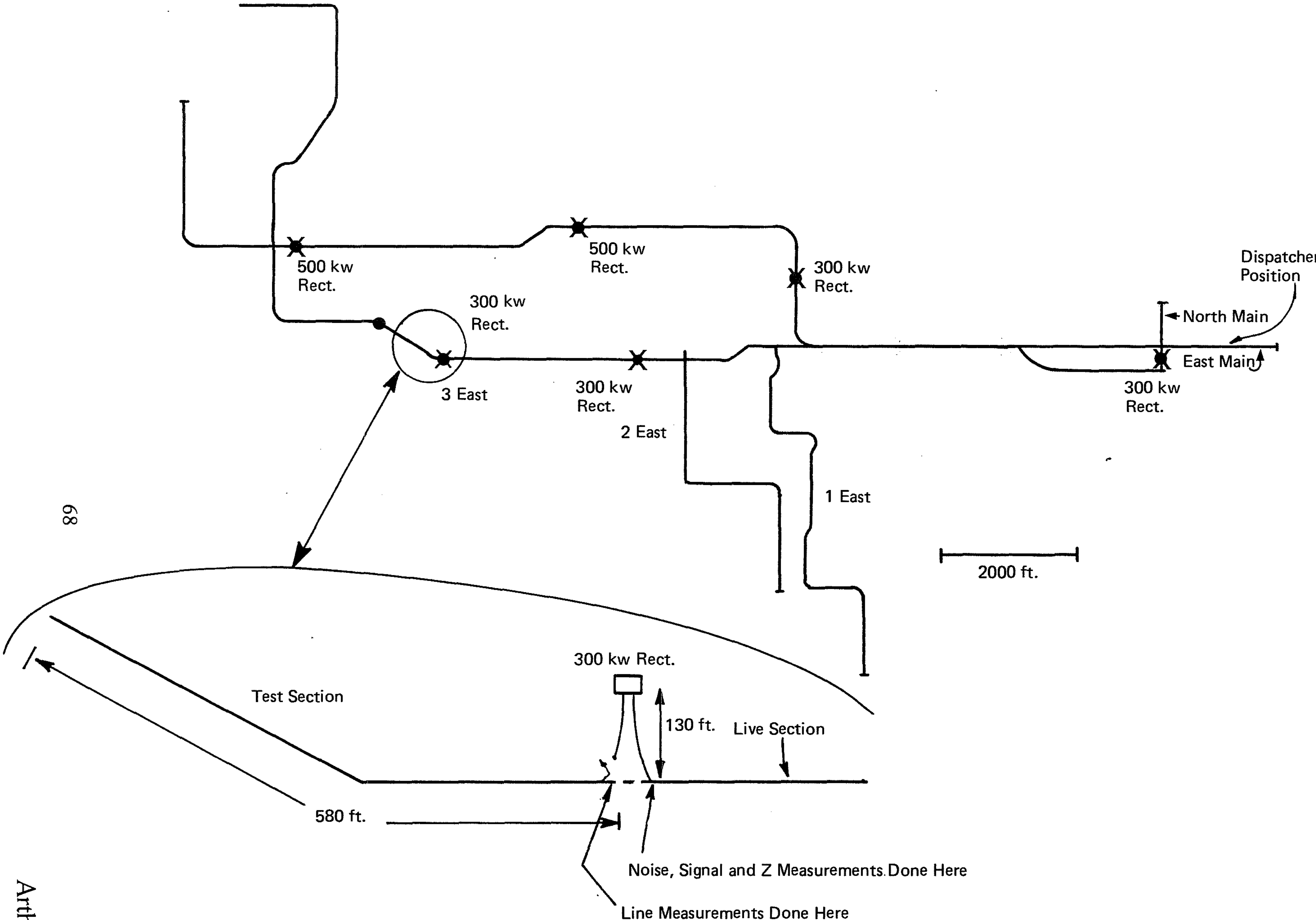


FIGURE III–6 RENTON MINE HAULAGEWAY

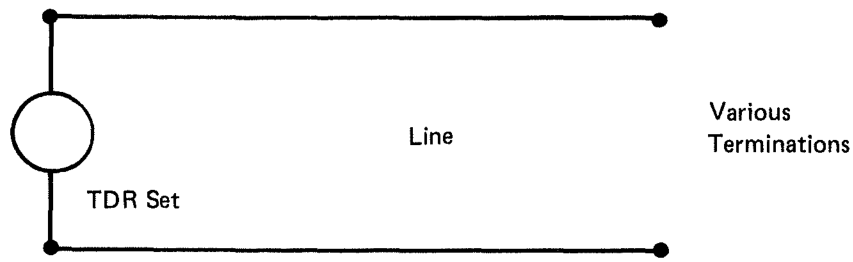


FIGURE III–7 TDR SET UP

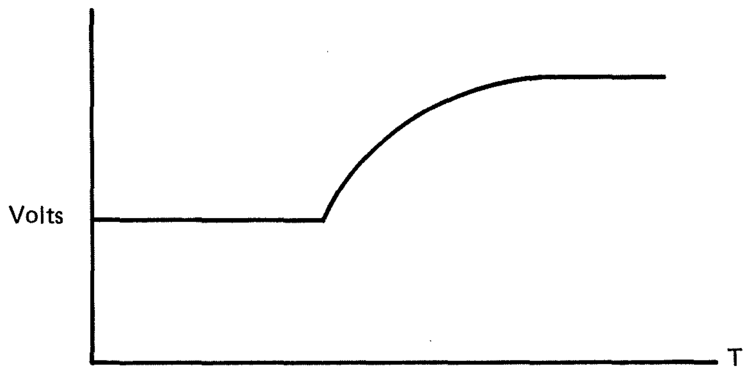


FIGURE III–8a TDR RESPONSE FOR OPEN TERMINATION

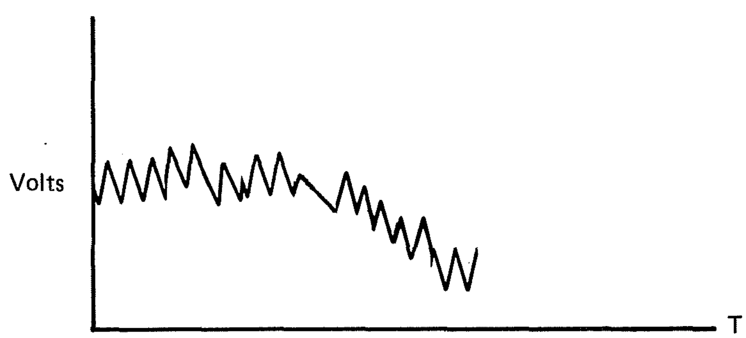


FIGURE III–8b TDR RESPONSE FOR SHORTED TERMINATION

ray oscilloscope of the TDR for a short on the far end were more difficult to make because of a substantial level of 360-Hz ripple (probably due to rectifier current flowing in the rail – open circuit measurements did not evidence this source of noise; see Figure III-8b).

Observations made when the far end termination was varied to seek a match to the line were similarly contaminated with noise. Nevertheless, it was possible to determine two limits within which a nominal "matched-line" condition (the apparent matching of the line) occurred.

The TDR finding was that matched resistive termination lies between 150 and 250 ohms.

4. Low-Frequency Measurements of Inductance

a. Resonant Frequency Method

The circuit shown in Figure III-9 was used to resonate the shorted line. A center frequency of 35.3 kHz was found with the circuit exhibiting a Q of 11.9 (loaded). At this frequency the tuning capacitor of 0.1 μF yields an apparent inductance of 203 μH for the section of line. The wavelength in free space for 35 kHz is 28,000 feet; hence the 580-foot test section is only 0.021 free-space wavelengths long. Thus, the approximation that the measured inductance is the per-unit value times the length of the line holds, and an inductance per unit length of 0.35 μH/ft is found for this line.

The loaded Q is 11.9; the corresponding unloaded Q is 14.5. If all of the loss attributable to this value of unloaded Q is assigned to series resistance of the line, the total series resistance becomes 3.11 ohms or 0.0054 Ω/ft. An estimate of line attenuation, α, can be made using a value of characteristic Z_o of 200 ohms from the results of Section B.3, and the low-loss line formula, $\alpha = R/2Z_o$, where R is the series resistance per unit length. Thus, an α of 0.000116 dB/ft (0.116 dB/1000 feet – 0.35 dB/km) is found.

Similar resonating experiments were done at 77.9 kHz and 109.6 kHz, yielding loss factors of 0.243 and 0.377 dB/1000 feet. These values are plotted in Figure III-10.

b. Current-Voltage Method

An alternate means of measuring inductance was also used, as illustrated in Figure III-11. Here a current source of known frequency was injected into the line (with a short at the far end). The resulting observed voltage across the low-loss line at the place of current injection yields an impedance which consists mainly of inductive reactance from which the line inductance can be determined. The values so obtained at a frequency of 99.4 kHz are:

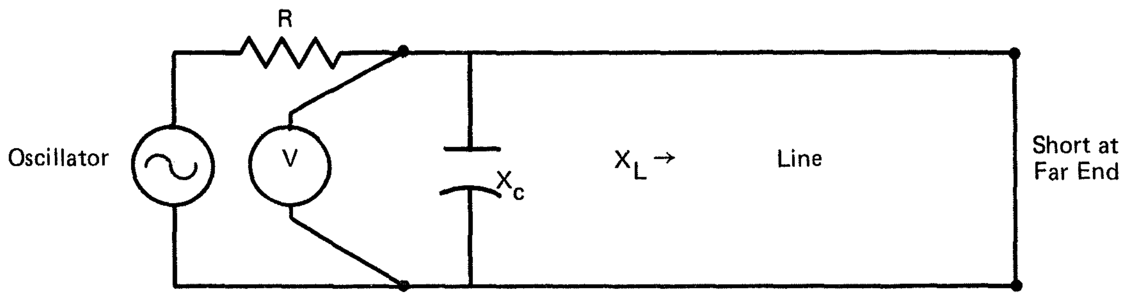


FIGURE III–9 ARRANGEMENT FOR RESONATING THE SHORTED LINE

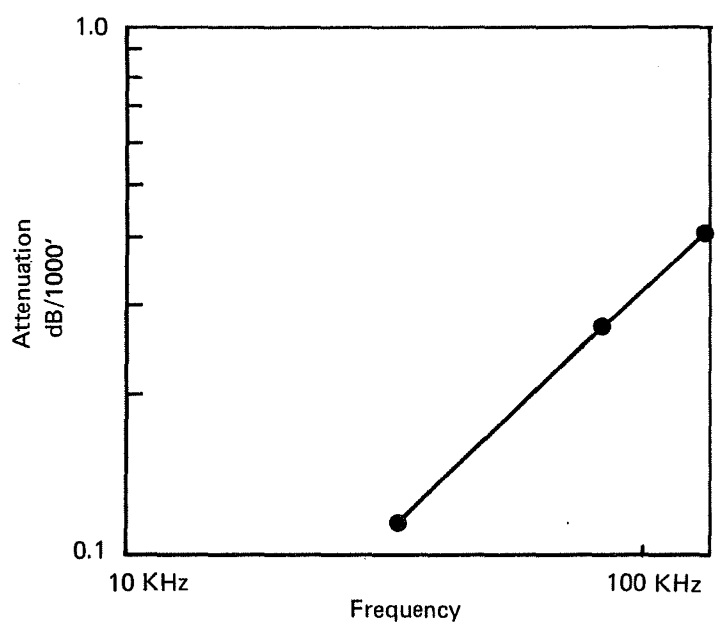


FIGURE III–10 LINE ATTENUATION ASSUMING ALL MEASURED LOSS IS SERIES LOSS

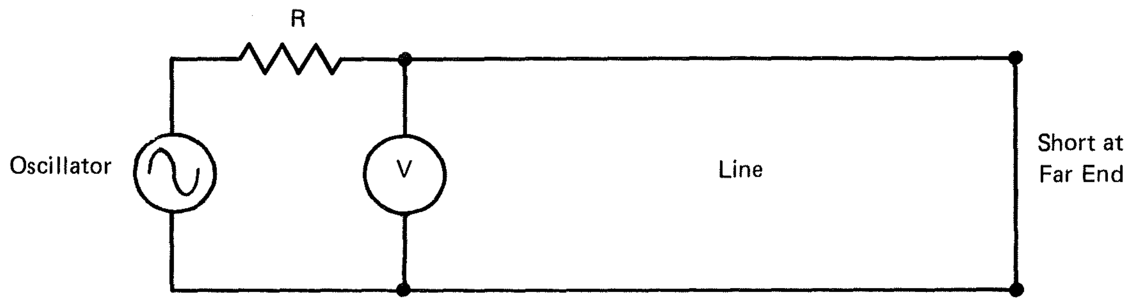


FIGURE III–11 ARRANGEMENT FOR MEASURING INDUCTANCE BY MEASURING IMPEDANCE

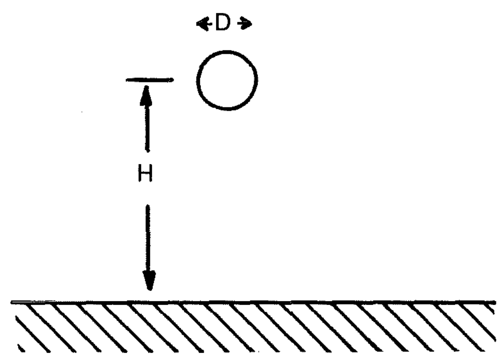


FIGURE III–12 CONFIGURATION OF TRANSMISSION LINE

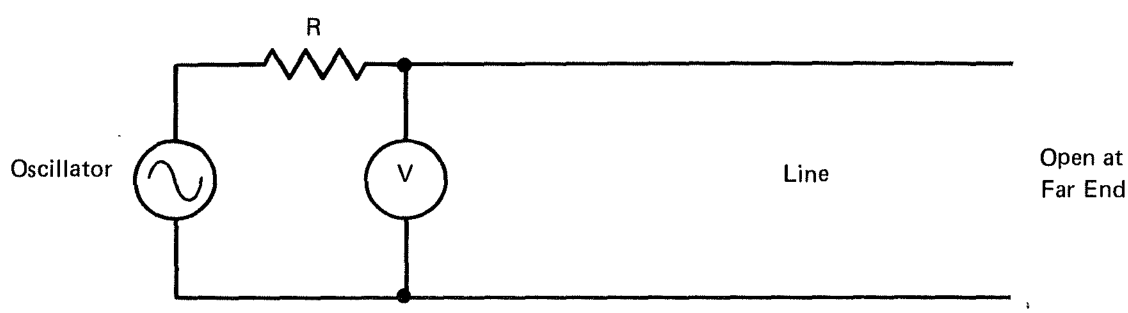


FIGURE III–13 ARRANGEMENT FOR MEASURING LINE CAPACITANCE

$$I = 4.66 \text{ milliamperes,}$$
$$V = 0.46 \text{ volt, and}$$
$$Z = 128 \text{ ohms.}$$

Thus, the inductance of the shorted section of line becomes 205 μH, or 0.35 μH/ft, which confirms the value of inductance obtained from the resonant frequency method.

c. Line Geometry Implications

A transmission line exhibiting an inductance per unit length, L, of 0.35 μH/ft implies a line characteristic impedance Z_O of 344 ohms (for a lossless line with air-dielectric, $L = 1.016 Z_O \times 10^{-3} \mu H/ft$). We examine here what dimension a wire above a conducting plane would be necessary to yield this value of Z_O. Using $Z_O = 138 \log_{10} 4H/D$ (see Figure III-12), an H of 72 inches and Z_O of 344 ohms would require a D equal to 0.93 inch. The feeder wire of the trolley wire is 1 MCM aluminum wire of a diameter slightly larger than 1.0 inch. Thus, the measured value of L is reasonable.

5. Determination of Velocity of Propagation

Measurements of the frequencies at which the shorted line exhibited the quarter- and half-wavelength maxima and minima, respectively, of impedance were made using the configuration of Figure III-11. Over the frequency range of the oscillator employed, the two maxima and the two minima were found to occur at the frequencies and corresponding wavelengths shown in Table III-1. Since the physical length of the line is known to be 580 feet, and $\lambda \times f = v$, the actual velocity of propagation v on the line can be determined relative to that of the velocity of propagation in free space v_O at each of these four frequencies. The values of v compared to v_O are shown below in Table III-1. These results indicate a velocity, and therefore wavelength, in the vicinity of 60% of the free-space values.

TABLE III-1

FREQUENCY MEASUREMENTS

Maxima and Minima Responses for a 580-foot Shorted Line	Wavelength, λ (feet)	Relative Propagation Velocity (v/v_O)
$\lambda/4$ Maxima @ 248.9 kHz	2320	0.588
$\lambda/2$ Minima @ 541 kHz	1160	0.639
$3\lambda/4$ Maxima @ 809 kHz	773	0.637
λ Minima @ 1135 kHz	580	0.670
		0.670 (average)

6. Low Frequency Measurements of Capacitance

Experiments similar to those of Section B.4 were made for the case of the far end of the trolley wire/rail having an open termination, as shown in Figure III-13.

a. Current-Voltage Method

Again, using the fact that for low frequencies the capacitance at the drive point is the capacitance per unit length times the length, the measured values of capacitance using the "current source" and measured voltages are found to be:

F (kHz)	Capacitance/Foot (pF)
22.1	13.1
36.8	12.2
55.1	11.7

The surprising fact is that the capacitance varies with frequency. We believe that this behavior is due to the properties of the insulators supporting the trolley wire (treated in Section B.10).

If we accept the value of 0.35 μH/ft as the true value of line inductance with a corresponding characteristic impedance of 344 ohms for an air-dielectric, then we would expect the capacitance per unit length to be:

$$C = \frac{1.016}{Z_o} \times 10^{-3}\ \mu\text{F/ft, or}$$

$$2.95\ \text{pF/ft.}$$

This represents the minimum value of C possible for this line, which is a factor of 4 less than the values measured.

b. Resonant Frequency Method

A second method for measuring C was used, as illustrated in Figure III-14. Here, the open circuit line resonated with a 1-mH inductor at 63.2 kHz, yielding a capacitance of the line of 6340 pF, or 10.9 pF/ft. A similar measurement using 0.5 mH produced a resonance at 88.5 kHz, and yielded a capacitance of 6470 pF, or 11.2 pF/ft.

c. Determination of Attenuation Factor

The loss factor of the line at 88.7 kHz was determined by measuring the Q of the line; this measurement showed that a loss attributable to a shunt resistance (line conductance loss) had a

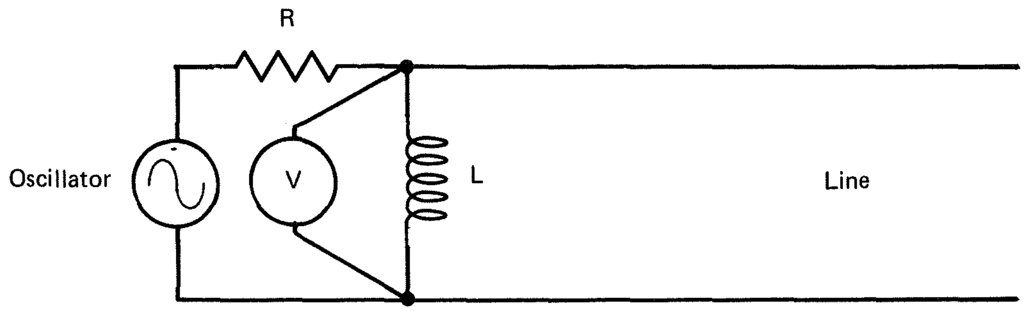


FIGURE III–14 ARRANGEMENT FOR RESONATING THE OPEN-CIRCUITED LINE

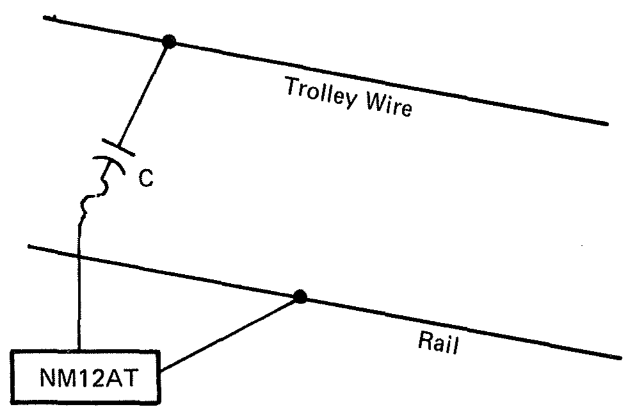


FIGURE III–15 MEASUREMENT OF TROLLEY WIRE VOLTAGE

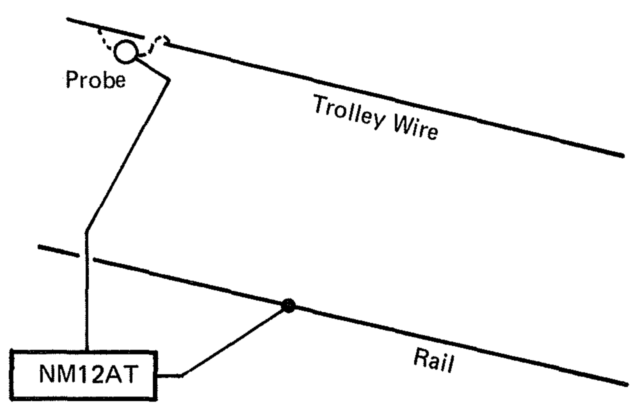


FIGURE III–16 MEASUREMENT OF TROLLEY WIRE CURRENT

value of 1990 ohms. Using the low-loss line attenuation formula,

$$\alpha = \frac{G}{2Y_o}$$

this shunt loss corresponds to a shunt attenuation factor of 0.75 dB/1000 feet.

7. Determination of Velocity of Propagation

Using the same experimental set-up as in Section B.5, and observing the half- and quarter-wavelength maxima and minima, respectively, of the input impedance, the results shown in Table III-2 were obtained:

TABLE III-2

FREQUENCY MEASUREMENTS

Minima and Maxima Responses for a 580-foot Open Line	Wavelength, λ (feet)	Relative Propagation Velocity (v/vo)
λ/4 Minima @ 270 kHz	2320	0.638
λ/2 Maxima @ 537 kHz	1160	0.634
3λ/4 Minima @ 841 kHz	773	0.662
λ Maxima @ 1056 kHz	580	0.623
		0.639 (average)

When compared to the previous shorted termination results, the average values for velocity of propagation agree very well.

8. Signals and Noise on Trolley Wire

The configurations of Figures III-15 and III-16 were used to measure* signal-to-noise ratios on the trolley wire. The measurements were made on the live section of trolley wire, as shown in Figure III-6. The setback of the rectifier was 130 feet from the rail. Figure III-17 plots the results. In this region of the mine, it is seen that the signal-to-noise ratio for signal currents from the dispatcher is better than the signal-to-noise ratio for signal voltages from the dispatcher. This result is not surprising in that the position of the measurement is one near a low-impedance shunt (the rectifier) that results in reduced values of signal voltages compared to signal currents, and which is also a local source of noise.

This figure also shows the rapid fall-off of both voltage and current noise as frequency increases, the rate falling somewhere between $1/f^2$ and $1/f^3$.

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*A discussion of the current probe used for this measurement is presented in the Appendix.

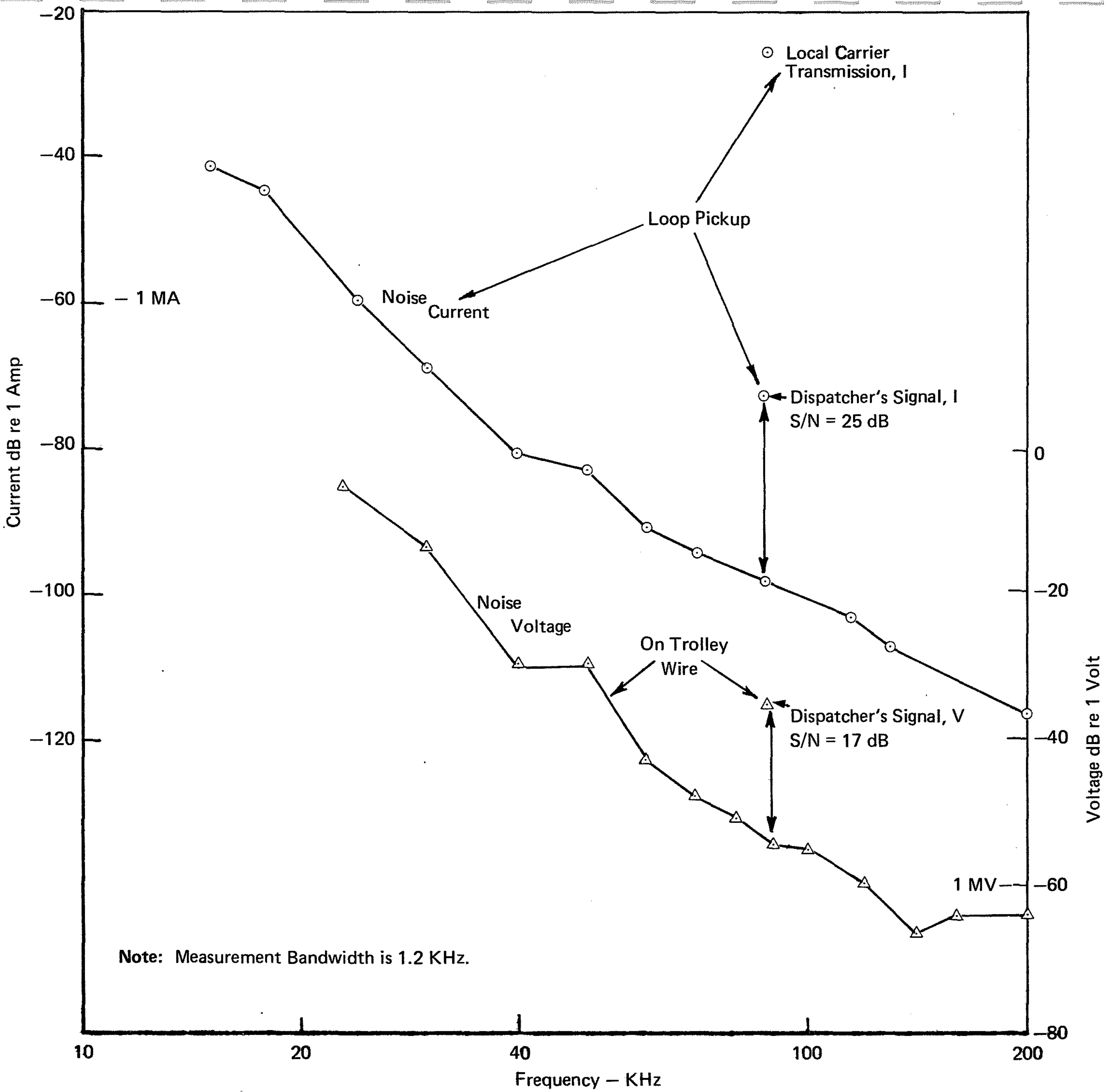


FIGURE III–17 TROLLEY WIRE VOLTAGES AND CURRENTS – RENTON MINE

9. Line Impedance in the Vicinity of a Rectifier

The configuration of Figure III-18 was used to measure the impedance that the trolley wire/rail presents to a shunt entry point located near a rectifier. A drive current was injected into the line and the voltage was measured at the entry point shown in Figure III-6. The rectifier was set back 130 feet from this point. The following results were obtained for a drive current of 1.67 mA:

Frequency (kHz)	V_o (mV)	Z (ohms)
60	35.5	21.3
80	39.8	25.8
100	50.1	30.0

The frequency behavior of Z suggests that the impedance is inductive. A value of L = 51 μH would result in the values of 19.2, 25.6, and 32.0 ohms at the test frequencies. If the 130-foot length of rectifier feeder wire is assumed to dominate, it would exhibit an inductance per unit length of 0.39 μH/ft. This is consistent with the values obtained for the trolley wire/rail, which has approximately the same geometry as the feeder line.

10. Insulator Characteristics

The 580-foot test section had 47 trolley-wire hangers and associated insulators supporting the trolley wire. The unexpectedly low velocity of propagation led us to suspect that the insulators may be an influence on producing this low velocity. For this reason we brought back a typical insulator and subjected it to tests in the laboratory. The results of these tests are plotted in Figure III-19. At the operating frequency of 88 kHz, the capacitance of the insulator is measured to be 37.5 pF, thus contributing 1762 pF, or 3.04 pF/ft to the line capacitance. The equivalent shunt resistance of 160 kilohms per insulator measured at 88 kHz means an equivalent shunt resistance of 3404 ohms across the test section containing 47 insulators. This results in a corresponding attenuation rate of 0.44 dB/1000 feet, using the equation, $\alpha = 2G/Y_o$.

For a low-loss line, the velocity of propagation is $v = 1/\sqrt{LC}$. We have found that the measured velocity of propagation is about 0.64 of the free space value. This value corresponds to a relative phase constant of 1.56. Using the above value of v and the measured value of line inductance, L = 0.35 μH/ft, we find from $1/v^2 L$ that the value of line capacitance per foot must be 7.2 pF (including contributions from all sources). For a line approximating the

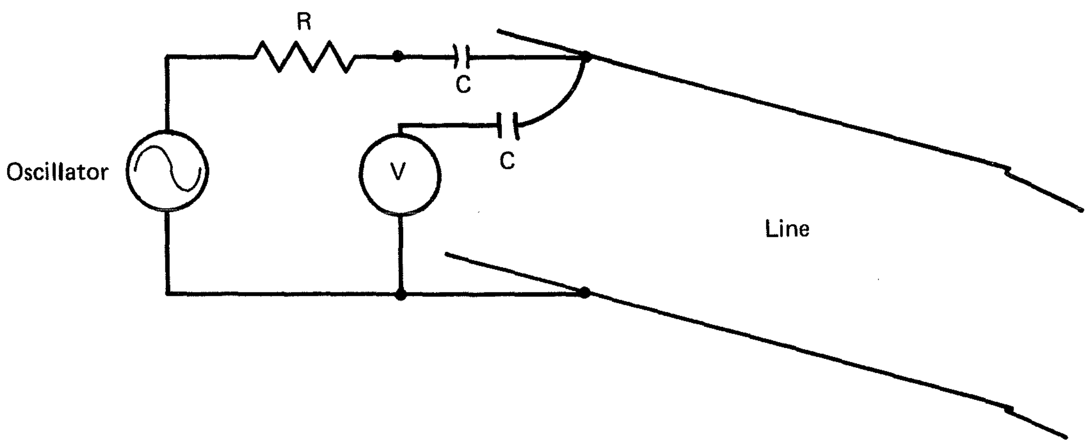


FIGURE III–18 ARRANGEMENT FOR MEASURING LINE IMPEDANCE PRESENTED AT A SHUNT POINT

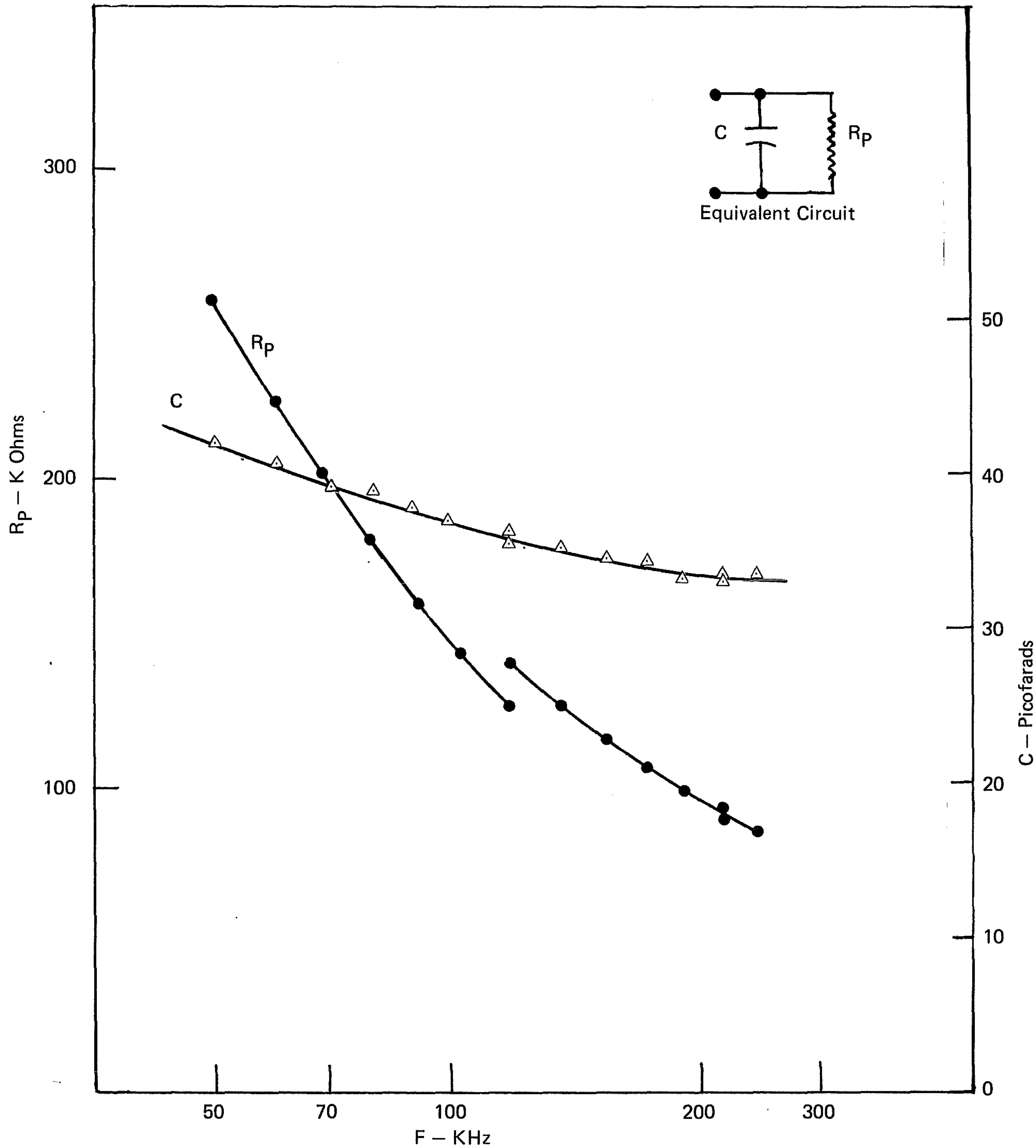


FIGURE III–19 INSULATOR CHARACTERISTICS

trolley wire/rail configuration of the Renton mine, without insulators, the theoretical results of Hill and Wait* show that a relative phase constant of 1.27 can be expected. A phase constant of that value can occur for a line having an L of 0.35 μH/ft, if the capacitance of the line is larger than the free-space capacitance by $(1.27)^2$ to 1, namely, a C per unit length of $2.95(1.27)^2 = 4.76$ pF/ft. If we add to this value our estimate of the additional capacitance per foot of 3.04 contributed by the insulators, we obtain a total value of 7.80 pF/ft for the transmission line, which agrees closely with the above value of 7.2 pF/ft.

On the other hand, our direct capacitance measurements showed a value of approximately 11.0 pF/ft. Such a value of capacitance is somewhat higher than the value of 7.2 pF and yields a velocity of 0.52 that of free space. The reason for this approximately 20% discrepancy has not yet been resolved.

The results of Hill and Wait also indicate that the 344-ohm characteristic impedance of a free-space line will be reduced by virtue of the added capacitance introduced by the surrounding medium by a factor of 1.27 to 271 ohms. This value will, in turn, be further reduced by the insulator capacitance to 211 ohms, which falls within the range of the values obtained from the TDR measurements.

11. Line Attenuation

The results from Section B.4, where shorted line data are treated, show an attenuation of 0.285 dB/1000 feet at 88 kHz, implying an α of 0.0328, or a series resistance of 13.1 ohms/1000 feet, and thus 7.6 ohms for the 580-foot test section (using $\alpha = R/2Z_0$). This result assumes that all loss is attributable to a series resistance.

Similarly, the results of Section B.6 where open line data are treated show an equivalent parallel resistance of 1980 ohms for the test section, again assuming all loss is in the shunt resistance.

It is clearly evident that the losses are not really separated in this way for the test conditions. Here we make the appropriate corrections to separate the losses. For the short-circuit termination, the 204 μH of line inductance yield a reactance of 113 ohms at 88 kHz. Thus, for the test current, the input voltage is 113/200, or 0.57 of that which would obtain for a matched line. The average value of the voltage squared over the test line is one-third

*Wait and Hill, *op. cit.*

of the input voltage squared, because the voltage decreases linearly from the input to the shorted termination. Thus, a representation of losses is:

$$I^2 R_{sm} = I^2 \quad R_s + \left[\frac{0.57^2 \, Z_o^{\,2}}{3R_p} \right]$$

where R_{sm} is the series resistance we arrived at in Section B.4 and R_s and R_p are the true values of line series and parallel resistances for the test section.

Similarly, for the open-circuit test where the input current is 0.72 V/Z_o and the assumed value of R_{pm} is 1990 ohms, we can write:

$$\frac{V^2}{R_{pm}} = V^2 \left[\frac{1}{R_p} + \frac{0.72^2 \, R_s}{3Z_o^{\,2}} \right]$$

Thus, we end up with simultaneous equations, as follows:

$$7.6 = R_s + \frac{4332}{R_p}$$

and

$$5.02 \times 10^{-4} = 4.32 \times 10^{-6} \; R_s + \frac{1}{R_p}$$

The solution of these two simultaneous equations yields a value of R_s = 5.53 ohms and R_p = 2090 ohms. Thus, there is a series attenuation of 0.12 dB for the test section, or 0.207 dB/1000 feet, and a parallel attenuation of 0.42 dB for the test section, or 0.72 dB/1000 feet. Thus, the attenuation of the line is approximately 0.93 dB/1000 feet.

If the insulators are assigned an equivalent parallel resistance of 3400 ohms for the test section, then the amount of parallel resistance for the line itself without the insulators would be 5430 ohms, yielding an attenuation of 0.160 dB for the test section, or 0.276 dB/1000 feet.

The total attenuation thus arrived at for the trolley wire itself would be approximately 0.483 dB/1000 feet, or 1.58 dB/km. The work of Wait and Hill* involves a model assuming a buried conductor to represent the rail which yields a value of attenuation between 0.5 and 1 dB/km for comparison purposes. The agreement with the work of Hill and Wait,* where a ground plane represents the rail return, yields somewhat lower attenuation and is in less agreement with the results obtained experimentally.

12. Conclusions

We reached the following conclusions regarding the electrical characteristics of the trolley wire/rail transmission line measured at the Renton mine:

- The velocity of propagation on the line is approximately 0.64 that of the velocity of propagation in free space;
- The inductance per unit length is 0.35 ± 10% μH/ft;
- The effective capacitance per unit length near the operating frequency of 88 to 100 kHz is 9 ± 2 pF/ft;
- The effective characteristic impedance is 200 ± 30 ohms;
- The attenuation contributed solely by the shunt resistance of the insulators supporting the trolley wire yields a calculated value of 0.44 dB/1000 feet at 88 kHz;
- The total line attenuation rate (unencumbered) is approximately 0.9 dB/1000 feet; and
- In comparison to the results of Wait and Hill,* our measured attenuation rates are somewhat greater than the theoretical values they calculated.

13. Instruments

The instruments listed below were used to make the measurements:

NM-12AT field strength meter,
Current probe for above,
Non-clamp-on current probe for above,
HP-427A voltmeter,
HP-204C oscillator,
CRO Tektronics 211,
HP-5302A battery-operated frequency counter, and
Tektronics 1501 TDR.

*Wait and Hill, op. cit.

C. TRANSMISSION MEDIUM III – BRIDGING LOADS

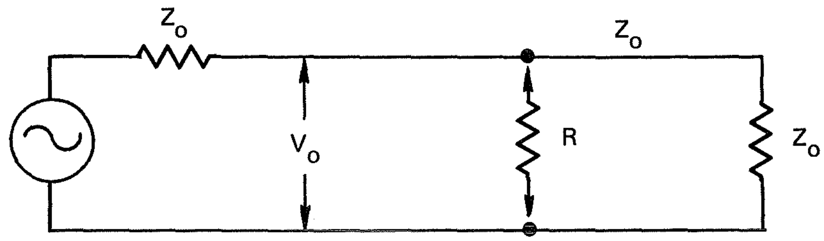
The major impediment to carrier signal propagation on the trolley wire/rail is the large number of bridging loads that are typically found in electric rail haulage systems. Each such load consumes carrier power and reflects power back toward the transmitter. The seriousness of these bridging loads can be assessed in a first-order fashion by examining the "insertion loss" that a single bridging load imposes on an otherwise matched transmission line. Figure III-20a is a representation of such a line with a bridging load about to be attached. A voltage V_o appears across the line at the point of attachment. When the load is attached, the voltage decreases; the ratio of the voltage before and after attachment is the insertion loss. Expressed in dB it is: 20 $\log_{10} V_o/V_1$. The simple equivalent circuit of Figure III-20b may be used to determine the ratio as

$$\frac{V_o}{V_1} = \frac{2R + Z_o}{2R}$$

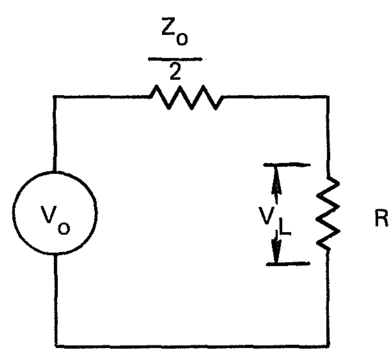
The plot of Figure III-21 illustrates the insertion loss as a function of the value of bridging resistance in ohms for a line of characteristic impedance Z_o = 200 ohms, the value accepted as representative of trolley wire/rail characteristic impedance.

For instance, if a bridging load of 20 ohms is imposed across the trolley wire/rail, an insertion loss of 15.6 dB can be expected. Given a value of 70 dB for total transmission loss available for a trolley carrier phone system (25 volts to 8 millivolts), only five such loads could be imposed on the trolley wire/rail between the two carrier phones; any more than that number would reduce the signal level to unusable values.

It should be remembered that a cascade of such bridging loads does not necessarily result in a cumulative loss equal to the sum of the individual insertion losses because of the standing wave phenomenon on the transmission line in the presence of such unmatched volts. Methods for exact solutions of such bridging loads are contained in Section D of this chapter. A first-order estimate of losses to be expected can, however, be made by adding the individual insertion losses for all loads found between a pair of carrier phones. Table III-3 lists important bridging loads that are found on trolley wire/rail systems, together with approximations for the resistance these loads represent and the corresponding insertion loss produced by such loads.



.a. Transmission Line With Bridging Load R About to be Attached



b. Equivalent Circuit For Load Voltage Computation

FIGURE III–20 CIRCUITS REPRESENTING BRIDGING LOAD

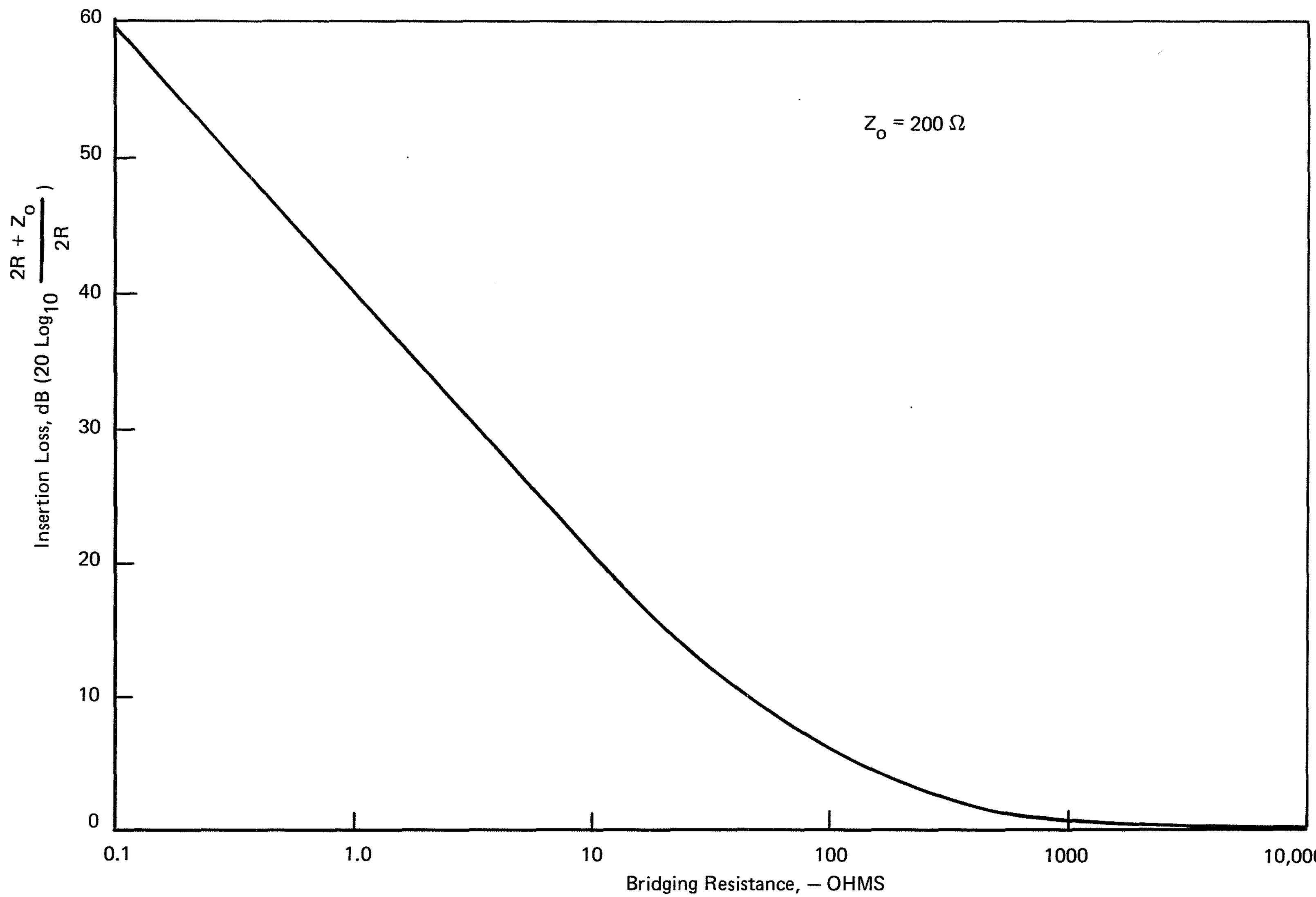


FIGURE III—21 INSERTION LOSS AS A FUNCTION OF BRIDGING RESISTANCE

TABLE III-3

CHARACTERISTICS OF BRIDGING LOADS

Bridging Load		Estimated Impedance at 100 kHz (ohms)	Insertion Loss* (dB)	Loss in Voltage
Rectifier with minimum setback		2	34.1	51 to 1
Rectifier with 50-foot setback†		9†	21.6	12 to 1
Rectifier with 100-foot setback†		19	15.9	6 to 1
Carrier phone with 20-Ω receiver		20 Ω	15.6	6 to 1
Carrier phone with 100-Ω receiver		100 Ω	6.0	2 to 1
Jeep or portal bus motor		500 Ω	1.6	1.2 to 1
44-ton locomotive motor		60 Ω	8.5	2.7 to 1
Vehicle with two 150-W, 32-V headlights isolated resistively**	300-V system	60	8.5	2.6 to 1
	600-V system	120	5.3	1.8 to 1
Illumination lights (assumed to be 200-W load)	300-V system	450	1.7	1.22 to 1
	600-V system	1800	0.5	1.06 to 1
Single insulator		200,000	0.0043	1.0005 to 1
1 mile of insulators with 12-foot spacings (440 insulators)		–	1.90	1.2 to 1
1000-W personnel heater	300-V system	90 Ω	6.5	2.1 to 1
	600-V system	360 Ω	2.1	1.3 to 1
5000-W personnel heater	300-V system	18 Ω	16.3	6.6 to 1
	600-V system	72 Ω	7.6	2.4 to 1

Notes to Table S-1

*This insertion loss is that calculated for an otherwise unencumbered trolley wire/rail having a 200-Ω characteristic impedance, using the formula

$$L = 20 \log_{10} \frac{2R + Z_o}{2R}$$

where R is bridging load resistance.

For a trolley wire/rail having a large number of loads, load interaction will cause the total net transmission loss, in most practical cases, to be less than the sum of these tabulated losses due to load interaction.

**At the trolley wire carrier frequency the bridging impedance of a locomotive or vehicle appears to be dominated by the headlights. Motors have impedances at carrier frequencies that are somewhat larger than these values and therefore the load imposed by the lights only is considered. Newer vehicles with DC-to-DC converters that supply the light circuits have appreciably less effect.

†The bridging impedance of a setback rectifier is higher in value than one with minimum setback due to the feed wire inductance. These figures assume a feed wire inductance of 0.3 μH/ft and a frequency of 100 kHz. The values of Z will be somewhat less, but not significantly for 88-kHz operation.

D. TRANSMISSION MEDIUM IV – EXACT METHOD FOR DETERMINING INSERTION LOSS

1. Introduction

This section presents a derivation for the insertion loss suffered by trolley wire carrier frequency signals when a shunt admittance load, Y, is placed across a lossless trolley wire/rail transmission line. Such loads can include untuned and tuned power rectifiers, heaters, motors, signal lights, and the like. Procedures are also included here for quickly determining the insertion loss, bandwidth, etc., from the Smith chart and its appropriate scales.

Consider the two cases illustrated in Figure III-22.

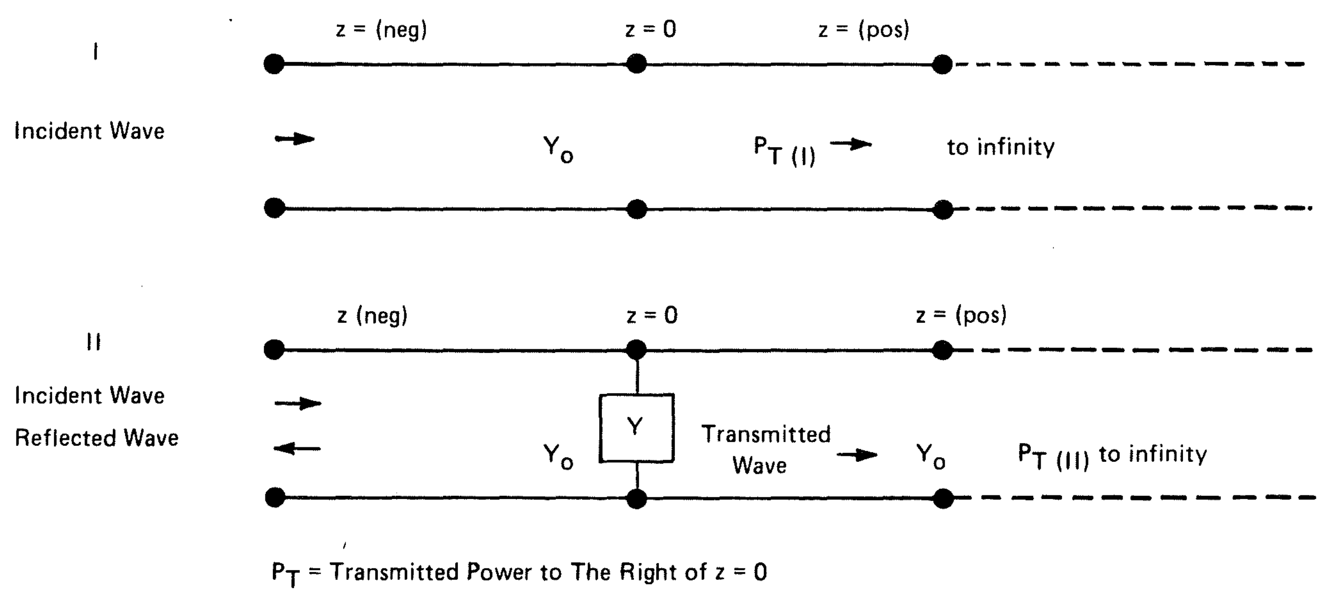


FIGURE III–22 TRANSMISSION LINE REPRESENTATIONS

Example I of Figure III-22 represents an incident wave down an infinite or "matched" transmission line of characteristic admittance Y_O. In this case, all the power in the incident wave travels unimpeded down the line.

Example II of Figure III-22 represents the same transmission line and incident wave, but now with an arbitrary shunt admittance Y placed across the line at position z = 0.

In this case, only a fraction of the power in the incident wave is transmitted down the remainder of the transmission line to the right of the position z = 0, since part of the incident power will be reflected back to the source and part will be dissipated in the shunt admittance, should the shunt admittance be lossy.

2. Insertion Loss

We wish to have a measure of the fractional decrease in power transmitted to the right of z = 0, when a shunt admittance Y is placed across the line at z = 0; namely:

$$\frac{\text{transmitted power in the presence of Y}}{\text{transmitted power in the absence of Y}} = \frac{P_{T(II)}}{P_{T(I)}}$$

The *dB loss* incurred by the insertion of the shunt admittance Y across the line is given by:

$$\text{dB (loss)} = 10 \log_{10} \left(\frac{P_{T(I)}}{P_{T(II)}} \right) \qquad \text{(III-1)}$$

which, as defined, will always be a *positive* number for passive devices.

In our particular application we wish to know: (a) the amount of insertion loss at resonance, and (b) the bandwidth for which the insertion loss is 3 dB greater than the insertion loss at resonance.

The following is a derivation of an analytical expression for the insertion loss, and its Smith chart implementation. Consider the line of case II, as shown in Figure III-23.

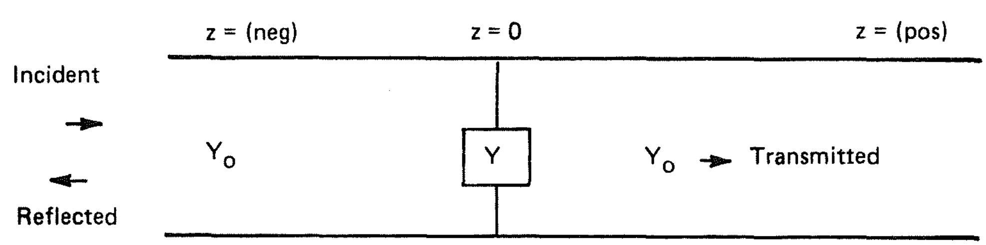


FIGURE III–23 TRANSMISSION LINE WITH SHUNT LOAD

To the *left* of z = 0, we have both incident and reflected waves, describing the resultant voltage and current on the line.

$$V(z) = V_+e^{-j\beta z} + V_-e^{+j\beta z} = V_+e^{-j\beta z}\left[1 + \frac{V_-e^{+j2\beta z}}{V_+}\right] \quad \text{(III-2)}$$

$$I(z) = Y_o\left[V_+e^{-j\beta z} - V_-e^{+j\beta z}\right] = Y_oV_+e^{-j\beta z}\left[1 - \frac{V_-e^{+j2\beta z}}{V_+}\right] \quad \text{(III-3)}$$

where

$$\frac{V_-e^{+j2\beta z}}{V_+} = \Gamma(z) \quad \text{(III-4)}$$

by definition, the complex reflection coefficient at any point z to the left of z = 0.

Therefore, $\Gamma(0) = V_-/V_+$, the reflection coefficient of the *effective* load as seen by the incident wave at z = 0. (See Figure III-24.)

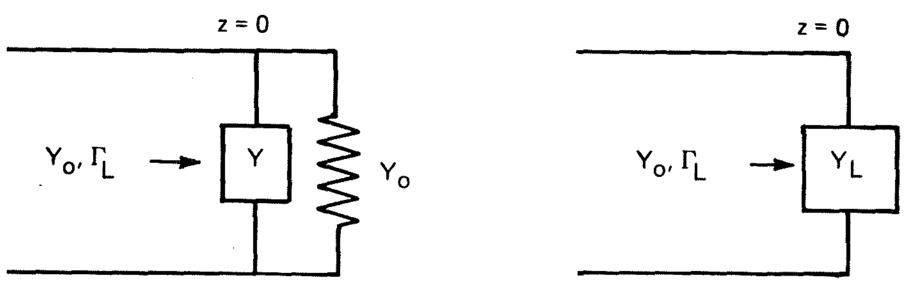


FIGURE III–24 COMBINATION OF 2 SHUNT LOADS

$$\Gamma_L = \frac{z_L - z_o}{z_L + z_o} = \frac{Y_o - Y_L}{Y_o + Y_L} = \frac{1 - \frac{Y_L}{Y_o}}{1 + \frac{Y_L}{Y_o}} = \frac{1 - Y_{Ln}}{1 + Y_{Ln}} \quad \text{(III-5)}$$

where Y_{Ln} is simply the normalized load admittance. Consequently, V(z) and I(z) may be represented by:

$$\left.\begin{aligned} V(z) &= V_+ e^{-j\beta z}\left[1 + \Gamma_L e^{+j2\beta z}\right] \qquad &\text{(III-6)} \\ I(z) &= Y_o V_+ e^{-j\beta z}\left[1 - \Gamma_L e^{+j2\beta z}\right] \qquad &\text{(III-7)} \end{aligned}\right\} \text{ for Negative z}$$

To the *right* of z = 0 we have *only* a single wave traveling to the right since there is no opportunity to get a reflection in our application. Consequently, the voltage and current to the right of z = 0 may be represented simply by:

$$\left.\begin{aligned} V'(z) &= V'_+ e^{-j\beta z} \qquad &\text{(III-8)} \\ I'(z) &= Y_o V'_+ e^{-j\beta z} \qquad &\text{(III-9)} \end{aligned}\right\} \text{ for Positive z}$$

To obtain V'_+ in terms of V_+ representing the voltage of the incident wave, we must satisfy the boundary condition at z = 0. Since Y is simply a shunt element, we have:

$$V(z = 0^-) = V'(z = 0^+) \qquad \text{(III-10)}$$

where the + and – superscripts on 0 indicate the voltages infinitesimally to the left and right of z = 0.

Therefore:

$$V(z = 0^-) = V_+\left[1 + \Gamma_L\right] = V'_+ = V'(z = 0^+) \qquad \text{(III-11)}$$

$$V'_+ = V_+\left[1 + \Gamma_L\right] \qquad \text{(III-12)}$$

$$\left\{\begin{aligned} V'(z) &= V_+\left[1 + \Gamma_L\right] e^{-j\beta z} \\ I'(z) &= Y_o V_+\left[1 + \Gamma_L\right] e^{-j\beta z} \end{aligned}\right\} \quad \text{for Positive z} \qquad \begin{aligned} &\text{(III-13)} \\ &\text{(III-14)} \end{aligned}$$

We are now in a position to evaluate the expression for the power in the transmitted wave to the *right* of the shunt admittance Y, and compare this to the power transmitted in the absence of Y.

The complex power traveling down a transmission line is given by:

$$P = \frac{1}{2} VI^* \tag{III-15}$$

where the asterisk denotes "conjugate," and V and I represent the resultant voltage and current.

For Case (I), in the *absence* of the shunt admittance, the transmitted wave is simply the *incident* wave. Consequently:

$$P_{T(I)} = \frac{1}{2} VI^* = \frac{1}{2} \overbrace{V_+ e^{-j\beta z}}^{V(z)} \overbrace{Y_o V_+^* e^{+j\beta z}}^{I(z)^*} \tag{III-16}$$

$$P_{T(I)} = \frac{1}{2} Y_o V_+ V_+^* = \frac{1}{2} Y_o |V_+|^2 \qquad P_{T(I)} = P_{incident} \tag{III-17}$$

As expected, it is totally *real* and *independent of z*.

For Case (II), in the *presence* of the shunt admittance, the transmitted wave is represented by V′(z) and I′(z) above. Therefore:

$$P_{T(II)} = \frac{1}{2} VI^* = \frac{1}{2} \underbrace{V_+\left[1 + \Gamma_L\right] e^{-j\beta z}}_{V'(z)} \underbrace{Y_o V_+^* \left[1 + \Gamma_L\right]^* e^{+j\beta z}}_{I'(z)^*} \tag{III-18}$$

$$P_{T(II)} = \frac{1}{2} Y_o V_+ V_+^* (1 + \Gamma_L)(1 + \Gamma_L)^* = \frac{1}{2} Y_o |V_+|^2 \; |(1 + \Gamma_L)|^2 \tag{III-19}$$

Again, a totally *real* and *independent of z* quantity, as expected.

Since

$$P_{T(I)} = \frac{1}{2} Y_o |V_+|^2, \quad \text{(III-20)}$$

$P_{T(II)}$ can be rewritten as:

$$P_{T(II)} = P_{T(I)} |(1 + \Gamma)|^2 = P_{incident} |(1 + \Gamma_L)|^2 \quad \text{(III-21)}$$

and the ratio of $\frac{\text{transmitted power in the presence of Y}}{\text{transmitted power in the absence of Y}}$ is simply given by

$$\frac{P_{T(II)}}{P_{T(I)}} = \frac{P_{T(II)}}{P_{incident}} = |(1 + \Gamma_L)|^2 \quad \text{(III-22)}$$

where Γ_L, as you recall, is the reflection coefficient of the combined load of Y in parallel with Y_o.

However, a more graphically useful relationship for

$$\frac{P_{T(II)}}{P_{T(I)}}$$

can be obtained by expanding the quantity

$$|(1 + \Gamma_L)|^2 = (1 + \Gamma_L)(1 + \Gamma_L)^* \quad \text{(III-23)}$$

$$(1 + \Gamma_L)(1 + \Gamma_L)^* = 1 + |\Gamma_L|^2 + (\Gamma_L + \Gamma_L^*)$$

$$= 1 + |\Gamma_L|^2 + 2Re(\Gamma_L)$$

$$= 1 + Re^2(\Gamma_L) + Im^2(\Gamma_L) + 2Re(\Gamma_L) \quad \text{(III-24)}$$

where Re ( ) and Im ( ) denote the real and imaginary parts of Γ_L, respectively.

However:

$$1 + Re(\Gamma_L) + 2Re(\Gamma_L) = [1 + Re(\Gamma_L)]^2 \quad \text{(III-25)}$$

Therefore:

$$\frac{P_{T(II)}}{P_{T(I)}} = [1 + \mathrm{Re}(\Gamma_L)]^2 + \mathrm{Im}^2(\Gamma_L) \tag{III-26}$$

which you will recognize to be simply the (magnitude)^2 of the complex vector Δ given by:

$$\Delta = [1 + \mathrm{Re}(\Gamma_L)] + j\mathrm{Im}(\Gamma_L) \tag{III-27}$$

So:

$$\frac{P_{T(II)}}{P_{T(I)}} = \frac{P_{T(II)}}{P_{incident}} = |\Delta|^2 \tag{III-28}$$

where it can be shown that $|\Delta|^2$ is always less than or equal to 1, as it must be for passive loads.

Therefore, in accordance with the definition of Eq. (4-2):

$$\text{dB (insertion loss)} = 10 \log_{10} \frac{1}{|\Delta|^2} \tag{III-29}$$

The importance of this representation is its usefulness in conjunction with the Smith chart.

If this expression is recast to use Z_o and Z_L, an alternate form for the insertion loss becomes:

$$20 \log_{10} \frac{2Z_L + Z_o}{2Z_L}$$

3. Smith Chart Application

Referring to the Smith chart of Figure III-25, we recall that the normalized load admittance of the shunt admittance Y in parallel with Y_o must always lie within the $G_n = 1$ circle when using the Smith chart as an admittance chart. Also recall that the actual reflection coefficient vector on such an admittance chart is equal to the "apparent reflection coefficient vector" rotated by 180 deg on the Smith chart,* where the "apparent Γ_L" is the vector drawn from the center of the chart to Y_n.

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*Adler, Richard B., et al., "Electromagnetic Energy Transmission and Radiation," MIT Press, 1968, p. 110.

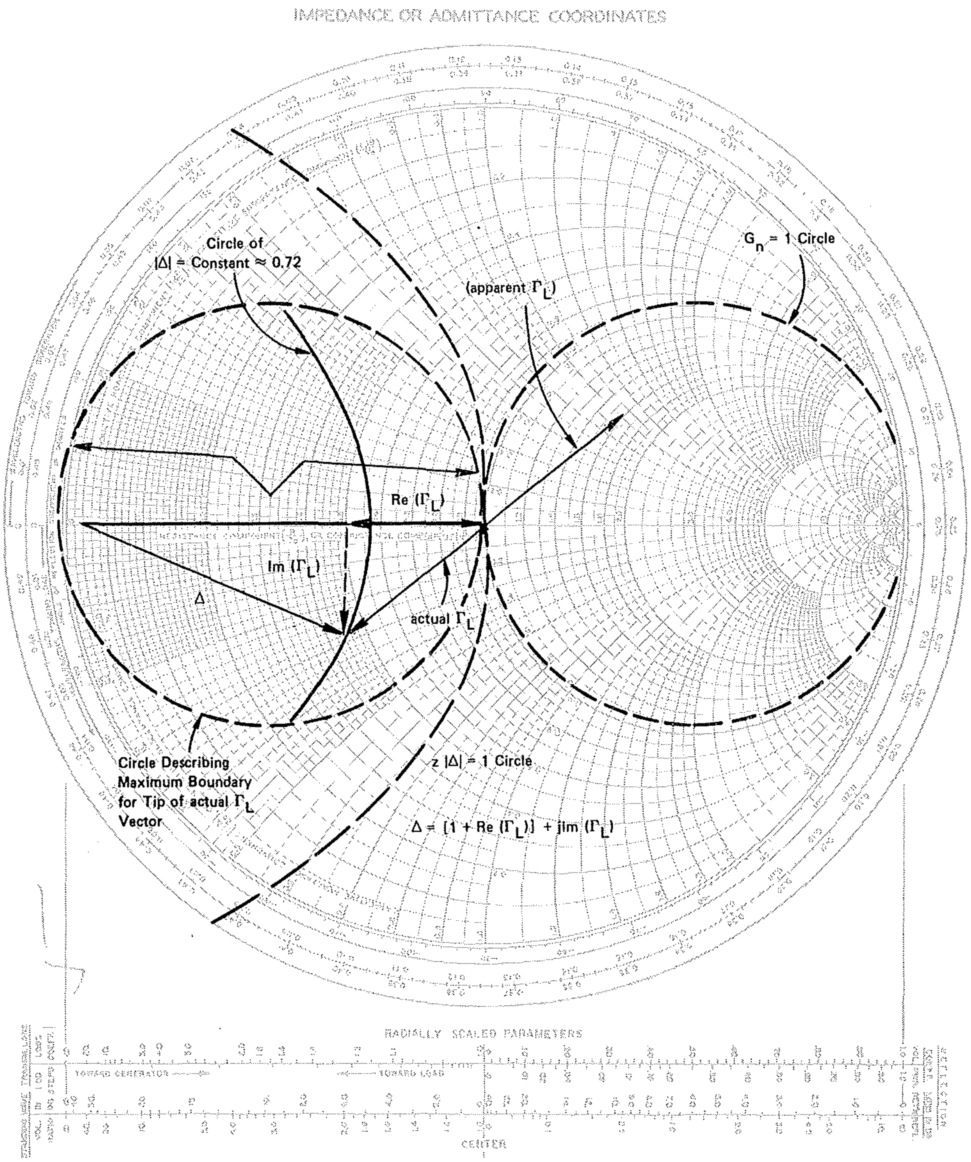


FIGURE III–25 LOCI ON ADMITTANCE CHART

Consequently, a simple construction of the vector Δ on the Smith chart according to Eq. (III-27)

$$\Delta = [1 + \mathrm{Re}(\Gamma_L)] + j\mathrm{Im}(\Gamma_L)$$

gives simply the vector shown, drawn from the *origin* of the "1" vector on the left, to the *tip* of the *actual* reflection coefficient vector. Note that for our application (1) the Re (Γ_L) will always be negative, and (2) $|\Delta|$ will *always* be less than or equal to 1 as it must, since the tip of the *actual* Γ_L vector must always lie within the pencilled circle, which in turn lies within the $\Delta = 1$ circle.

Therefore,* the locus of points describing a constant value of insertion loss on the Smith chart is a *circle centered* at the *origin* of the "1" *vector* on the left of the chart, with the radius of this circle being equal to the *magnitude* of Δ. To be of immediate and convenient use in the examination of the locus of the normalized load impedances, Y_{Ln}, the loci of constant insertion loss should be transformed to the other side of the chart where these admittances are plotted.

4. Procedures

(1) Generating loci of constant values of insertion loss within the $G_n = 1$ circle for examination Y_{Ln} behavior (bandwidth, loss at resonance, etc.):

a. Choose a value of insertion (loss expressed in dB);

b. Go to the reflection-loss in dB scales at the bottom of the Smith chart, in particular the *return* loss scale;

c. Measure the amount of dB desired with dividers;

d. Place one end of dividers on the 1.0 end of reflection coefficient, *voltage* scale;

e. The distance between the other end of the dividers and "0" end of the reflection coefficient *voltage* scale is the required length of the vector Δ, to generate the appropriate circle locus of constant insertion loss centered about $\infty \pm j\infty$, as shown in Figure III-26. The corresponding value of reflection coefficient on the *power scale* is equal to $|\Delta|^2$.

(2) Obtaining the insertion loss for a given value of Y_{Ln}:

a. Measure the distance from point Y_{Ln} to the point $\infty \pm j\infty$ on the Smith chart, which is the length of the Δ vector. Then work the steps of (1) above in reverse to end up with insertion loss in dB.

---

*Since the transformation from "actual Γ_L" to "apparent Γ_L" involves simply a reflection through the origin of the chart, the loci of constant values of insertion loss are simply, and ***most conveniently,*** transformed ***again*** to ***circles*** of radius equal to $|\Delta|$. However, they are ***now centered*** about the point $\infty \pm j\infty$ on the right of the Smith chart, as shown in Figure III-26.

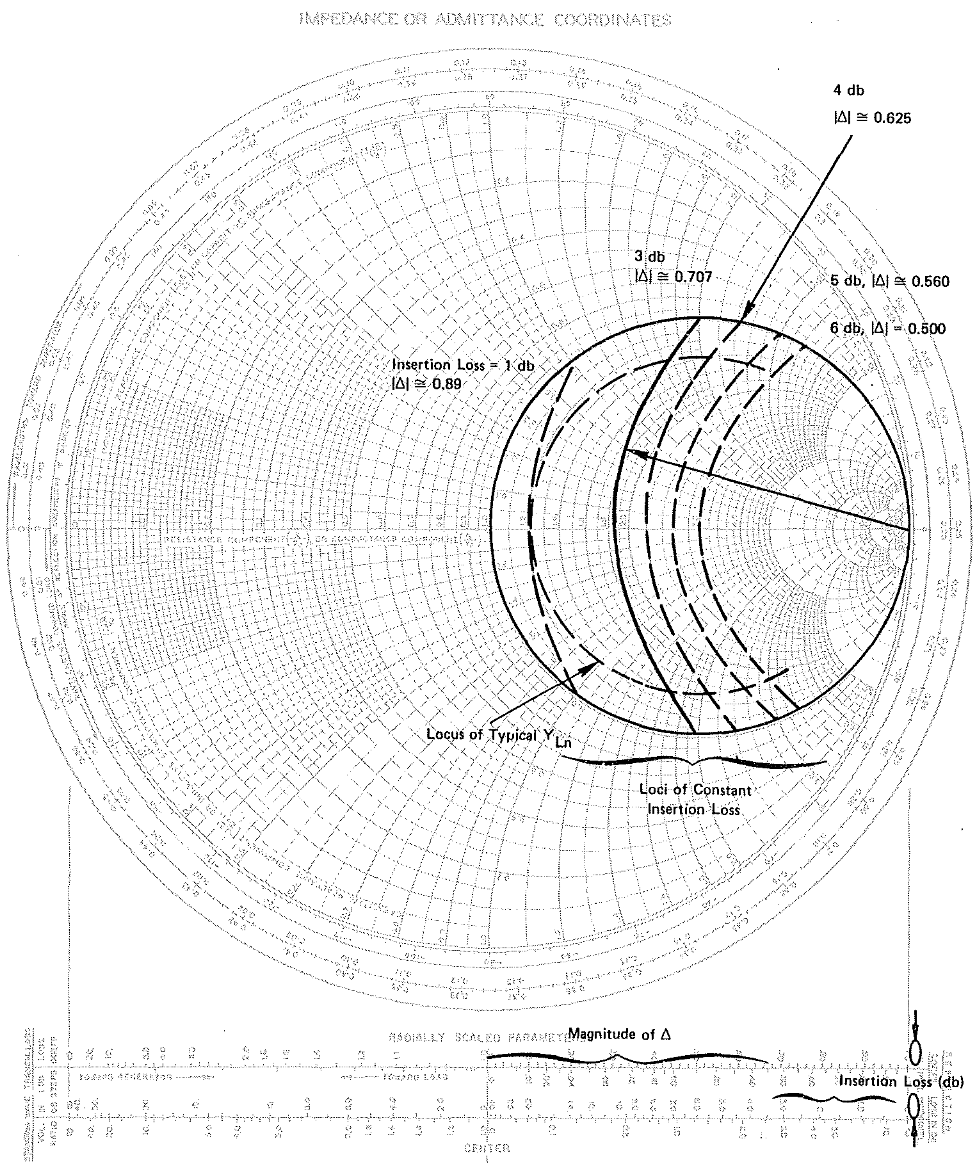


FIGURE III–26 LOCI OF CONSTANT INSERTION LOSS

(3) Obtaining the positions on the Y_{Ln} locus where the insertion loss is 3 dB greater than the insertion loss at resonance:

a. From the locus of Y_{Ln} on the Smith chart, determine the insertion loss at resonance, as described in (2) above (x dB).

b. Add 3 dB to get the resultant dB loss [(x + 3) dB].

c. Find the required length of the vector Δ corresponding to (x + 3) dB, as described, in (1) above.

(4) Transforming the insertion loss loci for examination of Y_n (shunt admittance alone) behavior:

a. Plot Y_{Ln} point, at least for resonance, to determine amount of insertion loss at resonance (x dB).

b. Then generate desired (x + N) dB loci within the G = 1 circle, as described above.

c. Transform these (x + N) dB loci to corresponding loci in the Y_n region by subtracting +1 from all the real parts of Y_{Ln} lying on each (x + N) dB locus.

As an example of (3) above, a "typical Y_{Ln}" locus sketched in the Smith chart (Figure III-26) exhibits a 1-dB insertion loss at resonance; therefore, the intersection of the Y_{Ln} locus with the 4-dB insertion loss locus determines the frequencies at which the insertion loss is 3 dB higher than at resonance.

5. Example of Use of Admittance Chart for Determining Insertion Losses on Trolley wire

Let us consider the insertion loss produced by a 2-ohm shunt resistance across a trolley wire/rail transmission line of characteristic resistance 200 ohms. Such a shunt load might be representative of a rectifier with a short setback from the trolley wire/rail. Point A locates the normalized Z of the shunt load and A′ the normalized Y. The addition of 1 to the normalized Y moves the position by an imperceptible amount from A′, and A′ is used to measure the vector length as noted in Figure III-26. A transfer of the vector length to the dB scale shows an insertion loss of about 35 dB (the calculated value is 34 dB).

Now we consider what can be done by adding an inductance in series with the shunt resistance and then examine what happens when we tune the resultant series resistance and inductance with a parallel capacitor. Suppose we choose an inductor of 62 μH inductance made up of trolley feeder wire formed into a coil (as discussed in our final report on Contract HO122026).* The inductor yields a reactance of 35.5 ohms at 90 kHz, 39 ohms at 100 kHz, and 43 ohms at 110 kHz, or 0.195, 0.178, and 0.215 normalized ohms. The location of the net impedance of the 2 ohms in series with the inductive reactances are shown on the Smith chart of Figure III-27 and are noted as B, B′, and B″. These points reflect to C, C′, and C″ as admittances, as shown in Figure III-27. We may find the corresponding insertion losses for these conditions by adding 1 to the Y and measuring the lengths of the vectors. The insertion losses are thus found to be 9.7, 8.7, and 7.7 dB, thus showing the variation of the loss over a total band of 20 kHz (wider than the nominal carrier phone band of ±5 kHz).

Now we consider the effect of tuning the series resistance-inductance circuit. On the Smith chart such tuning moves the admittance locus on a constant G line as shown from the C′s to the D′s. Tuning is done for the center frequency and it can be seen that this tuning requires a parallel B of 5.0 (normalized), bringing the real value of admittance to 0.2, as shown at D′. The values of added B are correct for the center frequency, but for a fixed capacitor yield two different B′s for the other two frequencies. These values of B are 5.5 and 4.5. The corresponding points on the Smith chart are D and D″, as illustrated. The process of adding 1 to these Y's yields the points E, E′, and E″, and shows insertion losses of 1.8, 0.8, and 1.5 dB, thus showing a variation of insertion loss of only ±0.5 dB over this wide frequency band. It is thus seen that what might be expected to be a high Q circuit and have narrow bandwidth turns out, in fact, to be perfectly adequate for this use on a trolley carrier system.

This kind of Smith chart representation may be used to treat almost any form of shunt load in a similar fashion.

*Arthur D. Little, Inc., "Survey of Electromagnetic and Seismic Noise Related to Mine Rescue Communications," Volume I, "Emergency and Operational Mine Communications," January 1974, p. 6.8.

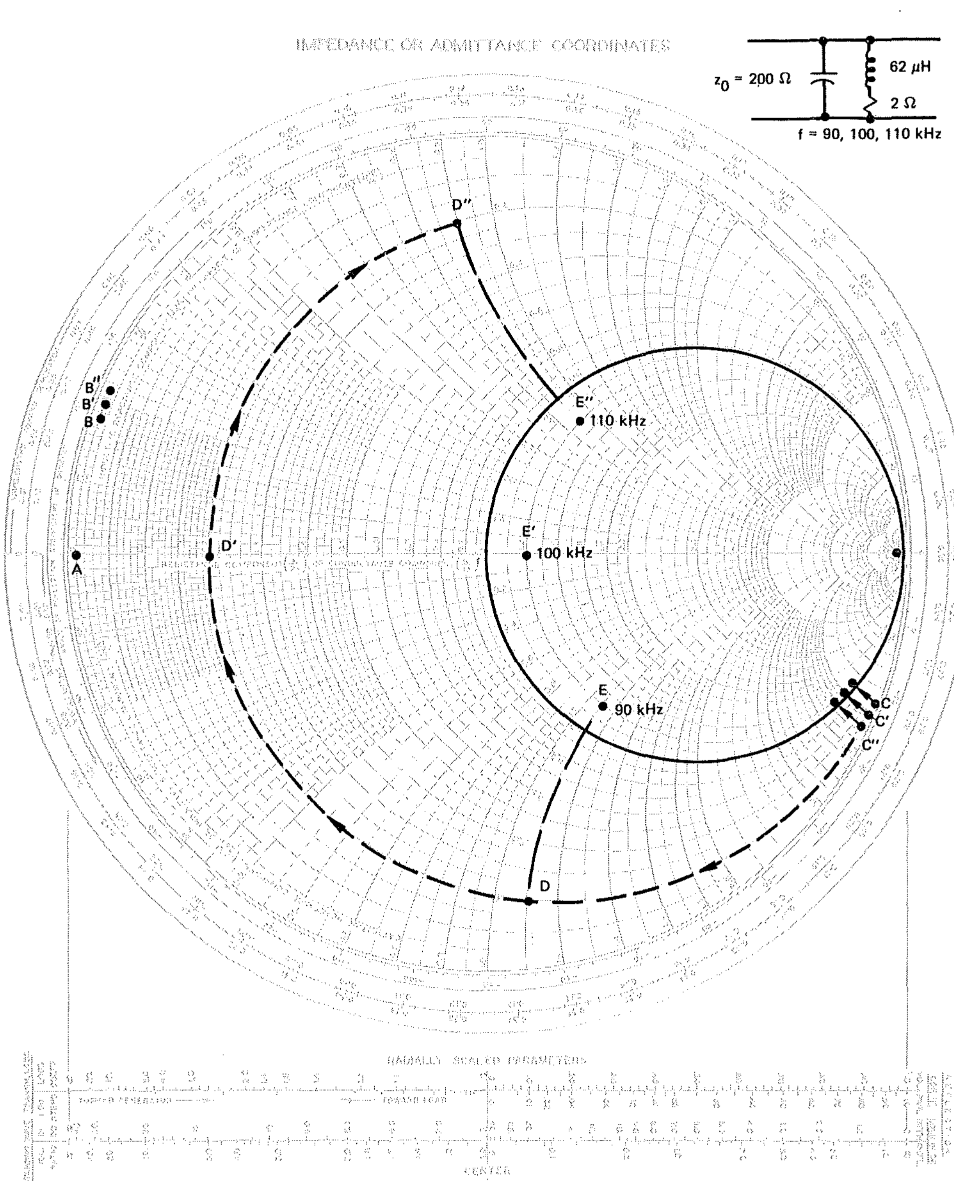


FIGURE III–27 USE OF ADMITTANCE PLOT FOR INSERTION LOSS DETERMINATION (See Text)

IV. THE LOW-IMPEDANCE TROLLEY WIRE

A. INTRODUCTION

The problem of overcoming the drastic impedance mismatches between the trolley wire/rail and the many bridging impedances across the line has been attacked in several ways. For example, various ways of increasing the impedance at carrier frequencies have been tried by adding inductors in series with the offending load and tuning those inductors and, in the case of power rectifiers, by tuning the rectifier feed wire.

In this chapter, we discuss the alternate approach of reducing the mismatches, not by raising the impedance of the offending loads, but by reducing the characteristic impedance of the trolley wire/rail transmission line. The means of altering the characteristic impedance is to lump-load the trolley wire/rail with fixed capacitors.

B. THE CAPACITOR-LOADED TRANSMISSION LINE

1. Insertion Loss

The common operating frequencies of trolley carrier phones are 88 and 100 kHz. At 88 kHz, we estimate that the trolley wire has the following characteristics:

Characteristic impedance, $Z_o \simeq 200$ ohms;
Wavelength, $\lambda \simeq 11{,}000$ feet; and
Attenuation rate, $\alpha < 1$ dB/mile.

We estimate the shunt impedances which power rectifiers place across the line to be as low as a few ohms, and hence they present a severe mismatch. If we could lower the value of the characteristic impedance, we could lessen the degree of the mismatch.

Suppose we lowered Z_o by a factor r, so that the characteristic impedance became rZ_o, and let Z_m be the value of the bridged impedance. Suppose further a generator, the internal impedance of which is rZ_o, is feeding a load of rZ_o via the line. Placing Z_m across the line at some point between the generator and the load will reduce the power received by the load. This loss is referred to as the insertion loss, L, and is defined by the ratio:

$$L = \frac{\text{Power received by load when } Z_m \text{ is absent}}{\text{Power received by load when } Z_m \text{ is present}}$$

It has been shown that the loss L, expressed in dB, is given by

$$L\,(\text{dB}) = 20 \log \; L = 20 \log \left(\frac{2\,Z_m + rZ_o}{2\,Z_m} \right) \text{dB} \qquad \text{(IV-1)}$$

Figure IV-1 shows a plot of L, expressed in dB, against rZ_o for various values of Z_m/Z_o, and hence can be used for any value of Z_o. For convenience, the scales at the top and right of the figure give values applicable to a line with Z_o = 200 ohms.

As an example, suppose a power rectifier whose impedance is 2 ohms is placed across the line. It would cause a loss of 34 dB in the power delivered to the load. If the characteristic impedance were lowered from 300 to 100 ohms, the loss would be 28 dB, an improvement of 6 dB. If we could lower Z_o to a tenth of its value, i.e., to 20 ohms, the improvement would be 19 dB.

Figure IV-2 shows another way of presenting the same data; it plots the improvement against the reduction factor r. It can be seen that Z_o must be reduced by a factor of 3 to 5 to obtain an improvement greater than 10 dB. Now let us examine the feasibility and practicality of reducing Z_o to these levels.

2. Nomenclature

Figure IV-3 displays the nomenclature and some of the equations we will be using. In general, a generator V_g whose internal impedance is Z_s is connected to a load Z_R via a transmission line whose characteristic impedance is Z_o. In our case, the line itself is nearly lossless (the attenuation factor, α, is less than 1dB/mile). For a nearly lossless line, the attenuation factor α is given by:

$$\alpha = \frac{R}{2Z_o}$$

where R is the resistance per unit length.

Decreasing Z_o to rZ_o, therefore, increases the attenuation by a factor of 1/r. For an r in the range of 0.1, the attenuation, α, increases by 10 to 1, which may offset some of the advantages shown in Figures IV-1 and IV-2.

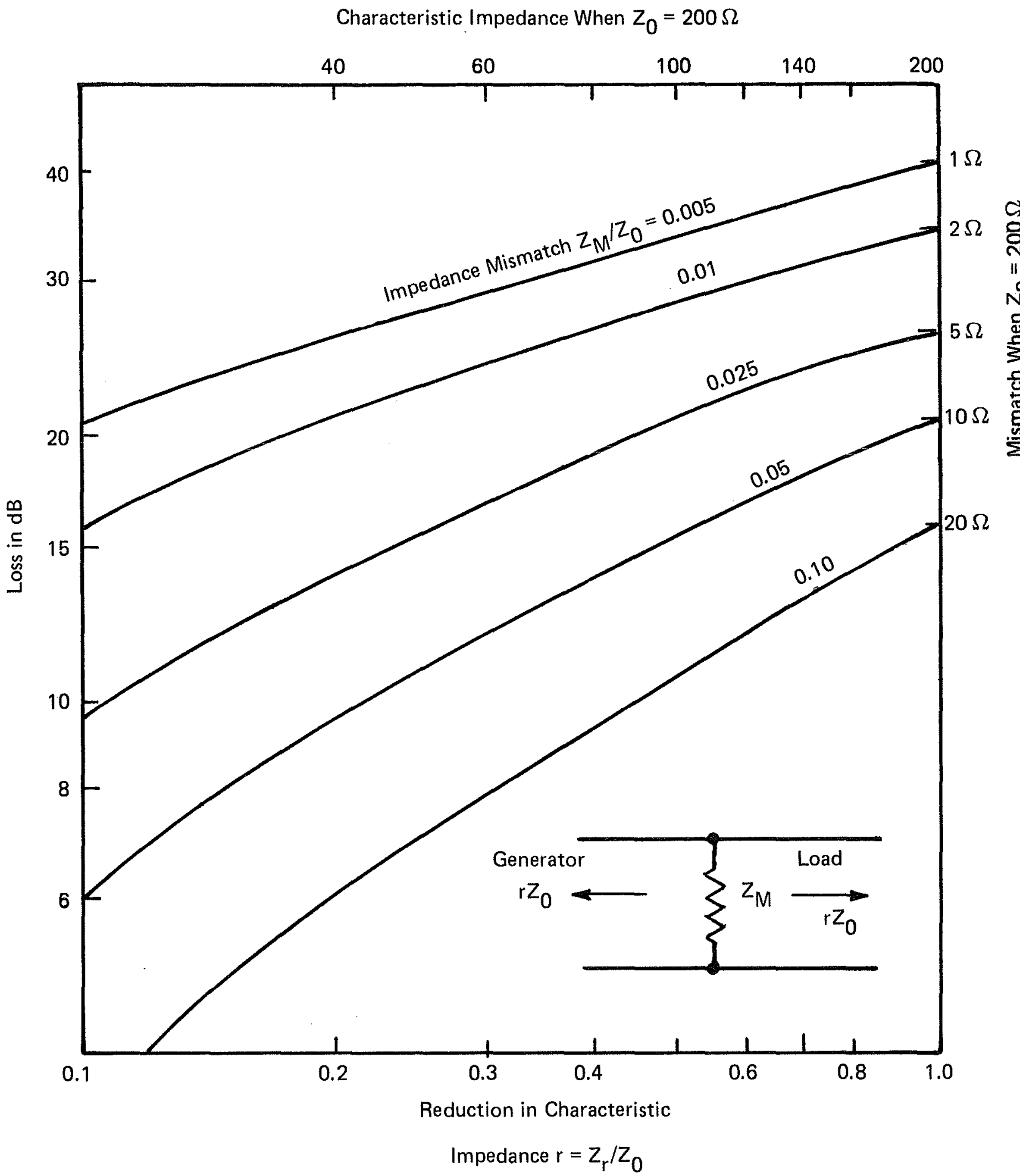


FIGURE IV–1 INSERTION LOSS OF BRIDGING IMPEDANCE Z_M

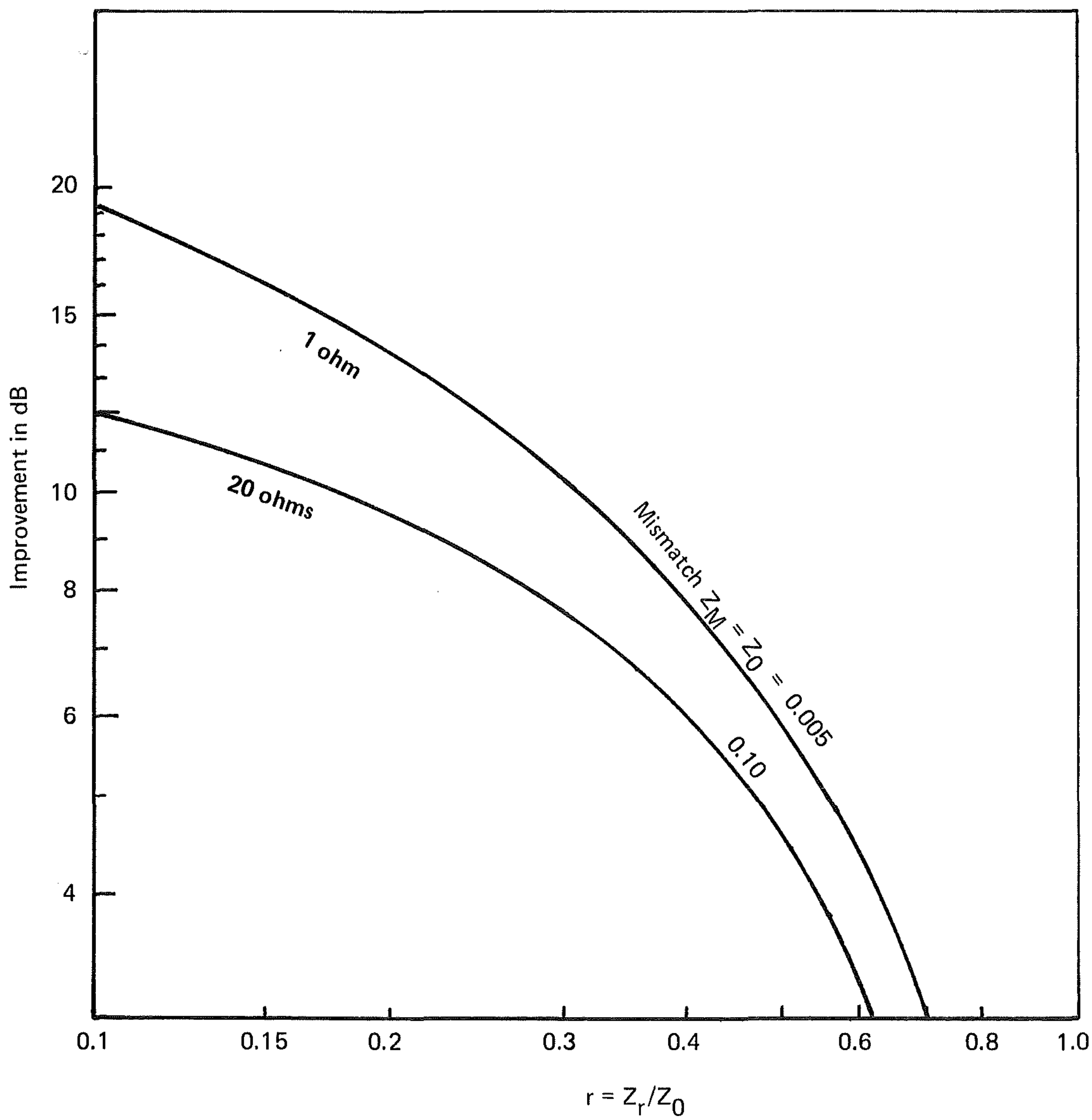
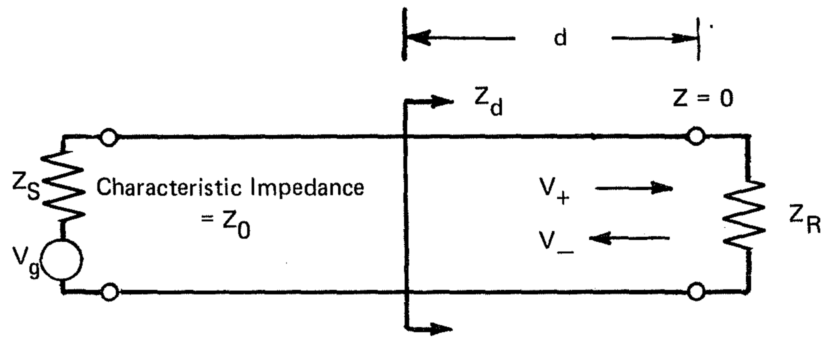


FIGURE IV–2 IMPROVEMENT OBTAINED BY LOWERING Z_0



Admittance $Y_d = \frac{1}{Z_d}$,

Reflection Coefficient $\Gamma_d = \frac{V_-}{V_+} = \frac{Z_d - Z_0}{Z_R + Z_0}$

For A Loss Less Line, Putting $t = \tan 2\pi \frac{d}{\lambda}$,

$$\frac{Z_d}{Z_0} = \frac{Z_R + jtZ_0}{Z_0 + jtZ_R} \quad \text{or} \quad \frac{G_d}{G_0} = \frac{G_R + jtG_0}{G_0 + jtG_R}$$

FIGURE IV–3 NOMENCLATURE

For example, if we use an attenuation rate of 0.5 dB/km (0.8 dB/mile), a 5 mile length of unencumbered trolley wire/rail would exhibit a total attenuation of 4.0 dB. If capacitive loading is used to reduce the characteristic impedance by 4 to 1, then the corresponding loss in the 5 mile section would be 16 dB. (This calculation assumes that the original attenuation rate of 0.8 dB/mile is dominated by series loss – if it were due to a parallel loss,** the capacitive loading would reduce the attenuation.) Pages 116 and 117 provide examples.

3. Capacitor Loading

For a lossless line, the characteristic impedance is given by:

$$Z_o = \sqrt{\frac{L}{C}}$$

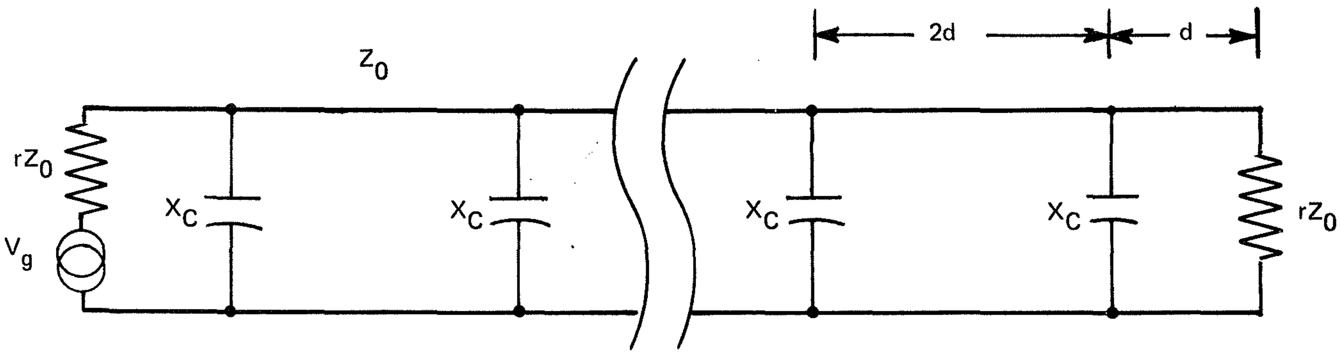
where L and C are the inductance and capacitance per unit length. In principle, Z_o can be lowered by increasing C. Suppose we increase C in the way shown in Figure IV-4a. Capacitors of reactance X_c are placed across the line at intervals of 2d. At the receiving end, on the right, the line is terminated with rZ_o placed a distance d from the last capacitor. The generator on the left, V_g, is similarly matched to the line with rZ_o placed a distance d in front of the first capacitor.

There is obviously a relation between X_c, d, and r. To find it, let us examine a section of the line as in Figure IV-4b. Looking to the right we see, by hypothesis, an impedance of rZ_o at A. Figure IV-5 shows the normalized impedance plotted on a Smith chart. In Figure IV-5, r is assumed to be 0.3 and A appears in the upper half of the figure. We will assume that r and d are specified and we wish to determine X_c. Proceeding a distance d toward the generator moves rZ_o to Z_B (refer to Figures IV-4b and IV-5 for the remainder of this paragraph). At B we insert the capacitor. On the Smith chart this implies reflecting Z_B through the origin to find its admittance, G_B, and adding the admittance of the capacitor Y_c to it. This brings us to the point $(G_B + Y_c)$ on the Smith chart. Reflecting this through the origin gives us the impedance at point C. Proceeding up the line from C to D will move the impedance round the arc of a circle. Now, since the impedance at D must be the same as at A, i.e., rZ_o, Y_c must be chosen so that $(G_B + Y_c)$ falls on the same circle about the origin as A, Z_B, and G_B. From Figure IV-5 we can see that Y_c must be:

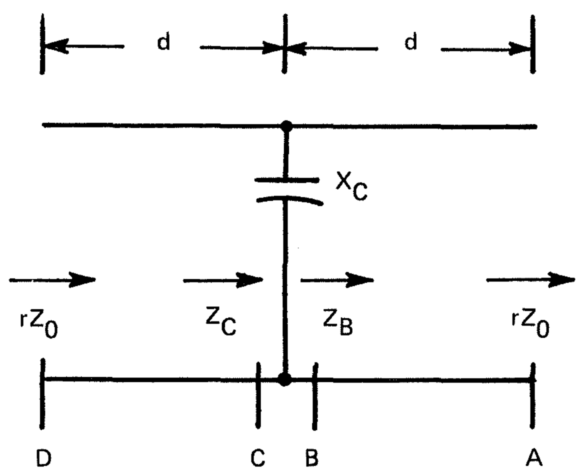
$$Y_c = 2 \text{ Imag } [G_B]$$

*Hill and Wait, *op. cit.*

**Such a parallel loss might be that of insulators acting as many shunt loads.



(a) Loaded Transmission Line



(b) Single Section of Loaded Line

FIGURE IV–4 CAPACITOR LOADED LINE

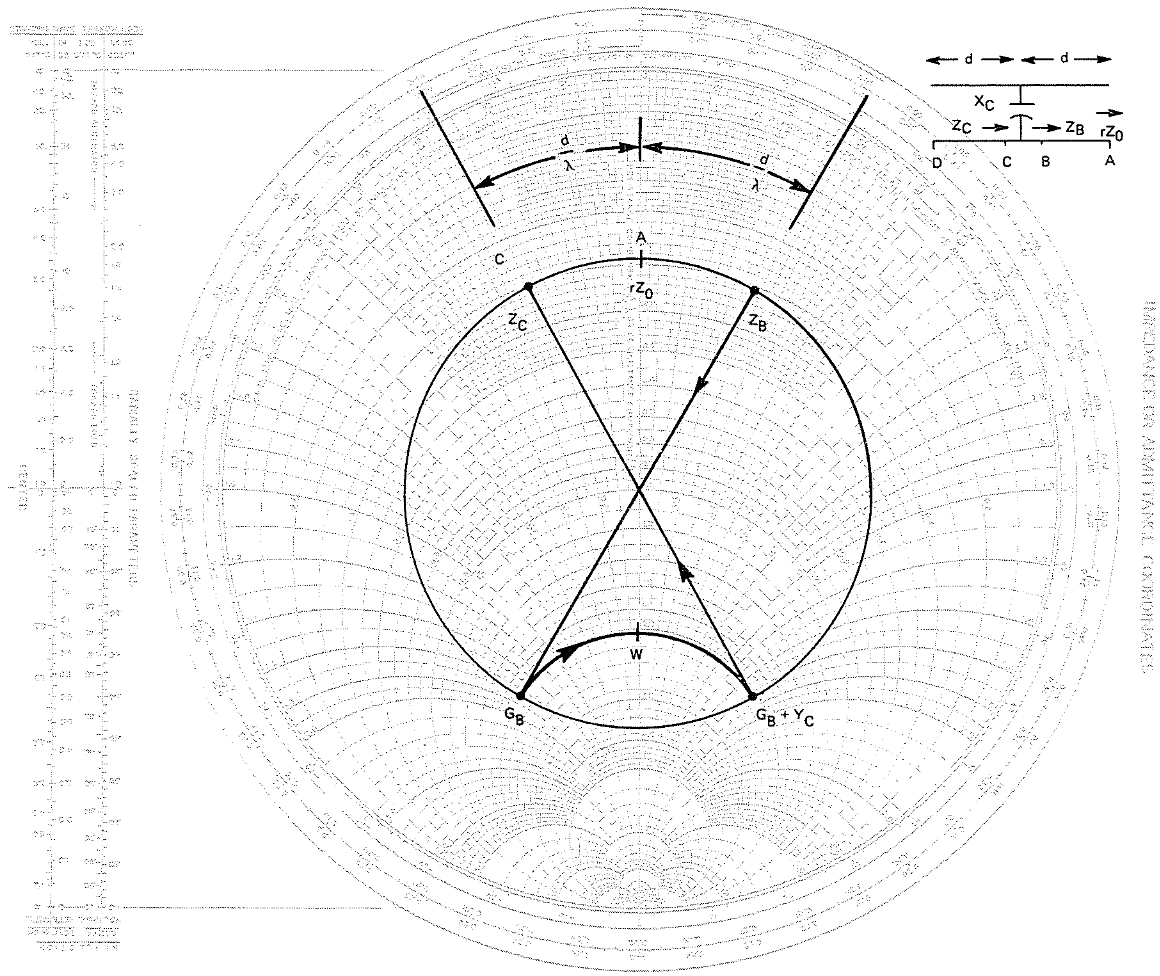


FIGURE IV–5 SMITH CHART REPRESENTATION

Using the equations of Figure IV-3, it can be shown that this means:

$$Y_c Z_o = -2 \frac{t\,(r^2 - 1)}{t_d^{\,2} + r^2} \qquad \text{(IV-2)}$$

where

$$t = \tan \frac{2\pi d}{\lambda}$$

Figure IV-6 plots this equation for the case when the trolley carrier phone frequency is 88 kHz and Z_o = 200 ohms. Each curve applies to a particular spacing of capacitors, and shows the value of the capacitor needed to effect a particular reduction in the characteristic impedance of the line, e.g., to reduce the characteristic impedance to $0.6Z_o$, i.e., from 200 ohms to 120 ohms, the following combinations could be used:

Capacitor Value (pF)	**Spacing (ft)**
370	40
920	100
1,850	200
3,600	400
9,300	1,000

Figure IV-7 is a similar plot for the lower values of r. The values of the capacitors needed in both Figures IV-6 and IV-7 are modest and practical.

From an installation point of view, one would like to space the capacitors as far apart as possible. The drawback is that the bandwidth of the transmission line decreases as the loading is lumped into bigger blocks, i.e., as larger capacitors are inserted at less frequent intervals, the attenuation at the edges of the band of frequencies occupied by the carrier signals increases. An understanding of what occurs when a loaded line carries signals slightly off the frequency for which it was designed can be obtained from the Smith chart illustration of Figure IV-8. The heavy lines in this figure are the same as Figure IV-5. The line has a characteristic impedance of $r_1 Z_o$, where r_1 = 0.3. It is loaded with capacitors whose admittance at the center frequency, f_1, is Y_1 = 2.8 (normalized), and these are spaced such that d/λ_1 = 0.03, where λ_1 is the wavelength of f_1. Now suppose that a frequency of f_2 is applied to the line such that d/λ_2 = 0.05. The radial lines on the chart, OP1 and OQ1, will move outwards to the positions indicated by the lines OP2 and OQ2. Now, since $\lambda_1 f_1 = \lambda_2 f_2$, the admittance of each capacitor will increase to:

$$Y_2 = \frac{\lambda_1}{\lambda_2} Y_1 \simeq \frac{0.05}{0.03} \times 2.8 = 4.7$$

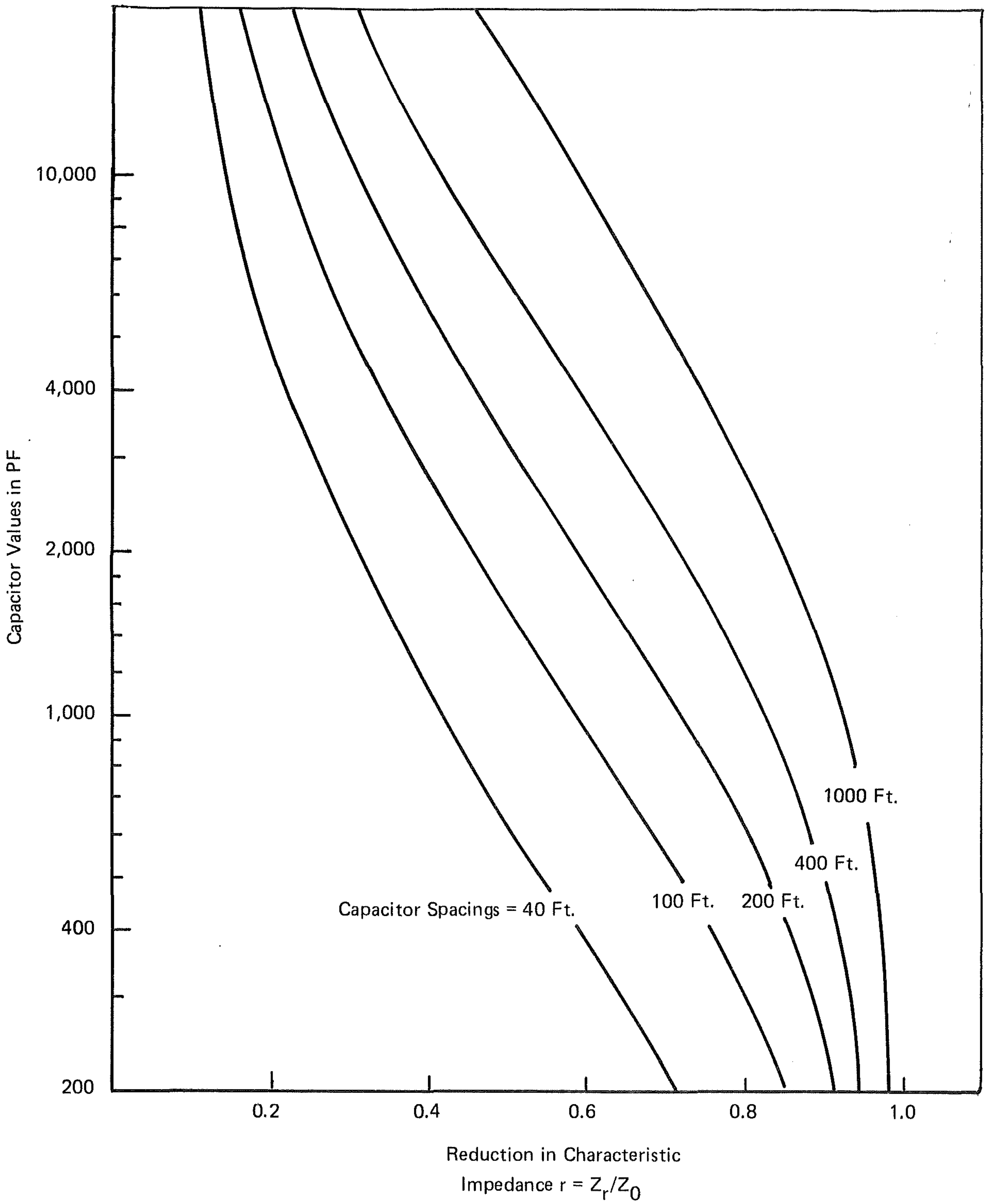


FIGURE IV–6 CAPACITOR VALUES FOR 88 KHz, Z_0 = 200 Ω

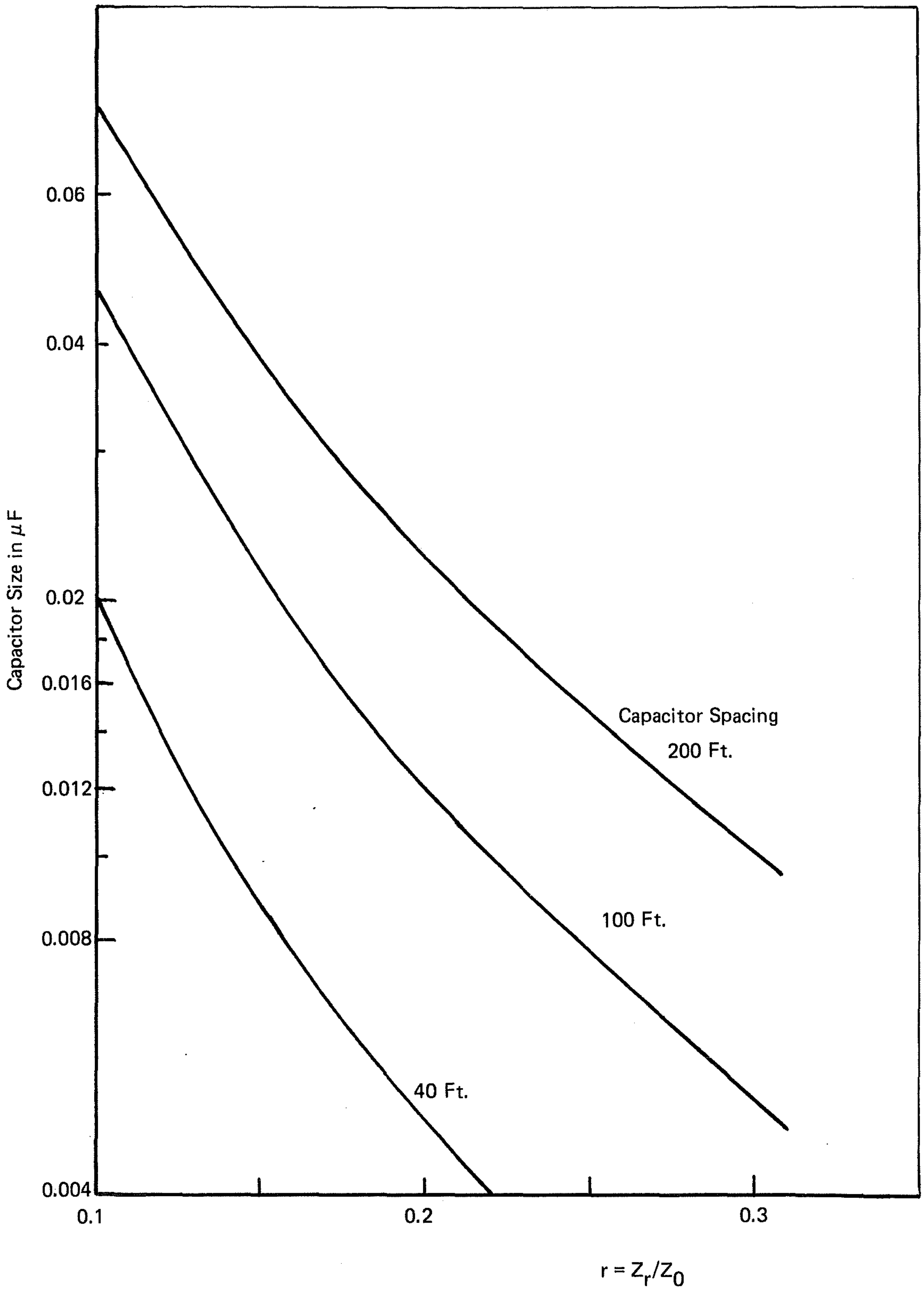


FIGURE IV–7 LOADING FOR f = 88 KHz, Z_0 = 200 Ω

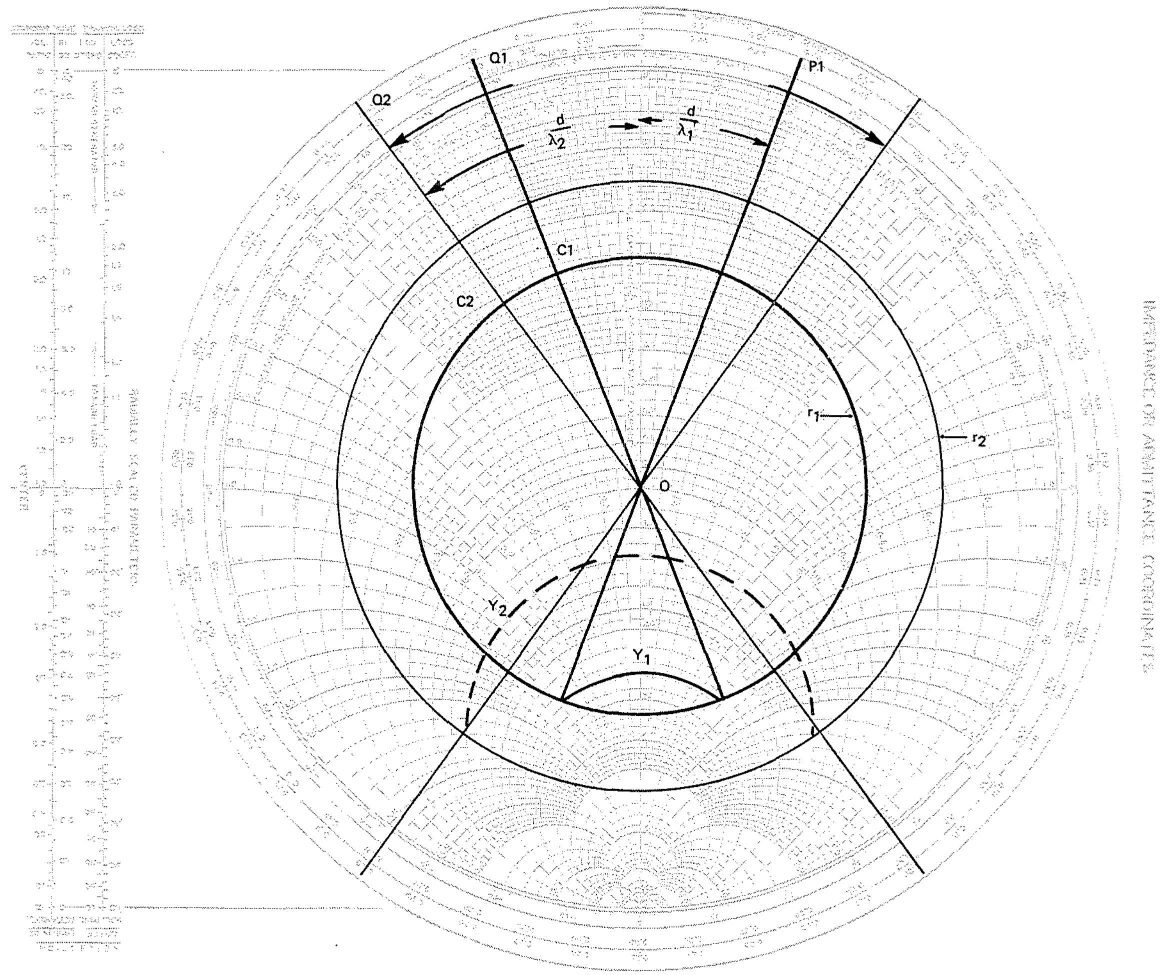


FIGURE IV–8　　SMITH CHART REPRESENTATION FOR OFF-FREQUENCY OPERATION

For the frequency f_2, the line is loaded with admittances of 4.7 every 0.05 of a wavelength. For f_2, this loading would be appropriate for a characteristic impedance different from $r_1 Z_o$. To find the new impedance, we look for the point of intersection of $Y_2/2 = 2.35$ with the radial lines OP2 and OQ2. We see that, for f_2, the loading makes the characteristic impedance of the line $r_2 Z_o$, where $r_2 = 0.18$. The load, or terminating impedance of the line, is still $r_1 Z_o$ though, and hence a fraction of the incident power at the load is reflected. The reflection coefficient is given by:

$$\Gamma = \frac{r_2 Z_o - r_1 Z_o}{r_2 Z_o + r_1 Z_o} = \frac{V_-}{V_+}.$$

Since

$$(1 - \Gamma^2) = \frac{V_+^2 - V_-^2}{V_+^2},$$

this quantity represents the ratio of the power absorbed by the load $(V_+^2 - V_-^2)$ to the incident power V_+^2. In the present case we are interested in the loss or attenuation suffered by signals of frequency f_2 as opposed to those of f_1. For f_1, the line is matched and the load absorbs all of the incident power $V_+^2 / r_1 Z_o$. For f_2, the loss, L, is given by:

$$L = \frac{4 r_1 r_2}{(r_2 + r_1)^2} \tag{IV-3}$$

For the example of Figure IV-8, L is only 0.28 dB. In this example r was reduced from 0.3 to 0.18. If the frequency were raised to the point where r was reduced to zero, L would become zero. The frequency at which this happens is called the cut-off frequency, F_c.* Equation (IV-2) can be written:

$$r_F^2 = \frac{t_F (1 + Z_o Y_{cF} t_F)}{(t_F - Z_o Y_{cF})}.$$

Both t and Y_c are frequency-dependent terms, and we use the suffix F to indicate that the expression gives the characteristic impedance $r_F Z_o$ of the loaded line for the frequency F. r_F becomes zero when the frequency is such that:

*The capacitor loading can be viewed as making the trolley wire/rail transmission line into a lumped constant delay line and hence it can be considered a broadband transmission line up to the first frequency cutoff when rapid attenuation occurs.

$$-Z_oY_{cF}t_F = 1$$

Calling f_o and λ_o the design frequency and wavelength of the line, this can be written:

$$(2\pi f_o C)\frac{f_c}{f_o}\tan\left(\frac{2\pi d}{\lambda_o}\frac{f_c}{f_o}\right) = \frac{1}{Z_o} \qquad \text{(IV-4)}$$

Putting $Y_o = -2\pi f_o C$ (C is capacitance),

$$\frac{2\pi d}{\lambda_o} = \theta_o$$

and approximating

$$\tan\left(\theta_o\frac{f_c}{f_o}\right) \simeq \theta_o\frac{f_c}{f_o},$$

Eq. (IV-4) becomes

$$\left(\frac{f_c}{f_o}\right)^2 = -\frac{1}{Z_oY_o\theta_o}$$

If r_oZ_o is the characteristic impedance of the loaded line for frequency f_o from Eq.(IV-2):

$$-Z_oY_o = \frac{\theta_o(1-r_o^2)}{r_o^2+\theta_o^2}$$

and hence:

$$\left(\frac{f_c}{f_o}\right)^2 = \frac{r_o^2+\theta_o^2}{\theta_o^2(1-r_o^2)} \qquad \text{(IV-5)}$$

Figure IV-9 is a plot of this equation showing f_c/f_o vs r_o for various values of capacitor spacing. It can be seen that the smaller the spacing, the higher the cut-off frequency becomes. The approximation we made, i.e., $\tan\theta \simeq \theta$, only significantly affects the accuracy of the curves for spacings of 200 and 500 feet for high values of f_c/f_o. For the 100-foot spacing, for example, when f_c/f_o is 4, the approximation introduces an error of less than 4%.

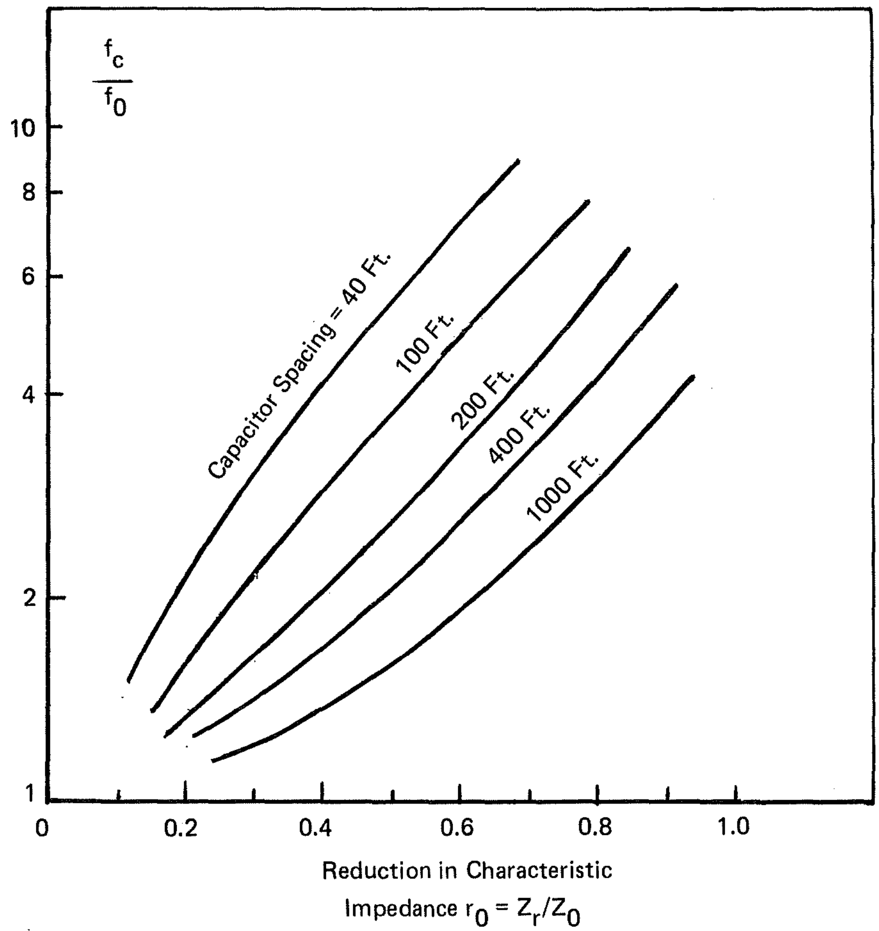


FIGURE IV–9 CUT-OFF FREQUENCY VS. LOADING

We certainly wish to stay away from loadings which cause the edge frequencies of the carrier channel to approach cut-off. But the limitations on load spacings must be examined more carefully to ensure that capacitor loading is not a narrow technique. This can be done using Eqs. (IV-1) and (IV-2). Results show that for capacitor spacings of 1000 feet or less, the attenuation at the edges of a band ±10% about the center frequency is 3 dB or less for values of r greater than 0.1.

4. Velocity of Propagation

One effect of the capacitive loading is to alter the velocity of propagation of carrier signals.* The velocity of propagation will vary directly with the r value used for low-loss lines, as can be seen from the approximate forms for

$$Z_o = \sqrt{\frac{L}{C}}$$

and

$$v = \frac{1}{\sqrt{LC}}$$

C. A CRITERION FOR SELECTING REDUCTION RATIO "R" FOR THE LOW-IMPEDANCE TROLLEY-WIRE

One may well ask what ratio reduction characteristic impedance yields the best performance. It will be remembered that artificially lowering the characteristic impedance by capacitive loading reduces shunt losses and increases series losses. This fact implies that an optimum reduction ratio exists, depending on the two attenuation rates. Here we treat the case of a distributed shunt loss and determine the optimum ratio by which to reduce the characteristic impedance. For conditions of relatively low loss, the expression for attenuation is approximated as $\alpha = \frac{1}{2} \left[\frac{R}{R_o} + \frac{G}{G_o} \right]$ where R_o is the characteristic resistance and G_o is $\frac{1}{R_o}$.

R is the series resistance of the line and G is the shunt conductance – both per unit length. For ease in understanding the relationship, we chose to represent the expression alpha as $\alpha = \frac{1}{2} \left[\frac{R}{R_o} + \frac{R}{R_s} \right]$, where R_s is the equivalent shunt resistance per unit length.

It is clear from the form of the expression that as R_o varied, a minimum α is found when R_o^2 equals R x R_s, or the best R_o is the geometric mean between the two R's. Under this optimum, the series and shunt attenuation become equal and each has a value equal to the geometric mean of the attenuation rates.

*Propagation velocity control by capacitor loading may also be used to advantage, for example, in adjusting the spacing in wavelengths between the significant low-impedance loads to an optimum value for good propagation.

Consider, for example, a line that has an attenuation due to series loss of 0.5 dB/km, an attenuation due to shunt resistance of 10 dB/km, and a natural characteristic impedance of 200 ohms. The shunt attenuation is 20 times the series attenuation, and the optimum change in R_0 is to reduce it by a factor equal to the square root of 20, yielding a new attenuation that is reduced from 11.5 dB/km to $2(0.5\sqrt{20}) = 4.47$ dB/km. Some examples are tabulated below.

Characteristic Impedance (Ω)	Series Loss (dB/km)	Shunt Loss (dB/km)	Net Attentuation (dB/km)	Attenuation per 20 km (dB)	Improvement (dB)
200	.5	10.0	11.50	230 dB	–
optimum 44.72	2.23	2.23	4.47	89.5	140.5 dB
200	.5	8.0	8.50	170 dB	–
optimum 50.0	–	2.0	4.0	80	90°
200	.25	10.0	10.25	205	–
optimum 31.6	1.58	1.58	3.16	63.2	141.8
200	.5	6.0	6.5	130	–
optimum 57.7	1.73	1.73	3.46	69.2	60.8
200	.5	4.0	4.5	90	33.6
optimum 70.7	1.41	1.41	2.82	56.4	–

D. IMPROVEMENT POTENTIAL

The theory for the low-impedance trolley line suggests that rather dramatic improvements in propagation of carrier signals can be achieved by lowering the characteristic impedance by capacitively loading the line. Unlike the single-point improvement achieved by tuning a rectifier, the low Z-line reduces mismatches at every place on the line that a mismatch exists, including power rectifiers, signal lights, pump motors, heaters, vehicles, and dirty insulators. The promise seems sufficient to warrant actual in-mine experiments to verify the expectations.

E. EXPERIMENT

1. Background

In Section B of this chapter, we discussed the theory of lowering the characteristic impedance of a trolley wire/rail transmission line by capacitive loading, and also included estimates of what performance improvements could be expected by such treatment.

Measurements made on an actual unencumbered mine trolley wire/rail show that the natural characteristic impedance of the trolley wire is near 200 ohms.

With the theory in hand, together with measurements to support the electrical properties of a trolley wire/rail, it became possible to simulate the performance expectations for a low-impedance trolley wire in the laboratory.

A convenient way of considering the insertion loss effects that a low-impedance line can produce is to treat a single shunt resistor applied across an otherwise matched transmission line. The insertion loss can be represented as:

$$L = 20 \log \frac{2R + Z_o}{2R}$$

For two different characteristic impedances, Z_o and Z'_o, the difference in insertion loss is simply:

$$L - L' = 20 \log \frac{2R + Z_o}{2R} - 20 \log \frac{2R + Z'_o}{2R} .$$

If the shunt resistance is quite small compared to Z_o,

$$L - L' = 20 \log \frac{Z_o}{Z'_o} .$$

For example, if Z_o is 300 ohms and Z'_o is 50 ohms, a difference of 15.56 dB occurs, and this favors the low-impedance line. Similar results obtain for any value of R and the exact values can be computed using the equations above.

We felt it would be instructive to verify the expectations for a low-Z line by experiments in the laboratory. For this purpose, we chose a length of 300-ohm twin-lead. This twin-lead* is fairly close to the unencumbered trolley wire/rail in terms of Z_o and thus in inductance and capacitance per unit length. The velocity of propagation is 80% that of free space, again corresponding fairly well to the theory and measurements of trolley wire transmission lines. Further, the construction of twin-lead easily lends itself to connecting shunt load resistors and to connecting the required loading capacitors.

---

*Belden Weldohm No. 8230.

2. Description of Experiment

Considerations of logistics, equipment performance, and complexity led us to simulate the trolley wire/rail configuration shown in Figure IV-10. Using a velocity of propagation of 80% that of free space yields a λ at 88 kHz of 8928 feet, or a half wavelength of 4464 feet. We chose to use a length of 250 feet of twin-lead to simulate the half wavelength. Hence, this required a frequency of 1.57 MHz to yield a half wavelength for the 250-foot length of line. We chose to reduce the characteristic impedance by a factor of 6 from 300 ohms to 50 ohms. The twin-lead has a capacitance of 4.4 pF/ft. Hence, to reduce the characteristic impedance by capacitive loading from 300 to 50 ohms requires a total capacitance per foot of 36 x 4.4 pF/ft, or an added capacitance of 35 x 4.4 = 154 pF/ft. A 2000-pF capacitor which requires a spacing of 12.99 feet is convenient. For the experiment the capacitor spacing was 13 feet, corresponding to 233 feet on a real trolley wire. The measurements were performed by suspending the twin-lead 5 feet above the ground outdoors and separating it by at least 2 feet from the nearest obstacles. One-quarter-watt carbon resistors were soldered across the twin-lead as shown in the figure. A signal generator at 1.57 MHz was used to drive the line, and the resulting voltages at the drive point and at all the resistive shunt load points were measured. After this measurement was made, nineteen 2000 pF microcapacitors were soldered across the line at 13-foot intervals. The voltage measurements were then repeated.

Results are presented in Figure IV-10 which shows the relative signal level for the two line conditions. It is seen that the low-Z line improves the transmission of signals from the transmitter and to the end of the line by more than 40 dB. Calculated signal levels are also shown on this figure. These values were obtained by use of the Smith chart, assuming that the line itself contributed no losses.

3. Conclusion

The improvement obtained in signal transmission is significant. The experiment verifies the theory of capacitive loading to reduce shunt losses. The technique is sufficiently promising that an in-mine trial should be considered. For such a trial, capacitors would have to be added at intervals along the trolley wire. Hard wiring to the rail would be required to assure a high-Q connection of the capacitors. Fusing would probably also be required for initial experiments to assure that a safe operation is obtained.

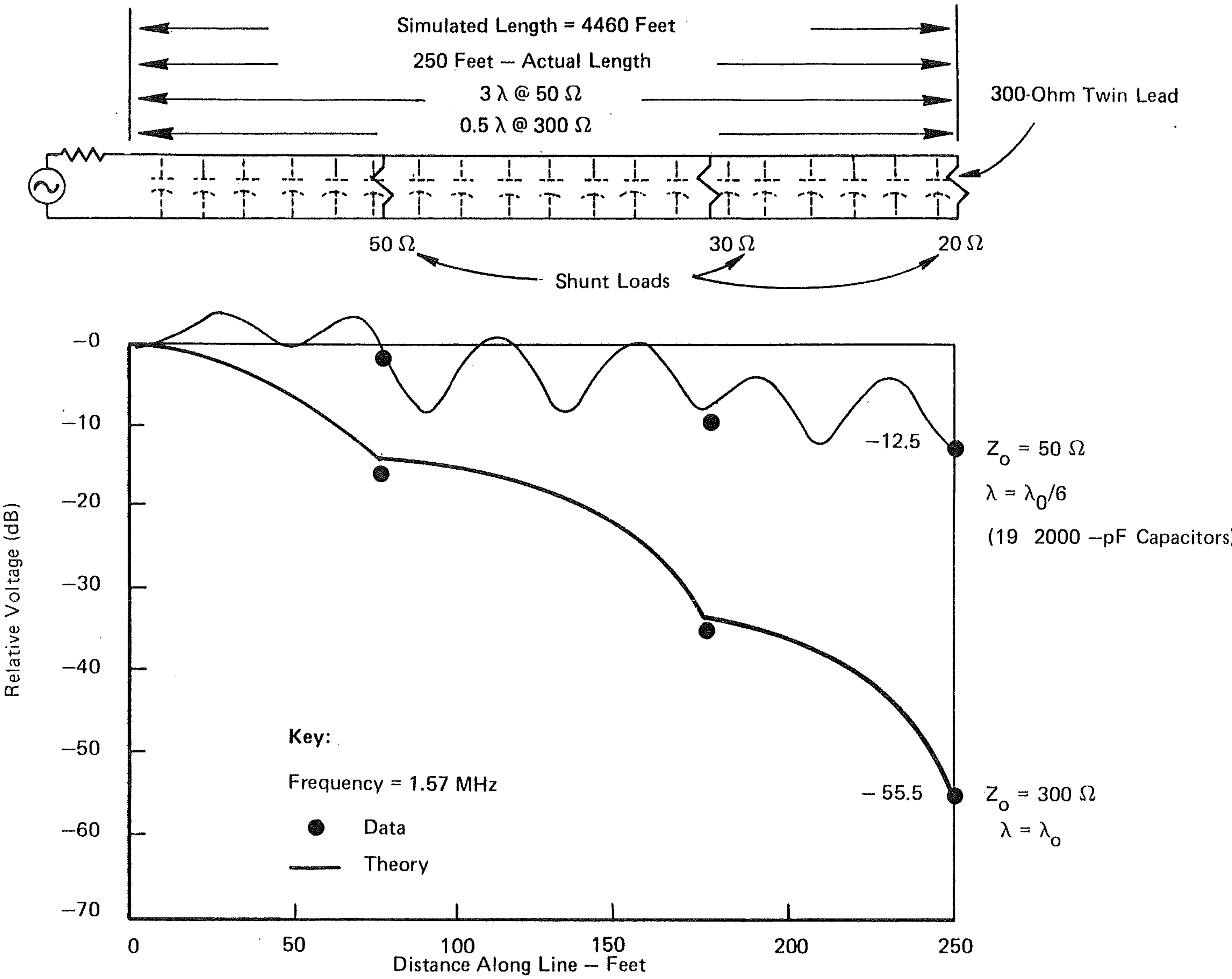


FIGURE IV–10 THEORY AND EXPERIMENTAL RESULTS FOR APPLICATION OF LOW-IMPEDANCE TECHNIQUE

V. THEORY OF THE "DEDICATED" WIRE AS A MEANS OF AIDING PROPAGATION ON A TROLLEY-WIRE

A. INTRODUCTION

The theory of radio frequency communication along an unloaded trolley-wire of a rail system used in a coal mine tunnel operating at frequencies in the range of 50-800 kHz has recently been given.*,**,† The authors cited below, using a wave theory approach, concluded that attenuation rates of the order of 1-2 dB/km are to be expected, and are due partly to the series resistance in the two conductors and partly to currents induced in the surrounding rock. Actual attenuation rates are much higher than these predicted values, owing to the shunting effect of low-resistance bridging loads including rectifiers, mine motors, lights, pumps, and personnel heaters which are distributed at intervals along the trolley-wire/rail system. Experience shows that these discrete shunt loads result in an effective attenuation over large distances comparable to a wavelength that is at least 10 dB/km and perhaps as high as 20 dB/km.

A concept for greatly reducing the attenuation rate is predicated on the use of a thin, "dedicated" wire attached near the roof or on the wall of the tunnel which, along with the rail, provides a low-loss transmission line coupled weakly to the trolley-rail transmission line. The idea is that the "dedicated" wire/rail transmission line, once it is excited either directly or by coupling to the trolley-wire/rail line, will act as a distributed power source and feed power back into the trolley-wire/rail line at great distances, thereby drastically reducing the signal attenuation rate.

The purpose of this section is to develop the theory of these two coupled transmission lines, with allowance both for the shunt losses in the trolley-wire/rail line and for the losses due to currents induced in the surrounding coal and rock, to determine the degree to which the loss rate of a high loss line can be reduced by mutual coupling to a nearby low loss line. Since the discrete shunt losses would be difficult to include in a wave theory analysis, we treat the problem by means of multi-conductor transmission line theory. The losses due to the rock are represented by appropriate resistances in series with the trolley-wire and the dedicated wire. These resistances are deduced from the loss rates given by Wait and Hill.** The discrete shunt loads placed across the trolley-wire/rail, typically at intervals short compared to wavelength, are approximated by a continuously distributed shunt loss across the trolley-wire/rail line that will produce the total loss equivalent to that produced by the discrete shunt loads over a long length of the line.

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*D.A. Hill and J.R. Wait, *Analysis of radio frequency transmission along a trolley wire in a mine tunnel,* November 1976 issue of IEEE, Electromag. Compat. pp. 170-174.

**J.R. Wait and D.A. Hill, *Radio frequency transmission via a trolley wire in a tunnel with a rail return,* to be published in the March 1977 issue of IEEE Trans. on Antennas and Propagation.

†J.R. Wait, *Theory of Transmission of Electromagnetic Waves along Multiconductor Lines* in a Proximity of Walls of Mine Tunnels, Proc. International Colloquium on Leaky Feeder Communication Systems, 8-10 April 1974, Gilford, Surrey, England, pp. 97-107.

The results of the calculations show that ranges of the order of 20 km should be possible with the help of the dedicated wire, in contrast to ranges on the order of 4 km in the absence of the dedicated wire or other means of extending range.

B. MODE ANALYSIS

Figure V-1 is a schematic diagram of the three-conductor transmission system, which can be regarded as two coupled transmission lines labeled 1 and 2. Line 1, with voltage V_1 and current I_1, is the trolley-wire/rail transmission line. Line 2, with voltage V_2 and current I_2, is the dedicated wire/rail transmission line. The electrically interconnected rails are represented by a single cylindrical conductor which also carries the return current $-(I_1 + I_2)$.

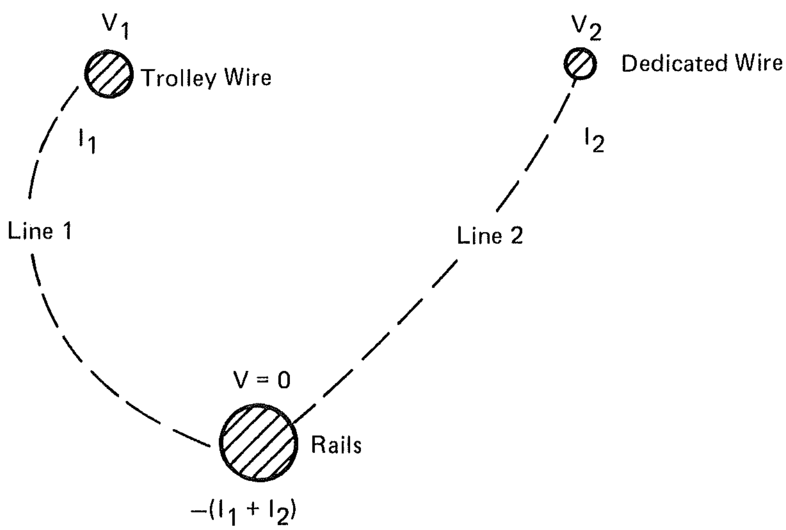

FIGURE V-1 THE THREE-CONDUCTOR TRANSMISSION SYSTEM

The voltages and currents are related by the following first-order differential equations:

$$\frac{dV_1}{dz} = -Z_{11}I_1 - Z_{12}I_2 \qquad \text{(V-1)}$$

$$\frac{dV_2}{dz} = -Z_{21}I_1 - Z_{22}I_2 \tag{V-2}$$

$$\frac{dI_1}{dz} = -Y_{11}V_1 - Y_{12}V_2 \tag{V-3}$$

$$\frac{dI_2}{dz} = -Y_{21}V_1 - Y_{22}V_2 \tag{V-4}$$

where z is the distance along the transmission lines and the Z's and Y's are impedances and admittances per unit length that include (1) effective series resistances per unit length due to currents induced in the nearby conducting coal and rock, and (2) the average shunt conductance per unit length due to bridging loads connected across the trolley-wire/rail transmission line.

On eliminating I_1 and I_2 from Equations (V-1) through (V-4), we obtain two coupled second-order equations for V_1 and V_2:

$$\frac{d^2V_1}{dz^2} = (Z_{11}Y_{11} + Z_{12}Y_{12})V_1 + (Z_{11}Y_{12} + Z_{12}Y_{22})V_2 \tag{V-5}$$

$$\frac{d^2V_2}{dz^2} = (Z_{22}Y_{22} + Z_{12}Y_{12})V_1 + (Z_{22}Y_{12} + Z_{12}Y_{11})V_2 \tag{V-6}$$

where we have used the general reciprocal relations $Z_{21} = Z_{12}$ and $Y_{21} = Y_{12}$.

The solution of Equations (V-5) and (V-6) can be expressed as a superposition of pure exponential modes of the form:

$$V_1, V_2 \propto e^{-\gamma z} \tag{V-7}$$

where $\gamma = \alpha + i\beta$ is the propagation constant. On substituting Equation (V-7) into Equations (V-5) and (V-6), we obtain the conditions:

$$(Z_{11}Y_{11} + Z_{12}Y_{12} - \gamma^2)V_1 + (Z_{11}Y_{12} + Z_{12}Y_{22})V_2 = 0 \tag{V-8}$$

$$(Z_{22}Y_{12} + Z_{12}Y_{11})V_1 + (Z_{22}Y_{22} + Z_{12}Y_{12} - \gamma^2)V_2 = 0. \tag{V-9}$$

Consistency of Equations (V-8) and (V-9) requires that:

$$\begin{vmatrix} Z_{11}Y_{11} + Z_{12}Y_{12} - \gamma^2 & Z_{11}Y_{12} + Z_{12}Y_{22} \\ Z_{22}Y_{12} + Z_{12}Y_{11} & Z_{22}Y_{22} + Z_{12}Y_{12} - \gamma^2 \end{vmatrix} = 0 \qquad \text{(V-10)}$$

which is the mode equation for the propagation constant γ. On expanding the determinant and solving for γ^2, we obtain the roots:

$$\gamma_{\pm}^2 = p \pm (p^2 - q)^{1/2} \qquad \text{(V-11)}$$

where

$$p = \tfrac{1}{2}(Z_{11}Y_{11} + Z_{22}Y_{22} + 2\, Z_{12}Y_{12}) \qquad \text{(V-12)}$$

and

$$q = (Z_{11}Z_{22} - Z_{12}^2)(Y_{11}Y_{22} - Y_{12}^2)\,. \qquad \text{(V-13)}$$

Equation (V-11) shows that there are four modes with propagation constants $\pm\gamma_+$, $\pm\gamma_-$. Two of these modes correspond to travel in the positive-z direction and two in the negative-z direction. We are interested only in the forward-going mode, for which the real parts of γ_+ and γ_- are positive, since the transmission lines are assumed to be so long or so terminated that no significant reflected waves exist.

The general solutions of Equations (V-5) and (V-6) for forward waves is a superposition of the two forward-going modes:

$$V_1 = Ae^{-\gamma_+ z} + Be^{-\gamma_- z} \qquad \text{(V-14)}$$

$$V_2 = r_+Ae^{-\gamma_+ z} + r_-Be^{-\gamma_- z} \qquad \text{(V-15)}$$

where A and B are arbitrary constants and

$$r_{\pm} = \frac{\gamma_{\pm}^2 - Z_{11}Y_{11} - Z_{12}Y_{12}}{Z_{11}Y_{12} + Z_{12}Y_{22}} \qquad \text{(V-16)}$$

Equation (V-15) results from inserting V_1 of Equation (V-14) into Equation (V-5) and then solving for V_2.

To obtain expressions for the currents in the two lines, we solve Equations (V-1) and (V-2) for I_1 and I_2 and then substitute for V_1 and V_2 from Equations (V-14) and (V-15). The results are:

$$I_1 = \frac{1}{Z_{11}Z_{22} - Z_{12}^2}\left[(Z_{22} - r_+Z_{12})\gamma_+Ae^{-\gamma_+z} + (Z_{22} - r_-Z_{12})\gamma_-Be^{-\gamma_-z}\right] \qquad \text{(V-17)}$$

and

$$I_2 = \frac{1}{Z_{11}Z_{22} - Z_{12}^2}\left[(r_+Z_{11} - Z_{12})\gamma_+Ae^{-\gamma_+z} + (r_-Z_{11} - Z_{12})\gamma_-Be^{-\gamma_-z}\right] \qquad \text{(V-18)}$$

C. APPLICATION OF THE BOUNDARY CONDITIONS

Next we have to apply specific boundary conditions to determine the arbitrary constants A and B. Two cases are of interest:

(1) where the transmitter applies a voltage V_o at $z = 0$ between the trolley-wire and the rail, and

(2) where V_o is applied between the "dedicated" wire and the rail.

1. Transmitter across Line 1

The boundary conditions at $z = 0$ are:

$$V_1 = V_o \qquad \text{(V-19)}$$

and

$$I_2 = 0. \qquad \text{(V-20)}$$

The reason for the second boundary condition is that the current in line 2 is antisymmetrical in z and continuous at $z = 0$.

Applying conditions of Equations (V-19) and (V-20) to Equations (V-14) and (V-18), respectively, yields:

$$A + B = V_o \qquad \text{(V-21)}$$

$$(r_+Z_{11} - Z_{12})\gamma_+A + (r_-Z_{11} - Z_{12})\gamma_-B = 0 \qquad \text{(V-22)}$$

whence

$$\binom{A}{B} = \frac{\gamma_{\mp}\left(r_{\mp}Z_{11} - Z_{12}\right)V_0}{\gamma_-\left(r_-Z_{11} - Z_{12}\right) - \gamma_+\left(r_+Z_{11} - Z_{12}\right)} \tag{V-23}$$

Then Equations (V-14), (V-15), (V-17), and (V-18) become:

$$\frac{V_1}{V_0} = \frac{\gamma_-\left(r_-Z_{11} - Z_{12}\right)e^{-\gamma_+z} - \gamma_+\left(r_+Z_{11} - Z_{12}\right)e^{-\gamma_-z}}{\gamma_-\left(r_-Z_{11} - Z_{12}\right) - \gamma_+\left(r_+Z_{11} - Z_{12}\right)} \tag{V-24}$$

$$\frac{V_2}{V_0} = \frac{\gamma_-r_+\left(r_-Z_{11} - Z_{12}\right)e^{-\gamma_+z} - \gamma_+r_-\left(r_+Z_{11} - Z_{12}\right)e^{-\gamma_-z}}{\gamma_-\left(r_-Z_{11} - Z_{12}\right) - \gamma_+\left(r_+Z_{11} - Z_{12}\right)} \tag{V-25}$$

$$\frac{I_1}{V_0} = \frac{\gamma_+\gamma_-}{\left(Z_{11}Z_{22} - Z_{12}^2\right)}\left[\frac{\left(Z_{22} - r_+Z_{12}\right)\left(r_-Z_{11} - Z_{12}\right)e^{-\gamma_+z} - \left(Z_{22} - r_-Z_{12}\right)\left(r_+Z_{11} - Z_{12}\right)e^{-\gamma_-z}}{\gamma_-\left(r_-Z_{11} - Z_{12}\right) - \gamma_+\left(r_+Z_{11} - Z_{12}\right)}\right] \tag{V-26}$$

$$\frac{I_2}{V_0} = \frac{\gamma_+\gamma_-\left(r_+Z_{11} - Z_{12}\right)\left(r_-Z_{11} - Z_{12}\right)\left(e^{-\gamma_+z} - e^{-\gamma_-z}\right)}{\left(Z_{11}Z_{22} - Z_{12}^2\right)\left[\gamma_-\left(r_-Z_{11} - Z_{12}\right) - \gamma_+\left(r_+Z_{11} - Z_{12}\right)\right]} \tag{V-27}$$

2. Transmitter on Line 2

When the transmitter is across line 2 the voltages and currents are given by Equations (V-24) – (V-27) with the subscripts 1 and 2 interchanged:

$$\frac{V_2}{V_0} = \frac{\gamma_-\left(r'_-Z_{22} - Z_{12}\right)e^{-\gamma_+z} - \gamma_+\left(r'_+Z_{22} - Z_{12}\right)e^{-\gamma_-z}}{\gamma_-\left(r'_-Z_{22} - Z_{12}\right) - \gamma_+\left(r'_+Z_{22} - Z_{12}\right)} \tag{V-28}$$

$$\frac{V_1}{V_0} = \frac{\gamma_-r'_+\left(r'_-Z_{22} - Z_{12}\right)e^{-\gamma_+z} - \gamma_+r'_-\left(r'_+Z_{22} - Z_{12}\right)e^{-\gamma_-z}}{\gamma_-\left(r'_-Z_{22} - Z_{12}\right) - \gamma_+\left(r'_+Z_{22} - Z_{12}\right)} \tag{V-29}$$

$$\frac{I_2}{V_0} = \frac{\gamma_+\gamma_-}{Z_{11}Z_{22} - Z_{12}^2}\left[\frac{\left(Z_{11} - r'_+Z_{12}\right)\left(r'_-Z_{22} - Z_{12}\right)e^{-\gamma_+z} - \left(Z_{11} - r'_-Z_{12}\right)\left(r'_+Z_{22} - Z_{12}\right)e^{-\gamma_-z}}{\gamma_-\left(r'_-Z_{22} - Z_{12}\right) - \gamma_+\left(r'_+Z_{22} - Z_{12}\right)}\right] \tag{V-30}$$

$$\frac{I_1}{V_0} = \frac{\gamma_+\gamma_-\left(r'_+Z_{22} - Z_{12}\right)\left(r'_-Z_{22} - Z_{12}\right)\left(e^{-\gamma_+z} - e^{-\gamma_-z}\right)}{\left(Z_{11}Z_{22} - Z_{12}^2\right)\left[\gamma_-\left(r'_-Z_{22} - Z_{12}\right) - \gamma_+\left(r'_+Z_{22} - Z_{12}\right)\right]} \tag{V-31}$$

where, from Equation (V-16):

$$r'_{\pm} = \frac{\gamma_{\pm}^2 - Z_{22}Y_{22} - Z_{12}Y_{12}}{Z_{22}Y_{12} + Z_{12}Y_{11}} \qquad \text{(V-32)}$$

D. CALCULATION OF THE IMPEDANCES AND ADMITTANCES

1. Inductance per Unit Length

We denote the radii of the trolley-wire, the dedicated-wire, and the rail by a, b, and c, respectively, and also use the same letters as subscripts to indicate these conductors.

Equations (V-1) – (V-4) define the Z's and Y's. For example, Z_{11} is given by the formula

$$Z_{11} = -\frac{1}{I_1}\left(\frac{dV_1}{dz}\right)_{I_2=0} = R_a + i\omega L_{11} \qquad \text{(V-33)}$$

where R_a is the effective resistance per unit length of the trolley-wire and L_{11} is the magnetic flux that links unit length of line 1 for currents of +1 ampere in the trolley-wire and - 1 ampere in the rail. Since the radii a and c are small compared with the distance S_{ac} between the axis of the two conductors, we can write

$$L_{11} = \int_a^{S_{ac}} \mu_o H_a dr + \int_c^{S_{ac}} \mu_o H_c\, dr'$$

$$= \int_a^{S_{ac}} \frac{\mu_o\, dr}{2\pi r} + \int_c^{S_{ac}} \frac{\mu_o\, dr'}{2\pi r'} = \frac{\mu_o}{2\pi} \ln\left(\frac{S_{ac}^2}{ac}\right) \qquad \text{(V-34)}$$

where H_a and H_c are the magnetic fields due to the unit currents in wires a and c and r, r′ are distances from the axes of wires a and c.

Likewise:

$$Z_{22} = R_b + i\omega L_{22} \qquad \text{(V-35)}$$

where

$$L_{22} = \frac{\mu_o}{2\pi} \ln\left(\frac{S_{bc}^2}{bc}\right) \qquad \text{(V-36)}$$

From Equation (V-1), the mutual impedance Z_{12} is defined as

$$Z_{12} = -\frac{1}{I_2}\left(\frac{dV_1}{dz}\right)_{I_1=0} = i\omega L_{12} \qquad \text{(V-37)}$$

where L_{12} is the magnetic flux linking line 1 due to +1 ampere in wire b and - 1 ampere in wire c. Figure V-2 shows the magnetic field lines H_b and H_c linking line 1 due to unit currents in wires b and c. On integrating the two fields to obtain the total flux, we find that:

$$L_{12} \cong \frac{\mu_o}{2\pi}\ln\left(\frac{S_{bc}}{S_{ba}}\right) + \frac{\mu_o}{2\pi}\ln\left(\frac{S_{ac}}{c}\right) = \frac{\mu_o}{2\pi}\ln\left(\frac{S_{bc}S_{ac}}{cS_{ab}}\right) \qquad \text{(V-38)}$$

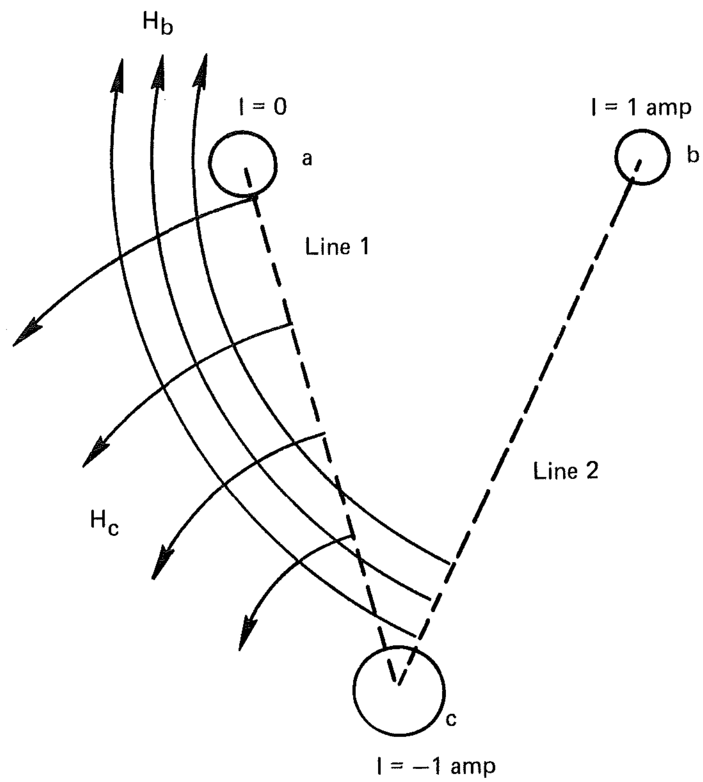

FIGURE V-2   FIELDS H_b AND H_c CONTRIBUTING TO L_{12}

2. Capacitance per Unit Length

From Equations (V-3) and (V-4), we find that

$$Y_{11} = -\frac{1}{V_1}\left(\frac{dI_1}{dz}\right)_{V_2=0} = G_{ac} + i\omega C_{11} \qquad \text{(V-39)}$$

$$Y_{21} = -\frac{1}{V_1}\left(\frac{dI_2}{dz}\right)_{V_2=0} = i\omega C_{21} \qquad \text{(V-40)}$$

where G_{ac} is the shunt conductance per unit length across line 1, and C_{11} and C_{21} are the charges per unit length induced on wires a and b by unit potential on wire a, while wires b and c are held at zero potential.

Now the potential V at any point due to charges $q_1, q_2, -(q_1 + q_2)$ per unit length on wires a, b, c, respectively, is given by the general expression

$$V = K - \frac{q_1}{2\pi\epsilon_o}\ell n\left(\frac{r_1}{a}\right) - \frac{q_2}{2\pi\epsilon_o}\ell n\frac{r_2}{b} + \frac{(q_1+q_2)}{2\pi\epsilon_2}\ell n\frac{r_3}{c} \qquad \text{(V-41)}$$

where K is an arbitrary constant and r_1, r_2, r_3 are distances of the chosen point from the axes of the three wires.

Under the conditions specified in Equations (V-39) and (V-40), the wires a, b, and c have potentials V_1, 0, and 0, and the corresponding values of (r_1, r_2, r_3) are (a, S_{ab}, S_{ac}), (S_{ab}, b, S_{bc}), and (S_{ac}, S_{bc}, c), respectively. We therefore have the following three conditions for the determination of K, q_1, and q_2 in terms of V_1:

$$V_1 = K - \frac{q_2}{2\pi\epsilon_o}\ell n\frac{S_{ab}}{b} + \frac{q_1+q_2}{2\pi\epsilon_o}\ell n\frac{S_{ac}}{c} \qquad \text{(V-42)}$$

$$0 = K - \frac{q_1}{2\pi\epsilon_o}\ell n\frac{S_{ab}}{a} + \frac{q_1+q_2}{2\pi\epsilon_o}\ell n\frac{S_{bc}}{b} \qquad \text{(V-43)}$$

$$0 = K - \frac{q_1}{2\pi\epsilon_o}\ell n\frac{S_{ac}}{a} - \frac{q_2}{2\pi\epsilon_o}\ell n\frac{S_{bc}}{b} \qquad \text{(V-44)}$$

On solving these equations for q_1 and q_2, we obtain the results:

$$q_1 = \frac{2\pi\epsilon_o V_1}{\Delta}\ell n\left(\frac{S_{bc}^2}{bc}\right) \qquad \text{(V-45)}$$

and

$$q_2 = -\frac{2\pi\epsilon_o V_1}{\Delta} \ell n \left(\frac{S_{ac} S_{bc}}{S_{ab} c} \right) \tag{V-46}$$

where

$$\Delta = \ell n \left(\frac{S_{ab} S_{ac}}{S_{bc} a} \right) \ell n \left(\frac{S_{bc} S_{ac}}{S_{ab} c} \right) + \ell n \left(\frac{S_{ac}^2}{ac} \right) \ell n \left(\frac{S_{bc} S_{ab}}{S_{ac} b} \right) \tag{V-47a}$$

which can be written in the symmetrical form

$$\Delta = \ell n \left(\frac{S_{ac}^2}{ac} \right) \ell n \left(\frac{S_{bc}^2}{bc} \right) - \left(\ell n \frac{S_{ac} S_{bc}}{S_{ab} c} \right)^2 . \tag{V-47b}$$

Therefore:

$$C_{11} = \frac{q_1}{V_1} = \frac{2\pi\epsilon_o}{\Delta} \ell n \left(\frac{S_{bc}^2}{bc} \right) \tag{V-48}$$

$$C_{21} = \frac{q_2}{V_1} = -\frac{2\pi\epsilon_o}{\Delta} \ell n \left(\frac{S_{ac} S_{bc}}{S_{ab} c} \right) . \tag{V-49}$$

By reciprocity, Equation (V-49) also gives the value of C_{12}. By symmetry we find from Equation (V-48) that

$$Y_{22} = i\omega C_{22} \tag{V-50}$$

where

$$C_{22} = \frac{2\pi\epsilon_o}{\Delta} \ell n \left(\frac{S_{ac}^2}{ac} \right) . \tag{V-51}$$

3. Series Resistance per Unit Length

The series resistance R_b of transmission line 2, acting alone in the tunnel, is chosen so that the attenuation constant a_2 lies in the range calculated by Wait and Hill.* The connection between R_b and a_2 is given by the transmission line formula:

$$a_2 + i\beta_2 = \left\{ \left(R_b + i\omega L_{bc} \right) i\omega C_{bc} \right\}^{1/2} \tag{V-52}$$

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*Wait and Hill, *op. cit.*

where

$$L_{bc} = \frac{\mu_o}{2\pi} \ell n\left(\frac{S_{bc}^2}{bc}\right) \tag{V-53}$$

and

$$C_{bc} = 2\pi\epsilon_o / \ell n\left(\frac{S_{bc}^2}{bc}\right) . \tag{V-54}$$

On separating the real and imaginary parts of Equation (V-52) and eliminating β_2, we find that:

$$R_b = \frac{2\alpha_2\left(\alpha_2^2 + \beta_o^2\right)^{1/2}}{\omega C_{bc}} \tag{V-55}$$

where

$$\beta_o = \omega / c_o \tag{V-56}$$

and c_o is the speed of light in free space. Since transmission lines 1 and 2 have comparable geometry relative to the rock, we assume that $R_a = R_b$.

The justification for representing the effect of the rock simply by a series resistance R_b lies in the fact that the skin-depth δ in the rock at the proposed operating frequency of 0.1 MHz (for rock conductivity of the order of 0.1 Mho/m) is 5 m. If the "dedicated" wire lies close to the surface of the rock, its image therefore lies at a complex distance 5(1 - i) m within the rock.†† Since the absolute value of this image distance is fairly large compared with the separation of the two conductors of the transmission line, most of the current flows in the conductors rather than in the rock. The shielding effect of the rock may therefore be neglected for our present practical purposes.

4. Shunt Conductance per Unit Length

The effective shunt conductance G_{ac} per unit length of line 1 may then be calculated from the transmission line equation

$$\alpha_1 + i\beta_1 = \left\{\left(R_a + i\omega L_{ac}\right)\left(G_{ac} + i\omega C_{ac}\right)\right\}^{1/2} \tag{V-57}$$

where

$$L_{ac} = \frac{\mu_o}{2\pi} \ell n\left(\frac{S_{ac}^2}{ac}\right) \tag{V-58}$$

††Bannister, P.R., IEEE Trans. EMC, Vol. 15, No. 4, November 1973, p. 158.

and

$$C_{ac} = 2\pi\epsilon_o / \ell n\left(\frac{S_{ac}^2}{ac}\right) \qquad \text{(V-59)}$$

On separating real and imaginary parts of Equation (V-57) and eliminating β_1, we obtain the expression

$$G_{ac} = \left[\left\{R_a\left(\frac{1}{c_o^2} + \frac{2a^2}{\omega^2}\right)\Big/L_{ac}^2\right\}^2 + \left\{\frac{4a_1^2\left(a_1^2 + \beta_o^2\right)}{\omega^2} - R_a^2 C_{ac}^2\right\}\Big/L_{ac}^2\right]^{1/2} - R_a\left(\frac{1}{c_o^2} + \frac{2a_1^2}{\omega^2}\right)\Big/L_{ac}^2 \qquad \text{(V-60)}$$

for the determination of G_{ac} for any given value of the attenuation constant a_1 of transmission line 1 acting alone.

Since the dedicated wire is assumed to be insulated from the rail, we assume that $G_{bc} = 0$.

E. COMPUTATION

1. Computation

Figure V-3 shows the locations of the three conductors relative to the tunnel cross-section. The separations of the axes of the conductors are given by:

$$S_{ab}^2 = \left(x_b - x_a\right)^2 + \left(y_b - y_a\right)^2 \qquad \text{(V-61)}$$

$$S_{bc}^2 = \left(x_b - x_c\right)^2 + \left(y_b - y_c\right)^2 \qquad \text{(V-62)}$$

$$S_{ac}^2 = \left(x_c - x_a\right)^2 + \left(y_c - y_a\right)^2 \qquad \text{(V-63)}$$

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, and placed at various points on the dotted contour in the tunnel cross-section in Figure V-3 for calculations of signal strength at fixed distance z and various locations of the wire on the contour.

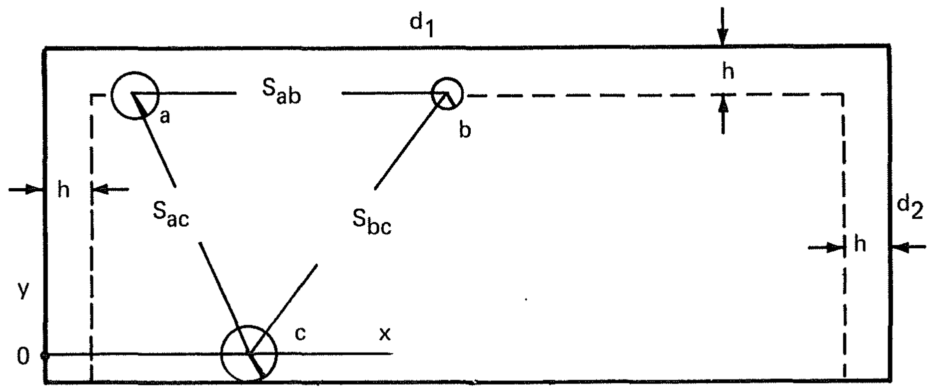


FIGURE V-3 CROSS SECTION OF TUNNEL (OF DIMENSIONS d_1 x d_2, SHOWING THE TROLLEY WIRE, DEDICATED WIRE, AND RAIL, OF RESPECTIVE RADII a, b, c, SEPARATED BY DISTANCES S_{ab}, S_{bc}, S_{ac}. THE TROLLEY WIRE AXIS IS AT A DISTANCE h BELOW THE ROOF, THE RAIL AXIS IS AT A DISTANCE c ABOVE THE FLOOR, AND THE DEDICATED WIRE CAN BE LOCATED AT ANY CHOSEN POINT ON THE DOTTED CONTOUR WHICH LIES AT A DISTANCE h IN FRONT OF THE SIDE WALLS OR ROOF.)

A time-sharing computer system (On-line Systems, Inc.) was used to evaluate the currents and voltages as functions of z for a variety of values of the parameters and two excitation conditions. The results obtained were plotted on graph paper and are discussed below.

F. DISCUSSION OF RESULTS

Results of our investigation of the potential improvements to be gained by the introduction of a "dedicated" wire parallel to a high-loss trolley-wire/rail transmission line are shown in Figures V-4 through V-11. These figures illustrate the performance capabilities to be expected by employing the dedicated wire to extend the range of trolley-wire carrier phone communication systems in mines. Figure V-4 illustrates the way in which voltages decrease with distance from transmitters in such a system. It should be noted that in conventional practice when the transmitter voltage is applied between the trolley-wire and the rail, severe attenuation of the signal occurs with distance due to the multitude of loss mechanisms present across the trolley-wire/rail transmission line. For the example shown in Figure V-4, a net attenuation rate of 10 dB/km is assumed for the trolley-wire/rail transmission path. The distances covered in this plot run to 20 km. Thus, the total signal loss would be approximately 200 dB on the trolley-wire/rail in the absence of the dedicated wire. For most trolley carrier

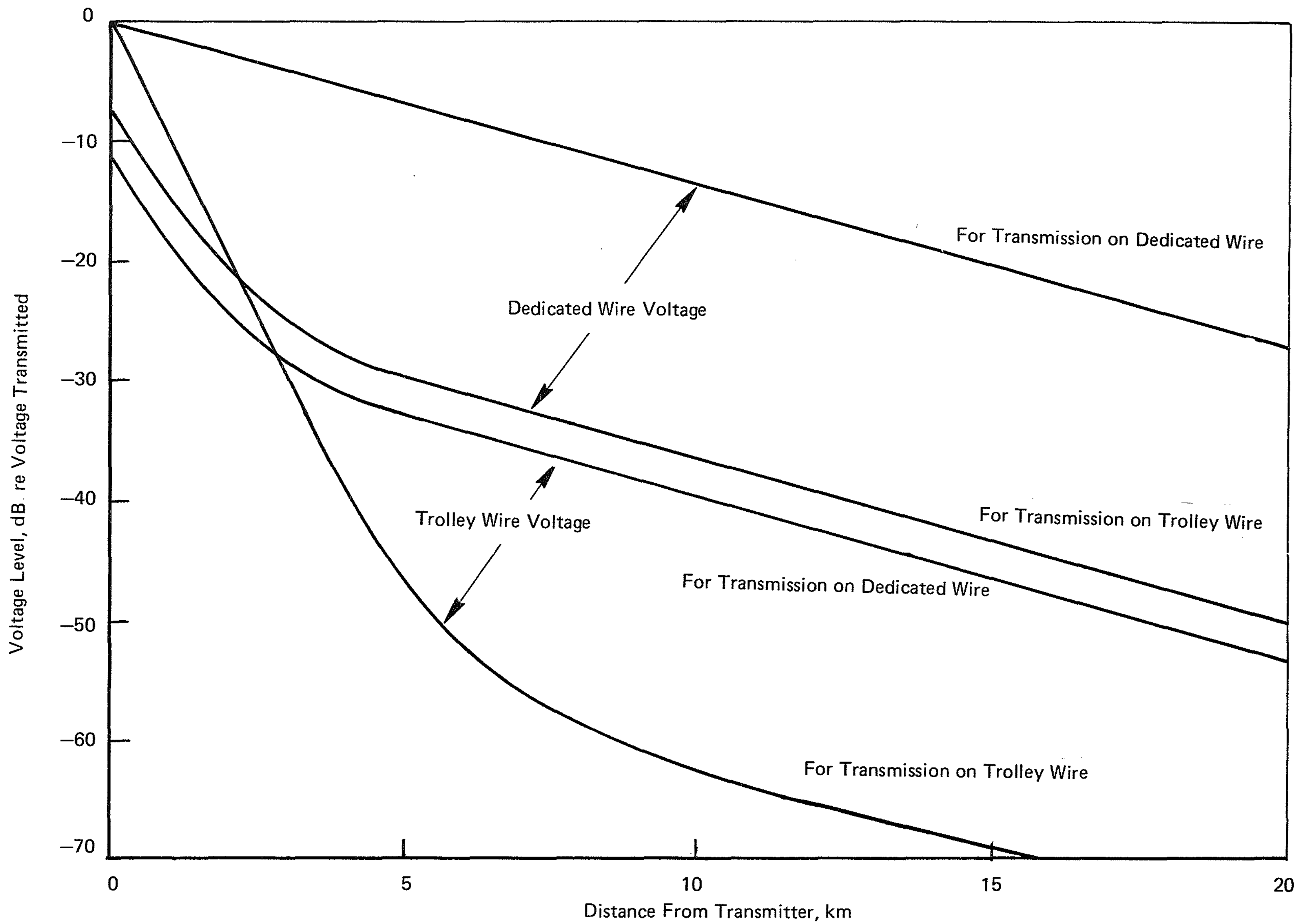


FIGURE V-4 VOLTAGE LEVELS VERSUS DISTANCE
α_T = 10 dB/km
α_D = 1 dB/km

phones a practical loss of between 60 and 70 dB can be tolerated depending on ambient noise conditions on the trolley-wire/rail.

Figure V-4 presents signal levels on both transmission lines as a function of distance, for transmitters feeding the trolley-wire/rail line such as would be the case for tracked vehicles in the mine, and for transmitters feeding the dedicated wire/rail line which could represent the feed arrangement for a dispatcher's transmitter. Figure V-4 shows that, at the end of 20 km, the loss from the dispatcher to a vehicle and the loss from vehicle to dispatcher are 53 dB and 49.5 dB, respectively. Thus, an improvement of 150 dB in signal level is achieved over conventional trolley-wire/rail transmission line systems in which both vehicle and dispatcher's carrier phones are connected across the trolley-wire/rail and no parallel dedicated wire or other signal-extending means is present. This figure also illustrates the fact that when beyond the "initial condition" region caused by the discrete source transmitter, signals on both lines alternate at a uniform and low rate closer in value to the rate of the dedicated wire/rail line alone. In addition, curve 4 shows that even conventional trolley-line communication; i.e. transmission and reception on the trolley-wire/rail line between two vehicles or a vehicle and the dispatcher, will be markedly improved just by the presence of a dedicated wire even though no signals are directly impressed onto the dedicated wire.

Figure V-5 presents results for the same conditions of operation as shown in Figure V-4, except for the fact that a higher attenuation rate of 20 dB/km is assumed for the trolley-wire/rail line. In this instance it can be seen that the signal levels resulting from transmission on the dedicated wire/rail line and reception on the trolley-wire/rail line, and vice versa, show only modestly increased losses over those for the 10-dB loss rate of Figure V-4. This illustrates the fact that the dominant feature in controlling the final attenuation rate is the quality of or loss associated with the dedicated line. The signal levels at the end of the 20-km test section are found to exhibit between 55 and 62 dB of loss, completely practical values for useful carrier phone systems.

Figures V-6 and V-7 show plots of the current levels in the trolley-wire and in the "dedicated" wire versus distance for the same conditions as those of Figures V-4 and V-5, respectively. Little comment is needed concerning the characteristics of these except to note that at zero distance one expects to find zero current in the line to which the transmitter is not connected; e.g., if the transmission is on the "dedicated" line, zero current will be found on the trolley-wire at the transmitter position. It is seen that the current on the line without the transmitter builds up to a maximum value within a relatively short distance and then decays at the uniform attenuation rate of the coupled transmission line system.

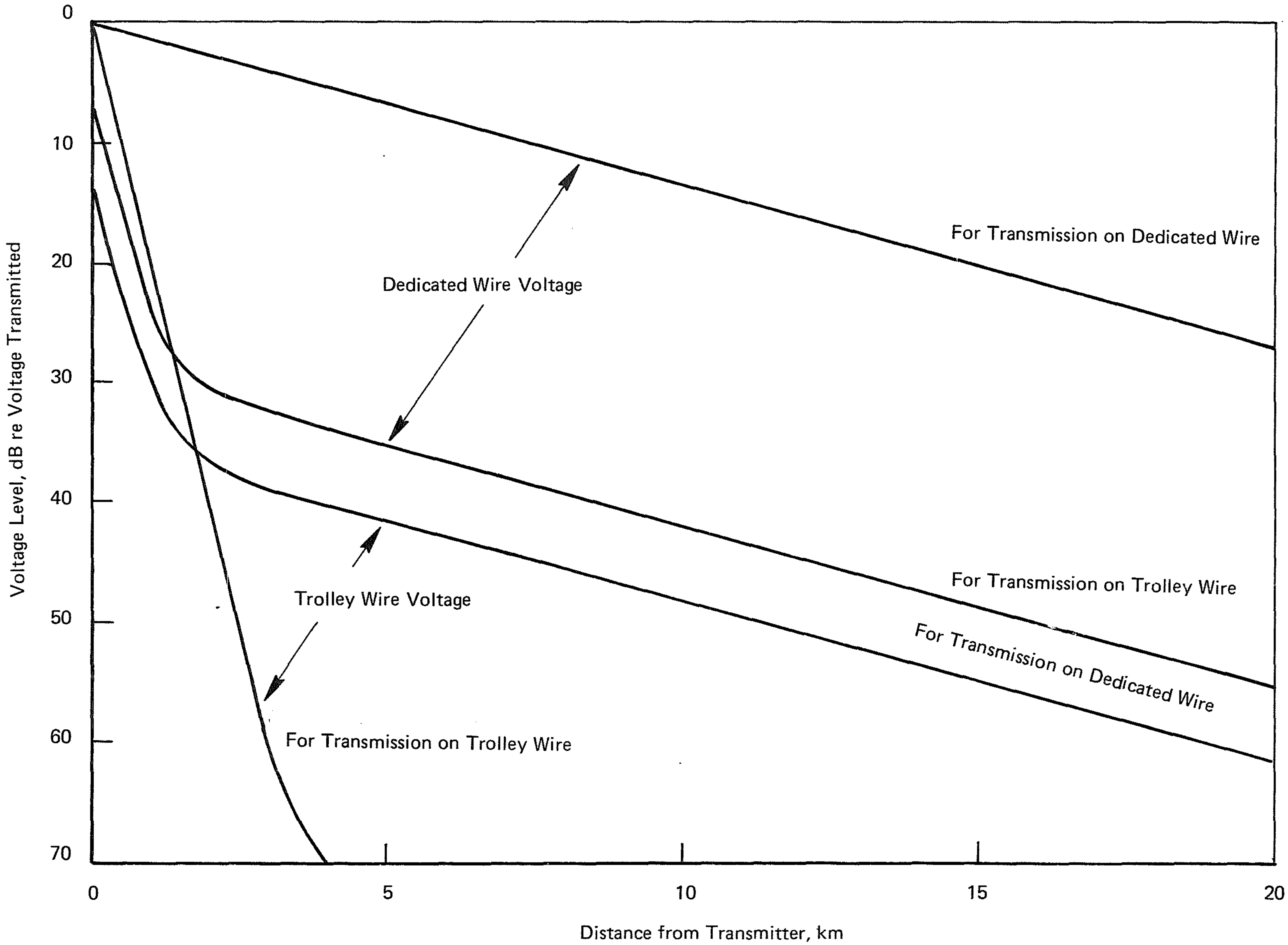


FIGURE V-5 VOLTAGE LEVELS VERSUS DISTANCE
α_T = 20 dB/km
α_D = 1.0 dB/km

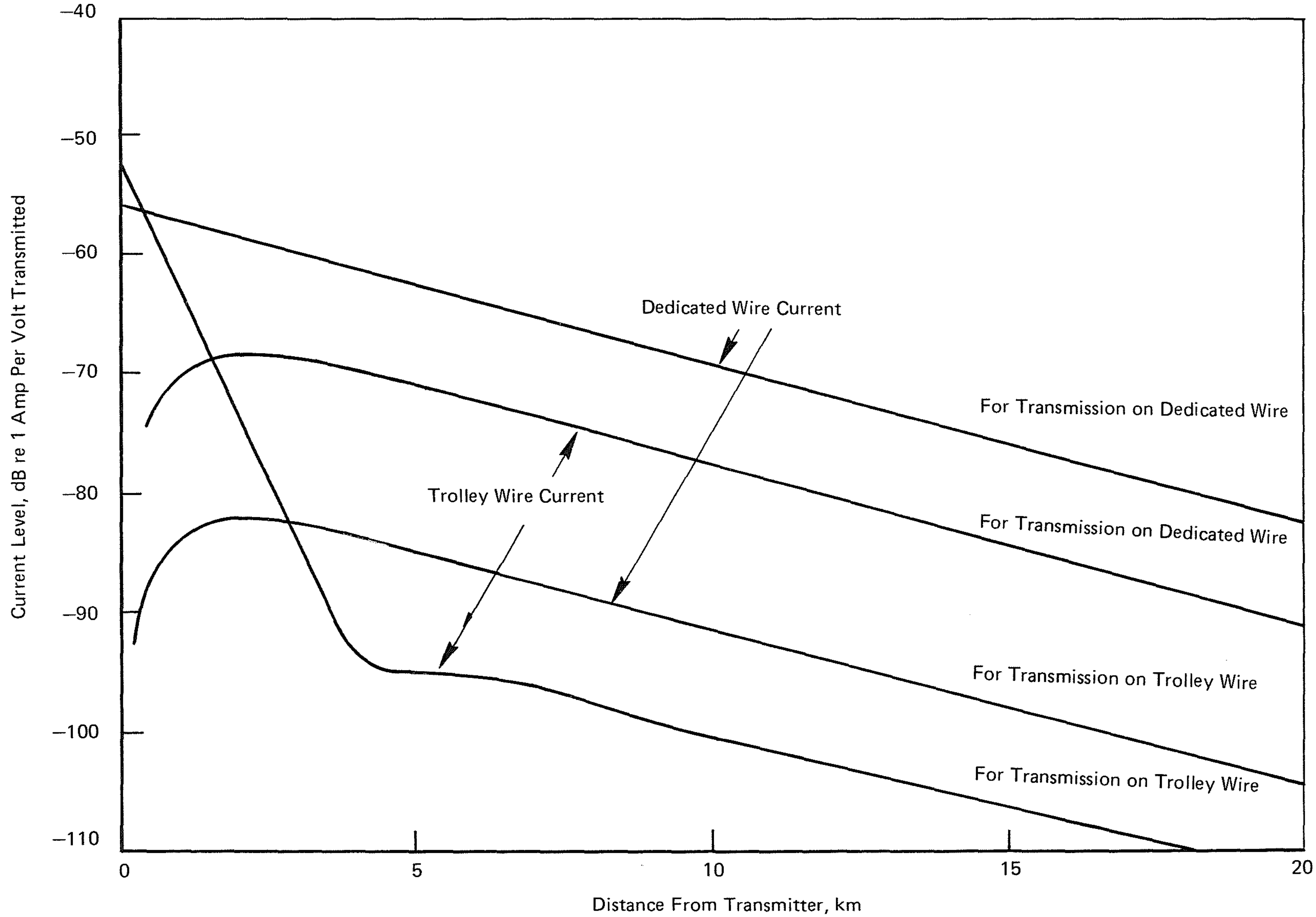


FIGURE V-6 CURRENT LEVELS VERSUS DISTANCE
α_T = 10 dB/km
α_D = 1 dB/km

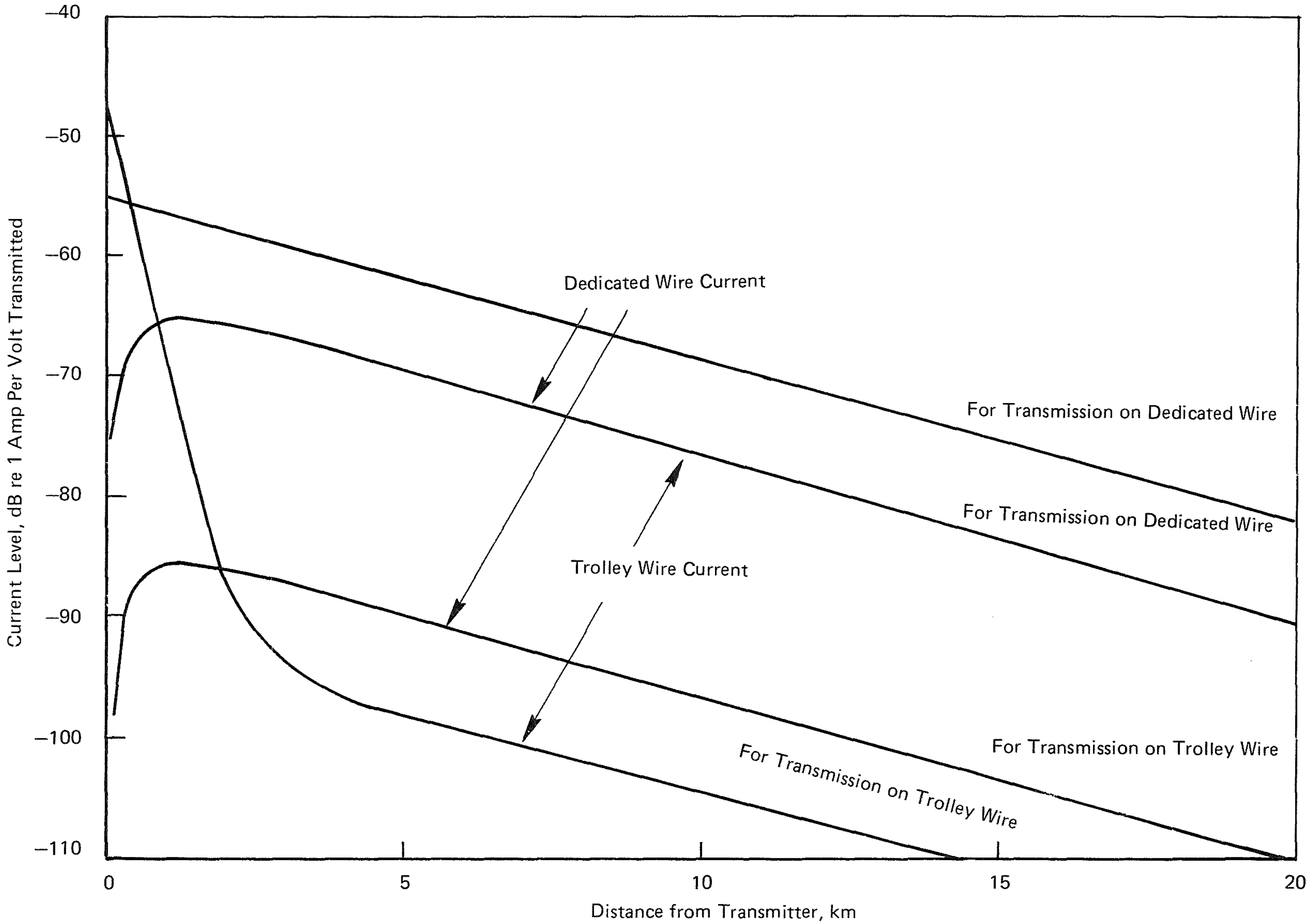


FIGURE V-7 CURRENT LEVELS VERSUS DISTANCE
$\alpha_T = 20$ dB/km
$\alpha_D = 1$ dB/km

One of the key questions we had when we undertook this investigation was, "Where is the optimum location for a 'dedicated' wire to obtain maximum extension of communication range?" Figures V-8 and V-9 illustrate what happens when the dedicated wire is moved along a grid representing the possible locations within the cross-section of a typical rail haulage way tunnel in a mine. We define this set of possible locations to be those at 30 cm spacing from the ribs and from the roof as illustrated in Figure V-3. Figure V-8 shows the values of voltages found at the far end of the transmission line system, 20 km away, as a function of the location of the dedicated wire on this grid. Figure V-8 assumes that the transmitter is connected across the trolley-wire/rail line and looks at trolley-wire/rail voltages and "dedicated" wire/rail voltages for two conditions of trolley wire/rail attenuation rate. As can be seen, there is no sharp maximum of signal level. Figure V-8 also shows that one should stay away from locations near the trolley-wire itself, and suggests that the wide side of the tunnel be used for location of the dedicated wire. In fact, it will be necessary to locate the dedicated wire on the wide side of the tunnel because of existing mine safety laws. Figure V-9 presents similar plots for the case where the transmitter is connected across the "dedicated" wire/rail line. One noteworthy feature is that when the transmitter is connected across the "dedicated" wire/rail, the "dedicated" wire/rail voltage 20 km away is hardly influenced by the value of trolley-wire/rail loss, and the two curves that correspond to 10 dB and 20 dB/km are virtually coincident.

Figure V-10 illustrates how the received voltage level 20 km from a transmitter on the trolley-wire/rail depends on the attenuation rate in dB/km of the "dedicated" wire/rail line, and on the attenuation rate of the trolley-wire/rail line. It further illustrates the minimal return one obtains by trying to improve signal level by decreasing the shunt loading on the trolley-wire/rail. Also illustrated is the way in which signal levels vary when the series attenuation rate of the "dedicated" wire/rail is varied. It shows that there is little utility to using an extremely low-loss "dedicated" wire line, since asymptotic values of 40 and 50 dB of loss are present even for dedicated wire lines having no loss.

Finally, in Figure V-11, received signal levels on the "dedicated" wire line at a distance of 20 km from a transmitter connected across the trolley-wire/rail are plotted as a function of the dedicated wire diameter. We found that the smaller diameter wire gives the larger signal level. However, the effect is a very weak one, and is probably of no practical consequence. The smaller size wire produced the smaller overall loss because the mutual inductances and capacitances are the controlling factors instead of the resistance of the wire for the propagation conditions of interest to the application in question.

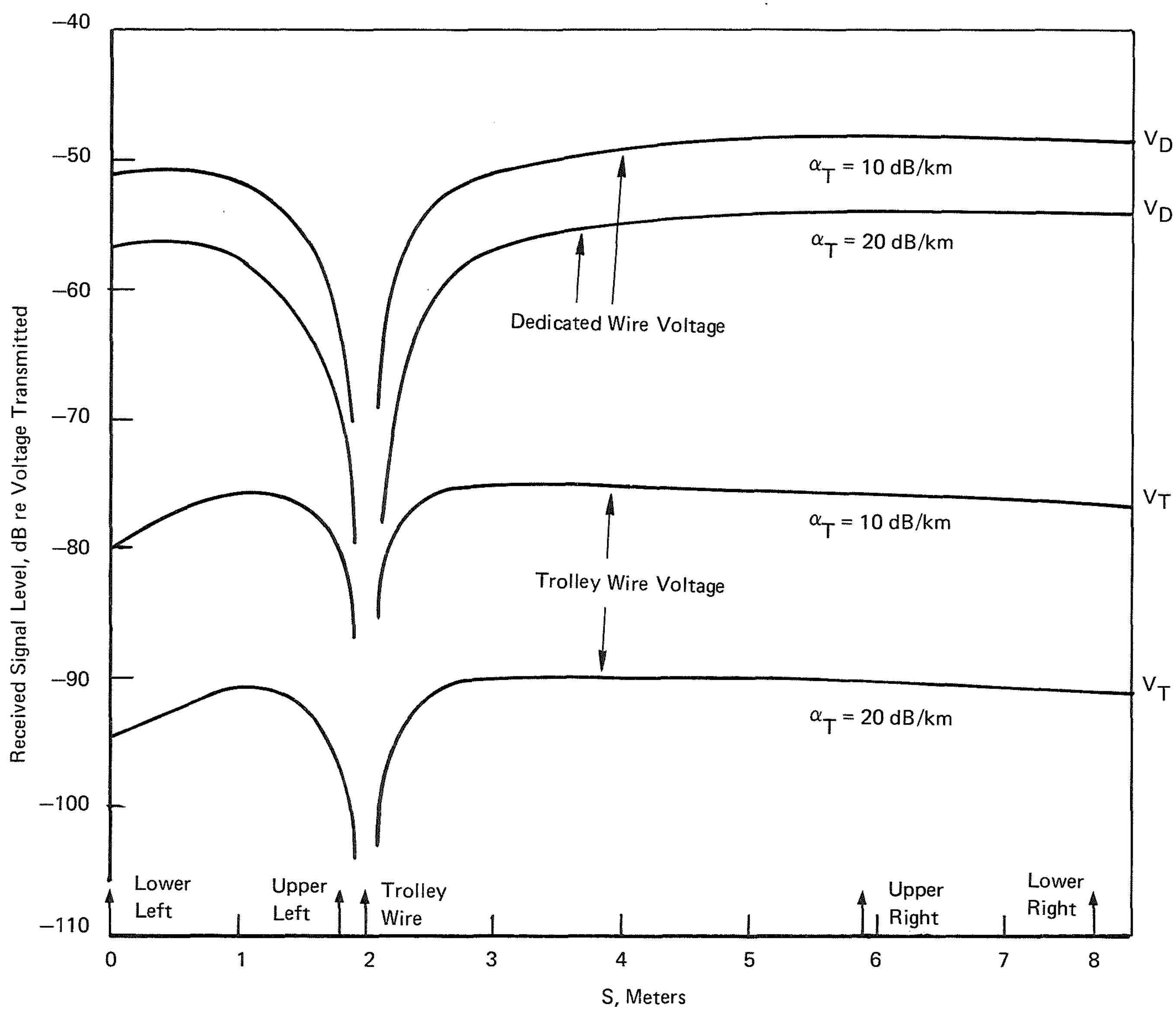


FIGURE V-8 VOLTAGE LEVELS 20 KM FROM TRANSMITTER ON TROLLEY WIRE AS FUNCTION OF DEDICATED WIRE POSITION (SEE FIG. V-3)

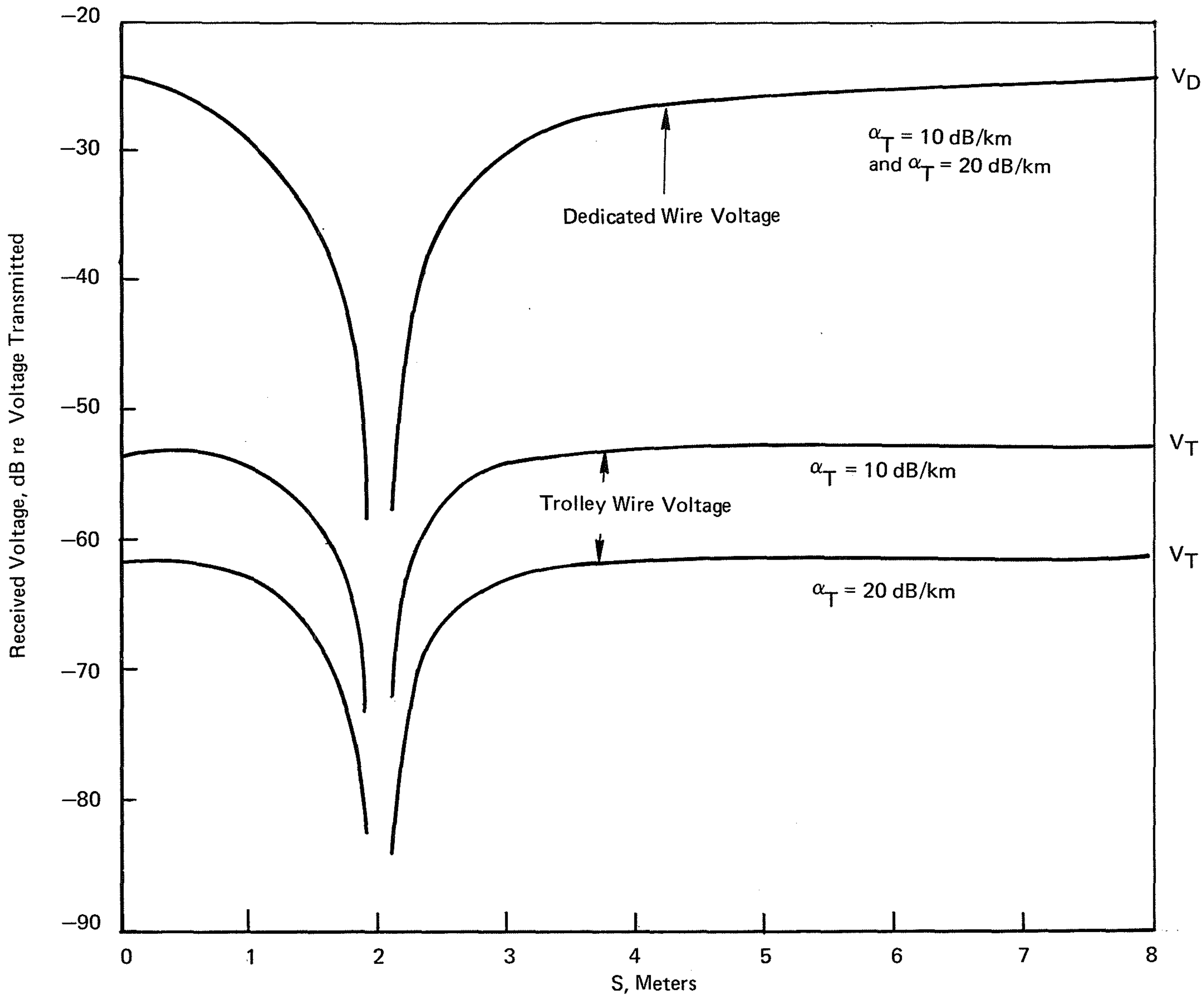


FIGURE V-9 VOLTAGE LEVELS 20 KM FROM TRANSMITTER ON DEDICATED WIRE AS FUNCTION OF DEDICATED WIRE POSITION (SEE FIG. V-3)

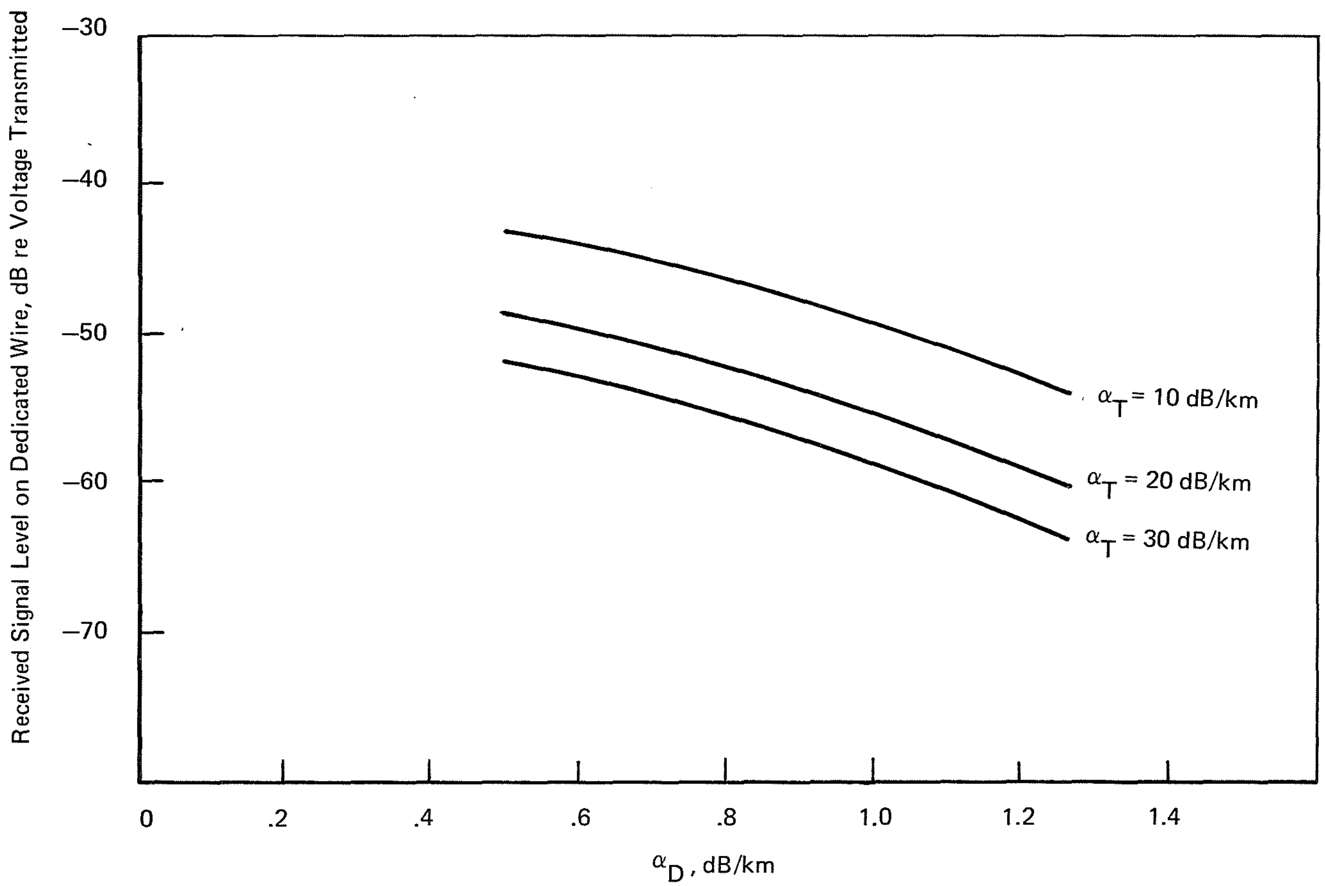


FIGURE V-10 VOLTAGE SIGNAL LEVEL 20 KM FROM TRANSMITTER ON TROLLEY WIRE

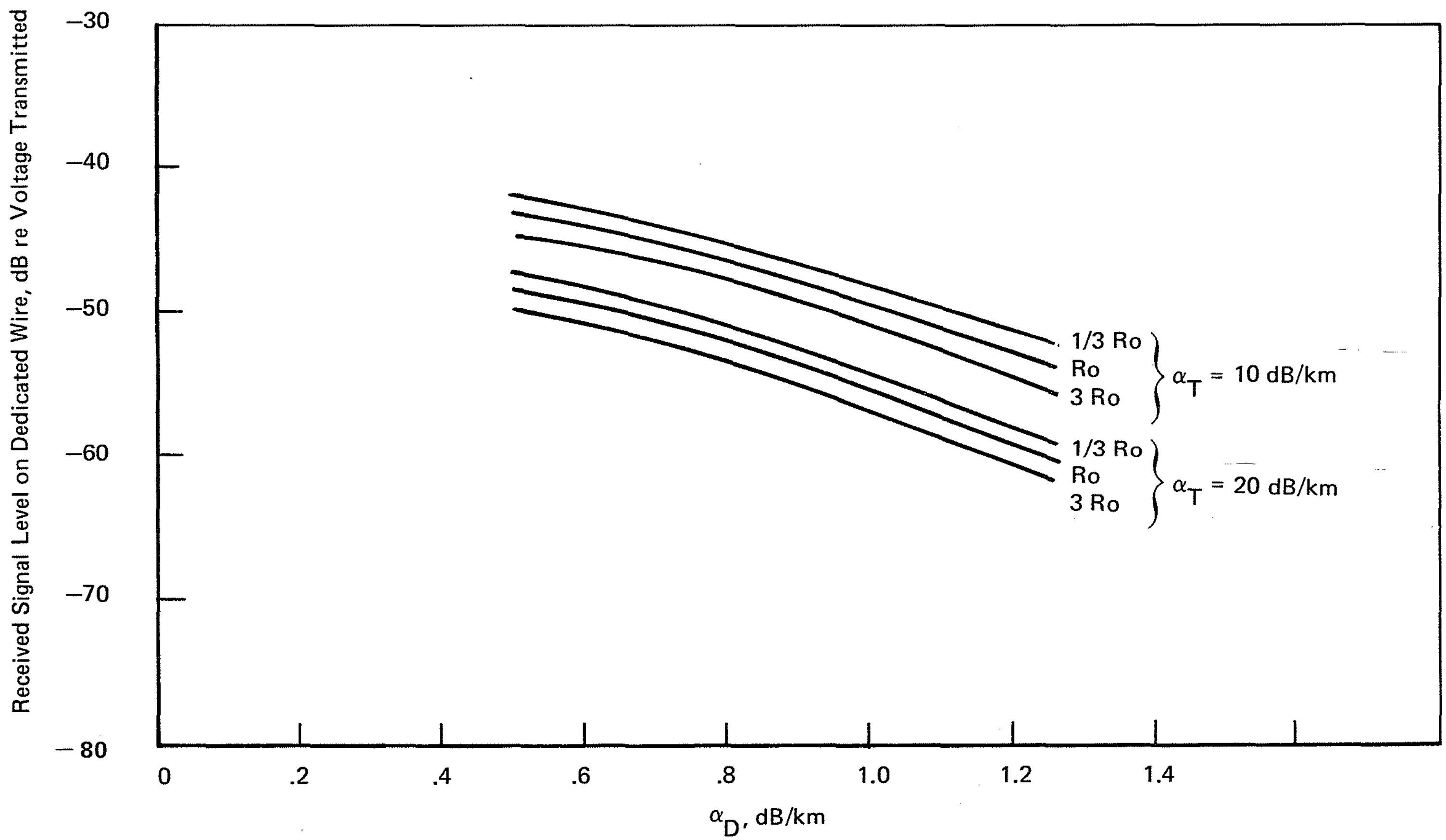


FIGURE V-11 VOLTAGE SIGNAL LEVEL 20 KM FROM TRANSMITTER ON TROLLEY WIRE

G. CONCLUSIONS

This investigation of the potential utility of a parallel low-loss "dedicated" wire line shows that it can be used to markedly extend the vehicle-to-dispatcher communication range on a high-loss trolley-wire/rail carrier phone communication system. The investigation shows that the ability of such a dedicated wire to extend range is not markedly influenced by its position relative to the trolley-wire/rail, or its diameter, nor the attenuation rate of the trolley-wire/rail. Detailed measurements are now required, preferably in mine tunnels, to provide a stringent test of the theory.

VI. ISOLATORS

A. CONCEPT

In the previous chapters, we have clearly established that one of the main impediments to carrier signal propagation on the trolley wire/rail is the presence of many bridging loads. One means used to overcome the loading effect of these impedances is to isolate them by means of filter circuits that permit the DC to pass through, but block carrier frequencies from passing through the filter. In this way the impedance at the carrier frequency may be raised to a much higher level and, hence, markedly reduce the deleterious effects on carrier frequency propagation.

Figure VI-1 illustrates the improvement possibilities for such bridging loads. The concept of adding isolators in series with bridging loads is relatively simple; however, the practical issue of finding inductors necessary to provide the isolation is not so simple in the case of rectifiers which typically supply on the order of 2000 amperes to the trolley wire. Hence, an inductor of that current capacity is required. The same situation is true for motor loads on vehicles, where again the ampere rating of such inductors has to be in the 2000-ampere range. For smaller loads, up to 5 amperes, there is little difficulty in finding small, commercial inductors that will provide the necessary isolation, either by themselves or in conjunction with tuning provided by capacitors. Figure VI-2 illustrates how an inductor may be placed in series with the feeder wire from a rectifier to provide impedance isolation of the rectifier from the trolley wire/rail. While this schematic is extremely simple and the values of inductance are not extreme, being of the order of 10's of microhenries to provide adequate isolation, the achievement of a 10-μH inductor of 1000-A capability would probably require on the order of 100 pounds of copper to produce. Alternatively, a more practical method of tuning such rectifiers would be to use the feed-wire inductance that is associated with a rectifier that is set back from the trolley wire/rail by more than 50 feet. In this instance, the inductance is sufficient that a resonating capacitor may be attached near the point of connection of the rectifier power to to the trolley wire/rail, as illustrated in Figure VI-3. Table VI-1 gives estimates for feed-wire inductance that may be expected at various points of attachment. The configuration often used for connecting a rectifier to a trolley wire/rail is to run two sets of feeder wire from the rectifier to the trolley wire/rail for feeding in both directions from that point. In this instance it is sufficient to tune only one of these sets; the mutual inductance between the pairs of feeder wires assures that tuning on one side will be effective on the other side as well.

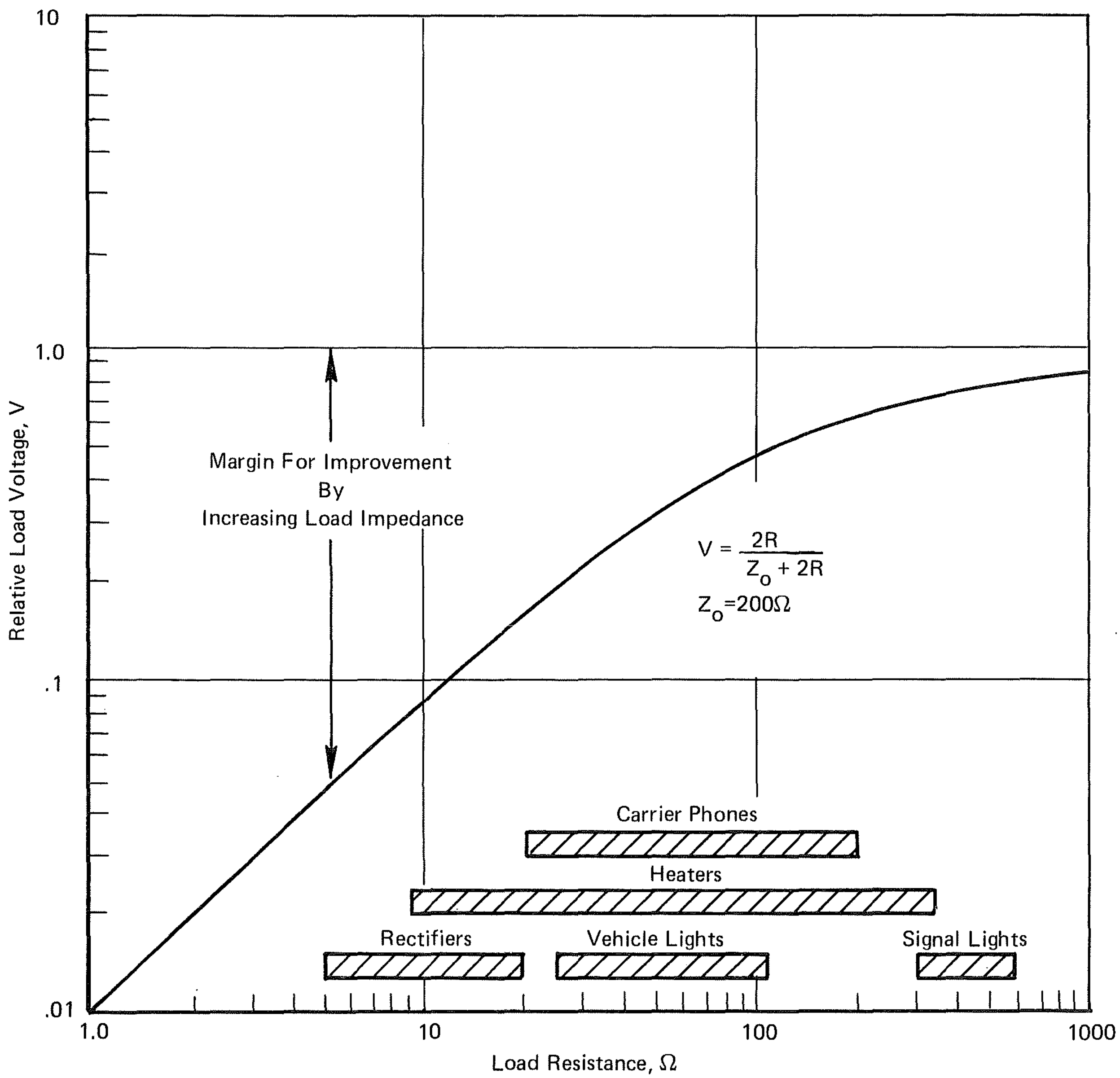


FIGURE VI–1 LOAD VOLTAGE AS A FUNCTION OF LOAD RESISTANCE

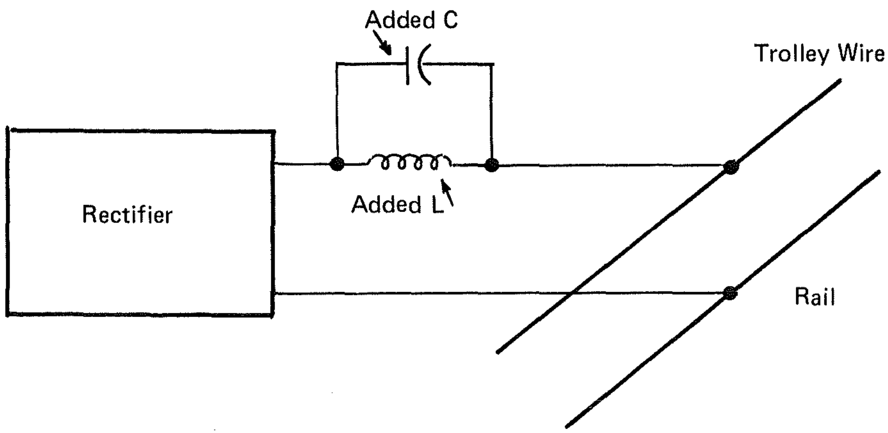


FIGURE VI–2 TUNED CIRCUIT PLACED IN SERIES WITH RECTIFIER

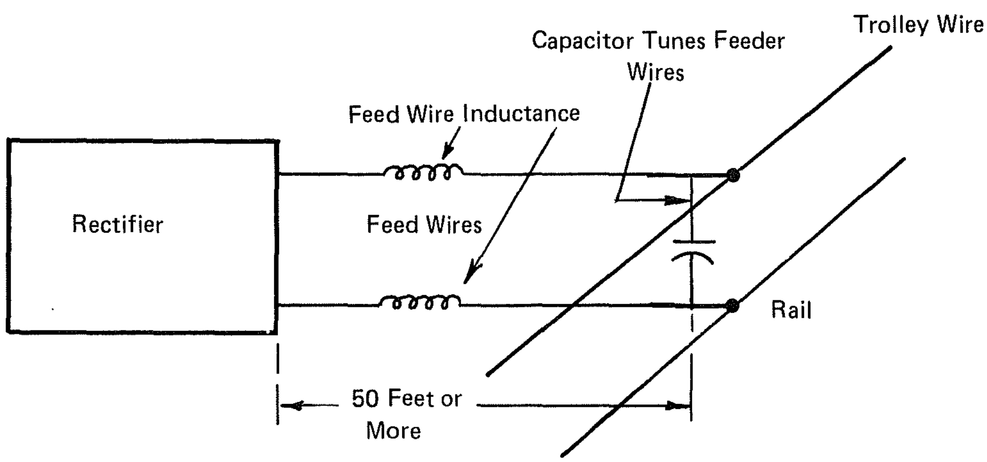


FIGURE VI–3 TUNING THE RECTIFIER FEED WIRES

TABLE VI-1

EXPECTED INDUCTANCE VALUES FOR RECTIFIER FEED WIRES
(μH/ft feed)

	Spacing between Feed Wires			
Wire Size:	**8 feet**	**6 feet**	**4 feet**	**2 feet**
500 MCM, r = 0.354″	0.67	0.65	0.61	0.54
1000 MCM, r = 0.500″	0.63	0.61	0.57	0.49
2000 MCM, r = 0.707″	0.59	0.57	0.53	0.45

The tabulated values of inductance are based on the equation*

$$L = 0.004\ \ell\ (\ell n\ \frac{d}{r} + \frac{1}{4} - \frac{d}{\ell})$$

where

L = microhenries (μH),

ℓ = length (cm),

d = separation between wires, and

r = radius of the feed wire

We use this equation to calculate the inductance per foot for various combinations of feed-wire separation and wire radius. To make the correction factor related to d/ℓ, we have chosen arbitrarily to use a setback distance of 25 feet. For setback distances less than this, the inductance values are believed to be too small to produce good tuning effects, while for distances greater than these, the correction gets smaller. It is, in any event, not a serious error in the calculations. The calculations are for wire separations of 8, 6, 4, and 2 feet and wire radii of 0.353, 0.500, and 0.707 inches corresponding to 500, 1000, and 2000 MCM wire sizes. It is interesting to note that these values are all very near 0.5 μH/ft and hence yield an impedance of approximately 0.3 Ω/ft of feeder length at 100 kHz.

*Grover, F.W., Inductance Calculations: Working Formulas and Tables, Dover Publications, Inc., New York, 1946.

The motors on mine vehicles constitute another place where difficulty in tuning is found. Additionally, a typical mine vehicle has two other sources of bridging impedance besides the motors; viz., the light circuits of the vehicle as discussed previously, and the vehicle's carrier phone which typically has an impedance somewhere between 20 and 100 ohms in the standby mode. To isolate the motors requires inductances of the order of those used in isolating a rectifier, probably requiring as much as 100 pounds of copper. We believe it is impractical to provide such isolation on locomotive motors. In the case of jeeps or portal buses, we believe it is unnecessary because the motors typically show much higher bridging impedance values and these vehicles are therefore dominated by their carrier phones and light circuits. The last remaining significant bridging load that can be treated is that attributable to personnel heaters often found in coal mines. A 5000-W personnel heater on a 300-V trolley wire has an impedance of 18 Ω. Such a heater would draw approximately 15 amperes from the trolley wire and would therefore require an inductor which could handle this DC current. Such an inductor would not have to be very large, and these personnel heaters may be relatively easily isolated by use of the series impedance isolator illustrated in Figure VI-4. Similarly, vehicle light circuits which draw 3 to 6 amperes are good candidates for using series insertion of tuned circuits to isolate them from the carrier frequencies.

B. USE OF TROLLEY WIRE/RAIL INDUCTANCE

The use of the feeder-wire inductance to aid in tuning out rectifiers has been discussed above. The trolley wire/rail shows a comparable inductance per foot. It is possible to use this inductance to resonate a localized low-impedance bridging load across the trolley wire/rail, such as a rectifier imposes. The schematic diagram of Figure VI-5 illustrates this means imposed on an otherwise matched transmission line. An equivalent circuit representation of this configuration is shown in Figure VI-6. It is quite apparent that, when one views this configuration of inductances and capacitances and a bridging resistance, the voltage delivered to point a on the transmission line is much higher in the presence of the tuning capacitors than it would be in the absence of such tuning capacitors. Hence, the power delivered to the bridging load and beyond to the rest of the transmission line is increased by the use of this method. A sample calculation is presented in Table VI-2, and illustrates the performance that may be obtained by the use of this method of tuning a rectifier bridging load.

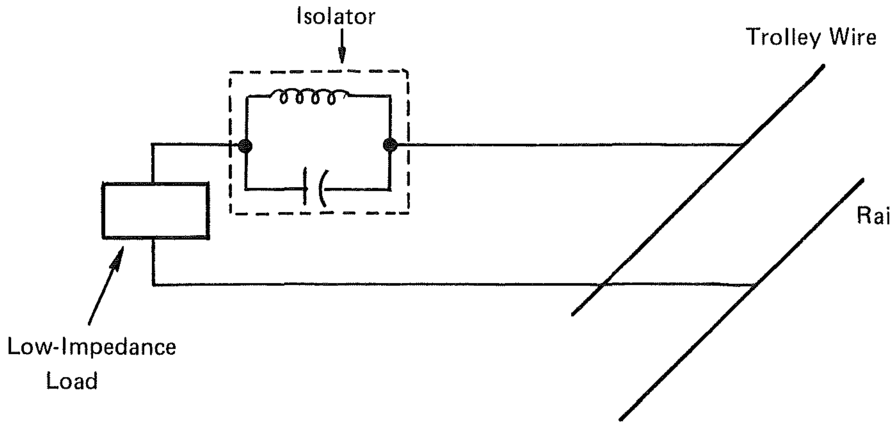


FIGURE VI–4 SERIES IMPEDANCE ISOLATOR

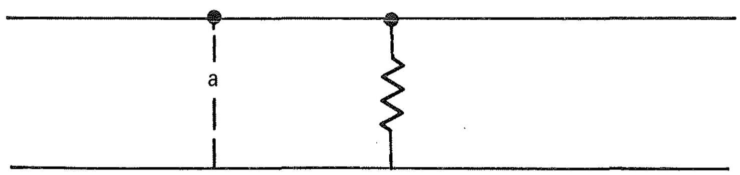


FIGURE VI–5 LOW-RESISTANCE BRIDGING LOAD ON TROLLEY WIRE/RAIL TRANSMISSION LINE

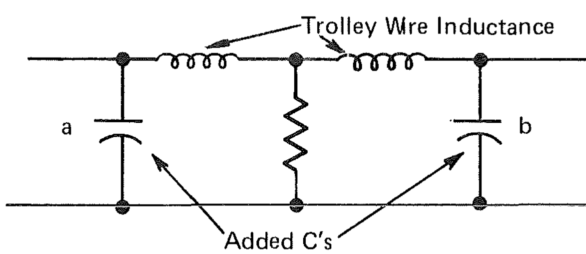


FIGURE VI–6 REPRESENTATION OF TUNING TO REDUCE EFFECT OF LOW-RESISTANCE BRIDGING LOAD

TABLE VI - 2

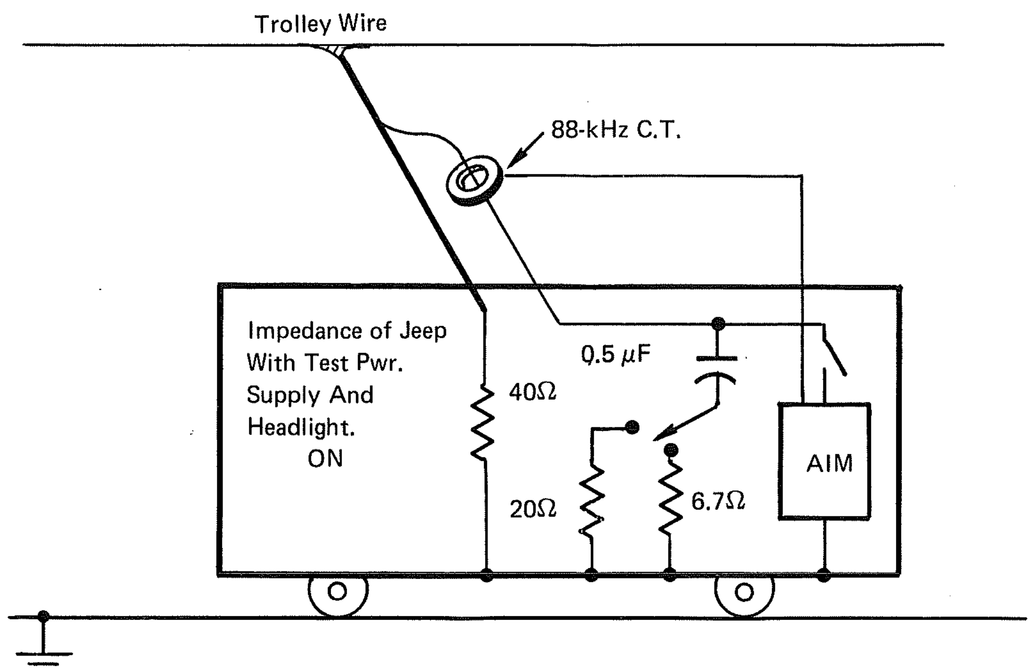
SAMPLE PERFORMANCE FOR TUNED TROLLEY WIRE/RAIL
(Figure VI-6)

Bridging Load	Insertion Loss
5 Ω	21/1 = 26.4 dB
Trolley Wire Rail Inductance	**Reactance**
50 μH (about 150 feet)	31.4 ohms
Tuning Capacitors for 100 kHz	
0.16 μF	31.4 ohms

"Insertion Loss" of tuned section = 1 dB

C. ACTIVE DEVICES

An alternative means of raising the impedance of bridging loads is one that has been derived from the work of Derek Paice.* Means by which the apparent impedance is made to appear larger is illustrated in Figure VI-7. In this example, the incoming current to the



*Paice, D., Op. Cit.

FIGURE VI–7 CONFIGURATION USED TO TEST ACTIVE IMPEDANCE MULTIPLIER*

*Paice, D., Development of an 88-kHz Active Impedance Multiplier, Phase III, Task A Report, U.S. Bureau of Mines Contract HO122058.

bridging load is measured by the current transformer. The output of this current transformer is amplified in an amplifier, the output of which drives the bridging load in a direction to reduce the amount of current at carrier frequency fed through the current transformer. This is a form of negative feedback used to increase the apparent impedance at carrier frequency. Mr. Paice has used this technique in an operating mine to decrease the loading effect of the locomotive in an effort to increase the carrier signal level in the mine. Details of Mr. Paice's work may be found in the referenced document. His technique is applied to trolley carrier communication systems as an outgrowth of his earlier work on a fault-detection system using a low-frequency carrier. It is uncertain how practical a solution to the isolation problem this technique represents.

VII. GUIDELINES

A. INTRODUCTION

The many findings of the program apply, in various ways, to the four interested parties:

- users of carrier phones in present mines;
- planners of communications for future mines;
- mine communication equipment manufacturers; and
- Bureau of Mines personnel.

Guidelines for consideration by these parties are included here with references, where appropriate, to details provided in the body of the report.

B. GUIDELINES FOR USERS IN EXISTING MINES

1. General

In this section, we present guidelines to the improvement of existing carrier communications systems operating on the trolley wire/rail of coal mines. We expect that these guidelines would be applied to communication systems which are characterized by marginal or poor performance.

2. Mapping of Signal and Noise Strength

a. The Trolley Wire

The most effective means of identifying problems associated with carrier communications in rail haulage systems is to make a detailed map showing signal-strength and noise-level measurements taken in all regions of the mine. The transmissions made by a dispatcher are measured and recorded using tuned voltmeters connected to the trolley wire in various parts of the mine. This map of the signal strengths and noise levels reveals regions where communication problems are dominated by weak signals and regions where communication problems are dominated by excessive noise. These measurements of trolley wire voltage should be made, whether or not the mine uses auxiliary wires to aid carrier signal propagation.

b. The Auxiliary Wire

Signal-strength measurements of the auxiliary wire used to extend carrier communication range in coal mines should also be made. The extension of communication using an auxiliary wire relies on maintaining a substantial signal level on the auxiliary wire throughout all regions of the mine. A map of the various signal levels will reveal where the auxiliary line is failing to perform its function.

3. Bridging Loads

The worst impediment to signal propagation on a trolley wire/rail is due to the very large number of bridging loads across the trolley wire/rail, as discussed in Chapter III. To assess the seriousness of these bridging loads, one should first determine the character of every bridging load across the trolley wire/rail and then estimate how much insertion loss each of these loads would produce. The aggregate sum of these losses is indicative of the impediments to carrier signal propagation on the trolley wire/rail. As many of these loads as is practicable should be removed from the trolley wire/rail and operated on mine AC power if possible. Of course, in many instances it will not be possible to do so. In this event, carrier-frequency isolation of the offending mode should be undertaken to raise the impedance level of each load (as discussed in Chapter VI).

4. The Use of Auxiliary Wires to Aid Propagation

In a mine with normal bridging loads, it is almost impossible to propagate carrier signals on the trolley wire itself for more than a few miles. Thus, an auxiliary wire of low loss and unimpeded by bridging loads is used to carry the signal to the far reaches of the mine. Historically, a pager phone line operated in common mode has often been used for this purpose. The preferred way is to use a single dedicated wire, so that the many offending branches and unterminated ends of the phone lines (and their attendant problems) are avoided. The preferred mode is to place the dispatcher's transmitter signal directly on the dedicated wire, and to terminate the ends of the dedicated wire, or wires, in the characteristic impedance of the wire, typically 200 to 300 ohms. It is unimportant to obtain an exact match for the termination. Impedance couplers are frequently used to connect the auxiliary wire to the trolley wire. We feel that these couplers should be used as sparingly as possible because at each place of installation power is taken away from the auxiliary wire and, of more importance, power is reflected, making it difficult to transmit high signal levels beyond the points of attachment of these couplers. For a dedicated wire, it seems unnecessary to provide discrete couplings to the trolley wire/rail. Instead, the natural coupling that occurs to the trolley wire/rail, as discussed in Chapter V of this report, should be used.

5. Central Transceiver

One of the simplest ways of improving carrier phone system performance, in certain instances, is to use a remote transceiver which can be located at the central region of a mine complex. Use of a transceiver would typically half the range-coverage capabilities that would be required if the dispatcher's transceiver were located at one or the other end of the mine. Commercial equipment for such use is available, and it permits the dispatcher to be located in his most favorable position and for the transceiver to be located in its most favorable position. The price paid for this improvement is the necessity of running one twisted pair between the dispatcher's office and the remote transceiver.

6. Equipment Considerations

We have just emphasized the problems of obtaining carrier communications on the trolley wire/rail in the face of the many bridging impedances. We point out here that carrier phones themselves show either 20 or 100 ohms approximately, or, in the case of some of the newer equipment, approximately 1000 ohms of bridging impedance in the standby mode. In a mine where there are many vehicles operating simultaneously, the use of low-impedance carrier phones just by themselves represents an extremely serious impediment to propagation on the trolley wire/rail. Thus, we would recommend that users seek trolley carrier phones with high standby impedance characteristics.

C. GUIDELINES FOR PLANNERS OF NEW MINES

A very substantial number of the problems associated with maintaining good carrier communication systems could be avoided by advanced planning. For those planning a communication system for a new mine, we offer the following suggestions to assure optimum operation of the trolley carrier phone system when installed:

- *Auxiliary Loads* – plan to operate as many auxiliary loads as is practicable on mine AC power rather than from the trolley wire power.
- *Dedicated Wire* – Plan to use a dedicated wire to aid signal propagation.
- *Carrier Phones* – Select carrier phone transceivers that show a high value of standby impedance.
- *Vehicles* – Insist that vehicle manufacturers indicate the 88 to 100 kHz operating impedance of their vehicles, and select vehicles that show a high operating impedance at the carrier frequency.
- *Rectifiers* – Plan to use at least a 50-foot setback for rectifiers that are to be installed in the mine; this setback will permit tuning of the rectifier leads to raise the impedance of the rectifier.
- *Internal Filtering for Rectifiers* – Ask the rectifier manufacturers to supply internal filters in series with the DC voltage to raise the carrier frequency impedance to a high level.

- *Isolators* – Plan and design isolators for all other appreciable bridging loads across the trolley wire rail.

D. GUIDELINES FOR MANUFACTURERS

During this program, we uncovered areas where trolley phones could be improved. These potentials for improvement should be considered by the manufacturers of mine equipment and mine communication equipment. These potential improvement areas are listed below and discussed in detail in Chapter II.

- *Interference Control* – It appears that the conditions in which trolley carrier phones will be operated in the future will require a decrease in the amount of out-of-band emissions as compared to that of present equipment. Manufacturers should be made aware of this development and be prepared to take necessary steps.

- *Performance Features* – Possible performance features which can now be incorporated into a trolley carrier phone with a minimum of additional cost are listed below for consideration by the manufacturers

  Tone-controlled squelch,
  Adaptive loudness,
  Linear modulators,
  High standby impedance,
  600-volt DC-to-DC converters,
  Loop receivers,
  Volume compressors, and
  Tailored audio frequency response.

- *Auxiliary Items* – Auxiliary items not directly related to carrier phone equipment, but important to obtaining and maintaining good carrier system coverage, include:

  Tuned voltmeters,
  Impedance isolators for various bridging loads,
  High-impedance vehicles, and
  Integrated rectifier/isolators.

E. GUIDELINES FOR THE BUREAU OF MINES PERSONNEL

During the program, we identified a number of areas where Bureau of Mines sponsorship or encouragement of various programs could lead to improved trolley carrier phone systems. In particular, we noted the following items that are elaborated on in Chapter VIII – Recommendations:

- Confirmation of the "dedicated" wire theory,
- Demonstration of a low-impedance line,
- Carrier phone integrated packaging,
- Adaptive speaker volume,
- High-input impedance receiver,
- Carrier phone with loop antenna receiver,
- Complete new design of transceiver,
- Alternator-powered carrier set,
- Inverter design,
- Noise blanking,
- Tone-controlled squelch
- Diversity receivers,
- Improved design for a carrier voltage-measuring device, and
- Task force.

VIII. RECOMMENDATIONS

A. INTRODUCTION

The trolley phone improvement program was conducted with the view to identifying means of improving present trolley carrier phone systems. In the study we identified a number of promising techniques which have been verified, or partially verified, by theory, computer modelling, laboratory experiments, and mine measurements. The large number of promising techniques uncovered in the course of this work suggests other programs that would lead to further improvement in the trolley carrier phone systems used in coal mines. We have listed below, in abstract form, a number of possible programs that we feel should be supported.

B. POSSIBLE CARRIER PHONE IMPROVEMENT PROGRAMS

1. Confirmation of "Dedicated" Wire Theory

The theory of the "dedicated" wire, developed in Chapter V, was exercised on a computer model to demonstrate expected performance capabilities. The promise of the dedicated wire suggests that an in-mine demonstration should be undertaken to verify the performance capabilities that would result if a dedicated wire were used to extend the trolley carrier phone communication range. Such a program would require the close cooperation of an operating coal mine and careful planning to make sure that the results obtained were valid. For this demonstration, the Robena mine, with its several miles of dedicated wire, might be suitable for obtaining the conditions needed to validate the performance capabilities expected.

2. Demonstration of the Low-Impedance Line

The current program has developed a theory for the low-impedance line, and the theory has also been supported on the basis of laboratory measurements. However, this technique has not been demonstrated in an operating coal mine. The technique is sufficiently promising that an in-mine demonstration is warranted. It will be necessary to select a mine carefully, so that the dominating phenomenon is the trolley wire/rail and not auxiliary wires.

3. Carrier Phone Integrated Packaging

The examination of equipment made in the course of the carrier phone improvement program revealed the possibility that the entire carrier phone – speaker, housing, power conditioner, and battery units – typically found in two or more packages in present carrier phones could readily be repackaged into a single unit. In fact, some of the present speaker housings are nearly adequate to provide this capability. Packaging in this direction would almost certainly require the use of a DC-to-DC converter to change the raw trolley voltage to a level suitable for operating circuits. Use of an integrated package would also provide the opportunity to include a number of circuit design improvements identified in the design study part of the program. A two-part program, comprised of a design study followed by an implementation phase, is envisioned.

4. Adaptive Speaker Volume

If an integrated package design for the carrier phone does not prove practical, other individual improvements which would be considered as add-on features or modifications to existing designs are worth undertaking. In particular, we feel that an adaptive speaker volume system in which the volume of audio presented by the speaker can be adjusted in accordance with measured ambient background is especially promising. This concept is elaborated on in the body of the report and we feel it is worth demonstrating in a breadboard phase.

5. High-Input Impedance Receiver

In our examination of equipment during the program, we found a serious shortcoming in receiver design; in particular, the presence of a quite low carrier phone impedance that was constantly presented to the trolley wire/rail whenever the receiver was in the "receive only" mode. The values of resistance for the various sets range from approximately 20 ohms for one brand to approximately 100 ohms for another brand. Either of these values of resistance imposes a severe loss of signal level on a trolley wire/rail carrier system. There is no reason that the receiver should be designed to abstract as much power as possible from the trolley wire/rail, because the receivers are external noise-limited rather than internal noise-limited. For this reason much higher input impedance receivers would alleviate the problem presented on extensive trolley carrier phone systems that have a large number of vehicles. We feel that the design of a high-input impedance receiver is worth undertaking.

6. Carrier Phone with Loop-Antenna Receiver

There are several reasons to expect that a trolley carrier phone using a loop receiver, in general, would perform just as well as one that receives on the trolley wire; in some circumstances, it might even be capable of providing better performance. They include:

1. In areas of a coal mine where either standing waves on the trolley wire or the presence of low-value bridging impedances cause a decrease of trolley wire voltage an increase, or at least a preservation of current, can be expected. This preservation of current in turn leads to the expectation that loop antenna receivers would be better.

2. The aforementioned problem of low-impedance receivers presently used on carrier phones would be dispensed with immediately by going to a loop receiver.

3. The large transients present on a trolley wire at very substantial power levels make it necessary to provide protection in the receiver. For a loop, this problem is much less aggravating because much less power could be abstracted from the loop.

A program demonstrating the advantages of loop receivers would be relatively easy to conduct and we believe is worth doing.

7. Complete New Design

Current technology, together with an improved understanding of trolley carrier phone systems, makes it possible now to provide an advanced design for such carrier phones. We believe it desirable to conduct such a design program for the benefit of carrier phone systems users. Such a design program could be terminated at the end of the design, or could be carried on to the fabrication and test stage. Important considerations in such a new design would be the use of a number of integrated circuits that have recently become available for communications use, out-of-band response, noise blanking, volume compression, tone-operated squelch, and linear FM modulators.

8. Alternator-powered Carrier Sets

There is an attractive feature to powering the carrier phone from an axle-mounted alternator on board vehicles in that it eliminates the need to convert from either 300- or 600-volt trolley wire voltages to the low voltages required to operate the sets. It further removes the large electrical transients appearing on the trolley wire from causing difficulty with the power conditioning circuits usually associated with carrier sets. A design study would be an appropriate first step in assessing whether the operating modes of all vehicles in a mine would provide enough alternator on-time to adequately charge a battery for carrier phone operation. Such a design study would settle issues related to the environment to which the alternator is exposed and would consider the economics and the trade-offs between problems solved and those created by this method. The results of such a design study should include a set of recommendations regarding its adoption.

9. Inverter Design

The state of the art in electronic components makes it attractive to consider inverter designs to directly convert the 600-volt trolley wire voltage into the typical 24 volts used for operating transceiver circuitry. The design of 300-volt converters is fairly advanced now with models already used in-mines. The 600-volt converters, which involve more serious technical problems, have not as yet been adequately developed. Therefore, this design study would be directed toward the 600-volt system. Two main features of such a design would be the immunity to the large transients on the trolley wires and the control of EMI that could conceivably be generated by an inverter. The economic and reliability aspects of such a design would have to be addressed to determine if such designs could be usefully employed in the carrier phones.

10. Noise Blanking

The concepts introduced in the design of many other communications systems include the use of noise blankers to improve the intelligibility of the voice messages in the presence of sporadic noise. A design study directed toward determining the feasibility of applying such noise blanking to carrier phones should be undertaken. The potential is improvement of carrier system performance in otherwise marginal signal-to-noise conditions often found in a mine.

11. Tone-Controlled Squelch

One of the recurring problems in the use of carrier phones in a mine environment is the difficulty of providing one adequate squelch-control setting that will provide good performance over the wide range of signal levels occurring in the mine and the wide range of noise levels typically geographically distributed within the mine. The use of a tone-controlled squelch would overcome this disadvantage in a relatively straightforward fashion and provide best performance throughout the whole range of these variables. Tone-controlled squelch is an old technique that has been applied to many communication systems, and it would not be a costly feature to include in trolley carrier phones. We believe a design study should be undertaken and that a system equipped with tone-controlled squelch be demonstrated.

12. Diversity Receiver

The concept of using a diversity receiver, in particular diversity between voltage on the trolley wire and field strength from a loop antenna, has been discussed in the past. We believe that a trade-off analysis of such a system should be made, with all factors bearing on the use of such a system for trolley carrier phones, considered. Thus, an evaluation of potential performance improvements could be made.

13. Improved Design for a Carrier Voltage-Measuring Device

A relatively compact carrier voltage measuring device is still needed to aid in mapping signal strength distribution. The device must be comprised of a voltmeter tuned to the carrier frequency of a bandwidth comparable to the operating bandwidth of the carrier phones, viz., 6 to 8 kHz. The device would have to have a wide dynamic range, since carrier voltages are known to vary from 50 volts rms to the 1-mV range. Presently available equipment of this type is somewhat bulky, has capabilities far beyond what is needed for checking trolley carrier phone systems, and does not meet the needs of such a device economically. We believe that a design study, followed by a breadboard demonstration of equipment, would be useful to the Bureau.

14. Task Force to Address Specific Operator Problems

It has become apparent from our study and results of another program to develop guidelines for carrier phone systems that the Bureau could respond to operator needs if it formed a cadre group experienced in carrier phone systems. When needed, such a group could consult with operators who had specific carrier phone problems, responding by mail, telephone, or by actually visiting the mines. The task force would be supported by sufficient test equipment and knowledge of the means of improving carrier phone performance that an expeditious transfer of information, techniques, and concepts to the operators could be made to the benefit of both the operators and the Bureau.

APPENDIX

PROBE FOR MEASURING TROLLEY-WIRE CURRENT

A. INTRODUCTION

The concept of the trolley carrier phone system is very simple. A transmitter places a carrier frequency voltage between the trolley wire and the rail, and a receiver somewhere in the distance across this trolley wire/rail receives a sufficient level of carrier voltage to permit the communication system to operate. In practice, the many impediments to carrier-signal propagation markedly alter this simple system. When measurements of the actual behavior of signals on a trolley wire/rail system are attempted, there is no difficulty in observing the voltage between trolley wires and rail on cathode ray oscilloscopes or tuned voltmeters. However, to measure currents in the trolley wire or in auxiliary wires used to assist signal propagation, the problem of making measurements is more difficult. The typical way of measuring current in a conductor is to use a clamp-on current transformer. This device may be used to measure current in an auxiliary wire, but it would be extremely hazardous for application to the trolley wire itself which has an elevated DC voltage. To fill this need we designed, constructed, and tested a special current-measuring probe, which can be used directly on the trolley wire, and is protected from the hazards of high voltage.

B. PRINCIPLES OF PROBE OPERATION

The probe uses a small, circular coil coplanar with the trolley wire. It is maintained at a fixed distance from the center of the trolley wires of various diameters. This fixed distance is made possible when, as the trolley wire becomes larger, one of the device's prongs that holds it against the trolley wire moves the trolley wire closer to the coil, while the other one moves it farther away. The trolley wire, in effect, pivots about a fixed distance from the center of the pickup coil. The details of this device are illustrated in Figure A-1.

The device is to be used with a 50-ohm input impedance tuned voltmeter. The Singer NM-12AT is one such instrument. The probe has been used on a live trolley wire to measure the current in the trolley wire. A photograph of the device is shown in Figure A-2. The calibration curve for the probe is shown in Figure A-3. Extreme care must be employed in the use of this probe.

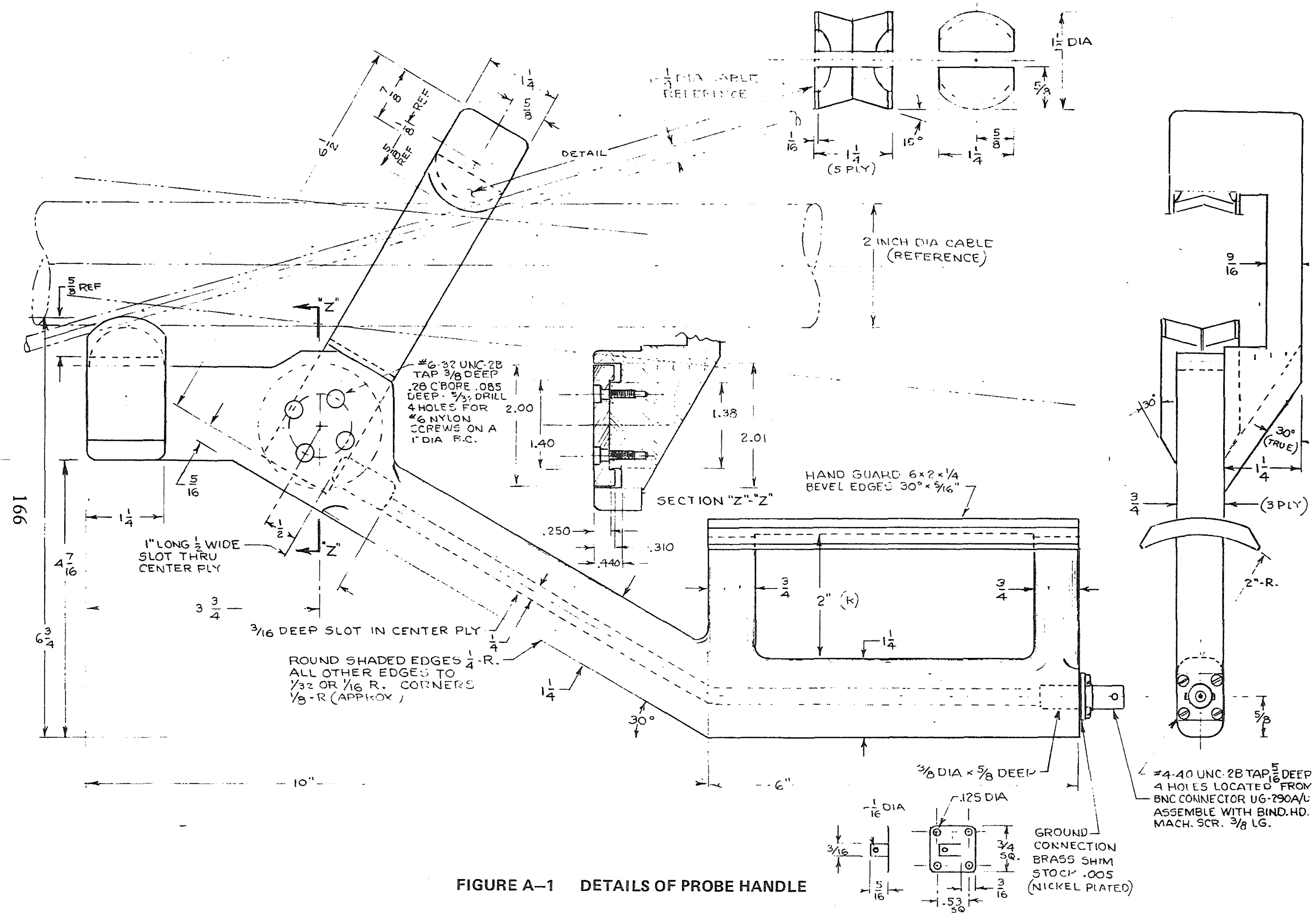


FIGURE A–1 DETAILS OF PROBE HANDLE

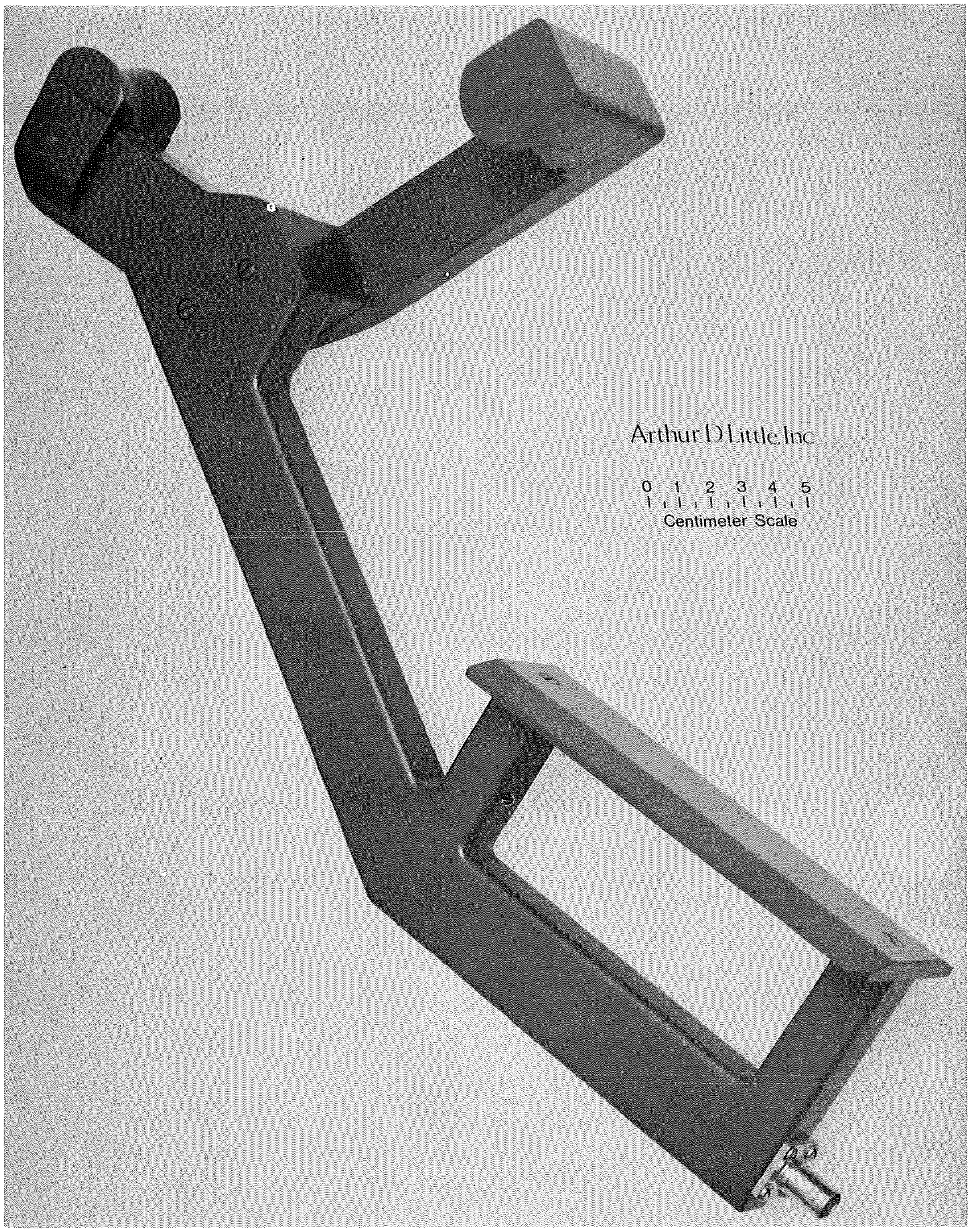


FIGURE A–2 PHOTOGRAPH OF PROBE

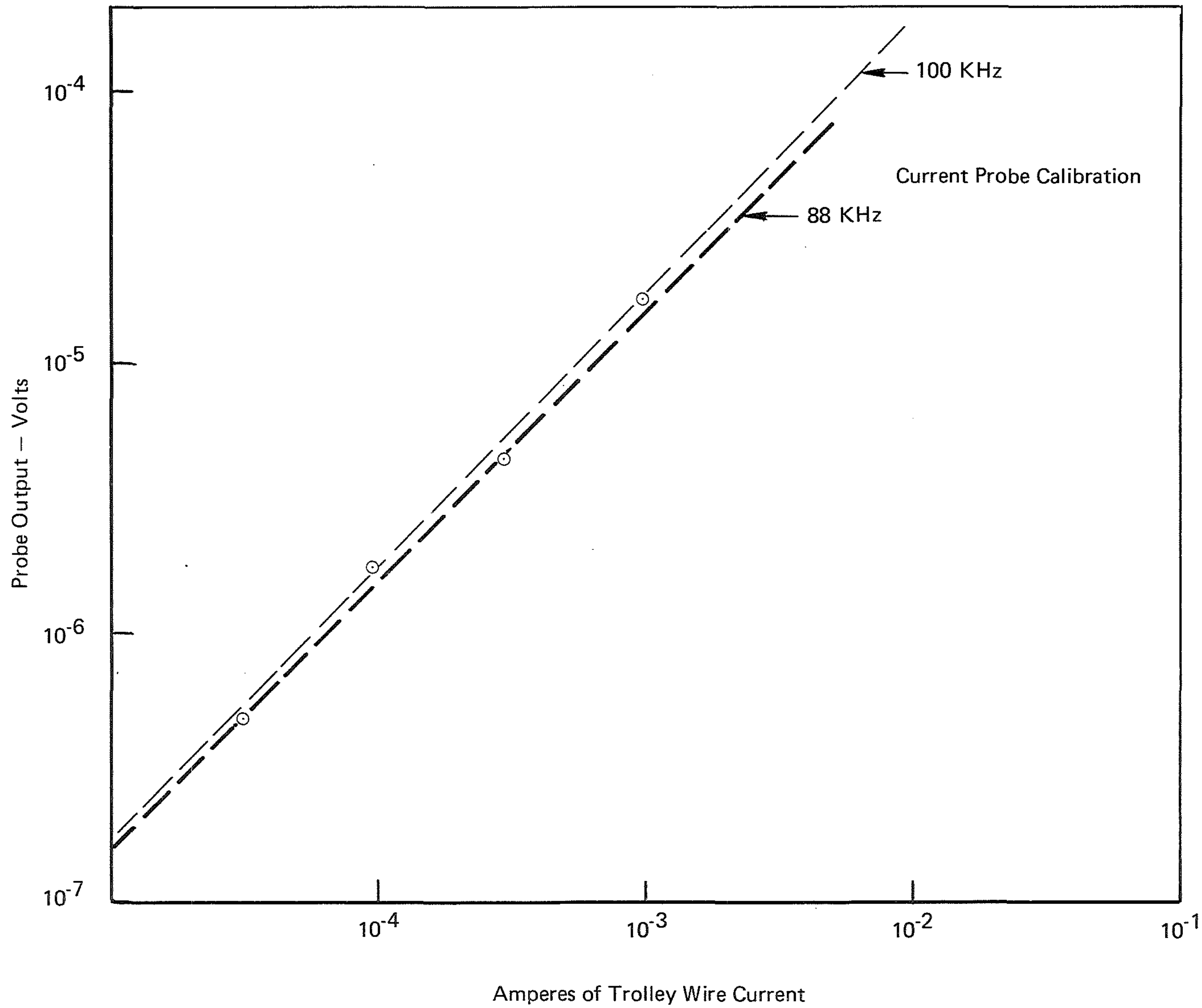


FIGURE A–3 PROBE RESPONSE