PART THREE

LEAKY COAXIAL CABLE FOR GUIDED WIRELESS MINE COMMUNICATION SYSTEMS

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PART THREE

LEAKY COAXIAL CABLE FOR GUIDED WIRELESS MINE COMMUNICATION SYSTEMS

INTRODUCTION

Coaxial cable structures form the subject of substantial theoretical and experimental investigations either directly related, or which can be extrapolated, to the communications needs and environments of U.S. coal mines. Communication systems based on "guided" waves, of which "leaky" coaxial cables are one implementation, are attractive candidates for providing a range of communication functions primarily along haulage ways, and possible also within sections up to the working face. (However, there are still strong reservations as to whether a practical coaxial cable system could provide sufficient communications coverage within a section.) In this Part, we present the results of some theoretical calculations of the performance of leaky coaxial cable communication systems. We also analyze the applicability of the theoretical and experimental results obtained by other researchers to the needs of U.S. coal mines. In particular, this investigation has been focused on the utility of relatively low cost, conventional, flexible, coaxial cable at frequencies covering the LF through HF bands and extending into the lower part of the VHF band, as opposed to relatively high cost, special semi-rigid, coaxial cable* at frequencies in the VHF and UHF bands.

There are three major design alternatives for coaxial cable communication systems considered in this chapter:

- Base station feeding a coaxial cable with high surface transfer impedance (holes in outer conductor, e.g., braid construction).
- Base station feeding a coaxial cable with repeaters (U.K. experiments).
- No base station, direct communication via a coaxial cable with periodic radiative structures.

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* The utility of special Radiax$^{T.M.}$ cable in the UHF band is treated in a paper coauthored by R. Lagace of ADL and H. Parkinson of PMSRC, and published in U.S. Bureau of Mines Information Circular No. 8635, and in Part Eight of this Volume.

Our discussion of the latter two alternatives consists primarily of descriptions of the progress and results achieved in Europe. In the first case, which is the simplest in the sense of requiring no special devices added to the coaxial cable, we have analyzed the performance that can be hoped for based on simplified theoretical models.

I. APPLICATION OF LEAKY COAXIAL CABLE COMMUNICATION SYSTEMS

The communication function for which coaxial cable structures are being considered is first and foremost:

- Two-way communication along main haulage ways up to 4-5 miles long, to vehicles and to key individuals on-the-move.

A less likely application involves:

- Two-way communication in sections up to working faces; all entries near the working face should be covered, but possibly only a limited portion of those at or near main haulage ways. Communication with roving personnel at up to 3,000 feet away from main haulage ways needs to be established. More than one kind of working face must be dealt with, i.e., room and pillar (predominant in the U.S.) and longwall.

A major disadvantage of conventional flexible coaxial cable structures in the latter application arises from their seeming inability to provide communications coverage at more than 10 to 20 meters lateral distance from the cable in the above mentioned frequency bands which are suitable for use with these cables. Thus in order to provide wide area communications coverage within the network of tunnels in a coal mine section, it would be necessary to string cables along most of them. There are however severe practical and economic obstacles to stringing all this cable in the continually changing geography of a section. Hence the majority of the remarks and analyses described in this chapter are directed towards the primary application of essentially longitudinal communication along haulage ways.

II. THEORETICAL CALCULATIONS OF PERFORMANCE OF LEAKY COAXIAL CABLE COMMUNICATION SYSTEMS

This section describes the methods and results of calculations of the leakage of electromagnetic energy from coaxial cable structures. These calculations were performed to give preliminary estimates of the optimum design of inductively coupled communication systems based on partially shielded transmission lines, and to suggest the experimental data needed to confirm or modify existing theories of their operation.

The situations considered include the behavior of fields in an air outer medium using a solid wall shield model approximation, and an ideally conducting braid shield model.

Electromagnetic fields in and around coaxial lines can be calculated using the simplest available geometrical model (Figure 1). The following assumptions are made:

1) As the outer shield of the coaxial line is made slightly "transparent" to the elctromagnetic fields, the inside fields (in Regions 1 and 2) are not affected drastically; hence the error introduced by using the "opaque" shield field distribution inside will be negligible.

2) The axial attenuation of the field, although always non-zero, is small enough that its effect on the radial components k_r of the propagation vector is negligible.

3) All four regions are non-magnetic, i.e., $\mu_1 = \mu_2 = \mu_3 = \mu_o$. This is not a significant restriction on the materials of the coaxial cable in the frequency range of interest (roughly 10^5-10^8 Hz).

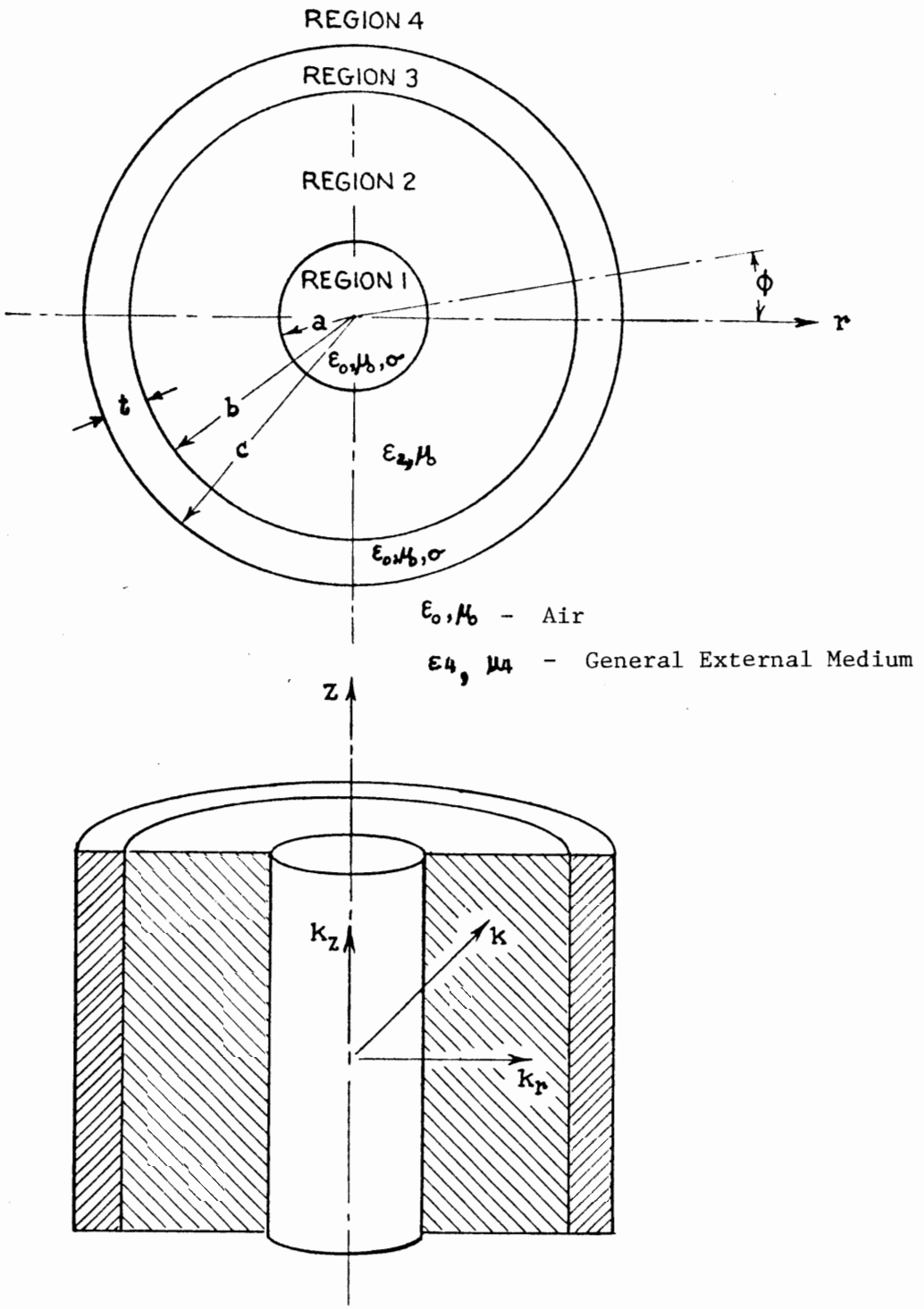

FIGURE 1 CHARACTERISTIC QUANTITIES AND DIMENSIONS ASSOCIATED WITH A FOUR REGION COAXIAL LINE GEOMETRY

The mathematical formalism of the wave theoretical analysis starts from the wave equation for the vector potential for a four-region system (3 concentric cylindrical boundary surfaces with radii a, b, c). The transmission line is straight, infinitely long, and uniform, and its cross-sectional dimensions are negligibly small with respect to the wavelength of the signals. There are six boundary conditions, since the tangential components of the electrical and magnetic field intensities are continuous across each of the three boundaries. We assume a coaxial line operating in a TEM mode.

The outer shield of the coaxial cable does not provide complete shielding at low frequencies, but in fact allows a more-than-adequate field to propagate as a loosely-bound surface wave along the outside of the cable. The wave phase velocity of the cable, and therefore the degree to which the external field is confined to the vicinity of the cable, can be adjusted by changing the cable internal dielectric constant. The higher the dielectric constant, the more confined the external field. Coaxial cable also assures that field behavior will be relatively insensitive to the surrounding physical environment, since most of the power is transported inside the cable. The insensitivity to the external environment not only simplifies analysis, but is an advantageous, if not indispensable, characteristic of the cable, particularly in those applications where the communications corridor may be strewn with large metal objects and contain several bends or corners.

A. Solid Shield Model

The external fields can be analyzed using a solid cylindrical shield model, since braided shields appear solid below about 5 MHz.[1]

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(1) K. Ikrath, "Leakage of Electromagnetic Energy from Coaxial Cable Structures", U.S. Army Signal Research and Development Laboratory, Fort Monmouth, N. J., USASRDL Tech. Dept. 1964 (1958).

The nature of the electromagnetic wave fields external to a long length of dielectric-filled coaxial cable placed in an air medium is described below. The field equations represent an external surface wave propagating in the positive axial (z) direction. The external wave has two electric field components E_r, E_z, and one circumferential magnetic field component H_ϕ, all circularly symmetric about the z-axis.

$$E_z = IS \frac{K_o(\eta r)}{K_o(\eta c)} e^{-jk_z z} \tag{1}$$

$$E_r = jIS \left(\frac{k_z}{\eta}\right) \frac{K_1(\eta r)}{K_o(\eta c)} e^{-jk_z z} \tag{2}$$

$$H_\phi = jIS \left(\frac{\varepsilon_o}{\mu_o}\right)^{1/2} \left(\frac{k}{\eta}\right) \frac{K_1(\eta r)}{K_o(\eta c)} e^{-jk_z z} \tag{3}$$

where the coordinate system is defined by Figure 1; and

E_r (volts/meter) is the component of electric field in the radial direction - r.

E_z (volts/meter) is the component of electric field in the axial direction - z.

H_ϕ (amperes/meter) is the component of magnetic field in the circumferential direction - ϕ.

E_z (volts/meter) is the component of electric field in the axial direction - z.

H_ϕ (amperes/meter is the component of magnetic field in the circumferential direction - ϕ.

$$S = \frac{E_z^{out}(\text{at shield})}{I} \tag{4}$$

; S is the complex surface transfer impedance. It represents the magnitude and phase of the axial component of electric field (E_z) at the outer surface of the coaxial cable shield per unit current in the center conductor.

$$S = \frac{\sqrt{2}e^{-t/\delta}}{\pi\sqrt{bc}\sigma\delta} \text{ ohms/meter, (for } t/\delta \gtrsim 1) \tag{5}$$

b,c are the shield radii shown in Figure 1 in meters

$t = c-b$ is the thickness of the cable outer shield (6)

$$\delta = \frac{\sqrt{2}}{\omega\mu\sigma} = \text{skin depth in the conducting shield} \tag{7}$$

ω is the radian frequency ($=2\pi f$)

ε_o, μ_o are the permittivity and permeability of free space in farads/meter and henries/meter respectively.

σ is the conductivity of the shield and center conductor in mho/meter

$k = \omega(\mu_o\varepsilon_o)^{1/2}$ is the resultant propagation vector in the external medium (8)

$k_z = \beta_z - j\alpha_z \simeq \omega(\mu_o\varepsilon)^{1/2} = (\frac{\varepsilon}{\varepsilon_o})^{1/2} k$ is the axial component of the propagation vector for the cable structure (z-attenuation constant α_z small) (9)

ε is the permittivity of the cable dielectric

$k_r = -j\,(\frac{\varepsilon}{\varepsilon_o} - 1)^{1/2} k$ is the radial component of the propagation vector in the external medium (10)

$$\eta = \left(\frac{\varepsilon}{\varepsilon_o} - 1\right)^{1/2} k = jk_r \tag{11}$$

z is the axial coordinate distance in meters

$K_o(\eta r)$ is the zero-order modified Bessel function of the third kind

$K_1(\eta r)$ is the first-order modified Bessel function of the third kind.

The external E_r and H_ϕ components are in phase with each other, thereby propagating power down the outside of the line. E_r and H_ϕ are simply related by the ratio

$$E_r/H_\phi = \left(\frac{\mu_o \varepsilon}{\varepsilon_o^2}\right)^{1/2},$$

which equals 570 ohms for polyethylene-filled cables such as RG-58 and RG-8. In applications where the radial distance r and frequency are such that $\eta r < 0.15$, $K_o(\eta r)$ and $K_1(\eta r)$ can be approximated by the simpler small argument forms

$$K_o(\eta r) = \ln(\eta r) \tag{12a}$$

$$K_1(\eta r) = 1/\eta r, \tag{12b}$$

to give:

$$E_z = \frac{IS}{\ln(\eta c)} \ln(\eta r)\, e^{-jk_z z} \tag{13}$$

$$E_r = -j\frac{IS}{\ln(\eta c)} \left(\frac{k_z}{\eta}\right) \frac{1}{\eta r}\, e^{-jk_z z} \tag{14}$$

$$H_\phi = -j\left(\frac{\varepsilon_o}{\mu_o}\right)^{1/2} \frac{IS}{\ln(\eta c)} \left(\frac{k}{\eta}\right) \frac{1}{\eta r}\, e^{-jk_z z}. \tag{15}$$

A coal mine haulage way communications system operating below about 100 kHz is one such application.

Equations 13 through 15 reveal that in the vicinity of the cable the radial electric field E_r and circumferential magnetic field H_ϕ fall off inversely with distance r from the cable, while the axial electric E_z field falls off as the logarithm of r. When $\eta r > 0.15$, i.e. at higher frequencies or greater distances form the cable, the exact expressions for K_o (ηr) and K_1 (ηr) must be used.

When air is the outside medium, the fields in Region 4 represent a surface wave along the outside of the coaxial shield. There is power transfer in the axial direction, and only reactive power in the radial direction (E_r and H_ϕ in phase, E_z in phase quadrature with both E_r and H_ϕ).

B. Leaky Braid Shield Model*

This model explores leakage of electromagnetic energy through the apertures in braided shields. The external magnetic field is obtained by superposition of the field configurations from each braid wire current as a function of the distance from the wire. Leakage through the conducting braid wire itself is neglected (ideally conducting assumption). The braid is regarded as a mesh of diamond shaped apertures (Figure 2) and the following assumptions are made in order to be able to apply the analytical results of a plane meshwire model to the curved shields of coaxial cables.

1. Stationary DC like behavior of the flux patterns in the immediate vicinity of the braid apertures is assumed at wavelengths which are large compared to the dimensions of the braid apertures.

2. Magnetic field distortions due to geometry and contact conditions at the braid wire crossing are neglected.

3. The number of mesh apertures is large in a surface portion of the braid which can be considered to be almost flat.

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* K. Ikrath, ref. (1).

Under symmetry conditions currents i′ and i″ are equal.

Figure 2a

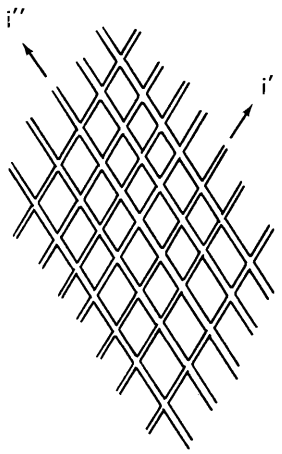


Figure 2b

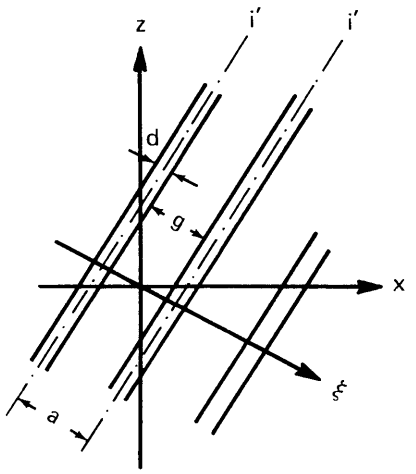
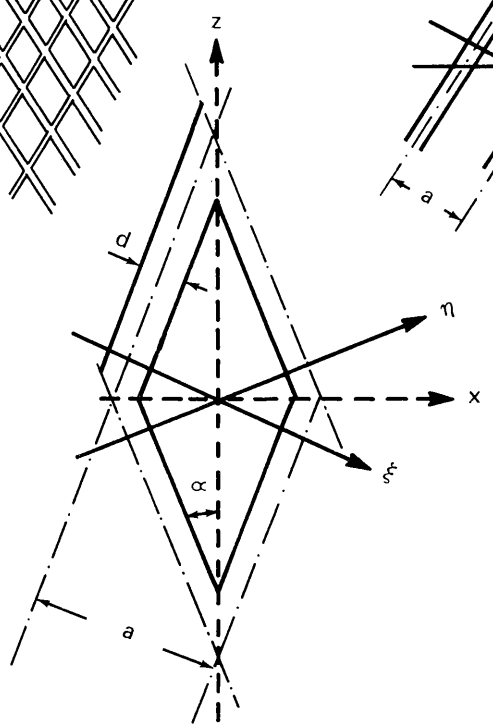


Figure 2c



* K. Ikrath, ref. 1

FIGURE 2 BRAID SHIELD MESH STRUCTURE*

4. Geometric symmetry and equal size of the diamond shaped braid apertures is assumed (a perturbation of the symmetrical model would exceed the scope of this presentation).

5. The braid is made of infinitely conducting material (leakage through the apertures only).

The expression for the surface transfer impedance per unit length is then*

$$S = 0.3 \frac{\mu_o f}{n} \left(\frac{g}{a}\right)^4 (1 + \tan^4\alpha - \sin^4\alpha), \tag{16}$$

for small leakage factor

$$\frac{g}{4a\sin^2\alpha} < 1 , \tag{17}$$

where n is the number of braid wire strands which form the diamond shaped mesh apertures. The leakage fields for the braid shield model can then be calculated from eqs. (13)-(15) or (1)-(3) by substituting the expression (16) for S.

C. Behavior Versus Operating Frequency

In Figure 3 the lateral leakage fields in air (again ignoring z dependence are shown as a function of frequency at two distances from RG 58/U cable. These plots were obtained using both the solid wall and ideally conducting braid shield approximations. The cable parameters and braid dimensions are given in Tables 1, 2 and 3. In these calculations the exact expressions for the Bessel functions $K(\eta r)$ were used when $\eta r > 0.15$.

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* K. Ikrath, ref. (1).

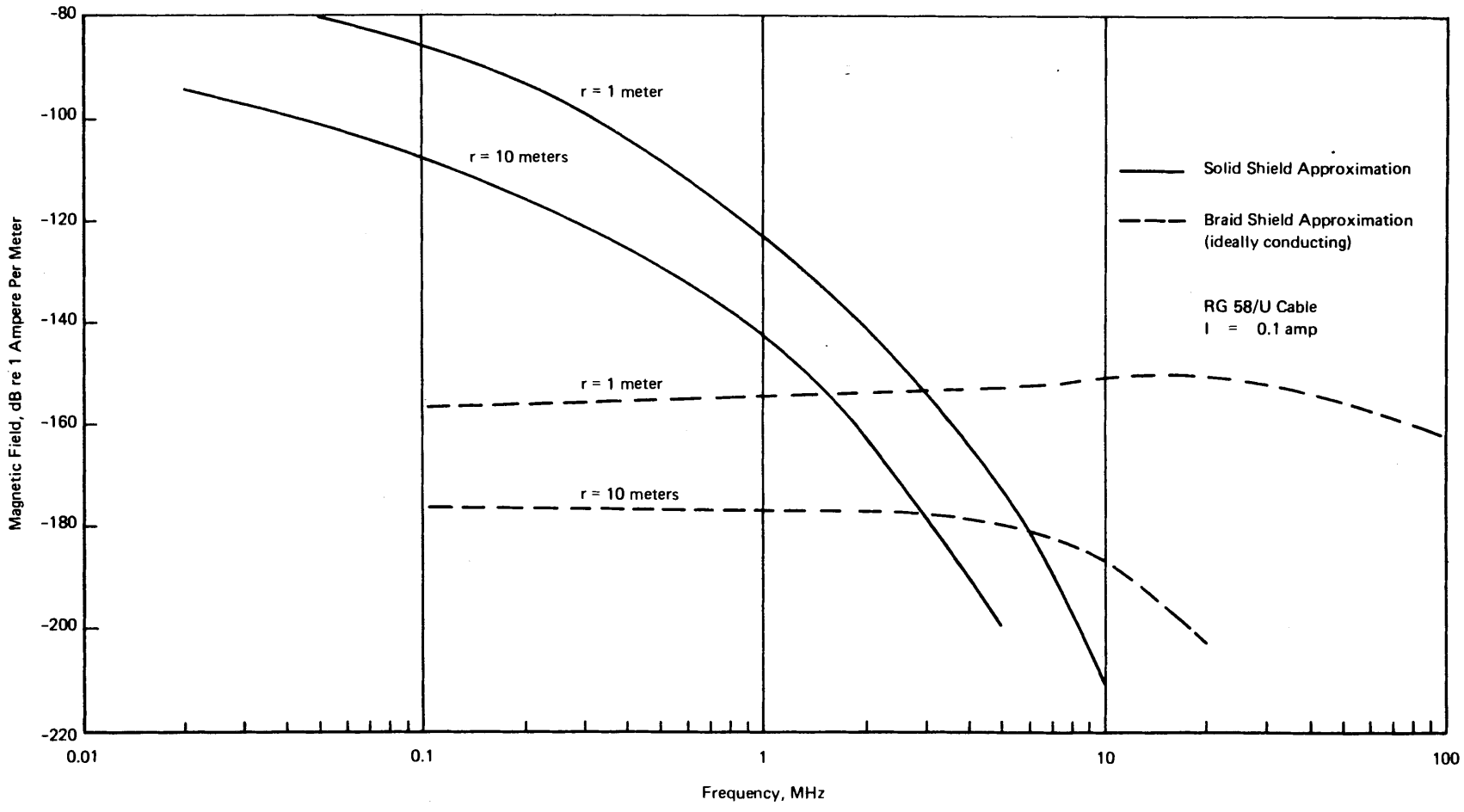

FIGURE 3 MAGNETIC FIELD $|H_\phi|$ AT r METERS FROM CABLE AXIS VS FREQUENCY

TABLE 1
COAXIAL CABLE PARAMETERS, RG 58/U CABLE
(For Figure 1 Geometry)

a	(meters)	4.13×10^{-4}
b	(meters)	1.524×10^{-3}
c	(meters)	1.816×10^{-3}
t	(meters)	2.92×10^{-4}
σ	(mho/m)	5.7×10^{7}
ϵ_2	(relative)	$2.26\ \epsilon_0$

TABLE 2
BRAID DIMENSIONS, RG 58/U CABLE
(as measured on a small sample)

$a = 1.02 \times 10^{-3}$ m.

$g = 0.18 \times 10^{-3}$ m.

$d = 0.84 \times 10^{-3}$ m.

$2\alpha = 45^{o}$

$n = 18$

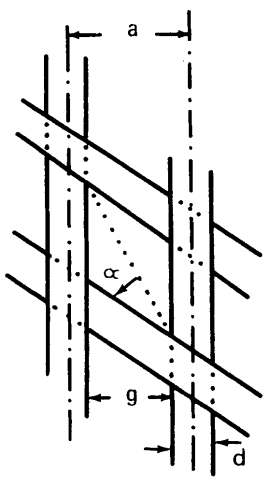

TABLE 3
LONGITUDINAL ATTENUATION (α), RG 58/U CABLE

Frequency (MHz)	.1	.5	1	2	5	10	15	20	50
α (dB per 100 ft.)	.1	.25	.35	.54	.95	1.45	1.8	2.1	3.6

Examination of Figure 3 reveals that leakage through the conducting shield material dominates over that through the braid apertures at frequencies below about 5 MHz. It is also clear that lower frequencies are favored overall with no optimum frequency occurring above 100 kHz in terms of achievable leakage fields. However, a secondary "plateau" region is produced between 5 and 50 MHz by the broad maximum in external field strength predicted when using only the braid shield model. The frequency band in which this field maximum occurs using the braid shield model varies with distance from the cable. At 1 meter from the cable the field maximum occurs between 10 and 20 MHz, while at a distance of 10 meters, the maximum occurs around 1 MHz.

It should be noted that the plots of Figure 3 have taken no account of longitudinal attenuation (Table 3) of the fields as they travel along the cable. This attenuation increases with frequency. In Figure 4 are shown plots of the open circuit voltage induced by the magnetic fields of Figure 3 into a transceiver loop antenna having a nominal effective area, A_{eff}, of $1m^2$. Unlike Figure 3, a frequency dependent attenuation factor which corresponds to transmission along 300 meters of RG-58/U cable has been applied to the signal. Again, no maximum is found in the signal above 100 kHz using the solid shield approximation; and broad <u>voltage</u> maxima for the braid shield model remain at roughly the same frequencies as the <u>field</u> maxima, falling between 10-20 MHz at the distance of 1 meter and between 1 and 5 MHz at a distance of 10 meters. The overall result is as before with the low frequencies favored and a secondary plateau region between 5 and 50 MHz. This result is similar to the original field results because of the approximate cancellation of two opposing effects, (a) the differentiating effect of the receive loop, which favors higher frequencies and (b) the attenuation within the cable, which is greater at higher frequencies. It will also be observed that the open circuit voltage of the receive loop is only a very weak function of frequency below 100 kHz down to about 20 kHz.

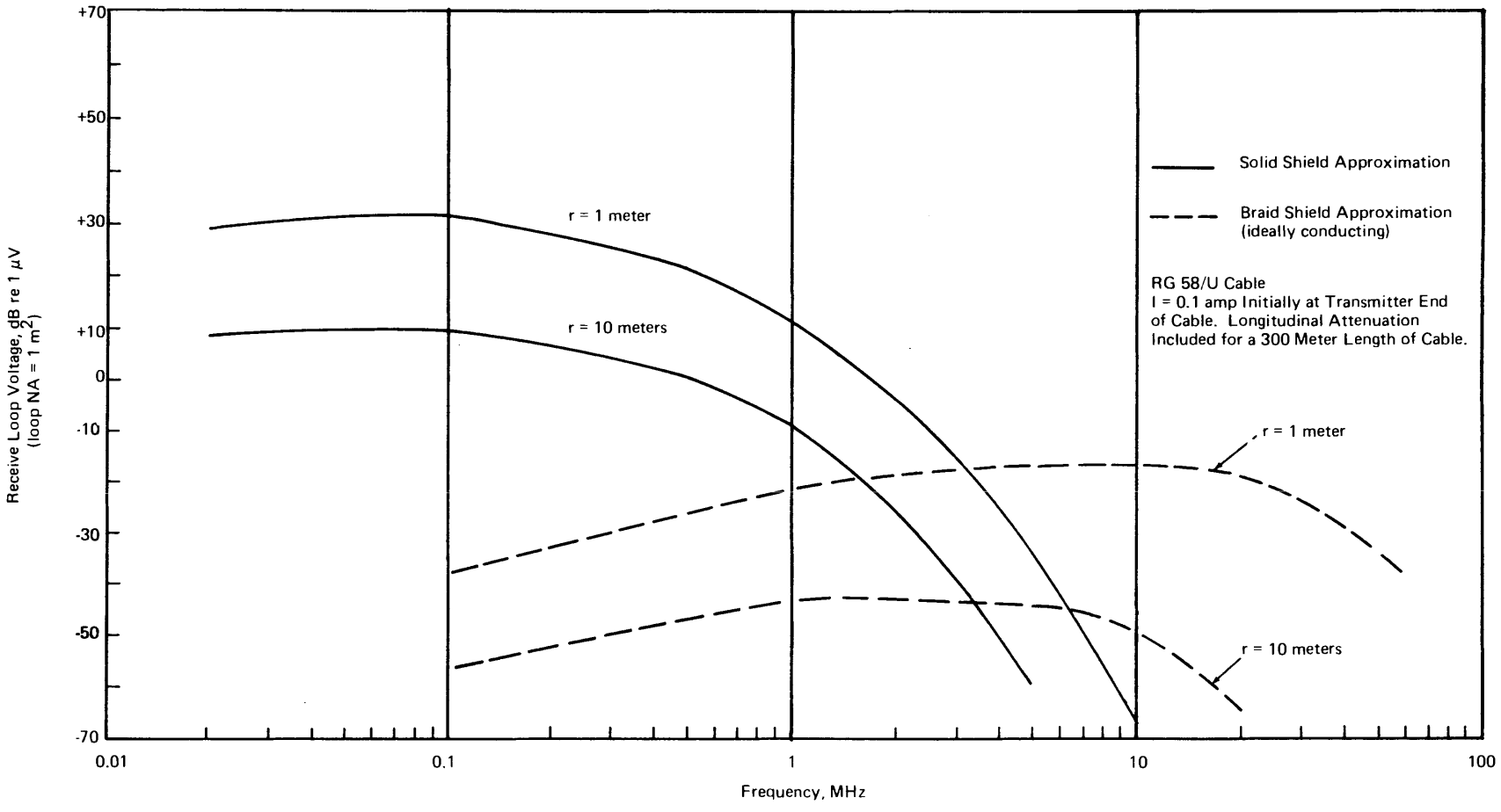

FIGURE 4 RECEIVE LOOP VOLTAGE AT r METERS FROM CABLE AXIS VS FREQUENCY
(For Loop Located 300 Meters From Transmitter End of Cable)

It is worth noting from Figure 4 that the receive signal voltage at a distance of 1 meter from the cable is about 39dB higher at 100 kHz (solid shield approximation) than the maximum value for the braid shield approximation around 15 MHz. At r = 10 meters, this difference increases to about 54dB, when comparing the voltage maximum for the braid shield approximation at about 3 MHz with the higher voltage at the same frequency of 100 kHz for the solid shield case.

D. Attainable Longitudinal Communication Range

This section contains the results of calculations of the two-way longitudinal communication range attainable between a roving miner with a portable transceiver and a fixed base station connected to a leaky coaxial cable hung against the rib of a haulage way. In these calculations it has been assumed that the haulage way environment does not appreciably affect the fields leaked out of the cable into the haulage way cross-section because most of the power is transported inside the cable. Thus, the calculated ranges are those for a cable in free space. Furthermore, the longitudinal range of the communication system has been defined as that point where the leakage field induces a voltage across the matched input of the receiver, at a lateral distance r meters from the cable, which is just equal to the sensitivity of that receiver.* In the following all quantities should be understood as having their RMS values where appropriate.

Assuming a loop antenna,

$$V_r = 1/2\ V_{oc} = \pi f \mu_c\ NAB \tag{18}$$

* This assumes that system performance will be limited by intrinsic receiver noise as opposed to external electromagnetic noise in the mine. As such, the ranges calculated in this section can be considered as upper bounds on performance that will only be further degraded by external noise levels. The electromagnetic noise data recently taken up to 32 MHz by the National Bureau of Standards in several coal mines should allow more realistic estimates of communication range to be made when the reduced data become available in the near future.

where V_r is the voltage across the receiver's matched input,

V_o is the open circuit voltage across the loop,

B is the magnetic flux density ($\mu_o H$) in webers/meter^2

μ_c is the effective permeability factor, and NA, the product of the number of turns times the area of the loop.

In more convenient units for this calculation, the maximum acceptable field intensity H_ϕ is given by

$$H_\phi \text{ (dB re 1 ampere per meter)} = V_r^s \text{ (dB re 1 } \mu\text{V)} - \mu_c NA \text{ (dB re 1m}^2\text{)} - f \text{ (dB re 1 MHz)} - 132, \quad (19)$$

where V_r^s is the sensitivity of the receiver.

The maximum longitudinal two-way communication range has been calculated for RG 58/U coaxial cable using equation (19), in conjunction with previous computations of H_ϕ and the longitudinal attenuation associated with this cable given in Table 3. The variation in longitudinal communication range with operationg frequency, lateral range, and loop effective area, based on the two simplified models of field behavior discussed earlier, is presented for RG 58/U cable in Table 4. These tabulated values, as noted in the table, are for a portable FM system having a nominal transmitter power of 1 watt and receiver sensitivity of 1 microvolt, under the most favorable signal conditions when the mobile unit antenna is oriented for maximum coupling to the coaxial cable leakage fields and no destructive interference (fading) is present. The range implications of nominal polarization and/or fading losses are also noted.

E. Discussion of Results

The results tabulated in Table 4 indicate that one can hope to achieve base station-to-portable unit communications along cable lengths of up to about one mile only at operating frequencies around 100 kHz and below, with reasonable portable transmitter and receiver parameters and without

TABLE 4

MAXIMUM TWO-WAY LONGITUDINAL COMMUNICATION RANGE VIA LEAKY COAXIAL CABLE (50Ω, RG 58/U)

FM System
Transmitter Power = 1 watt‡
Injected Current = 141 milliamperes rms
Receiver-Noise-Limited Case for a Receiver Sensitivity of $V_r^s = 1\mu V$ for 20 dB of Quieting
Loop Effective Area = $\mu_c NA$‡

Lateral Range (meters)	Frequency (MHz)	Maximum Longitudinal Communication Range§ (feet)		
		$\mu_c NA = 0.1m^2$	$\mu_c NA = 1m^2$	$\mu_c NA = 10m^2$
1	0.1	8,000	28,000	48,000
	0.5	400	8,400	16,400
	1	0	3,700	9,300
	2	0	0	3,900
	5	(0)*	(300)*	(2,500)*
	10	(0)	(800)	(2,200)
	20	(0)	(800)	(1,800)
2	0.1	2,000	22,000	42,000
	0.5	0	6,000	14,000
	1	0	1,900	7,700
	2	0	0	2,600
	5	(0)*	(0)*	(1,800)*
	10	(0)	(300)	(1,700)
	20	(0)	(400)	(1,400)
3	0.1	0	18,500	38,500
	0.5	0	4,600	12,600
	1	0	1,000	6,700
	2	0	0	2,000
	5	(0)*	(0)*	(1,400)*
	10	(0)	(300)	(1,700)
	20	(0)	(100)	(1,100)

*Ranges in parentheses are obtained by use of field strengths calculated from the leaky braid model. In all cases where ranges are given for the braid model, the solid shield model gives zero range.

‡ Representative values of effective loop area and transmitter power for portable personal tranceiver units are $0.5m^2$ – for a ferrite-loaded loop, and 1 watt, respectively; and for mobile vehicular units, $5m^2$ for an air-core loop, and 10 watts. The ferrite-loaded loop effective area reduces to unacceptable levels for a practical design as the frequency increases (falling to about $0.005m^2$ around 20 MHz), thereby indicating that a whip antenna about 2 feet long will be needed to obtain the required signal levels at the higher frequencies.

§ The maximum ranges tabulated above are for the most favorable signal and noise conditions. If a nominal safety margin of 14 dB is also included to account for likely polarization and fading losses (the former at lower frequencies and the latter at higher frequencies), ranges that are more realistic for routine use of portable units in haulage ways are probably those in the μ_c NA = $0.1m^2$ column above. The corresponding ranges for vehicular units should lie approximately half way between those in the $1m^2$ and $10m^2$ columns. These ranges apply when receiver noise, not external electromagnetic mine noise, is the dominating noise source. Longitudinal ranges for different values of power, loop area, safety margin, receiver sensitivity or corresponding levels of external noise, can also be obtained by relating the total dB change to the equivalent change in cable length using the Table 3 longitudinal attenuation values for each frequency.

Finally, though the lower frequencies offer the greatest signal levels for a given transmitter current, these levels unfortunately can require rf transmitter voltages on the order of 100 volts for a portable unit with a 100 milliampere loop current. Therefore, the implications of these voltage and current levels on the instrinsic safety of such portable units should be investigated if they are to be used in the face areas of working sections.

repeaters placed in the cable. Larger, higher-powered vehicle-mounted mobile units will achieve greater longitudinal ranges as indicated. Table 4 also reveals that lateral distance from the cable in the haulage way is not a significant factor with respect to determining the optimum frequency band. Furthermore, the evidence of Figure 4 shows that below about 100 kHz, there is not much to choose between frequencies in terms of signal strength. At longitudinal communication distances of more than one to two miles, frequencies of a few tens of kHz will be slightly favored over 100 kHz, from the point of view of signal strength, because of the lower attenuation along the cable at lower frequencies. However, these differences in signal strength with frequency are no larger and perhaps even smaller (2-3 dB) than the uncertainties presented by the external noise environment in the haulage way. This external noise may in fact turn out to be the limiting factor on communication range, and hence be the final influence on the choice of operating frequency.

The choice of an optimum operating frequency is a function of four factors* which vary differently with frequency, namely longitudinal attenuation of the signal within the line, leakage of the field to the outside, propagation of the "leaked" field outside the cable, and external noise levels. External noise levels were not included in the above calculations because significant data were not yet conveniently available to adequately characterize the haulage way noise environment. Preliminary data from noise measurements taken in mines by National Bureau of Standards personnel indicate that under some circumstances, external noise will be the limiting factor on performance. Therefore, it will be important to monitor and apply the results of NBS's noise measurement program in order to determine when and how seriously external noise may impede the performance of coaxial cable communication systems. It will then be possible to determine if a distinctly optimum operating frequency is identifiable from a practical standpoint within the presently favored 10 kHz to 100 kHz band or at higher frequencies for two-way base station-to-portable

* As mentioned in Table 4, intrinsic safety and practical design considerations may also play important roles, particularly for the portable units.

communications in haulage ways. On the other hand, a few brief calculations have shown that at no frequency is it possible to obtain portable-to-portable communication via conventional coaxial cable without repeaters or radiating devices inserted in the cable.

In the above work, the effect upon the leaked fields of the characteristics of the tunnels and rock found in mines has been neglected. This approximation is probably reasonably valid in the haulage way close to the cable itself (at a lateral separation of one to perhaps two meters, for example), but should be investigated further. On the other hand, the approximation should be grossly inadequate for predicting lateral range down entries crossing the haulage way containing the cable. As shown in Part Four of this report, radio waves propagating down entries without conductors will be severely attenuated by losses in the surrounding rock at frequencies suitable for the conventional leaky coaxial cables discussed in this Part (Three) of the report.

The theories of leakage fields used to derive the attainable communication ranges in Table 4 contain other assumptions and approximations which must of course be tested experimentally before the conclusions drawn using them can be regarded as firm. For example, the relative amplitudes of the leakage fields calculated in the regions of validity of the two different models (solid wall and infinitely-conducting braid shield approximations) have to be verified before definitive statements concerning the optimum operating frequency for a leaky conventional coaxial cable transmission system can be made.

The application of the braid shield model to the calculation of leakage fields from RG 58/U cable must also be viewed as subject to some uncertainty. It appears to us that the model as it stands may only give accurate results when applied to cables with braid shields in which the apertures and shield radius are substantially larger than is the case

with standard RG 58/U cable. However, while the absolute values of the leakage field for the braided shield model are subject to doubt, the predicted behavior of this field with frequency, i.e., a broad maximum between 10 and 20 MHz, is on more certain ground.

Relatively straightforward experiments are required to measure the magnetic field signal strengths as functions of frequency and distance from long lengths of conventional coaxial cables in air and in mine haulage ways. Then curves such as those shown in Figures 3 and 4 can be verified in terms of both shape and amplitude, or corrections made to them and the theory if appropriate. It would also be instructive and worthwhile to reconcile and compare the method of calculation described in this report with those followed by workers in other countries, notably France (1), the U.K. (2), and Canada (3), in their investigations of radio communication in mines by means of coaxial cable.

III. EUROPEAN WORK WITH LEAKY COAXIAL CABLE COMMUNICATION SYSTEMS

A. State-of-the-Art

Three major classes of coaxial cable communication systems designed for use in mines have been reported as being in various stages of development in Europe.

(1) INIEX/Delogne system (Belgium) employing regularly spaced radiating devices along conventional RG-8/U coaxial cable (4).

Much experimental and theoretical investigation of this system has been performed including trials at the Bruceton, Pa. Safety Research mine of the USBM. The optimum operational frequency is believed to fall in the range of 2-20 MHz. Prototype installations are on order in Belgium, at a price of about $2500/km. Firm production sales prices are not yet available. The INIEX/Delogne scheme appears potentially suitable for

application in U.S. mines, although several uncertainties regarding performance/cost trade-offs in typical U.S. mine environments still have to be resolved. These uncertainties are connected in particular with the restraint in U.S. mines of having to install the cable close to the rib with consequent increases in attenuation, in contrast to the more central location in an arched tunnel allowed in Europe, and with the influences on performance of dirt and water on the cable and radiative devices.

(2) Coaxial cable with high surface transfer impedance -- specially designed "leaky" braid outer conductor (France).

Theoretical investigations carried out at the University of Lille in France indicate that effective communication along several miles of mine haulage way may be achieved by use of a coaxial cable whose braid outer conductor is designed and fabricated for "optimum" leakage of radiation. Experimental investigations of this scheme in a French mine are planned to be carried out near the end of 1973. The optimum operational frequency is believed to be between 5-10 MHz.

Similar uncertainties exist with regard to the effects of dirt, water, and proximity to the walls of the tunnel on the performance of the proposed French scheme in U.S. mine environments, as were mentioned in the context of the Belgian cable system.

(3) Conventional coaxial cable with repeaters (U.K.)

It has been reported that a conventional coaxial cable communication system incorporating repeaters is being tested experimentally in the U.K. Little information on the cost and performance of this system is yet available in the U.S. Additional uncertainties in the performance and cost evaluations of this system are introduced by questions associated with the reliability and maintainability of the repeaters that can realistically be expected in a mine environment.

B. Discussion

Progress achieved in Europe in the development of the coaxial cable communication systems mentioned above should be carefully and continually monitored and evaluated. In particular, cost estimates and further operating performance data should be obtained.

Nevertheless, European results, while valuable and to date encouraging, cannot be directly applied to the different environment of U.S. mines. In particular it appears impossible to install communication cables in U.S. mines in the locations recommended by European researchers. Specifically, cables will have to be installed close to the ribs or walls in U.S. mines. Accordingly different attenuation rates, and correspondingly different optimum operating frequencies or tradeoffs between the rate of "leakage" of power and total communication system length may prevail than in the European situation. Experimental investigations in U.S. mines with the proposed European coaxial cable systems are required before their applicability in this country can be definitively confirmed or denied, and if confirmed, operational specifications written (for frequency, design of radiative structure or "leaky" outer conductor, and so forth).

IV. REFERENCES

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