ANTENNA DESIGN & COUPLING STUDIES AT MEDIUM FREQUENCY FOR IMPROVED COAL MINE COMMUNICATIONS

PREPARED FOR

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16. Abstract

This report covers antenna design, analysis, and development work suited for use with a wireless radio communication system operating at medium frequency. The work includes the test and evaluation of prototype vehicular antennas developed during the program.

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FOREWARD

This report was prepared by Terry S. Cory, P.E. for the U.S. Bureau of Mines under purchase order P038223. The work was initiated via an unsolicited proposal under Coal Mine Health and Safety Program. It was administered under the technical direction of the Bruceton Research Center with Mr. Robert Chufo acting as the Technical Project Officer. The BuMines Contracting Officer was Mrs. Chalene Wolper.

This report is a summary of the work recently completed; performed during the period 15 July 1978 through 1 December 1978. The report was submitted by the author on 15 December 1978.

Any reference to specific brands, equipment, or trade names either specifically written or implied does not imply endorsement by the Bureau of Mines. No patentable techniques have been developed or otherwise used during the course of this program. The vehicular antenna design may be patentable.

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1.0 INTRODUCTION

This report covers antenna design, analysis, and development work performed for the U.S. Bureau of Mines under Purchase Order P0382223 by Terry S. Cory, P.E. The anticipated usage of the antennas and accompanying analysis is for medium frequency wireless communications in coal mines.

The work has included a complete vehicular antenna design experience through the prototype development stage, design analysis and comparative tests to be useful in eventual development of optimized portable PA/antenna systems, and analysis of the coupling between vehicular antennas and existing mine wiring.

The vehicular antenna work was an extension of earlier configuration studies and preliminary design analysis performed under USBM Contract H0377013 (Collins/Rockwell) on Wireless Communications for Trackless Haulage Vehicles.

Medium frequency technology in coal mines is rapidly approaching the point where systems can be configured for use in particular mines. A key portion of the R&D invloves establishing a viable set of vehicular antenna parameters so that coupling loss into or out of existing mine wiring can be estimated for the case where the vehicle is in the same entry as the wiring. Such a set of parameters has been established and coupling estimates have been made as part of this work. Coupling for remotely located transmitters (and receivers) has been estimated as part of propagation measurement Contracts H0366028 and H0377053. The only part of the vehicular antenna problem for which there is no data is that where the antenna is simultaneously matched to two frequencies. The eventual mine wireless radio systems are expected to be two frequency systems to permit the use of repeaters.

Portable radio systems including antennas at medium frequency have been designed and have undergone limited testing in coal mines. An optimized portable system probably has not yet been designed; particularly when operation is expected in close proximity to existing mine wiring conductors. The integral design of the radio transmitter PA and the antenna matching/phasing network as a system is necessary for optimum design. Tests of the portable equipment available have, however, provided a starting point for the general inclusion of portables into a complete system design. The analysis performed as part of this work will help to bound the physical characteristics of portable antennas and data is given on the raw (untuned) character of flat-strip winding configurations.

2.0 SUMMARY

This program has provided antenna design analysis which has led to the design, building, and testing of a prototype mine wireless vehicular antenna prototype. The analysis also enabled the building of a portable antenna wiring configuration which was tested against the RACAL antenna and against another portable antenna wiring alternative provided by the Bureau. The antenna design activity also provided the basis for the prediction of antenna coupling into existing mine wiring which was performed using graphical field mapping.

The design of vehicular antennas is dependent on the operational utility of particular configurations mounted on vehicles, on optimizing the antenna parameters for achieving near-maximum NIA, on requirements for intrinsic safety, and to a lesser degree on the parameters of mine wireless radios.

The design of portable antennas is dependent on human factors of carrying and accomodation of variations in tuning due to the differences in human bodies, and on parameters of mine wireless radios to a greater degree than with vehicular antennas in addition to achieving high NIA and providing intrinsic safety.

The design of vehicular antennas is sufficiently independent of overall transceiver subsystem configurations that it is practical to build and evaluate such antennas separate from the complete subsystem. The design of portable antennas cannot so easily be divorced from the radio design and, therefore, should always be considered as part of the design of a complete portable subsystem.

The emphasis of this program has been placed on defining vehicular antenna designs. Information from the design analysis is available to help design portable antennas; however, the design of an acceptable portable antenna was beyond the scope of this program.

The coupling of mine wireless antennas to existing mine wiring is dependent both on the entry crossectional geometry (containingthe conductors and the antenna) and on the antenna parameters themselves. The graphical field mapping technique has been shown to provide a simple effective means to include all variables electromagnetically.

The departure point for this program has included the composite of technology provided from previous medium frequency programs as discussed in Section I. Assumed as the baseline for this work has been:

(1) use of medium frequencies in the 100-1000 KHz frequency range with particular emphasis on the range 500-1000 KHz which has previously been shown to provide the most effective coupling to existing mine wiring

(2) that coupling of carrier current into existing mine wiring provides the principal transmission means for wireless communications

(3) an effective mechanically rugged vehicular antenna design employing a multi-turn loop winding inside a rigid electrostatic shield is feasible

(4) an antenna design algorithm of proven validity is available to trade off the several antenna design parameters involved in optimizing antenna performance

2.1 ANTENNA DESIGN & PERFORMANCE

2.1.1 PERFORMANCE CONSIDERATIONS

Performance optimization and intrinsic safety are compatible bases for overall antenna design. That this is true was not obvious at the onset of the program.

For a multi-turn antenna of constrained crossectional dimensions, the achievable NIA is quasi-independent of the number of turns, when wire-resistance-limited, over a substantial range of turns. This range of turns, for a given power source voltage, also falls in the constant power region of the intrinsic safety curve of inductance vs current (ie, the current voltage curve for negligible circuit stored energy). The number of turns beyond which the NIA decreases markedly also roughly corresponds to the number of turns beyond which the methane ignition current becomes constant-energy-limited. The Q of a practical antenna is ultimately limited by the losses in the transforming/tuning circuitry but becomes wire-resistance-limited as the number of turns is increased or as the frequency is increased. At the design frequency range of interest, the wire resistance plus turns-dependent series tuning loss resistance when used with the maximum allowable inductance (to prevent NIA fall-off and energy-limited safety performance) is just about at the point where this resistance is equal to the resistance due to fixed (non-turn dependent) losses.

The NIA increases with decreasing antenna bandwidth and increasing antenna Q. If the choice is to design to a fixed bandwidth by either using the "inherent" wire resistance as a limit or by padding an inherently higher Q antenna with external fixed series resistance (non-frequency-dependent), the external padding technique is always the best. This is because its use gives higher NIA than the equivalent wire-resistance-limited design and also because the bandwidth can be held near-constant over a range of frequency. If external padding resistance is used, it also serves as a current-limiting resistance for intrinsic safety purposes because its value is nearly the same at mf as it is at dc; whereas, the wire resistance is much lower at dc than it is at mf.

As the NIA is quasi-independent of turns in the useful design range when wire-resistance-limited, the resistance level of the antenna can be arbitrarily chosen. The actual operating resistance level is dictated by the desired bandwidth and/or the fixed resistance of the circuit; so to maximize NIA for a finished design, the wire resistance level should be at the high end of the range (ie, approximately equalling the fixed resistance or else the wire resistance plus the turns-dependent tuning resistance such as from an assumed constant Q capacitor should be equal to the fixed resistance). This is accomplished by using as many turns as are allowable (per above definition).

The above discussion deals with the simultaneous happening of several fortuitous conditions. The use of Litz wire is germaine to this, where the strand size is made as small as possible (for vehicular antenna prototypes of this program, 1700/44 Litz was chosen; ie, 1700 strands of #44 wire having approximately 6800 circular mils of area per conductor).

The statement about maximizing NIA by having the wire resistance equal to the fixed resistance assumes that the fixed resistance already is the lowest allowable to give the desired (or required) operating bandwidth and/or to inhibit excessive current for intrinsically safe operation. A near-optimum overall design will result when:

(1) The inductance is made as large as is "allowable" and the wire resistance is designed to be less than that to give the minimum bandwidth per (2) below

(2) The minimum bandwidth (for comm system power level/detuning or intrinsic safety power source reasons) is established by fixed (non-frequency-dependent) external resistance.

This establishes the "inherent" intrinsic safety of the antenna.

If an argument can be made for intrinsic safety "inherency" based on series resistance (covering both open-circuit-fault arc discharge and sudden connection of the dc source to the antenna circuit arguments), then blocking capacitors per UL-913 may not be required. Actually, as with the vehicular antenna prototype where an impedance matching transformer is used, series current-limiting resistance can be added at the " ac 50 ohm level" with negligible performance degradation as is suggested in the next subsection. It should also be pointed out that when considering the antenna winding current itself as a current source for a potential short circuit fault, the use of the highest allowable inductance and low winding resistance will limit the peak ac current if the winding is shorted out as the time constant of the winding is maximized.

The minimum bandwidth for communication system performance reasons only is determined from both modulation bandwidth and detuning considerations. For modulation bandwidth; if the system is SSB the bandwidth could approach 3 KHz whereas if the system is FM with modulation index = 1, the bandwidth could approach 12 KHz. For vehicular antennas operating only with the loop in the vertical position, SSB and FM bandwidths of 3-6 and 12-16 KHz respectively may be feasible. For portable operation, the bandwidth must be larger due to the detuning of antennas by shape variations when worn by different men and by differences in human bodies and in garments. Insufficient information is available to select a portable antenna minimum bandwidth for communication purposes.

2,1.2 PROTOTYPE ANTENNA DESCRITION & PERFORMANCE

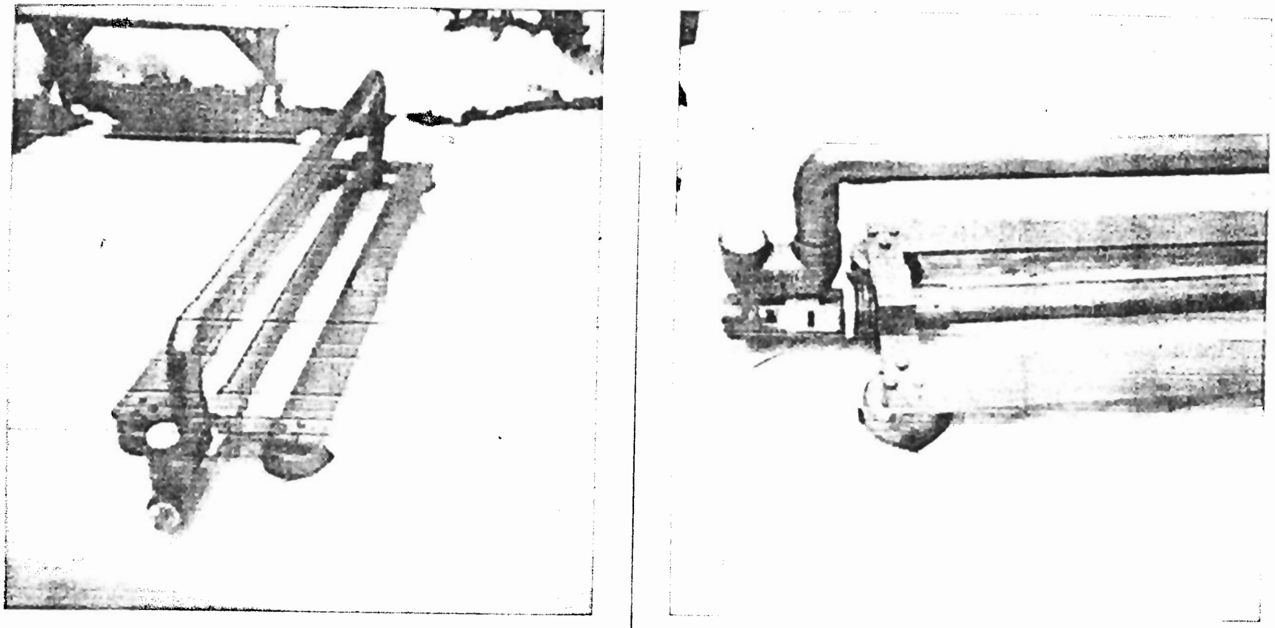
The vehicular antenna prototype(s) built and tested during this program is shown in Figure 1. The specifications for this antenna include:

ELECTRICAL-

Area	0.139 m^2 (6-inch x 36-inch)		
Turns	12 ea. #1700/44 Litz		
		diameter	0.115 inch
		strand diameter	0.002 inch
		area	6800 circ mils
	spaced 0.250 inch		
L_o	127.3 uh		
L @ 500 KHz	190 uh		
Bandwidth			
520 KHz model	14 KHz , Q = 37.1		
920 KHz model	20 KHz , Q = 46.0		
NIA (20 watts)			
520 KHz model	1.8		
920 KHz model	1.5		
Center frequency	variable ± 5% via external capacitor		
Detuning			
520 KHz model	7 KHz	steel vs dielectric mounting	
	10 KHz	vertical vs 45 degree orientation	
920 KHz model	10 KHz	steel vs dielectric mounting	
	10 KHz	vertical vs 45 degree orientation	
Maximum Power (limited by use of 350 VDC trimmer capacitors)			
520 KHz model	46 watts		
920 KHz model	9 watts		
Input impedance	50 ohms nominal		
Intrinsic safety	none inherent in prototypes except all-metal enclosure		

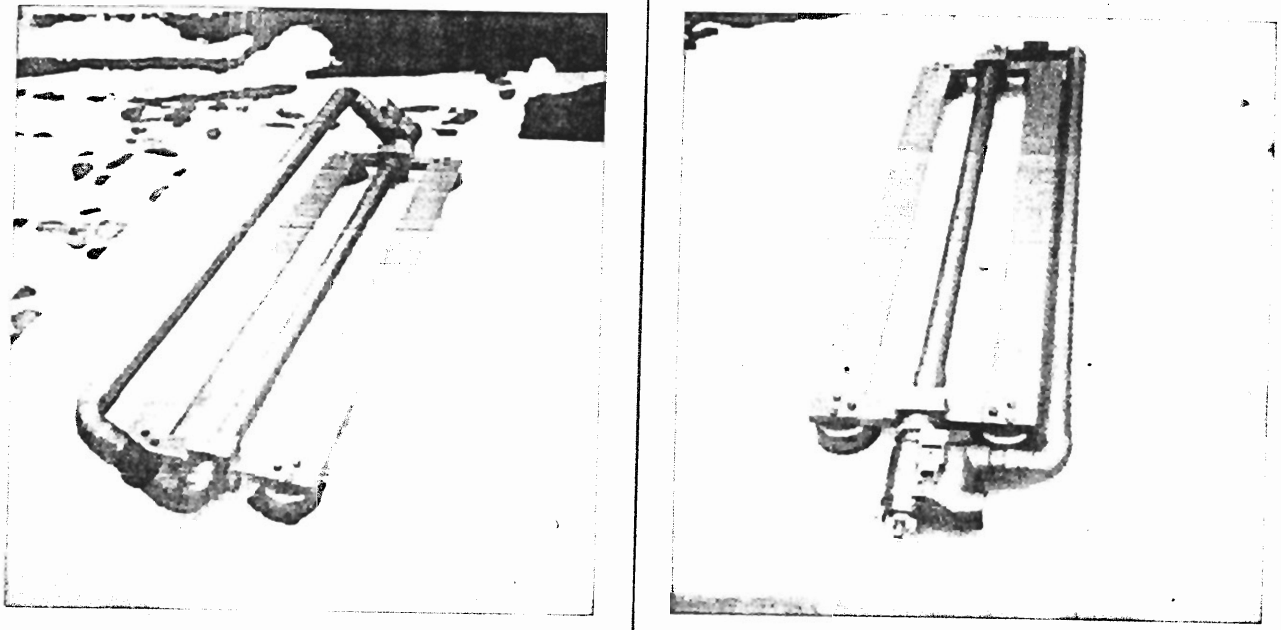
MECHANICAL-

Maximum length	40 inches (including circuitry enclosure)
Maximum width	12.3 inches w/ antenna horizontal 10 inches w/ antenna vertical
Maximum height	8 inches w/ antenna vertical 2.2 inches w/ antenna horizontal
Electrostatic shield	1½ inch diameter nominal
Element orientaion	vertical 45 degree horizontal



VEHICULAR ANTENNA PROTOTYPE
SHOWN WITH LOOP IN THE VERTICAL
ORIENTATION

VEHICULAR ANTENNA PROTOTYPE
SHOWING DETAILS OF THE LOOP/FRAME
MOUNTING AND OF THE CIRCUITRY ENCLOSURE



VEHICULAR ANTENNA PROTOTYPE
SHOWN WITH LOOP IN THE 45 DEGREE
ORIENTATION

VEHICULAR ANTENNA PROTOTYPE
SHOWN WITH LOOP IN THE HORIZONTAL
ORIENTATION

FIGURE I

VEHICULAR ANTENNA PROTOTYPE

The vehicular antenna mounts to a horizontal steel surface on the vehicle via 4 ea magnets located in the corners of the mounting frame. The antenna may be positioned in any of the three principal orientations by pushing the rear housing against the mounting frame (against the spring tension), rotating to the desired position, and releasing the element alowing it to seat in one of the three detent positions.

The mechanical configuration of the vehicular antenna has been made as close to that expected to be useful as possible. The basic antenna winding has been designed to be as close to optimum,providing that proper attention is paid to the matching circuitry, as possible. The prototype antennas have been provided with BNC connectors to facilitate evaluation. Each of the two prototypes provided have been tuned to a different single frequency; one to 520 KHz, nominal and the other to 920 KHz nominal. The winding sense of the turns is important to obtain minimum distributed capacitance and highest resonant frequency. The winding sence of one of the antennas was inadvertantly reversed in manufacture, resulting in a slightly higher reactance. This antenna was tuned to 520 KHz where the difference was negligible. To accomodate a two-frequency system plan, the matching circuitry may eventually have to be modified so the antenna is tuned simultaneously at two frequencies.

No attempt has been made to provide inherent intrinsic safety via fixed external series resistance. The particular Q of the finished prototypes is established by the tuning circuitry and the transformer package as mounted in the enclosure. The unloaded Q of the antenna(s) is approximately 400 @ 500 KHz. The tuning and matching circuitry used components which were available. The antenna(s) is tuned with a balanced capacitive L-section to 200 ohms and then transformed to 50 ohms using a 4:1 ferrite transformer supplied by the Bureau. Fixed silvered mica capacitors in the L-section were rated at 1000 VDC; however, theair variable trimmers were rated at only 350 VDC and thus provide the limiting condition for power handling. The voltage handling could be improved to at least 1000 volts by using only fixed capacitor combinations or else by substituting vaccuum variables for the air variable trimmers.

The antenna winding is protected from the primary power source via the transformer winding which operates at a 50 ohm level on the primary at ac. If used with a radio driven from a 12 volt source, for example, a series current-limiting resistor of 1.2 ohms wpuld limit the current to 10 amps. A current-limiting resistor of up to 5 ohms could be added to the antenna winding (2.5 ohms to each balanced side) with little performance degradation. In addition, the antenna is completely enclosed in metal except in the region of the feed gap in the electrostatic shield which is plastic. This should provide some inherent protection against methane ignition if the enclosure is made gas-tight.

The performance considerations presented early in this section are predicated on having an antenna of fixed dimensions which is not degraded by variations in mounting or by proximity to lossy objects when used. These considerations are, thus, more appropriate for vehicular antennas than for portable antennas. Knowledge of these considerations logically leads to a design procedure which will give a near-optimum antenna of either type, however.

A portable antenna has different and subjectively more severe design requirements than a vehicular antenna. To lend insight into the overall portable antenna problem, it will be useful to list several of these requirements. These include:

(1) The antenna must be flexible or at least semi-flexible. The antenna, to be operationally useful, must be "worn" by the operator in "bandolier" fashion (over one shoulder and under the opposite arm) to provide a non-restrictive "hands-off" user capability.

(2) The antenna tuning and matching circuitry should be provided integral to the radio enclosure to minimize bulk, potential damage, and to maximize current transfer.

(3) The antenna should be tuned for placement on a person's body. The antenna will be deQ'ed automatically by placement on a person's body (equivalent to added series resistance)

(4) According to (3), the antenna must accomodate a "detuning" bandwidth range due to shape changes when worn.

The approach to portable antenna design in this program has been to try and establish an upper bound on NIA performance for the raw unmatched antenna based on variations in antenna design parameters which can be handled with the antenna design algorithm; then to compare the effect on the raw antenna of "wearing" a configuration approximating this upper bound. This has been accomplished by using the antenna design algorithm to trade off antenna wire spacing, wire size, and number of turns; selecting a set of parameters; and running comparative tests of this configuration with other configurations. A configuration was chosen which represents the probable largest size of a flat strip configuration using equally spaced turns. The large size included the greatest length, width, and wire size conceivable to be feasible for such an antenna. The testing was conducted by BuMines comparing this configuration, first, with a similar spaced turn configuration of smaller size (and using stranded wire instead of the Litz wire used in the upper-limit configuration) and, second, with the RACAL antenna.

Previous experience with portable antennas has been with the rigid elliptical shaped antennas built by ECAM and by Collins whereby a "bunch" of stranded wires were placed inside an approximate 3/4-inch diameter plastic tube of 0.217 m^2 area. These antennas both had a self-contained matching network to 50 ohms. The Collins antenna used 7 turns of #18 wire and at 520 KHz, the antenna Q was 44 and the bandwidth was 12 KHz. The NIA was approximately 2.5 for an assumed 20 watts input.

This type of antenna has been since deemed impractical for use in coal mines because of its rigid configuration and because the coax connecting the antenna to the radio was always getting in the way. The Collins antenna, by virtue of the "bunched" rather than spaced turns was wire-resistance limited and unsuited for efficient operation above 1 MHz (resistance increases from 10 ohms at 1 MHz to 75 ohms at 1.5 MHz).

The choice for evaluation during this program was the flat strip consisting of equally spaced turns due to the expected improvement in raw antenna performance (higher sesonant frequency, higher Q, lower wire resistance, amd lower inductance). The range of practical antenna lengths for portable antennas was estimated to be from 5 feet (area of about 0.15 m^2) to about 6.2 feet (area of about 0.23 m^2. The wire configuration built for testing (illustrated in Figure 2 together with the comparable BuMines smaller configuration) conformed to the following:

ELECTRICAL

Area	0.23 m^2 (approx. for elliptical shape computation)
Turns	6ea #1700/44 Litz (same as vehicular) spaced 0.67 inches

		Measured (bench)	Measured (on body)	Computed
L_o		34.5 uh		30.6 uh
Q	500 KHz	310	250	
	1000 KHz	430	200	755 Litz 213 solid
Bandwidth	500 KHz	1612	2000	
	1000 KHz	2496	5714	1325 Litz 4691 solid

MECHANICAL

Maximum length	74 inches
Maximum width	3.5 inches (winding)
Construction	winding skin-packed (polyethylene) to 6-inch wide strip of fibreglass cloth

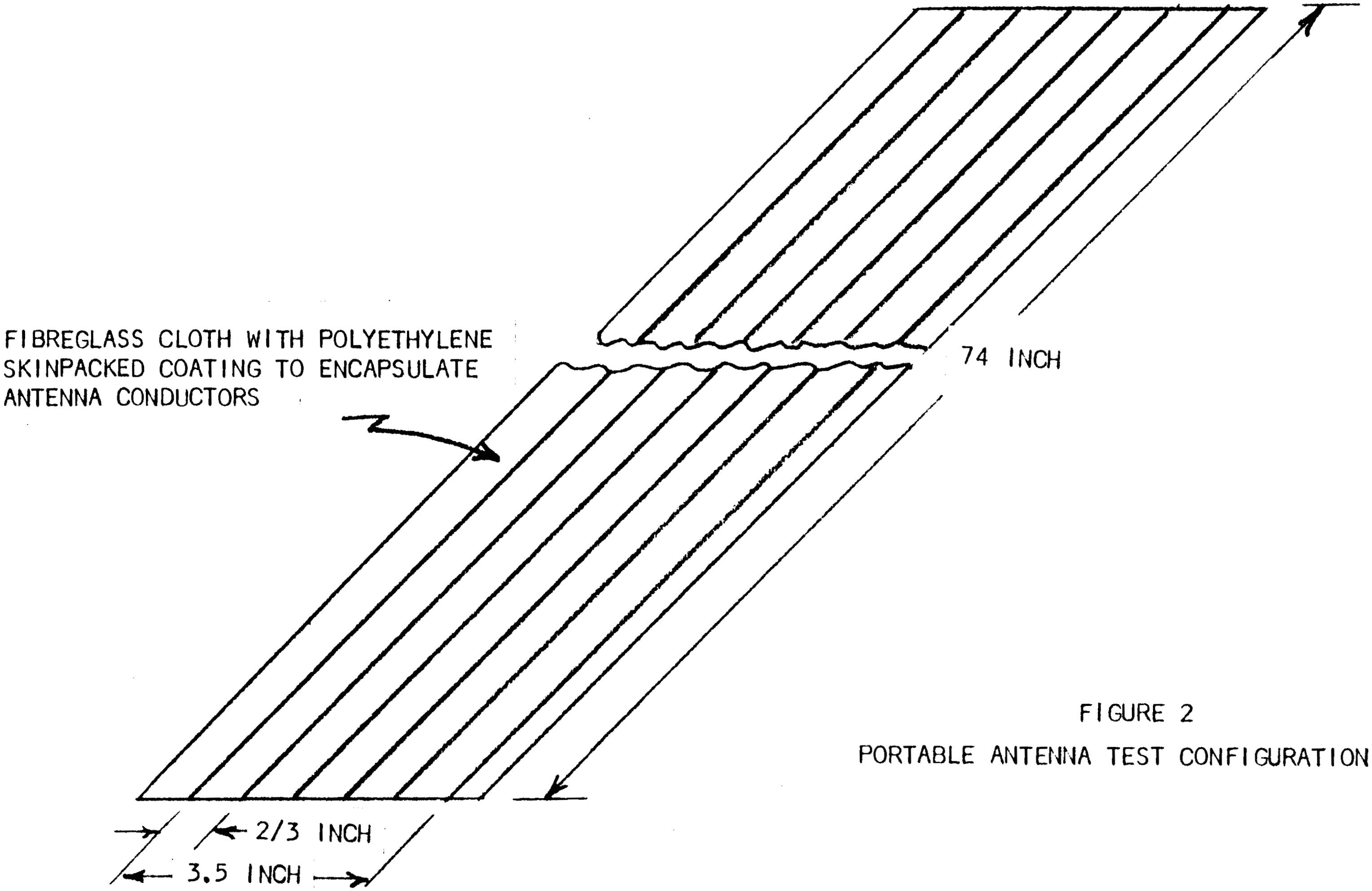


FIGURE 2

PORTABLE ANTENNA TEST CONFIGURATION

Six turns were used to provide compatability with existing designs for comparison purposes as the raw antenna data only was to be compared. The test design was not optimized in the sense previously discussed in this section. For a raw antenna, assuming a perfectly lossless matching basis, the highest NIA (and highest Q) occurs for 4-5 turns; so, 6 turns are adequate to enter the relatively flat quasi-turns-independent region in NIA at the low turns end of the region.

The comparative testing showed little if no advantage of the test design vs the smaller-in-crossection BuMines configuration when placed on the body (comparative Q's of 200 vs 160). There is a question of whether or not a final loaded Q of as great as 100 is feasible for portable antennas due to potential detuning variations.

There was substantial difference between the resonant frequency of all three antennas tuned on the bench compared with tuning on the body. For all three cases, the frequency shift (for the same tuning capacitance) varied from 20 KHz @ 500 KHz to about 50 KHz @ 1000 KHz. We know that tuning on the bench is not a realistic condition, however, and comparative tuning on several different bodies would have been better. Collins found, for an antenna Q of 44 @ 520 KHz, that careful tuning of their antenna in air (antenna suspended from the ceiling) did not differ significantly in frequency shift from tuning on a person's body. A truly optimized antenna may not permit this latitude, however.

As can be seen, considerably more work needs to be done to derive optimum portable antenna performance characteristics. The work accomplished on portable antenna design and analysis during this program has shown:

(1) there is probably no advantage in using antennas of large crossection (size of wire and wire spacing)

(2) there is probably no advantage in using Litz wire

(3) it would be very difficult to build an antenna with bandwidth of less than 6 KHz @ 1 MHz even if this low a bandwidth were proven to be feasible

(4) at least 5-6 turns are required on a portable antenna to enter the quasi-maximum NIA range.

To complete a design for a portable antenna, the following steps should be taken:

(1) determine the radio PA output source impedance level and the practical maximum drive current level

(2) determine the Q (equivalent added series resistance) which can be provided using high quality tuning components for a matching circuit implementable in the radio package

(3) determine the minimum allowable bandwidth from detuning and modulation considerations (12 KHz appears to be feasible from the previous Collins work)

(4) choose an antenna crossectional size including overall width and wire size

(5) use as many turns as possible while keeping within both the NIA-flat range and the constant power portion of the intrinsic safety curve(s)(this means trading off turns vs total equivalent series resistance in the PA-tuning circuit-antenna path)

(6) pad with additional current-limiting resistance to obtain the amplifier current limit and/or the minimum bandwidth

Note: The optimum design will probably be wire-resistance limited due to the added equivalent wire resistance caused by losses in the human body. Any padding will probably facilitate only intrinsicly safe operation and, if used, will result in some devrease in performance. The resulting design may still have an NIA comparable to a vehicular type design of the same size, however, as the impedance level will be lower than the 50 ohms dictated by use of coaxial cable connecting separated transmitter and antenna

3.0 TECHNICAL APPROACH

3.1 GENERAL DESCRIPTION

The departure point for this work is based on results obtained during the previously referenced Contract H0377013 (Wireless Communications for Trackless Haulage Vehicles). This work led to an antenna design algorithm for use in antenna parameter studies. Preliminary engineering model testing resulted in the definition of a vehicular antenna configuration and revealed several important results.

The antenna design algorithm will be delineated in the next subsection together with some new work which allows the incorporation of Litz wire. The results of this previous testing include:

(1) use of turns spaced as far apart as possible results in the lowest impedance, highest Q raw antenna configuration for a given number of turns

(2) a multi-turn winding may be enclosed within an electrostatic shield with only a single circumferential gap and still achieve the multi-turn effect

(3) If the turns are symmetrically located within the electrostatic shield and balanced-fed, then the shield has a negligible effect on antenna inductance

(4) If the electrostatic shield is constructed of non-ferrous metal and if the antenna winding is displaced slightly from a ferrous mounting surface, then the winding resistance is comparable to that in absence of the shield and the mounting surface

(5) If the individual turns are connected so that adjacent electrical turns are not physically side-by-side, then the distributed winding capacitance is minimized and the winding resonant frequency is maximized

These results led to defining the vehicular loop configuration illustrated in Section 3.2.4 where the electrostatic shield provides a rigid rugged enclosure suited for use on mine vehicles. The engineering model tested during the previous program employed 7 turns within a 3/4-inch ID shield. Analysis at that time suggested that up to 13 turns within a 1-inch ID (1 1/4-inch OD) shield would probably work better. The mounting concept for the vehicular antenna was that of using a magnetically mountable frame for the antenna.

The results lended further insight toward the use of parallel spaced turns arranged in a flat strip for portable antenna use.

3.2 THEORETICAL BASELINE

3.2.1 ANTENNA DESIGN ALGORITHM

During the Wireless Communication for Trackless Haulage Vehicles program (USBM Contract with Collins, H0377013) an algorithm was developed to compute the impedance and NIA of multi-turn loop antennas. Although the algorithm was originally intended for use with spaced turns in a single-layer solenoid configuration (suited for man-carried antenna analysis), it was found to be applicable for use with spaced turns in a circular configuration enclosed by an electrostatic shield (suited for vehicular antenna analysis) providing that the winding configuration was chosen for minimum distributed capacitance and providing that the winding was balanced-fed with the electrostatic shield being placed at ground potential.

The algorithm was programmed for the HP-67 calculator so that parametric antenna data could be computed. The algorithm is given again in this subsection.

The antenna inductance, L , is given by

$$L = \frac{L_o}{1 - \left(\frac{f}{f_r}\right)^2}$$

where, L_o is the low frequency inductance given by

$$L_o = 0.02339\, n^2 \left[(s_1 + s_2) \log_{10} \frac{2 s_1 s_2}{nD} - s_1 \log_{10} (s_1 + g) - s_2 \log_{10} (s_2 + g) \right] + 0.01016\, n^2 \left[2g - \frac{(s_1 + s_2)}{2} \right]$$

microhenries

s_1, s_2 are the side lengths in inches

g is the diagonal in inches

n is the number of turns

D is the wire separation in inches

f_r is the self resonant frequency given by

$$f_r = \frac{1}{2\pi\sqrt{L_o C}}$$

C is the distributed capacitance of one turn and is

$$C = \frac{\ell}{\cosh^{-1}\left(\frac{D_1}{d}\right)(36 \times 10^9)}$$

ℓ is the length of one turn in meters
d is the wire diameter in inches
D_1 is the effective wire separation in inches
D_1 is greater than D by about 17%

The antenna resistance, R , is given by

$$R = \frac{R_o}{\left[1 - \left(\frac{f}{f_r}\right)^2\right]^2}$$

where, for copper,

R_o is the low-frequency resistance given by

$$R_o = \frac{0.831}{d}\left[1 + 25.67\left(\frac{d}{D/\sqrt{\epsilon_r}}\right)^2\right]\sqrt{f}\ \ell_t \times 10^{-7} \text{ ohms}$$

$\ell_t = n\,\ell$ in inches

The NIA product for matched conditions into 50 ohms is given by

$$NIA = NA\ I_o\sqrt{\frac{50}{R}}$$

where, I_0 is the input current into 50 ohms
(exp. 0.632 amps for 20 watts)

The antenna resistance is that for solid or stranded copper wire. The use of Litz wire has been considered during this program to reduce the wire resistance component of the total antenna series resistance including losses external to the winding. The characteristics of Litz wire are considered in the next subsection.

3.2.2. LITZ VS SOLID WIRE COMPARISONS

Litz wire consists of a number of separately insulated strands woven or bunched together so that each strand tends to take all possible positions in the crossection of the entire conductor. The purpose of Litz wire is to reduce skin-effect losses by distributing the flow of radio frequency current more uniformly over the wire crossection.

The use of Litz wire may or may not have a practical advantage over normal solid or stranded wire for mf antenna designs, depending on the overall loss resistance in the complete matched antenna and the magnitude of the component of this loss resistance attributable to wire resistance. The objective of using Litz wire assumes that the wire resistance component will be significant and therefore (in at least the prototype development) is to minimize the dependancy of this total series antenna circuit loss resistance on the frequency dependent wire resistance component. This offers the possibility of obtaining near constant antenna bandwidth over a range of frequencies. This bandwidth is, in principle, obtained by adding a fixed non-frequency-dependent resistance at the antenna terminals.

The resistance of Litz wire is frequency dependent with the resistance being a function of the overall wire diameter, d, the strand diameter, d_s, and the wire-wire spacing, D. A low frequencies, the use of Litz wire results in a significant reduction in the low-frequency ac resistance, R_o. At higher frequencies, typically 1 - 3 MHz, the advantage disappears and Litz wire can actually have a greater resistance than solid wire. This latter effect is primarily a function of the strand diameter, d_s, and operation at higher frequencies requires a smaller strand diameter and, hence, more strands for a fixed desired wire diameter.

Terman gives an expression for the ratio of R_o to R_{dc} for Litz wire. Fo antenna design, we are most interested in the ratio R_{oLITZ} / R_{oSOLID} so that the R_{oLITZ} can be used with the loop antenna design algorithm. The author has never seen curves of this ratio plotted in the literature, so these curves as applicable to antenna design were developed as part of this program and should serve as a standard reference for the future.

The appropriate formulations for R_{oLITZ} / R_{dc} and R_{oSOLID} / R_{dc} will be derived and then ratioed to obtain the above measure of Litz wire advantage for antenna design.

For a solid wire,

$$R_{oSOLID} / R_{dc} = H + A \left(\frac{d}{D} \right)^2 G$$

where A for multilayered coils = $\frac{1}{4}\left(\frac{Kbm}{D} \right)^2$

with Kb/D = 5 typically and with m $\cong$ 3 layers typically, so that A = $\frac{1}{4}(15)^2$ = 56.25

G is a proximity factor for multilayer coils varying nearly linearly with x ($x = 0.1087\, d \sqrt{f}$ for copper) for larger values of x so that G is approximately equal to 0.0439 d f.

H is the ratio by which R_{dc} of an isolated wire is multiplied to give R_{ac} and = approximately $0.0962\ d\sqrt{f}$ for copper.

therefore,

$$R_{oSOLID} / R_{dc} = 0.092\ d\sqrt{f} + 2.469\ d\sqrt{f}\ \left(\frac{d}{D}\right)^2$$

For Litz wire,

$$R_{oLITZ} / R_{dc} = 1 + n^2\ G\ \left(\frac{d_s}{d}\right)^2 \left[2 + A\ \left(\frac{d}{D}\right)^2\right]$$

where, G = approx. $x^4/64 = 0.878 \times 10^{-4}\ d_s^4\ f^2$

$$R_{oLITZ} / R_{dc} = 1 + 0.878 \times 10^{-4}\ \left(\frac{d_s^3\ n\ f}{d}\right)^2 \left[2 + 56.25\ \left(\frac{d}{D}\right)^2\right]$$

The ratio of these quantities has been evaluated for a range of parameters useful in antenna design and the results are given as Figures 3 through 5 .

FIGURE 3

RESISTANCE OF LITZ WIRE COMPARED TO SOLID WIRE FOR FIXED OVERALL DIAMETER AND STRAND DIAMETER

VS WIRE-WIRE SPACING

1700/44 LITZ d_s = 0.002 IN
d = 0.115 IN

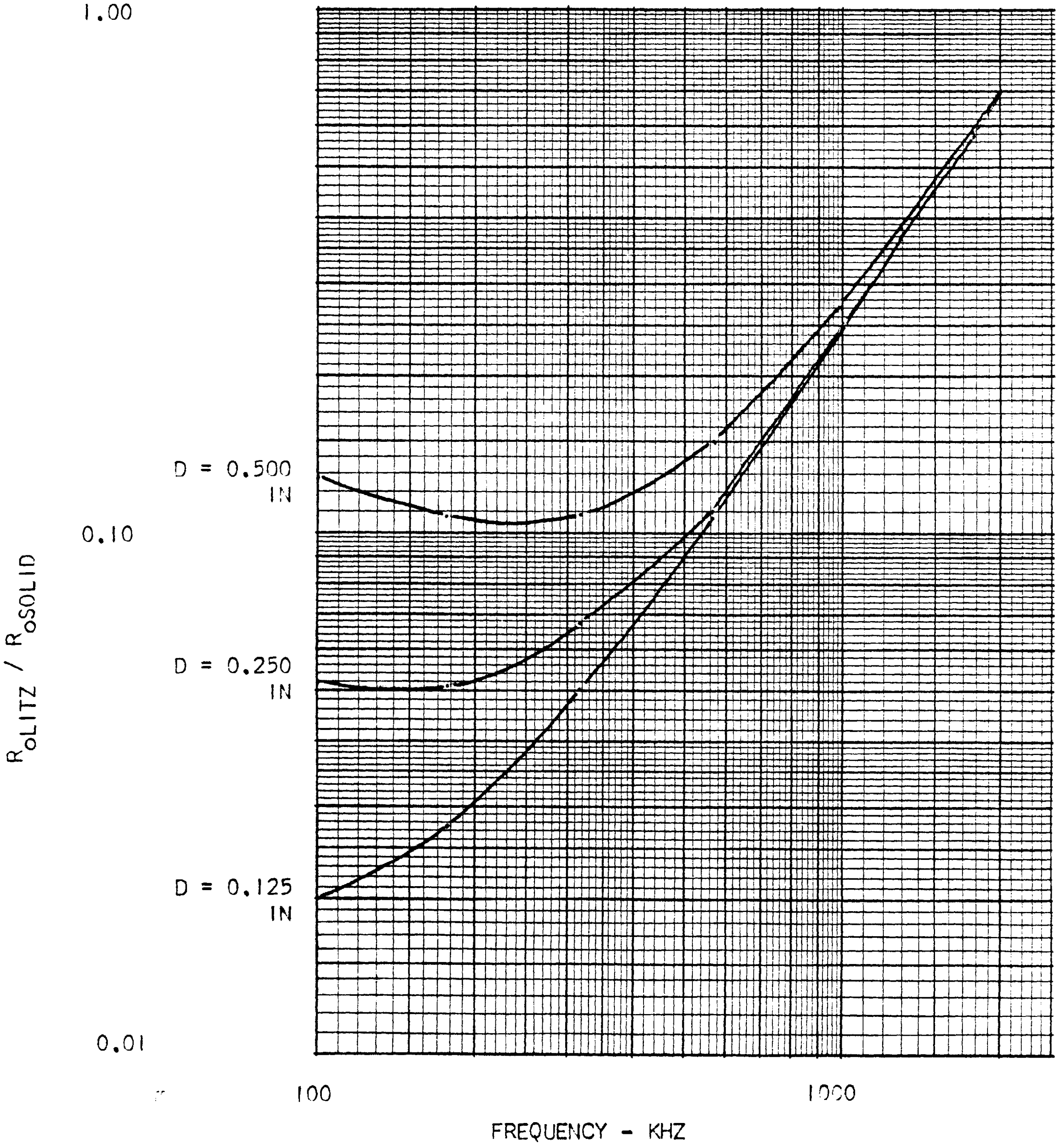


FIGURE 4

RESISTANCE OF LITZ WIRE COMPARED TO SOLID WIRE FOR FIXED STRAND DIAMETER AND WIRE-WIRE SPACING VS OVERALL WIRE DIAMETER

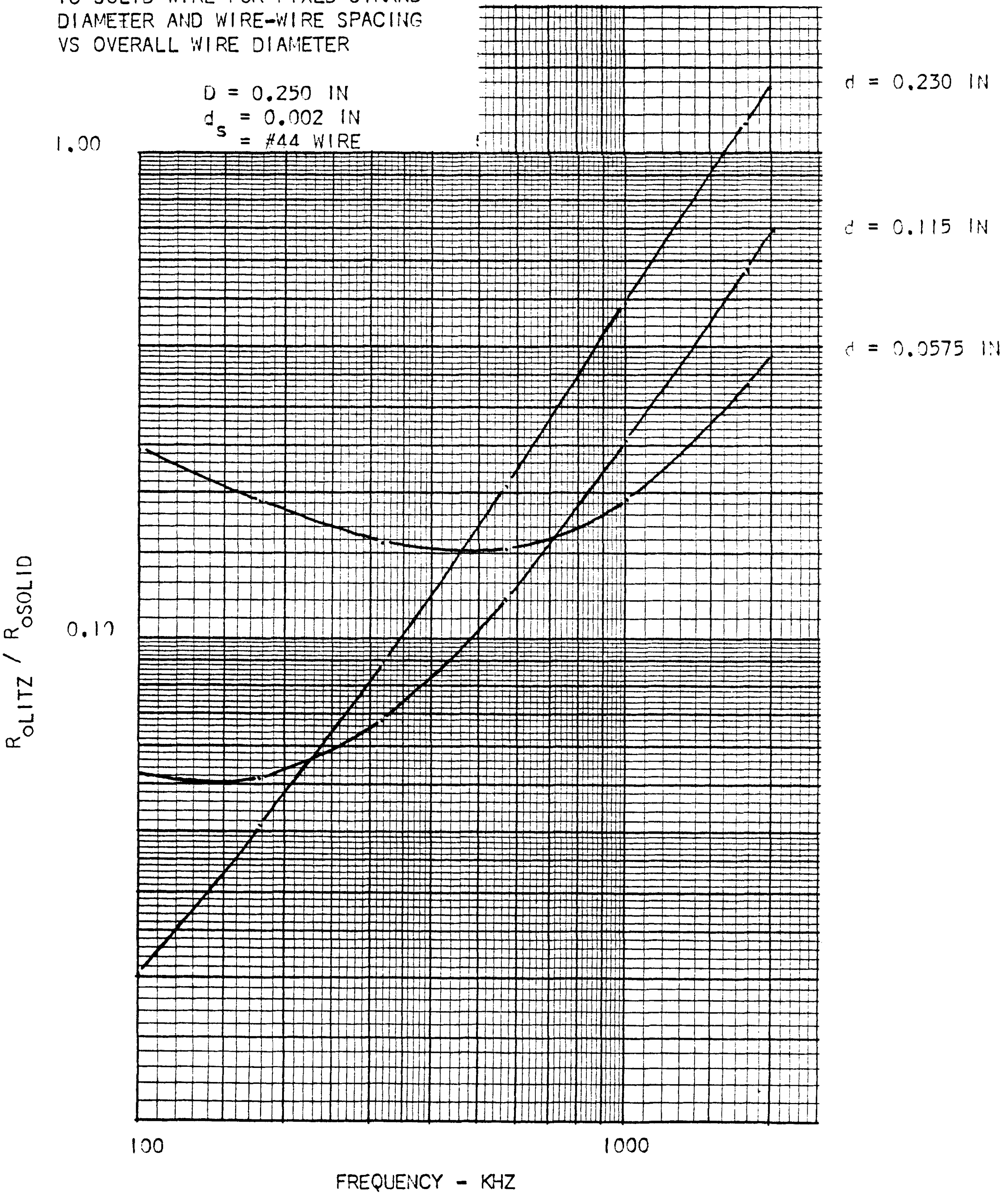
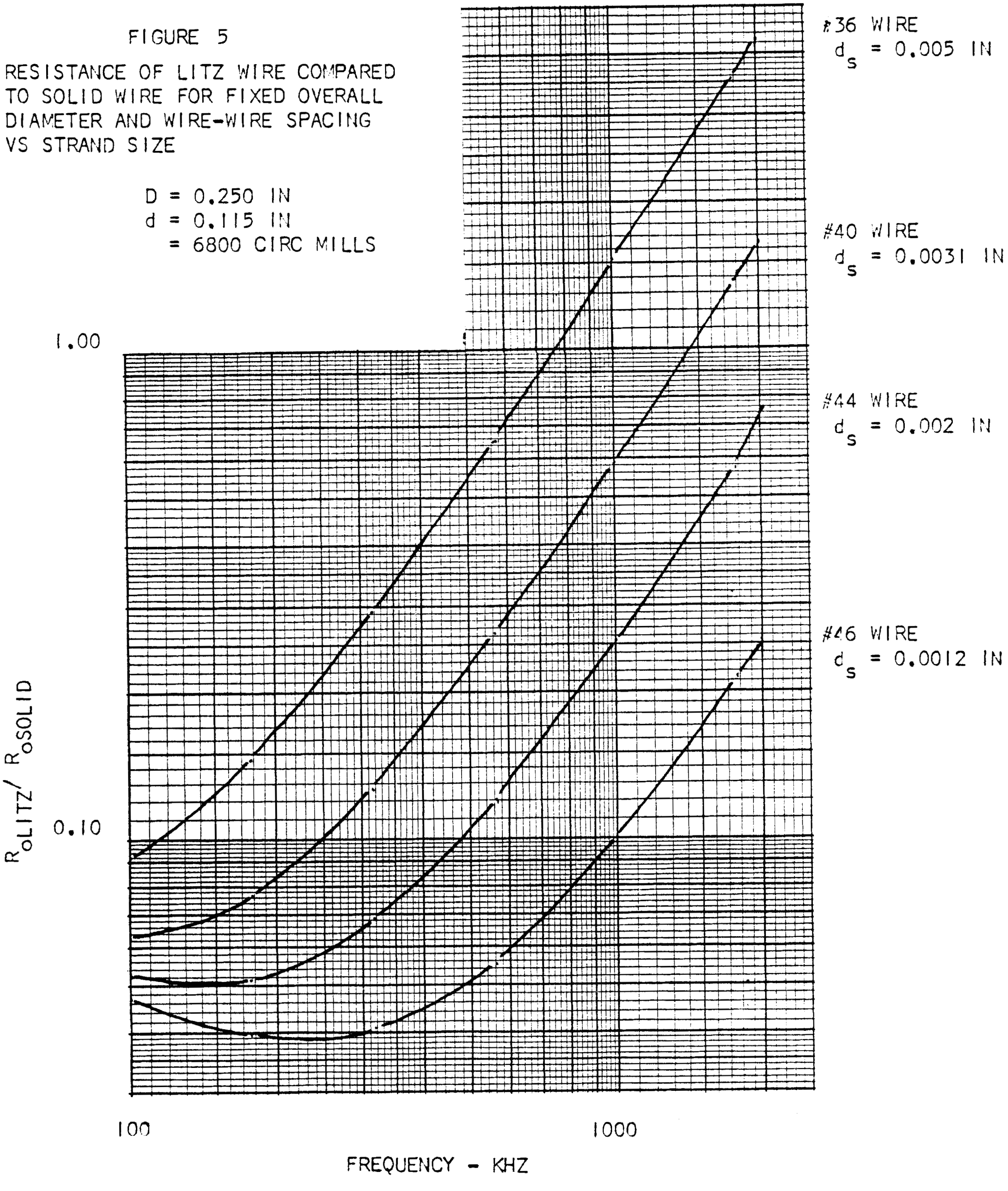


FIGURE 5

RESISTANCE OF LITZ WIRE COMPARED TO SOLID WIRE FOR FIXED OVERALL DIAMETER AND WIRE-WIRE SPACING VS STRAND SIZE



3.2.3 INTRINSIC SAFETY PARAMETERS

Intrinsic safety requirements are geared toward preventing potentially dangerous dc sources from producing arcs which might explode a methane-air mixture under fault conditions in coal mines. The curves for minimum voltage-current combinations, minimum ignition current in inductive circuits, and minimum ignition voltage in capacitive circuits apply strictly to dc excitation of circuits. The ac excitation of antenna circuits at radio frequencies are not explicitly covered by the curves. The proceedure for inductive circuit protection now being applied involves isolating the antenna circuit from potential dc sources through the use of blocking capacitors. The requirements for these blocking capacitors come from UL-913 whereby two capacitors are placed in series and then tested for voltage breakdown with an ac voltage level equal to twice the working (potential fault) voltage + 1000 volts rms.

It is reasonable to expect that arcs from ac sources at radio frequencies under fault conditions could explode a methane-air mixture in a circuit not intrinsicly safe at dc. It is also reasonable to assert that dc circuit performance represents the worst case; thus, a circuit which is "dc intrinsically safe" will also be "ac intrinsically safe".

It is probably to the designer's advantage to take any steps toward making an antenna "dc intrinsically safe", over and above any blocking isolation, if this can be accomplished without serious performance loss. This could be termed the "inherent safety factor" of the antenna.

Toward evaluating ac intrinsic safety, it may be worthwhile to define operating power levels for which the antenna would be intrinsicly safe if the dc and ac parameters were the same and the dc curves could be applied.

It is possible to at least partially protect a loop antenna without loss of performance so as to achieve some inherent safety. This is possible because the NIA of a loop antenna of restricted dimensions is relatively constant over a range of numbers of turns and because there are ac losses in the antenna other than those encountered in the wire resistance. Specifically:

(1) impedance level; the antenna low-frequency wire resistance should be as high as is practical without reducing NIA in order to minimize the peak current which could flow in the circuit. This is accomplished by using as many turns as possible.

(2) added series loss; the antenna matching circuitry losses will produce an equivalent series antenna loss resistance in addition to the wire resistance. A lumped current-limiting resistor of value comparable to the above loss resistance can be added without reducing the NIA significantly. The lumped resistance will retain its value at dc whereas the wire resistance will not.

> It is better, in designing to a fixed allowable wire resistance, to use Litz wire and then add a lumped current-limiting resistor than to use solid wire or stranded wire having the same resistance as the Litz plus the lumped resistor.

Assuming the dc curves apply, the current in the loop as a function of input power is given by

$$I^2 = \frac{P}{2\pi L(BW)} .$$

In terms of stored energy,

$$\tfrac{1}{2}LI^2 = \frac{P}{4\pi(BW)}$$

where, P is the input power
L is the inductance
(BW) is the 3 dB bandwidth

so that for a fixed maximum energy level, the allowable bandwidth is a function only of the input power. If for a fixed input power and bandwidth the current is to be minimized, then the current is inversely proportional to inductance, so the inductance should be as large as possible while still maintaining the bandwidth.

The minimum ignition current curve is given for 24 volts and essentially plots a constant energy level, which determines the bandwidth power relationship for that voltage level. For other voltage levels (as defined on the voltage-current curve), the constant energy level varies. If the antenna parameters are fixed, as in any particular design, then the power cannot be independent of energy level and must follow the voltage-current curve.

The inductance of the vehicular antenna @ 1 MHz will be shown in the next section to be approximately 190 uh . To illustrate possible power-bandwidth limits for "ac intrinsic safety", calculations were made assuming

(1) a constant energy of 0.5 millijoule
(2) energy-power as defined from voltage-current curve and antenna parameters
(3) inherent intrinsic safety provided by 5 and 10 ohm current-limiting resistors

The results of these calculations are given in Figure 6 . This figure shows the voltage-current derived condition to be the most stringent in restricting the minimum bandwidth for higher power levels for a 50 ohm matched antenna. Using this condition as the basis, a 10-ohm current limiting resistor (for example) provides inherent protection up to a power level of about 11 watts.

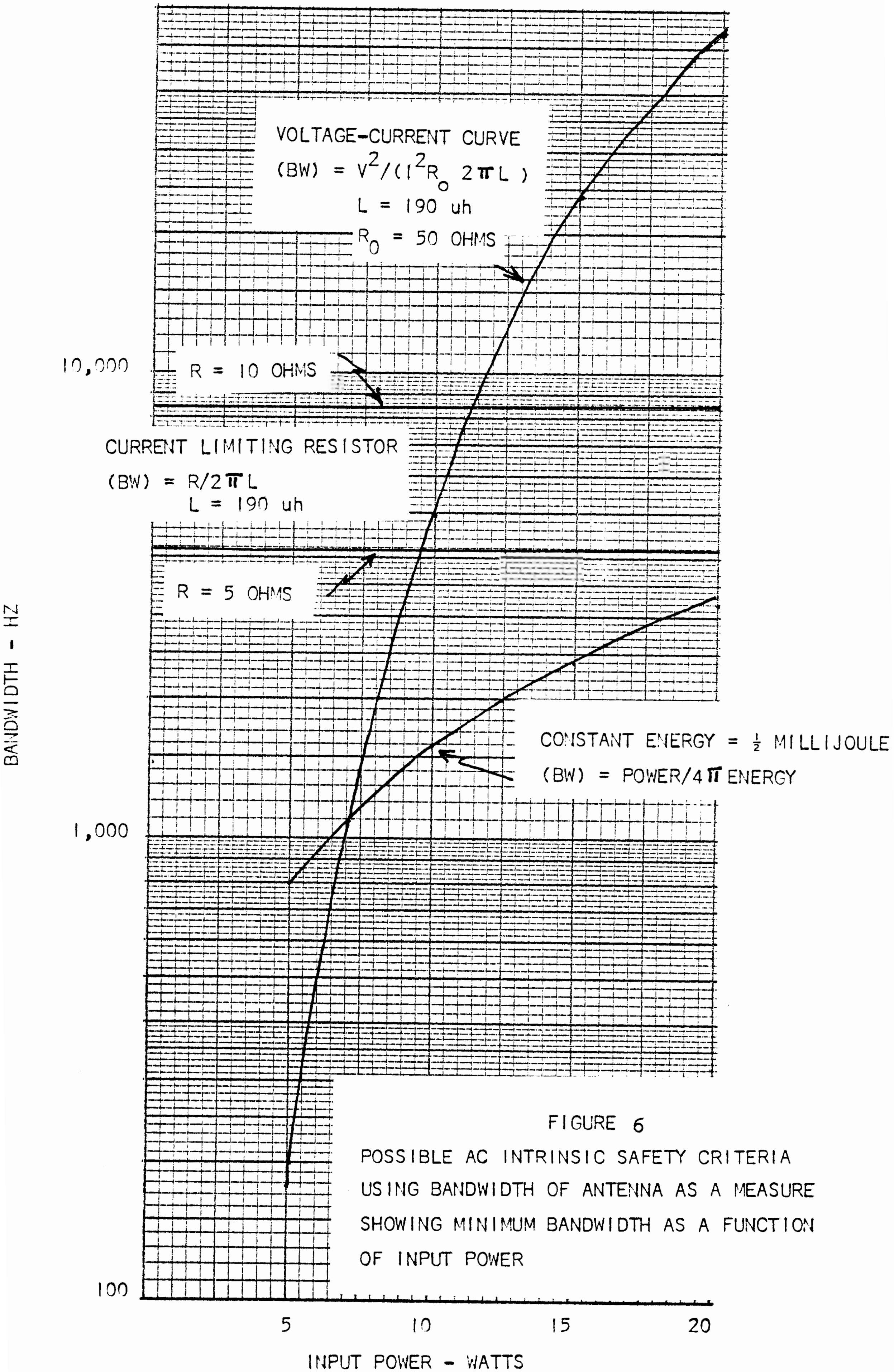


FIGURE 6

POSSIBLE AC INTRINSIC SAFETY CRITERIA USING BANDWIDTH OF ANTENNA AS A MEASURE SHOWING MINIMUM BANDWIDTH AS A FUNCTION OF INPUT POWER

3.2.4 ANTENNA WINDING CONFIGURATION CONSIDERATIONS

The generic configuration of the vehicular antenna winding is illustrated in Figure 7 . This shows both the winding and the electrostatic shield. The winding crossection has two important aspects; the wire connection arrangement and the symmetry of the circularly arranged spaced turns for balanced excitation. The overall winding acts as a near-perfect transformer, transforming the current in each winding turn into current flowing on the outside of the electrostatic shield considered as a single turn when transmitting. The net current flowing in the spaced turns excites a current flowing on the inside of the electrostatic shield which flows "around the corner" at the feed gap and on the outside of the shield as a single turn. This is truly low-impedance current coupling. On receiving, the converse happens; however, the open circuit voltage induced across the gap due to an incident electric field does not excite current flow in the internal windings.

The connection of the winding turns in relation to one another is made is a manner which distributes the turn-turn capacitance so that no adjacent turns are connected together consecutively and the adjacent turn is several turns away capacitively. Also, the entire winding potential is never across two closely spaced turns but is across turns spaced at least a third of the way around the circular arrangement. The connection arrangement shown in the figure is the one used for the prototype vehicular antennas to be described in the next section. The balance is illustrated by the + and - signs attached to the turns. For balanced excitation, there are as many + turns as - turns with symmetric potential so the distributed differential mode coupling to the inside of the electrostatic shield as appear across the winding concels out. There is, thus, no increase in distributed capacitance due to the electrostatic shield.

The generic configuration of the man-carried antenna is shown in Figure 2 . This is a flat spaced turn antenna of fixed total width so that an increase in the number of turns decreases the turn-turn spacing. Several connection arrangements of the winding turns are possible. As a final matched and evaluated antenna was not delivered to the Bureau for the man-carried configuration, no preferred configuration arrangement for the turns has been established.

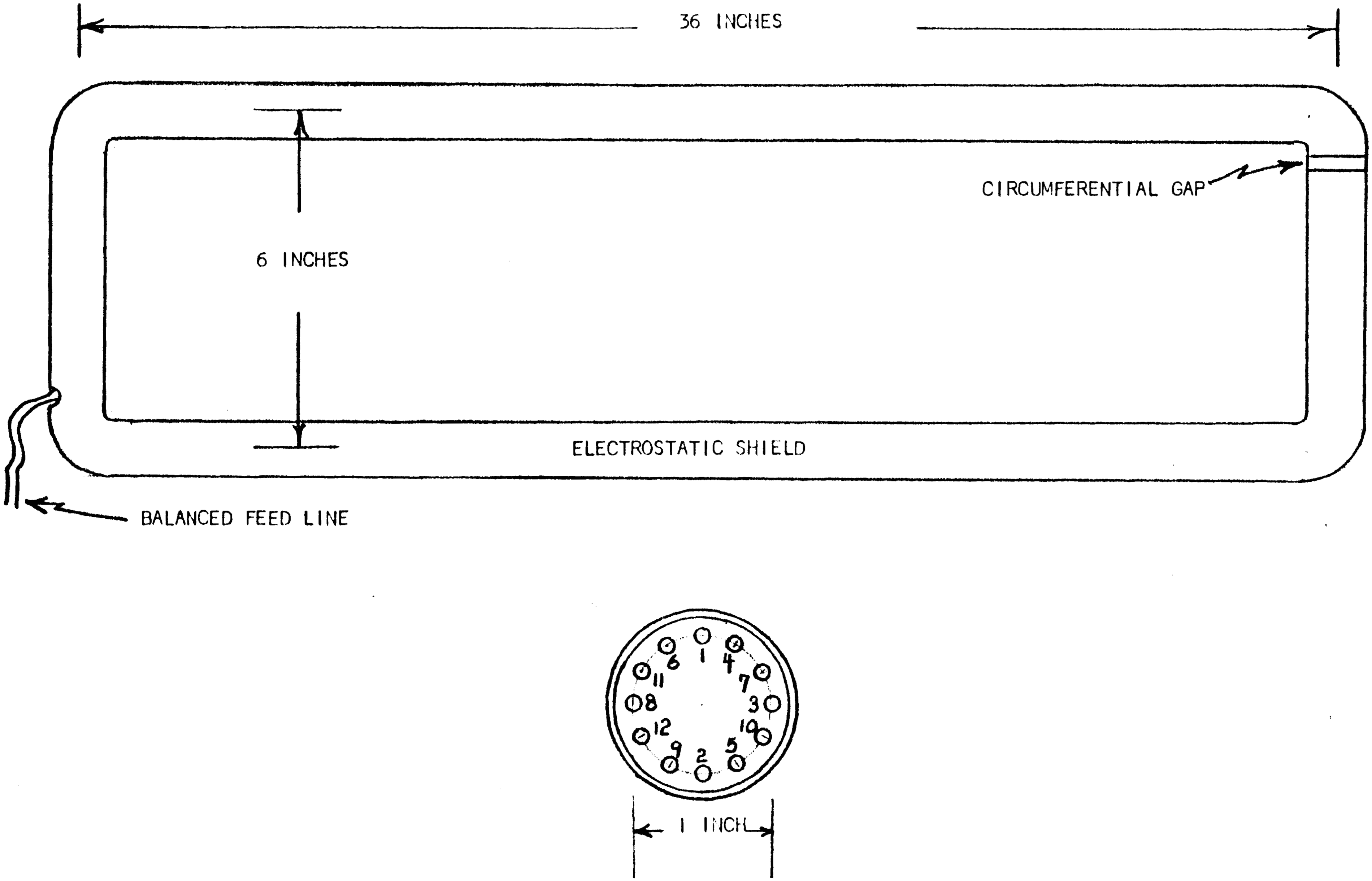


FIGURE 7

WINDING AND WIRING CONFIGURATION FOR THE VEHICULAR ANTENNA PROTOTYPE SHOWING THE CONNECTION ARRANGEMENT OF TURNS TO MINIMIZE DISTRIBUTED CAPACITANCE

3.3 SELECTION OF DESIGN PARAMETERS

This section covers the use of the antenna design algorithm to investigate parameters for the vehicular antenna, with the subsequent selection of a particular set of parameters for the prototypes.

The first winding parameter to be selected was the wire size within the constraint of providing a variable number of turns to fit within a nominal $1\frac{1}{2}$-inch copper electrostatic shield (ID = 1.265 inch) allowing for a small spacing between the wires and the inside wall of the shield tube. The effective maximum diameter of the antenna winding crossection, center-center, was chosen to be 1-inch. The tubing size itself was chosen as a compromise to provide a reasonable amount of antenna area for a maximum antenna height of about 8 inches when in the vertical position. The result was the selection of 6-inches center-center in vertical height between the winding crossectional centers with a standard tubing diameter of $1\frac{1}{2}$ inches. Based on the Trackless Haulage engineering prototype data, the number of turns was expected to be less than 20 with a guess of roughly 12 turns at maximum diameter as being nominal. The wire-wire spacing range was bounded to be within 0.125 - 0.50 inches; governed by the number of equally spaced turns in circumference around a 1-inch circle.

With the nominal spacing range chosen, the wire size range was bounded to lie roughly between $\frac{1}{8}$-inch as a maximum and a quarter of that as the minimum. Parametric data for the ratio of the resistance of Litz wire to solid wire was run for a range of Litz strand diameters; keeping the resistance ratio less than unity up to at least 1 MHz. The bounding range of strand diameters was placed to be from #46 to #36 wire. This parametric data is given in the previous subsection as Figures 3, 4, and 5. The wire size was chosen as being 0.115-inch in diameter corresponding to 6800 circular mils and consisting of 1700 strands of #44 wire.

The remaining major antenna parameters to be chosen were the antenna length and the number of turns (which also dictates the wire-wire spacing). These parameters were investiagted in terms of antenna NIA and bandwidth, assuming 1 amp into a 50 ohm antenna as a reference (50 watts). The bandwidth range for bounding purposes was taken to lie between 3 KHz as an absolute minimum for SSB modulation and 12 KHz as a minimum for FM modulation. It was recognized that these bandwidths could be used for analysis evaluation purposes even though the achievable "loaded" bandwidth in a practical design was, as yet, unknown.

Parametric data was run over a range of turns from 6 to 20 for antenna lenths from 2 to 4 feet.at a frequency of 1000 KHz (the optimum frequency as determined from the previous mf measurements for coupling into existing mine wiring). This data is shown plotted in Figures 8 and 9. These curves clearly show that NIA is fairly constant over a range of turns for a constrained antenna crossection (wire-wire spacing decreases linearly with increase in turns) and then rapidly drops off as the antenna resonant frequency is approached. At this point in the analysis, an antenna length of 3 feet was chosen.

Figures 8 and also show bandwidth conditions for the raw antenna. For the 3-foot antenna, the use of 12 turns (for example) provides just over a 3 KHz bandwidth for Litz wire compared to a 12 KHz bandwidth for solid wire. A calculation was made to determine if the NIA were higher for a 12 KHz bandwidth antenna limited by natural wire resistance (Litz) or limited by fixed resistance padding of the above lower bandwidth design. For this calculation, to increase the natural bandwidth to 12 KHz, the nominal 1-inch diameter of the spaced turns winding was decreased to $\frac{1}{2}$-inch with the nominal wire-wire spacing decreasing from 0.250 inch to 0.125 inch. Figure 9 shows that the padded NIA is always higher.

Recognizing the need to use as many turns as possible to keep the impedance level high in order to counteract losses in the antenna matching circuitry, the number of turns was chosen to be 12. This is the number of turns for which a 3-foot antenna and a 4-foot antenna deliver equal performance.

With these parameters chosen, NIA and bandwidth for the raw antenna were computed as a function of frequency from 100 KHz to 2000 KHz. These results are given in Figures 11 and 12. Figure 11 shows the effect of using fixed resistance padding to achieve the bounding minimum bandwidths of 3 and 12 KHz. Using this padding, the NIA is seen to be essentially frequency independent. This is an inherent property of an inductive circuit.

These raw (unmatched) antenna results will serve as a basis of comparison for the prototype performance actually achieved as discussed in Section 4.0.

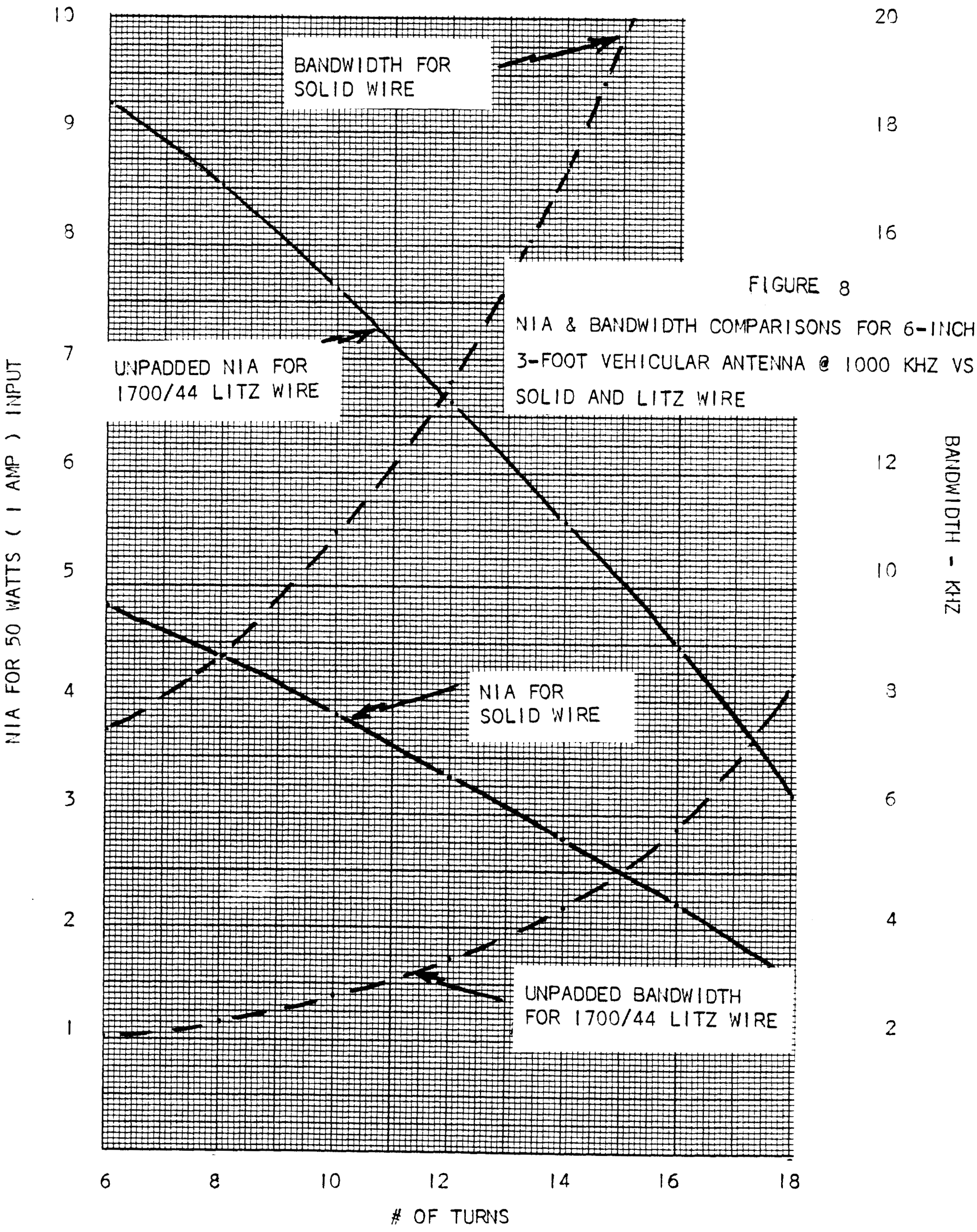


FIGURE 8

NIA & BANDWIDTH COMPARISONS FOR 6-INCH BY 3-FOOT VEHICULAR ANTENNA @ 1000 KHZ VS SOLID AND LITZ WIRE

FIGURE 9

NIA FOR VEHICULAR ANTENNAS 6-INCHES HIGH VS LENGTH AND NUMBER OF TURNS FOR 1700/44 LITZ WIRE FOR 3 KHZ MINIMUM BANDWIDTH @ 1000 KHZ AND BELOW - OPTIMUM FOR 1¼ INCH ELECTRO STATIC SHIELD

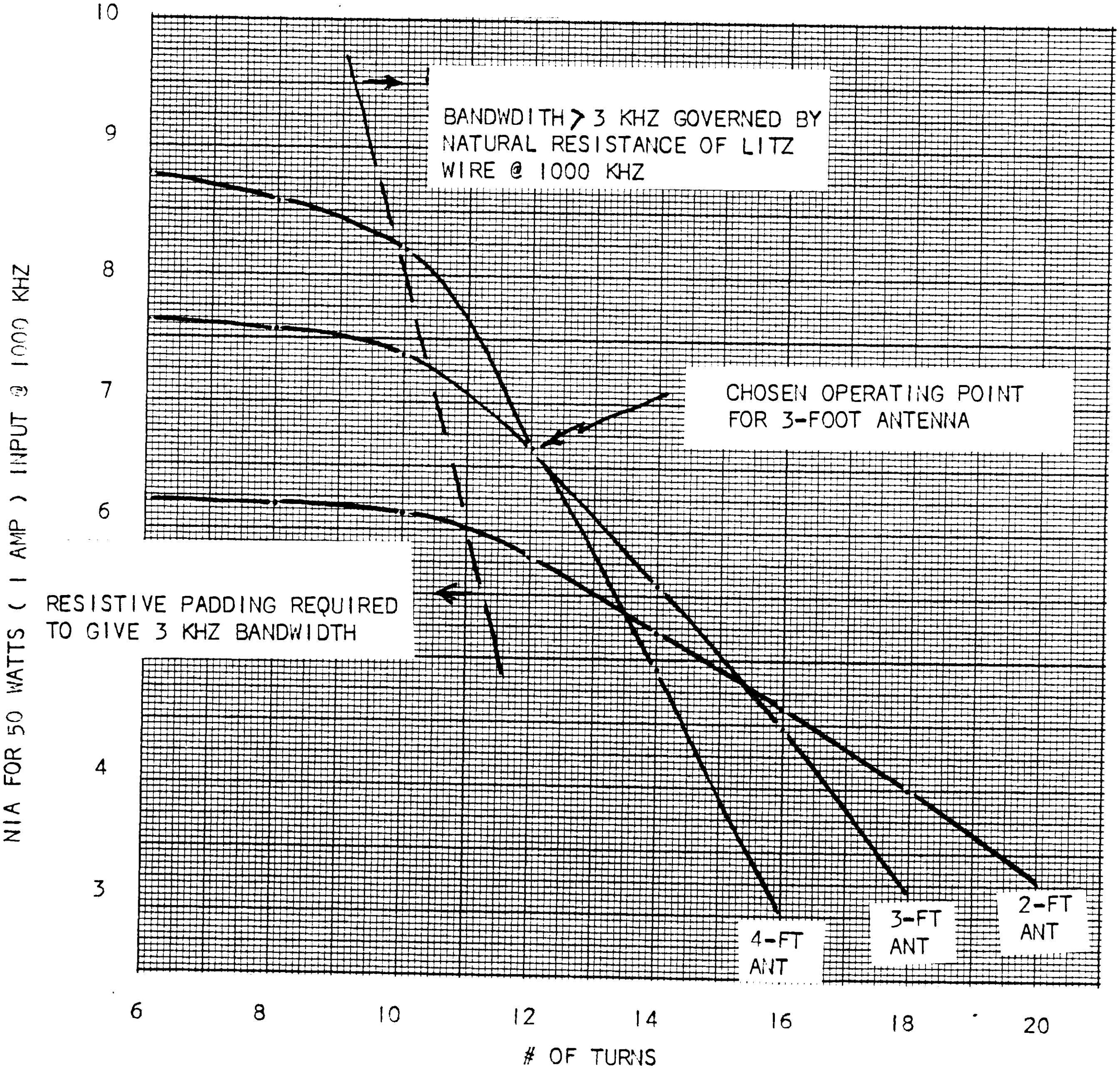


FIGURE 10

NIA COMPARISON FOR 6-INCH BY 3-FOOT VEHICULAR ANTENNA DESIGNS FOR 1700/44 LITZ WIRE FOR 12 KHZ MINIMUM BANDWIDTH @ 1000 KHZ AND BELOW - OPTIMIZED FOR 1¼ INCH ELECTROSTATIC SHIELD

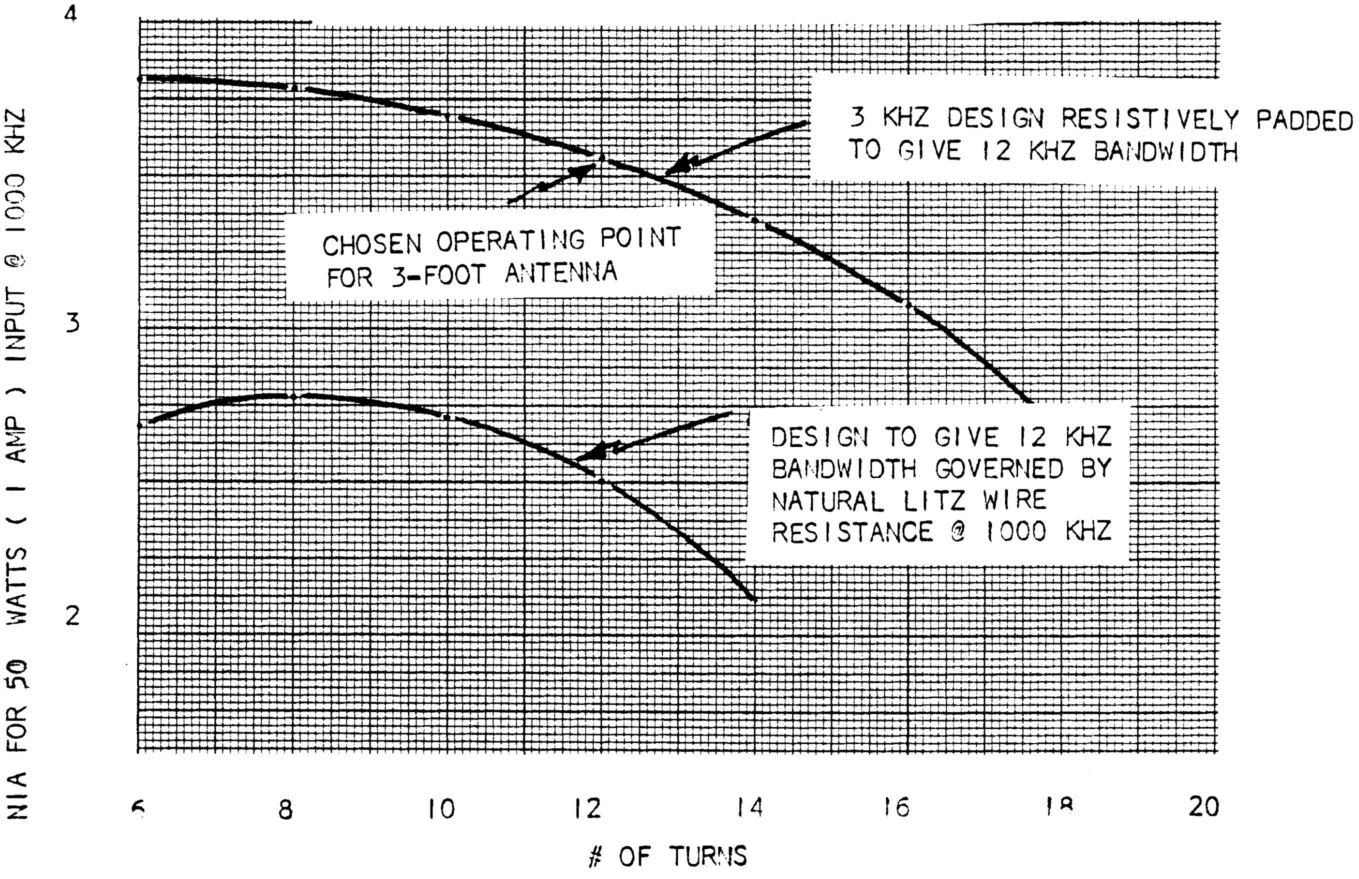


FIGURE 11

NIA VS FREQUENCY FOR 6-INCH BY 3-FOOT VEHICULAR ANTENNA OF 12 TURNS IN A 1¼ INCH ELECTROSTATIC SHIELD WITH 1700/44 LITZ WIRE

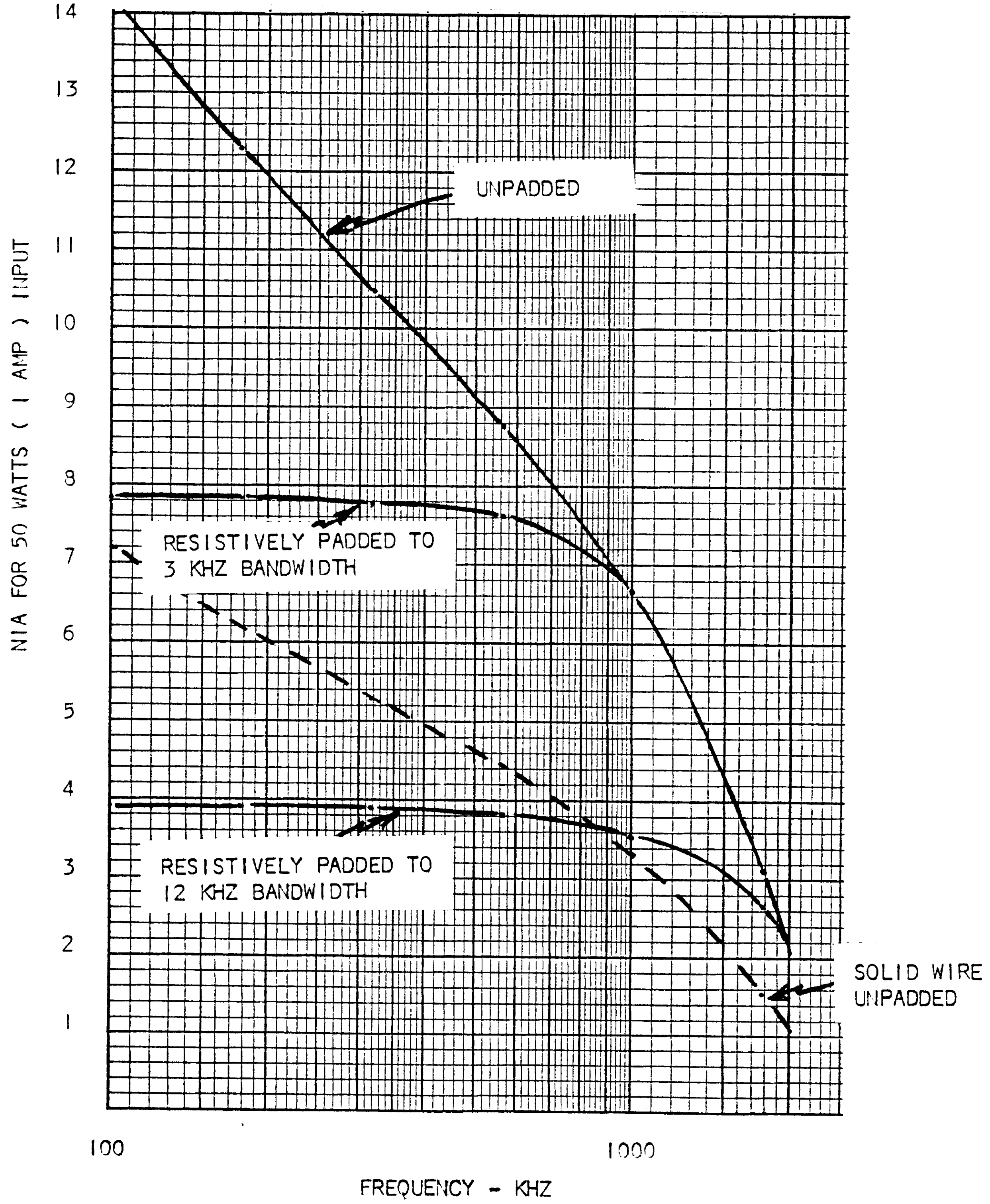
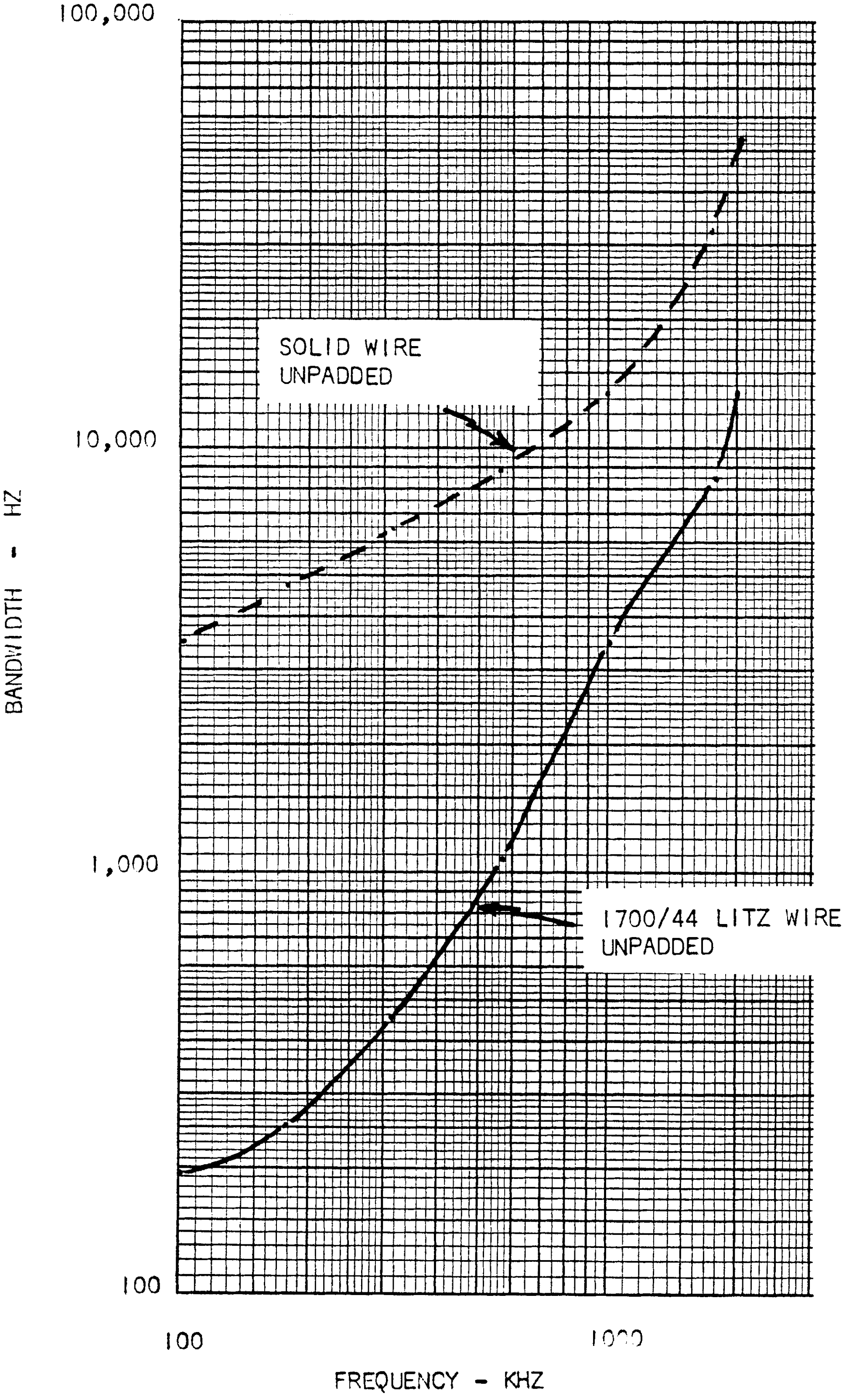


FIGURE 12

UNPADDED BANDWIDTH VS FREQUENCY FOR 6-INCH BY 3-FOOT VEHICULAR ANTENNA OF 12 TURNS IN 1¼ INCH ELECTROSTATIC SHIELD - WITH AND WITHOUT LITZ WIRE



4.0 VEHICULAR ANTENNA PERFORMANCE

This section presents selected design details of the vehicular antenna prototypes and measured performance characteristics. Conclusions are also drawn between the measured results obtained with the prototypes and increased performance achievable with additional design effort in the impedance matching area.

Two vehicular antenna prototypes were built. Originally, these prototypes were to differ in bandwidth; one to be as near 3 KHz as possible and the other to be as near 12 KHz as possible. Later in the program, it was decided to build them in an essentially identical manner' tuning them to different frequencies of nominally 520 and 920 KHz.

These antennas were wound with the connection arrangement illustrated in Figure 7. The turns were laid out and attached to a thin piece of styrofoam as individual wires (broken between turns 1 and 4) then folded into a circle and pulled through the tubing. The connection arrangement provided for a slight overlap between turns 6&1 and 4&7 when pulled through "corners" of the tubing having restricted diameter. The winding turns were then connected together in the junction box attached to the tuning (see Figure 1). Unfortunately, one of the antennas was inadvertently connected in a reverse arrangement to that shown in Figure 7 which resulted in higher distributed capacitance. It was decided to make this the 520 KHz unit where the lower frequency minimized the effect of this inadvertent mistake. The raw antenna reactance is shown plotted in Figure 13 along with the computed reactance.

The antenna matching was accomplished using a balanced capacitive L-section; transforming the antenna impedance to 200 ohms balanced. A ferrite 4:1 balun transformer (provided by the Bureau) was used to down-transform from 200 ohms balanced to 50 ohms unbalanced for the coaxial input. The capacitive L-section schematics are given in Figure 14. The ferrite balun is illustrated in Figure 15. The L-section components were braedboarded on a small piece of printed circuit board. The L-section components were chosen from those locally available. The limiting component type from a power handling standpoint was the trimmer capacitor. These are referred to in the figures as air variable; actually, they were of the layered type having strips of mica between metal plates and air. Increasing screw pressure provides increased capacitance with decreased spacing between the layers. The power handling properties could have been improved if vaccuum variables had been available. The L-sections provide for variable tuning via one of the series trimmer capacitors which is outboarded and available for external adjustment by removing the screw cap on the top junction box port. Wider adjustment range is possible by opening the tuning enclosure and adjusting the other series and shunt trimmers. No special provisions were made in the prototypes for intrinsic safety.

Tuning curves for the prototype antennas were obtained for both dielectric and ferrous metal surface mountings. Also, spot frequency shift data was gathered at the nominal tune frequencies for each antenna when the loop orientation was changed from vertical to the 45-degree position. The tuning curves are presented as Figure 16 and 17. The detuning data and the "loaded antenna bandwidths of 14 KHz @ 520 KHz and 20 KHz @ 920 KHz are summarized in Section 2.1.2.

The analysis of the prototype antenna performance is presented in Table I where the various antenna losses are partitioned. The prototype antenna bandwidths are limited by the ferrite transformer and tuning capacitor losses. These losses could be minimized by additional design selection of higher Q capacitors and through the use of higher frequency ferrite in the transformer. It is estimated that proper design selection could result in antenna Q's in the 100-150 range which would give unpadded bandwidths in the 3 - 5 KHz range using the same prototype antenna windings. This would permit the use of fixed padding resistance to adjust the bandwidth to the desired level to accomodate detuning and type of modulation. The increase in measured bandwidth with operating frequency was due to the frequency dependence of the matching circuit losses. Minimizing these losses and providing fixed resistive padding would provide near-constant bandwidth over the 500 KHz - 1000 KHz range.

Eventually, a two-frequency matching scheme will be required for these antennas. A possible means for accomplishing this would be to separately transform the series resonant resistance of the antenna (occurring at a lower frequency selectable by adjusting the 50-ohmd transformer primary impedance level for the L-section match) with a conventional transformer. Switching between the transformer inputs may be required when changing frequencies. This would circumvent the probable high circulating current of a multi-pole network to provide two frequencies on a strictly passive matching basis.

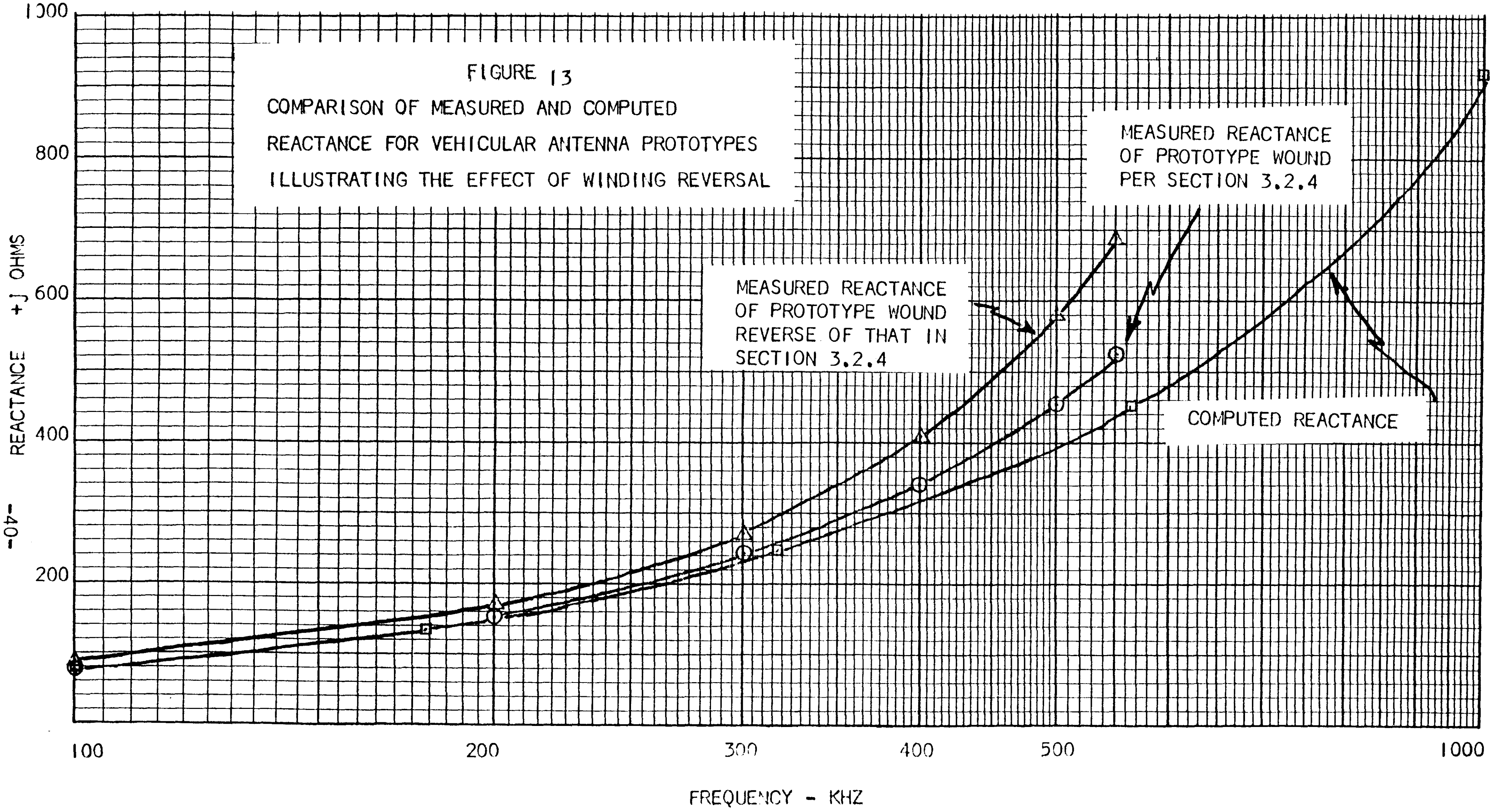


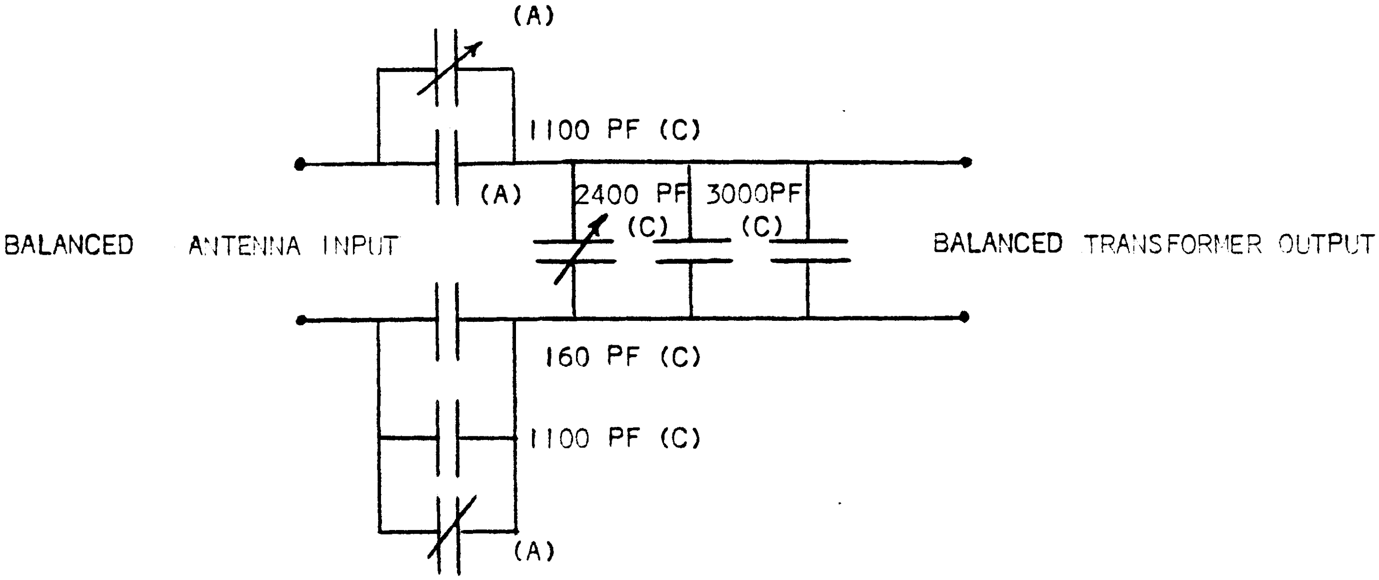
FIGURE 13

COMPARISON OF MEASURED AND COMPUTED REACTANCE FOR VEHICULAR ANTENNA PROTOTYPES ILLUSTRATING THE EFFECT OF WINDING REVERSAL

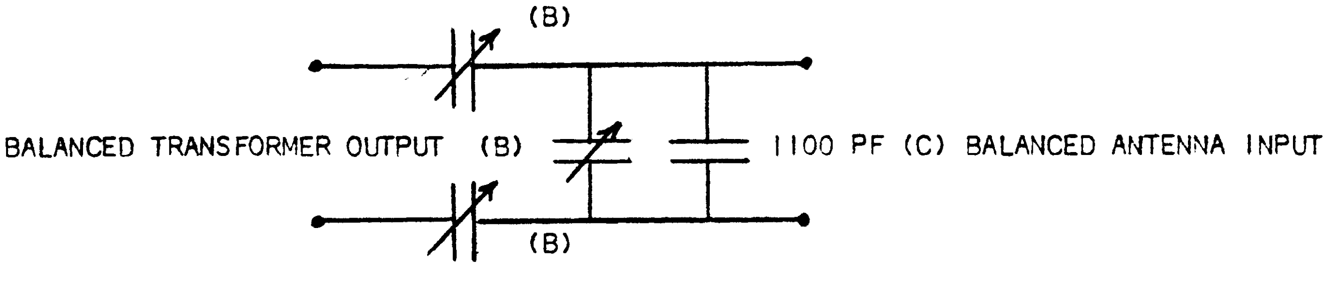
FIGURE 14

BALANCED TUNING CIRCUITS USED IN VEHICULAR ANTENNA PROTOTYPE MATCHING TO A MATCHED IMPEDANCE LEVEL OF 200 OHMS

520 KHZ CIRCUIT



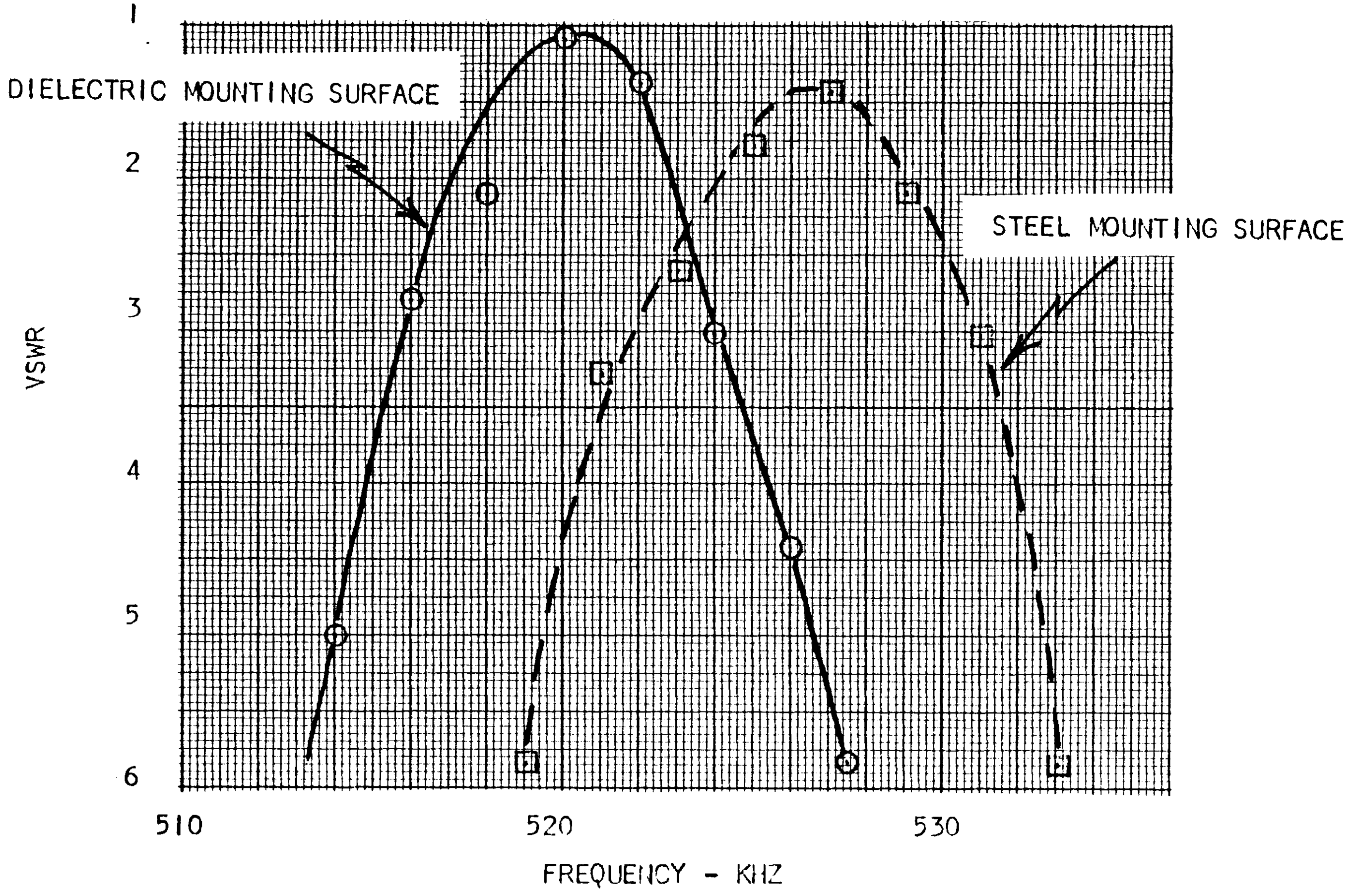
920 KHZ CIRCUIT



(A) 1135 - 680 PF AIR VARIABLE TRIMMER 350 VDC NOMINAL RATING
(B) 70 - 480 PF AIR VARIABLE TRIMMER 350 VDC NOMINAL RATING
(C) SILVERED MICA FIXED CAPACITORS 1000 VDC NOMINAL RATING

FIGURE 16

TUNING CURVE FOR PROTOTYPE VEHICULAR ANTENNA TUNED TO NOMINALLY 520 KHZ SHOWING FREQUENCY SHIFT DUE TO MEASUREMENT OVER DIELECTRIC AND STEEL MOUNTING SURFACES



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PER SECTION 3.2.4

FIGURE 17

TUNING CURVE FOR PROTOTYPE VEHICULAR ANTENNA TUNED TO NOMINALLY 920 KHZ SHOWING FREQUENCY SHIFT DUE TO MEASUREMENT OVER DIELECTRIC AND STEEL MOUNTING SURFACES

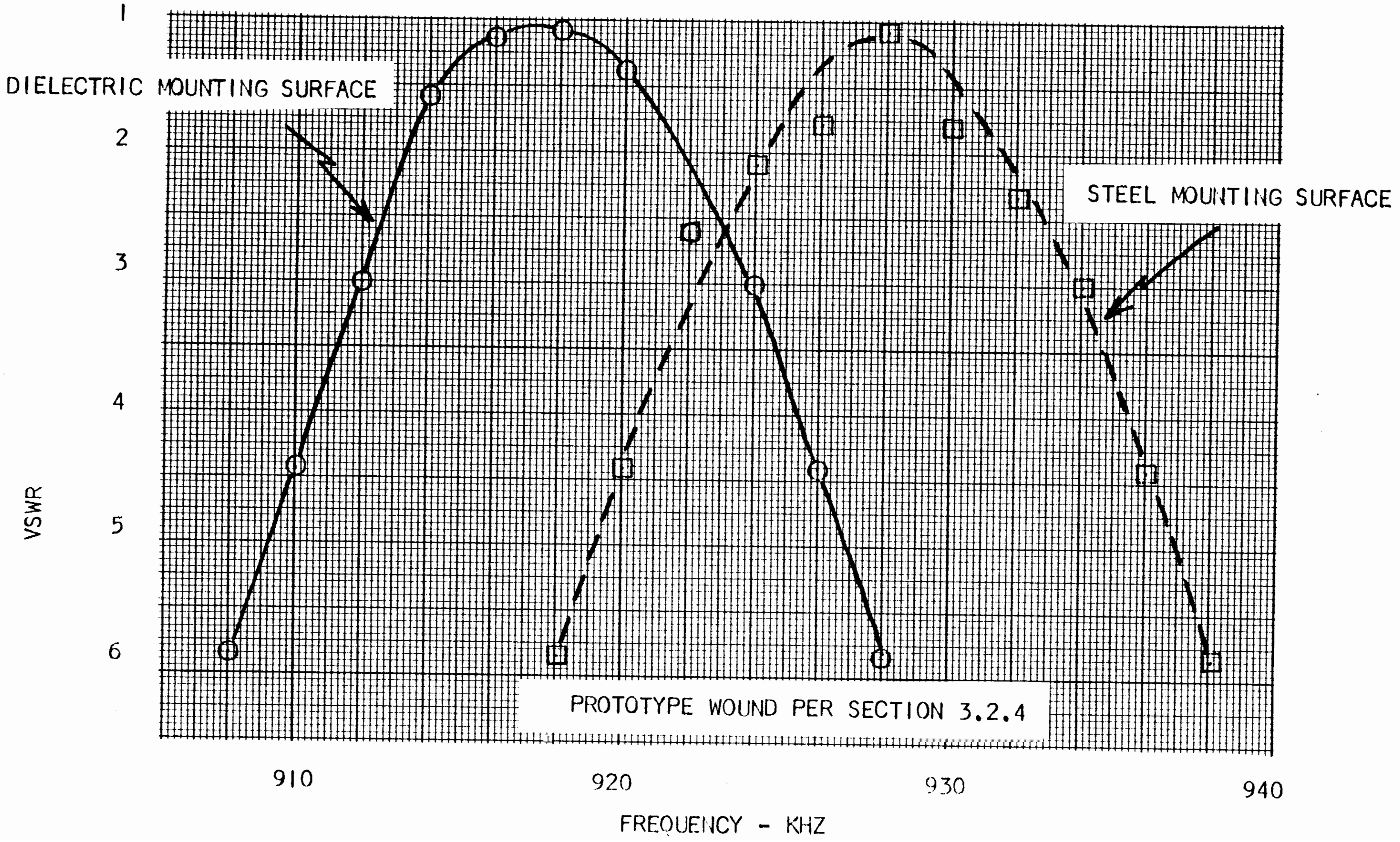


TABLE I

PERFORMANCE DIAGNOSIS FOR VEHICULAR PROTOTYPE ANTENNA (WOUND PER SECTION 3.2.4) AS OBTAINED DURING PRELIMINARY TESTING @ 476 KHZ

	Q	R_L	BW
ANTENNA TUNED AND TRANSFORMED WITH TUNING CKRT IN ENCLOSURE	37.1	11.3	12,830
ANTENNA TUNED AND TRANSFORMED WITH TUNING CKRT NOT ENCLOSED	47.2	8.9	10,084
ANTENNA TUNED BUT NOT TRANSFORMED WITH TUNING CKRT NOT ENCLOSED	90	4.67	5,289
ANTENNA NOT TUNED(RAW ANTENNA)	404	1.04	1,166

TUNING CAPACITORS(100 VOLT SILVERED MICA)	110	3.63 OHMS OF LOSS
TRANSFORMER		4.23 OHMS OF LOSS
ENCLOSURE		2.42 OHMS OF LOSS

5.0 ANTENNA COUPLING TO MINE WIRING

5.1 GENERAL CONSIDERATIONS

Antenna coupling to mine wiring is a function of antenna range away from the conductors, the antenna design parameters, and details of the mine topology including location of conductors relative to the crossectional geometry of entries and crosscuts.

Previous estimates of coupling (made by the author) have evolved from mf propagation studies with antennas located remotely from the conductors based on both measurements and computations, above ground measurements with a large loop close to conductors lying just above ground level, and calculated estimates in close proximity to conductors which neglect geometry effects. While the remote estimates are probably satisfactory for system design purposes, the previous conductor proximity estimates have not included geometrical effects or a set of representative antenna parameters.

The coupling is defined as the ratio of the current in the antenna to the net monofilar current in the conductor ensemble (or visa versa, depending on which is assumed to be the transmit current.

The previous conductor proximity coupling estimates place the coupling at -25 to -30 dB with the suggestion that the coupling varies only slowly with range away from the conductors as long as the antenna is in the same entry as the conductors.

Analytically derived coupling estimates are difficult, if not impractical, to perform due to the complex geometry of the entry crossections with conductors and because of the number of geometry related variables involved. As an alternative, the coupling can be estimated using graphical quasi-static field mapping. This technique has been proven over the years to yield results of sufficient accuracy for engineering purposes while permitting the inclusion of complicated geometries. As example of this is the coupling when an antenna is vehicular mounted compared to the coupling when the antenna is isolated or man carried.

The graphical field mapping technique, to be described more fully in the next subsection, provides a unique solution of LaPlace's equation for the geometry involved and depends only on the orthogonality between equipotential and flux lines which are plotted so as to form "curvilinear squares". The approach to be used in this work considers the static field to be set up by a net codirectional transmitted current in the line source conductor ensemble and the receiving antenna to be small so as not to disturb the field shape significantly. Using the field configuration for the conductor ensemble (as opposed to that from the antenna as a transmitter) make the problem a two-dimensional one as the field configuration is presumed to be invariant with longitudinal distance down the entry.

The computational technique involves determining the magnetic field strength at one or more desired locations on the field map proportional to current in the conductors, using the field strength and antenna geometry to compute an open circuit voltage at the antenna (also proportional to conductor current), and then to use the antenna impedance information to compute the current driven in the loop for a given open circuit voltage. The antenna impedance and bandwidth data used in the computations to follow are those determined from the vehicular antenna prototype development.

5.2 DESCRIPTION OF THE TECHNIQUE

The magnetic flux per unit length in a two-dimensional problem is related to the conductor current as

$$B = \frac{I_l \, \Delta\theta}{2\pi \mu \Delta r}$$

so that the magnetic field strength is given by

$$H = \frac{I_l \, \Delta\theta}{2\pi \, \Delta r}$$

where $\Delta\theta$ is the angular width of the flux tube
Δr is the differential range of the curvilinear square
I_l is the net monofilar conductor current.

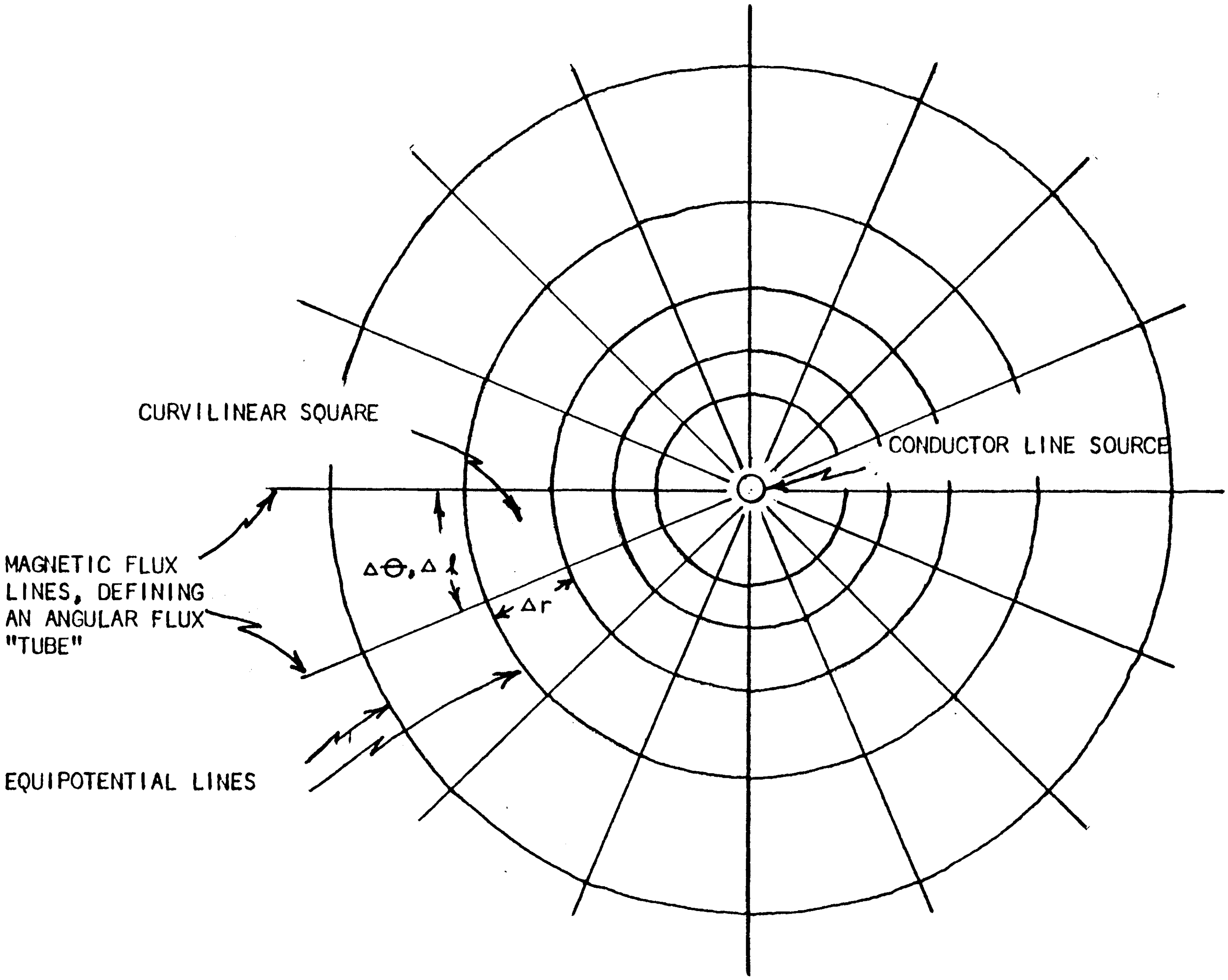
This relationship is illustrated in Figure showing the mapping of the flux and equipotential lines away from the familiar isolated line source. In this particular case, as $\Delta\theta$ and Δr become vanishingly small, the grid shape becomes a perfect square and

$\Delta r \rightarrow \Delta \ell$, the arc length subtended by $\Delta\theta$

as $\Delta \ell = r \, \Delta\theta$

$$\text{then} \quad \frac{\Delta\theta}{\Delta \ell} \cong \frac{\Delta\theta}{\Delta r} = \frac{1}{r}$$

$$\text{so that } H = \frac{I_l}{2\pi r}, \text{ the known result}$$



FIGURE

MAGNETIC FIELD MAPPING OF A CONDUCTING LINE SOURCE IN FREE SPACE

For each case, the flux and equipotential lines are drawn to form "curvilinear squares" and are subdivided with sufficient granularity to define the field at one or more desired points. The flux lines represent equally spaced angular divisions close to the conductor ensemble, so that

$$\Delta\theta = \frac{2\pi}{\text{number of lines/360 deg rotation around the conductor}}$$

$$= \frac{2\pi}{n}$$

Δr is read in meters off the scaled mapping graph.

The loop open circuit voltage is given by

$$|V_{oc}| = \omega\mu(NA)H$$

where (NA) is the loop area-turns product

Assuming matched conditions,

$$\frac{|V_{oc}|}{2R_L} = |I_L|\text{, the loop current, } = \frac{|V_{oc}|\ Q_A}{2\ X_L}$$

where, R_L is the loop tuned resistance
X_L is the loop reactance
Q_A is the antenna Q

so that the complete expression for the coupling ratio is

$$\frac{|I_L|}{|I_1|} = \frac{\omega\mu(NA)\quad Q_A}{4\pi\Delta r\ X_L} = \frac{\omega\mu(NA)\quad Q_A}{2n\Delta r\ X_L}$$

5.3 ENTRY CROSSECTIONAL GEOMETRY

Many geometries are possible. Generally, if the conductors are close to the antenna and ont obscured by a vehicle the coupling loss will be minimum. The worst cases are those with the conductor ensembles located either against the rib (on roof or floor) or near a vehicle with an antenna on it such that the vehicle "masks" the direct path from the conductor(s) to the antenna. These worst cases are not pathelogical worst cases, but are those commonly occurring and, so, are those which will be used in the analysis to follow.

Four cases were determined to be representative of these situations; particularly if more than one antenna location were chosen for evaluation per situation.

These situations include:

(1) Conductor ensemble near roof & rib corner w/o a vehicle present
Antennas assumed to be located respectively 1 and 2 meters away from the opposite rib and halfway between the roof and floor

Note: the results are essentially the same for conductors located near the floor & rib corner

(2) Conductor ensemble near roof & rib corner with vehicle present
Antennas located alternatively on the near-side and far-side of the vehicle with respect to the conductor(s)

(3) Conductor ensemble near floor & rib corner with vehicle present
Antennas located per (2)

(4) Conductor ensemble on floor close to the vehicle
Antennas located per (2)

A standard scale was used for the entry crossection and for the vehicle dimensions and location. The entry was chosen to be 2 meters high and 5 meters wide. The vehicle height was taken to be 2/3 meter and the vehicle width was taken to be 2 meters. The vehicle was assumed to be located 1 meter away from the rib opposite the conductor(s).

5.4 PRESENTATION OF RESULTS

The four above cases along with the graphical field mappings are given in Figures through . On each figure are given the appropriate computed couplings and coupling comparisons @ 1 MHz.

Antenna data used in the analysis included:

$(NA) = 1.67 \text{ meter}^2 \text{ turns}$

@ 500 KHz, $X_L = j456$ ohms, $Q_A = 41$

@ 1 MHz , $X_L = j1000$ ohms, $Q_A = 55$

The coupling data is given for 1 MHz only as the ratio $\dfrac{f\,Q_A}{X_L}$ is nearly the same (1.7 dB less @ 500 KHz than @ 1 MHz) for frequencies between 500 KHz and 1 MHz.

From these results, the following conclusions may be drawn:

(1) Based on the antenna data, the coupling is nearly flat with frequency in the 500 - 1000 KHz range (less than 2 dB difference).

(2) The antenna mounted on the vehicle is within ± 2 dB in coupling compared to the case w/o vehicle mounting
  (a) vehicle presence increases the coupling for high-mounted conductors.
  (b) Vehicle presence decreases the coupling for low-mounted conductors (on floor).

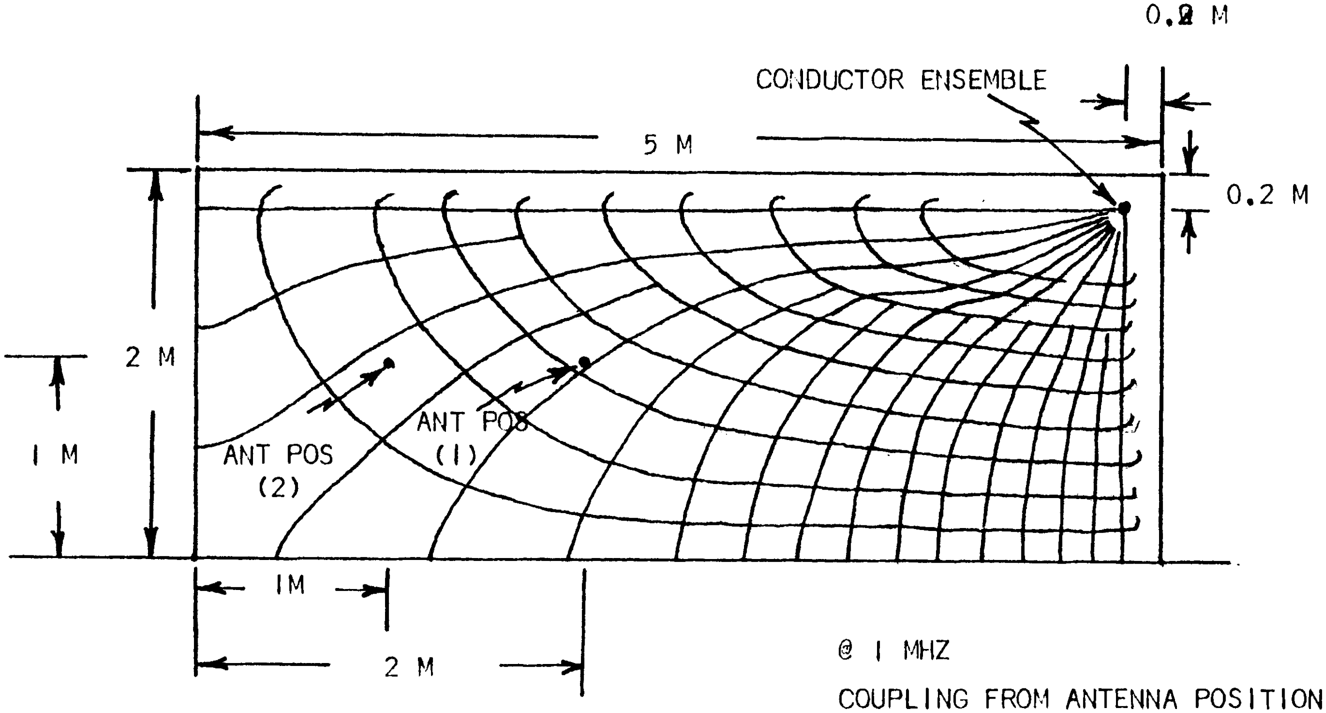
(3) Assuming the antenna is mounted on the battery box near one side of the vehicle, the antenna if mounted on the conductor side produces 3-11 dB more coupling than if the antenna were mounted on the side opposite the conductor(s)
  (a) 3 dB for conductor on floor against rib
  (b) 8 dB for conductor near roof and against rib
  (c) 11 dB for conductor on floor and ½ meter away from the vehicle.

(4) For vehiclular mounted antennas w/parameters of prototype for the assumptions of (3)
  (a) Coupling is -16 to -20 dB when antenna is on conductor side of the vehicle
  (b) Coupling is approximately -25 dB when antenna is on opposite side of vehicle from conductor(s)
  (c) Coupling is approximately -30 dB when antenna is on opposite side of the vehicle from conductor(s) but with conductor(s) on floor near vehicle

(5) For man-carried antennas symmetrically located between roof a nd floor, coupling is approximately -25 to -20 dB respectively 1 to 2 meters away from opposite rib for either roof-mounted or floor-mounted conductor(s).

FIGURE

GRAPHICAL FIELD MAPPING FROM CONDUCTOR NEAR ROOF & RIB CORNER WITHOUT
A VEHICLE PRESENT

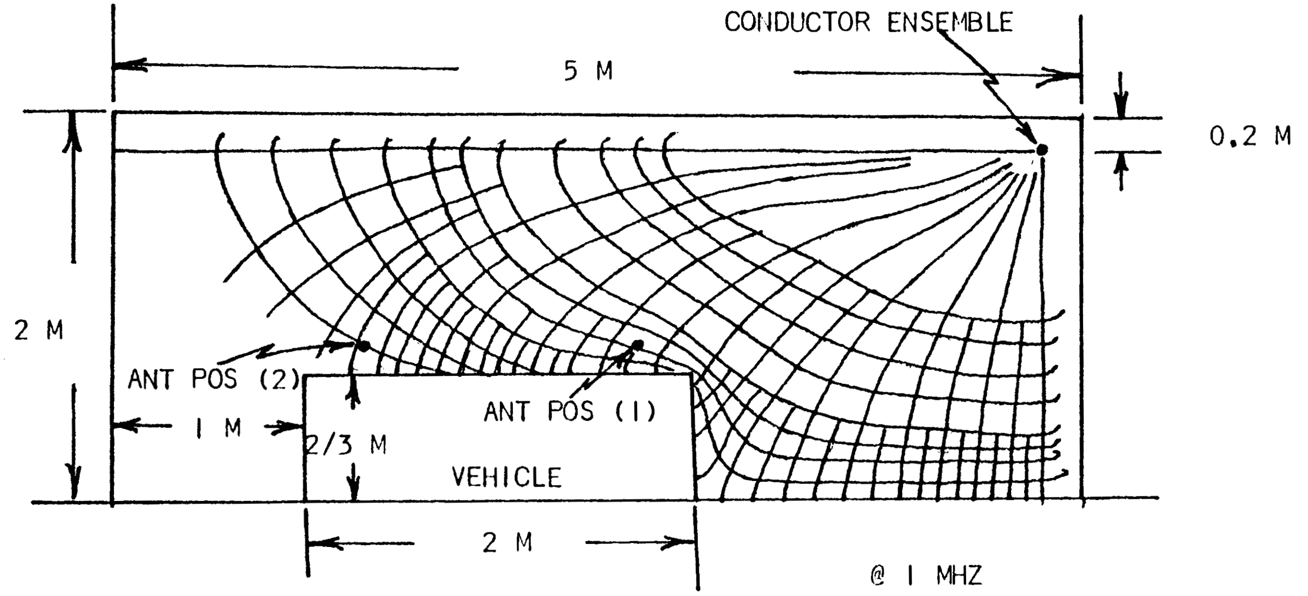


@ 1 MHZ

COUPLING FROM ANTENNA POSITION (1) -20.2 DB
COUPLING FROM ANTENNA POSITION (2) -24.6 DB

FIGURE

GRAPHICAL FIELD MAPPING FROM CONDUCTOR NEAR ROOF & RIB CORNER WITH
A VEHICLE PRESENT

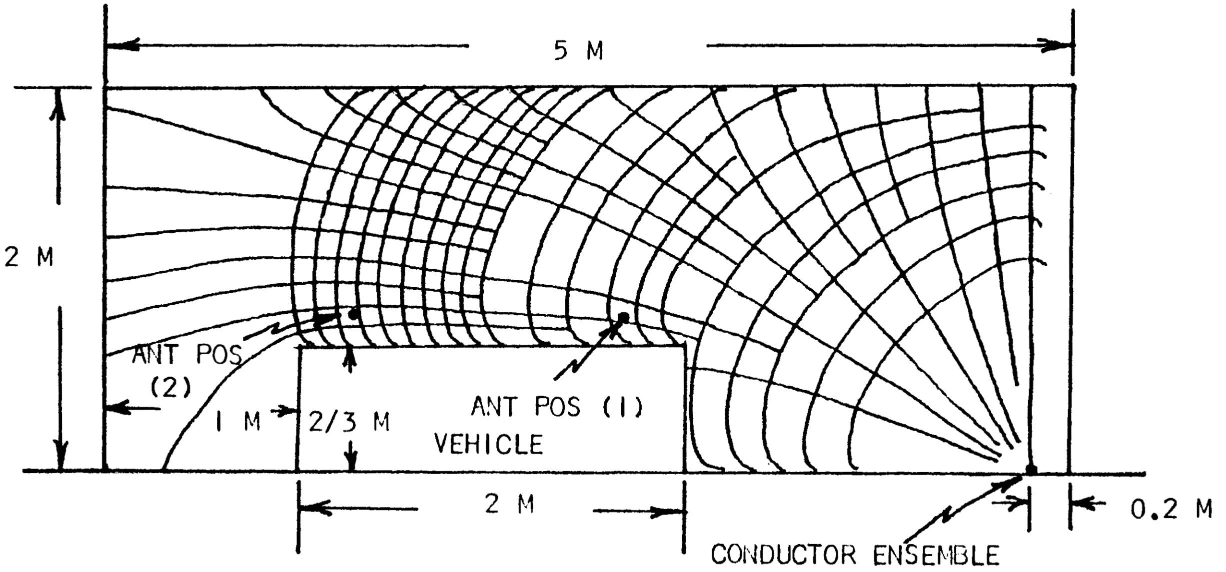


@ 1 MHZ

COUPLING FROM ANTENNA POSITION (1)	-16.6 DB
COUPLING FROM ANTENNA POSITION (2)	-24.9 DB
FOR ANTENNA POSITION (1) W & W/O VEHICLE PRESENT, RATIO W TO W/O	+ 2.0 DB

FIGURE

GRAPHICAL FIELD MAPPING FROM CONDUCTOR NEAR FLOOR & RIB CORNER WITH A VEHICLE PRESENT

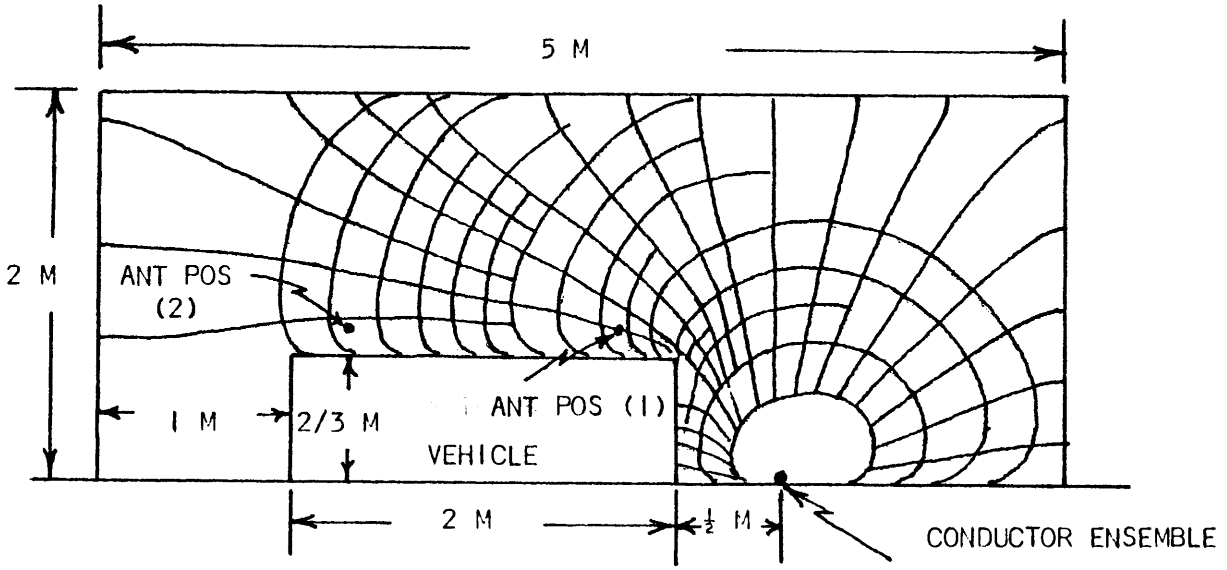


@ 1 MHZ

COUPLING FROM ANTENNA POSITION (1)	-20.0 DB
COUPLING FROM ANTENNA POSITION (2)	-23.2 DB
FOR ANTENNA POSITION (1) W & W/O VEHICLE PRESENT, RATIO W TO W/O	- 2.1 DB

FIGURE

GRAPHICAL FIELD MAPPING FROM CONDUCTOR ON FLOOR CLOSE TO VEHICLE



@ 1 MHZ

COUPLING FROM ANTENNA POSITION (1) -19.4 DB

COUPLING FROM ANTENNA POSITION (2) -30.3 DB