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Volume IV

Performance Test and Evaluation
of a Full Wave Location Transmitter

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Baltimore, Maryland

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The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies of the Department of the Interior, Bureau of Mines, or the U. S. Government.

PREFACE

This report is the last in a series of four volumes of a final report to the Bureau of Mines documenting work done by the Westinghouse Electric Corporation under Contract H0220073 between March of 1973 and May, 1973. The relatively short time period covered by this report is due to a basic contract modification which occurred early in 1973. Work done prior to the contract modification is contained in Volumes I, II, and III of the series of reports, and covers the period July, 1972 through March, 1973.

This report describes, in two parts, the design, test, and performance evaluation of a modified version of a CW transmitter. The work was conducted by the Westinghouse Georesearch Laboratory (WGL) during the month of March, 1973, for the Bureau of Mines as Part of Task I of Contract H0220073.

The primary objective of Task I was to obtain as rapidly as possible, an electromagnetic transmitter and receiver system for use in locating trapped miners. Since the transmitter would be used in coal mines, intrinsic safety was an important consideration. Other basic factors considered in the design included size, weight, cost, operating life, and ease of deployment. A miner's lamp battery was to be used as the source of prime power.

Two basic location systems have been designed, fabricated, and field tested. WGL was tasked with developing a continuous wave (CW) system*, and the Special Systems Department of Westinghouse concurrently developed a pulse type system.

Following the field tests and performance evaluation of these initial system configurations, technical discussions were held with the Contract Officer's technical representative, Mr. Howard Parkinson, who recommended that the balance of effort on this contract be directed toward reviewing** the merits of the pulse and CW systems, using the best features of each to design a modified CW

* A description of this effort is given in an earlier report on Task I entitled, "Development and Test of a CW Location System," by A. J. Farstad et al., USBM Task I Report (Contract H0220073) April 1973.

** Contract Modification Number 3 - Contract H0220073

transmitter, and to evaluate its performance. A primary objective was to optimize the system so the antenna current was at the maximum intrinsic safety level, using a 360 foot circumference antenna.

Subsequently, a new design concept, using four switching transistors to obtain full-wave drive to a resonated loop antenna, was developed. This design concept was breadboarded and evaluated at WGL using an outdoor testing area to deploy the antenna. Intrinsic safety tests were also conducted on this system at the Bureau of Mines Approval and Testing Laboratory in Pittsburgh, Pennsylvania.

Part I of this report describes the initial configurations and discusses their relative merits. The new system design concept is presented, and, using the results of tests on this full-wave system, an analysis is given on the factors which must be considered to implement an optimum intrinsically safe system.

Part II presents a detailed description of the circuitry involved in the full-wave transmitter and the results of laboratory tests and intrinsic safety tests which have been performed.

PART I
CHARACTERIZATION OF PERFORMANCE

by

R. F. Linfield

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1.0 INTRODUCTION AND SUMMARY

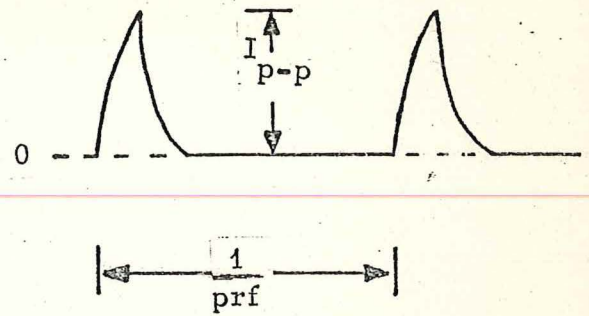
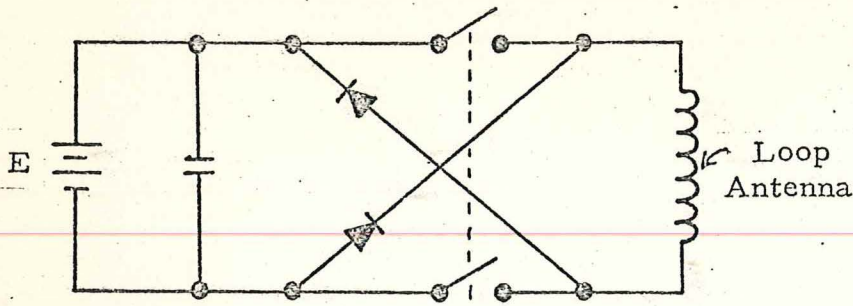
Figure 1-1 shows the basic transmitter design concepts used for the pulse system, the half-wave CW system, and the full-wave CW system. The antenna current waveform is also shown for each transmitter for typical operating frequencies and antennas. The switches shown in Figure 1-1 were actually implemented using solid state devices. In all three systems the signaling format may be interrupted to conserve power and thereby extend battery life. Frequency accuracy and stability is achieved using a tuning fork oscillator in the transmitters and tuning fork filters in the receivers for all three systems. This provides the narrow reception bandwidths needed to enhance signal detectability. All three systems also use frequency assignment for identification purposes. The location schemes employed are likewise identical, each being based on detecting the null (signal minimum) of the horizontal magnetic field on the surface. Since these systems are basically similar, the primary purpose is to select the system which gives the maximum signal detectability on the surface from a manpack transmitter operating in the mine.

Both the pulse and half-wave CW systems use a d. c. pulse to energize the loop antenna. However, with the pulse system, this pulse duration is short compared to the pulse repetition rate (prf), whereas with the half-wave CW system the pulse duration equals one-half the period of the switching frequency. In the pulse system, energy from the battery is stored in a capacitor so that during the switching interval the internal resistance of the power source can be considered almost negligible. Both transmitters must drive a loop antenna which is a reactive load having inductance, L , and resistance, R_a .

The current waveforms in both systems have a finite rise time whose time constant is given by L/R where R is the total resistance of the circuit, including internal resistance of the source, R_b , the switch resistance, R_s , and the antenna resistance, R_a . In the pulse system the diodes

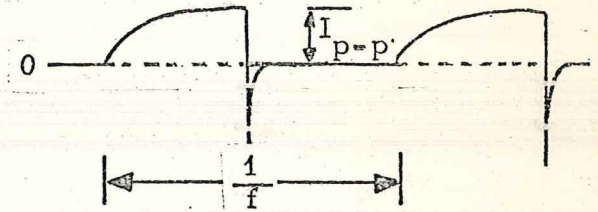
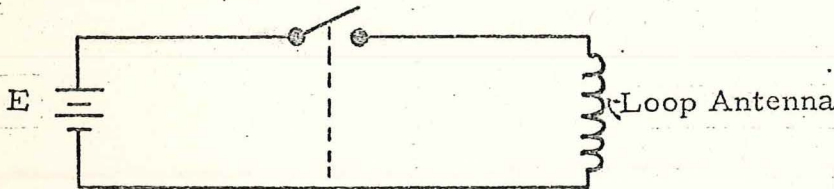
Equivalent Circuit

Antenna Current Wave form



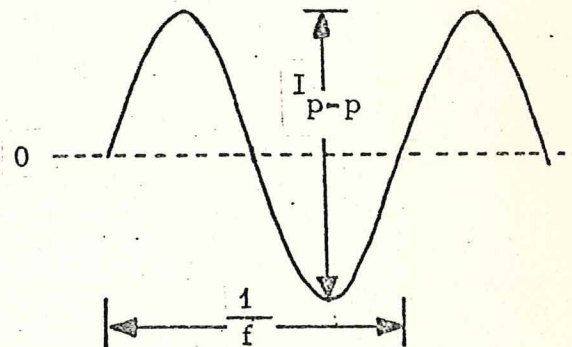
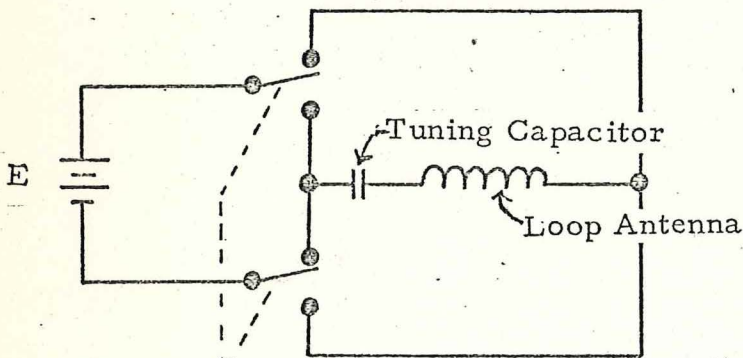
Pulse
Signal
Generator

1) Pulse System



CW
Signal
Generator

2) Half-Wave CW System



CW
Signal
Generator

3) Full-Wave CW System

Figure 1-1. Three Basic Transmitter Design Concepts.

with forward resistance, R_d determine the fall time whose time constant is $\frac{L}{R_a + 2R_d}$. In the half-wave system, there is no return path for energy stored in the inductive load except through the high back resistance of the switch. This causes a negative spike in the current waveform.

At typical operating frequencies and for practical antenna configurations, the antenna current waveform is a sawtooth for the pulse system, and a modified square-wave for the half-wave CW system, as shown in Figure 1-1.

In the full-wave CW system the antenna is resonated with a circuit Q given by

$$Q = \frac{\omega L}{R_b + 2R_s + R_a}$$

At typical operating frequencies and with practical circuit components, the realizable Q is sufficiently high so that the antenna current waveform is a sine wave.

All three systems utilize narrow bandwidth receivers (10 Hz or less) to detect the inductive field generated by the current waveform in the antenna. It is apparent from the waveforms shown in Figure 1-1 that the spectral content varies considerably with each transmitter.

With the pulse system, if the pulse interval is made sufficiently wide, then most of the spectral energy is contained in the fundamental, and the 2nd, 3rd, and 4th harmonics. The receiver is designed to accept any one or combinations of these. This technique has the potential advantage of eliminating frequency components which may be contaminated by man-made interference which, at frequencies of interest, consist of harmonics of 60 Hz. It is impossible, however, to select the prf's so that all of the signal harmonics fall midway between interference harmonics.

The half-wave system uses a narrowband receiver (≈ 6 Hz) designed for detecting only the fundamental. In order to achieve optimum performance with this system, it is necessary to select operating frequencies which fall between the 60 Hz harmonic interference lines. A similar receiver, with the same frequency selection limitations is used with the full-wave system.

The sinusoidal current waveform of the full-wave system has very little harmonic content. Therefore, nearly all of the usable power is contained in the fundamental. This improves efficiency and also there is less chance of the system being self-jamming when several transmitters are operating simultaneously on different frequencies.

From the standpoint of intrinsic safety, both the pulse system and half-wave system have a disadvantage because their current waveform has a d. c. component, whereas the peak current of the full-wave system is half the peak-to-peak current.

Performance comparisons between the full-wave transmitter and the half-wave transmitter are given in Section 2. This comparison shows that the full-wave system gives 10 dB more signal if both systems use identical antennas, or, viewed another way, with a constant battery life and antenna moment the full-wave system antenna weight can be reduced by a factor of four. With both systems operating at the limits of intrinsic safety, the full-wave system is capable of generating twice the antenna moment achieved with the half-wave system.

Similar comparisons between the full-wave system and the pulse system are not included here because a detailed theoretical analysis of the pulse technique is more complex and is beyond the scope of this report. However, from the standpoint of intrinsic safety, receiver complexity, self-jamming, source identification, signal detectability, efficiency, and operating ease, the full-wave system appears to have the advantage over both of the other systems. The main disadvantage is the requirement for four switching elements and a tuning capacitor which increases size, weight,

and cost. These increases, however, are not substantial. Therefore, the major emphasis here is devoted to determining the design parameters for an optimum intrinsically safe, full-wave CW system.

2.0 COMPARATIVE ANALYSIS OF TWO SYSTEM CONFIGURATIONS

The equivalent circuit for the two basic design configurations are shown in Figure 2-1a and 2-1b. Transistor switches are used in both configurations and these are operated on an intermittent duty cycle using continuous waveform generating circuit whose frequency is controlled by a tuning fork oscillator.

The nomenclature used in both equivalent circuits is as follows:

- E_b = Battery voltage
- R_b = Internal resistance of the battery
- R_s = Internal resistance of the switch
- R_a = Antenna resistance
- L_a = Antenna inductance
- C_a = Antenna tuning capacitance
- R_m = Current meter resistance.

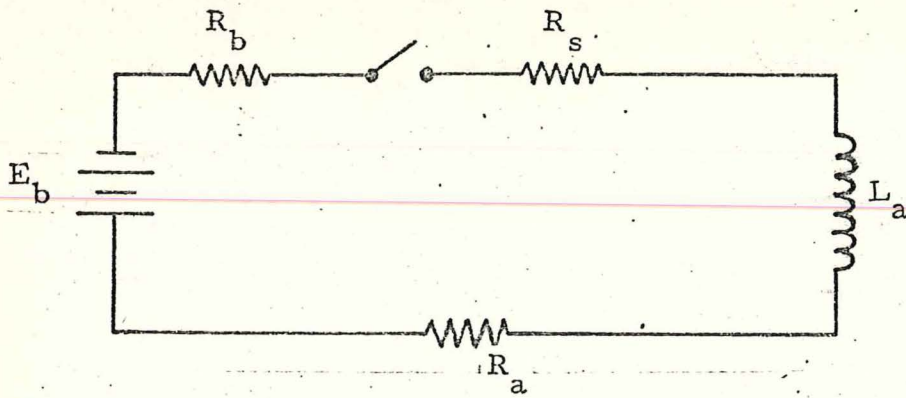
For configuration b, where the antenna is tuned to resonance, the inductive reactance, X_L , must equal the capacitive reactance, X_C , at the operating frequency of the tuning fork.

It is useful to compare the performance of both systems on two separate bases, first, in terms of the antenna moment achieved using identical antennas, and second, in terms of efficiency, or battery life, achievable with identical antenna moments.

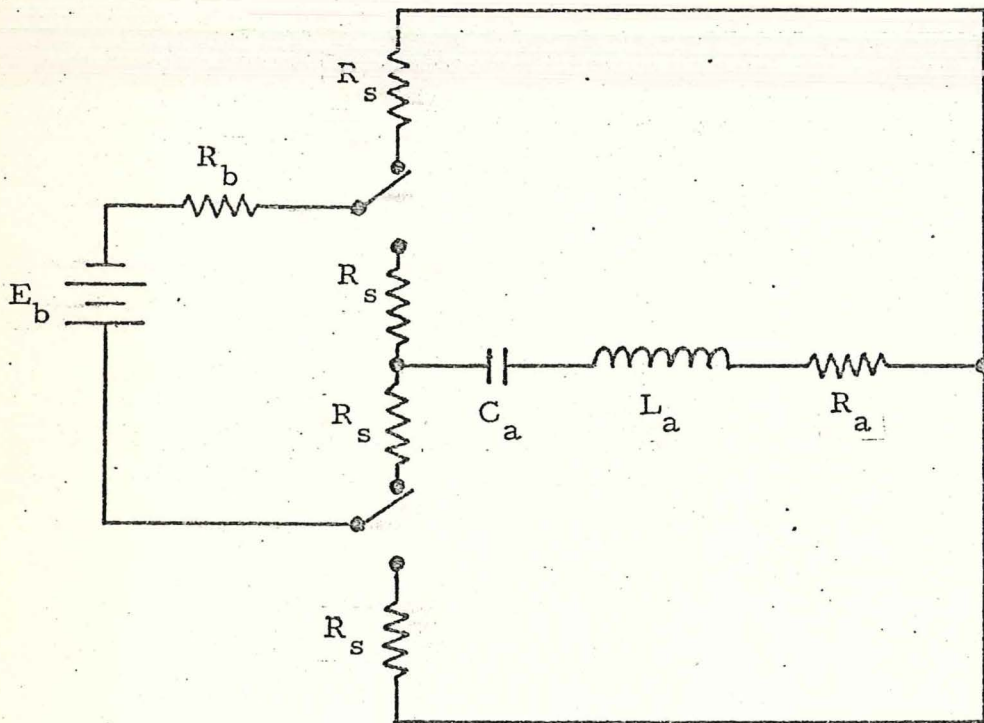
The maximum peak-to-peak current in system (a) is:

$$\left(I_{P-P} \right)_a = \frac{E}{R_b + R_s + R_a}$$

With no inductance in the circuit, this current would appear as a square wave varying between 0 and I_{P-P} at half cycle intervals. However, the antenna is inductive with a time constant of L/R . With frequencies and antennas of interest, the current wave form approaches a sawtooth on



a) Half-Wave System



b) Full-Wave System

Figure 2-1. Equivalent Circuits of CW Location Transmitters.

alternate half cycles. The peak-to-peak magnitude of the fundamental frequency component of such a wave form is approximately $3/\pi$ times its peak-to-peak value, and the rms value of this fundamental component is given by:

$$\left(I_{\text{rms}} \right)_a \approx \frac{3}{\pi} \times \frac{\sqrt{2}}{4} \times \left(I_{\text{p-p}} \right)_a = 0.337 \left(I_{\text{p-p}} \right)_a$$

For system (b) the current in the load with no reactive elements is a bi-directional square wave with a peak-to-peak amplitude of:

$$\left(I_{\text{p-p}} \right)_b = \frac{2E}{R_b + 2R_s + R_a}$$

When the antenna inductance is resonated with a capacitor, the current wave form is sinusoidal with rms amplitude given by:

$$\left(I_{\text{rms}} \right)_b = \frac{4}{\pi} \times \frac{\sqrt{2}}{2} \times \left(I_{\text{p-p}} \right)_b = 0.90 \left(I_{\text{p-p}} \right)_b$$

The antenna moment is given by INA , where I is the rms current, N the number of turns, and A the area enclosed by the loop. Usually INA is expressed in the international system of units, i. e., ampere-turns-meters². If identical antennas are used with both systems, then the ratio of antenna moments is equal to the ratio of the currents generated by the two systems.

$$\frac{\left(I_{\text{rms}} \right)_a}{\left(I_{\text{rms}} \right)_b} = \frac{0.337 \left(R_b + 2R_s + R_a + R_m \right)_a}{0.9 \left(R_b + R_s + R_a + R_m \right)_b}$$

R_m = Current meter resistance

If the switching elements in system (b) have half the internal resistance, as in system (a), so that $\left(R_s \right)_b = 2 \left(R_s \right)_a$, then the antenna

moment ratio becomes:

$$\frac{(I_{rms})_a}{(I_{rms})_b} = 0.375 .$$

This indicates that the moment achievable with system (b) is larger than (a) by a factor of 2.67 or approximately 9.5 dB. This assumes that both systems use identical voltage supplies, identical antenna configurations, and that $(R_{s_a}) = 2 (R_{s_b})$.

In a following section the results of laboratory measurements on the two systems operating with identical antennas are shown and these results compare favorably with the above calculations.

A comparison of the two systems is also possible assuming equal input powers. With a constant voltage source this implies equal currents so the battery life is the same for both systems. Under these conditions $(I_{rms})_a = (I_{rms})_b$, and it follows that:

$$(R_a)_b = \frac{5 R_b + 2 R_s + 8 (R_a)_a}{3}$$

Factors of improvement can be evaluated by substituting typical values for the resistance in this equation. Assuming that the antenna for system (a) consists of 100' of #10 wire, then $(R_a)_a \approx 0.1$ ohms. The source resistance of the battery, $R_b \approx 0.1$ ohms* and the switch $R_s \approx 0.5$ ohms. Therefore, the antenna resistance which yields the same current in System b) is:

$$(R_a)_b = \frac{5 (0.1) + 2 (0.5) + 8 (0.1)}{3} \approx 0.77$$

and the ratio of antenna resistance is:

$$\frac{(R_a)_b}{(R_a)_a} = 7.7 .$$

* The average of several measurements of the internal resistance of the Mine Safety Appliances Co., Mine Spot Cap Lamp Battery was 0.114 ohms.

This shows that system (b) can operate from the same battery for the same length of time using an antenna which has either: 1) the same moment but less antenna weight using smaller wire, or 3) a larger moment by enclosing larger area with a single turn of the same wire.

The actual improvement achieved for any one of these three conditions is indicated below for the example given, where $(R_a)_b = 7.7(R_a)_a$ and $(I_{rms})_a = (I_{rms})_b$.

<u>Condition</u>	<u>System (a)</u>	<u>System (b)</u>
1) Antenna Weight	3.2 lbs. of #10	0.8 lbs. of #16
2) Antenna Turns	1	7
3) Antenna Area	58 m ²	3440 m ²

The actual antenna moments, INA, achieved under these three conditions are tabulated below. This assumes a 4 volt supply and 1.93 amperes of antenna current for both systems.

<u>Condition</u>	<u>System (a)</u>	<u>System (b)</u>	<u>Improvement Factor</u>
1) INA =	112 amp-turn-m ²	112 amp-turn-m ²	1/4 weight
2) INA =	112 amp-turn-m ²	780 amp-turn-m ²	7 X moment
3) INA =	112 amp-turn-m ²	6650 amp-turn-m ²	58 X moment

Actually, conditions (2) and (3) of this example are not practical from an intrinsic safety standpoint,* because the energy storage capacity of the antennas' reactive elements increases with area enclosed, and as the square of the number of turns. The intrinsically safe limits are discussed in a subsequent section.

* Does not apply to metal mines.

3.0 LABORATORY TEST RESULTS

The two systems have been evaluated at the laboratory using the same antenna. This antenna consisted of 360 feet (110 meters) of AWG #10 copper wire deployed as a single turn loop with an area of 8100 feet² (750 m²).

The inductance of a single turn square loop is given by*

$$L_a \text{ (microhenries)} \approx 0.008 a \left[2.303 \log \frac{a}{d} - 0.52 \right],$$

where a is the length of one side in centimeters and d is the wire diameter in centimeters.

The inductance calculated for the antenna used was 192 μ henries and it was measured as 200 microhenries.

The d. c. resistance of #10 wire is 0.9989 ohms per 1000 feet, or approximately 0.360 ohms for the 360' loop. The a. c. resistance of this wire increases with frequency. At 2500 Hz, the ratio of a. c. resistance to d. c. resistance is given by*

$$\frac{R_{ac}}{R_{dc}} = 1.02 .$$

Therefore, the a. c. resistance at 2500 Hz is increased by 2%, so that $R_a = 0.368$ ohms.

This antenna was driven by system (a) at a switching frequency of 2010 Hz. The time constant is:

$$\frac{L}{R} = \frac{192 \times 10^{-6}}{0.1 + 0.5 + 0.368} = 196 \text{ microseconds,}$$

and the half cycle interval at 2010 Hz is approximately 250 microseconds.

* Radio Instruments and Measurements, National Bureau of Standards Circular C74, January 1937.

Therefore, the assumption of a sawtooth current wave form at half cycle intervals is valid at frequencies near 2 kHz.

This same antenna was resonated with a 20 μ f capacitor and driven with system (b) at a switching frequency of 2500 Hz. The switching resistance R_s of system (b) was 0.25 ohms, so the total circuit resistance remained the same.

The antenna Q is given by:

$$Q = \frac{\omega L}{R} = \frac{2\pi \times 2500 \times 192 \times 10^{-6}}{0.968} = 3.1 .$$

Calculated and measured values of the rms antenna current are shown below. In both cases the measured value was obtained using a narrow bandwidth (6 Hz) wave analyzer (HP-Model 302A) and measuring the voltage across a precision resistor of 0.02 ohms in series with the antenna. Efficiency values shown were calculated from:

$$\text{Efficiency (\%)} = \frac{I_{\text{rms}}^2 R_a}{IE} \times 100 .$$

where IE is the power drawn from the battery.

TABLE 3-1
System Performance Comparison

<u>System</u>	<u>I_{rms} (calc.)</u>	<u>I_{rms} (meas.)</u>	<u>Efficiency</u>
(a)	1.4 a	1.3 a	13%
(b)	3.7 a	3.7 a	34%

The current measured with system (a) is lower than the value calculated. This is attributed to the fact that the current could not rise to its maximum value because of the reactance of the circuit.

4.0 INTRINSIC SAFETY TESTS

The total energy of a LC resonant circuit at any instant in time is given by:

$$U = \frac{CV^2}{2} + \frac{LI^2}{2} .$$

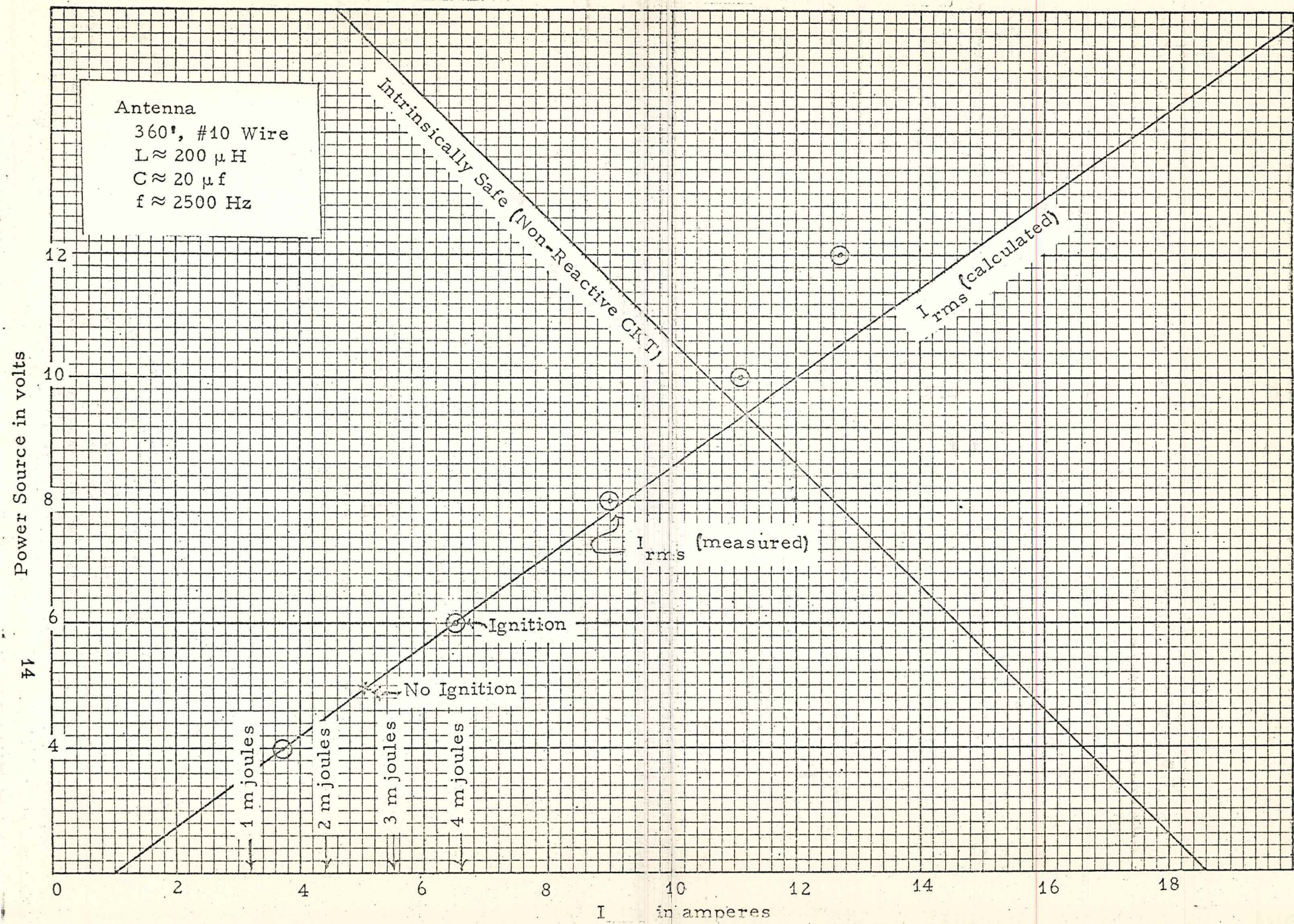
In order to be intrinsically safe, the spark generated by breaking the circuit should not ignite an 8.5% mixture of methane in air.

System (b) was tested at the U.S. Bureau of Mines Testing Laboratory in Pittsburgh for intrinsic safety limits, using a 360 foot, #10 loop antenna resonated to 2500 Hz. Antenna current was increased by increasing the voltage source in 1.2 volt increments until ignition occurred. Results are shown on Figure 4-1. Ignition occurred at about 4 millijoules, or with approximately 6.6 amperes (rms) in 200 microhenries. Between 2 and 3 millijoules the system was intrinsically safe. A value of 2.5 m joules is used in the following section as the intrinsically safe limit for a resonated circuit.

Values of I_{rms} measured in the laboratory using the same antenna are also shown in Figure 4-1 for comparison with calculated values of the current. The deviation of the measured points from the calculated curve at the higher current levels is attributed to increasing internal resistance of the switch elements because of heating.

Note that the intrinsically safe current limit is determined by the peak-to-peak value in the half-wave system (a) and just the peak value in the full-wave system (b). Thus it is possible to have at least twice the antenna moment with the system (b) than with system (a) and still maintain intrinsically safe conditions.

Figure 4-1. Intrinsic Safety Test Results.



5.0 PERFORMANCE BOUNDS ON OPTIMUM INTRINSICALLY SAFE SYSTEM

One basic criterion for judging the performance of an EM location system is the transmitter's antenna moment, INA, since this determines the detectable signal level as a function of depth and conductivity of the mine overburden.

It is possible to derive a relationship for the maximum intrinsically safe antenna moment which can be achieved in terms of length and size of wire used to form a loop. This is done in the following paragraphs.

The moment of a square loop can be expressed in terms of antenna length, l , and peak current, I_p , as:

$$I_{\text{rms}} NA = \frac{0.9 I_p l^2}{16 N} \quad \text{ampere turn meters}^2$$

It is obvious from this relationship that the maximum moment exists when $N = 1$.

Therefore,

$$I_{\text{rms}} NA (\text{max}) = 0.0562 I_p l^2$$

The peak current, I_p can be obtained from the energy storage equation,

$$I_p = \frac{\sqrt{2} U^{1/2}}{L^{1/2}}, \quad U = \int IE dt \quad \text{joules}$$

and the inductance of a single turn square loop in terms of the length of wire, l , and its diameter, d , can be obtained from:

$$L \text{ (henries)} = 0.008 \frac{l}{4} \left[2.303 \log \frac{l}{4d} - 0.52 \right] \times 10^{-4}$$

$$\approx 4.4 \times 10^{-7} l \log \frac{l}{4d},$$

where l and d are expressed in meters.

Substituting these relationships for I_p and l in the equation for maximum moment gives:

$$I_{\text{rms}} \text{ NA (max)} = \frac{0.0562 \times 1.414 U^{1/2} l^2}{\left[4.4 \times 10^{-7} l \log \frac{l}{4d} \right]^{1/2}}$$

$$\approx \frac{1.2 \times 10^2 U^{1/2} l^{3/2}}{\left[\log \frac{l}{4d} \right]^{1/2}}$$

The units are ampere-turn-meters² when l is expressed in meters and U in joules.

Tests conducted at the Bureau of Mines Testing Laboratory using a resonated loop antenna indicated that the maximum energy stored should notably not exceed approximately 2.5×10^{-3} joules in order for the system to be intrinsically safe. Substituting this value in the above equation gives:

$$I_{\text{rms}} \text{ NA (max)} \approx \frac{6 l^{3/2}}{\left[\log \frac{l}{4d} \right]^{1/2}}$$

Figure 5-1 shows a plot of $I_{\text{rms}} \text{ (max)}$ versus l obtained from this equation for a #10 AWG wire. The effect of wire size on the maximum intrinsically safe moment is shown in the following table for $l = 200, 500,$ and 1000 feet.

Figure 5-1. Maximum Intrinsicly Safe Antenna Moment Achievable with a Given Length of Wire for Resonated Square Loop Antenna.

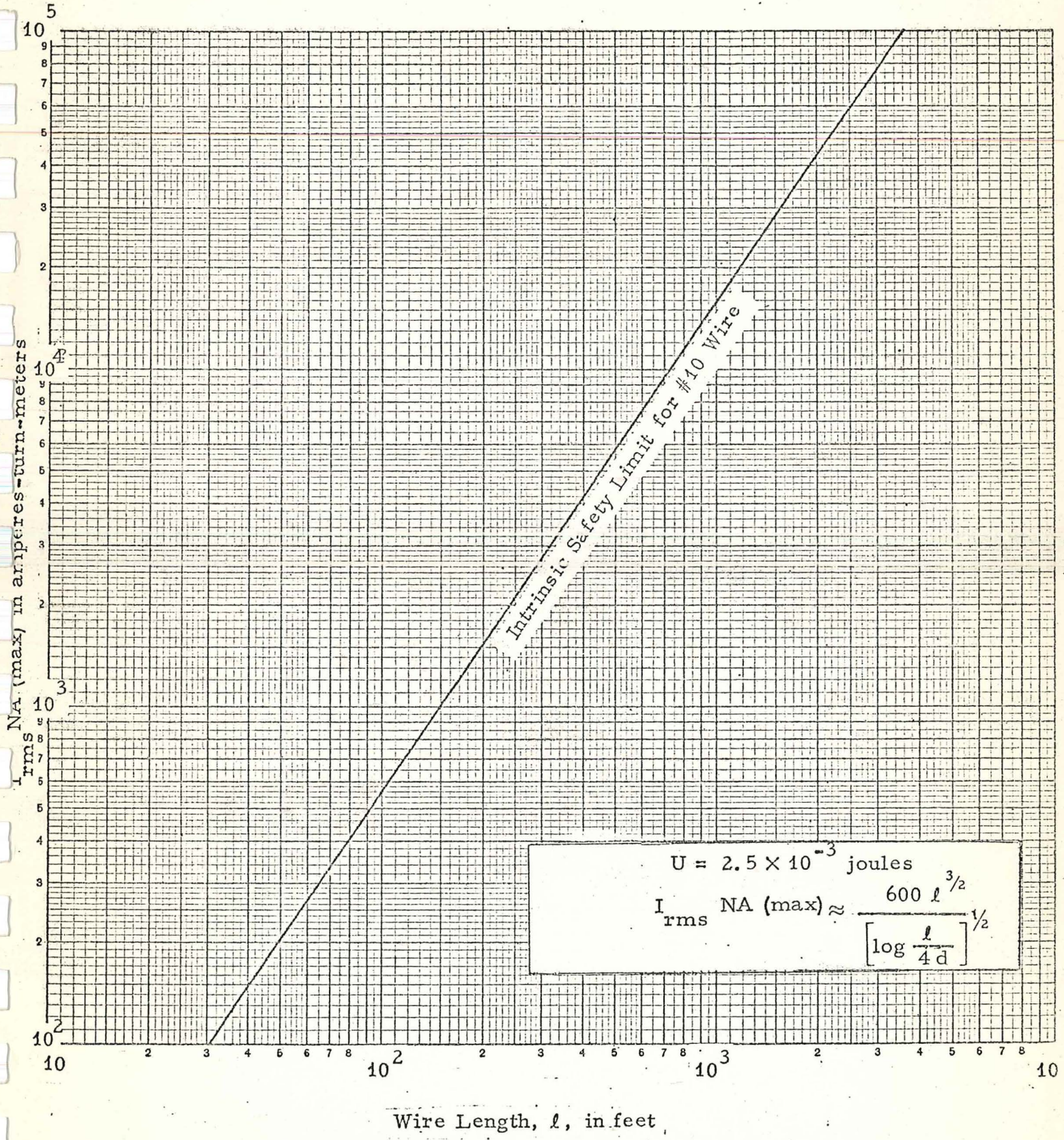


TABLE 5-1

Effect of Wire Size on Maximum Intrinsicly Safe Moment

AWG Wire Size	INA (max) in amperes-turn-meters ²		
	$l = 200'$	$l = 500'$	$l = 1000'$
#19	1390	5251	14390
#16	1416	5341	14622
#13	1442	5432	14855
#10	1471	5531	15106
# 7	1501	5632	15364
# 4	1533	5742	15643

Note that a moment increase is achieved as the wire size increases. This is because the inductance of the loop with a fixed length of wire decreases as the wire diameter increases.

Figure 5-2 shows the performance bounds on the EM location systems operating with a loop antenna consisting of 360 feet of #10 wire. Here the vertical component of the field, H_z , is plotted as a function of antenna moment and parametric in depth. A frequency of 2 kHz and effective earth conductivity of 10^{-2} mhos/meter is assumed.

On this curve the INA achievable with systems(a) and(b) are also indicated and these can be compared with the maximum intrinsically safe system assuming a 360', #10 wire is used for a square loop antenna in each case.

It is also possible to calculate the switching resistance required in the transmitter for achieving the maximum intrinsically safe moment, since:

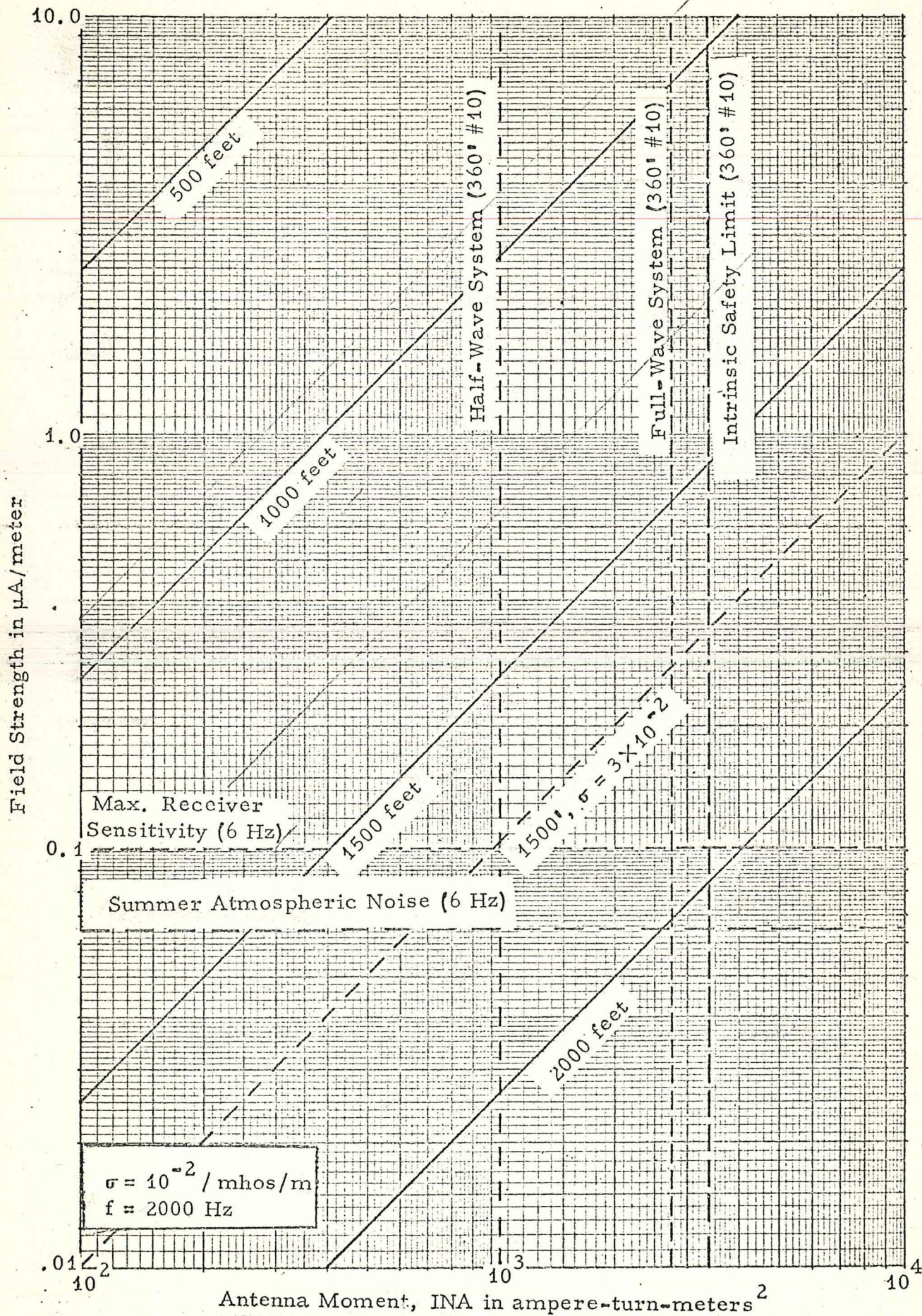
$$I_{\text{rms}} = \frac{0.9 E}{R_b + 2R_s + R_a} \approx \frac{6 l^{3/2}}{\left[\log \frac{l}{4d} \right]^{1/2}} \times \frac{16}{l^2} \approx \frac{96}{\left[l \log \frac{l}{4d} \right]^{1/2}}$$

Letting $R_b = 0.1$ ohms, $E = 4$ volts and solving for R_s yields:

$$R_s \approx 1.88 \times 10^{-2} \left[l \log \frac{l}{4d} \right]^{1/2} - 0.05 - \frac{R_a}{2},$$

where l and d are in meters and R_s and R_a are in ohms.

Figure 5-2. Performance Bounds on EM Location System.



Values for R_a , for a given length and size of wire can be found from wire tables. Results of this calculation are given in Figure 5-3, which indicates the minimum switch resistance that can be used for a given length of wire and still insure that the system is intrinsically safe. The negative values for R_s cannot, of course, be achieved in practice, but result from the fact that the equation is derived from maximum moment considerations.

Figure 5-3 can be used to show the range of usable wire lengths for a fixed switch resistance. For example, if the minimum switch resistance is 0.1 ohms and #10 wire is used, then the length of this wire must be either less than 120 feet or more than 1300 feet for the system to be intrinsically safe. Any length of #10 wire can be used if $R_s \geq 0.18$ ohms, $R_b = 0.1$ ohms, $E = 4$ volts, and a square loop configuration is used.

Figure 5-4 is derived from Figure 5-3 to show how the system design parameters, namely, wire size, internal switch resistance, and circumference of the square loop antenna, can vary for an optimum intrinsically safe system. Using this figure and the relationship for $I_{rms} NA$ (max) given previously, it is possible to calculate the maximum intrinsically safe moment as a function of internal switch resistance, R_s . Results are tabulated below for a 360 foot length of copper wire in a square loop configuration.

R_s (ohms)	Optimum Wire Size	Approximate Wire Weight (lbs.)	INA (max) ampere-turn-m ²
0.3	#4	50	3520
0.25	#7	25	3460
0.20	#9	15	3420
0.15	#10	12	3400
0.10	#11	9	3380
0.50	#12	7	3360
0.0	#13	5	3340

Figure 5-3. Switch Resistance Required For Optimum Inherently Safe Full - Wave System.

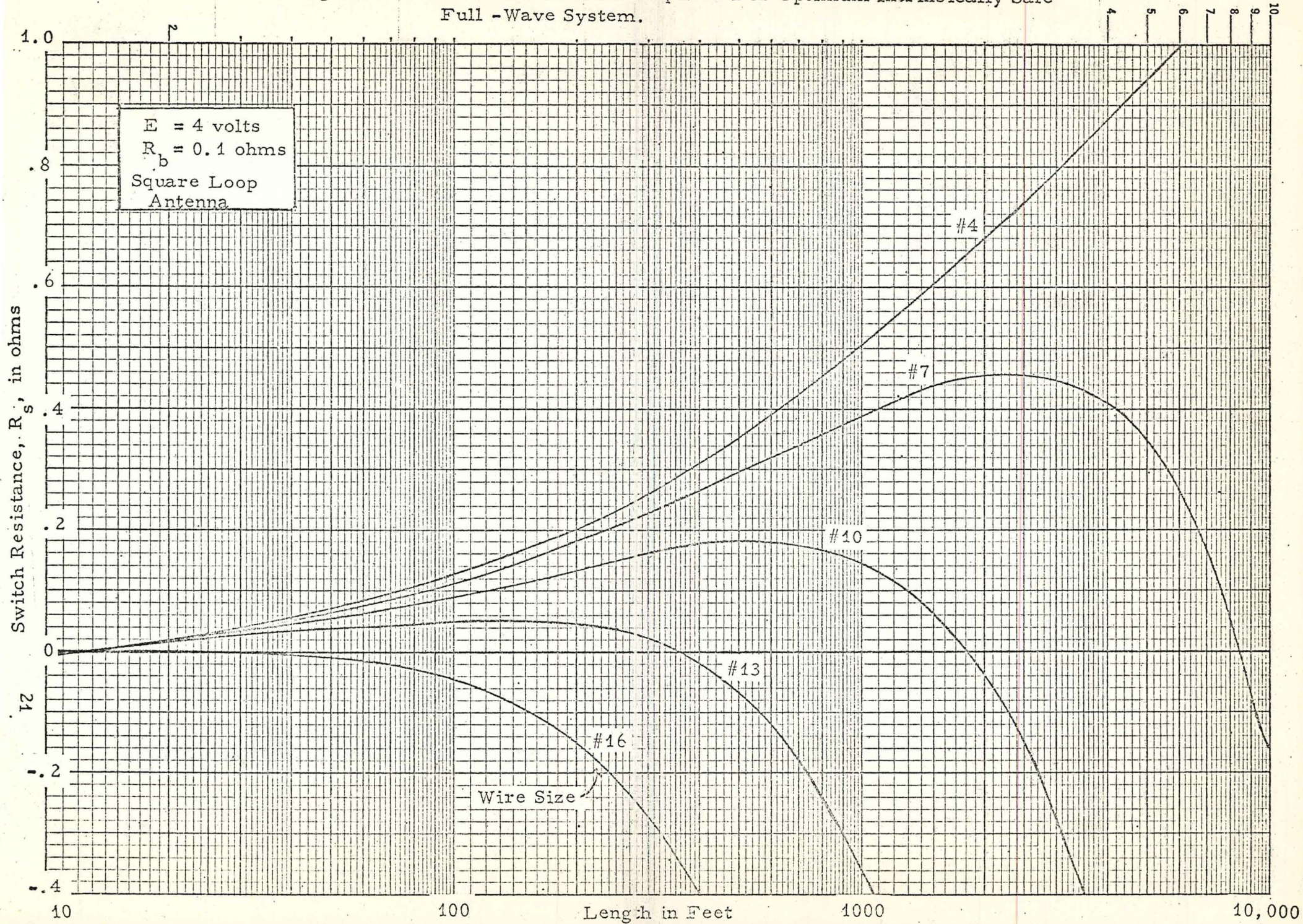
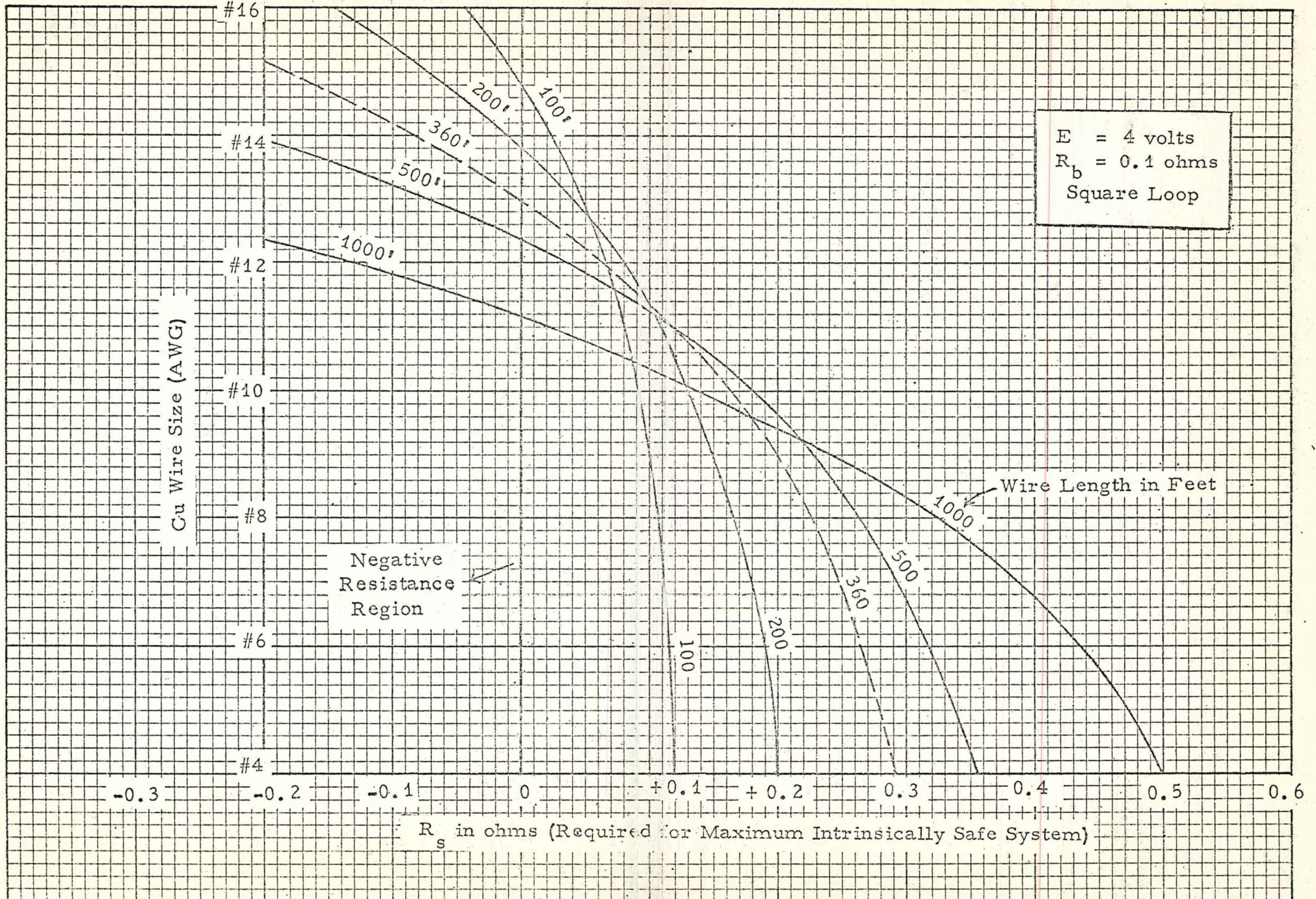


Figure 5-4. Wire Size vs. Switch Resistance for Optimum Intrinsicly Safe System.



22

This table indicates an interesting result. Reducing the switch resistance by a factor of two (0.3 ohms to 0.15 ohms) reduces the weight of copper required for the antenna by approximately a factor of four, but the maximum intrinsically safe moment decreases only about 3.5%.

Figure 5-5 indicates how the antenna current, I_{rms} , varies with antenna resistance, R_a , and switch resistance, R_s , assuming $E = 4$ volts, and $R_b = 0.1$ ohms. These curves can be used to determine the system's operating time for a given charge remaining on the battery, since

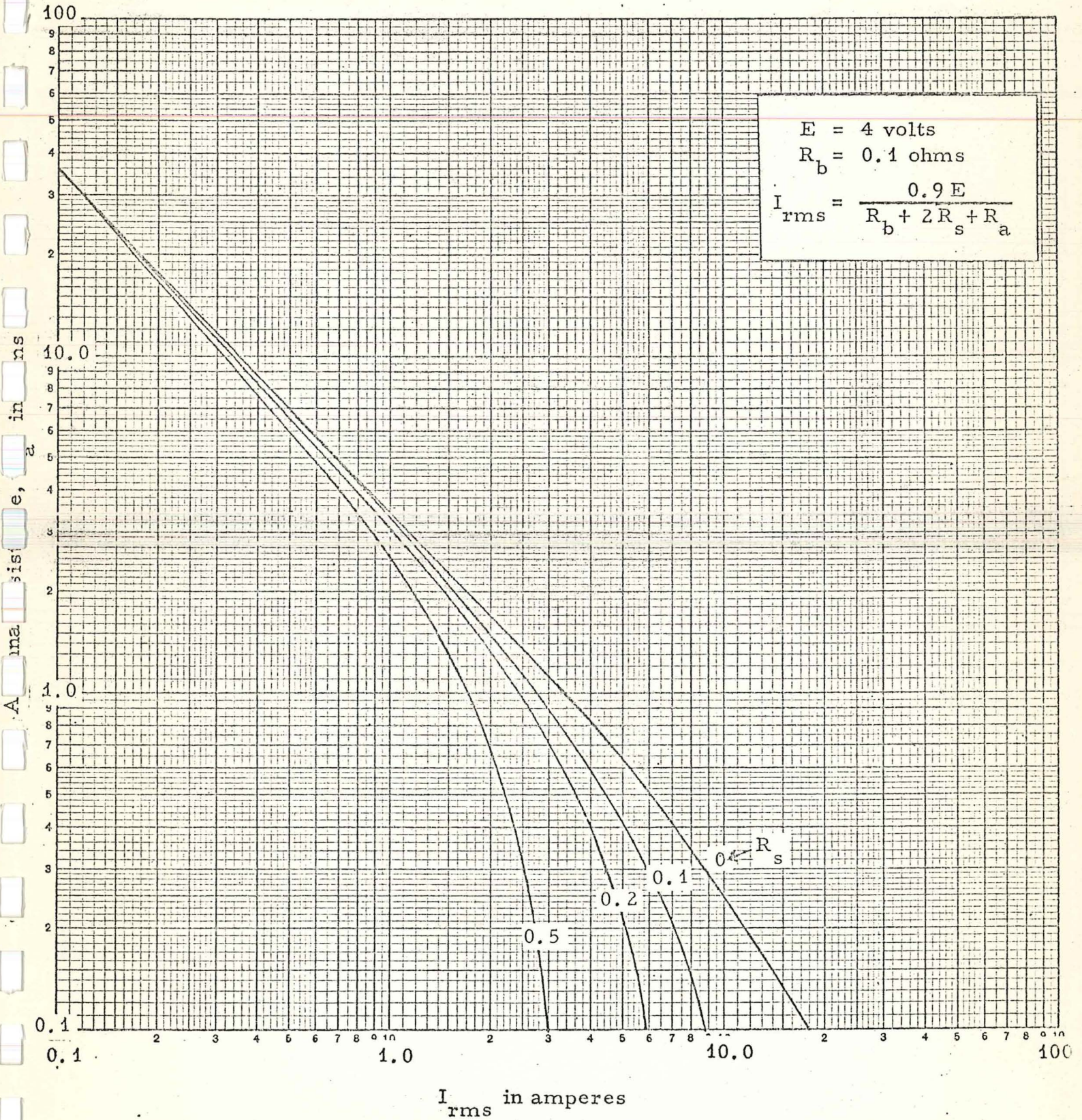
$$\text{Operating time} = \frac{\text{ampere-hours remaining} \times 100}{I_{rms} \times \% \text{ Duty Cycle}}$$

Take, for example, an optimum system using 360 feet of #10 wire and a fully charged battery and operating with a 10% duty cycle. From Figure 5-3, $R_s \approx 0.16$ ohms and from Figure 5-5, $I_{rms} \approx 4.5$ amperes.

$$\text{Operating time} \approx \frac{12 \times 100}{4.5 \times 10} \approx 27 \text{ hours}$$

Laboratory tests have been run (see Part II of this report) under conditions given above, except $R_s \approx 0.2$ ohms. The results obtained show a slow decrease in antenna current during the first day of operation and decreasing to almost half the initial value after 2 days of operation. This decrease is attributed to an increase of switch resistance as the source voltage decreases.

Figure 5-5. Antenna Current vs. Antenna Resistance for Full-Wave System.



6.0 PERFORMANCE SPECIFICATIONS FOR ONE OPTIMUM SYSTEM CONFIGURATION

We are now in a position to specify an optimum system from an intrinsically safe standpoint. The system considered here assumes a 360 foot square loop of #10 AWG wire for the antenna. The 360 foot length can be easily installed on a semi-permanent basis around coal pillars in most mines. The #10 insulated copper wire is readily available at electrical stores. The antenna weight is approximately 12 pounds. Table 6-1 specifies the characteristics of the intrinsically safe system. The system is only intrinsically safe if the antenna length and wire size given are not exceeded.

TABLE 6-1
Full-Wave Location Transmitter System Characteristics
(Intrinsically Safe System)

Power Source

Type:	Miner's Lamp Battery
Potential:	4 volts
Capacity:	≈ 12 ampere hours
Internal Resistance:	$R_b = 0.1$ ohms or higher

Transmitter Unit

Transmitter Type:	Full-wave, switching mode
Switching Resistance:	$R_s = 0.16$ ohms or more
Operating Frequency:	Single frequency selected to operate midway between 60 Hz harmonics (± 10 Hz) in 1000 to 3000 Hz frequency band
Frequency Accuracy:	± 2 Hz of selected operating frequency
Frequency stability:	$2 \times 10^{-5} / ^\circ\text{F}$
Signal Format:	Interrupted continuous square-wave into resistive load.
Duty Cycle:	On 0.2 seconds $\pm 10\%$ Off 2.0 seconds $\pm 10\%$

Antenna System

Type:	Insulated copper wire in square loop configuration
Length:	360 feet or less
Wire Size:	#10 AWG or larger gauge (smaller wire)

System Performance

Maximum Antenna Moment:	3400 ampere-turns-meters ²	
Operating Time: (fully charged battery)	Approximately 24 hours	
Maximum Detection Range: (assuming $\sigma = 10^{-2}$ mhos/m, receiver bandwidth = 6 Hz, and atmospheric noise limited)	<u>S/N (dB)</u>	<u>Range in ft.</u>
	0	2000
	20	1500
	40	1000

7.0 CONCLUSIONS AND RECOMMENDATIONS

Several useful (and interesting) conclusions can be drawn from the analysis. Some of the more important ones are enumerated below.

- a) The maximum moment (and therefore the performance) of a location transmitter for use in coal mines is limited by intrinsic safety considerations.
- b) Applications of intrinsic safe standards must consider the total system, i. e., both the transmitter power generator and the antenna used with that transmitter.
- c) In order to be intrinsically safe, the energy storage capacity of a resonated loop antenna should not exceed 2.5×10^{-3} joules.
- d) The resistance of each switch used in the full-wave transmitter determines the length and the size of wire which can be used for the loop antenna with that transmitter.
- e) The maximum antenna moment which can be achieved within the limits of intrinsic safety increases as $(\ell)^{3/2}$ where ℓ is the length of the wire. This maximum achievable moment also increases as the size of the wire increases.
- f) The maximum intrinsically safe antenna moment which can be achieved with 360 feet of #10 AWG wire is approximately 3400 ampere-turn-meters².

The transmitter development work described here is devoted primarily to systems for use in coal mines where intrinsic safety is an important consideration. The system can, of course, also be used in metal and hardrock mines where these intrinsic safety limitations no longer apply. However, in all types of mines where explosives may be used, the danger

of premature ignition of electric blasting caps resulting from location transmitters must be considered. It is recommended that a study be conducted and laboratory tests be performed to establish the susceptibility of blasting caps to this hazard. The breadboard unit, which can generate more than 10 amperes in a 360 foot #10 loop antenna by increasing the input voltage to 12 volts, could be used for this purpose. Measurements of the currents induced in nearby loops (simulating a blasting cap installation) should be measured as a function of range and orientation. Later similar tests could be performed at an independent testing laboratory using actual caps to verify the results.

Another aspect which should be considered is the use of a different type of antenna. The signal field strength observed on the surface using coaxial loop antennas is directly proportional to INA and an attenuation factor, $|G|$, which is related to skin depth and inversely proportional to the depth (Z) cubed, i. e., $H_z = \frac{INA |G|}{2\pi Z^3}$. Locations obtained by the null method are at the centroid of the loop antenna.

It is also possible to use a horizontal wire antenna terminated in the earth or on a roof bolt, whose length is equal to or greater than the depth. The field strength observed from this antenna is proportional to I and a different attenuation factor $|A|$ and inversely proportional to just the depth, i. e., $H_y = \frac{I |A|}{2\pi Z}$. The locations obtained by the null method are lines rather than points. This line on the surface should correspond to a vertical projection of the entry in which the antenna is installed.

A comparison of the two antennas can be demonstrated by assuming that a $10 \mu\text{A}/\text{meter}$ field must be available for location purposes. At a depth of 1000 feet and $\sigma = 10^{-2}$ mhos per meter, a 400 foot square loop of #10 wire carrying 4.3 amperes is required. Power consumed is approximately 18.5 watts on a continuous basis and the system operates at the limit of intrinsic safety.

Under these same conditions, a horizontal wire antenna 1000 feet long and carrying 0.7 amperes is required to give the same $10 \mu\text{A}/\text{m}$ field. Power consumed is 2.8 watts on a continuous basis. The difficulty with this

technique is that the total resistance of the system including the horizontal wire antenna cannot exceed 5.7 ohms, assuming a 4 volt power source. The resistance of 1000 feet of #10 wire is approximately 1 ohm and the existing transmitter resistance is about 0.5 ohms. Therefore, the antenna termination resistance would have to be less than 4.2 ohms. This low termination resistance would be difficult to achieve in low conductivity coal. By letting this system consume the same power as the loop system, the voltage can be increased to 26.5 volts and the total resistance to about 38 ohms, which is a more practical value for the termination resistance. This also puts the horizontal wire system at the intrinsic safety limits, assuming the circuit is non-inductive.

It is also recommended that several full wave transmitters be fabricated, using the design criteria established here. Each transmitter should be operated on a different frequency and field tested in a coal mine under simulated emergency conditions. Location receivers, both surface and airborne units, should be designed and constructed to operate in conjunction with these transmitters.

Further work is necessary to optimize the receiver. This is particularly true for the multifrequency airborne receiver, for use on a helicopter for signal search missions over the mine workings. The manpack location receiver's performance in terms of signal detectability and location resolution might also be enhanced by using differential electromagnetic field sensors. It is recommended that this technique be investigated, and if warranted, tested under operational conditions.

PART II

LABORATORY TESTS OF FULL WAVE TRANSMITTER

by

A. J. Farstad

C. Fisher, Jr.

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1.0 INTRINSIC SAFETY TESTS

Introduction

Part of the development effort in BuMines Contract No. H0220073 was spent on designing and testing a full-wave manpack transmitter circuit which would develop the maximum possible transmitting moment available from the 4 volt miner's cap lamp battery and operate within the intrinsic safety limits imposed by the Bureau of Mines for use in gassy mines. The most ignitable mixture of air and methane is one with approximately 8.5% methane. Such a mixture was prepared in a special test chamber at the Bureau of Mines Approval and Testing Group in Pittsburgh and was used to define the limit of intrinsically safe operation for this transmitter. The results of these tests and recommendations for increasing current moment while remaining within the bounds of intrinsic safety are given in the following sections.

Theory

By definition, an intrinsically safe circuit is a circuit in which any spark or thermal effect produced either normally or in specified fault conditions, is incapable under prescribed test conditions of causing ignition of a given gas or vapor [1]. Curves showing ignition characteristics of capacitive, inductive, and resistive circuits are given in Figures 1-3, respectively. These curves are based on dc experimental data obtained by Robert Wolfe of the Approval and Testing Group, U. S. Bureau of Mines, Pittsburgh, Pennsylvania. The test apparatus used to obtain these measurements consists of a rotating metal plate in contact with a metal whisker in a sealed enclosure. Grooves are cut in the metal plate and as it rotates, a break in the electrical circuit is produced everytime the groove passes under the whisker. The electrical circuit or apparatus to be tested is connected externally to the terminals of this enclosure and the plate is rotated in a gassy environment in the enclosure. The gas mixture used to

[1] British Approvals Service for Electrical Equipment in Flammable Atmospheres, "Intrinsic Safety" SFA 3012, 1972.

Figure 1. Intrinsic Safety for Capacitance as a Function of Voltage
 (8.1 - 8.6% by volume Methane - Air)

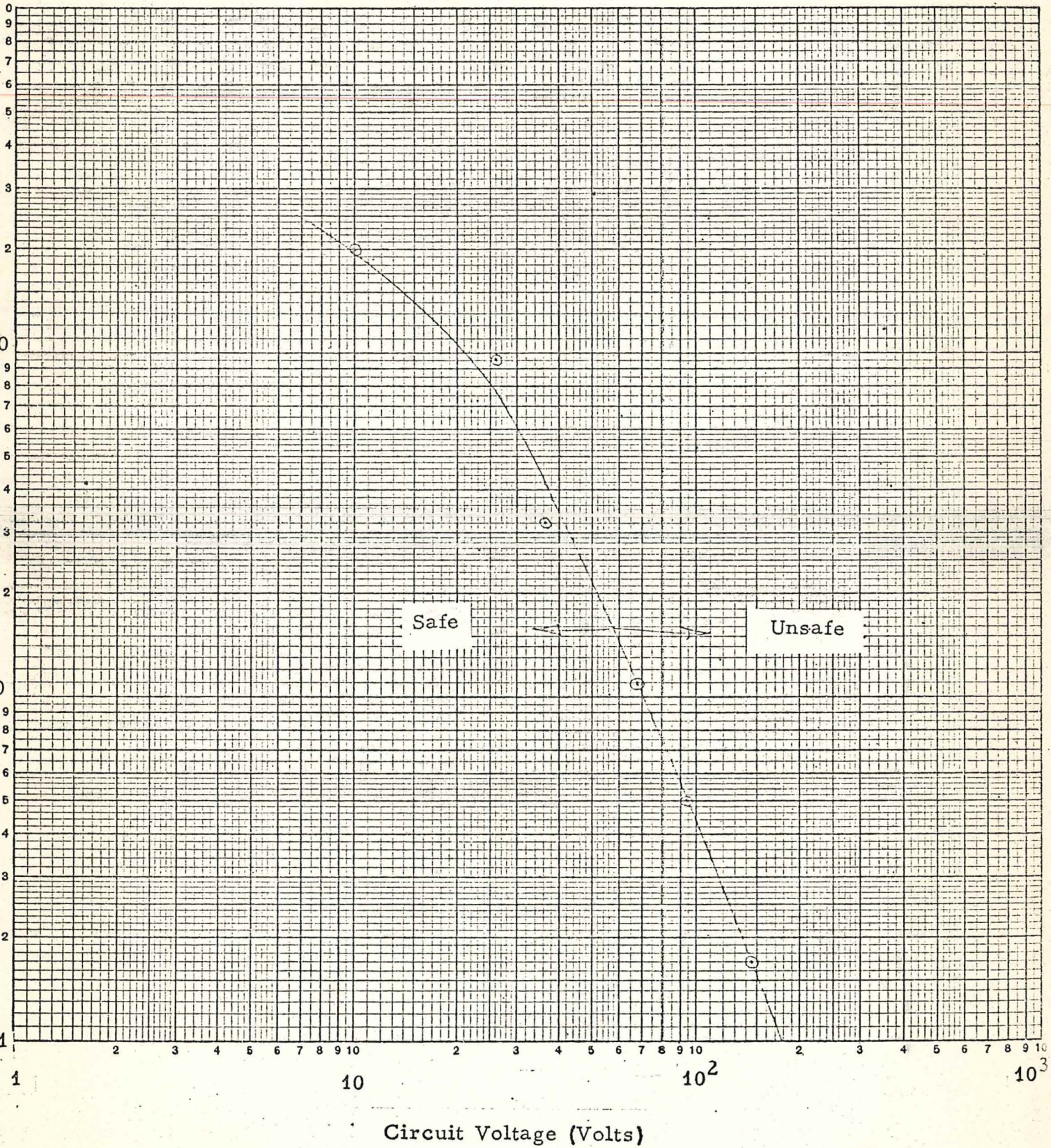
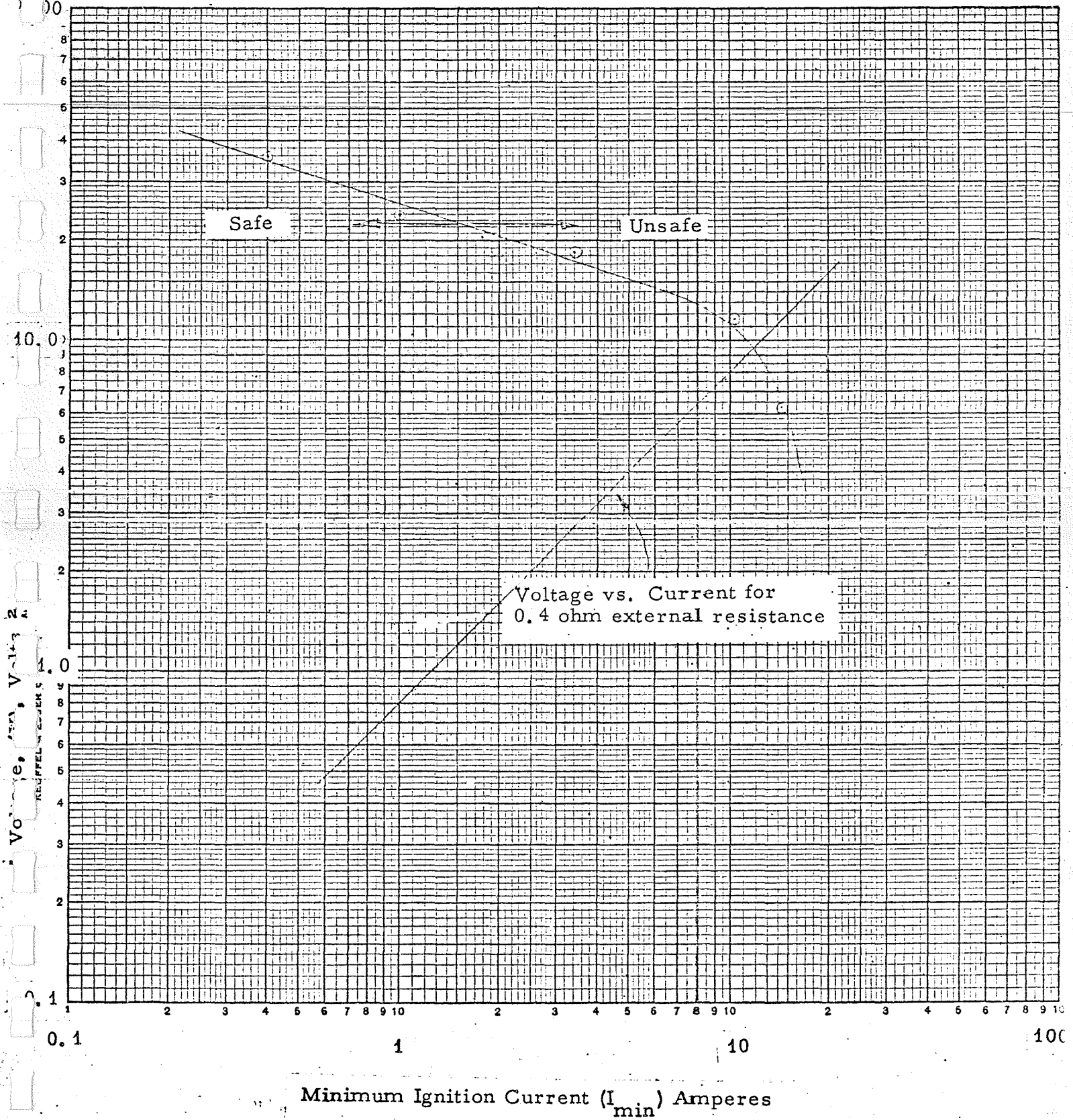


Figure 2. Intrinsic Safety for Inductance as a Function of Current
 (8.1 - 8.6% by volume Methane-Air)



Figure 3. Intrinsic Safety for Resistive Circuits as a Function of Voltage and Current.
 (8.1 - 8.6% by Volume Methane - Air)



obtain the curves in Figures 1 through 3 was a methane-air mixture with 8.1 - 8.6% methane by volume. The same apparatus was used to test the EM Full Wave Manpack Transmitter for intrinsic safety.

Test Configuration

A breadboard version of the EM Full Wave Manpack Transmitter was fabricated and taken to the BuMines Testing Lab. in Pittsburgh to determine its intrinsically safe operating limitations. This circuit is shown schematically in Figure 4. A simplified diagram of this circuit is shown in Figure 5 illustrating more clearly the full wave operating concept to obtain maximum output from the battery. The load in this case consists of a 350 ft.* length of No. 10 AWG wire wound in the form of a single turn loop and tuned by a series capacitor of 20 μ F.

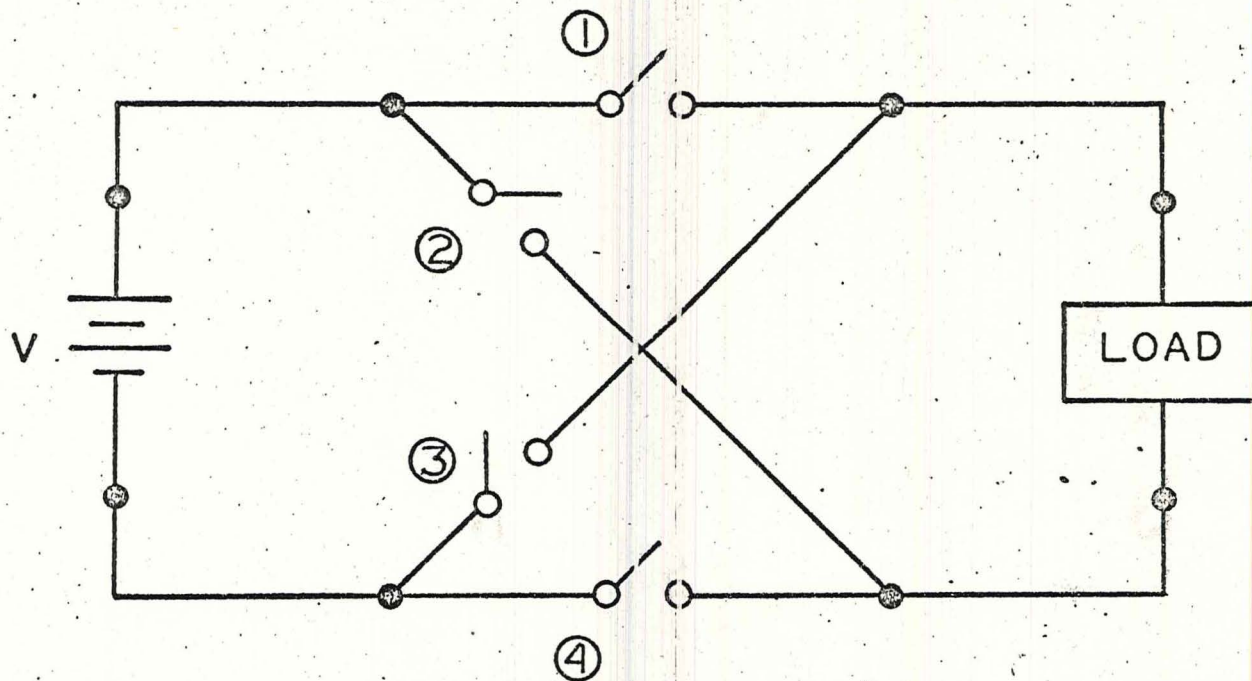
Prior to running these tests, an analysis was made to estimate what current levels could be handled by the inductance and what voltage levels could be handled by the tuning capacitance of 20 μ F under ac conditions operating at a frequency of 2500 Hz. For these conditions, the following reactances are observed in the series tuned antenna circuit:

$$C = 20 \mu\text{F} \quad X_c = \frac{1}{\omega C} = 3.2 \text{ ohms}$$

$$L = \frac{1}{\omega^2 C} = 205 \mu\text{henries} \quad X_L = \omega L = 3.2 \text{ ohms}$$

The maximum instantaneous voltage that a capacitor develops in an ac circuit such as this is the peak sine wave voltage. Figure 1 indicates that the maximum dc voltage that should appear across a 20 μ F capacitor to still be intrinsically safe is 9.6 volts. Since the capacitive reactance of 20 μ F is 3.2 ohms at $f = 2500$ Hz, this represents a limiting peak ac current of $\frac{9.6}{3.2} = 3$ amperes.

* There is an apparent discrepancy between the 350 ft. antenna referred to in this section and the 360 ft. antenna in Part 1. The actual antenna used in the experiments was measured at 350 ft. The 360 ft. length used in the theoretical calculations in Part 1 is based on a nominal 90 ft. \times 90 ft. coal pillar.



Drive for Transistors
① & ④ is 180° out of
phase with drive for
Transistors ② & ③

Figure 5 Full Wave Switching Arrangement.

Thus, the maximum rms current allowable in this circuit, based on dc data, is $3(0.707) = 2.12$ amperes. From an inductance standpoint, Figure 2 shows that the maximum current allowable in an inductor of 205 μ henries is 2.3 amperes peak or 1.62 amperes rms. (Note: The lower part of the curve in Figure 2 is an extrapolation of the curve defined by the measured points and could be somewhat in error. Using the curves given in Reference [1] for inductive circuits of 200 μ henries, the maximum allowable working current is 1.3 amperes dc.) Figure 3 shows that for purely resistive loads, the minimum ignition current for a four volt source is on the order of 16 amperes. The present system has a total circuit resistance of about 0.8 ohms when driving a 0.4 ohm resistive load. Figure 3 shows that the maximum dc voltage, that could be used safely to drive this non-reactive load, is 15 volts.

Measurement Results

Several different voltage sources were used in the laboratory to determine the intrinsically safe area of operation for the test transmitter. The antenna was tuned with a series capacitance of 20 μ F and the transmitting frequency was 2500 Hz with an on-off duty cycle of one second on and one second off. Table 1 gives a summary of the results obtained in this test.

TABLE 1

V_{dc} (volts)	Battery	I_l (amps, peak)	Ignition
3.6	Cad Lamp	3.75	No
4.0	Ni Cad	4.0	No
4.8	Ni Cad	4.38	No
6.1	Ni Cad	6.75	Yes
12.0	Dry Cell	7.5	Yes

The intrinsic safety test set-up is shown in Figure 6a and the current waveforms obtained for two of the conditions tested are given in Figure 6b. The lower figure is representative of operation at the highest intrinsically safe voltage that was tested. These results show that in practice a higher peak current is permissible than that predicted from the minimum ignition curves given in Figure 1-3. Part of the reason for this discrepancy may be in the fact that the minimum ignition curves were based on opening and closing a dc circuit with a 24-volt battery source, and the test results here were obtained for an ac source (square wave) driving a series-tuned LC circuit.

Conclusions

From these tests it can be safely concluded that the full wave switching amplifier in its present configuration is intrinsically safe when driving a series tuned, single turn 350 foot perimeter loop from a source voltage equivalent to a miner's cap lamp battery of 4 volts. To boost the source voltage to 6 volts in the present configuration would render the amplifier unsafe. Furthermore, if the total circuit resistance were lowered by using heavier wire in the antenna or improving the efficiency of the transistors such that the peak current would reach 6.75 amperes for a 4 volt battery source, it would also become unsafe. This does not mean that no benefit can be gained by improving the efficiency of the switches. If the switch resistance were less, however, then the antenna resistance would have to be increased proportionately (smaller wire for same length) in order to maintain intrinsically safe operation.

Tuning the antenna results in an effective increase in output current of more than a factor of 3 at 2500 Hz. These transmitters should therefore be designed to contain the proper tuning capacitor (built in) for the frequency of the particular tuning fork in the oscillator. In order for this scheme to be feasible, it is necessary to standardize the type of transmitting antenna so that in the event the antennas were predeployed in selected locations in the mine that each manpack transmitter would be compatible with each antenna.

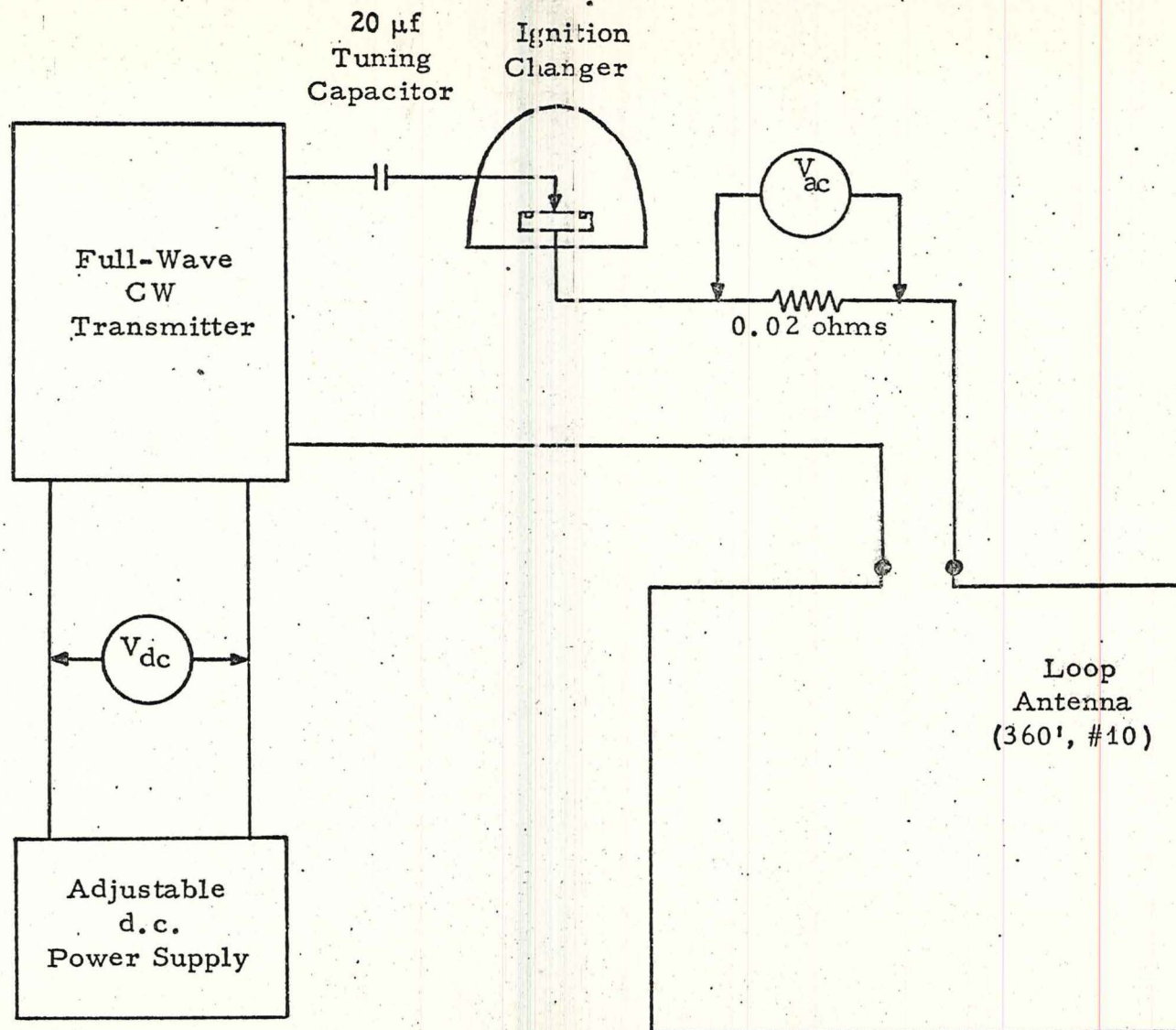
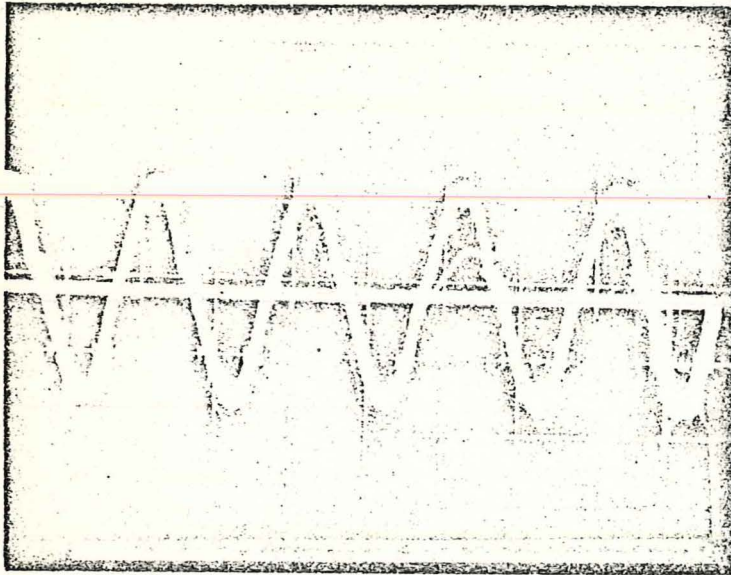
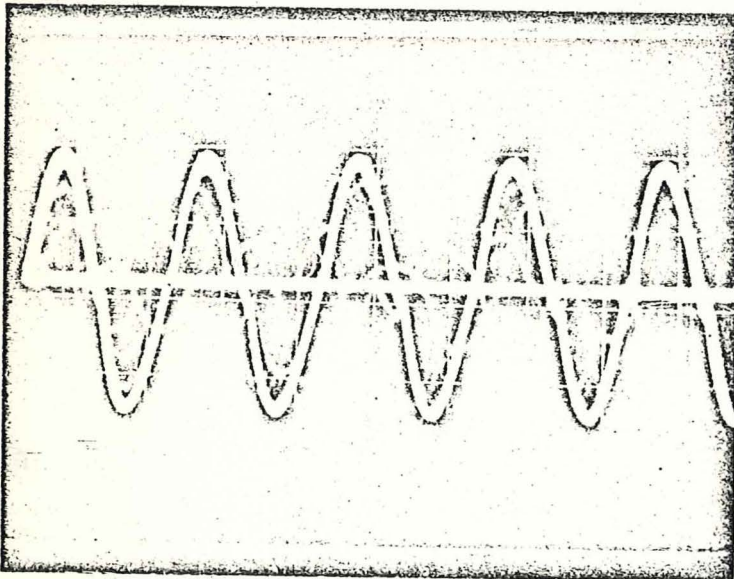


Figure 6a. Intrinsic Safety Test Set-up.



V = 3.6 volts
(Cap Lamp Battery)
I = 7.5 amps peak-peak

Frequency: 2500 Hz
Antenna: 350 foot, #10 Loop,
Resonated with 20 μ F



V = 4.8 volts
(Nickel Cadmium Batteries)
I = 8.75 amps peak to peak

Figure 6b. Antenna Current Waveforms under Intrinsically Safe Conditions.

However, tuning is not extremely critical in these relatively low Q antenna circuits. Assuming that a 3 dB current degradation was allowable, there could be as many as 14 different operating frequencies, 60 Hz apart, which would be compatible with a standard antenna tuned for a frequency of 2500 Hz.

2.0 BATTERY LIFE TEST FOR THE EM FULL-WAVE TRANSMITTER

The operating lifetime to be expected from the EM full-wave manpack transmitter with a 9 percent duty-cycle CW transmission; e. g., 2.0 seconds off and 0.2 seconds on, was found to be 57 hours of continuous operation. The battery life test was performed using a fully charged, 4-volt miner's lamp battery* to power the EM full-wave manpack transmitter with 350 feet of No. 10 wire as the antenna. Figure 7 is a block diagram of the actual test configuration.

The parameters measured during the test period were the battery supply voltage for both the transmitter "on" and "off" times and the antenna peak-to-peak sine wave current. As shown in Figure 7, the Esterline Angus graphic recorder provided a continuous record of the battery supply voltage throughout the test period with the HP 427A voltmeter being used to spot check the recorder's accuracy. A continuous record of the antenna load current was not obtained. However, it was measured and recorded at regular intervals using a 0.02 Ω resistor in series with the antenna load and a HP 141A storage oscilloscope.

Figure 8 is a plot of the measured parameters for a 90-hour period. The graph shows a continuous operating period of 57 hours. The steady decrease in the rms antenna current with time is the result of decreasing switching efficiency and/or increasing internal resistance of the complementary silicon power transistors driving the antenna load with decreasing power supply voltage. Note that the minimum discharge level of the miner's battery will be 3.62 volts dc and that the discharge is very slow and continuous; e. g., not a rapid discharge rate near the end of the transmitting period as seen when employing a continuous dc load on the battery. In an actual mine emergency situation, it would be advisable to place more than one battery in parallel to prolong the operating life even further.

* MINE SPOT cap lamp battery manufactured by Mine Safety Appliance, Co., Pittsburgh, Pa.

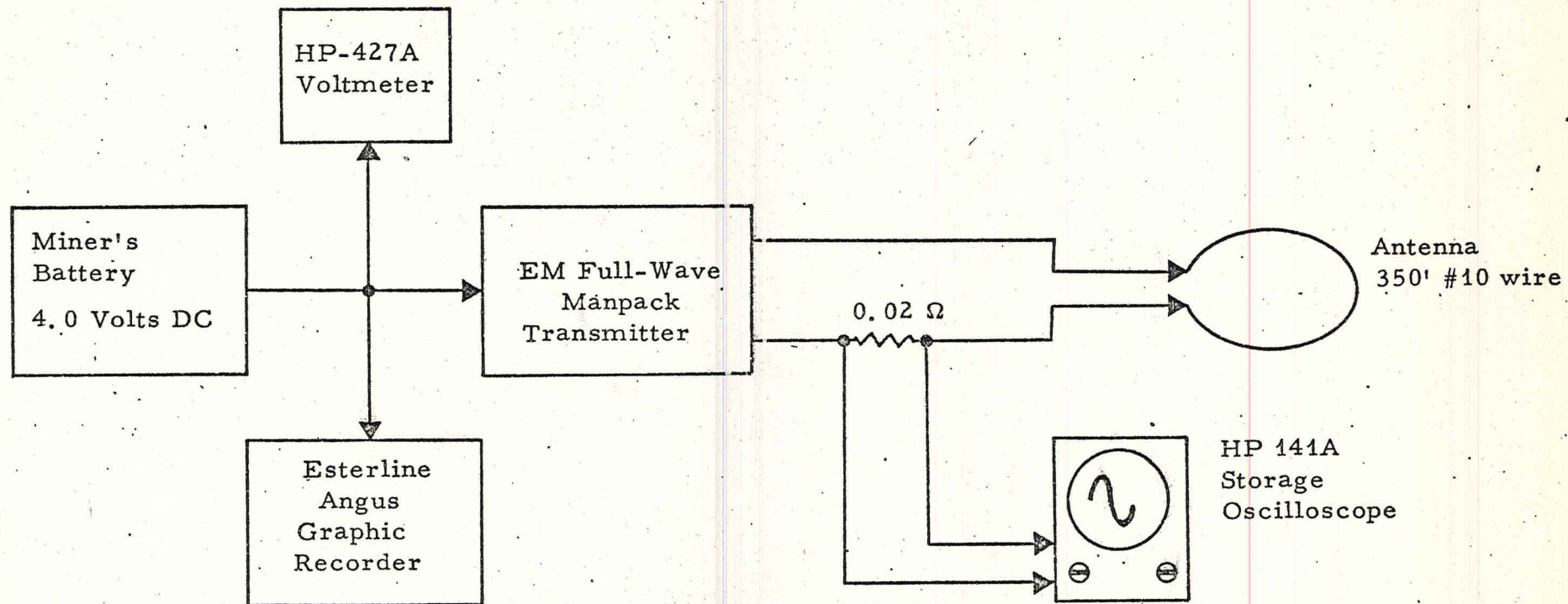


Figure 7. Block Diagram for Battery Life Test

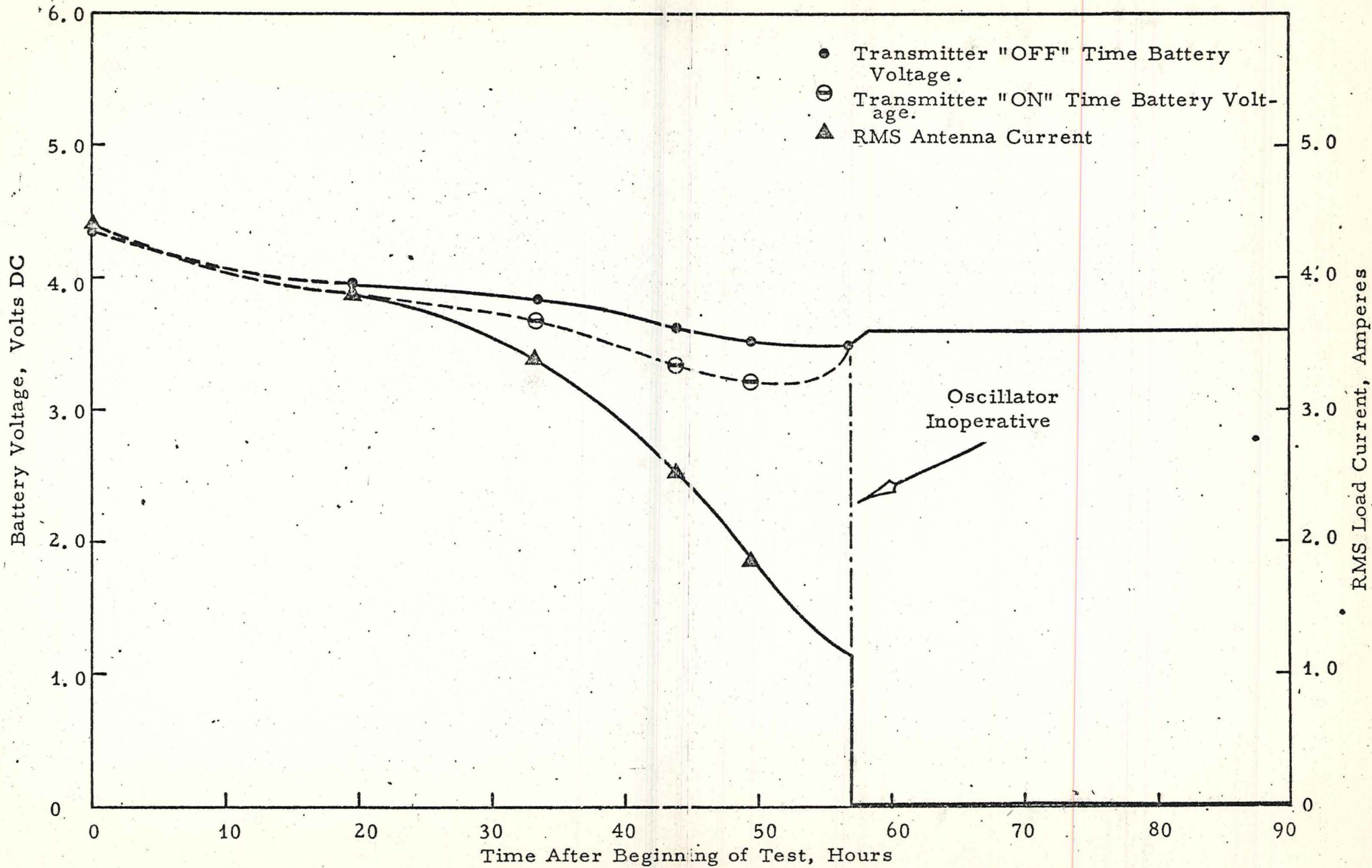


Figure 8. Battery Life Test for the Circuit Configuration Shown in Figure 4

3.0 COMPARISON OF TWO COMPLEMENTARY TRANSISTOR NETWORKS

The Westinghouse EM full-wave manpack transmitter tested initially incorporated type MJE 1090 (PNP) and MJE 1100 (NPN) medium-power complementary silicon transistors to drive a low impedance antenna load. In order to fully optimize the manpack transmitter's transmitting power capabilities, two each of the MJE 1090 and MJE 1100 power transistors were placed in parallel to effectively reduce the transistor's internal resistance and increase the transmitting antenna current for a specific dc power supply voltage.

It was subsequently reasoned that the use of a complementary silicon transistor pair with a higher power handling capability may eliminate the need to parallel the MJE 1090/MNE 1100 power transistors, and possibly increase the system's transmitting power capabilities. The type MJ4032 (PNP) and MJ4035 (NPN) medium-power complementary silicon transistors were selected for comparison purposes.

Figure 9 show the test configuration used to obtain data for this comparison. The fundamental sine wave component of the output signal was measured using a 0.02 Ω resistor in series with the antenna load using the R.M.S. reading HP 302A wave analyzer, and the Tektronix Model 503 oscilloscope was used to obtain a qualitative comparison of the square wave output distortion. The test was conducted for dc supply voltages ranging from + 3.5 volts to +10.0 volts. Tables 2 and 3 are a compilation of the data obtained for analysis.

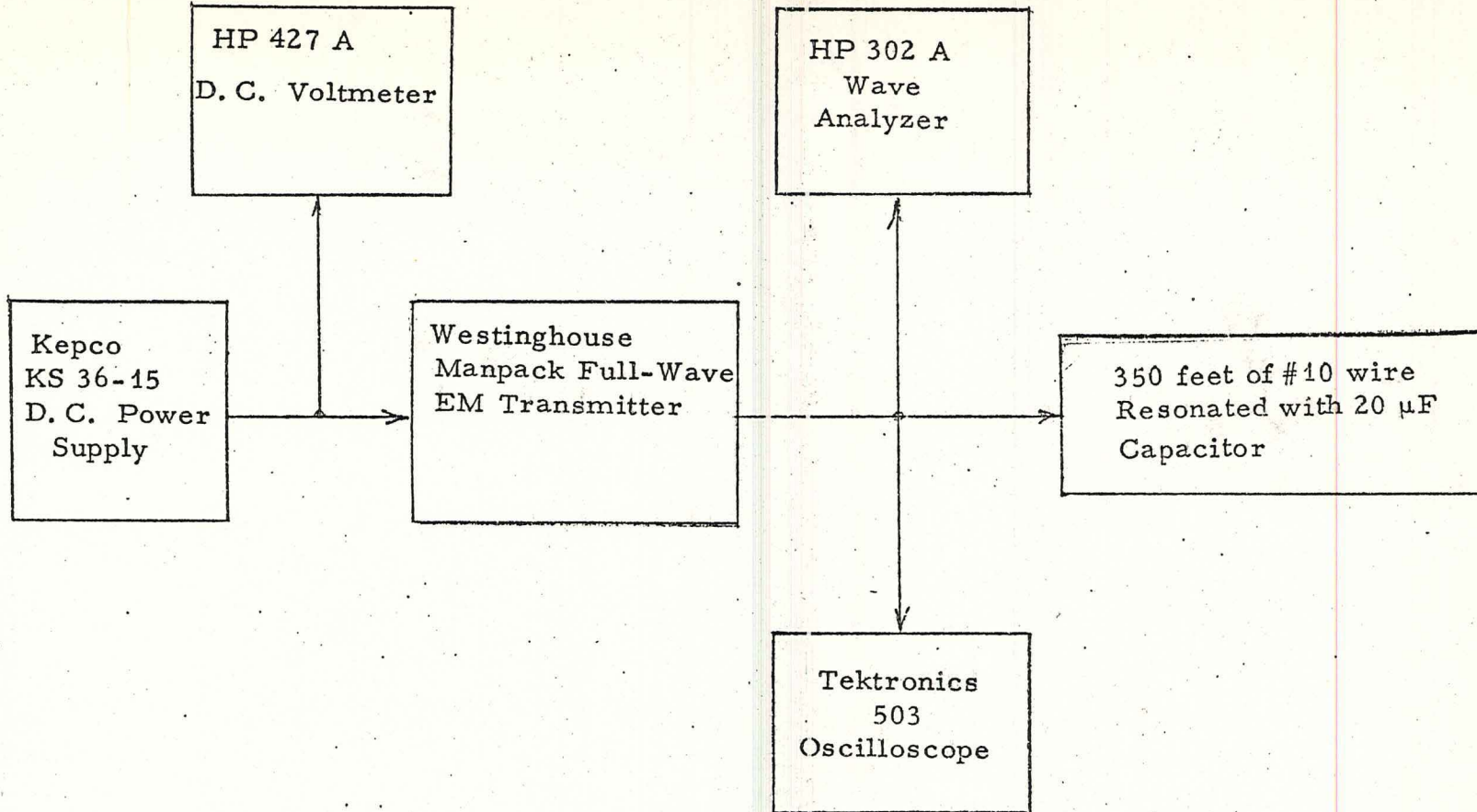


Figure 9. Block Diagram of Test Set-Up for the Comparison of Complementary Silicon Transistors.

The presently used circuit configuration, with the MJE 1100/MJE 1090 complementary power transistors, was tested initially and then the MJ4032/MJ4035 complementary power transistors were substituted directly into the circuit and the test repeated. The data shown in Tables 2 and 3 show that the MJ 4032/MJ 4035 complementary power transistors offers an advantage over the MJE 1100/MJE 1090 complementary power transistors for the entire power supply range tested. The most significant advantage becomes apparent at the +3.5 volt supply voltage point when the percent increase in fundamental sinewave output current is considered as shown in Table 4. The 14 percent increase at +3.5 volts is due to the greater switching efficiency of the MJ 4032/MJ 4035 transistors at low voltages and resulted in an output waveform that exhibited less signal distortion than the MJE 1100/MJE 1090 transistors.

Table 4

Percent Increase in Fundamental Sinewave Current of the MJ 4032 - 4035 Transistors over the MJE 1100-1090 Transistors

Power Supply (dc volts)	Increase in Fundamental Sinewave Current (%)
3.5	14
4.0	3
4.5	2
5.0	0
5.5	4
6.0	2
6.5	4
7.0	1
7.5	2
8.0	3
8.5	2
9.0	2
9.5	2
10.0	3

Table 2

Data for the MJ 4032 and MJ 4035 Complementary Power Transistors
Driving a 350 foot, #10 Wire Antenna Load

Supply Voltage (dc volts)	Sinewave Output across 0.02Ω (rms volts)	Output Current (rms amperes)	R_T Transistor (ohms)
3.5	0.063	3.2	0.30
4.0	0.078	3.8	0.27
4.5	0.083	4.4	0.26
5.0	0.099	5.0	0.26
5.5	0.120	5.9	0.22
6.0	0.134	6.6	0.21
6.5	0.152	7.5	0.19
7.0	0.163	8.0	0.19
7.5	0.177	8.8	0.19
8.0	0.187	9.4	0.18
8.5	0.201	10.0	0.18
9.0	0.212	10.6	0.18
9.5	0.226	11.2	0.18
10.0	0.237	11.8	0.18

Table 3

Data for the MJE 1100 and MJE 1090 Complementary Power Transistors
Driving a 350 foot, #10 Wire Antenna Load

Supply Voltage (dc volts)	Sinewave Output across 0.02Ω (rms volts)	Output Current (rms amperes)	R_T^* Transistor (ohms)
3.5	0.057	2.8	0.36
4.0	0.074	3.7	0.29
4.5	0.081	4.3	0.27
5.0	0.100	5.0	0.24
5.5	0.117	5.7	0.23
6.0	0.131	6.5	0.22
6.5	0.145	7.2	0.21
7.0	0.159	7.9	0.20
7.5	0.173	8.6	0.19
8.0	0.184	9.1	0.20
8.5	0.198	9.8	0.19
9.0	0.209	10.4	0.19
9.5	0.219	11.0	0.19
10.0	0.230	11.5	0.19

*. This is the resistance of a parallel combination of transistors. The single transistor resistance is twice the value shown.

The test results indicate three advantages for using the MJ 4032/MJ 4035 complementary power transistors instead of the MJE 1090/MJE 1100 complementary power transistors. The advantages are:

- (1) The MJ 4032/MJ 4035 transistors have a greater switching efficiency at low d-c supply voltages, below 6.0 volts dc, resulting in less square-wave output signal distortion and hence a higher fundamental sine wave current component.
- (2) The MJ 4032/MJ 4035 transistors have a higher power rating, 150 watts, than the MJE 1090/MJE 1100 transistors, 70 watts, which allows for operation at a level well below their maximum stress levels.
- (3) The internal resistance of the MJ 4032 and the MJ 4035 transistors is less than the individual MJE 1090 and MJE 1100 transistor units, thereby allowing the use of fewer discrete components to achieve the same function.

The cost comparisons show that the MJ 4032 and MJ 4035 are about three times more expensive than the single MJE 1090/1100 units. However, since only one unit is needed for each switch, the savings realized by a smaller number of parts and shorter fabrication time virtually nullifies this cost disadvantage.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The EM Full Wave Manpack Transmitter in its present configuration can be declared intrinsically safe when driving a 350-foot, AWG No. 10 wire loop antenna from a miner's 4-volt cap lamp battery by virtue of its passing the intrinsic safety test at the U. S. Bureau of Mines. This transmitter and antenna system would no longer be intrinsically safe if, for instance, two miners' cap lamp batteries were connected in series to provide an 8-volt power source. Resonating the antenna with a series capacitor effectively increases the output current by a factor equal to the Q of the transmitting circuit. At 2500 Hz, this amounts to an effective increase of about 3.5 over the nonresonated current. Another advantage of tuning the loop is that all of the transmitted energy is contained in the fundamental frequency eliminating any possible harmonic interference between more than one transmitter in a multifrequency system. Yet a third advantage gained by tuning the loop is the elimination of current transients in the output waveform, thus further enhancing the intrinsic safety of the device.

In view of the advantages gained by tuning the antenna, it is recommended that each individual transmitter contain its own tuning capacitor, compatible with a standardized transmitting antenna and the frequency of the self-contained tuning fork.

The effective battery life of the Full Wave Manpack Transmitting Antenna is almost 60 hours when driving a 350-foot, No. 10 AWG loop of wire at a nine percent duty cycle. The rms output current falls off in a nonlinear manner, decreasing slowly for the first 20 hours and falling off more rapidly after 30 hours until at 50 hours it has been reduced to half its initial value. This battery life should be sufficient for most coal mine rescue situations, since it has been shown in an earlier report that a reconnaissance EM survey can be flown by helicopter over a 4 x 2 mile section of a relatively deep mine in slightly more than one hour.

Finally, the Full Wave Manpack Transmitter initially bread-boarded and tested could be improved by replacing the double MJE 1100/ MJE 1090 complementary switch networks with equivalent single MJ 4035 and MJ 4032 higher power switches. With the latter transistors, the output current increases slightly, the waveforms are cleaner and half as many components are needed in the power output circuit. Therefore, in spite of a slightly higher cost, it is recommended that the MJ 4035 and MJ 4032 be used in place of the double MJE 1100's and MJE 1090's shown schematically in Figure 4.