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THE EFFECTS OF ELECTROMAGNETIC PULSE (EMP) ON STATE AND LOCAL RADIO COMMUNICATIONS

Paul R. Barnes

Oak Ridge National Laboratory

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HEALTH PHYSICS DIVISION

Civil Defense Research Section

THE EFFECTS OF ELECTROMAGNETIC PULSE (EMP)
ON STATE AND LOCAL RADIO COMMUNICATIONS

Final Report
by

Paul R. Barnes

for

Defense Civil Preparedness Agency
Washington, D. C.   20301

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ABSTRACT

The electromagnetic pulse (EMP) produced by a high-altitude nuclear detonation consists of a transient pulse of high intensity electromagnetic fields. These intense fields induce current and voltage transients in electrical conductors. If these transients are well coupled to electronic circuits, equipment malfunction or failure may result. In this study, analytical, numerical, and experimental techniques have been used to determine the effects of EMP on the two-way radio communication systems available for civil defense.

The results of this study indicate that the probabilities of failure for two-way radio communication systems without EMP protection is a strong function of the radio carrier frequencies that compose the electromagnetic links of the systems. The probabilities of failure are also a relatively strong function of the EMP's amplitude and time history, the active electronics components' employed in the communications equipment, gain and type of antennas in the system, the use of RF overload protection, and system configurations.

As a specific example, the probabilities of failure for some typical communication systems subjected to a long EMP with a higher than average amplitude are: (1) near 1.0 for Radio Amateur Civil Emergency Service (RACES) 3.997 MHz tube-type systems with vertical tower antennas, (2) near 1.0 for VHF low band and CB solid state systems with receiver RF overload protection of 10 dB, (3) about 0.8 for VHF high band solid state systems employing a repeater station with a 10 dB gain antenna and receiver RF overload protection of 10 dB, and (4) about 0.6 for UHF solid state systems employing a repeater station with a 10 dB gain antenna and receiver RF overload protection of 10 dB.

The probability of communications failure for these systems can be reduced to near zero by implementing a recommended emergency preparedness program. This program consists of providing low-cost EMP protection for the systems and emergency back-up equipment for some essential system components.

CHAPTER I

INTRODUCTION

1.1 BACKGROUND

Communications is a key element in civil defense (CD) efforts to mobilize and integrate the diverse human and material resources of the community, state, and nation in response to the threat of nuclear attack. Defense Civil Preparedness Agency (DCPA)* research studies have detailed the requirements and resources needed for CD emergency communications and have called attention to the vulnerability of communications systems to nuclear effects.

This study is a continuation of previous DCPA efforts to determine the effects of nuclear electromagnetic pulse (EMP) on CD communications systems. In this report we have focused on the problem of understanding the effects of EMP on two-way radio communications equipment and systems and, where possible, of proposing measures to reduce the probability of damage.

1.2 OBJECTIVE AND SCOPE

The objectives of Task Order 2213G, under which this report was prepared, are:

> "To determine what categories of radio communications systems available for civil defense operations at the state and local levels are vulnerable to EMP associated with high altitude nuclear explosions, and to develop cost-effective measures and equipment to reduce the probability of those communications systems being damaged by EMP."

The scope of this report is as follows:

> Review the two-way radio communications equipment and systems available for CD emergencies at the state and local levels to determine representative equipment and systems for analysis. Analyze the effects of EMP on such equipment and systems and categorize them according to the nature and probability of damage they would suffer as a result of EMP's of typical magnitudes. And propose measures and equipment to eliminate such damage or at least reduce the probability thereof.

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*Formerly the Office of Civil Defense.

Maritime and aeronautical radio communications systems are not considered in this effort. Also CD communications systems available for civil emergency operations at the national level are not considered within the scope of this work.

1.3 THE EMP ENVIRONMENT

The detonation of a nuclear weapon is accompanied by an electromagnetic pulse (EMP) with a large portion of its energy within the radio frequency spectrum. The characteristics of EMP have been described in previous reports.[1,2,3] A brief description is repeated here in order to give the assumptions used in this study.

The electromagnetic fields radiated from nuclear detonations vary greatly with the weapon yield and detonation location. A strong EMP is produced by both low and high altitude detonations. The fields produced by low altitude detonations attenuate quickly with distance from the blast and are normally accompanied by shock waves. Exoatmospheric detonations, however, produce high intensity fields that are relatively free from the other nuclear weapon's effects and can cover a large portion of the country. In the event of a nuclear attack, nearly all parts of the nation are expected to be subjected to numerous EMP's produced by the detonation of megaton-range weapons just outside the earth atmosphere. Since many CD radio communications have little or no blast protection and many others will not be confronted by low altitude bursts, the most significant EMP for our studies is that produced by high altitude explosions.

The interaction with the atmosphere of gamma radiation from a nuclear blast generates a Compton electron current. The high intensity electromagnetic fields radiated from high altitude bursts are largely the result of the interaction of this Compton electron current with the geomagnetic field. As a rule of thumb,[3] the direction of the electric field is at right angles to the earth's magnetic field. The geomagnetic dip angle is approximately 70 degrees for most of the continental United States. Thus, the incident EMP electric field is likely to lie between zero and 30 degrees off the horizontal depending on the direction of propagation of the incident wave.

In order to perform system analysis of the effects of EMP, an ana-
lytical representative pulse is used. The far zone electromagnetic
radiation is assumed to be a plane wave with the magnitude of the elec-
tric field E and the magnitude of the magnetic field H related by

$$E = ZH \quad , \tag{1.1}$$

where Z is the free space wave impedance approximately equal to 120π ohms.
The electric field unit direction vector $\vec{e}_2$ and the magnetic field unit
direction vector $\vec{e}_3$ are related to the unit direction of propagation vec-
tor $\vec{e}_1$ by

$$\vec{e}_1 \ X \ \vec{e}_2 = \vec{e}_3 \ , \tag{1.2}$$

where X is the vector cross product. The orthogonal field vectors are
related to their direction vectors by

$$\vec{E} = E \ \vec{e}_2 \tag{1.3}$$

$$\vec{H} = H \ \vec{e}_3 \quad . \tag{1.4}$$

It is assumed that the time history of the electric field associated
with such a representative pulse is given by

$$E(t) = E_0 f(t) \tag{1.5}$$

where

$$f(t) = \sum_{n=1}^{N} a_n \ e^{-\alpha_n t} \quad t \geq 0 \quad ; \tag{1.6}$$

and E_0 is a scale factor with units of volts per meter, $f(t)$ is the
wave shape, a_n is the nth linear constant, α_n is the nth inverse time
constant with units of inverse seconds, and N is a positive integer.

For the very high frequency (VHF) and ultra high frequency (UHF)
communications systems analysis in this report, a series for $f(t)$ con-
sisting of just the first two terms was used to calculate the system
response to EMP. A two-term series can well represent the EMP for the
frequencies in the frequency spectrum above the low frequency (LF) band.

Writing the first two terms of $f(t)$ gives a double exponential wave shape of the form

$$f(t) = e^{-\alpha_1 t} - e^{-\alpha_2 t} \tag{1.7}$$

where $a_1 = 1$ and $a_2 = -1$. Using $f(t)$ given by Eq. (1.7) in the analysis will result in an overestimate of the system response at low frequencies. However, the system response at frequencies below the LF band should be very small and contribute little to the overall response.

Equation (1.7) can be written in the Laplace domain as

$$F(s) = \frac{\alpha_2 - \alpha_1}{(s+\alpha_1)(s+\alpha_2)} \quad, \tag{1.8}$$

where s is related to the radian frequency ω by $s = j\omega$ and $j = \sqrt{-1}$. In the Fourier frequency domain Eq. (1.7) becomes

$$F(\omega) = \frac{\alpha_1}{\alpha_1^2 + \omega^2} - \frac{\alpha_2}{\alpha_2^2 + \omega^2} + j \left[\frac{\omega}{\alpha_2^2 + \omega^2} - \frac{\omega}{\alpha_1^2 + \omega^2} \right] \quad. \tag{1.9}$$

The magnitude of the electric field in the Fourier frequency domain is given by

$$\left| E(\omega) \right| = E_0 \sqrt{(R_e[F(\omega)])^2 + (I_m[F(\omega)])^2} \quad, \tag{1.10}$$

where $R_e[F(\omega)]$ is the first two terms of Eq. (1.9) and $I_m[F(\omega)]$ is the third term of Eq. (1.9) with j omitted.

The energy content is proportional to $\left| E(\omega) \right|^2$. A normalized energy spectral density of the pulse can be defined as

$$E_n(\omega) = \frac{\left| E(\omega) \right|^2}{\left| E(\omega_0) \right|^2} \quad, \tag{1.11}$$

where $\left| E(\omega) \right|^2$ is a maximum for $\omega = \omega_0$. The accumulative energy in the pulse can be useful in determining frequency end points for the calculations. The percent of accumulative energy up to ω_c is given by

$$P = \frac{\int_0^{\omega_c} E_n(\omega)\, d\omega \times 100}{\int_0^{\infty} E_n(\omega)\, d\omega} = \frac{\int_0^{\omega_c} \left| E(\omega) \right|^2 d\omega \times 100}{\int_0^{\infty} \left| E(\omega) \right|^2 d\omega} \quad \tag{1.12}$$

Substituting Eqs. (1.10) and (1.9) into (1.12) and evaluating the integral gives

$$P = \frac{200}{\pi(\alpha_2 - \alpha_1)} \left[\alpha_2 \ \tan^{-1} \frac{\omega_c}{\alpha_2} - \alpha_1 \ \tan^{-1} \frac{\omega_c}{\alpha_0} \right] \quad . \qquad (1.13)$$

The representative pulses used in this study have been chosen as a probable typical EMP environment for most CD communications systems. The pulses are given below:

Pulse A: $E_a(t) = E_{O1} f_1(t)$

Pulse B: $E_b(t) = E_{O2} f_1(t)$

Pulse C: $E_c(t) = 1.2 \ E_{O1} f_2(t)$

Pulse D: $E_d(t) = 1.2 \ E_{O2} f_2(t)$

where

$E_{O1} = 5.2 \times 10^4$ volts/meter

$E_{O2} = 2.3 \times 10^4$ volts/meter

$f_1(t) = e^{-\alpha_{11} t} - e^{-\alpha_{21} t}$

$f_2(t) = e^{-\alpha_{12} t} - e^{-\alpha_{22} t}$

$\alpha_{11} = 1.5 \times 10^8 \ \sec^{-1}$

$\alpha_{21} = 2.6 \times 10^8 \ \sec^{-1}$

$\alpha_{12} = 1.5 \times 10^7 \ \sec^{-1}$

$\alpha_{22} = 2.6 \times 10^8 \ \sec^{-1} \quad .$

The waveshape $f_1(t)$ is representative of a typical long pulse. Waveshape $f_2(t)$ is a shorter pulse used in the analysis to obtain a quantitative feel for the effects of pulse waveshape on system vulnerability.

Pulse A represents a typical above average long pulse. This pulse can be used as a likely horizontal component of $\vec{E}$ and a likely vertical component of $Z\vec{H}$ and a much above average vertical component of $\vec{E}$ field.[*] Pulse B represents a typical long pulse with a smaller magnitude than Pulse A. This pulse can be used as a typical "around average" vertical component of the fields.

Pulses C and D have applications similar to pulses A and B respectively and are representative of pulses with shorter time histories.

[*]Horizontal and vertical are with respect to the ground plane.

In Fig. 1.1, the representative pulses are shown as a function of time. In Fig. 1.2a, the normalized energy spectral density of the pulses are plotted as a function of frequency $f = \omega/2\pi$. The percent of accumulative energy as a function of frequency for the pulses is shown in Fig. 1.2b.

The effects of EMP are often compared with the effects of lightning. This is a useful comparison since most people are familiar with the damage that can result from a lightning strike. Lightning also generates electromagnetic transients which can be observed in the form of a distorted television picture during a thunder storm. The electromagnetic fields due to lightning have a rise time on the order of 10 times that of EMP and a fall time that is several orders of magnitude that of EMP. The peak value of the electric field generated by a lightning discharge one mile away from the observer is on the order of 10^{-3} that of an EMP produced by a nuclear detonation several hundred miles away. Although the electromagnetic environment due to lightning rarely causes damage to communications systems other than a momentarily distorted reception, EMP can potentially cause damage as a result of the orders of magnitude higher EMP energy content in HF, VHF, and UHF bands.

1.4 METHOD OF APPROACH

The approach used to determine the EMP vulnerability of radio communications systems available to CD emergencies is to classify typical available radio communications systems and equipment, select representative circuits and perform system analysis of the effects of representative EMP's, and categorize the systems by the nature and probability of damage.

A limited survey was conducted to determine "typical" available radio communications systems and equipment. Communications engineers at state and local emergency operating centers (EOC's), other state and local governmental departments and those in industry were contacted. The results of the survey are believed to be representative for the purpose of EMP analysis of common radio communications systems used in public and industrial service. In addition to public and industrial service, some common radio equipment used in amateur radio and citizen's band service are considered in the study.
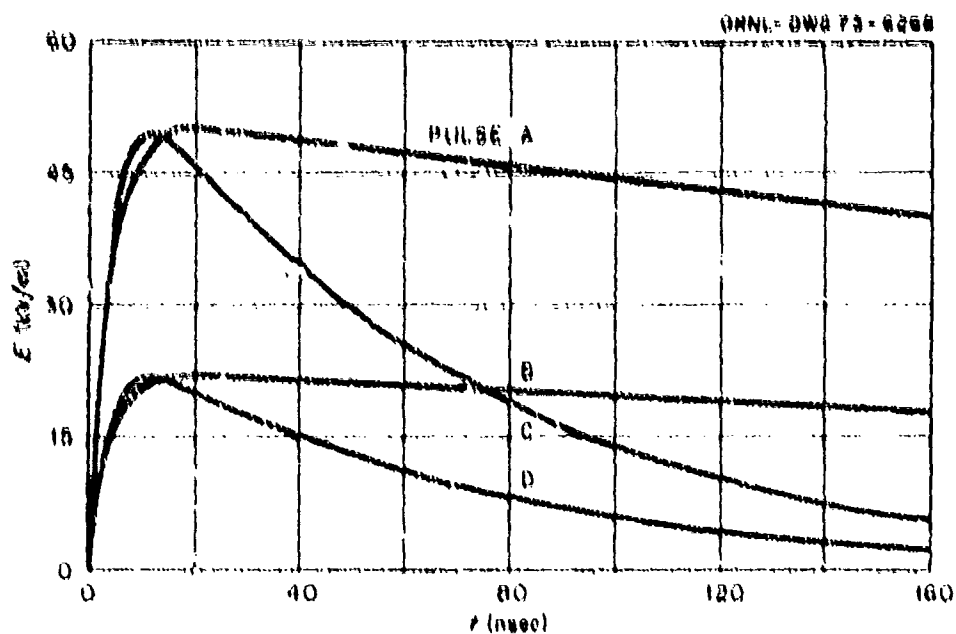
(a) EARLY TIME
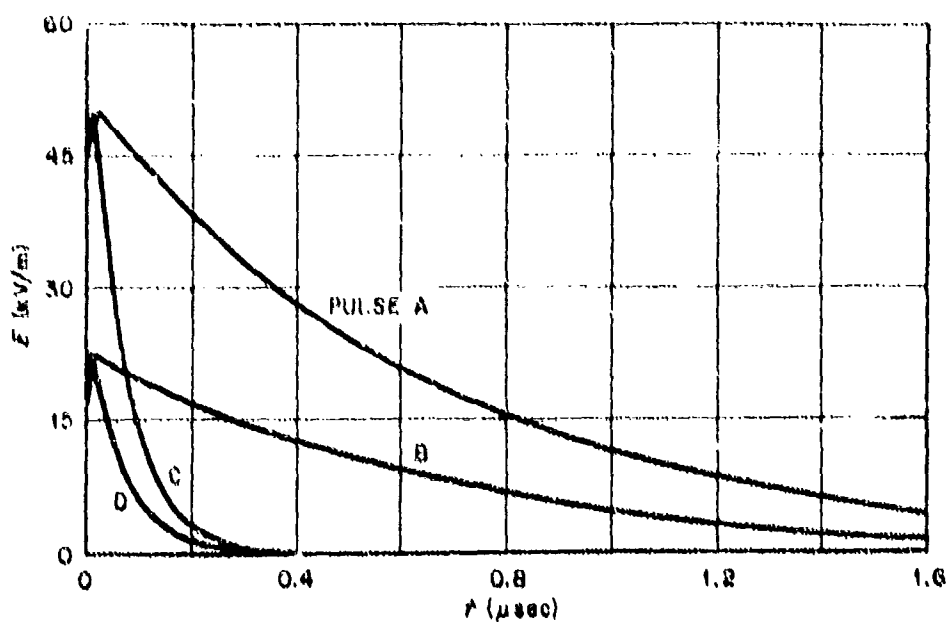
(b) LATE TIME

Fig. 1.1.   The Electric Fields Associated with the Representative EMP's.

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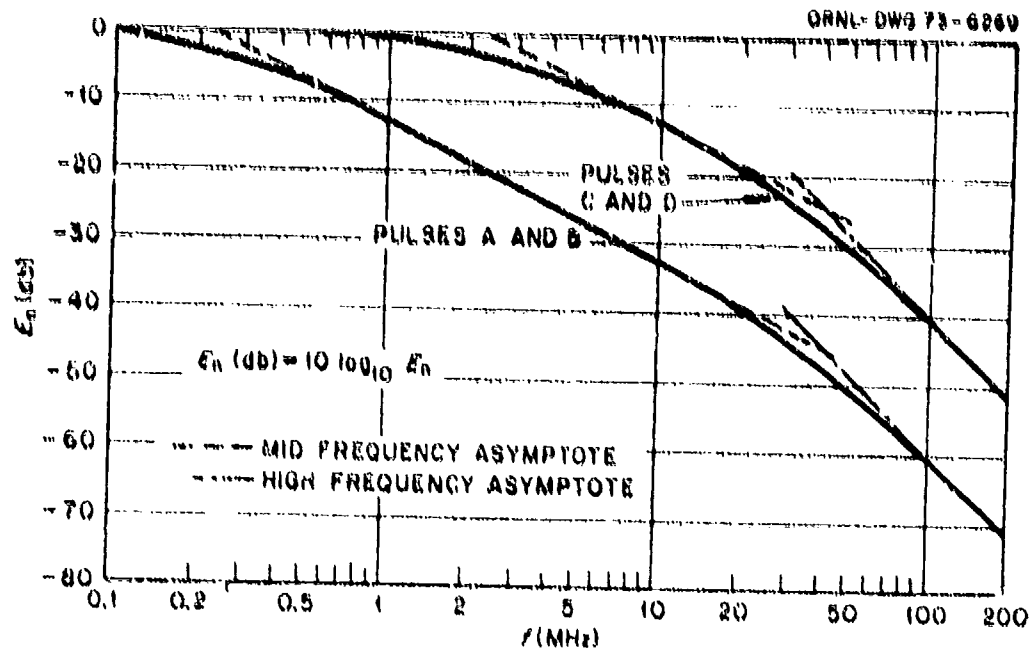
(a) NORMALIZED ENERGY SPECTRAL DENSITY FOR REPRESENTATIVE EMP's
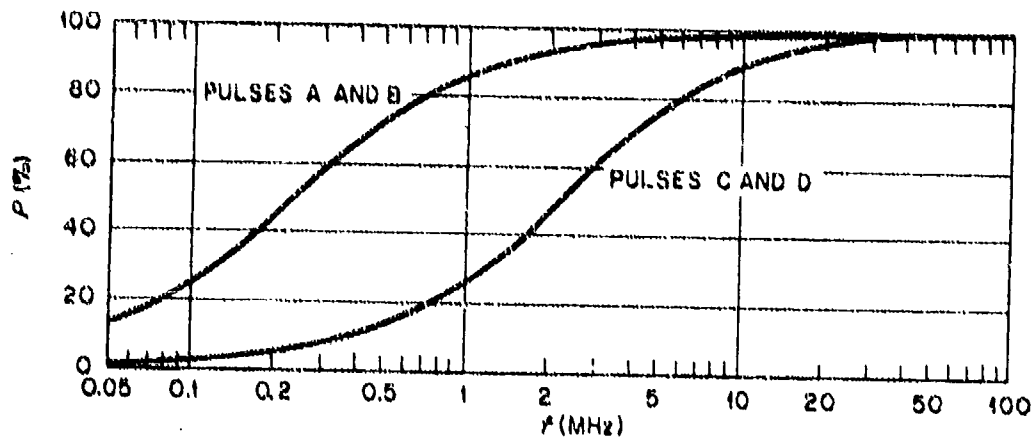
(b) PERCENT OF ACCUMULATIVE ENERGY vs FREQUENCY FOR REPRESENTATIVE EMP's

Fig. 1.2. Energy Quantities Associated with Representative EMP's.

(a) Normalized Energy Spectral Density of Representative EMP's

(b) Accumulative Energy in Representative EMP's

The approach used in the EMP analysis and assessment of the radio communications systems is as follows:

1. determine the points of entry (POE's) for each piece of equipment in the system;

2. obtain quantitative estimates of the energy and/or power entering the equipment through the POE;

3. compare the electrical destructive mechanisms at the POE with the minimum values that cause degradation effects on electrical components that are closely coupled to the POE; and

4. perform a detailed circuit analysis for electrical components that have questionable survivability.

To obtain additional data on the nature and probability of damage of communications equipment, an experimental test was conducted. Selected communications antennas and radio equipment were subjected to a simulated free-field EMP environment. The results of that test are presented in Chapter IV.

CHAPTER II

STATE AND LOCAL CD TWO-WAY RADIO COMMUNICATIONS

2.1 GENERAL

A very hostile environment consisting of radiation fallout, fires, and the direct effects of blast will exist over much of the nation during and following a nuclear attack. State and local governments must be prepared to provide the necessary emergency services to ensure national survival and eventual recovery. To this end, communications are essential.

Telephone and telegraph common carrier communications are the principal means considered to be available to all elements of CD operations.[4] However, much of the telecommunications except in some local areas are likely to be damaged by the nuclear attack. In the event that telecommunications are not available, two-way radio communications will be required to fulfill the communications requirements.

2.2 AVAILABLE TWO-WAY RADIO COMMUNICATIONS

State and regional emergency operating centers (EOC's) have the primary functions of coordinating and controlling CD operations across local jurisdictional boundaries. The available two-way radio communications for state CD operations are primarily those communication networks that can provide statewide coverage. Such networks are those of the state and local civil defense organization, state police, forestry, park, and highway departments, Radio Amateur Emergency Service (RACES), statewide utilities companies, Corps of Engineers, etc.

Local governments have the primary functions of providing the necessary emergency services to save lives, limit damage, and speed recovery. Public and private resources also would be called upon to assist in local CD operations.

Immediately following a nuclear attack, the essential actions required by the local governments are those related to countering the threats to life and property by radiation fallout and fires. Other operations will be feasible only to the extent that radiation and fire situations permit.[4] The two-way radio communications associated with the Radiological Defense (RADEF) and the fire department nets will likely have large communications traffic requirements during the early period following the attack.

Other services such as police, medical, rescue and evacuation, welfare, restoring resources services, etc. will be provided as the environment permits. Public safety and public utilities forces will be the agencies that will provide these services. The primary two-way radio communications associated with these services are those that are normally used by these agencies.

In addition to the radio communications available for local CD operations from CD, public safety, and public utilities organizations; industrial businesses, and transportation as well as other local, state, and federal government agencies communication systems are available. These systems could be used as backups to the primary communications nets. Also the radio communications used by private individuals would likely support local CD operations.

In general, the basic two-way radio communications that are available for state and local CD operations are those of government and non-government owned land mobile radio systems and the amateur and citizens radio services. Some other elements of national, state, and local government communications systems would also be available. The Maritime and Aviation Radio Services will be available for CD operations only on a very limited scale since these services have their own priority commitments during emergency periods.

The land mobile radio systems are considered to consist of public safety, industrial, land transportation, and domestic public service groups. The public service group consists of local government, police and fire departments, hospitals, physicians, rescue organizations, etc. The industrial group consists of manufacturers, businesses, utilities companies, etc. The land transportation group is composed of radio services for buses, taxicabs, railroads, etc. The domestic public service is primarily the mobile radiotelephone service.

Most of the assignable frequencies for the land mobile radio systems lie within three bands; 20 to 50 MHz, 150 to 174 MHz, and 450 to 470 MHz which are commonly called the VHF low and high and UHF bands, respectively. Also some frequencies in the 72 to 76 MHz band are used (primarily for control and repeater stations). Nearly all the land mobile radio systems use frequency modulation (FM).

The amateur radio service consists of groups of amateur radio operators. These groups provide emergency communications nets with little or no sponsorship. Amateurs are authorized to use FM, amplitude modulation (AM), and single sideband (SSB) in various frequency bands ranging from 1800 KHz to 21,000 MHz and frequencies above 40,000 MHz. RACES are authorized to use the amateur band frequencies ranging from 1800 KHz to 224.92 MHz. Longer range frequencies such as in the 80 meter band have been allocated to states for CD operations. RACES can provide efficient local communications by frequencies in the 50, 144, and 220 MHz bands.

The citizens radio service consists of four classes: Class A, B, C, and D. Classes A and B operate within the 460 to 470 MHz band and Classes C and D operate within the 26.96 to 27.23 MHz band or on 27.255 MHz. A large majority of the licensed stations are in Class D which is authorized for AM communication with an input power of 5 watts or less.

2.3 TYPICAL COMMUNICATION SYSTEMS

Communications networks consist of stations connected by links. The station types are portable, mobile, fixed, base, remote, console, etc. Radio and wire links provide communications channels between the stations. The radio equipment at each station is a radio unit and consists of all or part of the following: transmitter/receiver equipment, antennas, the power supply, and other local equipment that is connected to the radio.

The relevant differences in typical communications systems are the number and type of points of entry (POE's) that EMP energy can enter potentially vulnerable equipment. Also the total dependence of the system or network on one particular unit or station is an important consideration for determining the probability of system failure.

Nearly all portable and mobile units have a similar configuration consisting of an antenna, a receiver/transmitter, controls, a battery power supply and a microphone and a speaker. The antenna, battery, controls, etc. are normally located on, or within, the case of the transmitter/receiver or connected to it by relatively short cables. The POE's for portable units are the antenna and direct coupling. The POE's for mobile units are the antenna and interconnecting cables.

Most of the differences relevant to EMP coupling analysis are in the base and control portion of the communications systems. Four typical base and control station configurations are shown in Figs. 2.1 and 2.2. Typical two-way radio base/control stations are either extension or combinations of the ones shown.[5] The complete network may consist of portable, mobile, and/or other fixed stations which are not shown in the figures. The four basic communications base and control stations are discussed below.
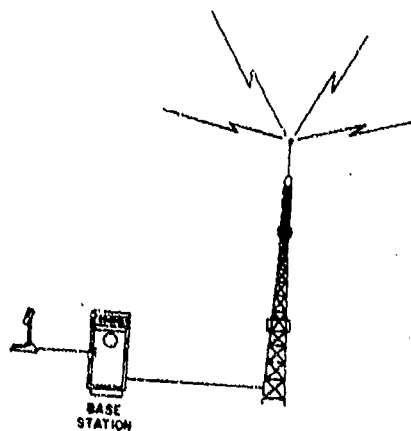
2.3.1 Local Base Station

The local base station system has the base transmitter/receiver equipment physically located at the dispatch point. The antenna is normally located on a roof top or tower and is connected to the transmitter/receiver via a coaxial cable. The station normally uses commercial power available in the building. The local base station is shown in Fig. 2.1a.

The local base station may be part of a simplex (single frequency) or a duplex (two frequency) system. All units transmit and receive on the same frequency in a simplex system, thus direct communications between mobile and/or portable units are possible. In a duplex system, the base stations transmit to other units on one frequency and receive communications from the other units on a second frequency. No communications between units is possible. Thus, loss of the base station in a duplex system causes failure of the entire system.

2.3.2 Remote Base Station

The remote base station system has the base station located at a remote location such as on a mountain top. The base station is operated by a remote control console at the dispatch/control point. A remote control station and the remote base station may be connected by a private line or telephone cable link as shown in Fig. 2.1b or by a microwave, VHF, or UHF radio link. The remote base station system may be a simplex or duplex system with the effective operation of the system the same as that of the local base station system.

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(a) LOCAL BASE STATION
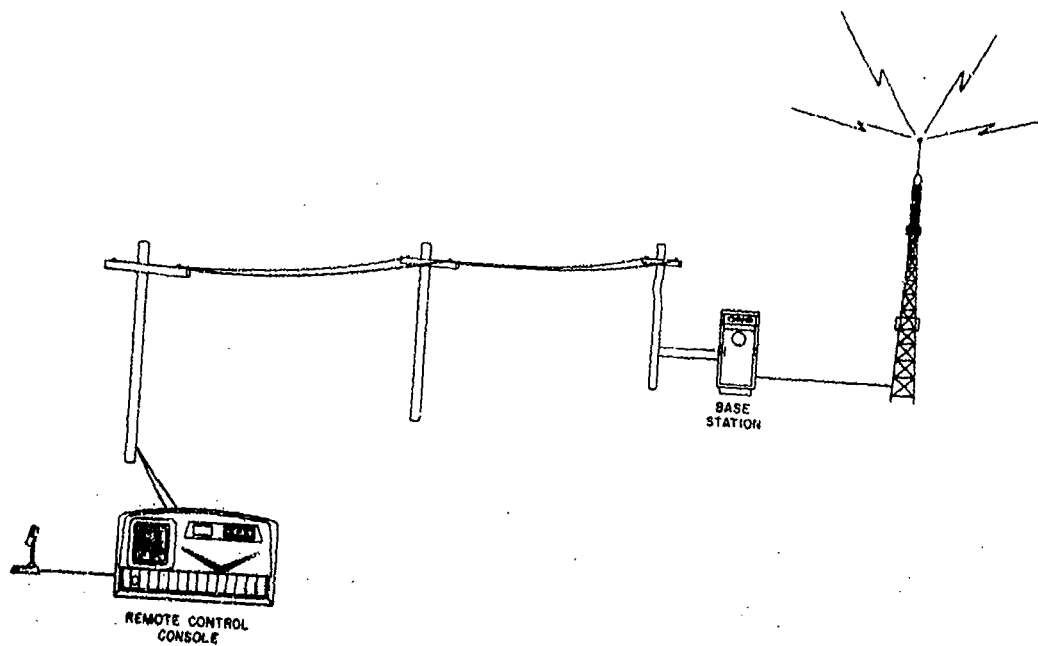
(b) REMOTE BASE STATION

Fig. 2.1. Typical Communications Systems Relevant to EMP.
(a) Local Base Station   (b) Remote Rase Station

ORNL-DWG 73-6271

DESK
MICROPHONE

JUNCTION BOX

BASE
STATION

(a) LOCALLY REMOTE MICROPHONE-SPEAKER UNITS

REPEATER
STATION

BASE
STATION
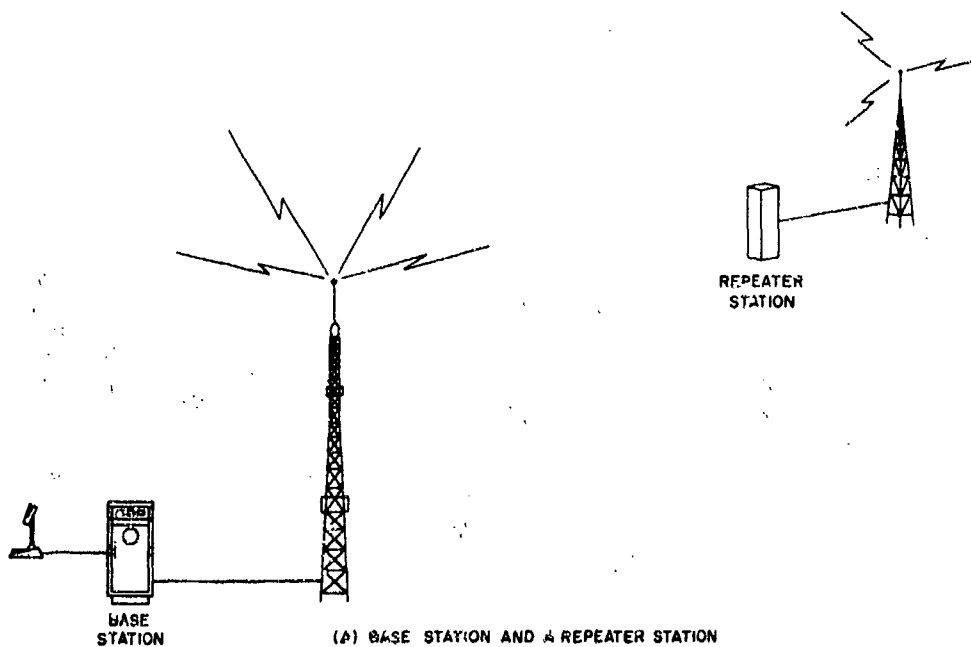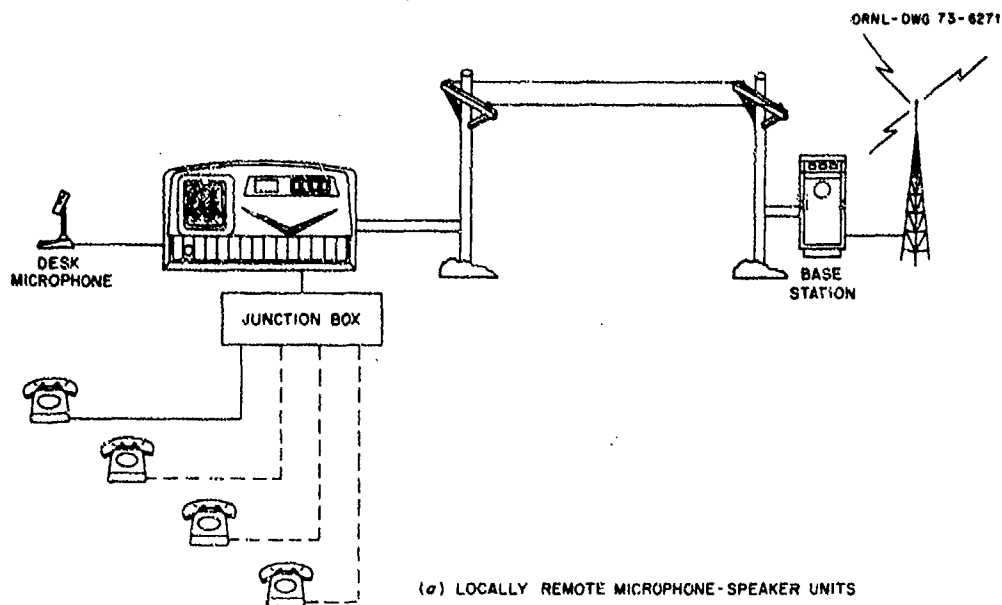
(b) BASE STATION AND A REPEATER STATION

Fig. 2.2.   Typical Communications Systems Relevant to EMP.

(a) Locally Remote Microphone-Speaker Units

(b) Base Station and a Repeater Station

2.3.3 Locally Remote Control Consoles

Base and console stations may be operated remotely using remote control consoles, telephone-type desk sets, or remote microphone speaker units. Normally there is one master console that has overall control. A remote base station system with remote telephone-type desk sets is shown in Fig. 2.2a. Locally remote control consoles may be used with all types of systems to extend radio communications capabilities without the necessity of adding additional transmitter/receivers.

2.3.4 Repeater Station

The repeater station system is a duplex system. All units transmit to the repeater on one frequency and the information is immediately retransmitted by the repeater and received by all units on a second frequency. Loss of the repeater causes failure of the entire system.

The repeater station system permits the use of low-power units and has the effect of giving base station transmit power to all units. If multiple repeaters are used, reliable communications can be provided over a very large area or over long distances.

The base or control station may be connected to the repeater station by a cable link or microwave, VHF, or UHF control link. The 72 to 76 MHz band is commonly used for the RF control link. A base station connected by an RF link to a repeater station is shown in Fig. 2.2b.

2.3.5 Other Systems

Other typical communications systems are extensions and/or combinations of those mentioned above. The remote base concept can be extended to multiple low-power remote stations located throughout a city for city-wide UHF coverage. The repeater can be mobile to perform as a local mobile relay to give low-power portable units the effective transmit power of a mobile transmitter.

It is possible of course to find radio communications systems that are not included in the above mentioned system types; however, these systems are not commonly used. Our concern is with those typical communications systems that would be available in a CD emergency. A very large majority of the commonly available systems are included in the classifications listed above.

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CHAPTER III

COMPONENTS OF COMMUNICATIONS SYSTEMS

3.1 INTRODUCTION

The electrical and geometric properties of typical components of communication systems are required in order to perform an EMP analysis. The principal system components of the four basic communication systems mentioned in Chapter II are listed below.

The components of the local base station system are:

1. transmitter/receiver units
2. antennas and feedlines
3. power sources;

the components of the remote base station system, in addition to those named above, are:

4. a remote control chassis and console
5. a communications and control link between the remote base and control stations;

the components of the repeater station system, in addition to those named above, are:

6. a repeater control circuit;

the components of the locally remote control consoles system include all or some of the components named above, and

7. locally remote control consoles.

Some general considerations of the electrical and physical characteristics for these components are presented in this chapter. Some of the circuits and properties detailed here will be referred to later in the EMP analysis and assessment of communications systems.

3.2 TRANSMITTER-RECEIVER UNITS

A transmitter-receiver unit consists of a transmitter and a receiver that use the same power supply and antenna. The transmitter and receiver circuitries are completely separate although both are mounted on the same chassis. A transmitter/receiver unit is sometimes called a transceiver. However, in this report, the word transceiver will mean a unit composed of a transmitter and receiver that use many of the same amplifier circuits. Such transceivers are commonly used for small low-power, low-cost CB walkie talkies.

The receiver front-end of a transmitter-receiver unit is normally connected to an antenna through the relay switch. When the transmitter-receiver unit is used for transmitting, the antenna relay disconnects the antenna from the receiver and connects it to the transmitter. The probability that the antenna will be connected to the receiver at any given time is high since a transmitte.-receiver unit is normally in the receiving mode. Even during times of heavy communications traffic the antenna is likely to be connected to the receiver more than fifty percent of the time.

The receiver front-end stage is required to handle low RF power relative to the transmitter output stage. The RF power received from the antenna is typically less than a microwatt. The receiver front-end stage normally consists of relatively low-power electrical components. The transmitter output stage, on the other hand, is designed for relatively high RF power. Typical transmit power ranges from one watt for portable units to about a kilowatt for amateur service. Typical transmit power for the land mobile service ranges from 30 to 110 watts. Since the power handling requirement of the receiver input is very low relative to the transmitter output, the most EMP-vulnerable circuitry connected to the antenna is that associated with the receiver. Accordingly, we shall place the emphasis of our study on the receiver.

Most of the receivers in service today are transistorized. The same receiver circuitry is normally used for base, mobile, and repeater station applications. The basic block diagram configurations for receivers used in the land mobile service are shown in Fig. 3.1. In general, the front-end circuitry consists of bandpass filter stages, radio frequency amplifier stages (RF Amp), mixer stages, and injection oscillator stages (OSC).

In Fig. 3.1a, the bandpass filter is located between the antenna and the RF amplifier. This configuration without the RF pre-amplifier is commonly used in many older (6 to 12 years old) UHF and VHF high band receivers. This configuration is also commonly used in newer (2 to 5 years old) UHF and VHF low and high band receivers. However, the RF amplifier stage is often omitted and the RF pre-amplifier stage is used only in ultra-high sensitivity receivers. In Fig. 3.1b, the RF amplifier

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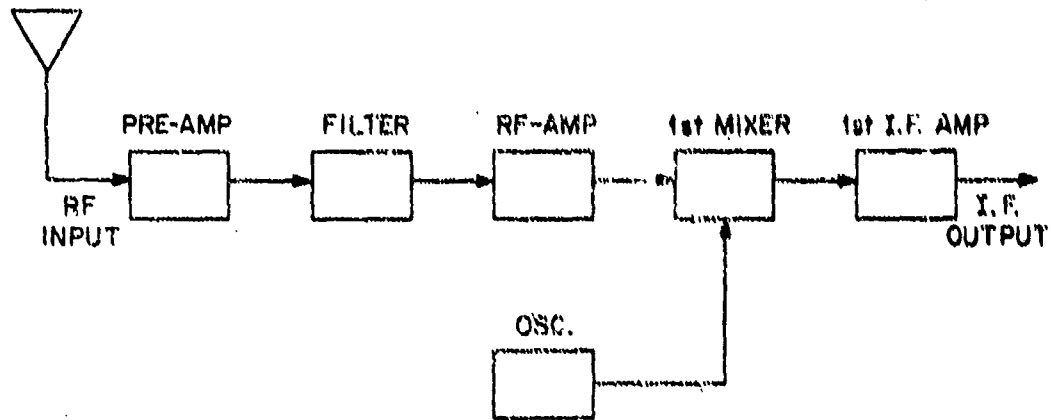
(a) RF AMPLIFIER AFTER FILTER
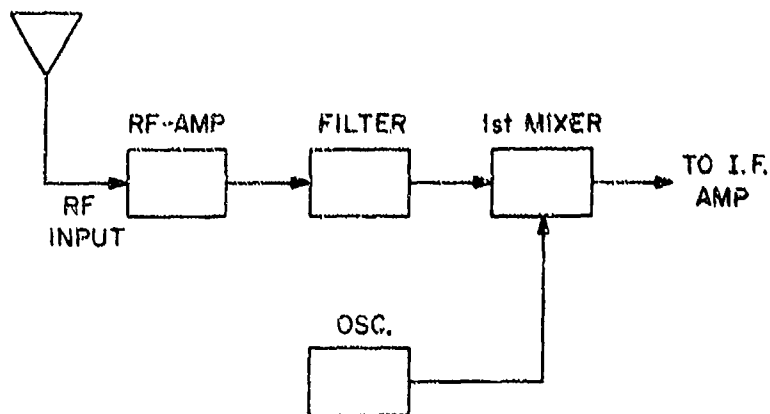
(b) RF AMPLIFIER BEFORE FILTER

Fig. 3.1. Front-End Block Diagrams for VHF and UHF FM Receivers.

(a) RF Amplifier After Filter

(b) RF Amplifier Before Filter

is located between the antenna and the bandpass filter. This configuration is commonly used in older VHF low band receivers. The location of the bandpass filter with respect to the RF amplifier may be an important consideration in our assessment of the receivers.

The specifications associated with the front-end of receivers in the land mobile class are the selectivity, sensitivity, and input impedance. The selectivity for 20 dB quieting is typically - 100 dB at ± 15 kHz for VHF units and - 100 dB at ± 35 kHz for UHF units. The sensitivity for 20 dB quieting is normally .5 microvolts for units without a pre-amplifier stage and .25 microvolts for units with a pre-amplifier. The input impedance is normally rated at 50 ohms.

The specifications for receivers used in the citizen's and amateur bands vary over a wide range and depend on the cost and intended use of the equipment. In general, these receivers have less selectivity and sensitivity than the receivers used for public safety and industrial applications in the land mobile class. Typical specification for above average quality CB receivers are: a sensitivity of .5 microvolts for 10 dB signal-to-noise ratio and a selectivity of -30 dB on the adjacent CB channels. High quality amateur band receivers have specifications comparable with those used for public safety service. The input impedance of CB and amateur band receivers ranges from 50 to 75 ohms.

Several commonly used and typical receiver front-end electrical schematic diagrams are shown in Appendix A. The figures include circuits of relatively old and new equipment used in the land mobile class as well as common circuits used in citizen's and amateur band receivers. The amateur band receiver shown in Fig. A-8 of Appendix A is typical of many home-brew amateur radios. This circuit was obtained from Ref. 6.

In the front-end circuits of base, mobile, and repeater receivers, 500 V capacitors and 1/4 and 1/8 watt resistors are normally used. In portable equipment, 75 V capacitors and 1/8 watt resistors are normally used.

Many later model receivers employ the Field Effect Transistor (FET) in the RF amplifier and/or mixer stages as can be seen in Appendix A. The voltage ratings of capacitors, power ratings of resistors, and the type of transistors used in the front-ends are important considerations for EMP analysis.

Another significant aspect of the receiver front-end is the protection against RF overload and static charges. Many receivers have a neon bulb to provide protection against static charge on the antenna. The neon bulb is connected between the antenna and the system ground. And many receivers also have a semiconductor diode in the circuit near the first transistor to provide protection against the reception of high radio frequency (RF) power.

For the purpose of a more detailed analysis, consider the electrical and physical description of a commonly used and generally typical transmitter-receiver unit, the Motrac MHT series. The principal POE's are the antenna terminals, the microphone lead connector, the external power cord, and direct coupling. Schematic diagrams of circuits that are closely coupled in the POE's are shown in Figs. 3.2, 3.3, and 3.4. In Fig. 3.2 the transmitter output and receiver front-end circuits are shown. In Fig. 3.3, a RF pre-amplifier and the transmitter audio amplifier are shown. And in Fig. 3.4, a typical power supply circuit is shown. With a few exceptions, capacitors in the figures are given in microfarads (μf) and resistors are shown in ohms (Ω) or kilo-ohms ($k\Omega$). These circuits will be referred to later in this report.

3.3 ANTENNAS

The antennas used in VHF and UHF communication systems in the land mobile, citizen's band, and amateur service are normally oriented perpendicular to the ground. The omnidirectional horizontal radiation pattern of the simple vertical antenna is desired in order to make communications between the base and mobile stations independent of the vehicle's orientation. If a directional antenna is desired for base station applications, the vertical antenna can be easily made directional by the addition of parallel antenna elements. The antennas that are most commonly used for VHF and UHF two-way communications are the simple half-dipole, the folded half-dipole, the coaxial dipole, and the collinear array. Other antenna types such as the yagi, corner reflector, and loop antennas are also used but to a lesser extent.

The antennas used in amateur HF communications systems can be horizontal or vertical to the ground. The antenna types that are commonly
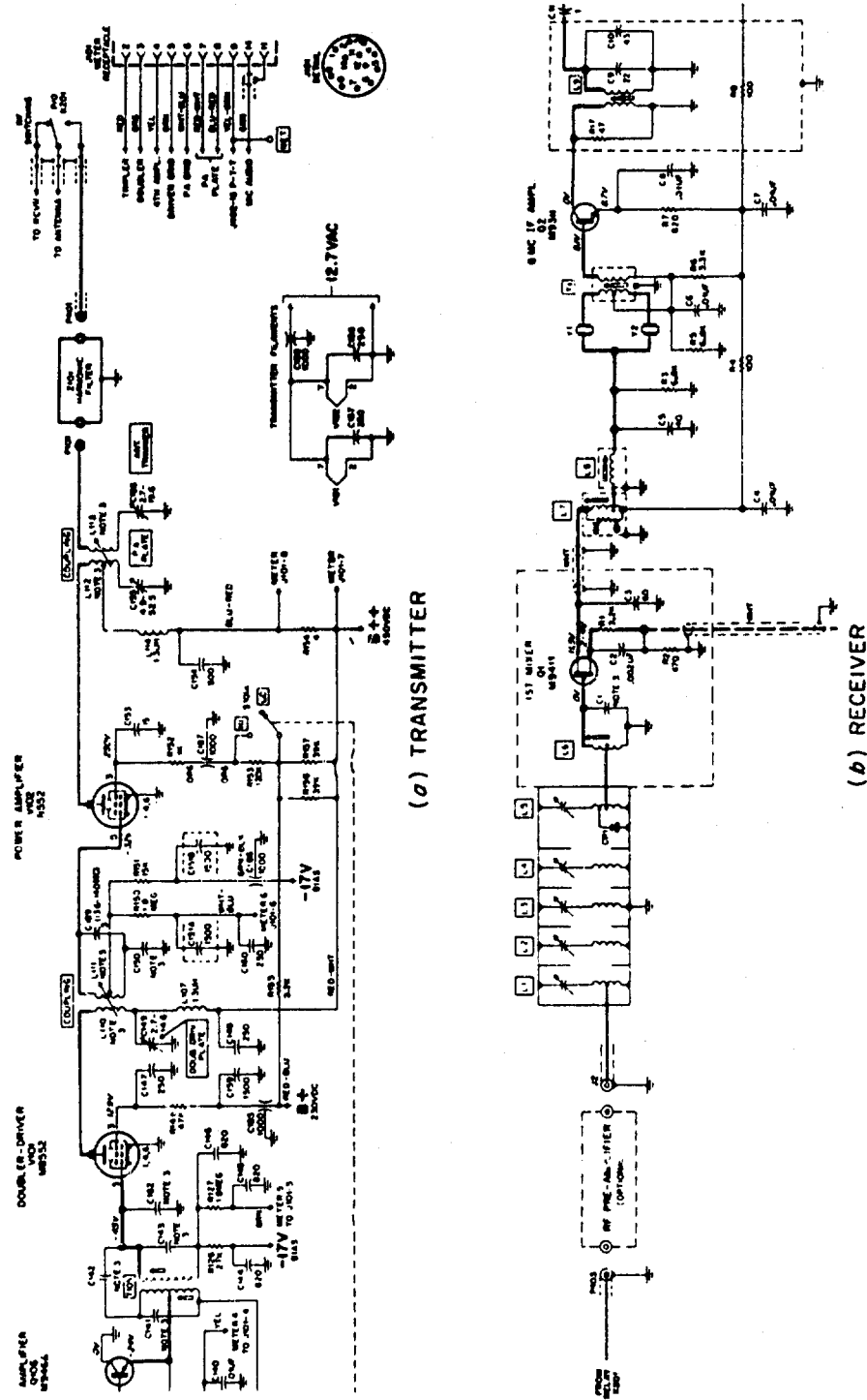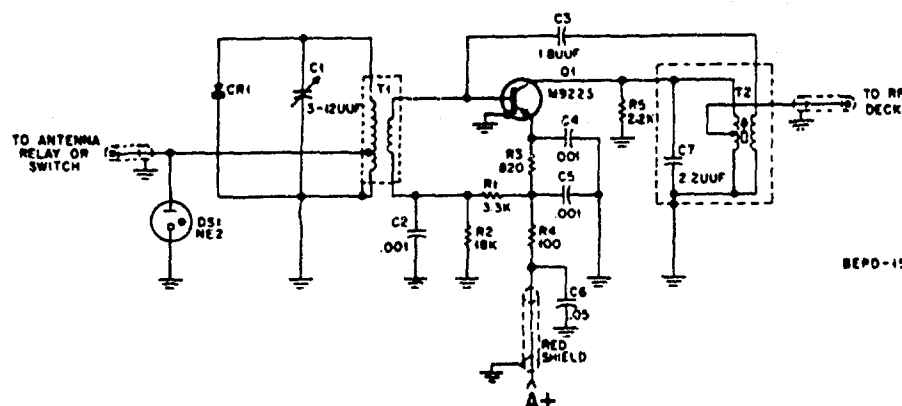
ORNL-DWG 73-6273

(a) TRANSMITTER

(b) RECEIVER

Fig. 3.2. Partial Schematic for the Motrac MHT Series Transmitter-Receiver.
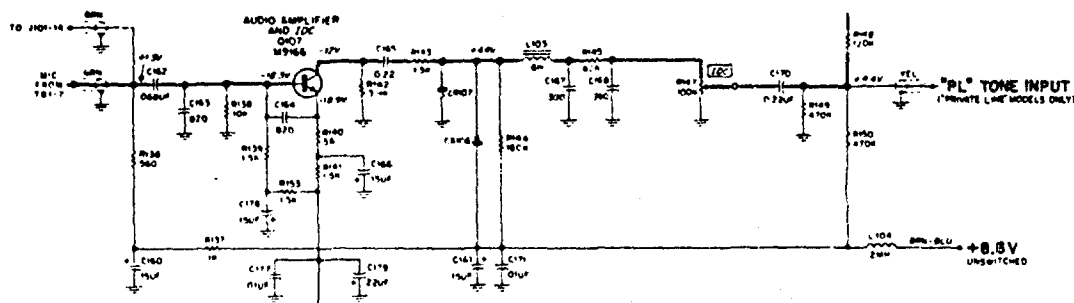
(a) Transmitter

(b) Receiver

ORNL—DWG 73-6275

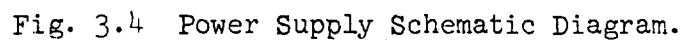(a) RADIO FREQUENCY PREAMPLIFIER

(b) AUDIO AMPLIFIER FOR THE MOTRAC MHT SERIES TRANSMITTER

Fig. 3.3. Radio Frequency and Audio Amplifier Schematic Diagrams

(a) Radio Frequency Preamplifier

(b) Audio Amplifier for the Motrac MHT Series Transmitter

ORNL-DWG 73-6274

Fig. 3.4 Power Supply Schematic Diagram.

used are the simple half-dipole, the simple horizontal dipole, and the rhombic antenna.

The more commonly used and typical antenna types are discussed below.

3.3.1 The Half-Dipole

The half-dipole antenna is often called a monopole or whip antenna. It consists of a metal rod or tube erected perpendicular to a ground plane as shown in Fig. 3.5a. Consequently, the metal rod is one half of the antenna and its ground plane image is the other half as shown in Fig. 3.5b. The length, ℓ, of the unloaded half-dipole is normally about a quarter wavelength of the antenna's designed frequency. The half-dipole antenna is commonly driven by a coaxial feedline as shown in Fig. 3.5a. The coaxial cable characteristic impedance is normally 50 ohms which is a fairly good match to the 37 ohm half-dipole resonant impedance.
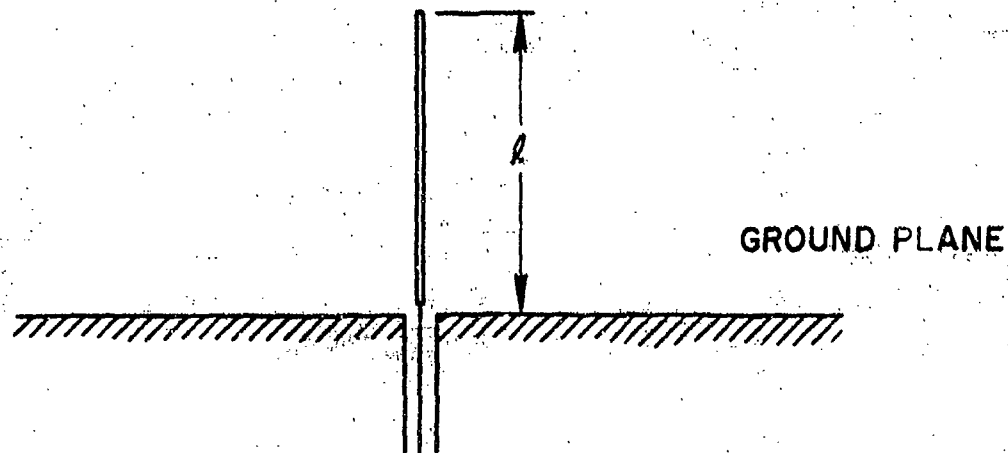
For mobile applications, the half-dipole antenna is normally mounted on the rooftop, fender, or bumper of the vehicle. The metal vehicle serves as the ground plane. The antenna feedline commonly used for mobile units is RG-58U cable.

For base-station applications, it is desirable to mount the antenna above the earth to achieve better coverage. Base-station antennas are usually mounted on masts above buildings where a ground plane is not present. The ground plane is normally simulated by radials, wires extending radially from the base of the antenna in a symmetric arrangement. The half-dipole antenna with a radial ground plane is shown in Fig. 3.6a. The half-dipole with a radial ground plane resembles a dipole in free space with respect to the vertical radiation pattern in the horizontal plane. And the power gain is typically within 0.1 dB that of a free space dipole.[7] For base-station antennas, RG-8U coax cable feedlines are commonly used.

3.3.2 The Folded Half-Dipole

The folded half-dipole antenna is shown with a radial ground plane in Fig. 3.6b. The radiating element of the folded half-dipole is folded back and is electrically connected to the base of the antenna. The

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ℓ

GROUND PLANE

(a) THE CYLINDRICAL HALF-DIPOLE ANTENNA

2ℓ
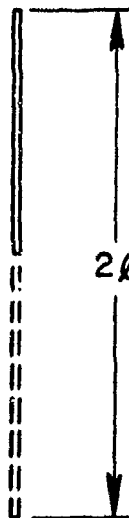
(b) THE CYLINDRICAL HALF-DIPOLE AND IMAGE
HALF-DIPOLE ELEMENTS

Fig. 3.5. The Half-Dipole Antenna.

(a) The Cylindrical Half-Dipole Antenna

(b) The Cylindrical Half-Dipole and Image Half-Dipole Elements

ORNL-DWG 73-6277

(a) THE HALF-DIPOLE ANTENNA

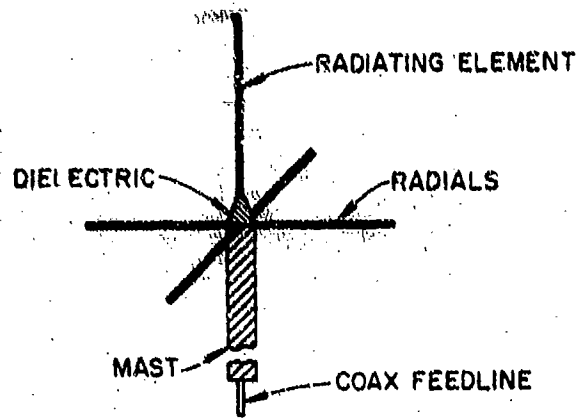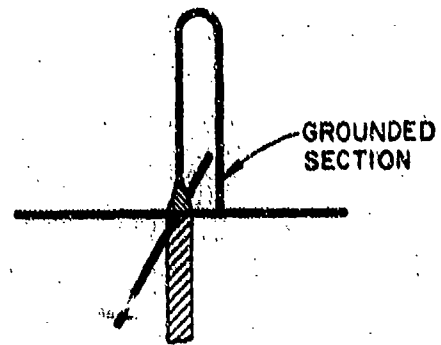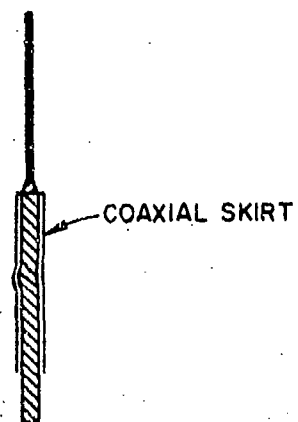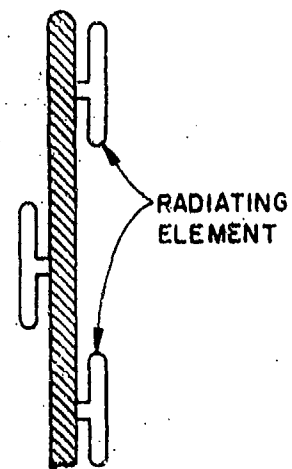(b) THE FOLDED HALF-DIPOLE

(c) THE COAXIAL DIPOLE

(d) COLLINEAR ARRAY

Fig. 3.6. Common Two-Way Radio Antennas.

folded configuration is inherently more broadbanded than the single radiating element. Also, the dc path formed by the grounded section provides protection against lightning surges. The grounded radiating element does not, however, provide EMP protection.

The resistive radiative impedance of the folded dipole is nominally 150 ohms. In practice, the grounded section of the antenna is made smaller in diameter than the other part of the fold to lower the impedance to 50 ohms. Thus, the folded half-dipole provides a better impedance match to the conventional feedline than is obtained from the half-dipole antenna. The gain of the folded half-dipole associated with the vertical radiation pattern in the horizontal plane is unity with respect to a dipole antenna.

3.3.3 The Coaxial Dipole

The coaxial or sleeve dipole is shown in Fig. 3.6c. It consists of two radiating elements; the upper element is a metal rod similar to that used for the half-dipole and the bottom element is a metal coaxial skirt. A choke which is not shown in Fig. 3.6c is often used to isolate the antenna from the mast. The coaxial dipole behaves as a half-wave dipole in free space.

3.3.4 The Collinear Array

The collinear array antenna is commonly used for base and repeater station applications with high gain requirements. The power gain depends on the number, type, and arrangement of the radiating elements. A typical range for the gain referenced to a dipole is from 6 to 10 dB.

A radiating element which is commonly used in collinear arrays is the coaxial dipole. The coaxial dipoles are normally series-fed by a coaxial line. The entire antenna is enclosed in a fiberglass radome for protection and rigidity. This antenna has an omnidirectional radiation pattern.

Another radiating element which is commonly used in collinear arrays is the folded dipole as shown in Fig. 3.6a. The dipoles are series-fed by a coaxial line. This antenna can be made omnidirectional or directional depending on the arrangement of the folded dipole elements. A tower-mounted collinear array is shown in Fig. 3.7.

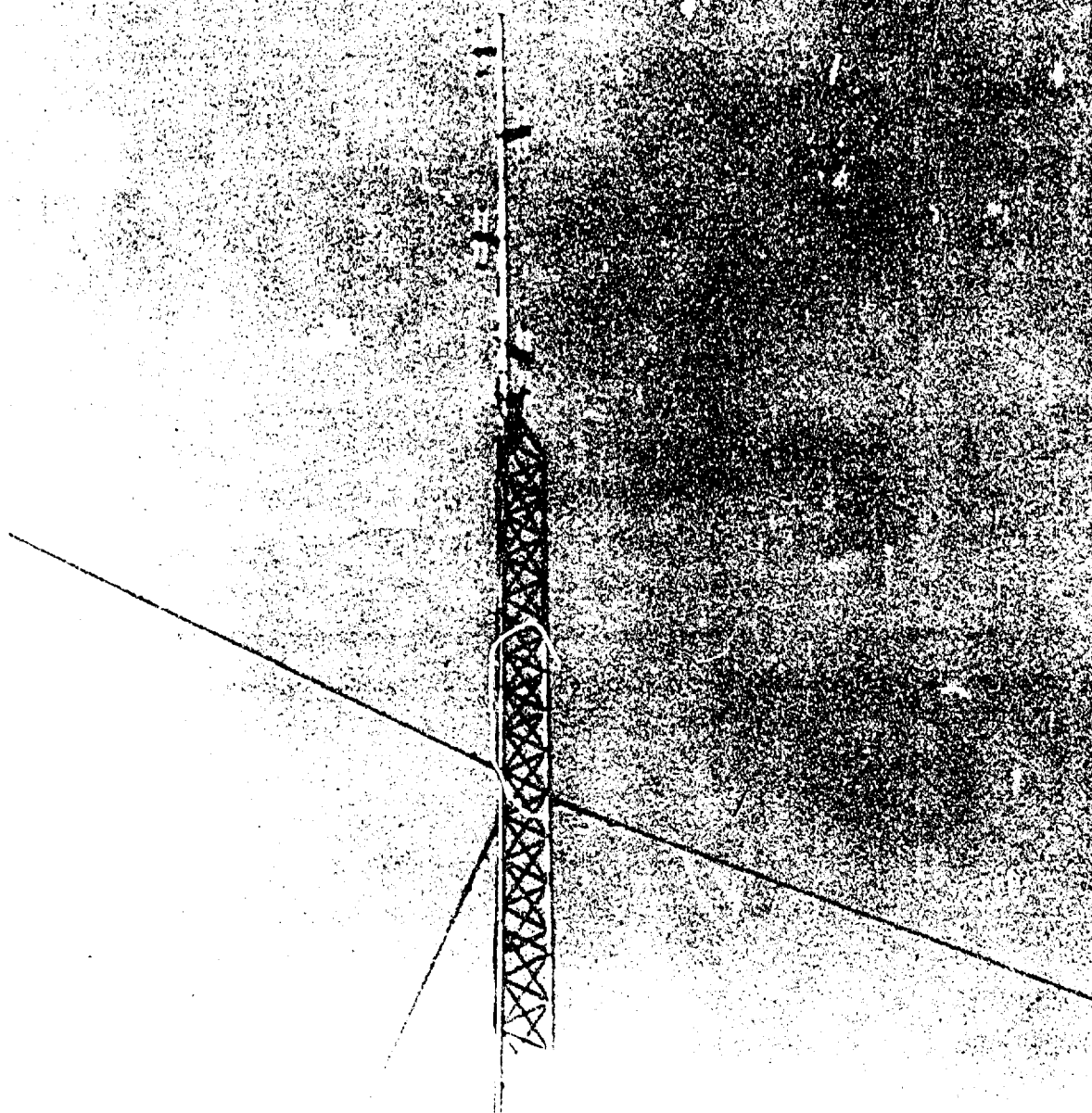Fig. 2.7. A Tower-Mounted Collinear Array VHF Antenna.

The radiation resistance of the collinear array antenna is nominally 50 ohms. This is achieved by impedance-matching techniques used in the design of the antenna. Some of the matching techniques are short-circuited lines, coaxial chokes, and phasing sections.

3.3.5 Tower-Mounted Antennas

Several antennas are often mounted on the same tower. The antennas may be part of an array or separate antenna systems that operate at different frequencies. The tower itself may be part of a side-mounted antenna by performing as an antenna reflector element. Figure 3.8 shows an example of several antennas mounted on one tower. The top antenna is a folded half-dipole. A side-mounted half-dipole and a yagi array are also on the tower. The vertical lines within the tower near the left side are coax cable feedlines.

3.4 POWER SOURCE

Commercial electric power is normally used by fixed stations. Portable and mobile stations generally are battery powered. Many walkie talkies have rechargable batteries. When not in use, walkie talkies are typically connected to commercial power through a battery charger.

Commercial power is transmitted from the power generation plant by high-voltage overhead transmission lines. These lines are located about 20 meters above the ground with a typical line-to-ground voltage of several hundred kilovolts. The transmission line voltage is stepped down to about 13 kilovolts by one or more distribution substations.

Electrical power is supplied to the local area from the substation by primary distribution lines. Primary distribution lines are located about 10 meters above the ground and range from about one-half to several miles in length depending on the power requirements of the local area.

The primary distribution line voltage is stepped down to a secondary line voltage by the distribution power transformer. For three-phase power, a three-phase transformer, or a three-transformer bank is used. The transformer or transformer bank is generally located near the building being supplied with electrical power. Each transformer is normally protected against overload by a primary line fuse. In high or moderate lightning areas, each transformer is also protected against lightning
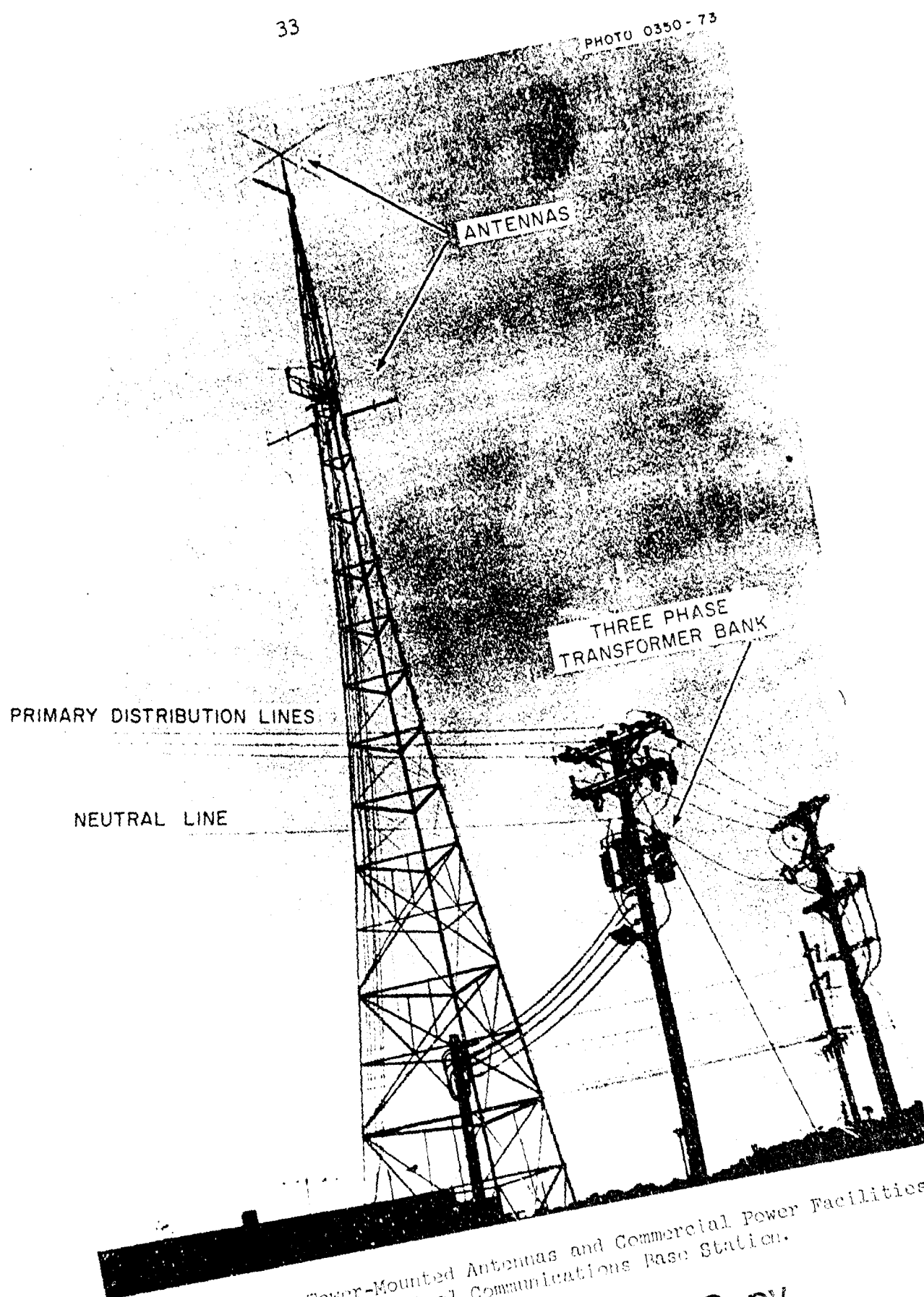
PHOTO 0350-73

ANTENNAS

THREE PHASE
TRANSFORMER BANK

PRIMARY DISTRIBUTION LINES

NEUTRAL LINE

Fig. 3.3. Tower-Mounted Antennas and Commercial Power Facilities
that Serve a Dispatch-Control Communications Base Station.

Best Available Copy

surges by a lightning arrester connected to the primary distribution lines near the transformer. Examples of primary distribution lines, a transformer bank, and a secondary building service are shown in Fig. 3.8.

Most communication equipment uses single-phase 120-volt ac power. This power can normally be obtained from either the single-phase or three-phase power that is supplied to the building at the main switch box. In small buildings, the 120-volt ac wall plug is likely connected directly to the main switch and fuse box by the internal building wiring. In large buildings, the 120-volt ac wall plug is likely connected to the main switch box through several distribution and fuse boxes.

3.5 REMOTE CONTROL CHASSIS AND CONSOLE

The remote control chassis is a unit at the remote base station used to provide the specific switching functions necessary for the operation of the station. Remote control functions are accomplished by applying various dc line currents to the chassis via the control line from the associated remote control console at the main dispatch/control point. The remote control console permits the operator to monitor all messages received by the remote base station and to transmit by means of the remote base station transmitter.

The remote control chassis consists of amplifier and logic circuitry. Audio and control signals are input to the circuitry from the control line through a line transformer and filter. The switching functions of the control chassis are commonly provided by transistorized logic circuits; the transistor switch, the Schmitt trigger, and the bistable multivibrator are the most common circuits used. These circuits generally consist of low-level, low-power components which are vulnerable to transients. To protect the remote control chassis from surges on the control line, transient suppressor circuits are normally provided at the line transformer and filter. A line transformer and filter with surge protection is shown in Fig. 3.9. The surge protection is provided by the bridge circuit which becomes a short circuit when triggered by a surge. An example circuit of the remote control chassis is not shown due to the extensive amount of circuitry involved.

The remote control console consists of a control panel, control circuits, audio circuits, a power supply, and a microphone and speaker.

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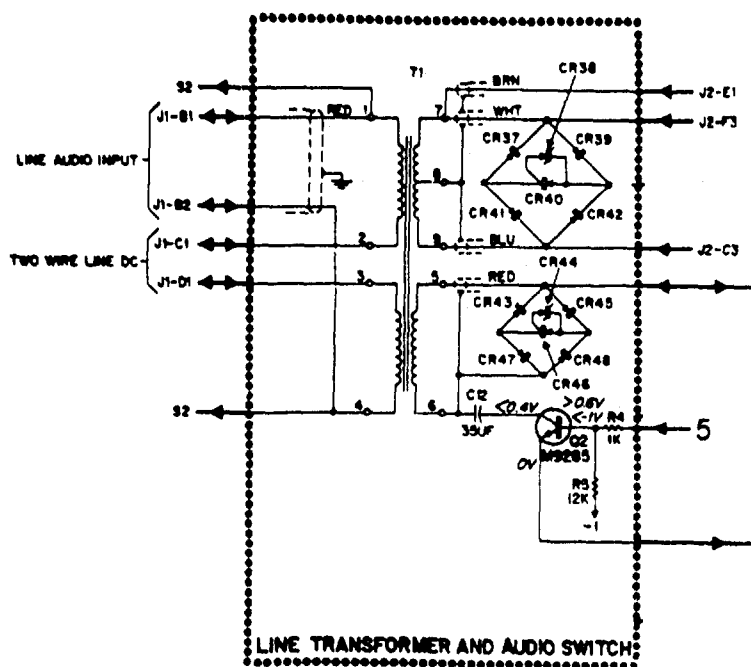
(*a*) LINE TRANSFORMER
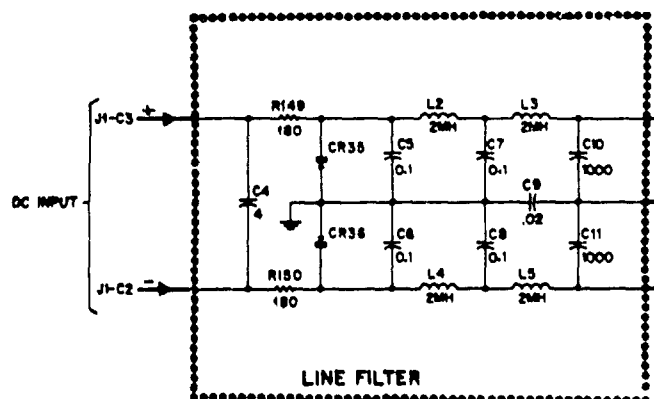
(*b*) LINE FiLTER

Fig. 3.9.   Line Transformer and Filter with Surge Protection.

(a) Line Transformer   (b) Line Filter

The control circuitry provides dc control voltages for transmitter and receiver control. The audio circuit consists of a transmit audio amplifier, a receive audio amplifier, and a compression-type line amplifier. Input and output to the remote control console is accomplished through a balanced line transformer.

Figure 3.10 shows a partial schematic diagram for a remote control console. The circuits for the receive and transmit amplifiers are shown as example circuits for possible future reference. Notice that the line transformer in Fig. 3.10 has the bridge surge protection circuit. In Fig. 3.11, the power supply for the console is shown. Reference to component values in these circuits will be made as required during the assessment of the remote control console.
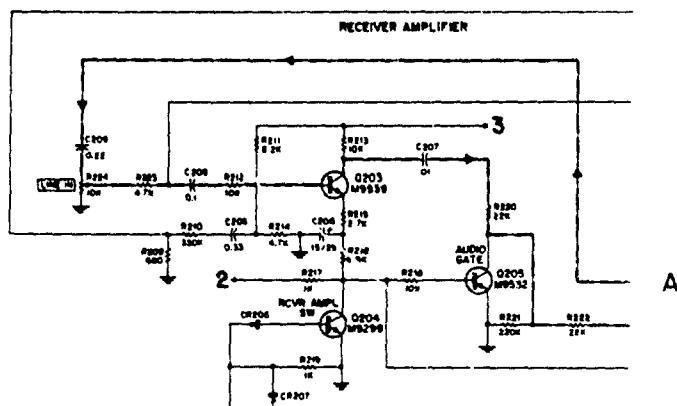
3.6 CONTROL LINKS

The control link electrically connects the remote control console with the remote base or repeater station. Both communications and control signals are transmitted by the link. The most common types of links are the transmission line cable and the radio frequency electromagnetic links.

Cable links are the most common control links and are usually obtained from the facilities installed for normal telephone services. For service up to about 20 miles, cable facilities are generally used. If there are no repeater coils or other telephone equipment in the line, dc control can be provided over the same pair of wires used for audio transmission. This is called two-wire control. If the audio line will not transmit dc voltages, separate wires can be used for dc control in a four-wire audio/control link.

The telephone line control link is likely to be connected through switching facilities and thus does not provide a direct line between the control point and the base station. The audio/control pair is likely to be part of a shielded multi-wire cable for most of the route and an insulated two-wire cable for some of the route near the remote station. Overhead lines are normally placed about 4 meters above the ground. An example of a telephone line control link is shown in Fig. 3.12.

The type of telephone line facilities that are normally used for control links are those used for speech transmission with equipment

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(*a*) RECEIVER AMPLIFIER

TO A
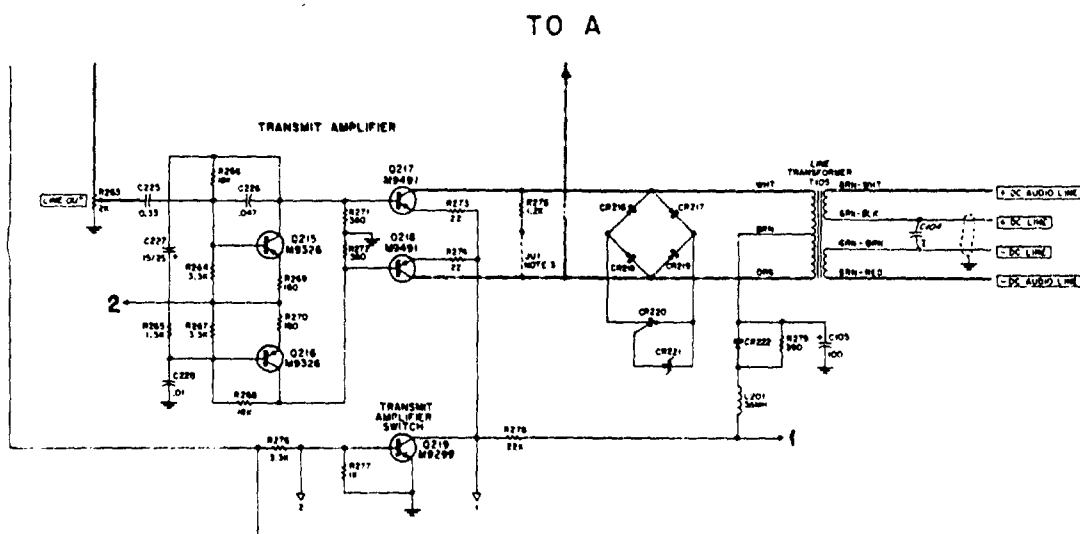
(*b*) LINE TRANSFORMER AND TRANSMIT AMPLIFIER

Fig. 3.10. Partial Schematic Diagram for the Motorola T1360A Series Remote Control Console.

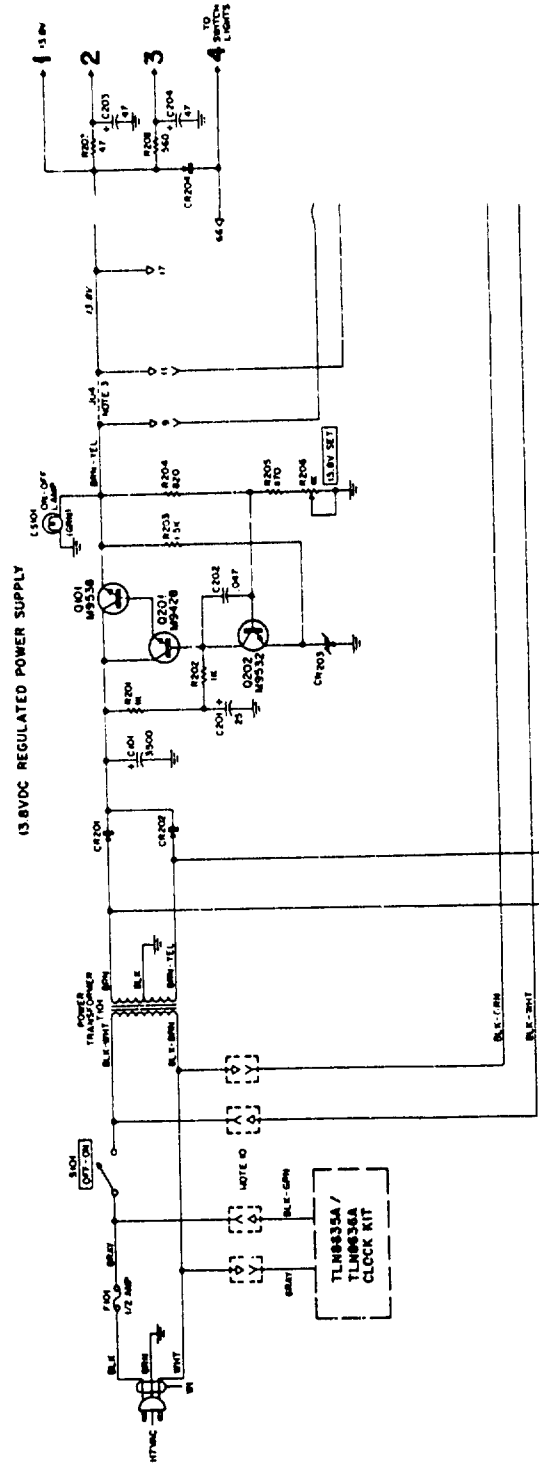(a) Receiver Amplifier　　　(b) Line Transformer and Transmit
Amplifier

38

Fig. 3.11. Partial Schematic Diagram for the Power Supply of the Motorola T1360A Series Remote Control Console.

PHOTO 0346-73

A MULTI-WIRE CABLE

SEVERAL TWO-WIRE CABLES
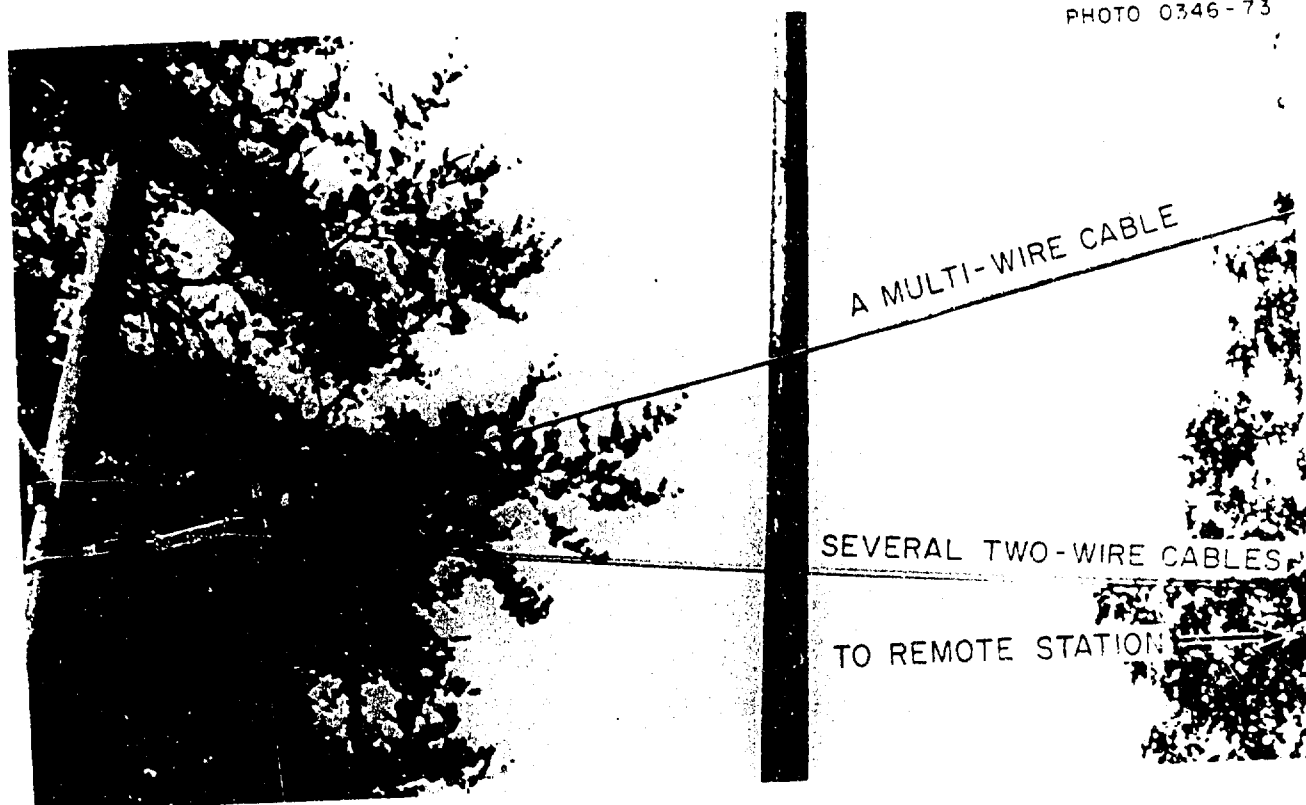
TO REMOTE STATION

Fig. 3.12.   Telephone Line Facilities Serve as Control Links for Remote Base and Repeater Stations.

designed for 600-ohm circuits. For this reason, the remote control
console and chassis are designed for input-output circuits with 600-ohm
impedances.

RF control links are also used in remote base and repeater station
systems. RF links are not, however, as common as telephone control
links. The control frequency that is normally used is about 75 MHz.
RF control links employ two-way radio transmitters and receivers for
the transmission of audio and control signals. Control functions are
performed by carrier and tone-controlled logic circuits.

3.7 REPEATER CONTROL CIRCUIT

A repeater station system is a duplex system. The function of a
repeater station is to receive transmission from the control-dispatch
station on frequency f_1 and repeat the transmission to other stations
in the system on frequency f_2. And the repeater station receives
transmission from the other stations on f_1 and again repeats the trans-
mission on f_2 which is received at the control point.

The repeat function is performed by a repeater control circuit
that connects the repeater receiver and transmitter. The repeater con-
trol circuit in its simplest form consists of an audio coupler circuit,
a carrier-operated switch, and a drop-out delay timer. The audio cou-
pler matches the receiver discriminator output to the transmitter input.
The carrier-operated switch keys (activates) the repeater transmitter
and applies the audio signal to the transmitter modulator. The drop-out
delay timer decreases the repeater transmitter on-off cycles by keeping
the transmitter keyed for a delay period after the receiver squelches.
The delay period is normally set for about one second. After the delay
time lapses and no signal is applied to the repeater receiver, the trans-
mitter keying circuit de-energizes and the transmitter turns off.

The keying, timing, and audio coupler circuits are, in general,
transistorized. Transistor switches, Schmitt triggers, and timing cir-
cuits are used. Electromechanical relays are, however, used in older
repeater control circuits. The electronic components used in the re-
peat r control circuit are normally low-power circuit elements; resis-
tors typically have 1/2-watt power ratings and capacitors typically
have 1 to 100 VDC ratings.

3.8 LOCALLY REMOTE CONTROL CONSOLES

Several remote control consoles may be installed at dispatch points.
In this type of system, the locally remote control consoles, typically
telephone-type desk sets, are connected in parallel to the primary re-
mote control console. The primary remote control console is designated
as the control point. The console at the control point has supervisory
control and monitor features for the control of the local and remote
base station. The control point console has been described under
paragraph 3.5.

The locally remote control console circuitry is, in general, simi-
lar to that of the control point console except for the supervisory con-
trol features. Locally remote consoles commonly use two-wire telephone
lines having an impedance of 600 ohms. The two-wire line of each con-
sole is connected in parallel with the audio-line pair on the line side
of the control point console line transformer (see Fig. 3.10). The
locally remote control consoles use a balanced line transformer to con-
nect the console circuitry to the two-wire line. The line transformer
is normally protected by a surge protection circuit similar to that used
on the control point console line transformer. Since the audio and power
supply circuits of the locally remote control console are similar to
those described in section 3.5, an example circuit is not shown.

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CHAPTER IV

EMP TEST OF SELECTED RADIO COMMUNICATIONS EQUIPMENT

4.1 INTRODUCTION

On 12 and 13 December 1972, a test on the effects of simulated EMP interaction with selected communications equipment and antennas was performed by ORNL. The test was limited to radio equipment and antennas used in the land mobile, amateur, citizen's, and commercial broadcast band radio classifications with emphasis on the land mobile class.

The objectives of the test are: (1) to compare theoretical and experimental results of communication antennas responses to EMP, (2) to determine field strength threshold levels at which obvious malfunctions occur in the selected radio equipment due to direct, indirect, and antenna EMP coupling, and (3) to check the effectiveness of special EMP and standard lightning protection devices for protecting radios against EMP energy collected by the antenna.

The test was divided into two parts: (1) the antenna response and EMP protection effectiveness test, and (2) the effects of EMP on two-way and broadcast radios test. Both parts of the test were performed using the same field environment.

4.2 EXPERIMENTAL ARRANGEMENT AND TEST FACILITY

The test was performed at the Air Force Weapons Laboratory's ALECS bounded wave EMP simulation facility located on Kirtland AFB, Albuquerque, New Mexico. The acronym ALECS is derived from the facility's name: Air Force Weapons Laboratory and Los Alamos Scientific Laboratory Electromagnetic Pulse Calibration and Simulation Facility.

The ALECS Facility consists of a parallel plate transmission line, a high-voltage pulse generator, and a data acquisition system. The data acquisition system consists of EMP environment sensors located in or near the test volume and an array of oscilloscopes in a shielded room located under the ground plane of the facility. The geometry of the ALECS Facility is shown in Fig. 4.1. The dimensions of the test volume are given in meters (m).

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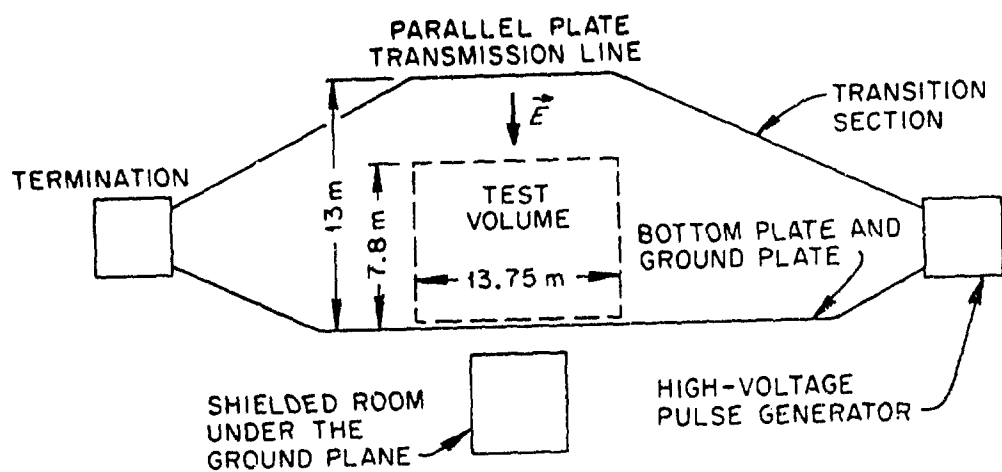
(a) SIDE VIEW
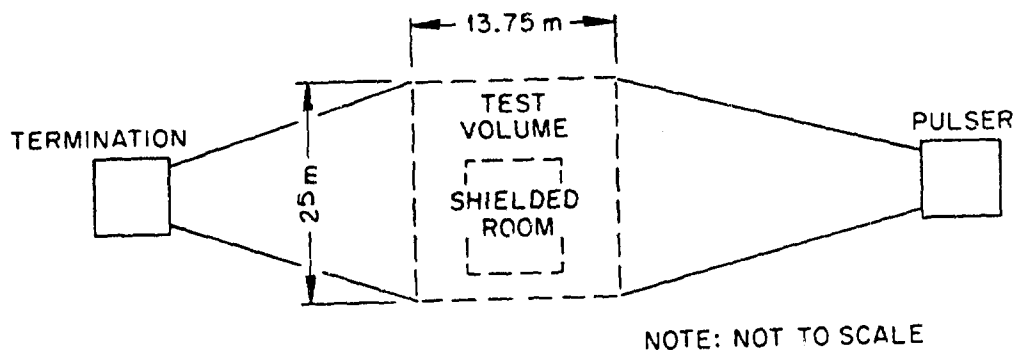
(b) TOP VIEW

Fig. 4.1. The ALECS EMP Simulation Facility

The experimental setup is shown in Fig. 4.2. The antennas were mounted on the ground plane over existing sensor ports. Measurements of the antenna responses were performed under the ground plane as shown in Fig. 4.2a. The locations of the portable radios and mobile units tested are shown in Fig. 4.2b.

The interaction between the vehicle and the UHF antenna located 18 feet away at sensor port No. 1 was negligible in this test. This can be seen from the fact that the 50 ohm load current response of the UHF antenna theoretically decays to near zero in approximately 25 nanoseconds (ns), and the wave scattered from the vehicle reached the UHF antenna about 36 ns after the incident wave. This back scattered wave did not distort the measured response and, in fact, could not be detected in the measured data.

Photographs of some of the antennas and radios in the test volume are shown in Figs. 4.3 through 4.7. Figures 4.3 and 4.4 show the VHF high band half-dipole and folded half-dipole antennas respectively. Figure 4.5 shows Alburquerque Fire Department Chief Ray Huhn with a VHF high band mobile unit in the test volume. The microphone and microphone cord held by Chief Huhn is a non-deliberate antenna for the EMP (see Fig. 4.7). In Fig. 4.6, the UHF mobile unit is shown in the test volume. And in Fig. 4.7, a VHF high band portable unit with an external microphone is shown in the test volume.

4.3 THE ALECS EMP ENVIRONMENT

The EMP generated by the ALECS Facility closely simulates a plane wave within the test volume. The time history of the electromagnetic wave is approximately a double exponential function of time. The rise time of this double exponential is between 4 and 10 nanoseconds (ns) and the pulse decays to near zero in about 500 ns. The peak value of the electric field waveform, i.e., the amplitude of the electric field, within the test volume can be adjusted to desired values ranging from 5 kV/m to 100 kV/m. Peak values greater than 100 kV/m can be obtained in the transition section.

The early time history of the waveform may be one of two types depending on whether the amplitude of the electric field lies above or below 12 kV/m. The difference between the two types is primarily the high frequency oscillations added to the double exponential waveform of the electric field pulse with an amplitude below 12 kV/m. The early time waveforms of the ALECS

ORNL-DWG 73-3009
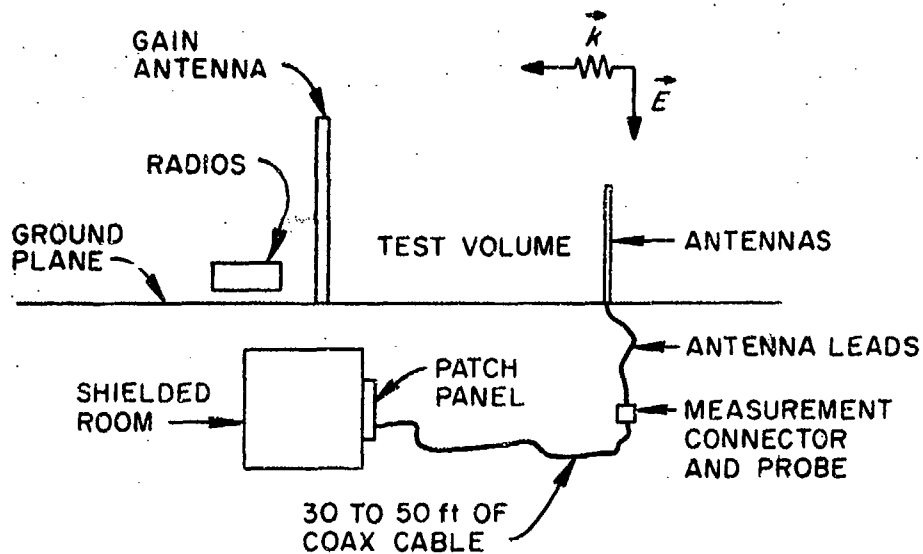
(a) SIDE VIEW
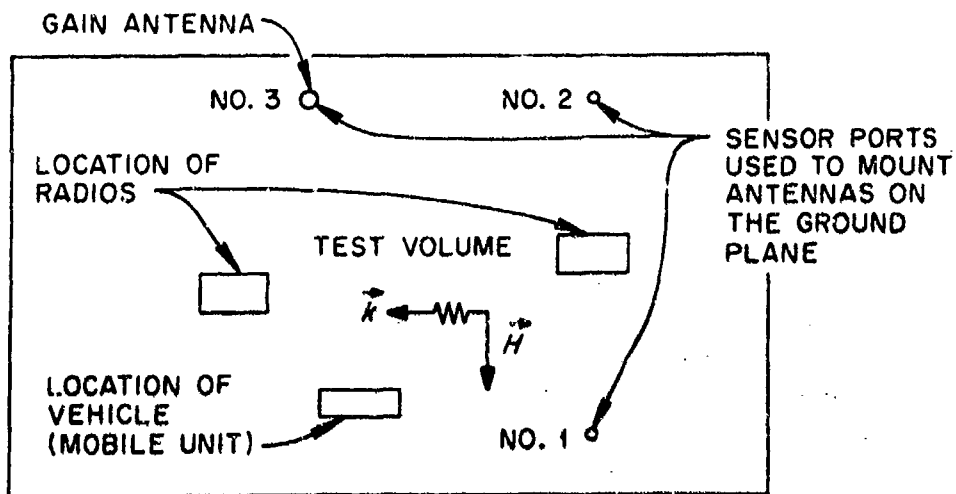
(b) TOP VIEW

Fig. 4.2. Arrangement of Antennas and Radios for the Test.

PHOTO 0338-73

Fig. 4.3. VHF Half-Dipole Antenna Mounted Over a Ground Plane Sensor Port.

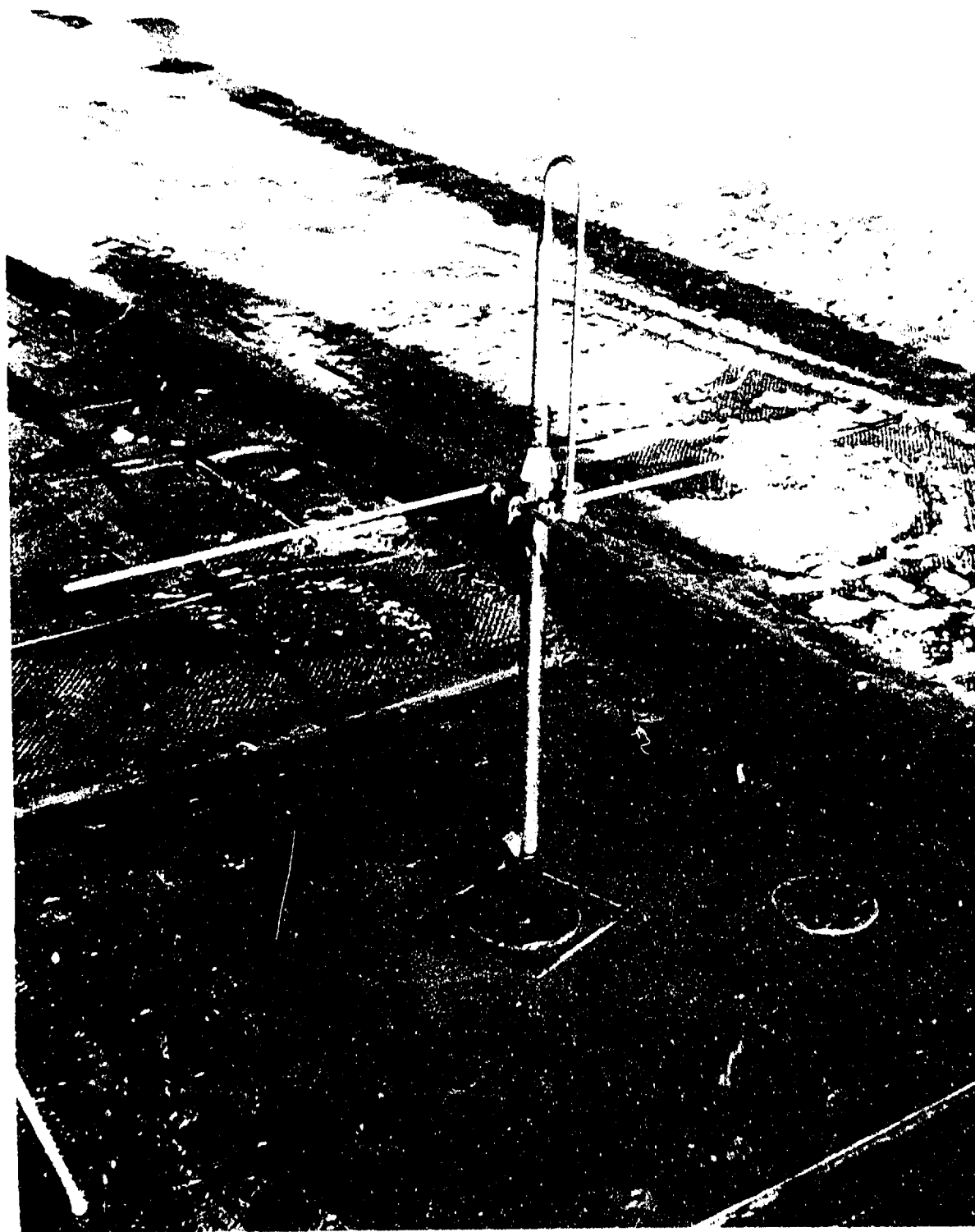Fig. 22. VHF Folded Half-Dipole Antenna Used in the Test.
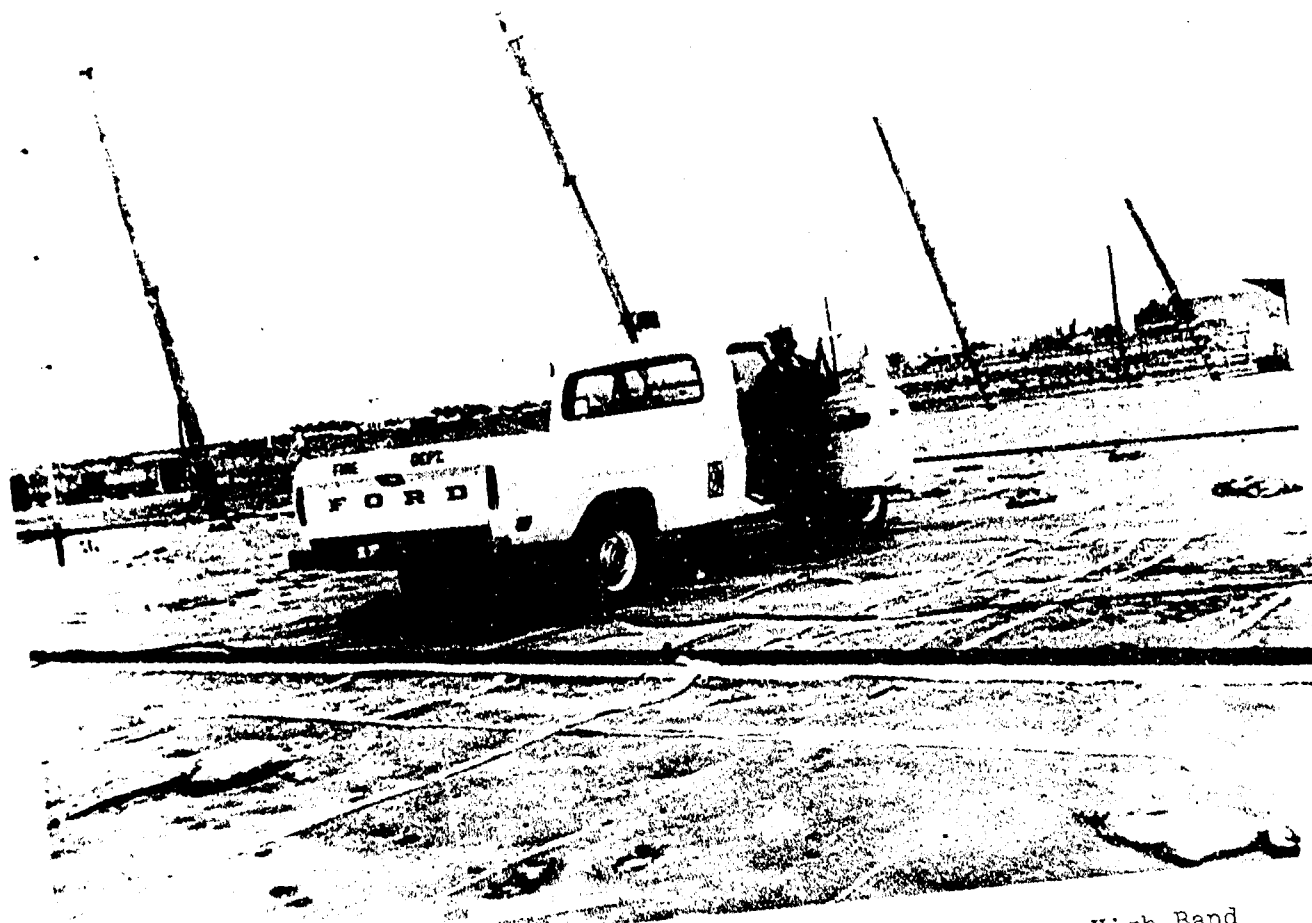
Fig. 4.5.   Albuquerque Fire Chief Ray Huhn and the VHF High Band
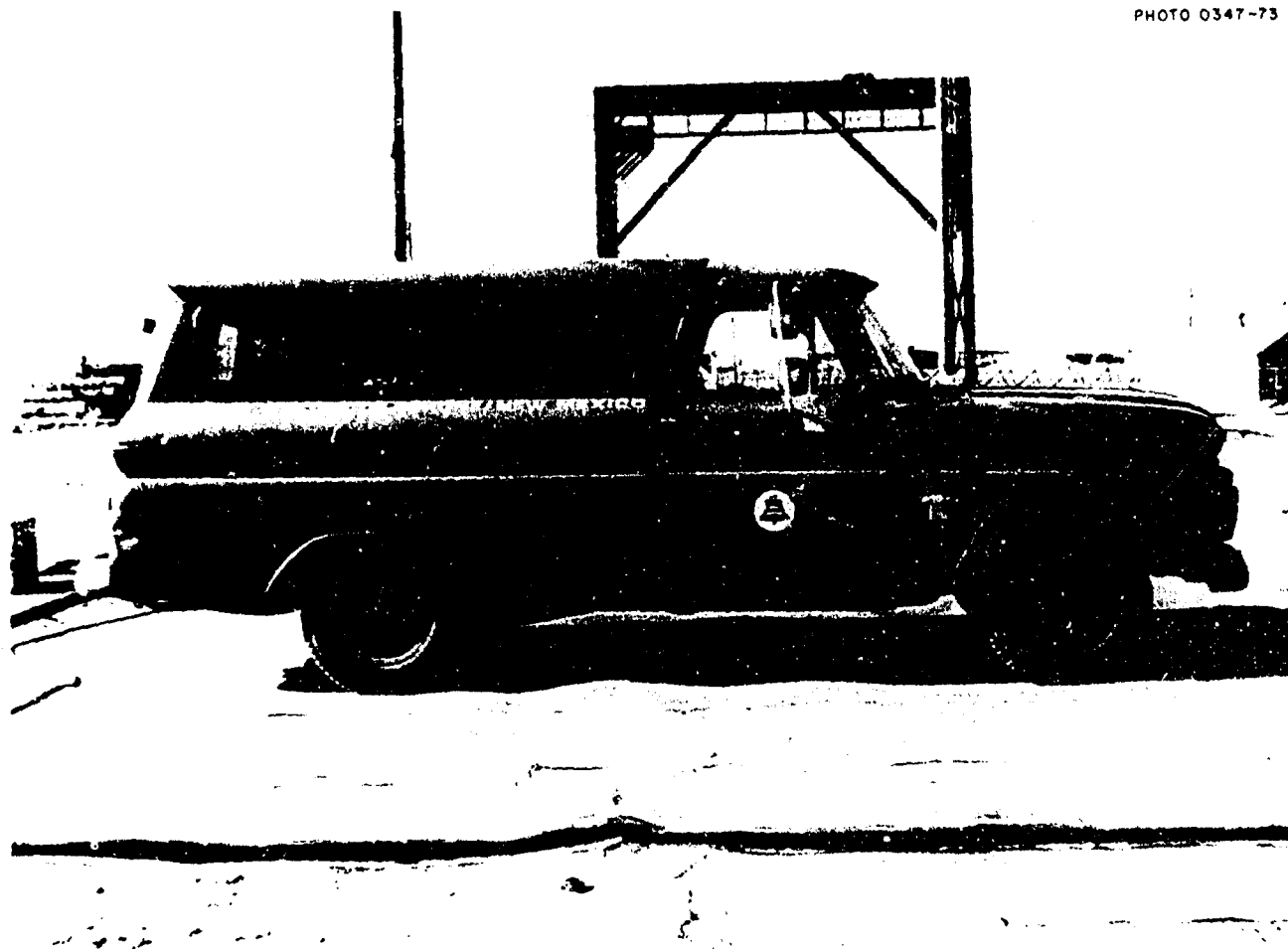Mobile Unit in the Test Volume.
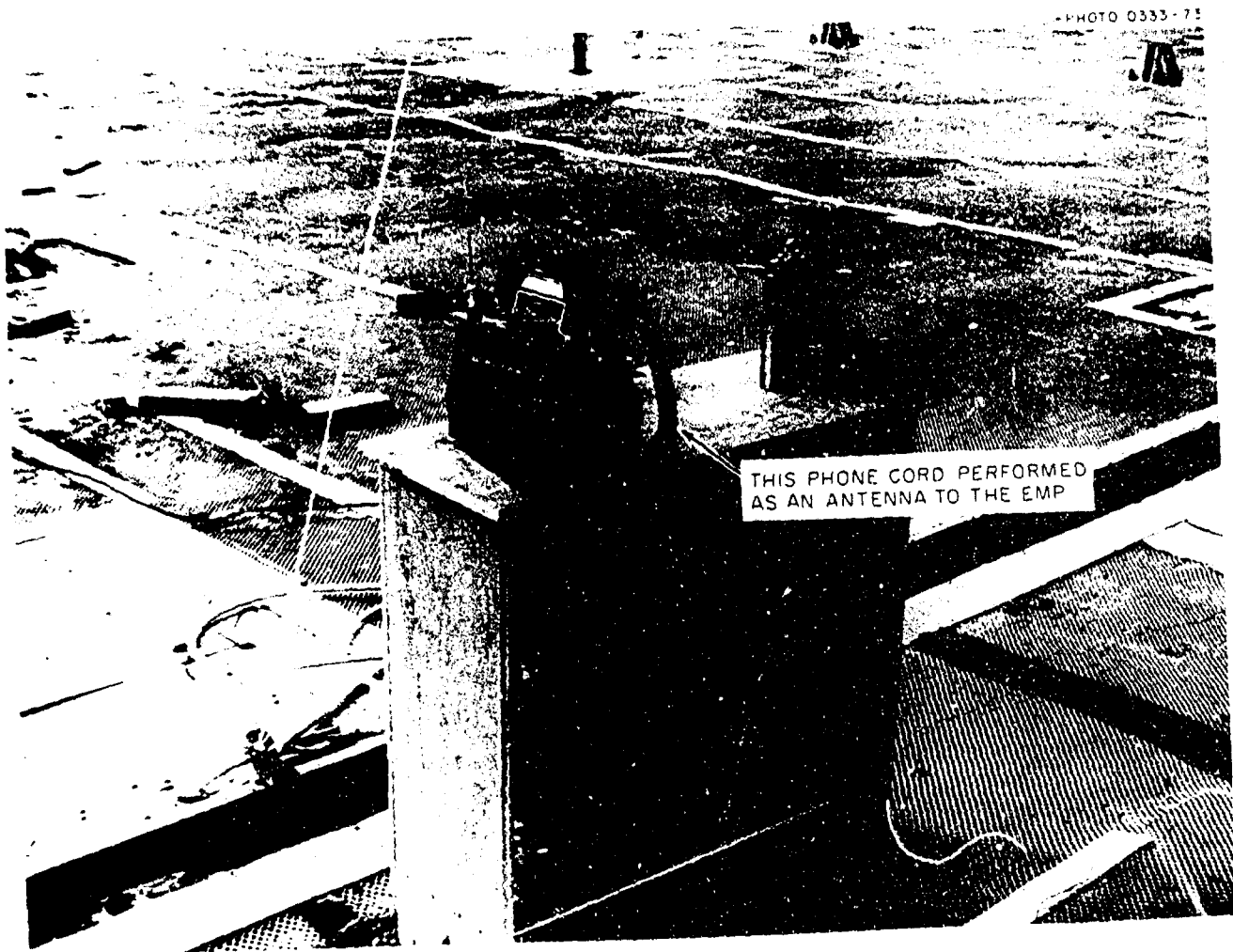
Fig. 4.6.   UHF Mobile Unit in the Test Volume.

Fig. 4.7. VHF Portable Unit in the Test Volume.

electric field with peak values below and above 12 kV/m are shown in Figs. 4.8a and 4.9a respectively. In Fig. 4.8a, oscillations appear as soon as the pulse has reached a near peak value, i.e., after about 4 ns of pulse time history. These oscillations have an amplitude on the order of 10% of the double exponential waveform.

For pulses of all amplitudes there is a significant departure from the double exponential after about 10 ns of pulse time history. An oscillatory wave is added to the double exponential waveform. The amplitude of this oscillatory wave is about 25% of the peak value of the double exponential and the period is about 20 ns. This corresponds to frequencies near 50 MHz. This discrepancy from the double exponential waveform is evident in waveforms of all adjustable amplitudes and is a characteristic of the high voltage pulser.
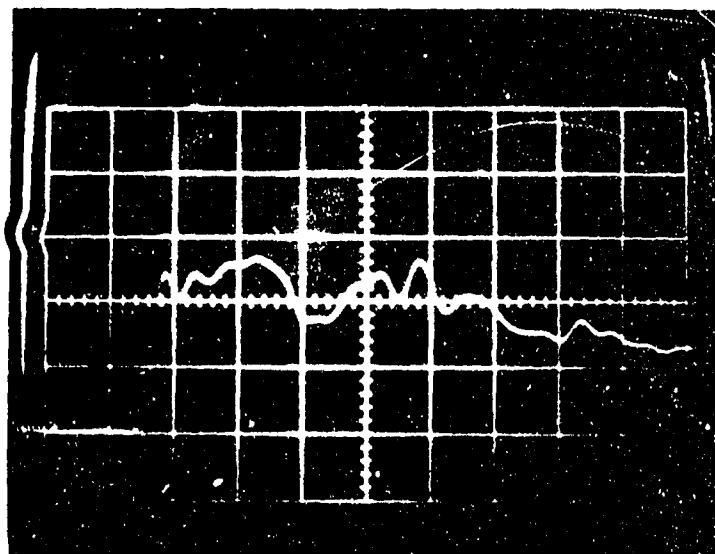
One effect of the oscillations riding on the double exponential waveform is that the amplitude of the double exponential is not readily available from the measurements. The definition of pulse amplitude E_p used by the ALECS Facility personnel is the value of the first peak. In Fig. 4.8a, the first peak is not the highest peak of the waveform. In Fig. 4.9a, the first peak is the maximum value of the waveform.

This difference between the electric field waveforms for $E_p \leq 15$ kV/m and $E_p \geq 10$ kV/m and the significance of the large oscillatory wave will be referred to later in this report in the evaluation of the data.

4.4 THRESHOLD FAILURE LEVELS

The EMP electric field amplitude threshold failure levels of selected communications equipment were experimentally determined. The radios that were tested are: two-way radios used in the land mobile class, citizen's band transceivers, an amateur band receiver and a broadcast band radio. The two-way VHF and UHF radios were provided by the Albuquerque Office of Emergency Preparedness - Bernalillo County Civil Defense Department. That office obtained the radios from within its own organization, from the Albuquerque City Fire Department and from the Mountain Bell Telephone Company. The citizen's band transceivers were provided by the Oak Ridge Communications Company and the broadcast and amateur band receivers were provided by David Nelson of ORNL.

(a) EARLY TIME

VERTICAL 1.94 kV/m/div

HORIZONTAL 10 ns/div

(b) LATE TIME

VERTICAL 1.94 kV/m/div

HORIZONTAL 100 ns/div

Fig. 4.3. The ALECS EMP Electric Field Time History for $E_p = 1.95$ kV/m.

ORNL-DWG 73-3012

VERTICAL 19.4 kV/m/div

HORIZONTAL 10 ns/div

(a) EARLY TIME

VERTICAL 19.4 kV/m/div

HORIZONTAL 100 ns/div

(b) LATE TIME

Fig. 4.9. The ALECS EMP Electric Field Time History for $E_p \approx 100$ kV/m.

The procedure used to test the radios is to attempt to receive communications after each test shot and record any malfunctions that are observed. The equipme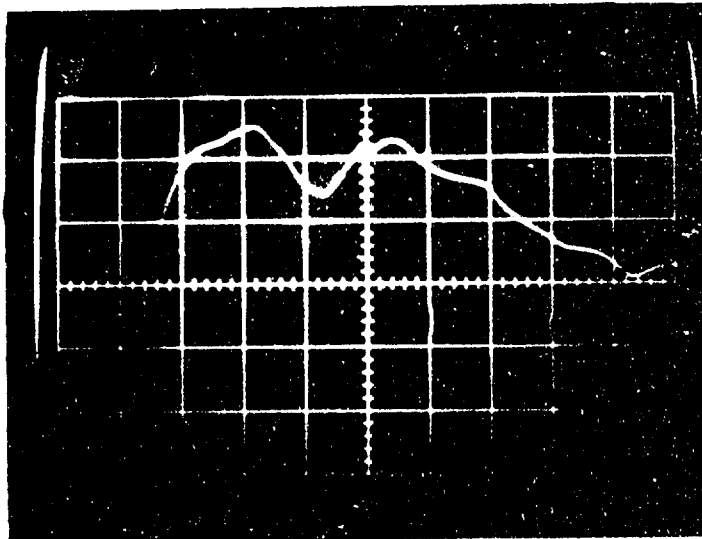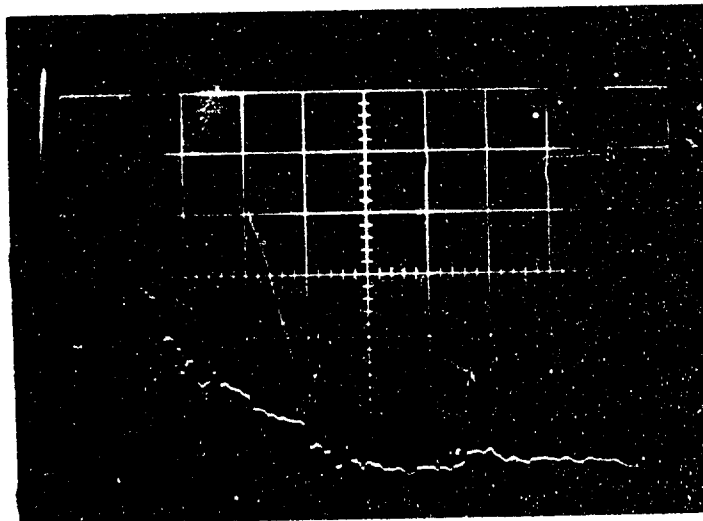nt was first subjected to a low field level of 5 kV/m. The electric field strength levels were then increased incrementally by 5, 10, or 20 kV/m, and the above test procedure was followed for each field level. Also for each field level, the radios were first tested with EMP protection and then again without EMP protection. Since the equipment was tested with incremental field strength levels, the upper and lower bounds of the EMP electric field threshold failure level E_f were determined for the particular orientation of the antennas in the test electric field.

Table 4.1 summarizes the results of the radios test. Eight of the thirteen radios tested had obvious malfunctions resulting from the simulated EMP. The lowest threshold failure level of the radios tested lies in the range $5 \text{ kV/m} < E_f \leq 10 \text{ kV/m}$ for the CB transceiver. As will be shown in Section 4.6, the corresponding threshold failure level of that transceiver for EMP with a direction of incidence that induces the maximum response in the antenna lies in the range of $2.14 \text{ kV/m} < E_f \leq 4.28 \text{ kV/m}$.

The CB transceiver front-end schematic diagram is shown in Fig. 4.10. As indicated in the figure the receiver RF transistor was damaged. The collector to emitter junction of the transistor was shorted by the EMP energy that was coupled to the antenna.

Most of the damaged equipment had semiconductor components that were destroyed by the ALECS EMP-induced, electrical transients. The receiver RF transistor is the circuit element that was most often damaged. In Fig. 4.11, the damaged RF transistor M9481 is shown in the front-end schematic diagram of the Motorola VHF high band H-21 Handie Talkie. As we can see, this transistor was protected against RF overload by diodes CR1 and CR6. This protection likely increased the threshold failure level of the Handie Talkie.

The VHF low band tube-type mobile unit had damaged electrical components although it continued to function and communications were possible for a short time after the test. It became non-operational during the post-test equipment check after the EMP test. This unit, although survivable for a short time, is vulnerable to the ALECS EMP; tuning coils and the wiring throughout the equipment was damaged by the effects of high voltage arcing which produced shorts in the circuit. It is uncertain to what extent this damage was caused
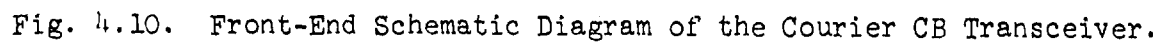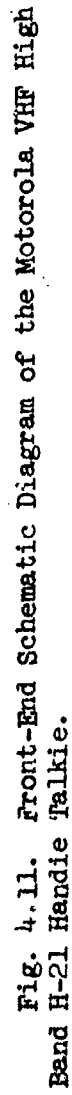
Table 4.1. Summary of Information on Radios Tested

No.	Class and Type	Frequency Band	Manufacturer and Model	Receiver Type	Threshold Failure Level E_f(kV/m)	Obvious Malfunctions	Damaged Components
1	Amateur Base Receiver	20 meters	Hallicrafters Co. Model S-40B	Tube	$100 < E_f$	None	Not checked
2	Citizen's Band Walkie Talkie	11 meters	Courier Model CWT-30	Transistor	$5 < E_f \leq 10$	No reception	RF transistor
3	Citizen's Band Walkie Talkie	11 meters	Courier Model CWT-30	Transistor	$10 < E_f \leq 20$	No reception	RF transistor
4	Land Mobile - Public Safety Portable Unit	VHF Low band	Motorola HT 21-16	Hybrid tube and transistor	$30 < E_f \leq 100$	No transmission	Tuning coils, RF transistor, and power supply diodes
5	Land Mobile Public Safety Mobile Unit	VHF Low band	Motorola T41GGV	Tube	$30 < E_f \leq 100$	Non-operational*	Antenna matching circuits, tuning coils, and wiring
6	Land Mobile Public Safety Walkie Talkie	VHF High band	Motorola HT 220	Transistor, and integrated circuit	$100 < E_f \leq 200$	No reception	RF transistor
7	Land Mobile Public Safety Portable Unit	VHF High band	Motorola HT Radiophone	Transistor and an integrated circuit	$70 < E_f \leq 100$	No transmission	Audio integrated circuit
8	Land Mobile Public Safety Mobile Unit	VHF High band	Motorola Motrac HHT Series	Transistor and integrated circuit	$100 < E_f$	None	No damage
9	Land Mobile Public Safety Base Station Unit	VHF High band	General Electric ET 35A, ET 35B	Tube	$100 < E_f$ 9 dB gain antenna	None	No damage
10	Land Mobile Industrial Service Walkie Talkie	UHF	Motorola H 24	Transistor	$100 < E_f$	None	No damage

Table 4.1 (Continued)

No.	Class and Type	Frequency Band	Manufacturer and Model	Receiver Type	Threshold Failure Level E_f (kV/m)	Obvious Malfunctions	Damaged Components
11	Land Mobile Industrial Service Mobile Unit	UHF	Motorola Motrac MHT Series	Transistor	$100 < E_f$	None	No damage
12	Commercial Radio	AM Broadcast	Realtone 2424	Transistor	$400 < E_f \leq 500$	Weak reception	RF transistor
13	Commercial Radio	FM Broadcast	Realtone 2424	Transistor	$400 < E_f \leq 500$	Little or no reception	Oscillator transistor

*Observed non-operational during the post-test equipment check.

Fig. 4.10. Front-End Schematic Diagram of the Courier CB Transceiver.

Fig. 4.11. Front-End Schematic Diagram of the Motorola VHF High Band H-21 Handie Talkie.

by the actual EMP-induced transients or by follow-on surges from the power
supply. One of the tuning circuits that was damaged during the test is shown
in Fig. 4.12a.

The VHF low band portable unit also had high voltage damage to the wiring
and tuning coils. This radio was powered by a 30-foot power cable connected to
a 12-volt battery. The power supply rectifier diodes were destroyed; this and
some of the other damages are likely due to transients induced in the power
cable.

The VHF high band portable unit had an integrated circuit (IC) that was dam-
aged during the test. The damaged IC was in the audio amplifier stage of the
transmitter. The audio circuit is shown in Fig. 4.12b. Since the IC in the
audio circuit is the only circuit component that was damaged, it is likely that
EMP-induced surges in the microphone cord destroyed the audio circuit. Thus,
the phone cord performed as an effective non-deliberate antenna for the ALECS
EMP.

4.5 COMMUNICATION ANTENNAS RESPONSES TO EMP

The Phelps Dodge Communications Company provided four of the six antennas
used in the test. The four antennas are: a quarter-wave whip, a vehicular base
loaded gain antenna, a folded half-dipole, and a broadband array gain antenna.
All of these antennas are designed for the VHF high band and are commonly used
in the public safety, industrial, and transportation services.

The two remaining antennas were provided by ORNL. They are a UHF quarter-
wave whip and a RG-8U coaxial cable non-deliberate antenna. The specifications
for the six antennas are listed below:

	Antenna	Frequency	Bandwidth	Gain
1.	Quarter-wave whip	154.43 MHz	--	Unity*
2.	Vehicular loaded whip	154.43 MHz	5-6 MHz	2.5 dB*
3.	Folded half-dipole	154.43 MHz	3 MHz	Unity**
4.	Gain antenna	154.43 MHz	14 MHz	9 dB**
5.	UHF quarter-wave whip	450 MHz	--	Unity*
6.	RG-8 coax cable	(5 meters long)	--	--

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*The gain is referenced to a quarter-wave half-dipole.
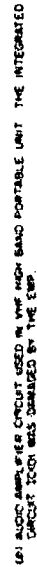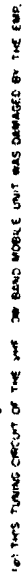
**The gain is referenced to a half-wave dipole.

Fig. 4.12. Partial Schematic Diagrams of the VHF Mobile and Portable Units.

The two types of antenna responses that were successfully recorded are the short circuit current and the 50 ohm load current responses. The open circuit voltage response was not measured accurately due to erroneous signals introduced in the data acquisition system. Examples of 50 ohm load current measurements for the five communications antennas are shown in Figs. 4.13 and 4.14. The current responses through a 50 ohm load were recorded for the five antennas for values of $E_p \approx 5$, 10, 20, 30, 40, 50, 70, and 100 kV/m.

The short circuit current responses were recorded for the five communications antennas with $E_p \approx 5$ kV/m. In Fig. 4.15, an example of a short circuit current measurement is shown for the folded half-dipole antenna. The short circuit current waveform has about the same ringing frequency as that of the 50 ohm load current. As expected, the short circuit current is less damped than the current through a primarily resistive load.

In Fig. 4.16, the 50 ohm load current and short circuit current responses are shown for the VHF quarter-wave whip. It can be observed that the amplitude of the 50 ohm load current for the first half cycles is about 70% that of the short circuit current.

4.6 ANTENNA RESPONSE CALCULATIONS

The direction of incidence of the ALECS EMP wave was approximately broadside to the antennas since the electric field within the test volume is nearly perpendicular to the ground plane. This direction of incidence corresponds to a polar angle of $\Theta = \pi/2$, measured from the axis of the antenna. Half-dipole antennas have a maximum response for a direction of incidence with polar angle Θ_m corresponding to the maximum lobe of the radiation pattern. The ratio of the values of the electric fields at the maximum lobe and at $\Theta = \pi/2$ of a transmitting half-dipole antenna is given by[7]

$$\frac{E(\pi/2)}{E(\Theta_m)} = .428 \quad . \tag{4.1}$$

By the Reciprocity Theorem for antennas we know that the radiation patterns of a given antenna are the same whether the antenna is used for radiation or reception. Also, the response of a receiving antenna is proportional to the electric field.[8] If $I(\Theta_m)$ is the half-dipole 50 ohm load current response to an electromagnetic wave with the magnetic field polarized perpendicular to the antenna and

ORNL-DWG 74-7048
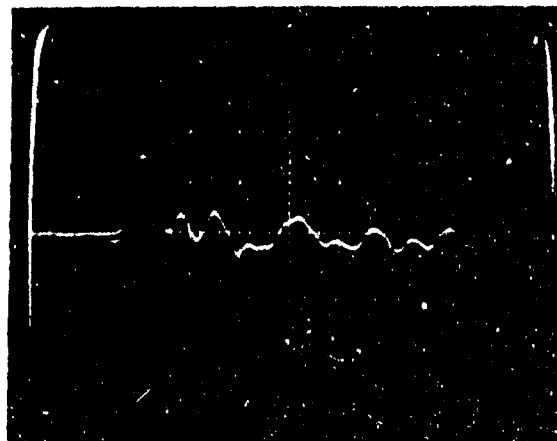
VERTICAL 10A/div

HORIZONTAL 10ns/div

(*a*) QUARTER WAVE WHIP
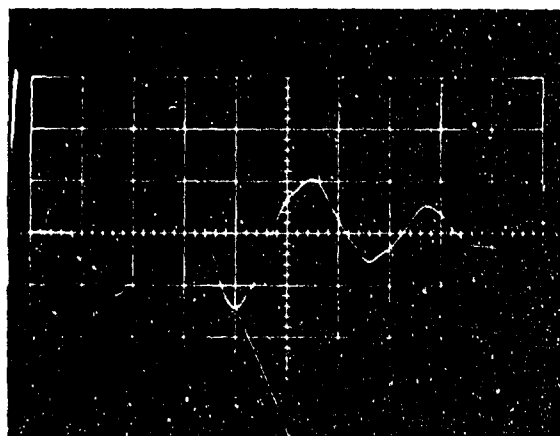
VERTICAL 10A/div

HORIZONTAL 10ns/div

(*b*) FOLDED MONOPOLE
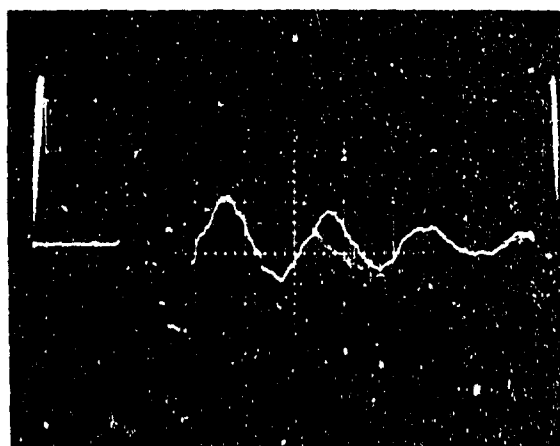
VERTICAL 20A/div

HORIZONTAL 50ns/div

(*c*) GAIN ANTENNA

Fig. 5.12. Current Measured Through a 50 ohm Load When 150.5 MHz Antennas are Illuminated by ALECS EMP with E_p = 75.5 kV/m.

ORNL—DWG 73—3017
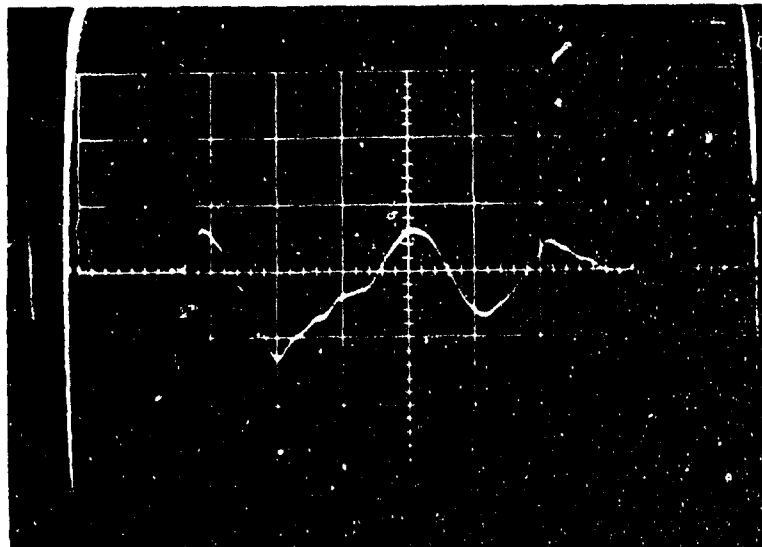
VERTICAL 10A/div

HORIZONTAL 10ns/div

(a) FIVE—EIGHTS WAVELENGTH LOADED
ANTENNA DESIGNED FOR 154.43 MHz.
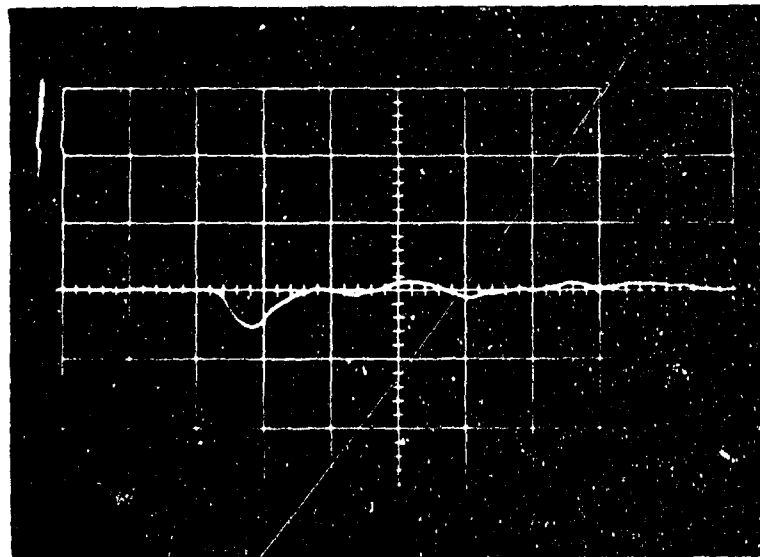
VERTICAL 5A/div

HORIZONTAL 10ns/div

(b) UHF MONOPOLE DESIGNED FOR 450 MHz.

Fig. ... Current Measured Through a 50 ohm Load When VHF
and UHF Antennas are Illuminated by ALECS EMP with $E_p \approx 100$ kV/m.
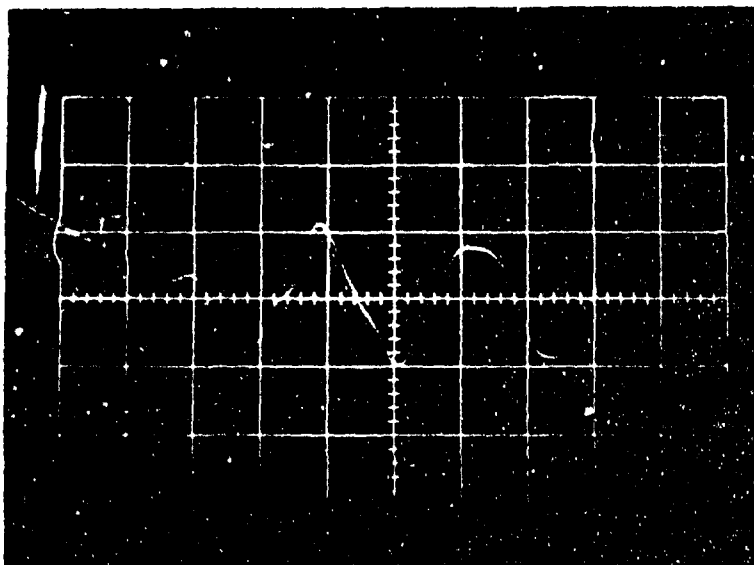
(a) EARLY TIME

VERTICAL 5A/div

HORIZONTAL 10ns/div
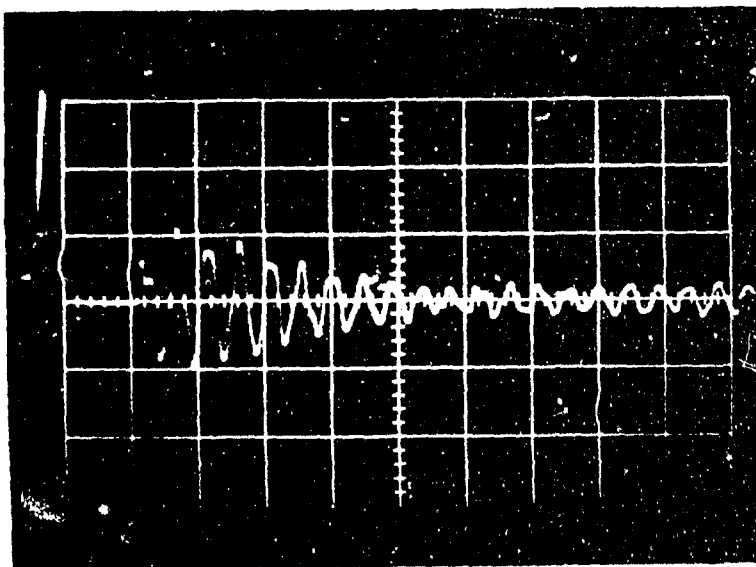
(b) LATE TIME

VERTICAL 5A/div

HORIZONTAL 50ns/div

Fig. 5.15. Measured Short Circuit Current Response for the Folded Monopole Antenna Subjected to ALECS EMP with $E_p = 5.4$ kV/m.

ORNL-DWG 73-3016
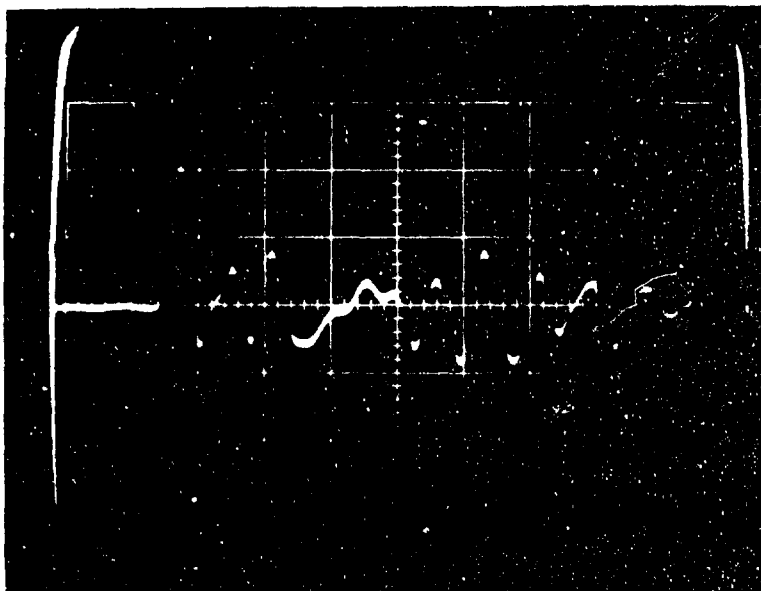
VERTICAL 1A/div

HORIZONTAL 10 ns/div

(*a*) 50-ohm LOAD CURRENT
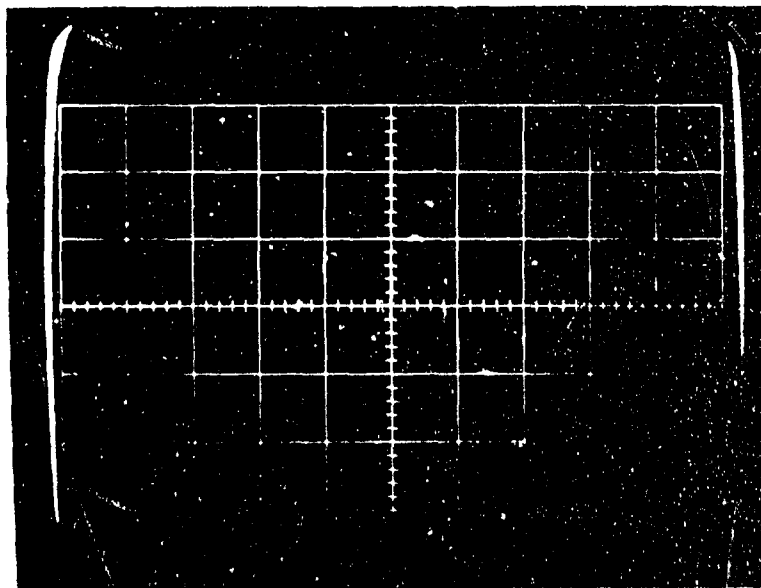
VERTICAL 1A/div

HORIZONTAL 5ns/div

(*b*) SHORT CIRCUIT CURRENT

Fig. 4.15. Measured Current Response of a 154.43 MHz Quarter-Wave Half-Dipole Subjected to ALECS EMP with $E_p \approx 4.65$ kV/m. These traces are difficult to see due to the fast oscilloscope sweep speeds.

with a direction of incidence equal to Θ_m, then the antenna response to broadside incidence is

$$I(\pi/2) = .428\ I(\Theta_m)\ .\qquad\qquad (4.2)$$

Equations (4.1) and (4.2) arise from the effect of the finite size of the effective antenna ground plane. This effect, however, is practically independent of the ground plane size.[7] For an infinite antenna ground plane, $\Theta_m = \pi/2$ and Eqs. (4.1) and (4.2) are not valid.

The maximum response, $I(\Theta_m)$, can be theoretically calculated from the idealized problem of a half-dipole mounted on an infinite ground plane and subjected to an EMP with broadside incidence. A technique to calculate the dominant terms in the time-domain solution of the electric dipole and half-dipole responses to broadside EMP has been described in a previous report.[8] It consists of applying recent work involving the Singularity Expansion Method which expresses the solution in terms of the natural modes of the dipole structure. This technique in conjunction with Eq. (4.2) has been used to calculate the half-dipole responses to the ALECS EMP; the results are shown in Figs. 4.17b and 4.18b for the VHF and UHF quarter-wave whips respectively. The measured responses are shown in Figs. 4.17a and 4.18a such that we can easily compare the theoretical and experimental results.

The ALECS EMP electric field was approximated by a double exponential waveform for the calculations. The approximate ALECS EMP electric field time history used in the calculations is

$$E(t) = E_o\ (e^{-\alpha t} - e^{-\beta t})\qquad\qquad (4.3)$$

where

$\alpha = 7 \times 10^6\ \text{sec}^{-1}$

$\beta = 2.2 \times 10^8\ \text{sec}^{-1}$

and

$E_o = 1.15\ E_p$

where E_p is the measured amplitude of the waveform. The waveform defined by Eq. (4.3) has a rise time of about 10 ns and a fall time of about 600 ns. The 600 ns fall time is the time in which the waveform has decreased to 2% of its peak value.

ORNL-DWG 73-3020
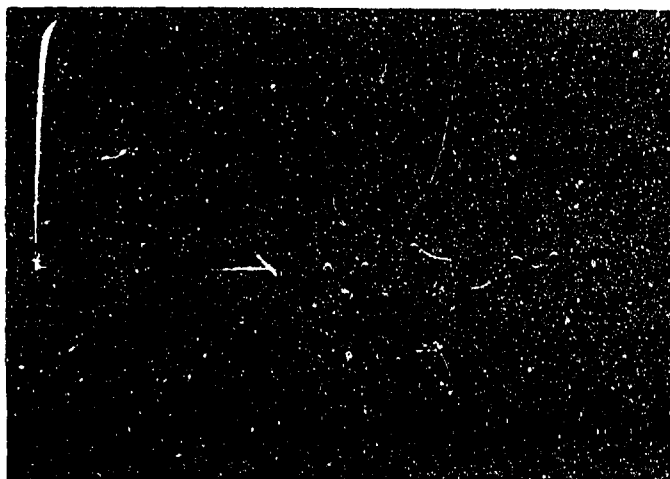
VERTICAL 5 A/div
HORIZONTAL 10ns/div

(a) MEASURED RESPONSE
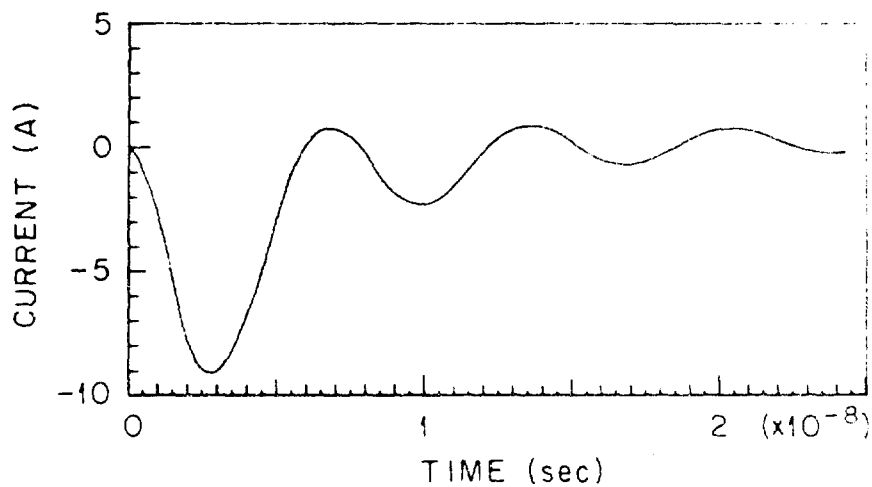
(b) CALCULATED RESPONSE

Fig. 4.17. Current Through a 50 ohm Load when a 150.43 MHz
Half-Dipole is Illuminated by ALECS EMP with E_p = 29 kV/m.

ORNL-DWG 73-3024
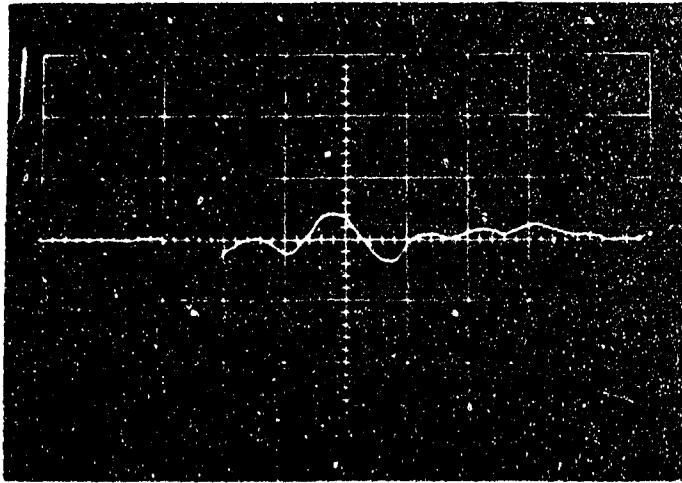
VERTICAL 1 A/div
HORIZONTAL 10 ns/div

(*a*) MEASURED RESPONSE
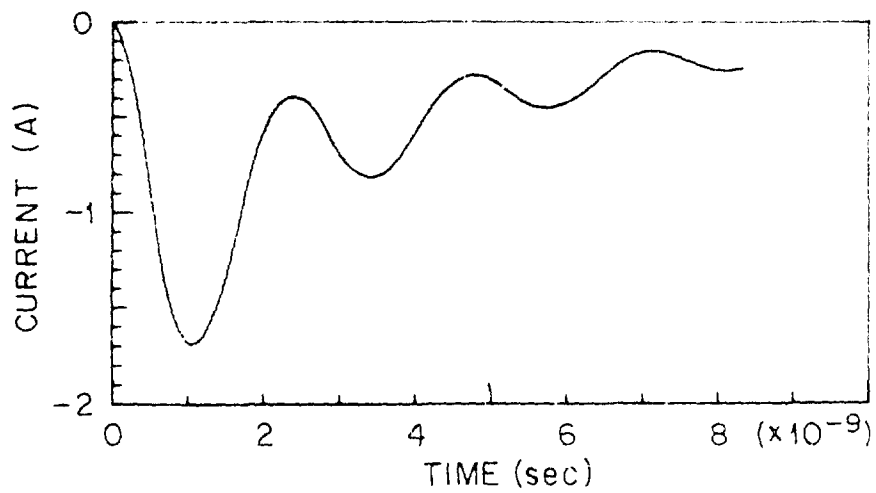
(*b*) CALCULATED RESPONSE

Fig. 4.13. Current Through a 50 ohm Load when a 450 MHz
Monopole is Illuminated by ALECS EMP with $E_p \approx 33$ kV/m.

In Fig. 4.17, the current through a 50 ohm load is shown for a half-dipole antenna, designed for 154.43 MHz, illuminated by the ALECS EMP with $E_p \approx 29$ kV/m. The peak value of the measured response I_m over the first half-cycle is about -7 amperes (A) whereas the calculated value I_c is about -9A. The percent of relative difference between the measured and calculated values is

$$D = \left| \frac{I_m - I_c}{I_m} \right| \times 100\% \qquad\qquad (4.4).$$

which is equal to 28.5% for I_m = -7A and I_c = -9A.

For the second negative peak, the measured value is about -2A and the calculated result is about -2.2A. The relative difference is 10%.

The time of the first zero crossing for the calculated waveform t_c is about 6 ns and the first zero crossing for the measured waveform t_m is about 8 ns. The relative difference is 25% where t_m has been substituted for I_m and t_c has been substituted for I_c in Eq. (4.4).

In Fig. 4.18, the 50 ohm load current response is shown for a 450 MHz UHF half-dipole antenna illuminated by the ALECS EMP with $E_p \approx 38$ kV/m. The amplitudes of the first peak for the measured and calculated results are -1.3A and -1.7A respectively. The relative difference is 38%.

The time histories of the theoretical and experimental results for the UHF antenna response are not in very good agreement. This is due primarily to the limited response capability of the 454 Tektronic oscilloscope used for the test. The rise time capability of the 454 scope is 2.4 ns. This is about the same as the rise time of the measured response in Fig. 4.18a.

Antenna feedlines are non-deliberate antennas for EMP. A 5-meter RG-8U braided coax cable non-deliberate antenna was tested in the same manner as the other antennas. One end of the cable was positioned through a metal plate over a sensor port. The shield of the cable was electrically connected to the ground plane at the plate. The other end of the cable was erected perpendicular to the ground plane. Response measurements were made at the bottom end of the cable under the ground plane and with the top end of the cable unterminated.

To estimate the open-circuit voltage response of the coax antenna, we observe that the shield of the cable is, to a good approximation, a shorted half-dipole. Thus, we can compute the shield current by the same method used for the quarter-wave whips.

To calculate the open-circuit voltage, we can apply a rule of thumb, i.e., for typical EMP pulses, the attenuation of common single-braided coax cables of length comparable to the radiation length or longer is on the order of 48 dB. Thus, the internally induced current through a 50-ohm load for RG-8U cable is on the order of 1/250 that of the shield current.

The Thevenin equivalent voltage for the coax cable and the electromagnetic environment is approximately related to the shield current $I(\omega)$ by

$$V(\omega) \simeq \frac{50.0 + Z_c(\omega)}{250} \; I(\omega) \tag{4.5}$$

where $Z_c(\omega)$ is the impedance of the coax cable. The period of the dominant waveform in the solution of the shield current response to the ALECS EMP is about 72 ns. The impedance of the 5-meter RG-8U coax cable for the waveform is about 50 ohms for the first 72 ns.

In Fig. 4.19, the measured and calculated results for the coax cable antenna open-circuit voltage response to the ALECS EMP with $E_p = 5$ kV/m are shown. Equation (4.5) was used for the calculation with the coax cable impedance equal to 50 ohms. Except for the first half-cycle, the measured and computed results compare very well.

Thus far we have compared theoretically estimates with measured responses for the VHF and UHF quarter-wave whips and the coax cable antenna. Now we turn our attention to the more complicated gain antenna. For typical EMP's the dominant response of a quarter-wave VHF half-dipole is composed of two damped sinusoids.[3] The angular frequency of the response is equal to the antenna's first resonant frequency which is normally the antenna design frequency.

The power received by a gain antenna at the design frequency is related to that of a dipole by the power gain G. Since the dominant response of the simple dipole VHF antenna has a frequency equal to the design frequency of the antenna we can postulate that

$$I_g \leq \sqrt{G} \; I_d \tag{4.6}$$

where G is the power gain at the design frequency referenced to a dipole, and I_g and I_d are the 50 ohm load current responses to typical EMP's for the gain and dipole antennas respectively.

ORNL-DWG 73-3019
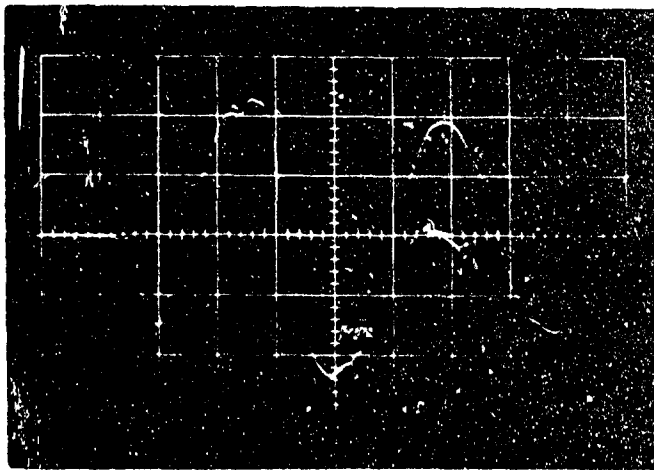
VERTICAL 10 V/div
HORIZONTAL 20 ns/div

(*a*) MEASURED RESPONSE
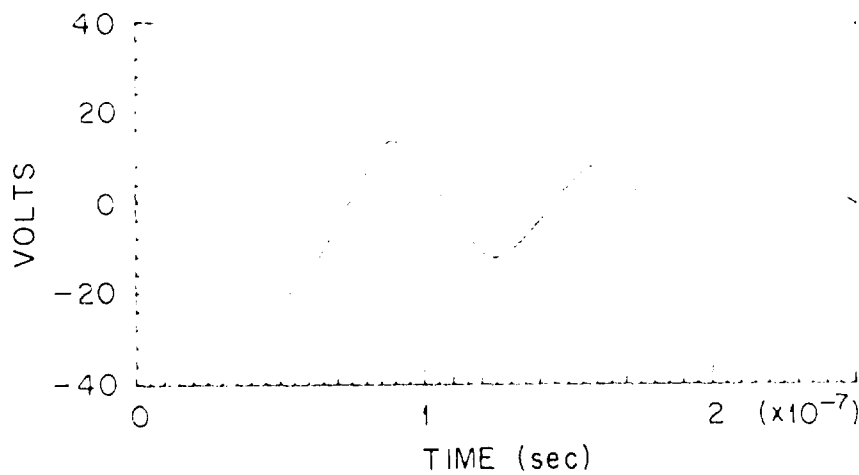
(*b*) CALCULATED RESPONSE

Fig. 4.19. The Open Circuit Voltage Response of a 5-Meter RG8 Coaxial Cable Monopole Antenna Subjected to ALECS EMP with $E_p \approx$ kV/m.

Equation (4.6) can be checked by the measured results in Fig. 4.12. The peak response for the 154.43 MHz quarter-wave whip is about 16 amperes. The peak response for a 154.43 MHz half-wave dipole would be about the same since their gains are about equal.[1] For the gain antenna used in the test, $\sqrt{G}$ = 2.82. Applying Eq. (4.6) gives the peak value of the gain antenna response as equal to or less than 2.82 x 16A = 45.2A.

The peak value of the measured gain antenna 50 ohm load current response is about 40A. Thus, in our example calculation, Eq. (4.6) gave an upper bound as was postulated.

4.7 NON-LINEAR EFFECTS

The response to EMP of the half-dipole antenna located in free space varies linearly with the amplitude of the electric field. This assumption was used in Section 4.6 to estimate the half-dipole response to the ALECS EMP. However, for the antenna in an air medium, one must take into account the effects of corona discharge and spark-over associated with high field strengths.

In Fig. 4.20, the peak current response through a 50 ohm load I_p is plotted against E_p, the measured amplitude of the electric field, for four of the communication antennas tested. The plot for the fifth antenna, the folded half-dipole, is not shown since it is about the same as that of the quarter-wave whip.* There are three types of non-linearities that can be observed from Fig. 4.20: an apparent non-linearity associated with $E_p < 15$ kV/m, a non-linear effect associated with relatively high field strengths, and a non-linearity associated with the 5/8 wavelength VHF loaded antenna.

For field strengths less than about 15 kV/m, the measured peak current is larger proportionally than that measured at higher field strengths. This phenomenon is likely due to the difference in the ALECS EMP waveforms for low and high field strengths as was discussed in Section 4.3. If the electric field amplitudes for field strengths less than 15 kV/m were defined as the maximum measured peak value of the waveform instead of the first peak value, then the results would appear nearly linear for low field levels. It is, therefore, plausible to attribute the non-linear effects at low field levels to the change in the waveform characteristics and not directly to the field level. Thus, this non-linearity is an apparent non-linear effect associated with the electric field strength.

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*The comparison was made for the first half-cycle responses.

ORNL-DWG 73-3021

(a) VHF HIGH BAND ANTENNAS

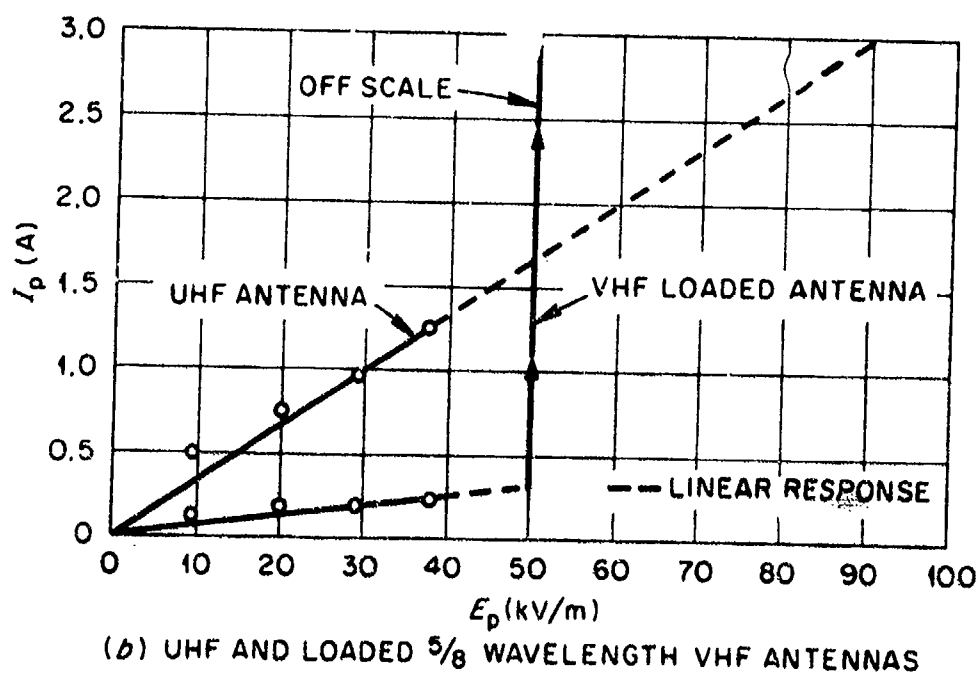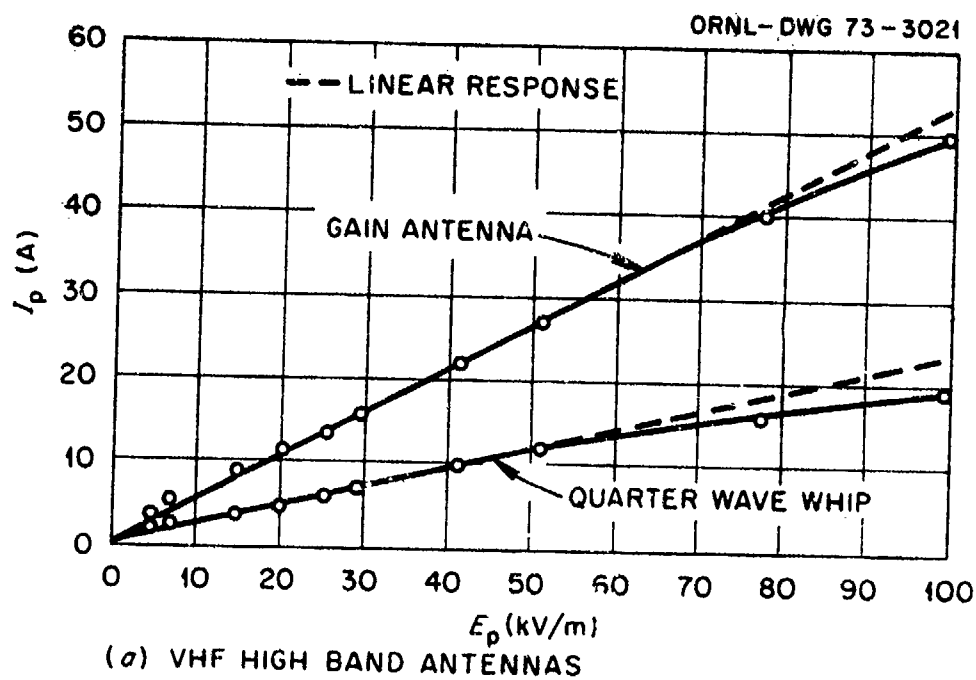(b) UHF AND LOADED ⅝ WAVELENGTH VHF ANTENNAS

Fig. 4.20. Peak Current Through a 50 ohm Load for Antennas Illuminated by the ALECS EMP.

For field strength levels above 50 kV/m, the 50 ohm load current responses become non-linear and do not increase proportionally with E_p as can be seen from Fig. 4.20a. This phenomenon first occurred at $E_p \simeq 50$ kV/m for the quarter-wave whip and at $E_p \simeq 70$ kV/m for the gain antenna. The gain antenna consisted of a collinear array of folded dipole elements. The radius of each folded dipole element is about one and a half times that of the quarter-wave whip. Since this phenomenon occurred for the smaller radius antenna, at lower field levels, it is likely due to corona discharge. The effect of this phenomenon on the quarter-wave whip is to reduce its 50 ohm load current response to ALECS EMP by about 20% for $E_p = 100$ kV/m.

The response for the 5/8 wavelength loaded antenna appeared to be non-linear at about 50 kV/m. However, after careful study of the data we feel that the non-linear effect shown on Fig. 4.20b is due to a poorly connected antenna lead. The antenna lead was checked on or about test shot No. 61. Figure 4.21 shows the difference in the measured waveforms. There is, however, a non-linear effect associated with the 5/8 wavelength antenna. The response at 50 kV/m was about the same amplitude as that of the quarter-wave whip and the maximum value of the current occurred during the first half-cycle of the waveform. For high field strength levels, the waveform of the response is different from that at low levels. This can be seen by comparing Figs. 4.21b and 4.14a. This effect is likely due to spark-overs in the loading coil. Spark-overs in the coil would change the antenna-loading coil impedance which would change the waveform of the 50 ohm load current response.

4.8 PROTECTION AGAINST EMP-INDUCED SURGES

The effectiveness of a standard lightning arrestor and some special transient protective devices for suppressing EMP-induced current surges was experimentally determined. The devices were tested with the collinear array gain antenna for various electric field strength levels. The devices that were tested are a coaxial lightning arrestor manufactured by Phelps Dodge Communications Company, the 250 and 35° series Spikeguard transient protectors manufactured by Fischer Custom Communications, and a prototype semiconductor diode transient protector constructed by ORNL. The Spikeguard and diode-type protectors are constructed within standard coaxial tees. The semiconductor diodes used in the ORNL prototype are 1N3653's switching diodes each with a forward bias current rating of 400 milliamperes.

ORNL-DWG 73-3023
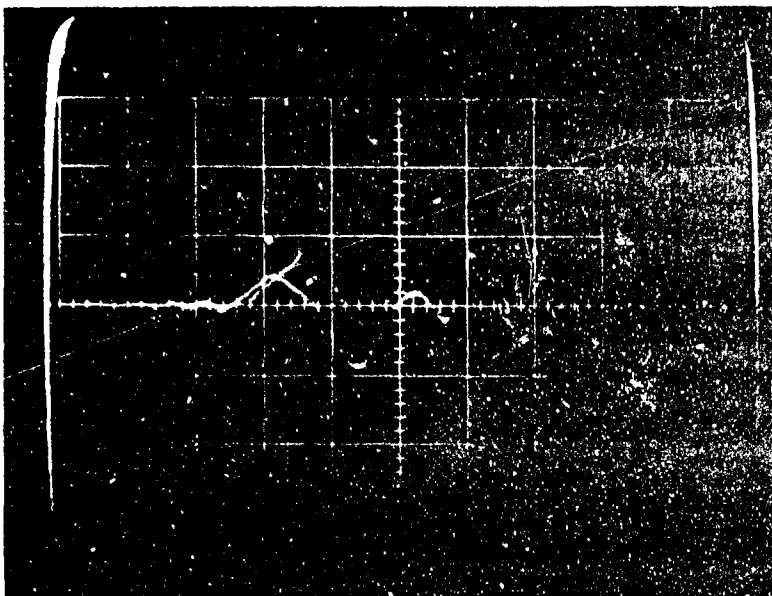
VERTICAL 0.1 A/div

HORIZONTAL 10ns/div

(*a*) MEASURED RESPONSE BEFORE
SHOT NO. 61
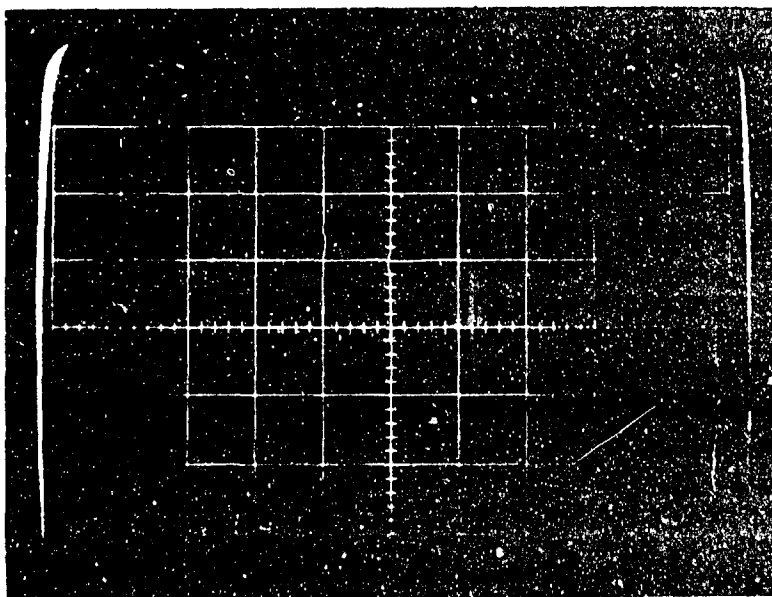
VERTICAL 5A/div

HORIZONTAL 5ns/div

(*b*) MEASURED RESPONSE AFTER
SHOT NO. 61

Fig. 4.21. Current Through a 50 ohm Load when a 154.43 MHz Five-Eighths Wavelength Loaded Monopole is Illuminated by ALECS EMP with E_p = 20 kV/m. These traces are difficult to see due to the fast oscilloscope sweep speeds.

The specifications for the protective devices are listed below:

Device	DC Breakdown Voltage	Voltage Standing Wave Ratio
Lightning Arrestor	500 to 1200 volts	Under 1.03:1 to 500 MHz
Spikeguard 250-N	230 volts	Under 1.8:1 to 400 MHz
Spikeguard 350-N	550 volts	Under 1.8:1 to 400 MHz
Spikeguard 350-UHF	550 volts	Under 1.5:1 to 250 MHz
Prototype diode	Under 1 volt	Not measured

The lightning arrestor, Spikeguards 250-N and 350-N, and the diode protector have type N coaxial connectors. The Spikeguard 350-UHF has a UHF type connector.

Figures 4.22 through 4.27 show the measured results of the effect of the surge protectors on the gain antenna 50 ohm load current for various field levels. In Fig. 4.22, $E_p \cong 9.5$ kV/m and the peak voltage on the antenna feedline is about 550 V. The Spikeguard 350-UHF is not effective at this field level as can be seen in Fig. 4.22b.

In Fig. 4.23, $E_p \cong 20$ kV/m and the Spikeguard 350-UHF becomes effective after the first full cycle of the induced current. As we can see from Fig. 4.23, the addition of the diode protection to the Spikeguard 350-UHF almost totally suppressed the current waveform.

At $E_p \cong 30$ kV/m, the Spikeguard 350-UHF is an effective surge suppressor as can be observed by Fig. 4.24b. The Spikeguard 350-UHF is more effective than the 350-N as can be seen by comparing Figs. 4.24a and 4.24b.

At $E_p \cong 50$ kV/m, we observe from Fig. 4.25a that the lightning arrestor has little or no effect on the EMP-induced current. Although the peak feedline voltage was about 1400 V, which exceeds the lightning arrestor breakdown voltage, the arrestor failed to respond. The initial rate of rise of the feedline voltage was about 300 V/ns. The time of the first zero crossing for the waveform was about 30 ns. The fast rise time and short duration of the pulse evidently did not allow sufficient time to activate the arrestor. The lightning arrestor also failed to respond at higher field strength levels used in the test.

Figures 4.25b and 4.25c show the effectiveness of the Spikeguards 250-N and 350-N protectors. Both devices are effective as a surge suppressor after the first half-cycle. During the first half-cycle, the 250N protector clipped

ORNL-DWG 73-3022
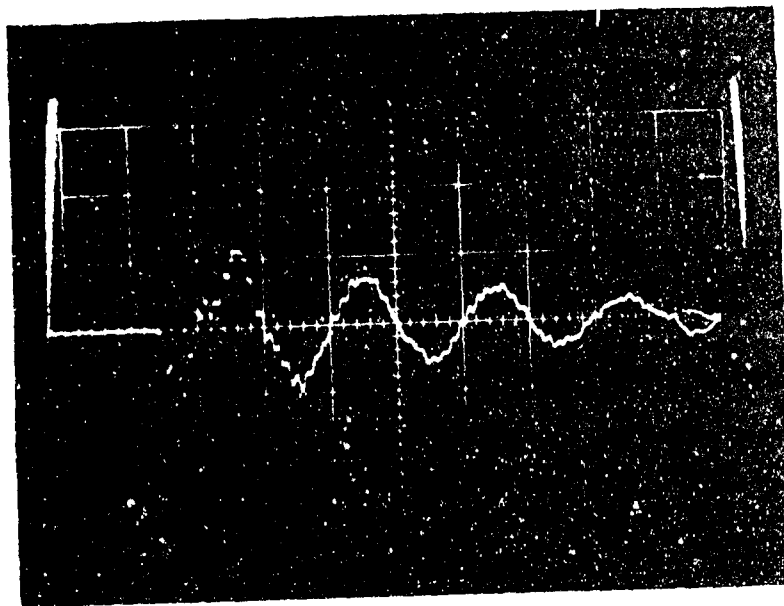
VERTICAL 10A/div

HORIZONTAL 50ns/div

(a) WITHOUT EMP PROTECTION
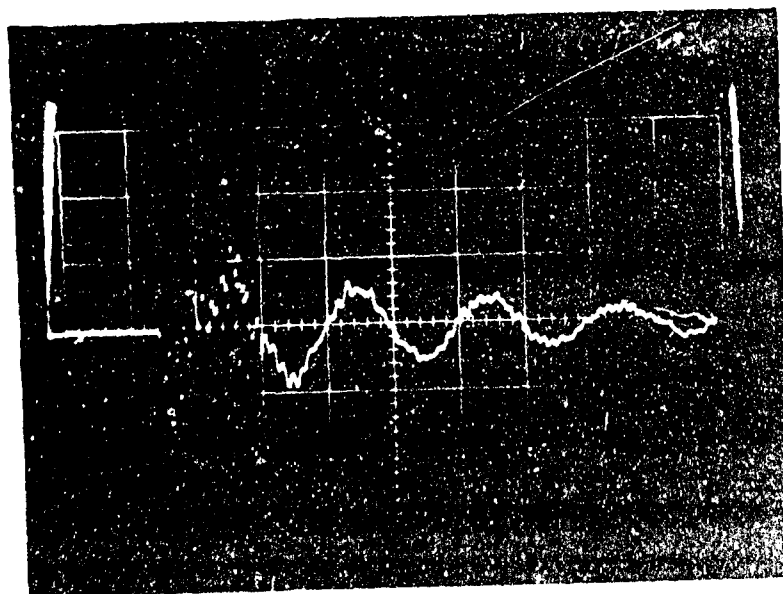
VERTICAL 10A/div

HORIZONTAL 50ns/div

(b) WITH 350 UHF

Fig. ...... Measured Current Through a 50 ohm Load when the
Gain Antenna is Illuminated by ALECS EMP with $E_p \approx 0.5$ kV/m.

ORNL-DWG 73-3013
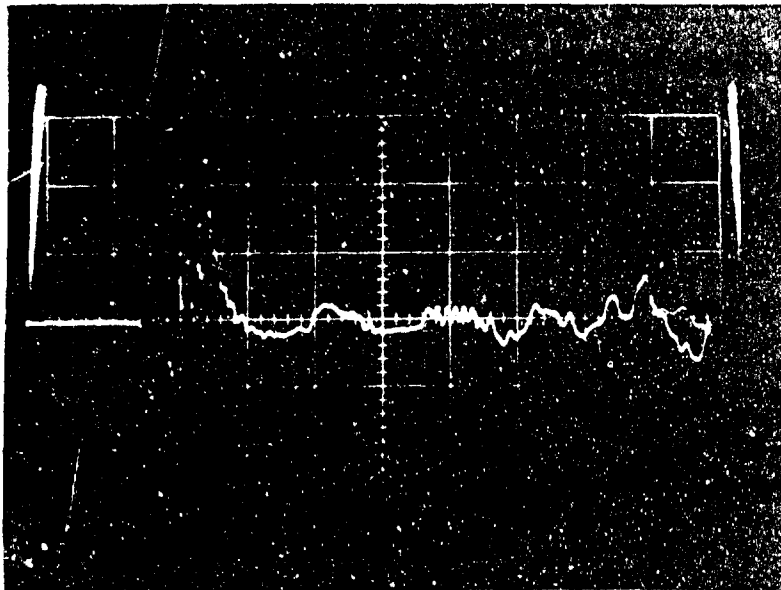
VERTICAL 5A/div

HORIZONTAL 50ns/div

(*a*) 350 UHF PROTECTION
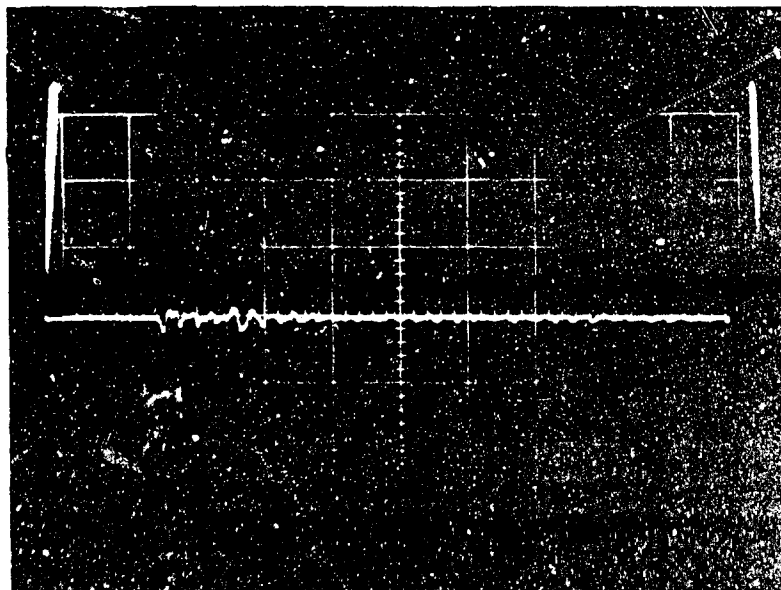
VERTICAL 5A/div

HORIZONTAL 50ns/div

(*b*) 350 UHF PLUS DIODE PROTECTION

Fig. 4.25. The Effects of EMP Protection Device on the Current Measured Through a 50 ohm Load when the VHF Gain Antenna is Illuminated by ALECS EMP with E_p = 100 kV/m.

ORNL–DWG 73–3014
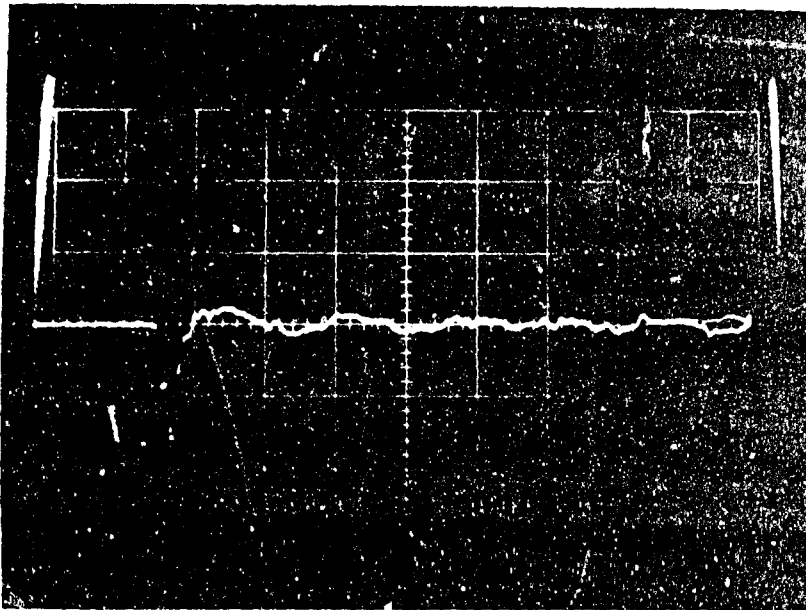
VERTICAL 10A/div

HORIZONTAL 50ns/div

(*a*) 350 N PROTECTION
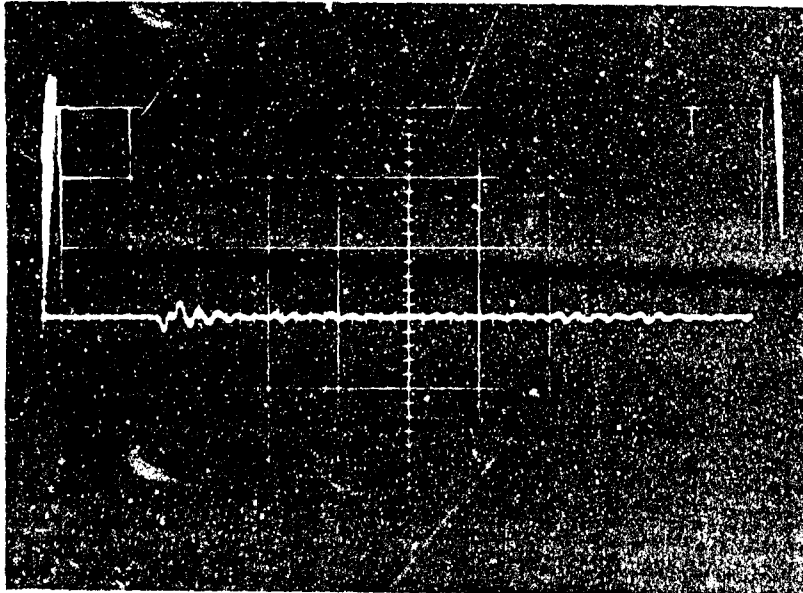
VERTICAL 10A/div

HORIZONTAL 50ns/div

(*b*) 350 UHF PROTECTION

Fig. 4.29. Current Measured Through a 50 ohm Load with EMP Protection when the VHF Gain Antenna is Illuminated by ALECS EMP with $E_0 \approx 40$ kV/m.

(a) LIGHTNING ARRESTOR PROTECTION

VERTICAL 10A/div

HORIZONTAL 50ns/div

(b) 250 N PROTECTION

VERTICAL 10A/div

HORIZONTAL 50ns/div

(c) 350 N PROTECTION

VERTICAL 10A/div

HORIZONTAL 50ns/div

Fig. 4.25. Current Measured Through a 50 ohm Load with EMP and Lightning Protection when the VHF Gain Antenna is Illuminated by AFWL EMP with $E_p \approx 51.5$ kV/m.

ORNL-DWG 73-362?

VERTICAL 20A/div

HORIZONTAL 50ns/d.

(a) NO PROTECTION

VERTICAL 10A/div

HORIZONTAL 50ns/div
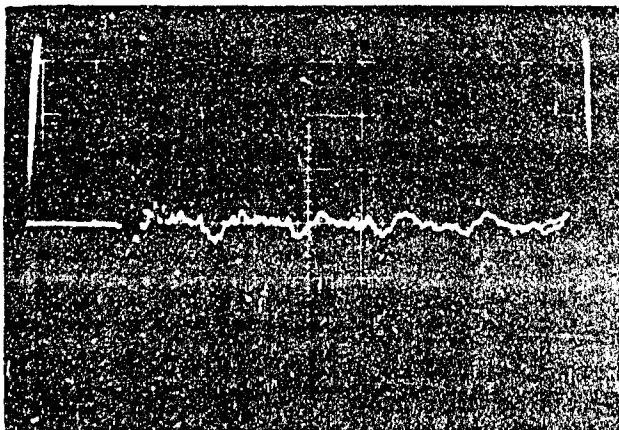
(b) 250 N PROTECTION

VERTICAL 10A/div

HORIZONTAL 50ns/div

(c) 1 kW(?) PROTECTION

Fig. ____. Current Measured Through a 50 ohm Load with EMP Protection when the VHF Whip Antenna is Illuminated by ALECS EMP with $E_p = 1$ kV/m.

ORNL-DWG 73-3026

(a) 350 UHF PROTECTION

VERTICAL 10A/div
HORIZONTAL 50 ns/div

(b) DIODE PROTECTION
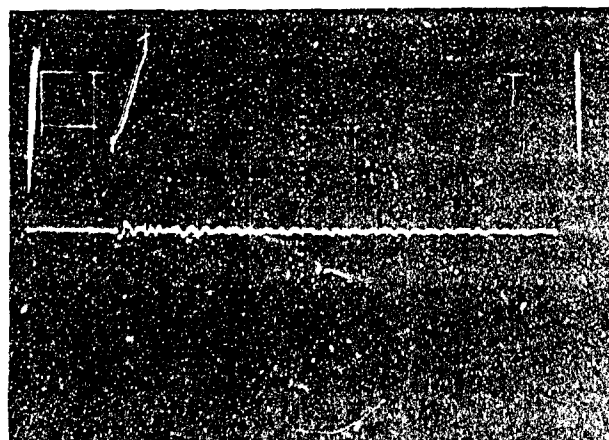
VERTICAL 10 A/div
HORIZONTAL 50ns/div

(c) 350 N PLUS DIODE PROTECTION
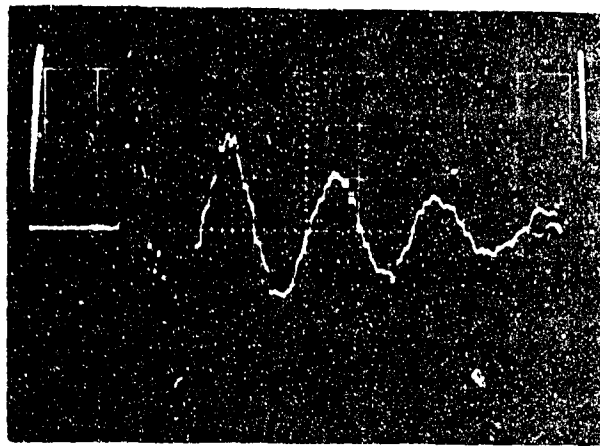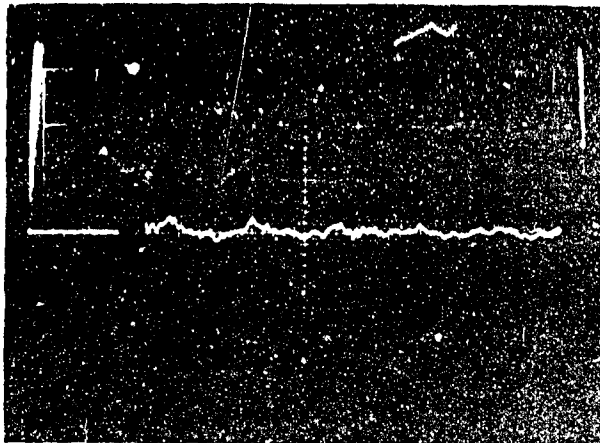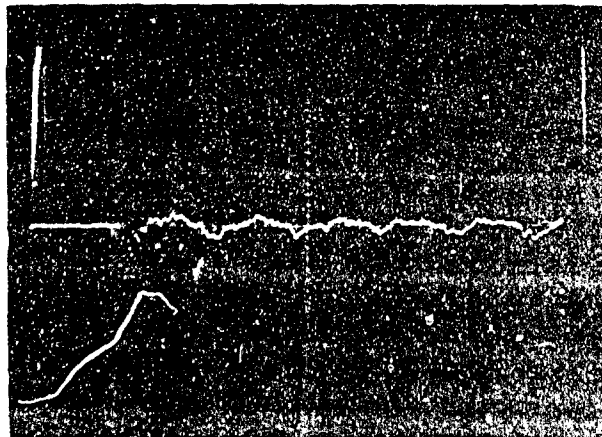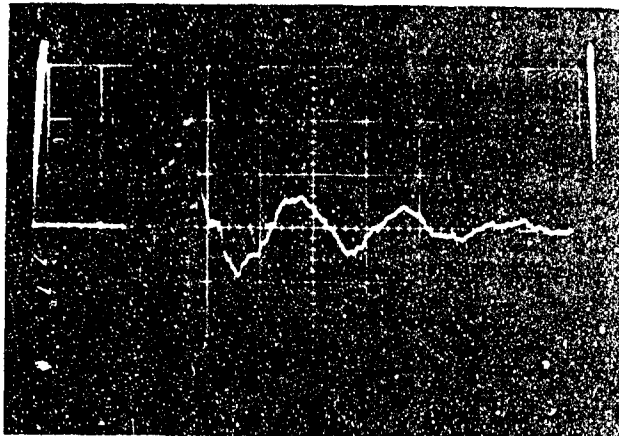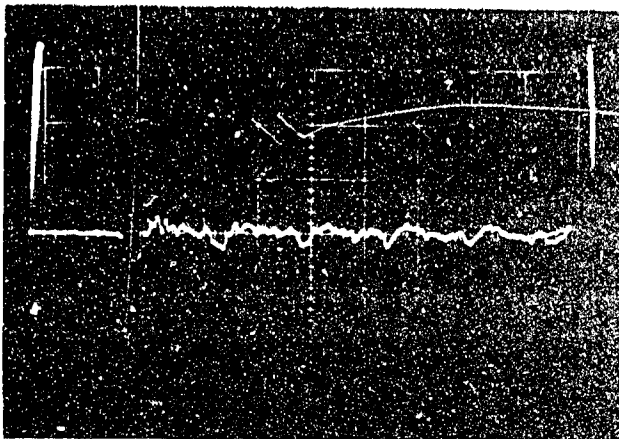
VERTICAL 10A/div
HORIZONTAL 50ns/div

Fig. 1.57. Current Measured Through a 50 ohm Load with EMP Protection when the VHF Coil Antenna is Illuminated by ALECS EMP with E_p = 1 kV/m.

the 50 ohm load current to about 20A and the load voltage to about 1000 volts. The 350-N Spikeguard clipped the current to about 10A and the voltage to about 500 volts.

In Figs. 4.26 and 4.27, the waveforms of the current through a 50 ohm load with various EMP protection are shown for $E_p \approx 100$ kV/m. The effectiveness of the devices as surge suppressors are presented in order of increasing effectiveness, i.e., the Spikeguards 250-N, 350-N, and 350-UHF, the diode protector, and the parallel combination of the 350-UHF and the diode protectors.

The 250-N protector suppressed the first half-cycle load voltage to about 1500 volts, whereas the 350-N suppressed the load voltage to about 500 volts. The effectiveness of the 350-UHF at this surge level is about the same as that of the 350-N protector. The diode protector suppressed the load voltage to approximately 300 volts. The most effective device tested is the parallel combination of the Spikeguard 350-UHF and the diode protector. It suppressed the 50 ohm load voltage from 2500 volts to about 50 volts. This represents a reduction of the energy supplied to the load over the first half-cycle by 2500.

4.9 CONCLUSIONS

We have demonstrated that EMP is a potential threat to radio communications. The EMP electric field threshold failure level can be as low as 4.28 kV/m for some communications equipment. Other communications equipment, however, are not vulnerable to the ALECS EMP at a high electric field level of 100 kV/m. The important EMP energy collectors for the radios tested are the antenna, the microphone cord, and the power cable. Direct coupling of the EMP into the equipment had no observable effects.

We have shown that the technique described in Reference 8 for estimating the EMP responses of the cylindrical electric half-dipole antenna gives reasonable results. The relative difference between the measured and calculated results is conservative by about 28%. This difference would be smaller if the ALECS EMP had been better represented analytically and if the experimental error could be reduced to zero. The test has shown that the calculated results are sufficiently accurate for the purpose of EMP analysis and assessment of communication systems. Also, the test has provided experimental data on the responses of the coax cable non-deliberate feedline antenna and complicated gain antennas.

The test on the effectiveness of some selected surge protection devices has demonstrated that it is possible to suppress transients induced on VHF and UHF antennas by EMP. The fast gas-diode and the hybrid fast gas-diode and switching-type semiconductor diode devices can provide almost total suppression of the induced surges. The hybrid device is the most effective EMP protector that was tested.

CHAPTER V

EMP COUPLING ANALYSIS

5.1 INTRODUCTION

The EMP energy and/or power that is coupled to communications equipment is estimated in this chapter. The EMP energy collectors that are important to communication systems are: antennas, antenna feedlines, commercial power, microphone cords, control lines, direct coupling, and indirect coupling.

5.2 ANTENNA ANALYSIS

Antennas are a major concern in the EMP vulnerability analysis of communication systems. The two primary reasons for this concern are: (1) antennas are normally connected through feedlines and tuning circuitry to some of the most sensitive electrical components in the system and (2) antennas that operate at frequencies below several hundred MHz normally perform well as nuclear EMP energy collection devices.

In considering an antenna as a receiving device, it is useful to employ Thevenin and Norton equivalent circuits to calculate the antenna's load response. For the Norton circuit, the current through the load is given by

$$I(\omega) = \frac{I_a(\omega) \ Y_L(\omega)}{Y_a(\omega) + Y_L(\omega)} \tag{5.1}$$

where I_a is the Norton equivalent current source of the antenna and the electromagnetic environment, Y_a is the admittance of the antenna, Y_L is the admittance of the load, and ω is the angular frequency. $I_a(\omega)$ and $Y_a(\omega)$ are generally complicated functions of frequency and, even for a simple antenna type such as the cylindrical electric half-dipole, are difficult to calculate. There are, however, antenna theories that approximate those functions over certain frequency ranges. These approximating theories can be used to estimate $I(\omega)$ and then to calculate numerically the time domain antenna load current response $i(t)$ via the Fourier transform. However, these piece-wise approximations to $I(\omega)$ may introduce large errors in $i(t)$.

A new technique to calculate the dominant electric cylindrical dipole and half-dipole load current responses to EMP has been described in a previous report.[8] Basically, it involves applying the results of the singularity expansion method formulated by Baum.[8] This method expands the time-domain solution of the electromagnetic quantity in terms of analytical functions. Each term comes from an inverse transform of the corresponding term in the frequency domain singularity expansion. In this manner all of the important singularities that contribute significantly to i(t) are considered.

When this new technique is applied to the cylindrical half-dipole antenna, the Norton equivalent current source for a double exponential EMP as defined by Eqs. (1.5) and (1.7) is[8]

$$i_a(t) = 4E_o\ell \sum_{m=1}^{M} \{D_{m1} e^{-\alpha_1 t} - D_{m2} e^{-\alpha_2 t}$$

$$+ e^{-\gamma_m t}[D_{m3} \cos \omega_m t + D_{m4} \sin \omega_m t]\} , \qquad (5.2)$$

where the incident electric field is in the direction of maximum sensitivity of the antenna. The constants E_o, α_1, and α_2 are defined by Eqs. (1.5) and (1.7). M is the number of poles employed in the solution and ℓ is the length of the half-dipole. The constants γ_m and ω_m are the natural damping constants and the natural resonant frequencies respectively and are functions of the antenna parameters only. The constants D_{m1}, D_{m2}, D_{m3}, and D_{m4} determine the amplitude of the current and are functions of the antenna parameters and the incident wave.

It was shown in Ref. 8 that for a resistive load, i(t) is similar to $i_a(t)$ times an exponential damping factor which is a function of the resistive load and the antenna parameters. The natural resonant frequencies are only slightly altered by the admittance function.

The most significant contribution to the load current response is made by the first mode, which corresponds to the pole nearest the imaginary axis in the complex frequency plane, i.e., M = 1. At M = 1, the approximate response is

$$i(t) \approx 4\,E_o\ell\,\{D_1\,e^{-\alpha_1' t} - D_2\,e^{-\alpha_2' t} + e^{-\gamma' t}\,[D_3\,\cos\,\omega t + D_4\,\sin\,\omega t]\} \quad (5.3)$$

where the m subscripts have been dropped and the primes on the inverse time constants indicate that they have been modified by the admittance transfer functions. The constants in Eq. (5.3) can be computed from formulas given in Ref. 8. The constant $\omega = \omega_1$ is the normal design frequency of the quarter wavelength half-dipole antenna. At the design frequency, the receiver load resistance is about 50 ohms.

In Figs. 5.1 through 5.4, the singularity expansion method has been applied to calculate the 50-ohm load current responses of some quarter-wave half-dipoles. Five singularities were used to compute the Norton equivalent current and the antenna admittance. A length-to-radius ratio equal to 259 was used in the calculations.

The responses are presented for both Pulse A, the long pulse, and Pulse C, the short pulse. The responses to Pulses B and D can be obtained from those of Pulses A and C respectively by multiplying the ordinates scale on the figures by 0.442 since the responses are linearly proportional with E_o.

In Fig. 5.1 the current through a 50-ohm load is shown for an 80-meter-band RACES frequency half-dipole antenna. Pulse A induces the largest response with this antenna. In Fig. 5.2 the load current response is shown for a citizen's band quarter-wave whip. A slightly larger response is obtained with Pulse C for the citizen's band antenna.

In Figs. 5.3 and 5.4 the load responses of a VHF and a UHF antenna are shown respectively. Pulse C induces the larger response for both of these antennas. Additional plots of 50-ohm load current responses of half-dipole antennas with designed frequencies that are typically used in the land mobile class are shown in Appendix B. Also, the short-circuit current responses of various half-dipole antennas are shown in Appendix B.

The damage to an electronic component from a short damped sinusoidal pulse is due primarily to the energy deposited in the device during the first half-cycle of the waveform. By treating the load current response during the first half-cycle as a sine wave, we may estimate the
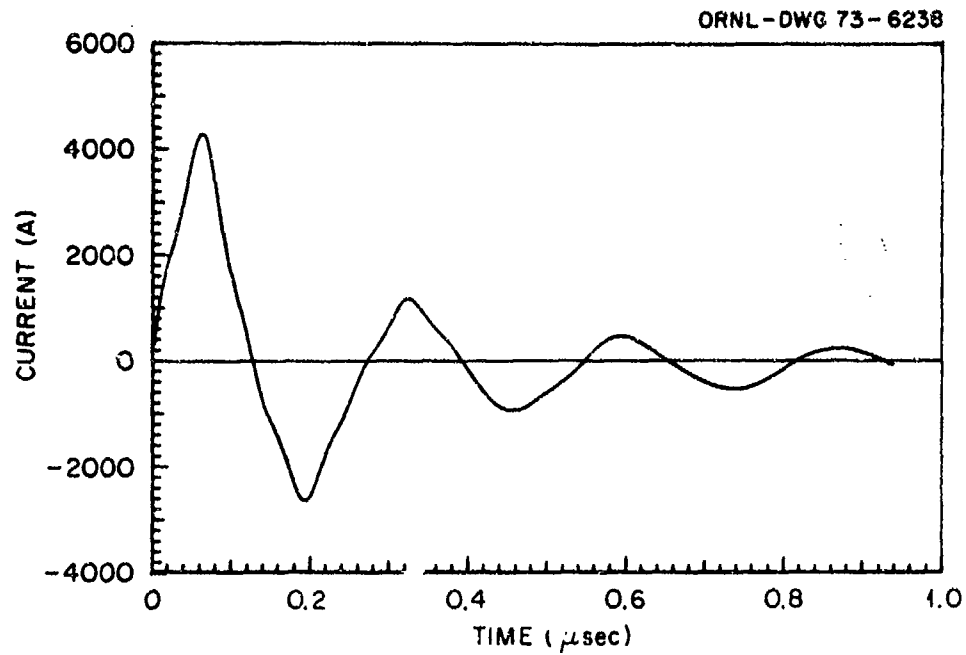
ORNL-DWG 73-6238

(a) RESPONSE TO PULSE A.
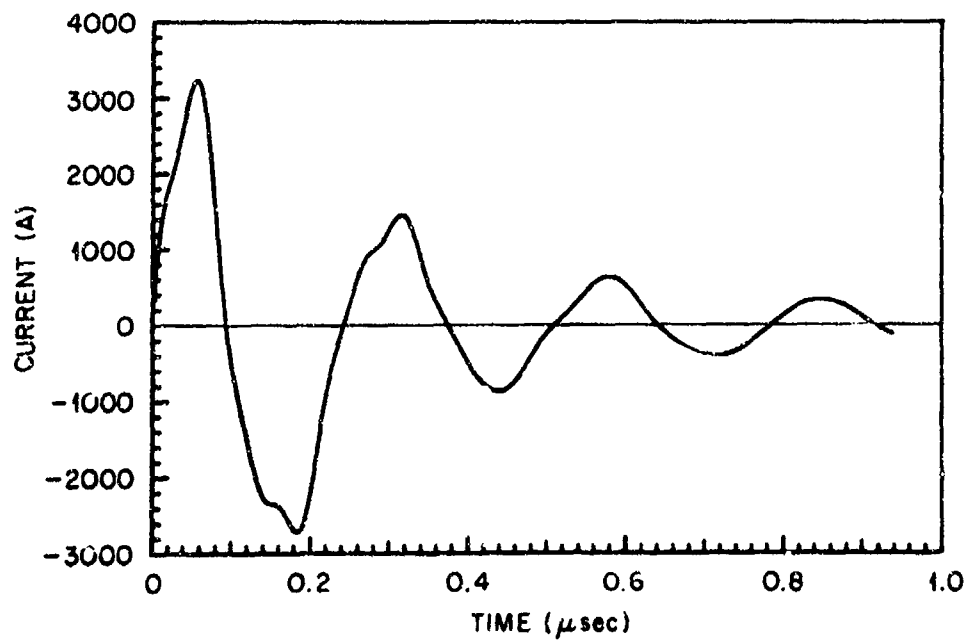
(b) RESPONSE TO PULSE C.

Fig. 5.1. Current Through a 50 ohm Load when a 3.997 MHz
Half-Dipole is Illuminated by Representative EMP.
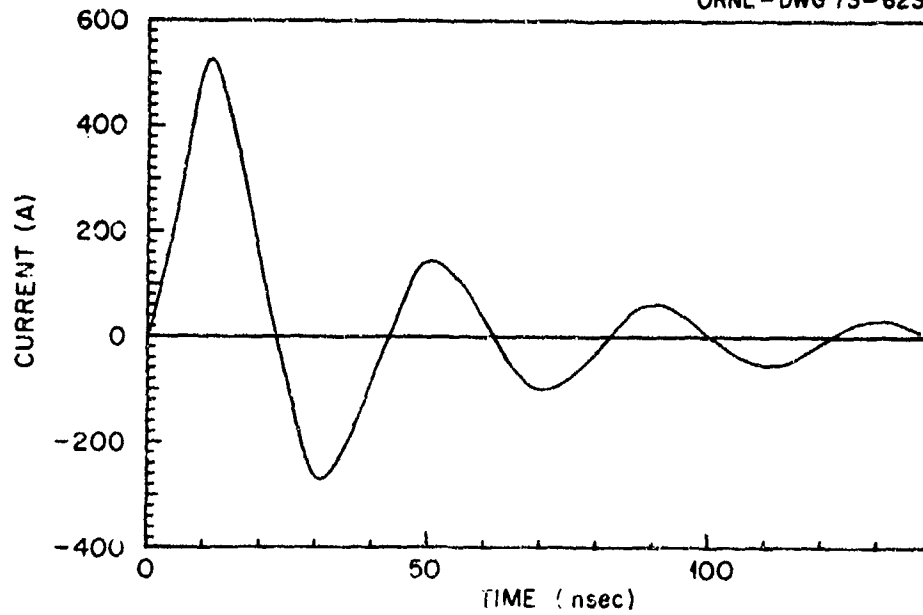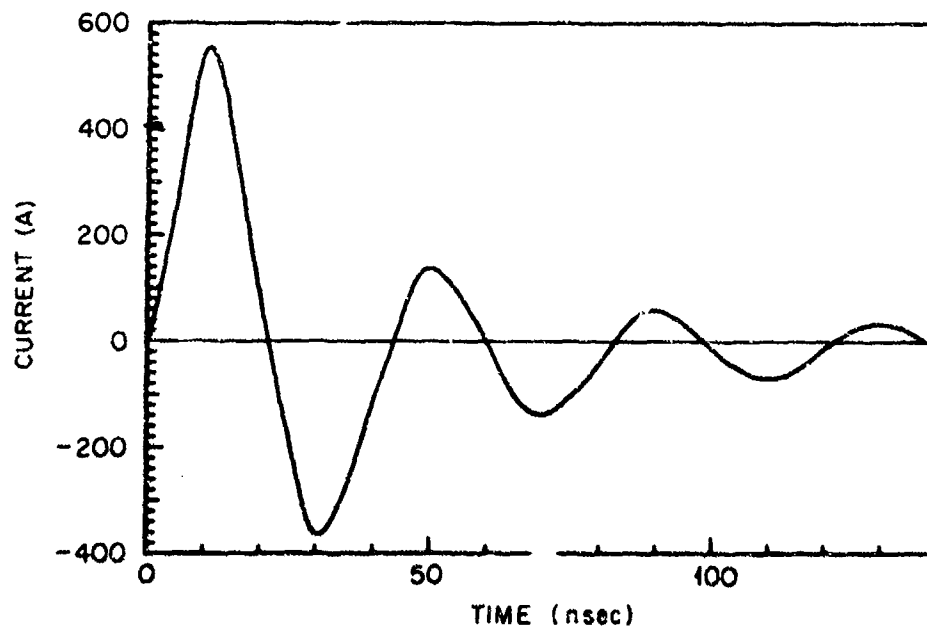
Fig. 5.2. Current Through a 50 ohm Load When a 27.23 MHz
Half-Dipole is Illuminated by Representative EMP.

ORNL-DWG 73-6236
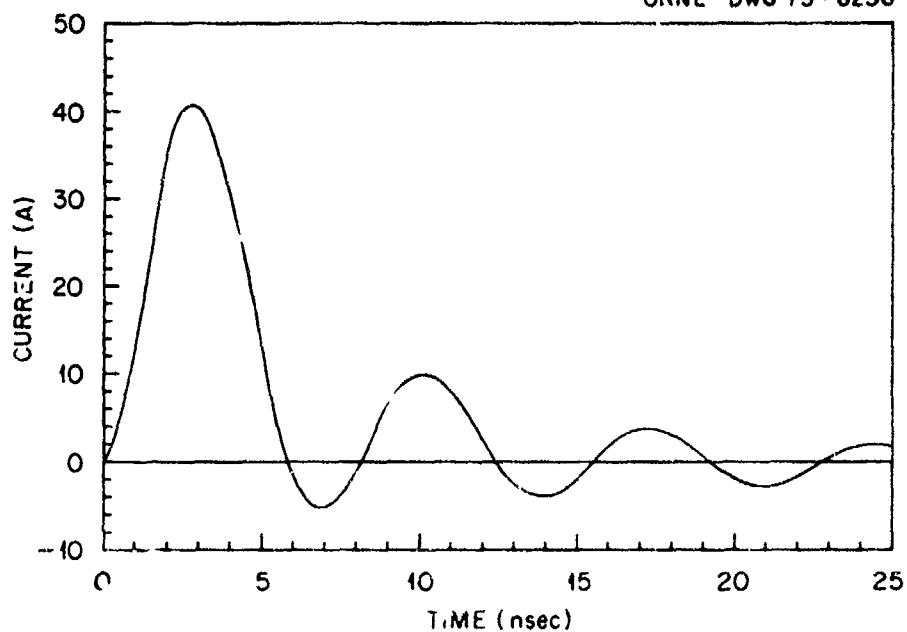
(a) RESPONSE TO PULSE A.
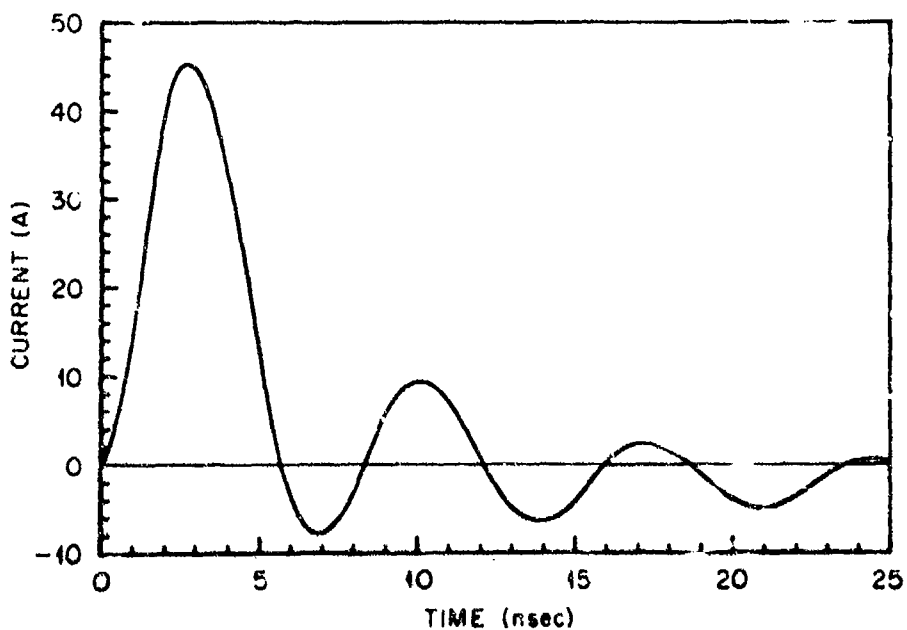
(b) RESPONSE TO PULSE C.

Fig. 5.3. Current Through a 50 ohm Load When a 150 MHz Half-Dipole is Illuminated by Representative EMP.

ORNL—DWG 73—6237
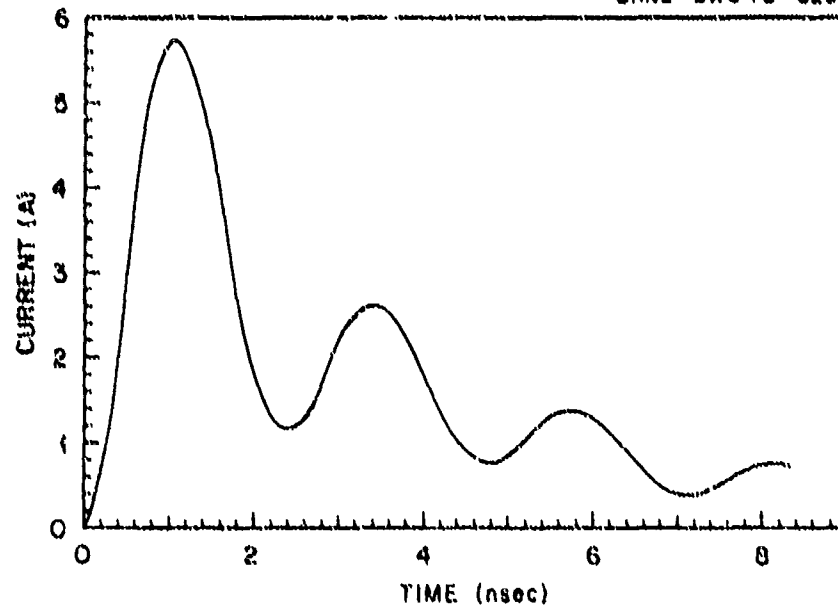
(a) RESPONSE TO PULSE A.
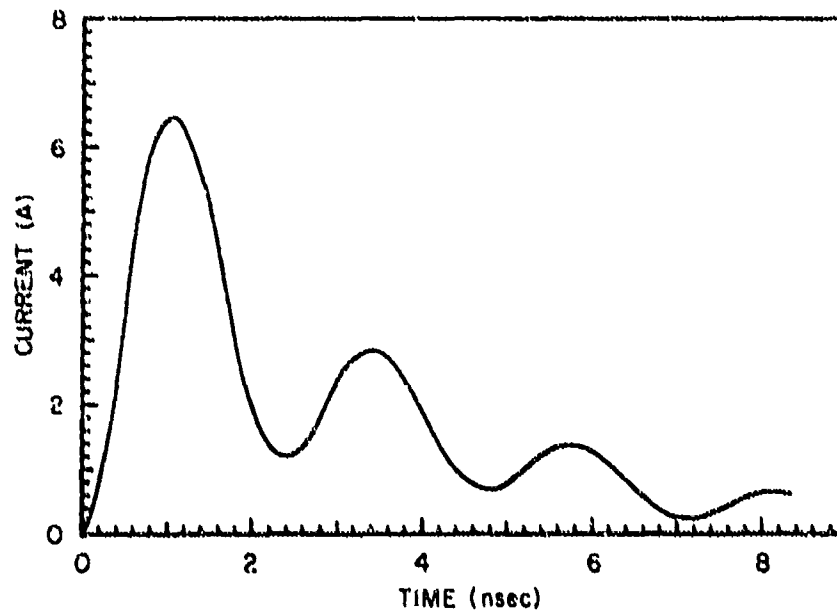
(b) RESPONSE TO PULSE C.

Fig. 5.4. Current Through a 50 ohm Load when a 450 MHz
Half-Dipole Is Illuminated by Representative EMP.

energy delivered to a 50-ohm load as

$$E_n \approx 25 \; t_c \; I_p^2 \; , \tag{5.4}$$

where I_p is the peak current in amperes and t_c is the first half-cycle period in seconds.

The energies received by a 50-ohm load have been computed by Eq. (5.4) for half-dipoles of various designed frequencies for the four representative pulses. The results of this calculation are presented in Table 5.1. The peak load current and voltage and the half-cycle period are also presented in Table 5.1. For a step-function EMP, the energy received by a resistive load during the first half-cycle of the load current is inversely proportional to the cube of the design frequency.[8] We can see from Table 5.1 that this "inverse cube" rule-of-thumb is within a factor of 2 for the double exponential EMP's used in the calculations.

It was shown in Chapter IV that an upper bound of the load current for the gain antenna is equal to the product of the current gain and the peak value of the half-dipole load current. Also, it was shown in the experimental data that the half-cycle period of the gain antenna current is on the order of three times that of the half-dipole due to the broad band effect of the gain antenna. Thus, the energy received by the load of the more complicated gain antenna can be conservatively estimated as three times the product of the energy level for the half-dipole antenna as shown in Table 5.1 and the antenna's power gain. Table 5.2 shows approximate energy levels for gain antennas that have been calculated by the procedure outlined above.

5.3 ANTENNA FEEDLINE ANALYSIS

The antenna feedline collects EMP energy and thus performs as a non-deliberate antenna. Consider a RG8/U coaxial cable feedline for a base station antenna mounted on a wooden pole 20 meters above the earth. The pole is located next to the building that houses the communications equipment and the coaxial cable shield is grounded at a point near the earth for lightning protection. The antenna feedline configuration is shown in Fig. 5.5.

Table 5.1. Summary of 50-ohm Load Response Data for the
Half-Dipole During the First Half-Cycle

Frequency (MHz)	Pulse	Current Peak (A)	Voltage Peak (kV)	Half-Period (ns)	Energy Received (J)
3.997	A	4120.0	206.0	125	53,045.0
3.997	B	1821.0	91.0	125	10,302.6
3.997	C	3200.0	160.0	97	24,832.0
3.997	D	1414.0	70.7	97	4,848.5
27.23	A	525.0	26.3	23	158.5
27.23	B	232.0	11.6	23	30.9
27.23	C	555.0	27.8	21	161.7
27.23	D	245.0	12.3	21	31.5
40.0	A	315.0	15.8	17	42.2
40.0	B	139.0	10.0	17	8.2
40.0	C	340.0	17.0	16	46.2
40.0	D	150.0	7.5	16	9.0
75.0	A	125.0	6.3	10	4.0
75.0	B	55.0	2.8	10	0.7
75.0	C	138.0	6.9	9.7	4.6
75.0	D	61.0	3.1	9.7	0.9
150.0	A	40.8	2.04	5.8	0.241
150.0	B	18.0	0.9	5.8	0.047
150.0	C	45.2	2.3	5.6	0.290
150.0	D	24.0	1.2	5.6	0.080
450.0	A	5.8	0.30	2	0.002
450.0	B	2.6	0.13	2	0.001
450.0	C	6.4	0.32	2	0.002
450.0	D	2.8	0.14	2	0.001

Table 5.2.   The Energy Received During the First Half-Cycle
by a 50-ohm Load Connected to a Gain Antenna

Frequency (MHz)	Pulse	Energy Received[a]				
		Unity Gain	3 dB Gain	6 dB Gain	10 dB Gain	15 dB Gain[b]
3.997	A	53.1 J	318.6 J	637.2 J	1593.0 J	5044.5 J
3.997	B	10.4 J	62.4 J	124.8 J	312.0 J	988.0 J
3.997	C	24.8 J	148.8 J	297.6 J	744.0 J	2356.0 J
3.997	D	4.9 J	29.4 J	58.8 J	147.0 J	465.5 J
27.23	A	158.5	951.0	1.9 J	4.8 J	15.1 J
27.23	B	30.9	185.4	370.8	927.0	2.9 J
27.23	C	161.7	970.2	1.9 J	4.9 J	15.4 J
27.23	D	31.5	189.0	378.0	945.0	3.0 J
40.0	A	42.2	253.2	506.4	1.3 J	4.0 J
40.0	B	8.2	49.2	98.4	246.0	779.0
40.0	C	46.2	277.2	554.4	1.4 J	4.4 J
40.0	D	9.0	54.0	108.0	270.0	855.0
75.0	A	4.0	24.0	48.0	120.0	380.0
75.0	B	0.7	4.2	8.4	21.0	66.5
75.0	C	4.6	27.6	55.2	138.0	437.0
75.0	D	0.9	5.4	10.8	27.0	85.5
150.0	A	0.241	1.5	2.9	7.2	22.9
150.0	B	0.047	0.28	0.56	1.4	4.5
150.0	C	0.290	1.7	3.5	8.7	27.6
150.0	D	0.080	0.48	0.96	2.4	7.6
450.0	A	0.002	0.012	0.024	0.06	0.19
450.0	B	0.001	0.006	0.012	0.03	0.09
450.0	C	0.0021	0.013	0.025	0.06	0.20
450.0	D	0.001	0.006	0.012	0.03	0.09

[a]The energy is given in millijoules unless stated.

[b]15 dB gain antennas are not commonly used for HF and VHF.

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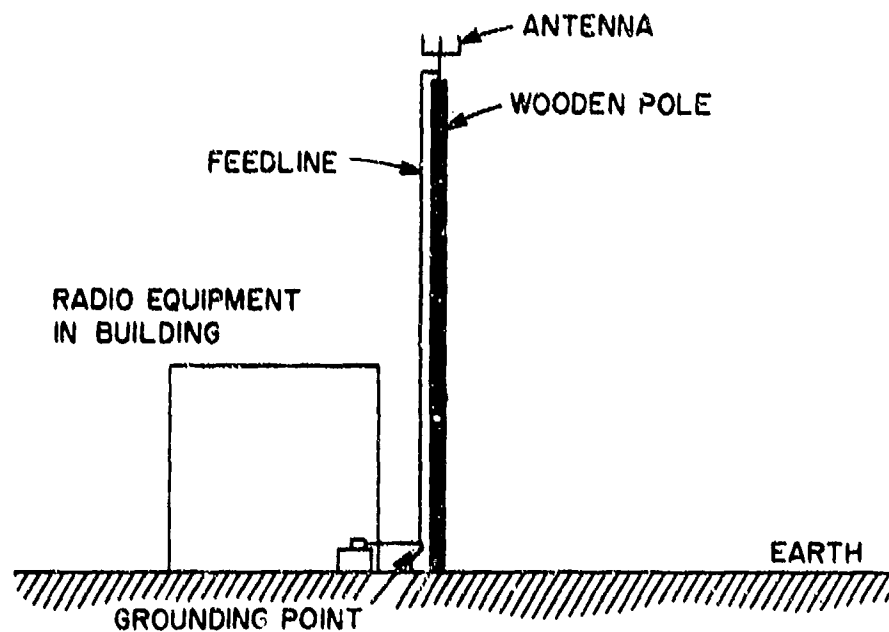
(a) A COMMON BASE STATION FEEDLINE
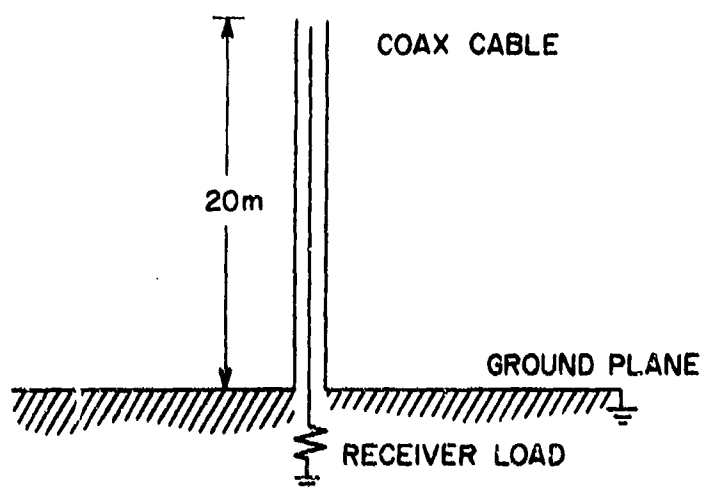
(b) IDEALIZED FEEDLINE PROBLEM

Fig. 5.5. Coax Cable Antenna Feedline.

To make this a more tractable problem, we further specify that the 20-meter vertical section of the line is much, much longer than the horizontal portion. This is a common feedline arrangement. Thus, the 20-meter segment of the cable will have much larger shield currents induced on it by the EMP than will the remaining portion of the line, and the major contribution of shield-to-inner-conductor coupling will occur along the 20-meter section.

To calculate the EMP-induced shield current, we model the vertical portion of the line as a short-circuited half-dipole antenna as shown in Fig. 5.5b. The upper end of the cable is unterminated for the analysis. This should be a good approximation to the antenna impedance termination for the relatively low frequencies of the induced shield current.

The short-circuit current response of a 20-meter half-dipole antenna is shown in Appendix B, Fig. B-4, for the representative EMP's A and C. Pulse A induces the larger response; the peak current is about 5500 A and the half-cycle period is 0.14 µs.

The open-circuit voltage that will appear at the receiver's input during the first 120 ns due to shield-to-inner-conductor coupling along the vertical section of the cable is, approximately

$$v(t) = i(t)/2.5 \quad \text{volts} \tag{5.5}$$

where Eq. (4.5) has been used with the coax cable impedance equal to its characteristic impedance of 50 ohms and $i(t)$ is the induced current on the cable shield. The peak of the open-circuit voltage for the nondeliberate feedline antenna is, from Eq. (5.5), on the order of 5 kV.

The input of a receiver is normally an RF amplifier or RF preamplifier or a band-pass filter. The amplifier circuits and most bandpass filter circuits have tapped-coil input tuned circuits. Some bandpass filters use capacitive-divider input circuits. At the relatively low frequencies of the Thevenin equivalent voltage source, the receiver input impedance is inductive and nearly a short circuit for the tapped-coil input and is capacitive and nearly an open circuit for the capacitor-divider input.

For the tapped-coil receiver input, the peak current through the coil resulting from the feedline antenna interaction with Pulse A is

on the order of 100 amperes, i.e., 5 kV divided by the 50-ohm character-
istic impedance of the cable. Of course, the time history of the induced
current is, in general, not the same as that of the open-circuit voltage
due to the reflections in the horizontal segment of the cable. This
oscillating induced coil current pulse will decay to near zero after
several microseconds of time history since the driving voltage is near
zero at that time.

5.4 COMMERCIAL POWER LINE ANALYSIS

The current induced on power lines by the EMP has been considered
in a previous report.[10] In Fig. 3.7 of Ref. 10, an estimate of the in-
duced current has been obtained by the application of transmission line
theory for a wire with frequency dependent resistance located 10 meters
above a finitely conducting ground. The EMP source used in the calcula-
tion has a time history similar to Pulse A; the magnetic field unit vec-
tor $\vec{e}_3$ is polarized perpendicular to the axis of wire and the direction
of incidence unit vector $\vec{e}_1$ is 10° above the horizon.

The voltage induced between wire and ground by an incident plane
wave, such as EMP, is the product of three factors. The first two fac-
tors are, as is usual in transmission theory, the characteristic imped-
ance and the current. The third factor is the cosine of the angle be-
tween the direction of propagation of the incident wave and the direction
of positive current along the transmission line. The total voltage is the
sum of the induced voltage and the voltage (the line integral of the elec-
tric field) of the incident plane wave.

In Fig. 5.6a, the transmission line voltage is shown for a 400-ohm
line carrying the current given in Fig. 3.7 of Ref. 10. The electric
field (with direction $\vec{e}_1$) lies in the vertical plane of incidence.

The use of this EMP is overly conservative since (1) polarizations
of the electric field greater than thirty degrees off the horizon are not
likely in the continental USA, and (2) the effects of corona discharge
have not been taken into account.

In Fig. 5.6b, a more realistic polarization is used, approximate
effects of corona discharge have been included in the calculation. The
values of the voltage in Fig. 5.6b were computed from those in Fig. 5.6a

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(a) ELECTRIC FIELD 80° WITH RESPECT TO HORIZONTAL

(b) ELECTRIC FIELD 30° WITH RESPECT TO HORIZONTAL
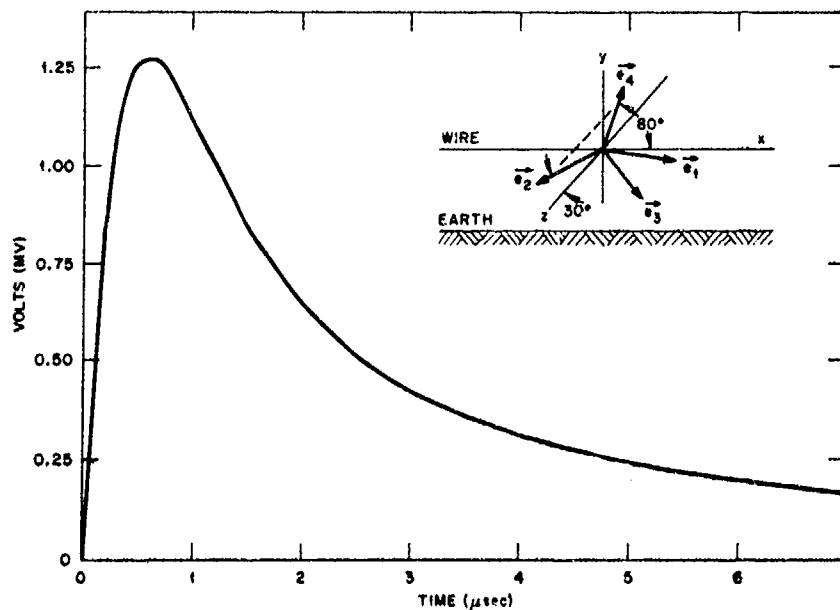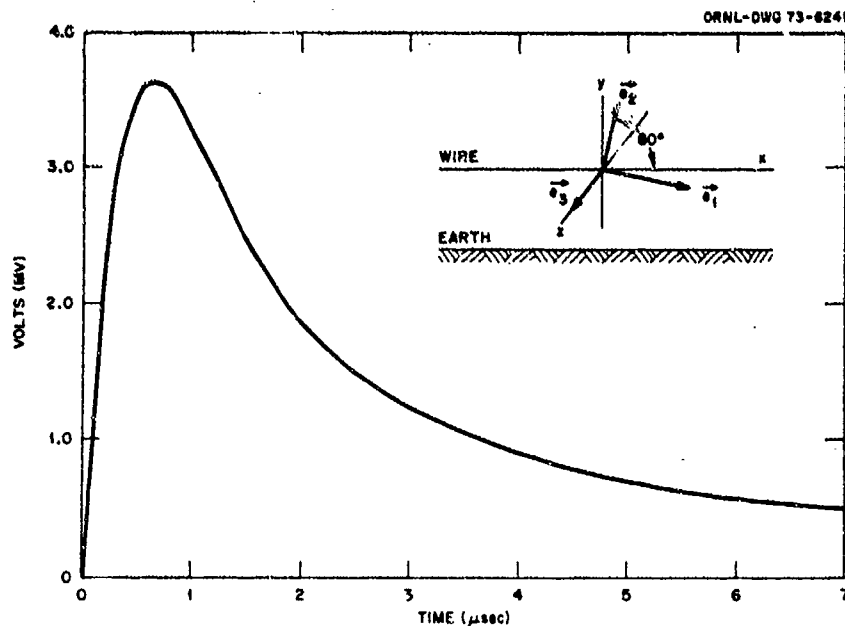
Fig. 5.6. Transmission Line Voltage Induced on a Finitely Conducting Wire 10 Meters Above a Finitely Conducting Earth by Pulse A Located 10° Above the Horizon. Figure (b) includes the effects of corona discharge.

simply by multiplying by the factor 0.35. This factor arises from the following considerations. The vector $\vec{e}_4$ is the normalized projection of the electric field vector in the vertical x-y plane. As can be seen from Fig. 5.6b, the component of the electric field in the direction of $\vec{e}_4$ is one-half the incident electric field and it has an angle of $80°$ with respect to the axis of the wire. Thus, the induced voltage, without accounting for corona discharge, is one-half that shown in Fig. 5.6a since the induced current is linearly proportional to the magnitude of the electric field. Corona discharge further reduces the voltage by about 25% as was observed in Chapter IV. Thus, the voltage in Fig. 5.6b is about 0.35 that in Fig. 5.6a.

For the purpose of analysis, we can represent the power line voltage by the analytical approximation

$$V(t) = V_o \, (e^{-\beta t} - e^{-\gamma t}) \quad 0 \leq t \leq \frac{2}{\beta} \quad , \tag{5.6}$$

where

$$V_o = 1.6 \text{ MV}$$
$$\beta^{-1} = 2.5 \, \mu\text{sec}$$
$$\gamma^{-1} = 0.2 \, \mu\text{sec} \quad .$$

After about five microseconds, the decay of the induced voltage shown in Fig. 5.6b is not well approximated by an exponential function and Eq. (5.6) should not be used.

At this point we can make some observations concerning the EMP response of commercial power systems. Most of the energy in the pulses induced in power lines by the EMP is between 0.1 and 1 MHz in the frequency spectrum. Thus, the behavior of the commercial power system at 60 Hz has little bearing on the EMP response of the system. Furthermore, the pulses induced in the lines by the EMP propagates primarily as common-mode signals. Therefore, the phase line to earth response of each phase of a balanced three-phase system is similar to that of a single-phase system with equivalent electrical and electromagnetic characteristics. And the phase-to-phase response of a three-phase system is small relative to the phase-to-ground response. Also, the differential transmission line mode is used for the transmission and conversion of 60-Hz power;

the behavior of power system components as differential-mode devices is
not necessarily applicable to our analysis. This is particularly true for
phase-to-phase differential-mode devices.

To estimate the EMP energy available to communications equipment at
the wall plugs, consider the single-phase system shown in Fig. 5.7a.
The system consists of a primary distribution line, lightning arrestor
and fuse, a 13 kV to 120/240 V transformer, and a secondary drop to the
weatherhead. The transformer is electrically characterized by primary
and secondary windings; an interwinding capacitance, C_i; a primary wind-
ing to system ground capacitance, C_p; and two secondary windings to
system ground capacitances, C_s's. At the weatherhead the secondary con-
ductors enter a conduit riser as shown. Also, the primary neutral sys-
tem ground is connected to earth ground by a vertical ground wire 9 m
long. The conduit is also connected to earth ground by a short ground-
ing wire inside the building.

There are two long transmission lines than can collect large amounts
of EMP energy. One is the transmission line formed by the primary line
and the earth. And the other is the transmission line formed by the
primary neutral and the earth. The characteristic impedance Z_o of each
line is around 400 ohms. A mid-frequency model of the commercial power
source is shown in Fig. 5.7b. The voltages induced by EMP on the primary
and neutral lines are designated V_p and V_n respectively and are approxi-
mately equal to the voltage given in Fig. 5.6b. Since we are concerned
with the coupling at frequencies well above 60 Hz, the transformer wind-
ings are not included in the model.

The lightning arrester is modeled as a voltage-activated switch S_a
in series with a non-linear resister R_a. The switch is activated at
voltages between fifty and several hundred kilovolts; the exact value
depends on the rate of rise of the voltage surge. An average value for
R_a is about 5 ohms. The vertical ground wire is modeled as a voltage
source V_g which is the voltage induced at the upper end of the wire by
the EMP. This source is in series with a ground wire impedance repre-
sented by Z_g. For frequencies lower than the lowest resonant frequency
of V_g, the impedance of the ground wire approaches that associated with
the inductance of the wire, L_g. The first resonance of V_g is about the

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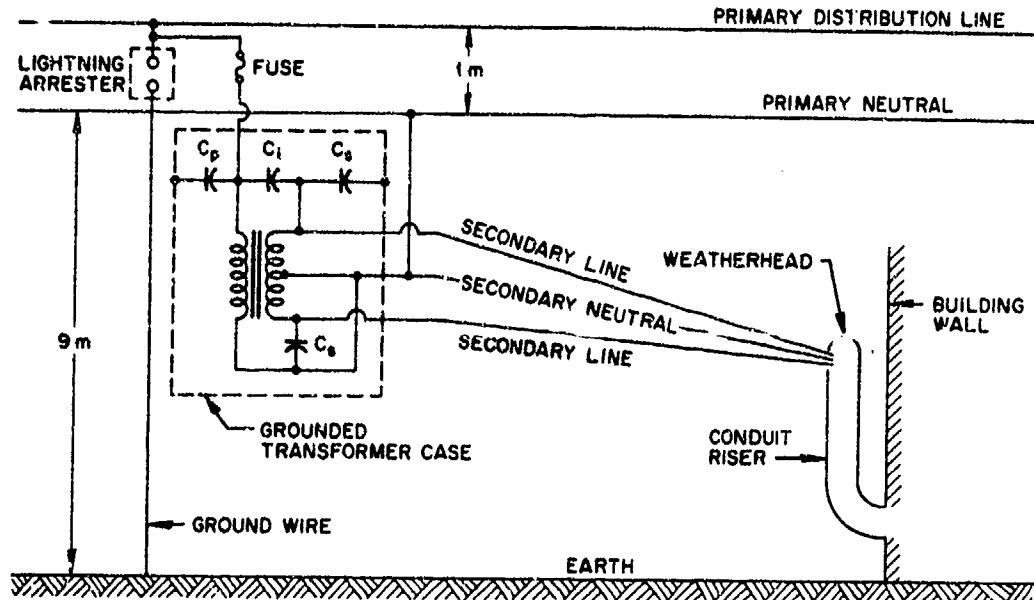
(a) SINGLE PHASE TRANSFORMER AND ASSOCIATED EQUIPMENT
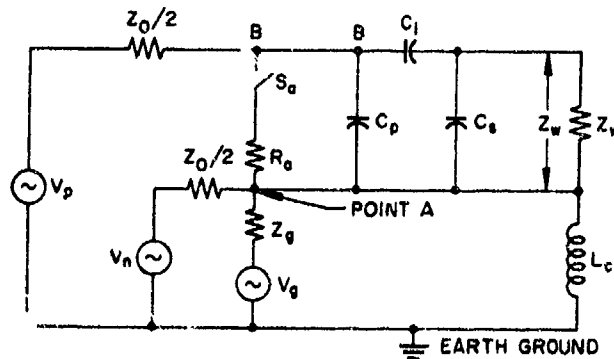
(b) APPROXIMATE MID-FREQUENCY MODEL FOR A SINGLE SECONDARY LINE
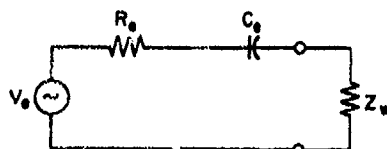
(c) SIMPLIFIED MID-FREQUENCY MODEL FOR COUPLING ANALYSIS

Fig. 5.7. Mid-Frequency Equivalent Circuit for a Simple Phase Commercial Power Source.

same as that for a 9-m half-dipole, i.e., about 8 MHz. The inductance L_c in Fig. 5.7b is the inductance of the conduit riser from the weatherhead to earth ground. This inductance is about 5 μh.

In order to simplify the circuit shown in Fig. 5.7b, consider the relative importance of the circuit elements for the frequencies of interest. The ground wire inductance L_g is about 10 μh. The voltage across L_g at node A due to V_n is small relative to the voltage at the primary bushing of the transformer at node B for frequencies such that

$$ f < \frac{Z_0/2}{2\pi\, L_g} \quad , \tag{5.7} $$

which are frequencies below 3 MHz $f \;.\; L_g = 10\ \mu$h. For frequencies above 3 MHz, the magnitude of the voltage at node A due to V_n may be on the same order of magnitude as that at node B. And the voltage drop across S_a may not be sufficient to activate the switch.

The order of magnitude of V_g is about the same as the voltage between the primary line and earth ground.[11] This voltage will likely have a ringing frequency associated with the length of the ground wire. The polarity of the waveform of V_g is a function of the vertical component of the incident electric field. To calculate the exact time history of the voltage induced on the ground wire will require further investigation.

The above discussion concerning the voltage between node A and earth ground suggests that the time required to fire the lightning arrester may be longer for EMP-induced surges than for lightning surges. For times greater than 0.2 μsec, the voltage at node A due to both V_g and V_n will likely be small relative to that at node B. The time required to activate the arrester is likely to be about 0.2 μsec after a fast rising pulse is applied to the device.[12] The exact time depends on the arrester characteristics and the pulse. For our analysis we shall assume that the arrester fires after 0.4 μsec of pulse time history.

The inductance L_c will have little effect on the pulse that reaches the weatherhead after about 100 ns since its value is only about 3 to 5 μh and the time constant $2\,L_c/z_0$ is only about 25 ns. Thus, we may consider the weatherhead neutral at near earth ground potential after 0.1 μsec and L_c is not very important for the analysis.

The values of the transformer capacitance C_p, C_1, C_s depend on the transformer design. Normally the relative values of the capacitances are such that $C_p \ll C_s < C_1$. Reasonable values for these capacitors are: $C_p = 50$ pf, $C_s = 300$ pf, and $C_1 = 900$ pf.

The mid-frequency model shown in Fig. 5.7b can be approximately reduced to that shown in Fig. 5.7c for frequencies f, such that

$$f < \frac{1}{\pi Z_o C_s} < \frac{1}{\pi Z_o C_p} \quad , \tag{5.8}$$

which is about 3 MHz for $Z_o = 400$ ohms and $C_s = 300$ pf.

The values of the circuit elements in the simplified mid-frequency model are given for S_a open by

$$V_e = K V_p \quad , \tag{5.9}$$

$$R_e = K Z_o/2 \quad , \tag{5.10}$$

$$C_e = C_1/K \quad , \tag{5.11}$$

and

$$K = \frac{C_1}{C_1 + C_s} \quad . \tag{5.12}$$

For S_a closed, the values are

$$V_e = \frac{2 V_p K R_a}{2 R_a + Z_o} \quad , \tag{5.13}$$

$$R_e = \frac{K R_a Z_o}{2 R_a + Z_o} \quad , \tag{5.14}$$

and the values of K and C_e are the same as those given for S_a open.

The voltage across V_w is given by

$$V_w(s) = \frac{Z_w}{R_e + Z_w} \frac{s V_e(s)}{(s + \tau)} \quad , \tag{5.15}$$

where s is the Laplace frequency domain variable and τ is the circuit

inverse time constant equal to

$$\iota = \frac{1}{C_s (R_a + Z_w)} \quad , \tag{5.16}$$

The substitution of Eqs. (5.6), (5.9), and (5.10) or Eqs. (5.6), (5.13), and (5.14) into Eq. (5.15) gives

$$V_w(s) = \frac{2 R_a Z_w V_o (\gamma - \beta)}{(R_a + Z_w) Z_o} \; \frac{s}{(s+\beta)(s+\gamma)(s+\iota)} \quad , \tag{5.17}$$

and the inverse Laplace transform of V_w is

$$V_w(t) = \frac{2 R_a Z_w V_o}{(R_a + Z_w) Z_o} \left[\frac{\gamma \, e^{-\gamma t}}{\iota - \gamma} - \frac{\beta \, e^{-\beta t}}{\iota - \beta} - \frac{\iota (\gamma - \beta) \, e^{-\iota t}}{(\beta - \iota)(\gamma - \iota)} \right] \quad . \tag{5.18}$$

The transmission line formed by the secondary conductors and the conduit riser has a characteristic impedance equal to about 40 ohms. If the conduit is long, compared with the wavelengths of the impressed signal, the weatherhead input impedance is effectively that of the conduit transmission line. If, on the other hand, the conduit is short compared with the wavelengths, the weatherhead impedance is approximately the load impedance of the building. For most commercial power sources, the conduit is short relative to the wavelength of the frequencies associated with the EMP-induced voltage.

The voltage that is coupled to the weatherhead of a relatively short conduit as shown in Fig. 5.8 for a 10-ohm resistive load. The source voltage V_p is that shown in Fig. 5.6b. The switch S_a has been assumed to be activated at 0.4 μsec and the transition voltage at times slightly greater than 0.4 μsec has been plotted from those shown in Ref. 12. The other parameters used in Eq. (5.18) to calculate the values plotted in Fig. 5.8 are those given in this section; namely, $R_a = 5$ ohms, $Z_o = 400$ ohms, $C_s = 300$ pf, and $C_1 = 900$ pf.

As we can see from Fig. 5.8, the EMP-induced power line surge is rather poorly coupled to the secondary circuit. This is due primarily to the attenuation of the distribution transformer and the mismatch
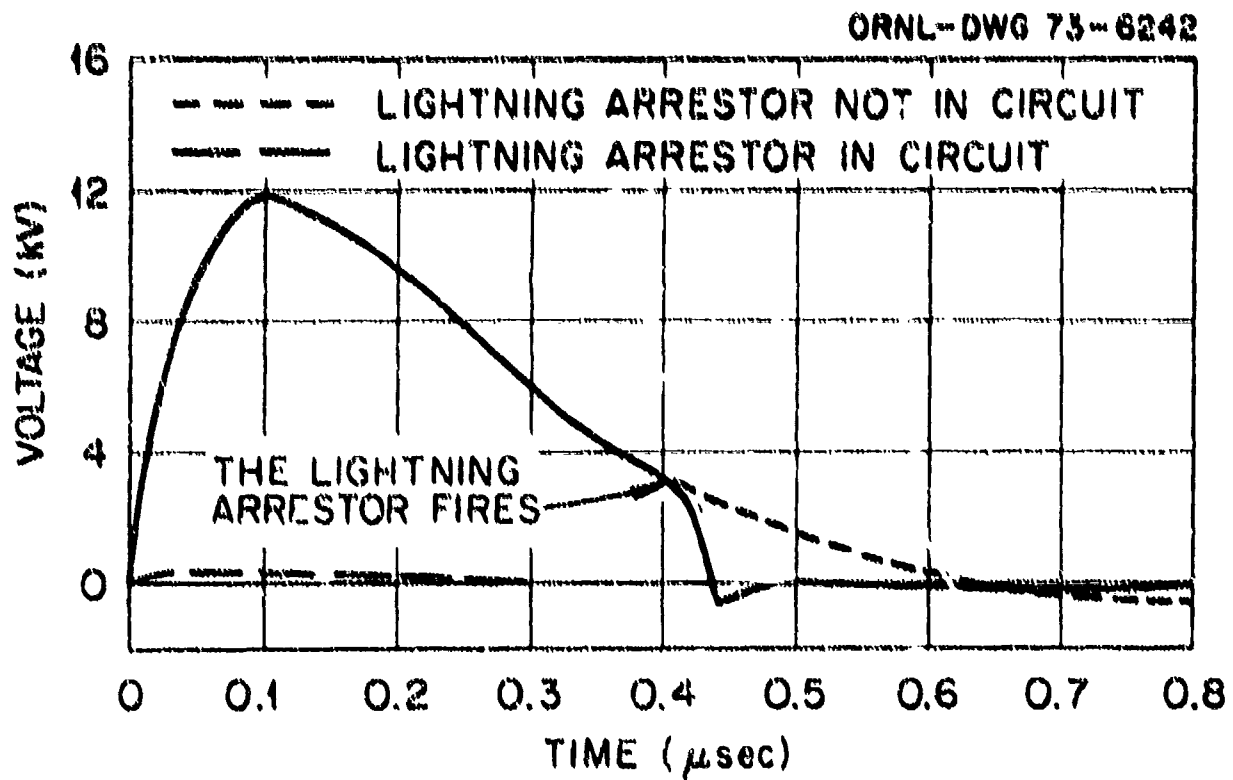
Fig. 5.8. The Voltage Coupled to the Weatherhead with a 10 ohm Resistive Load for the Power Line Source Voltage Given by Fig. 5.2b.

between R_e and Z_w. For Z_w = 40 ohms, more energy is transferred to the secondary circuit, and the voltage peak is about 50 kV.

The voltage at the wall plug which is located a short distance from the main switch box will be about the same as that at the switch box and the weatherhead. The voltage at the wall plug which is located hundreds of feet from the main switch box will be modified by the internal building wiring. The rise time of the pulse will be increased due to the effects of the additional inductance of the wiring. And the voltage pulse will have damped oscillations with ringing frequencies associated with the wiring in the megahertz range.

5.5   THE MICROPHONE CORD

The microphone cord normally consists of a coiled cable containing four wires; two of the four wires connect the microphone cartridge to the transmitter audio circuit through a switch and the other two wires are used to switch the radio from the receive mode to the transmit mode. A push button, double-pole switch is mounted in the microphone case.

When the microphone cord is subjected to EMP, currents will be induced in the wires within the cable. The four conductors form a non-deliberate antenna with an effective radius approximately equal to the radius of a single conductor. The effective length of this antenna is near the maximum value when the cord is extended its full length.

For the purpose of EMP coupling analysis, consider a possible worst case situation of a 1-meter, straight microphone cord connected perpendicular to a metal radio case. The microphone cord and the metal case form a half-dipole antenna. We shall further specify that the orientation of the incident EMP is such that a maximum response is induced in the microphone cord, non-deliberate antenna. And that the communications equipment is located in an unshielded building high above the earth such that the ground-reflected EMP arrives at the microphone cord about 40 ns after the direct incident EMP.

The 50-ohm load current and short circuit current responses of the microphone cord, non-deliberate antenna as described above are given for the first 40 ns by Figs. B-2 and B-8 respectively. The currents in each of the conductors within the cable are approximately equal for equal

loads. Thus, the responses of each wire are about 1/4 those shown in Figs. B-2 and B-8. If some wires have 50-ohm loads and others have short circuits, the responses of each of the wires during the first half-cycle will be about the same as those for equal loads since there is little difference between the two types of responses during this period.

5.6 CONTROL LINK ANALYSIS

As stated in Chapter III, telephone lines and VHF, UHF, and microwave antennas are used to provide control links. The VHF and UHF antennas have been considered under Section 5.2. In this section we shall consider the EMP coupling to microwave antennas and to a special two-wire control line.

Aperture antennas are employed for point-to-point radio communications service in the 952 to 960 MHz and the super high frequency (SHF) bands. The total energy received by an aperture antenna from a double exponential EMP as given by Eq. (1.7) has been investigated by IITRI.[13] IITRI assumed that the effective area A_{eff} of the antenna has no frequency dependence and that the aperture antenna performs as a perfect bandpass filter with upper and lower radian cutoff frequencies ω_1 and ω_2 respectively. The total energy received by the antenna is given by[13]

$$E_T = A_{eff} \frac{F_o^2 (\alpha_2 - \alpha_1)}{\pi (\alpha_2^2 - \alpha_1^2)} \{ \frac{1}{\alpha_2} \tan^{-1} \frac{\omega}{\alpha_2} - \frac{1}{\alpha_2} \tan^{-1} \frac{\omega}{\alpha_2} \} \Big|_{\omega_1}^{\omega_2} \quad . \quad (5.19)$$

The effective area of an aperture antenna is of the same order as the physical area S , a typical effective area is

$$A_{eff} = 0.6 \ S \quad . \quad (5.20)$$

The total energy received from Pulse C by an aperture antenna with an effective area given by Eq. (5.20) and upper and lower cutoff frequencies 950 and 960 MHz respectively is

$$E_R = 0.06 \ S \ \text{mj} \quad . \quad (5.21)$$

For S equal to 0.5 m², the total energy received is 0.03 mJ. This energy level is an upper bound for the more realistic aperture antenna with an effective area which is a function of frequency such that the power gain of the antenna is 3 dB down at the cutoff frequencies. The time required to deposit 90% of the received energy is approximately given by[14]

$$T = \frac{4.5}{\omega_2 - \omega_1} \quad .$$
(5.22)

For the cutoff frequencies used above, the deposit time is about 70 ns. The time history of the aperture antenna response to EMP is not given by Eqs. (5.19) and (5.22). For a resistive load R_L, the total energy is related to the time-domain load current $i(t)$ by

$$E_T = R_L \int_0^\infty i^2(t) \, dt \quad .$$
(5.23)

If we assume that the current is proportional to a decaying exponential function of time given by

$$i(t) = I_0 \, e^{-\alpha t} \quad ,$$
(5.24)

then the total energy is

$$E_T = I_0^2 \, R_L \, T/\ln 10$$
(5.25)

and

$$\alpha = \frac{\ln 10}{2 \, T} \quad .$$
(5.26)

For $E_T = 0.03$ mJ, $T = 70$ ns and $R_L = 50$ ohms, the peak value of the load current is 4.44 A and $\alpha = 1.6 \times 10^7$ sec^{-1}.

Consider now the EMP energy coupled to communications equipment by a two-wire telephone control line. Assume that the control link is a long unshielded two-wire cable terminated in a balance transformer load. The induced current in the cable has dominant frequencies high above the audio range; thus, we can expect the signal to be capacitively coupled

from the primary to the secondary side of the line transformer. This capacitive coupling characteristic of a line transformer was experimentally verified for a five-microsecond pulse.

A mid-frequency model for each wire of the telephone cable and half of the line transformer termination is shown in Fig. 5.9a. The capacitance C_1 in the figure is the inter-winding capacitance and C_2 is the secondary to system/earth ground capacitance. R is the equipment load impedance on the secondary and h is the height of the wire above the earth.

The EMP-induced transmission line voltage across the equipment load is shown in Fig. 5.9b for R = 600 ohms, C_1 = 92 pf, C_2 = 8 pf, and H = 5 meters. The EMP source used in the calculation is the same as that used to calculate values for Fig. 5.6b. This calculation was performed by first calculating the current induced on an infinite copper wire with an effective radius equal to 0.4 mm and then applying transmission line theory to calculate the current through the load. The energy received by the load from the pulse shown in Fig. 5.9b is about five millijoules. The values for C_1 and C_2 used in the calculation are approximate values for the line transformer examined by ORNL.

5.7 DIRECT EMP COUPLING

Electromagnetic pulse radiation can couple directly to electronic equipment. The connecting wires within electronic equipment can collect small amounts of EMP energy by performing as small loaded loop antennas. Consider the wire loop shown in Fig. 5.10a; the length of the wire is ℓ, the area formed by the wire, circuit elements, and the chassis is S, and the total impedance of the circuit is Z_L. Since the loop is physically small compared to the wavelength of the EMP, quasi-static approximations can be used. The current I_L through the load is given approximately for late times, t > 5 L/R, by

$$I_L = \frac{\mu_o}{Z} \frac{S}{R} \frac{\partial E}{\partial t} \quad , \tag{5.27}$$

where the magnetic field vector of the EMP is oriented perpendicular to the plane of the loop, R is a resistive load, L is the lo   impedance,

ORNL-DWG 73-6244

TELEPHONE LINE   LINE TRANSFORMER
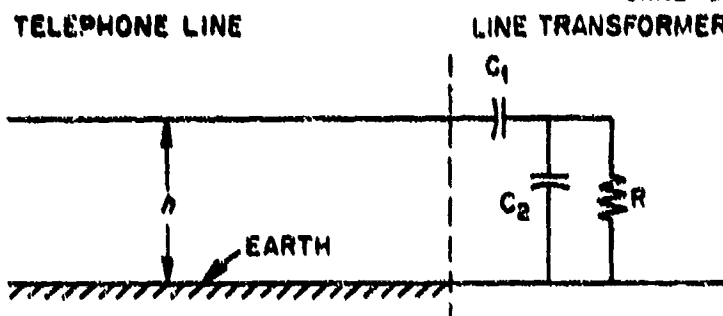
(a) MID-FREQUENCY MODEL FOR EACH WIRE OF A
BALANCED TWO-WIRE TELEPHONE CONTROL LINE
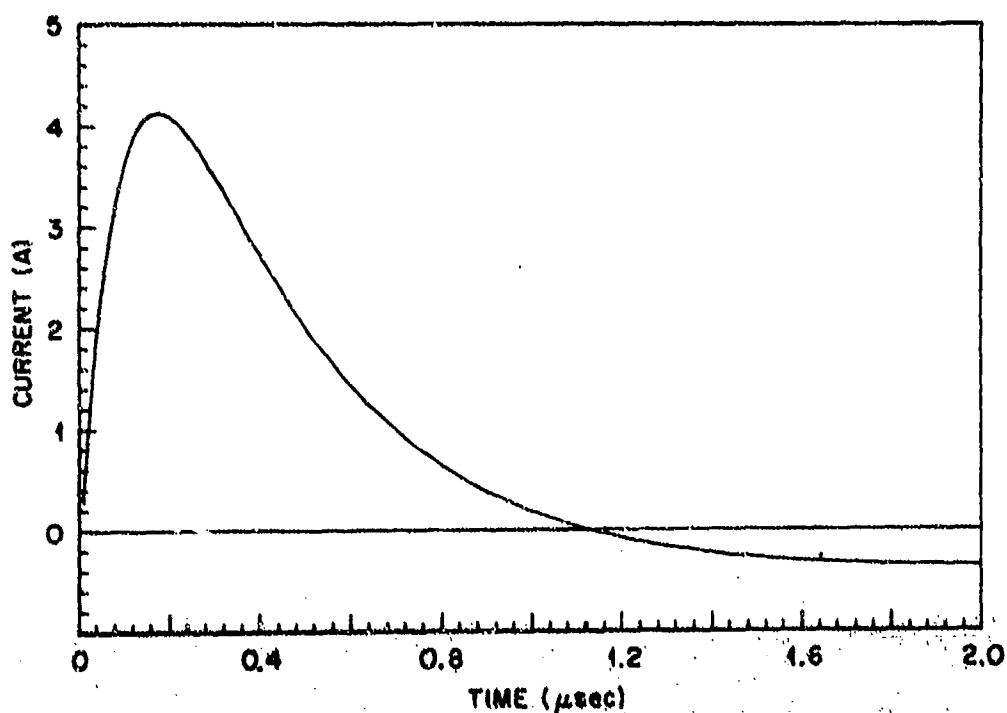
(b) THE EMP INDUCED CURRENT THROUGH THE SECONDARY 600 ohm LOAD
OF LINE TRANSFORMER CONNECTED TO A TWO-WIRE TELEPHONE LINE.
THE EMP SOURCE IS THE SAME AS THAT USED TO CALCULATE VALUES
FOR FIGURE 5.2 b.

Fig. 5.9.   The Telephone Control Link.

ORNL—DWG 73—6245
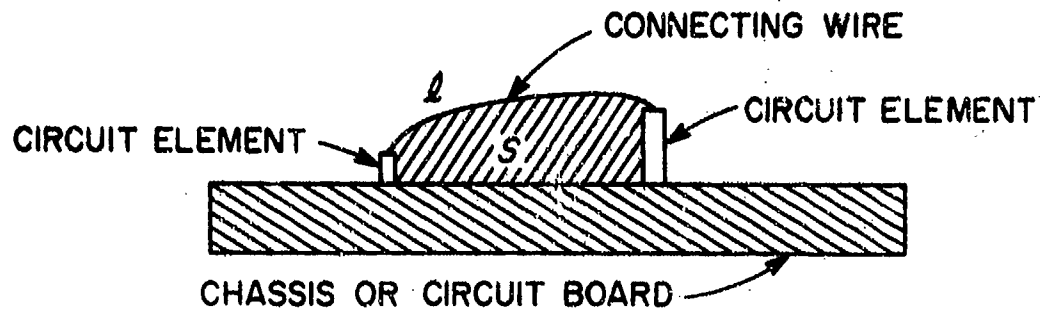
(*a*) SHORT CONNECTING WIRE
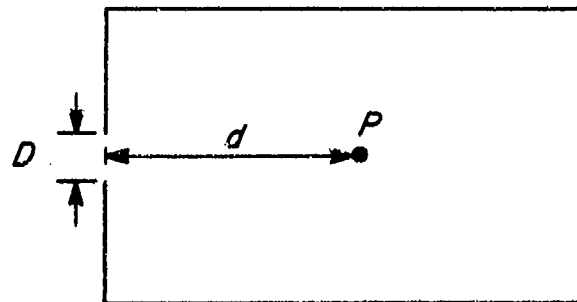
(*b*) METAL SHIELD WITH A SMALL HOLE

Fig. 5.10. Direct Coupling to Electronic Circuits.

μ_o is permeability of free space, and Z is the free space wave impedance. The loop inductance is

$$L \approx \frac{\mu_o \, \ell}{\pi} \, [\ell n \, (8 \, \ell/\pi a) \, -2] \quad , \tag{5.28}$$

where a is the radius of the wire. For a No. 18 gage connecting wire 20 cm long, the loop inductance is equal to about $0.4 \, \mu h$. If the total load is a resistance equal to 100 ohms, Eq. (5.27) applies for times greater than 20 ns.

The energy received by the load from the double exponential EMP given by Eq. (1.7) is

$$E_R = R \int_0^\infty I_L^2(t) \, dt = \frac{\mu_o^2 \, S^2 \, E_o^2 \, (\alpha_2 - \alpha_1)^2}{2 \, Z^2 \, R \, (\alpha_1 + \alpha_2)} \quad , \tag{5.29}$$

which, for Pulse A, is equal to about $4 \, \mu j$ for $S = 0.1 \, m^2$ and $R = 100 \, \Omega$.

If the electronic circuit is located in a shielded enclosure such as an iron case, the incident electromagnetic fields at the connecting wire are reduced. To estimate the effectiveness of a metal case as a shield enclosure, consider the electromagnetic fields in the metal box shown in Fig. 10b. The circular hole has a diameter D and the point of interest P is located a distance d from the hole on the axis of the circle as shown.

The magnetic field at P is given to a zero[th] order approximation by[14]

$$H_{int} = \frac{9}{\pi} \left(\frac{D}{d}\right)^4 H \quad , \tag{5.30}$$

where the quasi-static formula given by Eq. (46) of Ref. 14 for the electric field tha. penetrates a perfectly conducting sphere with a circular aperture for $D/d \ll 1$ has been used.

The substitutions of Eqs. (5.30), (1.1), and (1.7) into Eq. (5.29) gives the maximum energy received by the connecting wire loop located in a metal case which has a single circular hole as

$$E_R = \frac{81 \, \mu_o^2 \, S^2 \, E_o^2 \, (\alpha_2 - \alpha_1)^2 \, D^8}{32 \, Z^2 \, R \, (\alpha_2 + \alpha_1) \, d^8} \quad . \tag{5.31}$$

For $R = 100 \ \Omega$, $S = 0.1 \ m^2$, $D = 2$ cm, and $d = 20$ cm, the energy received from Pulse A is reduced from $4 \ \mu J$ to about 10^{-14} joules. Thus, the attenuation of the shield enclosure is about 10^{-7}. Since the time period required to receive the EMP energy is about the same for shielded and unshielded loops, the power attenuation of the enclosure is about 70 dB.

Equation (5.31) is a very rough approximation of the energy received by the connecting wire loop. The fields that penetrate the enclosure are no longer plane waves and thus, Eq. (5.30) does not precisely apply. However, Eq. (5.31) does indicate the benefits of the shielded enclosures.

5.8 INDIRECT COUPLING

Electromagnetic energy can couple to electronic circuits from the fields that are radiated from the EMP-induced currents in long conducting structures. Metal structures such as pipes and air ducts that are 40 m long can be expected to have about 5 kA maximum peak current induced in them by Pulse A as is shown in Fig. B-4. Very long structures could have on the order of 10 kA induced in them by Pulse A.[10] The other pulses, B, C, and D, will induce smaller currents.

To estimate the effects of the re-radiated fields, consider modeling the long metal structure by a cylinder with an effective radius a_e. For times $t \gg a_e/c$ where c is the speed of light in free space, the magnetic field radiated by the structure is

$$H_r = \frac{I}{2\pi r} \ , \qquad (5.32)$$

where I is the EMP-induced current and r is the radial distance from the axis of the effective cylinder. The magnetic field unit direction vector is the same as the phi unit direction vector of the cylindrical coordinate system with the z axis coincident with the axis of the effective cylinder.

The effective value of the current induced in a perfectly conducting infinite cylinder by a double exponential EMP with broadside incidence is approximately given by[15]

$$I_m = \frac{2\pi \ c \ E_0}{Z \ \alpha_1 \ \ell n \ \left(\frac{c}{a_e \ \alpha_1}\right)} \ . \qquad (5.33)$$

Substituting Eq. (5.32) into Eq. (5.33) gives the maximum re-radiated magnetic field for broadside EMP incidence as

$$H_{rm} = \frac{c\, E_o}{r\, Z\, \alpha_1\, \ln\left(\frac{c}{a_e\, \alpha_1}\right)} \quad . \tag{5.34}$$

The distance from the structure, for which the maximum re-radiated magnetic field is equal to or less than ten times the incident EMP magnetic field, is

$$r_c \geq \frac{c}{10\, \alpha_1\, \ln\left(\frac{c}{a_e\, \alpha_1}\right)} \quad . \tag{5.35}$$

The value of r_c for Pulse A is

$$r_c \geq \frac{20}{\ln\, (200/a_e)} \quad \text{meters} \quad , \tag{5.36}$$

which equals 2.6 m for $a_e = 0.1$ m. Equation (5.36) gives an upper bound for the r_c associated with a non-perfectly conducting structure. The peak value of the EMP-induced current in a copper cylinder is about 1/6 that of the perfectly conducting cylinder.[10] Thus, for the non-perfectly conducting structure, r_c equals about 0.43 m for $a_e = 0.1$ m and Pulse A EMP.

CHAPTER VI

EFFECTS OF EMP ON COMMUNICATION SYSTEMS

6.1 INTRODUCTION

In Chapter VI, calculational techniques along with experimental data are used to determine the EMP-induced voltages across and currents into POE's of communications equipment. To determine equipment vulnerability to these transients and the probability of equipment and ultimately system failure is very difficult, if not impossible, due to the limited amount of statistical data. Nevertheless, apparent probabilities based on the available information are computed, and superficial estimates of the actual probabilities are obtained. These provide approximate values of the probabilities of damages and failures and furnish a basis to classify communications equipment and systems according to their relative probabilities of failure.

6.2 ELECTRONIC COMPONENT VULNERABILITIES

The electronic components that are most susceptible to electrical transients are semiconductor diodes, IC's, transistors, low voltage capacitors and vacuum tubes, and low power resistors and conductors. Some rules-of-thumb that are used for the vulnerability analysis of resistors and capacitors are: (1) quarter-watt carbon resistors can be damaged by 25 kilowatts of pulse power dissipated during several microseconds, (2) thin-film resistors can be damaged by voltages slightly above the resistor's voltage rating, and (3) capacitors can be damaged by voltage transients that exceed their rated values by at least a factor of ten. Unfortunately, there is not a large amount of available experimental data on resistor and capacitor vulnerabilities and the probabilities of damages to these components by surges cannot be assessed. The nature of transient damages to resistors and capacitors is that the device is normally short or open circuited by the effects of the surge.

The most sensitive electronic components are semiconductors. A solid state device is considered to have been damaged if the parameters of any p-n junction have been seriously degraded, or if a junction has become an open or short circuit. The threshold pulse for semiconductor

damage is inversely proportional to the square root of the pulse width and is given by[16]

$$P = K t^{-1/2} \qquad t \geq 100 \text{ ns} \quad , \qquad (6.1)$$

where P is the average power, t is the pulse time, and K is the damage factor constant. For pulse widths of 100 ns or less, a pulse power failure dependence of t^{-1} is more appropriate.[16] Thus, the threshold failure energy for a short pulse is

$$E_{nf} = 3.16 \text{ K} \quad \text{mj} \quad . \qquad (6.2)$$

The value of K can be estimated from the junction capacitance c_j and breakdown voltage V_{bd} for silicon planar transistors by the semi-empirical formula[16]

$$K = 8 \ c_j \ V_{bd}^{(1.63)} \times 10^{-6} \quad \text{watt-sec}^{1/2} \qquad (6.3)$$

where c_j has units of picofarads. Other semi-empirical formulas are given in Ref. 16 for germanium and silicon nonplanar devices.

Experimental values of E_f for some typical solid state devices have been determined by semiconductor vulnerability studies.[16] The threshold failure energies to cause burnout for some typical devices used in radio communications are presented below:

Device	E_{nf} (mj)
Ge audio transistor 2N331	10
Si audio transistor 2N327A	16
Ge UHF transistor 2N2188	.1
Si RF analog IC RCA CA3005	.008
Si VHF FET 2N4224	.03
Si microwave diode 1N23B	.1 µj
Si general purpose diode 1N647	2
triode vacuum tube 66N8	2 joules

For the Motorola communications transistor M9481, the base-to-collector junction capacitance is 0.5 pf and the breakdown voltage[*] is about 67.5 V. The value of K computed from Eq. (6.3) is 0.00465 watt-sec$^{1/2}$. The value of K was also determined from a thermal resistance model presented in Ref. 16 and the result is K ≈ 0.00463. The threshold energy level corresponding to this value of K is 0.015 mJ.

The value of E_{nf} is the energy threshold failure level at which the device failure probability is roughly 0.5. This can be observed from the experimental data presented in Ref. 16. It can also be observed, for the semi-conductors tested, that the experimental value of E_{nf} for a particular device may differ from that computed by Eq. (6.2) by plus or minus an order of magnitude. Thus, it is reasonable to assume that the device failure cumulative distribution function F(x) is a logarithmic (base 10) function of the normalized dissipated energy x defined by

$$x = \frac{E_n}{3.16\ K} \quad , \qquad (6.4)$$

where E_n is the energy dissipated by the device. The value of F(1) is 0.5. Since the probability of device failure for x ≤ 10 is high, we set F(x) = 1 for x ≥ 10. The cumulative distribution function with the above mentioned properties is presented in Fig. 6.1. The probability of device failure p for a given normalized dissipated energy b can be determined from Fig. 6.1 by

$$p(x = b) = F(b) \quad . \qquad (6.5)$$

6.3 EQUIPMENT VULNERABILITIES

Electronic equipment is vulnerable if one or more essential circuit elements are severely damaged. In order to simplify the assessment of equipment vulnerabilities, we shall assume that the probalities of component damages are independent. This is a reasonable assumption since most of the sensitive essential components are largely decoupled. The probability of equipment damage is related to independent probabilities of circuit component damages by

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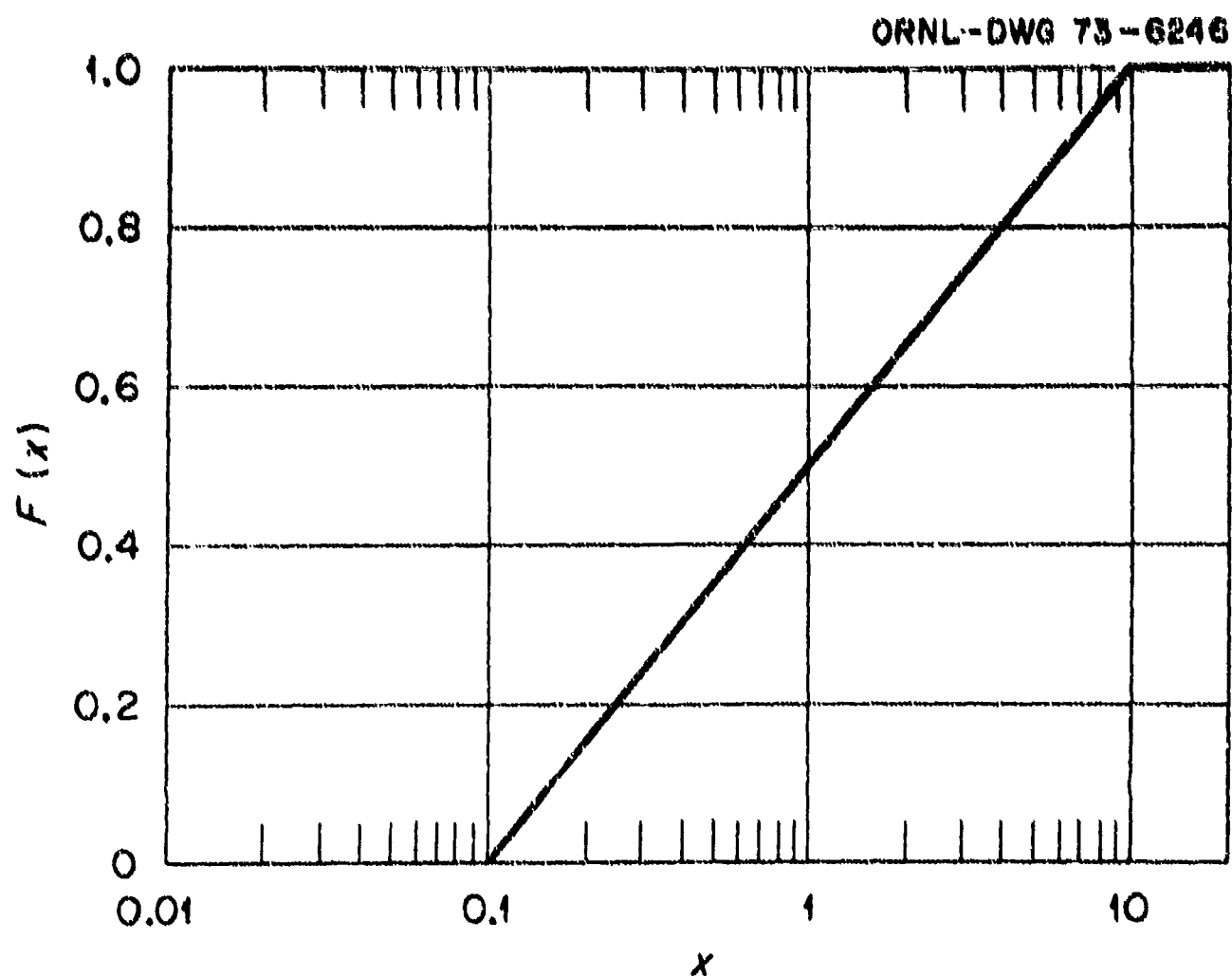[*]The breakdown voltage is estimated as 50% larger than the rated value.

Fig. 6.1. Cumulative Distribution Function Used to Estimate the Probability of Semiconductor Damage.

$$P = 1 - (1-p_1)(1-p_2)(1-p_3) \cdots (1-p_n) \quad , \tag{6.6}$$

where n is the number of vulnerable essential circuit components and p_n is the damage probability of the nth component.

6.3.1 Transmitter-Receiver Units

Base station transmitter-receiver units have four important POE's: the antenna and feedline, the microphone cord, the commercial power source, and the direct coupling. Mobile units have only two important POE's, the antenna and microphone cord. And portable units can have all the POE's of base station units *including* the commercial power at times when the portables are being recharged.

Consider first the antenna and feedline POE. It was determined in Chapter V that the current induced on the inner conductor of a coaxial feedline connected to a tap-coil receiver input circuit is about 100 A maximum for Pulse A. Since the duration of the current is only a fraction of a microsecond, there is little chance of damage to the coil. For the capacitor-divider input, the maximum peak voltage is about 0.5 kV. Since this value is ten times the normal capacitor rated value of 500 V, it is likely that the capacitor-input circuit will be damaged by Pulse A or C, particularly if it is subjected to multiple pulses. For Pulse B or C, the capacitor-input circuit would not likely be damaged by a single pulse but the probability of damage is much higher for many pulses due to the cumulative effects on the capacitors.

Very little of the energy of the feedline non-deliberate antenna response will pass through the receiver's input bandpass filter since the dominant frequencies are below the filter's cutoff frequency. However, most of the energy of the antenna's response, in contrast, will pass through the filter since the dominant frequencies are within the bandpass frequency band. The power attenuation of the antenna relay, the bandpass filter, and bias circuitry is about 4 dB between the antenna input terminal and the first active device. Additional attenuation to large pulses is provided on some units by the RF overload protection.

To estimate the effectiveness of the RF overload protection against the effects of EMP, consider the Motorola HT 220 unit, item 6 in Table 4.1,

that failed at 200 kV/m during the EMP test. The RF transistor that was damaged, the M9481, has an E_{nf} equal to about 0.015 mj. The energy that the transistor would receive at E_p = 100 kV/m without RF overload protection is approximately 0.075 mj. The probability of damage from Fig. 6.1 for b = 5 is 0.85. However, the RF overload protection likely reduces this probability. The extent of the reduction of the damage probability can only be conjecture without further investigations.

After several pulses at E_p = 100 kV/m, the unit did not fail even though the total multipulse probability of damage was about 0.98. At E_p = 200 kV/m, the unit was damaged by the first pulse for which additional EMP protection was not used. For E_p = 200 kV/m, B = 20; thus for this particular unit the attenuation provided by the RF overload protection was less than 23 dB and was likely about 10 dB since the unit was destroyed on the first shot. We shall assume, because of the lack of any other information, that a 10 dB surge attenuation is typical for RF overload protection circuits.

The probabilities of damages to RF receiver components by Pulses A, B, C, and D are displayed in Table 6.1 for a range of components, frequency bands, and antenna gains. The threshold energy levels for a 0.5 probability of damage that were used to compute the probabilities given in Table 6.1 are: 2 j for the tube, 0.1 mj for the transistor, and 0.03 mj for the sensitive transistor or FET. A 4 dB attenuation was used for the tube, transistor, and FET calculations. For the FET with RF overload protection, 14 dB attenuation was used for a 10 dB protection factor, and 24 dB was used for a 20 dB protection factor.

Now consider the vulnerability of components in the transmitter audio stage that are closely coupled to the microphone cord. It was determined in Chapter V that the maximum response of the microphone cord is similar to that of a 75 MHz half-dipole. When the transistor in Fig. 3.3b is reverse-biased at a level exceeding the breakdown voltage, the input impedance is near 50 ohms. If we assume a typical reverse-biased, base-to-emitter breakdown voltage of 20 V, the energy dissipated in the transistor is about 0.015 mj. This amount of energy has a near zero probability of damage to an audio transistor with E_{nf} = 10 mj. However, for an FET with an E_{nf} of 0.03 mj, the probability of damage is 0.35. And

Table 6 1. Probabilities of Damages to RF Components of Receivers
Connected to a Linear Antenna

Antenna Gain	Frequency Band	Pulse	Probability of Damage[a]				
			Tube	Transistor	FET or Sens. Tran.	FET and RF Protection	
						10 dB	20 dB
Unity	HF	A	1	1	1	1	1
		B	0.86	1	1	1	1
		C	1	1	1	1	1
		D	0.7	1	1	1	1
	CB	A	0	1	1	1	1
		B	0	1	1	1	0.9
		C	0	1	1	1	1
		D	0	1	1	1	0.52
	VHF Low Band	A	0	1	1	1	0.98
		B	0	1	1	1	0.52
		C	0	1	1	1	0.9
		D	0	1	1	1	0.54
	VHF High Band	A	0	0.49	0.75	0.24	0
		B	0	0.24	0.39	0	0
		C	0	0.53	0.79	0.29	0
		D	0	0.25	0.51	0.01	0

Table 6.1. (Cont'd)

Antenna Gain	Frequency Band	Pulse	Probability of Damage [a]				
			Tube	Transistor	FET or Sens. Tran.	FET and RF Protection	
						10 dB	20 dB
	UHF	A	0	0	0	0	0
		B	0	0	0	0	0
		C	0	0	0	0	0
		D	0	0	0	0	0
10 dB	VHF High Band	A	0	1	1	0.99	0.49
		B	0	0.87	1	0.65	0.12
		C	0	1	1	1	0.52
		D	0	0.39	1	0.75	0.25
	UHF	A	0	0.19	0.45	0	0
		B	0	0.04	0.3	0	0
		C	0	0.19	0.45	0	0
		D	0	0.04	0.3	0	0
15 dB	UHF	A	0	0.44	0.7	0.2	0
		B	0	0.28	0.54	0.04	0
		C	0	0.45	0.71	0.2	0
		D	0	0.28	0.54	0.04	0

[a] The numeral 1 is used for approximately one and 0 is used for approximately zero.

for an IC audio amplifier with an E_{nf} of 0.0075 mh, p is equal to 0.65 for a dissipated energy level of 0.015 mj.

We shall now consider the effects of the EMP energy from the commercial power line on the equipment's power supply. Referring to Fig. 3.4, the EMP-induced voltage at the wall plug will capacitively couple across the power transformer T201. The fraction of the voltage that will couple across each winding depends on the relative values of the inter-winding and winding-to-ground capacitance.

One of the most vulnerable portions of the power supply is the transmitter-exciter supply circuit which is connected to winding E in Fig. 3.4. This circuit typically has rectifier diodes with a forward current rating of about 200 ma. These diodes are frequently damaged by lightning. Since the wall plug voltage due to lightning can be as high as 10 kV and the voltage due to EMP may be 10 kV or greater, it is likely that the EMP voltage will damage the small current rectifier diodes in the power supply circuit.

The probability of damage to the power supply by EMP surges depends on the EMP source voltage, source impedance, and the values of the inter-winding capacitances. For our analysis, consider an interwinding capacitance of 100 pf and a wall plug EMP-induced voltage with a 10 Ω source impedance defined by Fig. 5.8. If we assume that the total induced voltage is coupled across winding E of Fig. 3.4, the energy dissipated by a diode with a 0.6 V forward breakdown voltage is 0.016 mj. A larger source impedance or coupling capacitance would result in a larger dissipated energy.

The threshold failure energy for diodes with forward current ratings of several hundred milliamperes can be computed from the experimental data presented in Ref. 16 as equal to about 0.03 mj. The probability of damage to these diodes from an EMP surge that deposits 0.015 mj of energy is near 0.4.

A probability of damage to the power supply equal to 0.4 is likely an optimistic value. The probability of damage will be larger than 10 ohms and a coupling capacitance larger than 100 pf. Also, the damages to other semiconductors and the transformer windings have not been considered. Therefore, the probability of damage to the power supply by

EMP is at least 0.4 for Pulses A and C. For Pulses B and D, the energy dissipated by the power supply is reduced by a factor of 4. And the probability of damage is reduced to about 0.11.

Finally, we consider the effects of direct coupling on electronic circuits. The maximum energy received by a circuit-connecting wire from direct coupling is about 4 μj. If this energy were completely dissipated by an integrated circuit it could possibly result in damages to an IC. However, for most circuit components 4 μj should not cause any problems. We shall consider the probability of damage due to direct coupling as near zero for our analyses.

Now consider the overall probability of damage to representative transmitter-receiver units. We have selected as representative equipment, the most commonly used equipment in service at the present time. Representative HF units have tubes in all stages except for the semiconductor diodes. Citizen's band units normally have transistorized receivers. And UHF and VHF units commonly have transistorized receivers and transmitter audio stages. The VHF or UHF RF receiver stage normally has a sensitive RF transistor or FET and may or may not have RF surge protection. For our analysis, we specify that the representative VHF and UHF units have 10 dB RF overload protection.

The probabilities of damage to representative transmitter-receiver units are presented in Table 6.2. Modern equipment employing FET's, IC's, etc. will have higher probabilities of damage. And older equipment employing tube RF and audio amplifier stages will have a lower probability of damage. Also, the probabilities of damages to HF, CB, and VHF low-band units given in Table 6.2 are optimistic values since the likelihood of the probable damages to coils and relays have not been taken into account.

6.3.2 Remote Control Consoles and Chassis and the Repeater Control Circuit

Remote control consoles and remote base and repeater stations that use commercial power will have probabilities of damages from the power source POE similar to those for the transmitter-receiver unit, i.e., $p \approx 0.4$ for Pulse A or C and $p \approx 0.1$ for Pulse B or D. The primary remote control console and the locally remote control consoles can also

Table 6.2. Probabilities of Damages to Representative
Transmitter-Receiver Equipment

Frequency Band	Pulse	Probability of Damage[a]		
		Portable[a]	Mobile[b]	Fixed[c]
HF	A	Not	Not	1
	B	Commonly	Commonly	0.92
	C	Used	Used	1
	D			0.82
CB	A	1	1	1
	B	1	1	1
	C	1	1	1
	D	1	1	1
VHF Low Band	A	1	1	1
	B	1	1	1
	C	1	1	1
	D	1	1	1
VHF High Band	A	0.24	0.24	0.54
	B	0	0	0.1
	C	0.29	0.29	0.57
	D	0.01	0.01	0.1
UHF	A	0	0	0.4
	B	0	0	0.1
	C	0	0	0.4
	D	0	0	0.1

[a]The numeral 1 is used for approximately one and 0 is used for approximately zero.

[b]The unity gain antenna energy was used in the calculations.

[c]The 10 dB gain antenna energy was used in all calculations except for HF and CB units which normally have unity gain antennas.

receive EMP energy from the microphone cord. However, this energy is
not likely to cause damages to the audio transistors that are commonly
used in console circuits since they have relatively high threshold fail-
ure energy levels.

The last important source of EMP energy for consoles and remote con-
trol chassis and repeater circuits is that energy received from the con-
trol link. For a telephone line link, the energy received by the line
transformer's secondary load is about 5 mj. The probability of damages
to logic circuits employing sensitive switching transistors such as the
2N706 with a threshold failure energy of 60 μj is about 1.0 for Pulse A
or C and near 0.7 for Pulse B or D.* If the line transformer has a surge
suppressor circuit across the secondary winding terminals to the system
ground, the probability of damages to logic circuits should be near zero.

On the primary side of the line transformer, the EMP-induced voltage
from each line to ground is on the order of 1.5 kV. However, the voltage
across the transformer is near zero since the telephone wires are termi-
nated by a balance load. Thus, the probability of damage to the primary
side of the transformer should be very small.

For systems that employ an RF control link as many as two additional
transmitter-receiver units have to be considered; one at the control point
and another at the remote station. For a 75 MHz control link, the proba-
bility of damage to a representative transmitter-receiver with a 10 dB
gain antenna is near 1 for Pulse A or C, about 0.83 for Pulse B, and about
0.87 for Pulse D.

6.4 PROBABILITY OF SYSTEM FAILURES

The four communications systems as defined in Chapter III consist
of a fixed control and base stations network and portable and mobile units.
A system has experienced a failure when communications between the fixed
station and mobile stations are no longer possible. If the fixed station
is destroyed, then the system has failed. On the other hand, if the fixed
station continues to function and a few mobile stations become non-
functional, the system is only degraded. If many mobile stations cannot
communicate, then the system has been degraded to the extent that it can
no longer perform its mission and should be considered to have failed.

*One-tenth of the total energy is assumed to be dissipated by the
transistor.

For this study, we shall consider the system to have failed if 50% or more of the mobile units fail. The probability that one-half or more of the mobile units will fail is given by

$$p_m = \sum_{[N/2]}^{N} \binom{N}{x} p^x (1 - p)^{n-x} , \qquad (6.7)$$

where N is the number of mobile units and p is the probability of failure for a single unit. For N = 50, the probability of failure for 25 or more VHF high-band representative mobile units is about 0.002 or less for Pulse A, B, C, or D. The probability of failure for 25 or more of 50 representative units is near 0.1 for lower frequency bands and near zero for the UHF band.

The probabilities of failure for communications systems consisting of stations with representative equipment are presented in Table 6.3. The locally remote control console system has not been included in Table 6.3 since its probability of failure is about the same as that of the remote base station system due to the surge protection used on the representative consoles. The probabilities of failure for the remote base station system have been computed for a telephone line control link with the assumption that the probability of damage to the telephone facilities is zero. The probabilities of failure for the repeater station system are for a system with an RF control link at a frequency equal to one of the repeater frequencies. If a 75 MHz RF control link is used, the probabilities of failures for VHF high-band and UHF systems would be larger than those in Table 6.3.

The mobile-to-mobile system listed in Table 6.3 is an emergency system consisting of a mobile unit used as a base station and the other mobile units. The probability of failure for this system is based on the probability that 25 or more mobile units out of a total of 50 mobile stations will fail. This emergency communication system, although limited to a relatively small area of coverage and to simplex frequency mobile equipment, has a low probability of failure at VHF high-band and UHF frequencies.

Table 6.3. Probabilities of Failure for Two-Way Communication
Systems Consisting of Stations with Representative Equipment

Frequency Band	Pulse	Probability of System Failure[a]			
		Local Base	Remote Base	Repeater	Mobile-to-Mobile
HF[b]	A	1	Not	Not	Not
	B	0.99	Commonly	Commonly	Commonly
	C	1	Used	Used	Used
	D	0.97.			
CB	A	1	Not	Not	1
	B	1	Commonly	Commonly	1
	C	1	Used	Used	1
	D	1			1
VHF Low Band	A	1	1	1	1
	B	1	1	1	1
	C	1	1	1	1
	D	1	1	1	1
VHF High Band	A	0.54	0.72	0.79	0
	B	0.1	0.19	0.19	0
	C	0.57	0.74	0.82	0
	D	0.1	0.19	0.19	0
UHF	A	0.4	0.64	0.64	0
	B	0.1	0.19	0.19	0
	C	0.4	0.64	0.64	0
	D	0.1	0.19	0.19	0

[a]0 is used for approximately zero and 1 is used for approximately one.

[b]Local base to local base station communications.

CHAPTER VII

EMP PROTECTION OF COMMUNICATIONS SYSTEMS

7.1 INTRODUCTION

To protect communications equipment from EMP-induced transients, the pulse energy dissipated by sensitive electronic components must be limited to values below the components' threshold energy failure levels. This can be accomplished by the addition of filters, transient suppressors, shielding, etc. The EMP protective measures must significantly reduce the probability of damage to the equipment and also be practical and cost effective. Of course, not all of the conceivable protective schemes meet the last two requirements.

In this chapter, the specifications for protective devices are determined for the more important PUE's of communications equipment and some devices that meet these specifications are recommended. Methods of providing a sufficient ground and shielding as an EMP protective measure have been adequately covered in a previous report[17] and will not be discussed here.

7.2 THE ANTENNA

One protective measure against the EMP energy received by the antenna is to limit the effective area of the antenna by limiting its length. This method can be used for portable units with a stub or collapsible-telescoping antenna at the expense of area coverage. An upper bound for the energy received during the first half-cycle by a 50 ohm load is[8]

$$E_n = 2.4 \ E_o^2 \ \ell^3 \times 10^{-9} \quad mj \quad , \tag{7.1}$$

where ℓ is the length of the antenna and the antenna's length-to-radius ratio is 259. If we assume a 4 dB power attenuation between the antenna terminals and the first RF transistor and $E_o = 50$ kV/m, then the maximum antenna length in terms of the transistor's threshold energy failure level is

$$\ell = (E_{nf}/2.4)^{1/3} \quad meters \quad , \tag{7.2}$$

where E_{nf} has units of millijoules and the receiver has no RF overload protection. For a sensitive FET with an $E_{nf} = 0.024$ mJ, ℓ is equal to 0.22 m (about 8-1/2 in.) for a less than 0.5 probability of damage.

For a receiver with RF overload protection that provides 10 dB surge attenuation, the antenna's length should be no longer than

$$\ell' = (E_{nf}/0.24)^{1/3} \quad , \tag{7.3}$$

which is equal to 0.46 meters for $E_{nf} = 0.024$ mJ. Since the operator may not know if his portable unit has RF overload protection, it is recommended that the antenna's length of units with FET's be limited to about 8 inches.

For one of the CB transceivers that was destroyed during the ORNL EMP test (see Chapter III), the threshold electric field level for EMP with a direction of incidence that induces the maximum response in the 62-inch-long antenna is no greater than 5 kV/m. At 50 kV/m, the minimum antenna length to collect enough EMP energy to cause failure in that transceiver is 0.34 m (13.5 in.). The transceiver did not have RF overload protection, thus from Eq. (7.2), $E_{nf} \sim 1$ mJ for the RF transistor which is fairly typical for non-sensitive RF transistors. If the transceiver had had RF overload protection, with 10 dB surge attenuation, then the minimum antenna length to cause failure would have been about 0.75 m. For a very hard RF transistor with $E_{nf} = 2.4$ mJ, the minimum antenna length to cause failure to a unit with RF overload protection is greater than 2 meters. However, since the operator normally will not have knowledge of the RF transistor's sensitivity to transients or the RF surge protection, it is recommended that the antenna's length of non-FET units be limited to 12 inches.

For most fixed and mobile stations, however, limiting the length of the antenna is undesirable. These stations can be protected by surge suppressors similar to those described in Chapter III. Surge suppressors are recommended over filters because most of the energy collected by the antenna is at the antenna's designed frequency.[8] A filter that would attenuate the surge would, in most cases, also attenuate the RF carrier signal.

The transient suppressor should be able to conduct currents equal to about five times the expected short-circuit current for a duration of about ten times the expected half-period. For the CB, VHF, and UHF antennas, a device capable of conducting 3 kA for 200 ns will meet these requirements. For HF antennas, a suppressor that can handle 30 kA for a microsecond should be used. If 30 kA devices are not available, a device capable of conducting no less than 10 kA for 9 μsec should be used.

The surge attenuation required for the suppressor is that which reduces the pulse energy to at least 1/10 the threshold failure level of a FET or sensitive transistor and is given by

$$A = 10 \ E_n/E_{nf} \quad , \qquad (7.4)$$

which is equal to 32 dB for a CB antenna and $E_{nf} = 0.01$ mj.

The maximum clamping voltage of the device for a unit with 4 dB signal attenuation to reduce the energy dissipated by the solid state device to 1/10 E_{nf} is

$$V_c = (\frac{12.5 \ E_{nf}}{T})^{1/2} \quad , \qquad (7.5)$$

where T is the half-period, a 50 ohm load has been assumed, and the units of E_{nf} and T are joules and seconds respectively. If the unit has RF overload protection with a 10 dB surge attenuation, the maximum clamping voltage is

$$V_c' = (\frac{125 \ E_{nf}}{T})^{1/2} \quad . \qquad (7.6)$$

For a CB unit with an FET front-end, $V_c = 80$ V and $V_c' = 250$ V. If the CB unit has an RF transistor with an $E_{nf} = 0.1$ mj, then $V_c = 250$ V and $V_c' = 790$ V. For a VHF high band unit with an FET or sensitive transistor RF stage with $E_{nf} = 0.01$ mj, $V_c = 160$ V and $V_c' = 500$ V.

The Spikeguard 350 series surge suppressors tested by ORNL have a 500 V clamping voltage and can handle pulses with rates of rise on the order of a kV/ns. This device uses a gas-gap diode with a small response time and it has very little overshoot above its clamping voltage. During

the second half-period of the pulse waveform the voltage across the diode is suppressed to near zero and is maintained at that level. The clamping voltage can be reduced to about 50 V by the addition of semiconductor diodes to the gas-diode suppressor. This hybrid semiconductor/gas-diode device was tested by ORNL and it performed very well as a suppressor.

In Fig. 7.1, the gas-gap diode and the hybrid gas-gap and semiconductor diodes protection circuits are shown. The recommended use of these protection devices is presented in Table 7.1 and is based on the required protection levels for near zero probability of damage. The diode protection device indicated for UHF equipment with an FET or sensitive transistor RF stage is the hybrid circuit shown in Fig. 7.1b without the gas-gap diode. In addition to the protection devices shown in Fig. 7.1, it is recommended that base stations also employ a standard antenna lightning arrester at the antenna.

7.3 THE COMMERCIAL POWER SOURCE

The voltage transient available to communications equipment from the commercial power source due to the EMP has a rate of rise on the order of 0.3 kV/ns and a peak voltage of 10 to 50 kV. The peak current that will flow through a low impedance surge suppressor is about 1 kA. A surge suppressor that can respond to these transients within 10 ns and clamp the voltage to several hundred volts should provide adequate protection. The suppressor should be rated for at least 5 kA of current for a duration of at least 5 μsec. Such a device is the Joslyn surge arrester P/N 2001-06. It has a pulse breakdown voltage of 1.8 kV for a transient voltage with a 0.5 kV rate of rise.[18] And it clamps the voltage pulse to about 230 V after 8 ns of pulse time history. It is rated at 10 kA for a 20 μsec triangular surge test pulse.

Recommended power line transient protection circuits are shown in Figs. 7.2a and 7.2b. These circuits suppress both common and differential mode surges. For the three-wire power cable shown in Fig. 7.2b, two of the wires are normally connected to earth ground. The gas-gap diode connected to the two ground wires is not necessary and can be omitted if the same two wires are always connected to ground at the various power receptacles available for the equipment.

ORNL-DWG 73-6247

TRANSMITTER-RECEIVER
ANTENNA INPUT

TO ANTENNA

GAS-GAP DIODE
IN A COAXIAL TEE
SPIKE GUARD 350
OR SIMILAR

(a) GAS GAP PROTECTION

RF FROM XMTR

TO ANTENNA

RF TO RCVR

SWITCHING DIODES
1N3653 OR SIMILAR
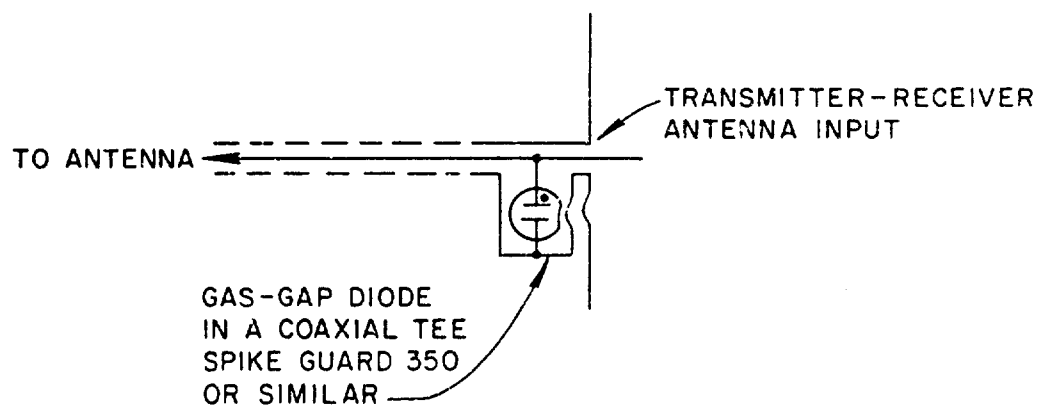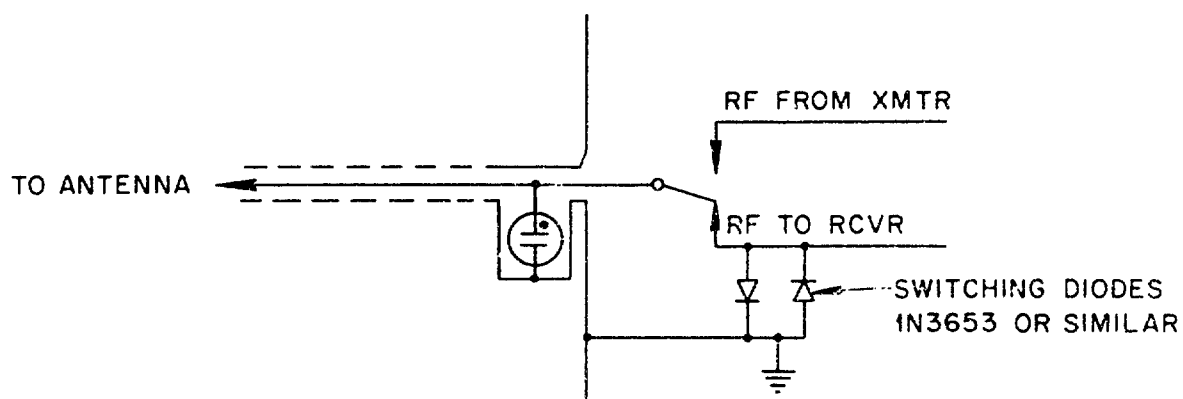
(b) HYBRID GAS-GAP AND SEMICONDUCTOR DIODE PROTECTION

Fig. 7.1. Devices for the Protection of Equipment from Transients
on the Antenna.

Table 7.1. Protection Levels to Obtain Zero Probability of Damage to
Communication Equipment by Transients from the Antenna

Frequency Band	Protection Level for Equipment RF Front-End				
	Tube	Transistor	Transistor with RF Protection	FET[a]	FET[a] with RF Protection
HF	Gas Gap	Hybrid	Hybrid	Hybrid	Hybrid
CB[b]	Gas Gap	Hybrid	Gas Gap	Hybrid	Hybrid
VHF[b] - Low Band	Gas Gap	Hybrid	Gas Gap	Hybrid	Hybrid
VHF - High Band	None	Gas Gap	Gas Gap	Hybrid	Gas Gap
UHF[c]	None	None	None	Diode	None

[a] FET or sensitive transistor.

[b] Gas-gap protection is recommended for tube sets for the protection of coils and capacitors.

[c] Gas-gap protection should be used with gain antennas.

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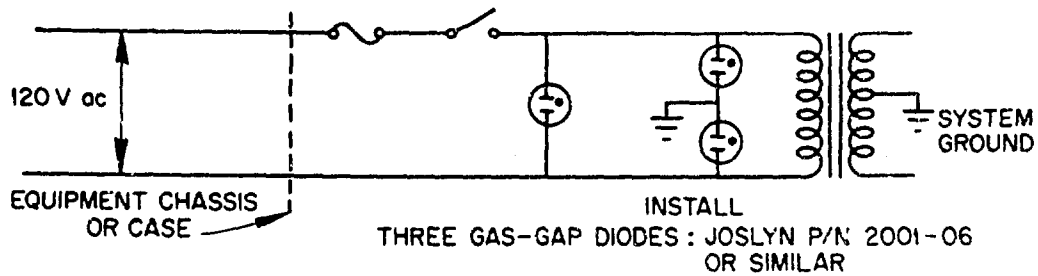
(a) POWER LINE TRANSIENT PROTECTION FOR EQUIPMENT WITH TWO--WIRE POWER CABLES
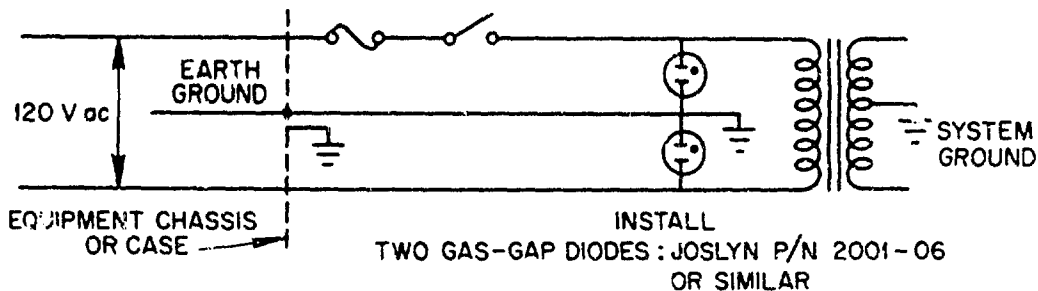
(b) POWER LINE TRANSIENT PROTECTION FOR EQUIPMENT WITH THREE-WIRE POWER CABLES
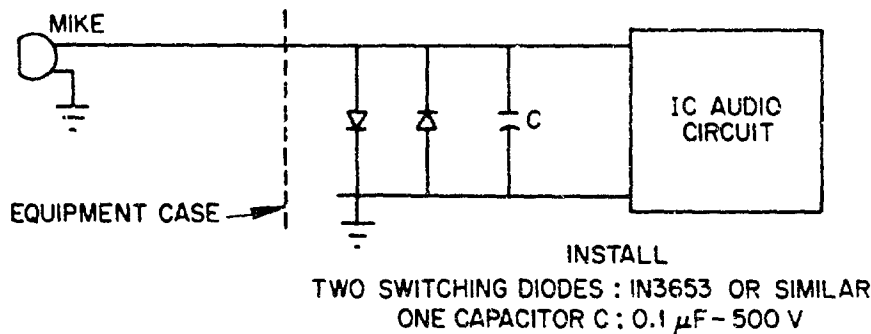
(c) MICROPHONE CABLE TRANSIENT PROTECTION FOR TRANSMITTER AUDIO IC AND FET AMPLIFIER CIRCUITS.

Fig. 7.2. Recommended Surge Protection Circuits for Communications Equipment.

We recommend that these protection circuits be employed on all communications equipment connected to commercial power even though these circuits have not been experimentally verified. Equipment such as the primary remote control consoles, local and remote base transmitter-receiver units, repeater stations, and walkie-talkie battery chargers should be protected. In addition to installing protection at the power input of each piece of equipment, we strongly recommend that fast response gas-diodes with at least a 10 kA current rating be installed at the switch box where the commercial power enters the buildings or the sections of the buildings where the communications equipment is located. The diodes should be connected between each 120 V line and ground.

It is possible that 60 Hz power "follow-on" for the first half-cycle after the diode has fired could cause the equipment's power fuse to blow. Therefore, we recommend that extra fuses be kept handy. Power follow-on will not likely cause the commercial power line fuses to open.

7.4 THE MICROPHONE CORD

Transmitter audio amplifier circuits employing integrated circuits or sensitive FET's should be protected against the EMP energy collected by the microphone cord. For some delicate IC's this is a difficult task. We cautiously recommend the surge protection circuit shown in Fig. 7.2c for FET and IC audio circuits. However, the surge attenuation of this circuit may not be sufficient to protect some IC's that are very sensitive to voltage transients, i.e., IC's that can be damaged by several volts above the normal values. To protect such delicate IC's, additional effort will likely be required.

The protection circuit shown in Fig. 7.2c may have to be modified for the particular audio circuit being protected. The added capacitor C may reduce the audio signal supplied to the amplifier circuit and thus degrade the transmitter. If so, the value of the capacitor should be reduced but kept as large as possible without degrading the system. Also, the switching diodes will not work in the circuit if the bias voltage at the microphone cord input is 0.6 V or greater. This problem can be solved by connecting the switching diodes to ground through a capacitor. The value of the capacitor should be about 0.5 to 1 μf with

a voltage rating of 500 V. Another solution to this problem is to replace the switching diodes by a Zener diode with a Zener voltage rating greater than the bias voltage. The Zener diode should have a pulse current capability of several hundred amperes for a duration of about a millisecond.

7.5 CONTROL LINKS

The protection of radio frequency electromagnetic links has been covered in Section 7.2. Microwave links appear to have a high probability of damage to the EMP's with directions of incidences that couple the maximum energy to the antennas. However, microwave aperture antennas are highly directive and the probability of damage to a particular microwave link is a function of the orientation of the link with respect to the probable EMP sources. Since the probability of damage to microwave links is likely low for many of the radio communication systems available for civil defense operations, protection for microwave links is not covered in this report.

To protect communications equipment from the EMP energy collected by telephone line control links, gas-gap diodes can be installed between each line and earth-ground by the telephone company. The telephone company provides gas-gap diodes, called gas-tube protectors, etc., on lines that have a history of lightning problems. It is recommended that these protectors be installed on the line side of all line transformers of the primary and secondary or locally remote control consoles, repeaters and remote control chassis. These protectors, along with any surge suppressor circuits on the equipment side of the transformers, should significantly reduce the probability of damage to communications equipment. It should be pointed out, however, that the probability of damage to the telephone facilities was not considered in this effort, thus protection recommendations for the telephone relay, switching, etc. circuits should be determined through other investigations.

7.6 EMERGENCY PREPARATIONS

State and local civil defense emergency operating centers, police and fire departments, emergency rescue organizations, and other important elements of civil defense should prepare against the EMP threat. EMP protective measures will also provide good protection against lightning surges.

The emergency preparations we recommend are relatively low-cost and simple. These preparations can be classified into two types: preventative measures and emergency operating procedures. Emergency operating procedures are actions that can be taken, providing the preparations have been accomplished, to further ensure that communications will be maintained. And the preventative measures are the use of the EMP protective devices and techniques described in this report. The preventative measures include:

1. Install EMP protective devices at the antennas, commercial power source, and the telephone line POE's as described in this chapter.

2. Install an EMP protective circuit at the microphone cord POE if FET's and/or IC's are used in the transmit audio circuit.

3. Ensure that a low impedance ground system is available to gas-gap diode protectors, particularly at the equipment's antenna input connector and at the main switch box where commercial power enters the building. Also, the antenna tower and feedline shield should be well grounded.

4. Keep equipment and building fuses handy.

5. If a shielded room is available, locate the communications equipment within the shielded enclosure and install surge protectors on all wires entering the room.

6. Locate the communications equipment at least 10 feet from long conducting structures to minimize indirect coupling. This rule should also be applied to the antenna feedline and telephone control link if possible.

7. Use equipment housed in a metal case when possible for better protection against direct coupling.

Some emergency operating procedures include:

1. Switch to auxiliary power, if available, as soon as the threat of a nuclear attack is known.

2. If protected equipment fails to operate, check for blown fuses.

3. If the equipment is damaged, instruct the repairmen that semiconductors in the receiver RF stage and the power supply may be "burned out."

4. If the normal control/base station communications equipment is damaged, set up emergency auxiliary station.

An emergency auxiliary base station can consist of a base station transmitter-receiver unit and a roof-mounted antenna. The transmitter-receiver unit can be an old secondhand set. It should have EMP protective devices installed and be stored with the microphone cord and, if applicable, the power cord disconnected. The antenna may be a whip or gain antenna; the antenna's feedline should be grounded when not in use. If the department or organization is planning to upgrade its communications equipment, consideration should be given to retaining any old local base station equipment for an emergency back-up station. An auxiliary battery/inverter power system should be maintained for the back-up unit if generator power is not available.

An emergency auxiliary base station can also be set up by employing a mobile unit. The mobile unit in a simplex system performs as a relay station. Communications between the dispatch station and the mobile relay unit can be accomplished by the use of battery powered direct-line telephones. Some experimentation may be required to determine a good location for the mobile relay such that adequate communications coverage is obtained.

A rough estimate of the cost of providing EMP protection and emergency operating equipment to a police repeater station communications system with simplex/duplex mobile units is presented below:

No.	Item	Cost
1	Hybrid diode-coaxial tee protector for repeater antenna	$ 50.00
2	Installation charge for No. 1	15.00
3	Commercial power surge protection for the repeater station[a] (4 gas-gap diodes)	8.00
4	Commercial power surge protection for the remote control console station	8.00
5	Installation charge for No. 3 and No. 4	34.00
6	Coaxial-tee gas-gap diode protectors for 5 mobile units	150.00
7	Installation charge for No. 6	5.00

8	Used duplex base station back-up unit	300.00
9	Coaxial tee protector for back-up unit	35.00
10	Roof-top 3 dB gain antenna, installed	60.00
11	Battery powered phones for mobile relay	15.00
12	Telephone control line protection	no charge
		$ 680.00

----

[a] Two gas-gap diodes for the repeater unit and two diodes for the main switch box.

The cost of protecting the base station equipment is about $115.00. This assumes that the station already has a low impedance ground system and standard lightning protection on the antenna. The total cost of the emergency preparedness is about $700.00, including a low-cost back-up communications system. This is only a small amount of the total investment in the radio communications system required to save life and property during local emergencies and nuclear crisis.

CHAPTER VIII
SUMMARY

The two-way radio communications available for civil defense activities at the state and local levels are those used by government and business in the land mobile class as well as those used by private individuals in the citizen's band and amateur classes. Four two-way radio communications systems have been considered in this study; namely, the local base station, remote base station, and repeater station systems and systems with extended remote control consoles. All or most of the two-way radio communications networks consist of combinations of these four systems.

The EMP from a high-altitude nuclear detonation will induce voltage and current transients in electrical conductors associated with the communications systems. Four representative EMP's were considered in this study: Pulse A, a long pulse with a large amplitude; Pulse B, a long pulse with a moderate amplitude; Pulse C, a short pulse with a large amplitude; and Pulse D, a short pulse with a moderate amplitude. Of the four pulses, Pulse A induces the largest current surge in power and telephone lines and in RACES HF antennas. And Pulse C induces the largest current and voltage transients in CB, VHF, and UHF antennas.

The EMP-induced surges in antennas, power lines, telephone control lines, and inter-connecting wires will couple to communications equipment. These surges may damage some electronic components and cause communication systems to malfunction or fail. Of the four communications systems considered in this study, the Local base station system is the least vulnerable to the EMP. The remote base and repeater station systems have about the same vulnerability to the EMP, whereas systems with extended locally remote control console units without transient protection have increased vulnerability compared to systems without extended remote control.

Communications equipment and systems can be categorized according to the nature and probability of damage they will suffer by the EMP. Solid state equipment will likely have damaged semiconductor components. HF, CB, and VHF low-band units may have tuning circuits damaged by the EMP-induced high voltage transients. Fixed station units will likely

have some damages inflicted on the power supply circuit by the EMP-induced surges on the power lines.

Communication systems can be classified according to their probability of failure by: (1) the frequency band of operation, (2) the active electronic components, (3) the use of RF overload protection, (4) the antenna gain, and (5) the type of control link employed, if applicable. In general, the lower the carrier frequency within the range 3 to 450 MHz, the higher the probability of failure. The more vulnerable the active devices used in the receiver RF, transmit audio, line amplifier, power supply, etc. stages of the various equipment in the system, the higher the probability of failure. In order of increasing vulnerability, the active components used in communications equipment are: tubes, transistors, FET's, and IC's.

The probability of failure is lower for receivers with RF surge suppressor circuits than those units without protection. Communication systems that employ high gain antennas have a higher probability of failure than those that use unity gain antennas. The higher the gain, the higher the probability of failure. And systems that employ lightning-protected telephone control lines have a lower probability of failure than systems that use a 75 MHz RF control link which is unprotected against EMP. This is based on the assumption that the telephone facilities will not be damaged.

The probability of failure of typical communication systems without EMP protection is listed below:

Frequency Band	Active Components	Probability of Failure
HF (RACES 3.997 MHz)	Tube	Moderate to High
VHF - low band	Tube & Transistors	Moderate to High
VHF - high band	Solid State	Moderate
UHF	Solid State	Low to Moderate

The probability of failure of communications systems can be significantly decreased for both lightning and EMP surges by the addition of EMP protection. This protection is low-cost and easy to install. Furthermore, the probability of system failure can be decreased to near

zero with tolerable degradation by the use of both EMP protection and emergency back-up communications equipment.

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APPENDIX A

FRONT END SCHEMATIC DIAGRAMS

The following figures show the front end schematic diagrams for some circuits commonly used in communications equipment. The type of equipment in the figures are listed below.

Figure	Equipment
A-1	Typical VHF low-band receivers
A-2	Modern VHF low-band receiver
A-3	Typical UHF high-band receivers
A-4	Typical VHF high-band receivers
A-5	UHF receivers
A-6	RF Preamplifiers
A-7	Walkie Talkies
A-8	Citizeh's and Amateur band receivers

ORNL-DWG 73-6250
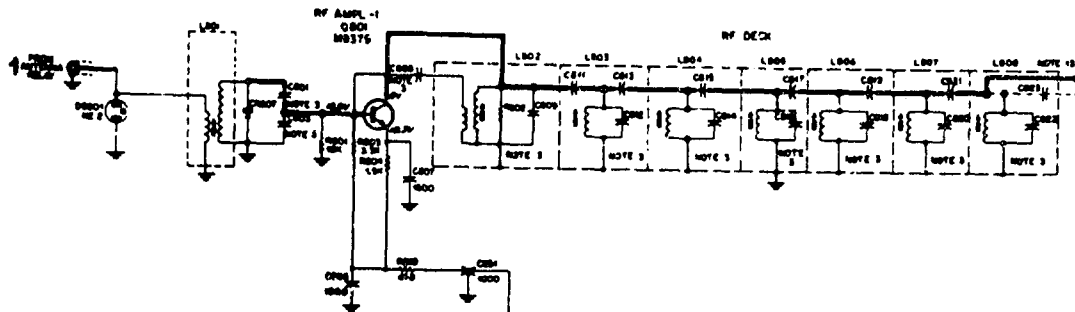
(*a*) MOTOROLA MOTRAC

(*b*) RCA SERIES 700

Fig. A-1. VHF Low Band Receiver Front End Schematics.
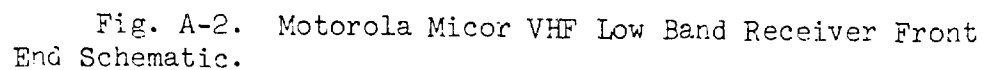
ORNL-DWG 73-6249

Fig. A-2. Motorola Micor VHF Low Band Receiver Front End Schematic.

ORNL—DWG 73—6251
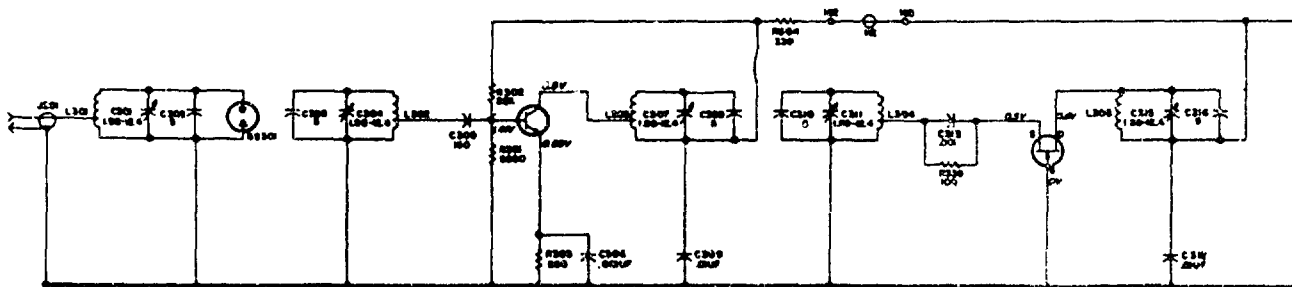
(a) G.E. MASTER PROGRESS LINE-EXECUTIVE SERIES
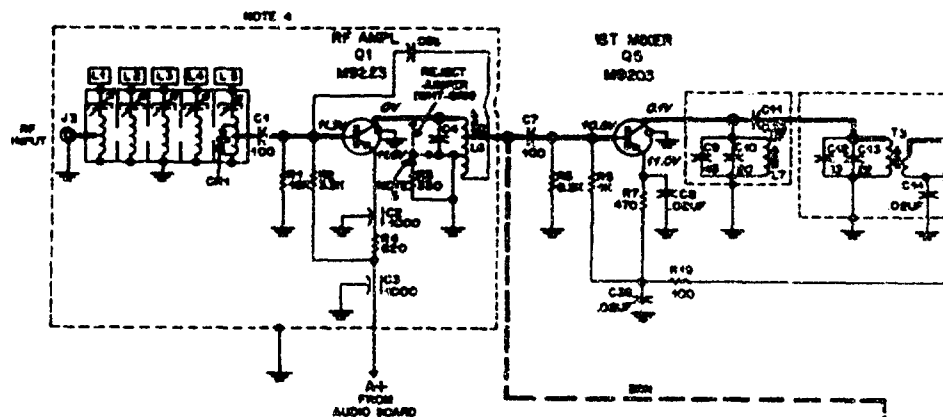
(b) MOTOROLA MOTRAC-L SERIES

Fig. A-3. VHF High Band Receiver Front End Schematics.

ORNL-DWG 73-6252
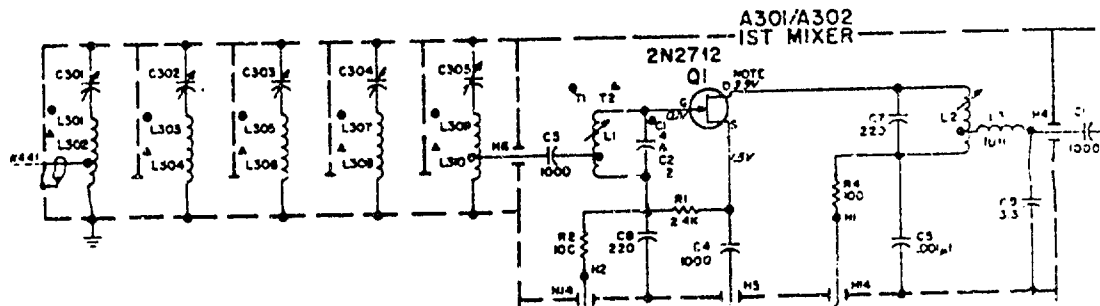
(a) G.E. MASTER-PROGRESS LINE
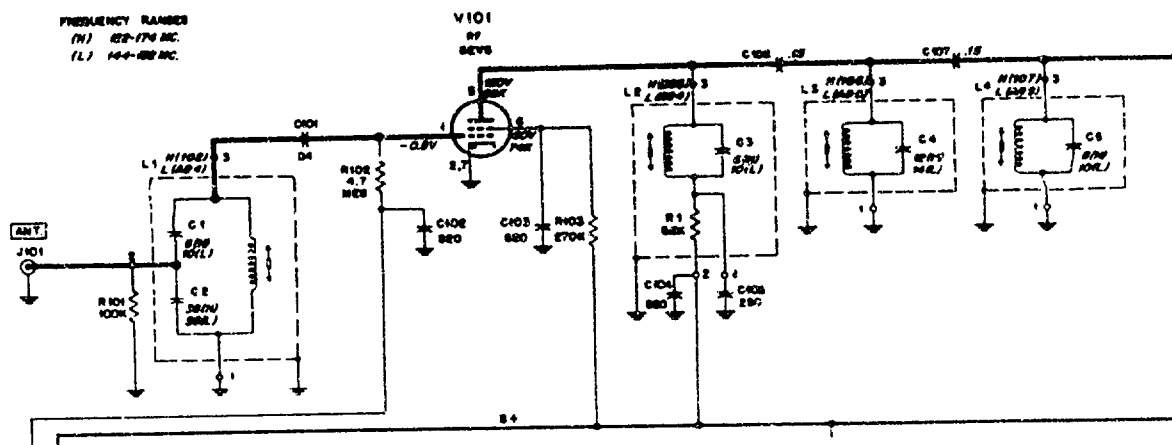
(b) RELATIVELY OLD MOTOROLA RECEIVER

Fig. A-4.   VHF High Band Receiver Front End Schematics.

152
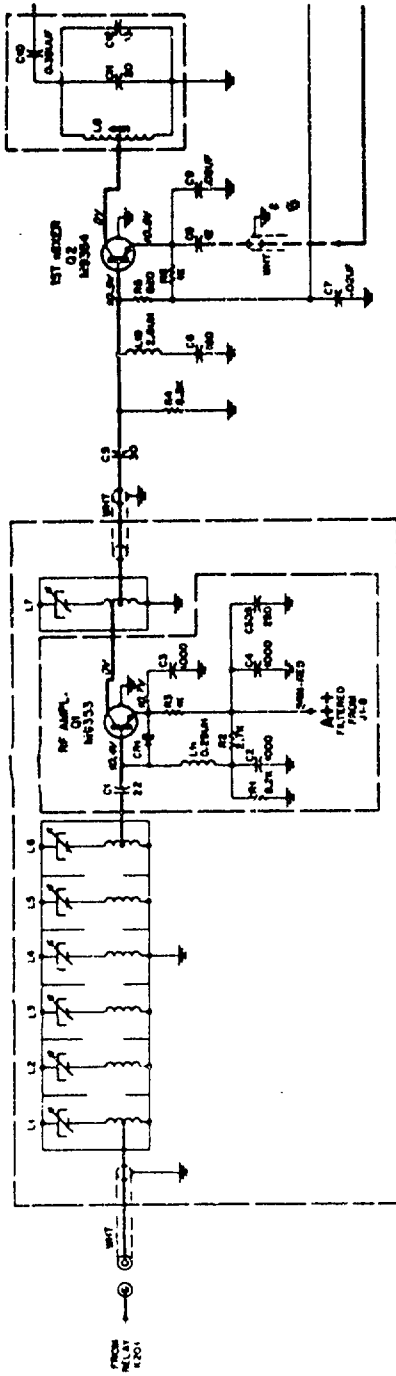
ORNL-DWG 73-6253

(a) EARLIER MODEL MOTRAC
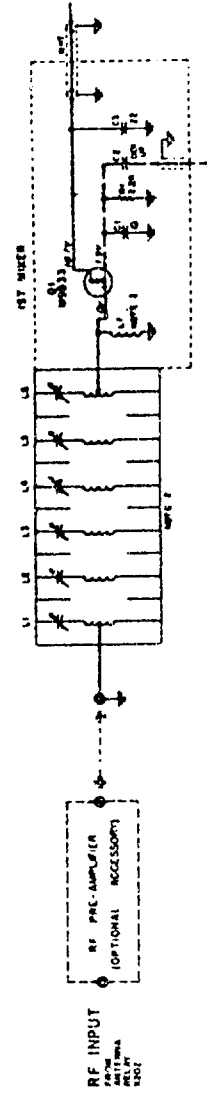
(b) LATER MODEL MOTRAC

Fig. A-5. Motorola Motrac UHF Receiver Front End Schematics.

ORNL-DWG 73-6254
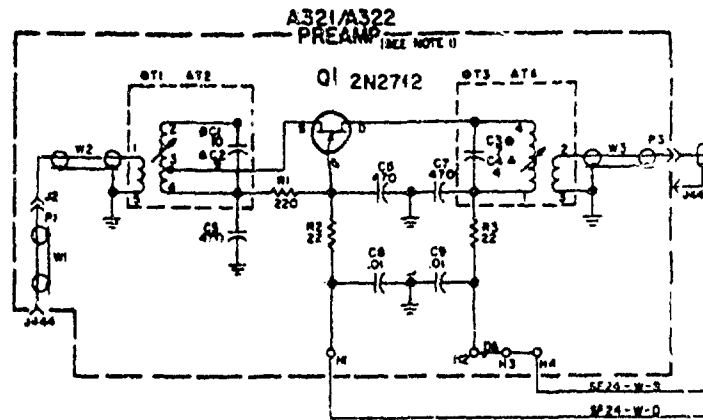
(a) G.E. VHF HIGH BAND PREAMPLIFIER
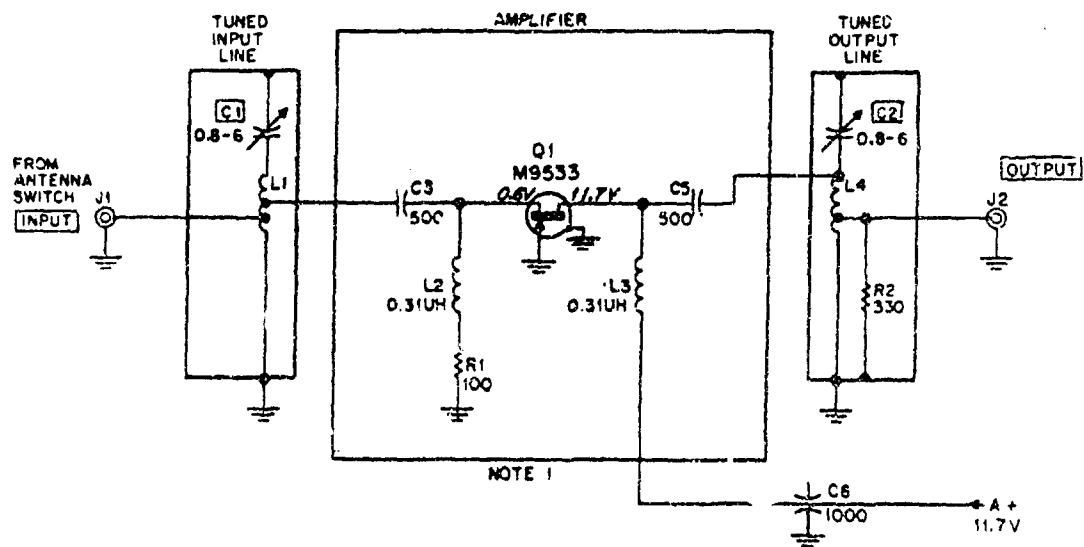
(b) MOTOROLA MOTRAC UHF PREAMPLIFIER-LATER VERSION

Fig. A-6. Radio Frequency Preamplifier Schematics.

ORNL-DWG 73-6255
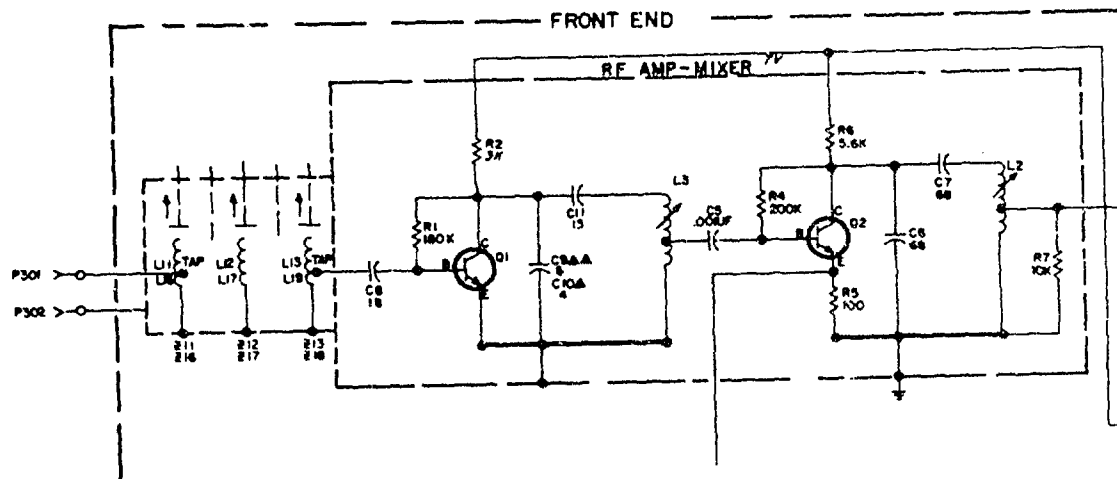
(a) G.E. UHF MASTER PROGRESS LINE-PERSONAL SERIES
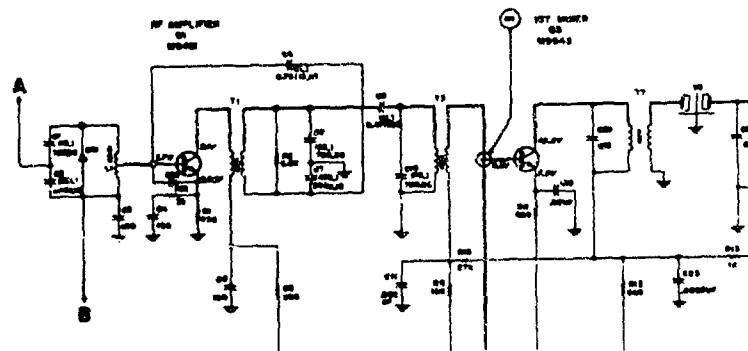
(b) MOTOROLA VHF HIGH BAND HANDIE TALKIE

Fig. A-7.   Walkie Talkie Receiver Front End Schematics.

ORNL-DWG 73-6256
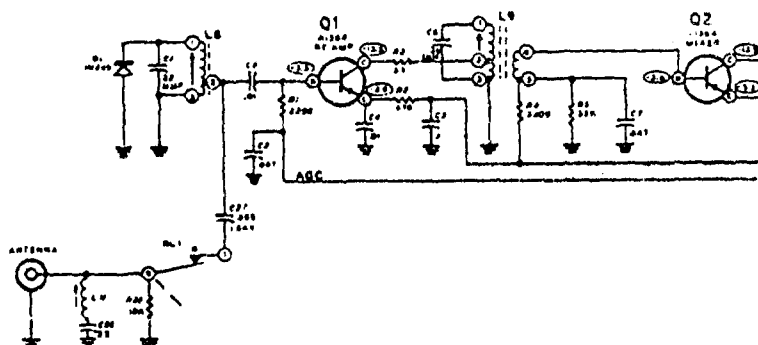
(a) CITIZEN'S BAND MOBILE UNIT

Single Sideband

(b) A TYPICAL AMATEUR RECEIVER FOR COVERAGE OF THE 80 THROUGH 6 meter BANDS

Fig. A-8. Receiver Front End Circuits for a Citizen's Band and Amateur Radio Receivers.

APPENDIX B

THE CYLINDRICAL ELECTRIC HALF-DIPOLE RESPONSE TO EMP

The following figures show the time domain responses of the cylin-
drical electric half-dipole to EMP's A and C. Pulse A is the long EMP and
Pulse C is the short EMP defined in Chapter I. The magnetic fields of
the EMP's are polarized perpendicular to the axis of the antennas. The
direction of incidence of the EMP's is the direction that the maximum
response is obtained. If the antennas are mounted on a perfect ground
plane of infinite size, the direction of incidence is broadside to the
antennas. If the antennas are mounted on a perfectly conducting ground
plane of finite size, the direction of incidence that induces a maximum
response is not broadside, but is on the order of 20° to 30° off broad-
side, i.e., the angle of incidence is about 70° measure from the axis of
the antenna. The exact angle depends on the electrical and physical
properties of the ground plane.

A list of the figures that follow is given below:

Figure	Antenna Response
B-1	50 ohm load current for a 40 MHz antenna
B-2	50 ohm load current for a 75 MHz antenna
B-3	50 ohm load current for a 158.5 MHz antenna
B-4	Short circuit current for a 20-m-long antenna
B-5	Short circuit current for a 3.997 MHz antenna
B-6	Short circuit current for a 27.23 MHz antenna
B-7	Short circuit current for a 40 MHz antenna
B-8	Short circuit current for a 75 MHz antenna
B-9	Short circuit current for a 150 MHz antenna
B-10	Short circuit current for a 158.5 MHz antenna
B-11	Short circuit current for a 450 MHz antenna
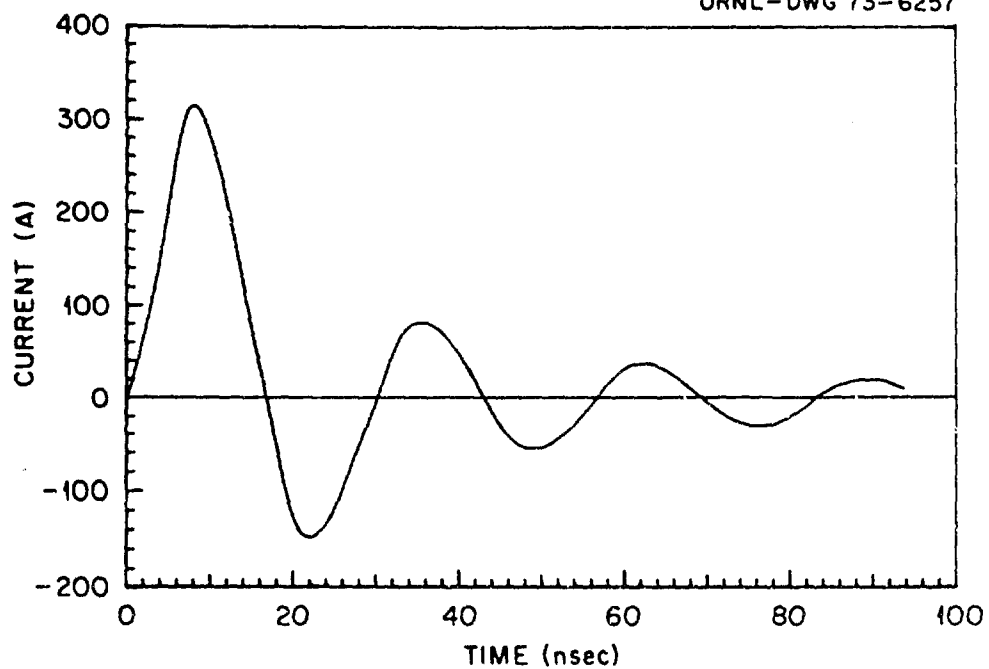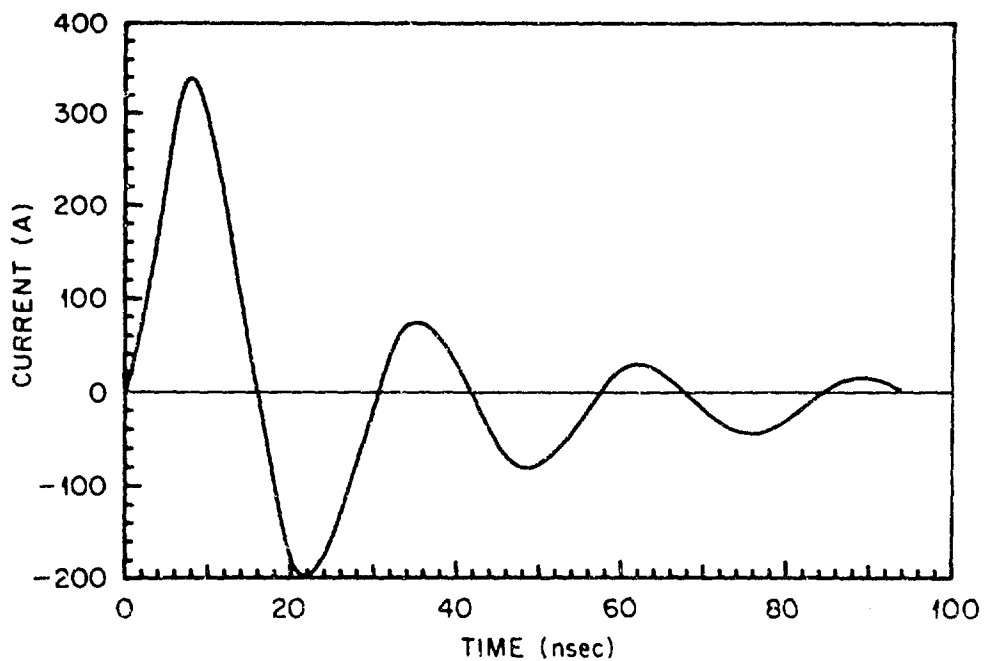
Fig. B-1. Current Through a 50 ohm Load When a 40 MHz Half-Dipole is Illuminated by Representative EMP.

ORNL-DWG 73-6258
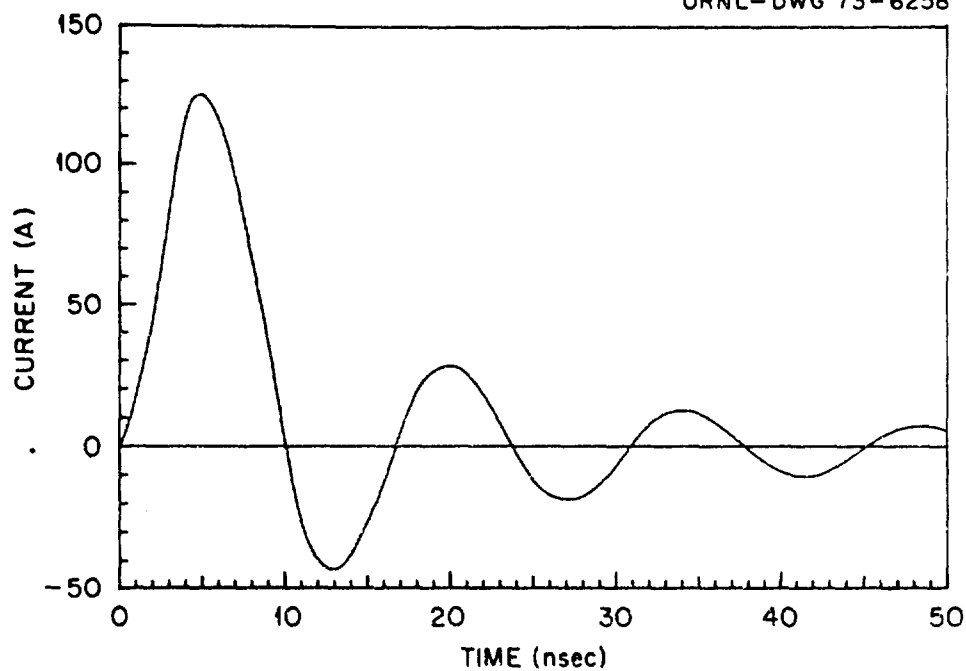
(*a*) RESPONSE TO PULSE A.
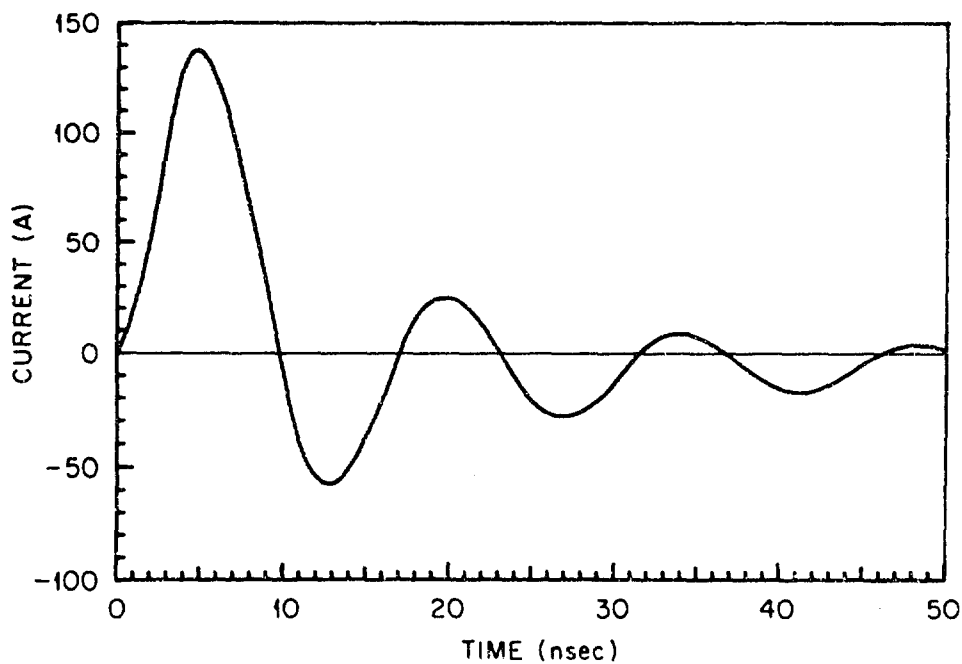
(*b*) RESPONSE TO PULSE C.

Fig. B-2. Current Through a 50 ohm Load when a 75 MHz Half-Dipole is Illuminated by Representative EMP.
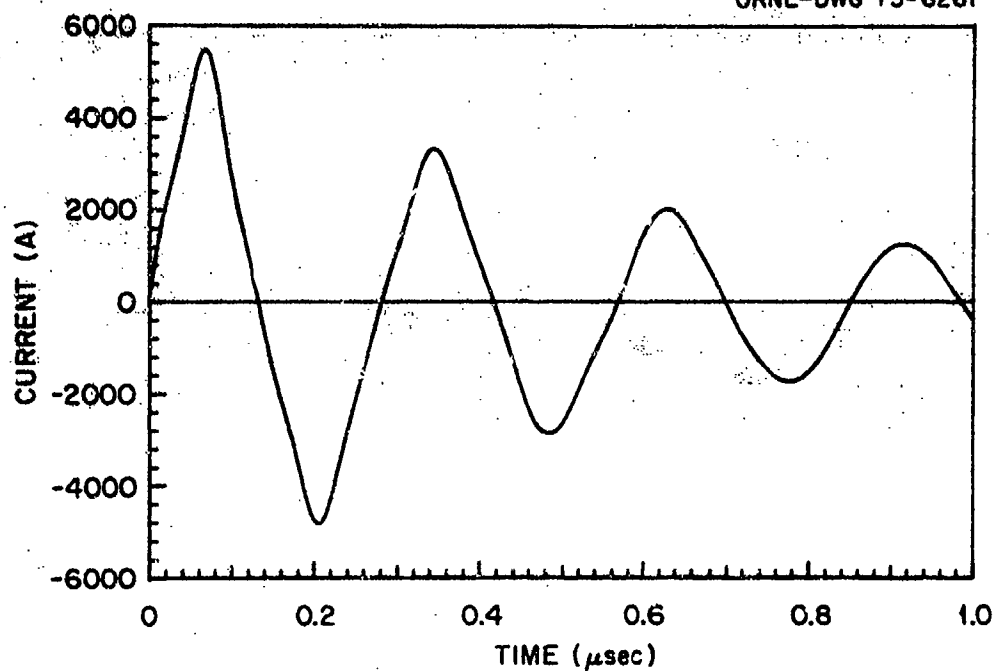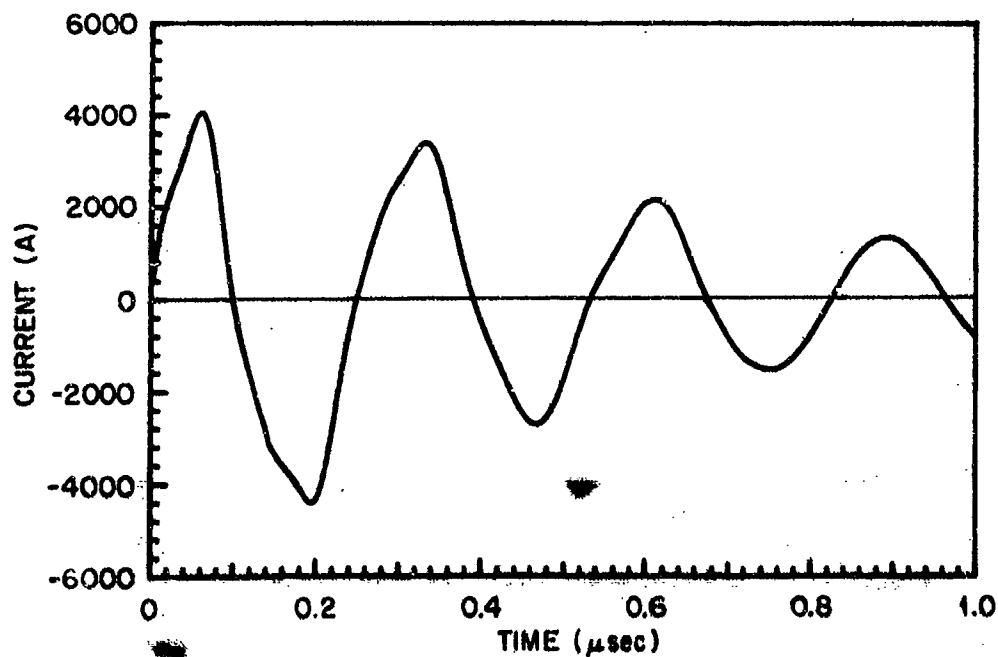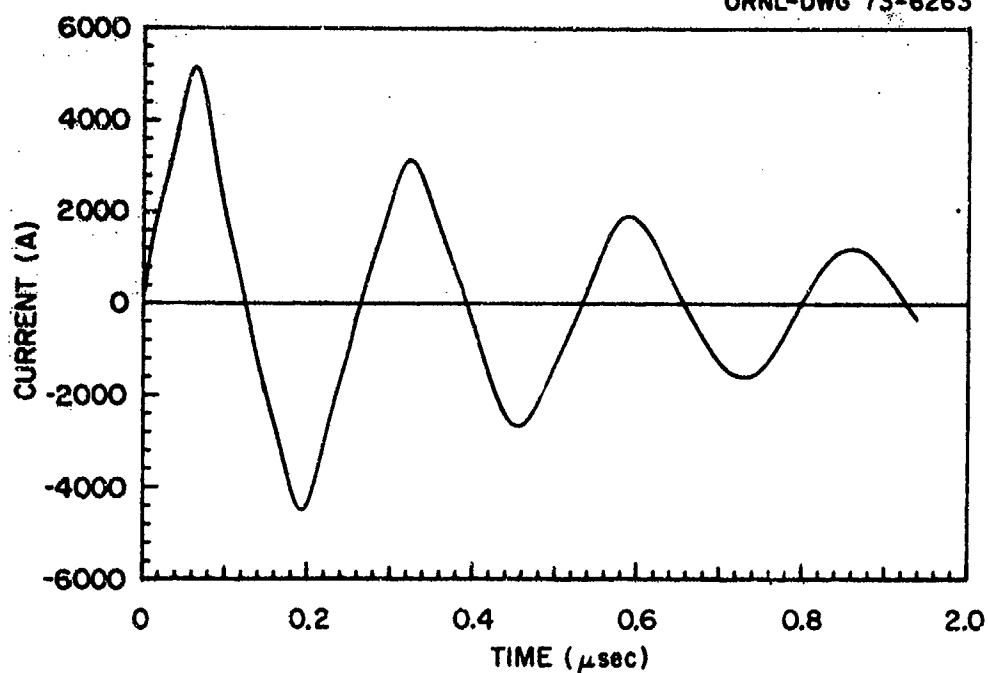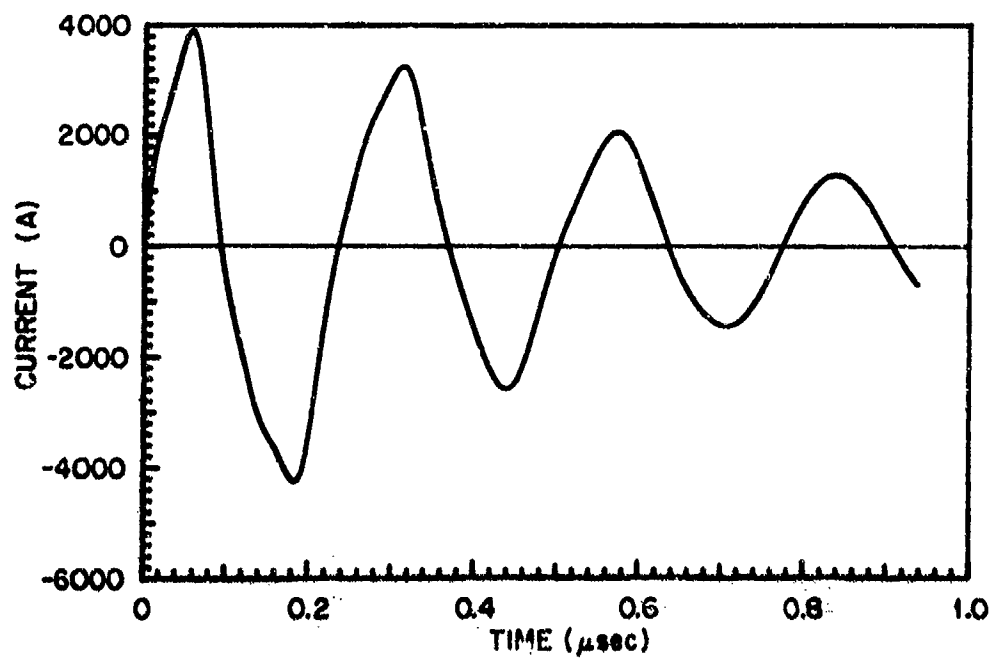
ORNL-DWG 73-6259
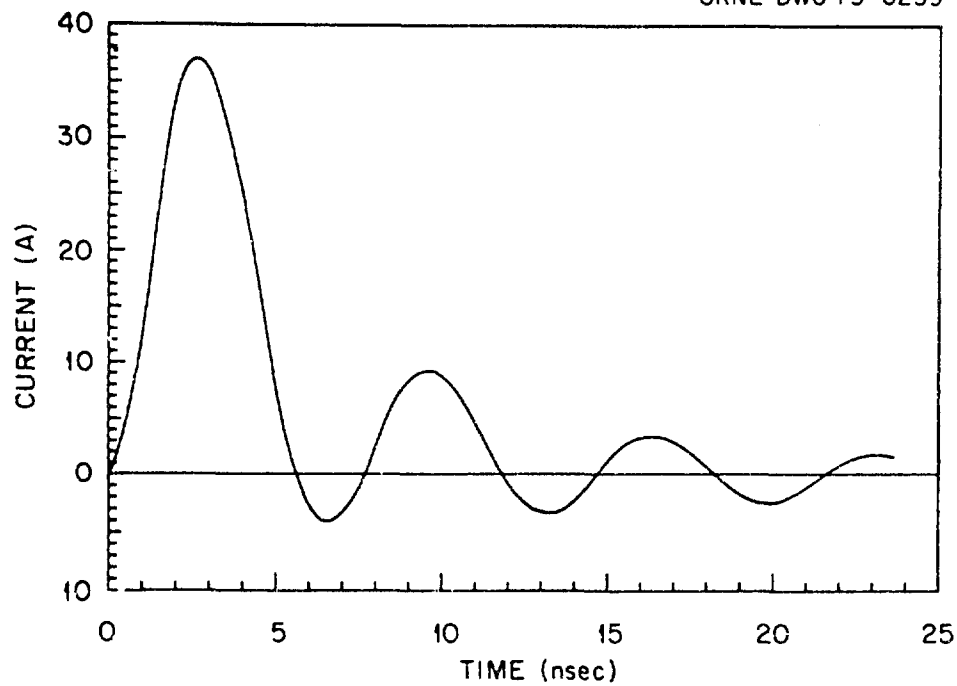
(a) RESPONSE TO PULSE A
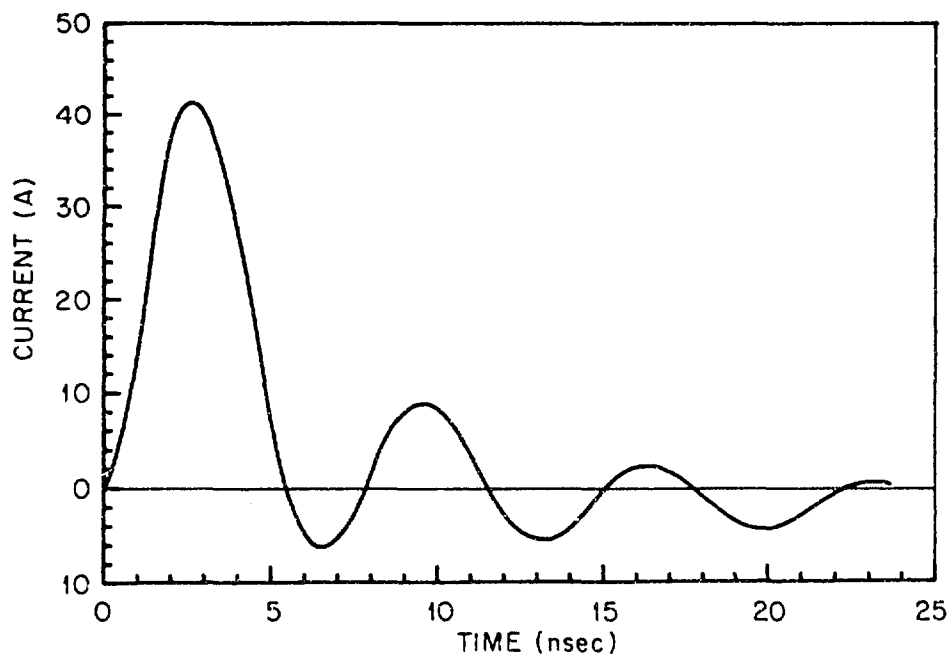
(b) RESPONSE TO PULSE C

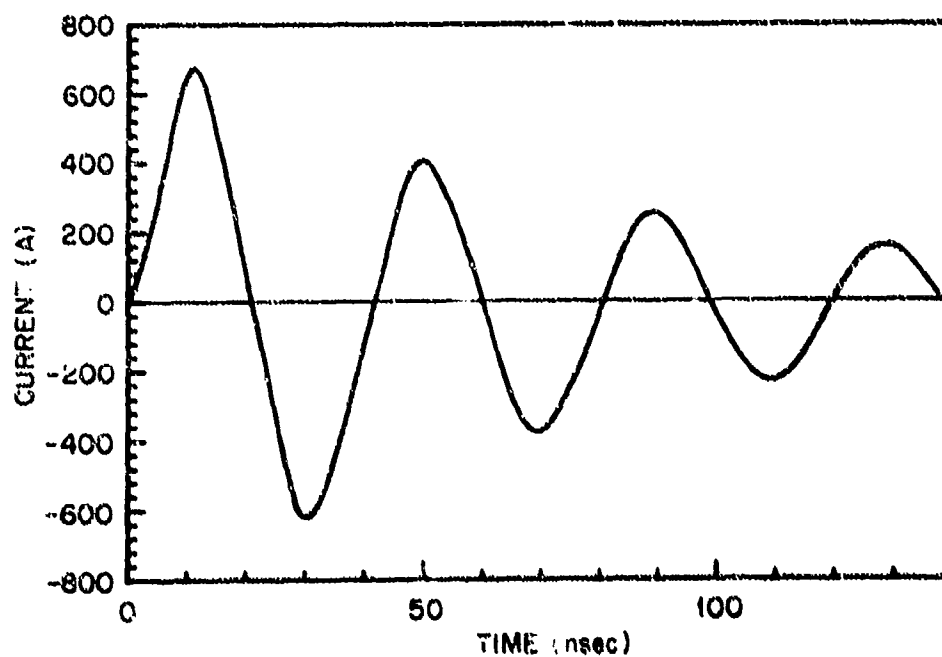Fig. B-3. Current Through a 50 ohm Load when a 158.5 MHz Monopole is Illuminated by Representative EMP.
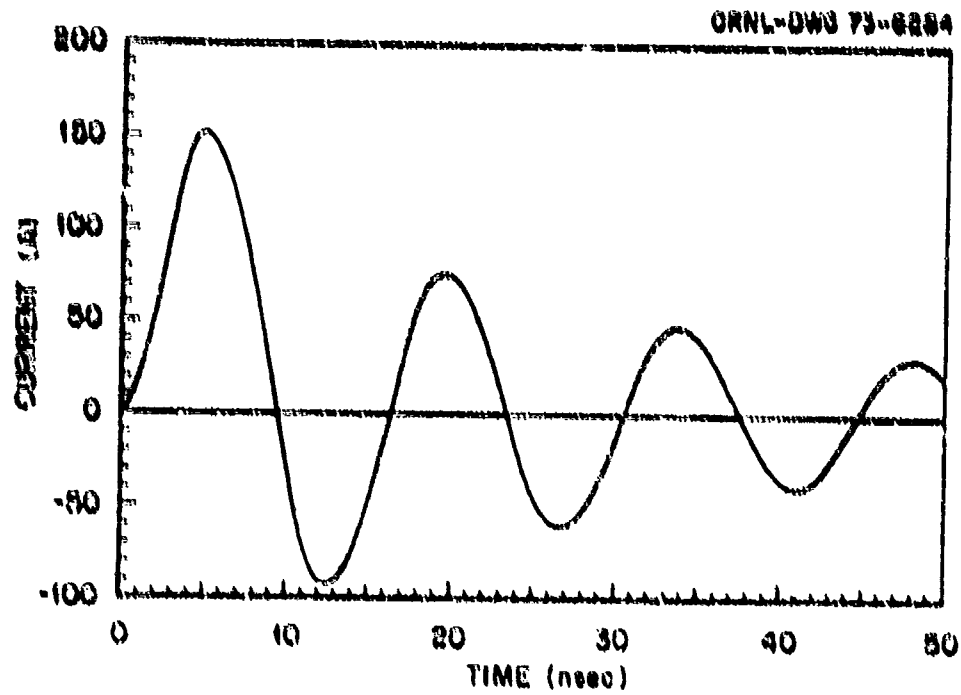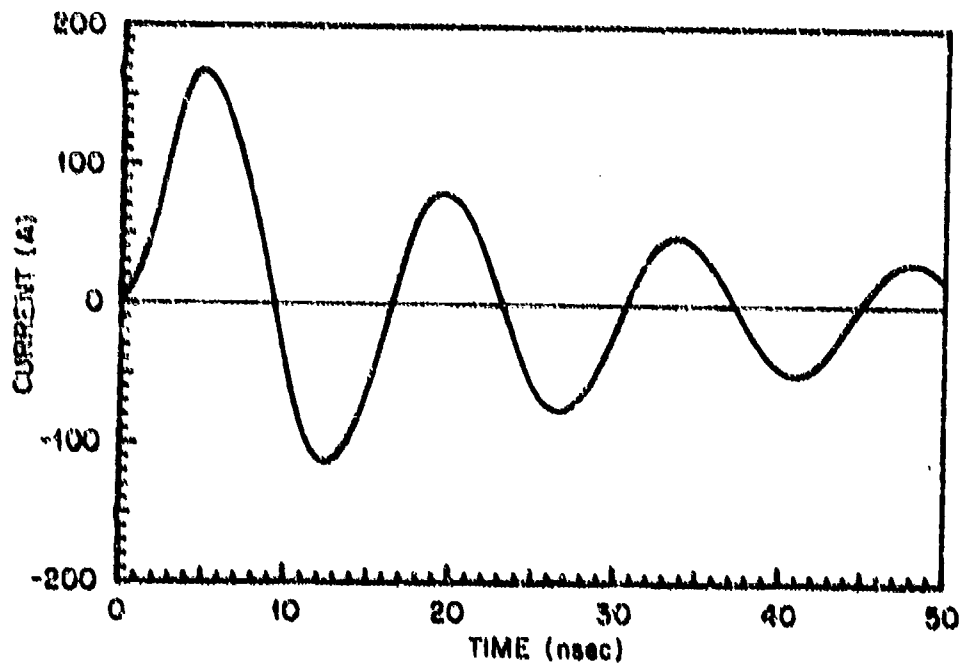
ORNL-DWG 73-6261

(a) RESPONSE TO PULSE A

(b) RESPONSE TO PULSE C

Fig. B-4. Short Circuit Antenna Current when a 20-Meter-Long Half-Dipole is Illuminated by Representative EMP.

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ORNL-DWG 73-6263

(*a*) RESPONSE TO PULSE A

(*b*) RESPONSE TO PULSE C

Fig. B-5. Short Circuit Current when a 3.997 MHz
Half-Dipole is Illuminated by Representative EMP.
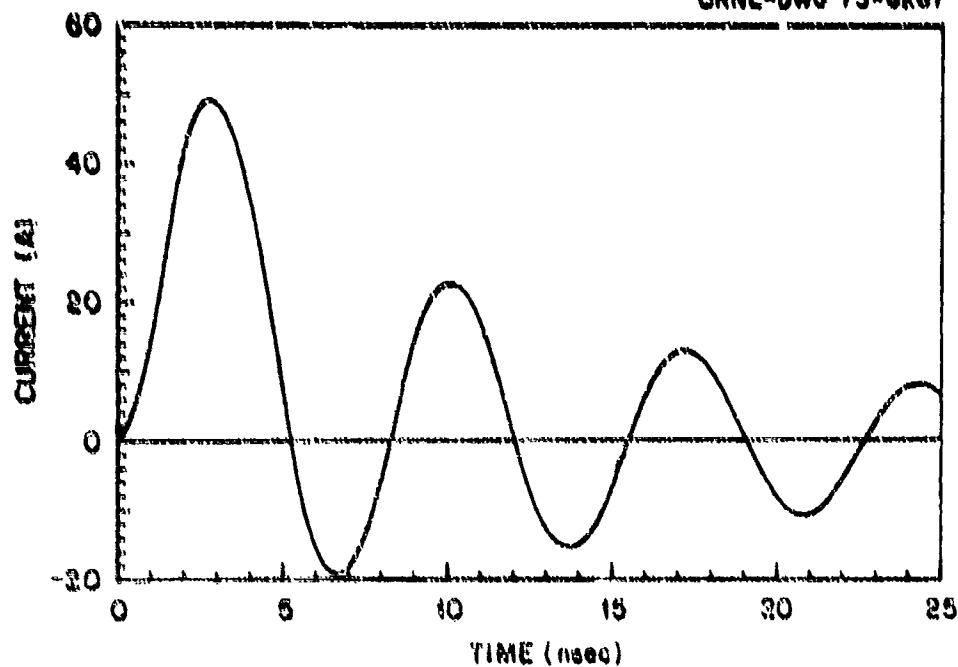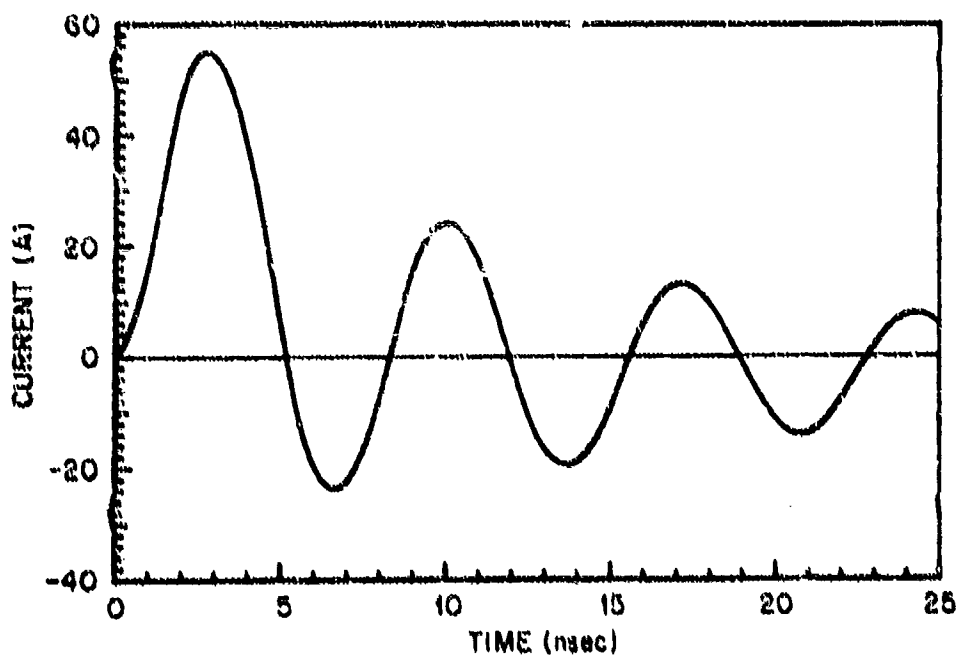
ORNL-DWG 73-6263
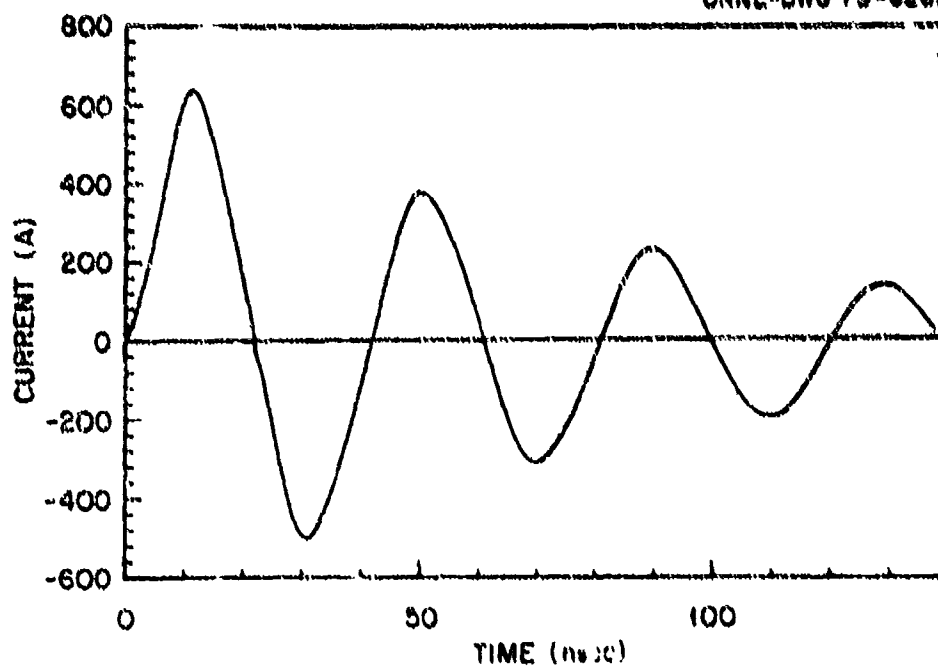
(a) RESPONSE TO PULSE A

(b) RESPONSE TO PULSE C

Fig. B-6.   Short Circuit Antenna Current when a 27.23 MHz
Monopole is Illuminated by Representative EMP.
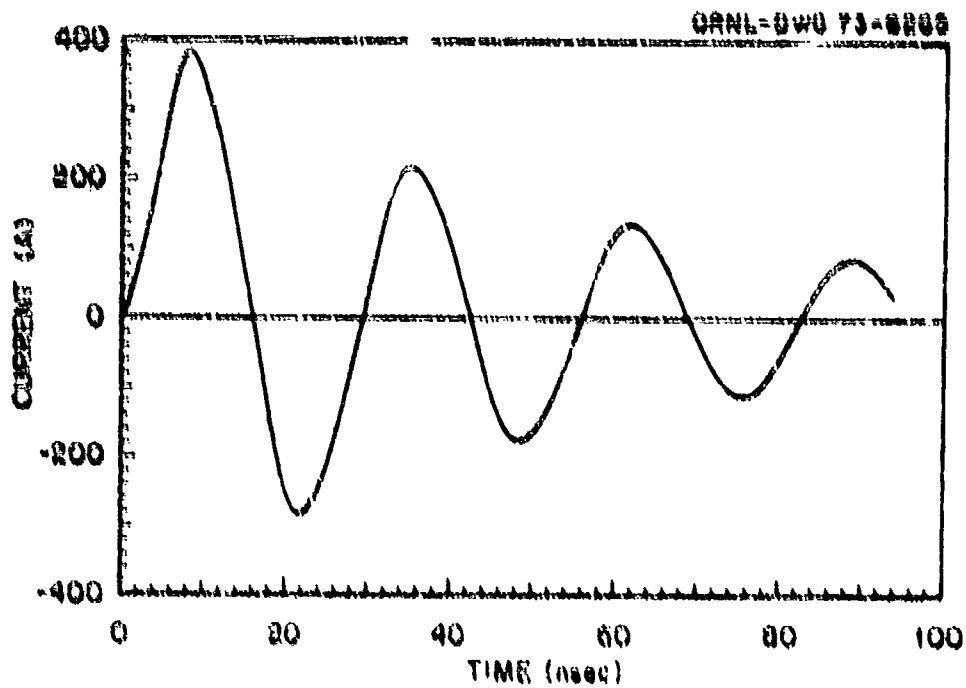
Fig. B-7. Short Circuit Antenna Current when a 40 MHz Half-Dipole is Illuminated by Representative EMP.

(a) RESPONSE TO PULSE A

(b) RESPONSE TO PULSE C

Fig. B-8. Short Circuit Antenna Current when a 75 MHz
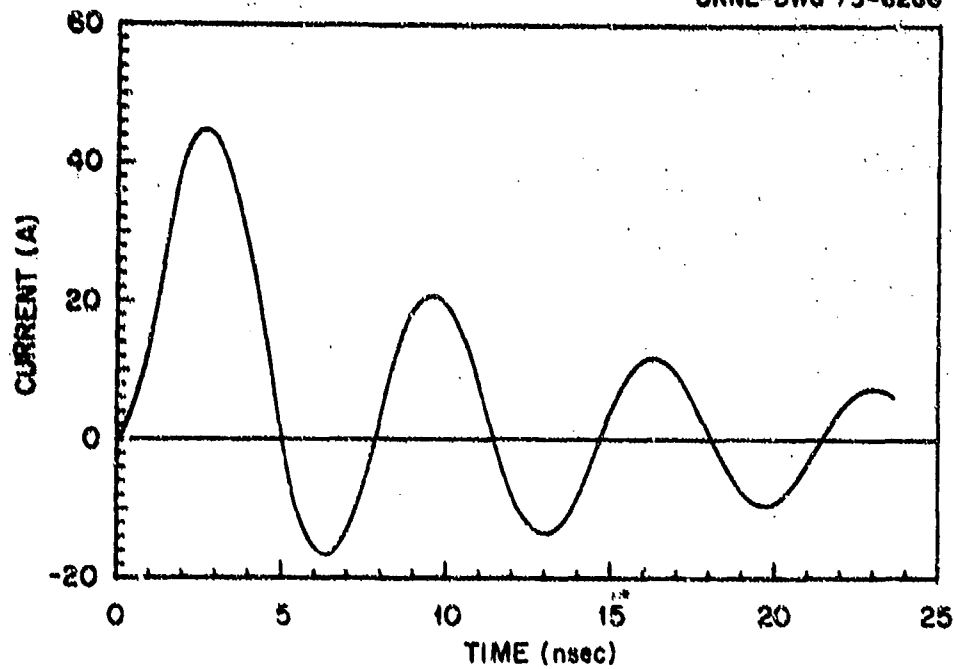Half-Dipole is Illuminated by Representative EMP.

ORNL-DWG 73-6R67
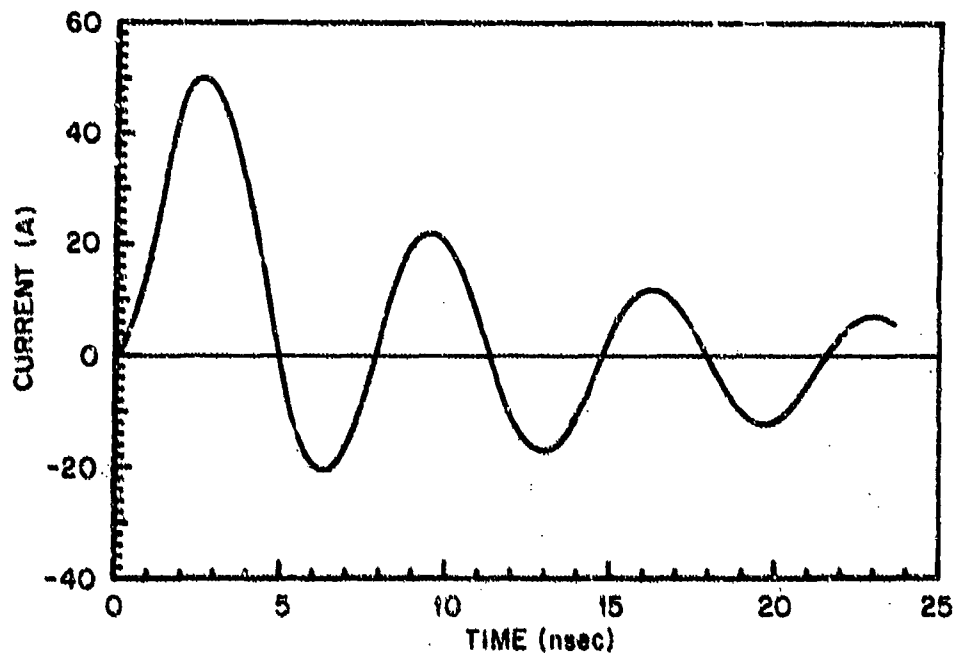
(a) RESPONSE TO PULSE A

(b) RESPONSE TO PULSE C

Fig. B-9. Short Circuit Antenna Current when a 150 MHz
Half-Dipole is Illuminated by Representative EMP.
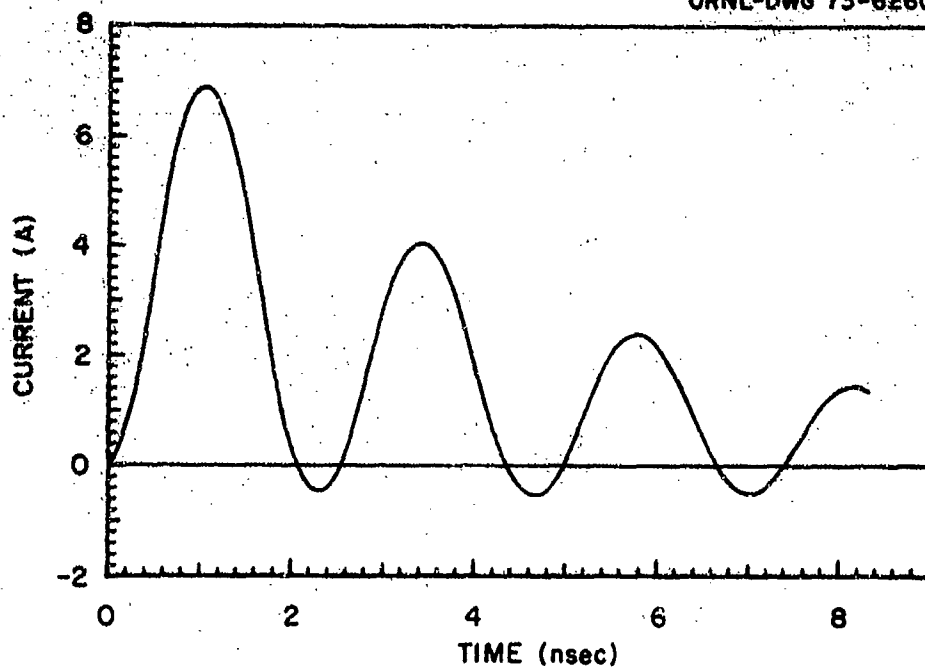
ORNL-DWG 73-6266

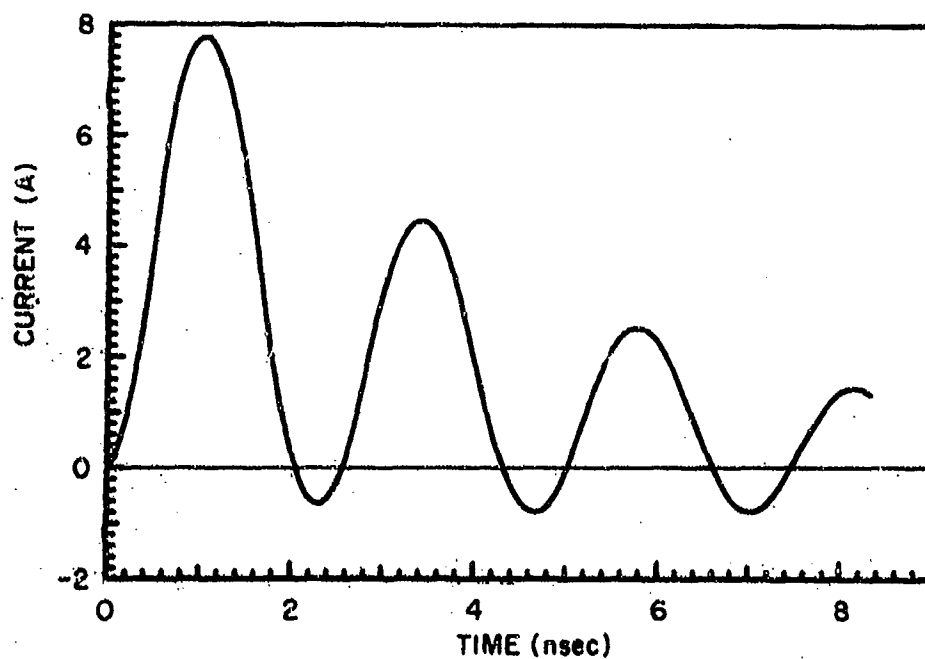(a) RESPONSE TO PULSE A

(b) RESPONSE TO PULSE C

Fig. B-10. Short Circuit Antenna Current when a 158.5 MHz Half-Dipole is Illuminated by Representative EMP.

ORNL-DWG 73-6260

(a) RESPONSE TO PULSE A

(b) RESPONSE TO PULSE C

Fig. B-11. Short Circuit Antenna Current when a 450 MHz
Monopole is Illuminated by Representative EMP.

REFERENCES

1. J. E. Bridges and J. Weyer, EMP Threat and Counter Measures for Civil Defense, Office of Civil Defense (1968).

2. D. B. Nelson, "EMP Impact on U.S. Defenses," Survive, 2(6), Nov-Dec 1969 (U).

3. J. K. Baird, J. H. Marable, and D. B. Nelson, "Studies of Nuclear Electromagnetic Pulse (EMP) Effects on Power Systems," Annual Progress Report Civil Defense Research Project, March 1971-March 1972, ORNL-4784. (U)

4. A. M. Wiegand, C. A. Hall, Jr., and R. W. Strunk, Optimum Utilization of Government and Non-Government Communications Resources, Oct. 1971, SRI Project 6300-730 prepared for the Office of Civil Defense.

5. J. A. Russell, Private communications on the Types of Two-Way Radio Communications Systems, 25 July 1972.

6. P. W. Arnold and C. R. Allen, "Some Ideas in a Ham-Band Receiver," Single Sideband, 1965, pp. 181-188.

7. Henry Jasik, Editor, Antenna Engineering Handbook, McGraw-Hill, Inc., 1961, Chaps. 3 and 22.

8. Paul R. Barnes, The Analysis and Simulation of the Electric Cylindrical Dipole Antenna Response to EMP, ORNL-TM-4086, August, 1973.

9. Carl E. Baum, Interaction Note 88, "On the Singularity Expansion Method for the Solution of Electromagnetic Interaction Problems," published at the Air Force Weapons Laboratory, December 1971.

10. James H. Marable, James K. Baird, and David B. Nelson, Effects of Electromagnetic Pulse (EMP) on a Power System, ORNL-4836, December 1972.

11. Edward F. Vance and Gerald August, "Preliminary Analysis of the WS-133 AM Launch Facility Power-System Response to EMP," SRI Technical Report 3, prepared for AFWL under contract F29601-69-C-0127, October 1970, Appendix B (U).

12. Allan Greenwood, Electrical Transients in Power Systems, Wiley-Interscience, 1971, p. 291.

13. P. P. Toulios et al., Effects of EMP Environment on Military Systems, IIT Research Institute, Final Report, Vol. I, for U.S. Army contract DAAK02-68-C-0377, February 1969, Appendix G.

14. M. I. Sancer and A. D. Varvatsis, "Electromagnetic Penetrability of Perfectly Conducting Bodies Containing an Aperture," Interaction Note 49, published at the Air Force Weapons Laboratory, August 1970.

15. Paul R. Barnes, "The Axial Current Induced on an Infinitely Long, Perfectly Conducting, Circular Cylinder in Free Space by a Transient Electromagnetic Plane Wave," Interaction Note 64, published at the Air Force Weapons Laboratory, March 1971.

16. D. C. Wunsch, R. L. Cline, and G. R. Case, "Theoretical Estimates of Failure Levels of Selected Semiconductor Diodes and Transistors," Semiconductor Vulnerability Phase II Report, Braddock, Dunn, and McDonald, Inc., 14 August 1970.

17. EMP Protective Systems, DCPA TR-61B, July 1972.

18. S. Smandra, Electromagnetic Pulse (EMP) Hardware, IITRI, DCPA Work Unit 2213F, January 1973.