Interaction Notes

Note 159

July 1971

EFFECTS OF NUCLEAR EMP ON AM RADIO BROADCAST STATIONS IN THE EMERGENCY BROADCAST SYSTEM*

by

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ABSTRACT

The electromagnetic pulse, one of the effects of the detonation of a nuclear weapon, consists of intense transient electric and magnetic fields. The considerable energy in these fields can cause malfunction or damage of electrical and electronic equipment exposed to EMP. In this report we investigate the effects of EMP on AM broadcast stations of the Emergency Broadcast System.

This study included interviews with station personnel and other efforts to identify typical station construction and practice, as well as analytical treatments of the transients induced by EMP on station antennas and power lines. Most likely sources of damage are determined and the possibility and time requirements of effecting repairs are estimated. Station experience with lightning and a comparison of direct lightning strokes to the antenna with the EMP-caused surges are included.

Recommendations are given for measures which may reduce EMP damage or the extent of its effects. In most cases these are limited to procedures or low cost improvements. Conservative overdesign to achieve very high reliability is not currently recommended for stations participating in the EBS.

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*Research sponsored by the Defense Civil Preparedness Agency (Interagency Agreement No. OCD-PS-64-284) under Union Carbide Corporation's contract with the U.S. Atomic Energy Commission.

CHAPTER I
INTRODUCTION

1.1 OBJECTIVES OF THE STUDY

The objectives of Work Unit 2213B, under which this report was prepared, are

> "To analyze the vulnerability of the AM, FM, and TV-radio broadcast service to the electromagnetic pulse effects of a thermonuclear attack upon the United States and to prescribe countermeasures therefor."

1.2 SCOPE, METHOD, AND CONTENT

For this study we have focussed on the Emergency Broadcast System, particularly, the individual AM broadcast stations rather than the national and regional links which relay information and program material. The reasons for this are that the EBS is the vehicle for essential broadcast service during an enemy attack, and the AM stations are the only stations designated to broadcast directly to the public. The feed lines for the EBS, including broadcast networks and wire services, are leased from common carriers, chiefly AT&T. The effects of EMP on these communications channels is similar to that on many other services supplied by these carriers. Research in this general problem area of EMP effects is currently being carried out, and it was deemed unwarranted to duplicate that effort in this study report.

Similarly, we have not concentrated specifically on FM or TV stations because their role in an attack is to provide backup feeds to stations, not to broadcast to the public. In general, these transmitter sites are not equipped with fallout protection or emergency generators (unless these are co-located with the AM transmitter) and hence, are somewhat less reliable. However, many of our findings are applicable to these stations, and in Section VI we include comments addressed specifically to them.

Research for this study involved two types of effort. The first was the gathering of information on typical station practices relevant to their EMP vulnerability. This included visits to five AM broadcast stations in the

EBS plan and interviews with station engineering personnel (see Appendix). Also included in this effort were conversations with engineering personnel active in station and transmitter design or operation which further elucidated "typical" practices and configurations.

Concurrent with this effort theoretical analyses were carried out on surges induced by EMP on typical broadcasting antennas and on power lines into the stations. The effect of matching networks and lightning protection was included in this.

The representative EMP wave form used in this study for quantitative examples was determined in collaboration with other AEC and DOD installations. While not definitive, it is believed to be reasonably accurate and incorporates the best theoretical data as of mid-1969.

The areas singled out for examination - antenna, power line, and studio to transmitter links - were chosen because they represent the most likely sources of EMP damage which would be detrimental to the EBS function. Current EMP effects knowledge indicates fields penetrating directly into the transmitter will not cause any damage because of the rugged components commonly used and because of shielding and filtering normally employed to reduce RFI.

The conclusions present estimates of the likelihood of damage and components most likely to be damaged. Based on statements given by station personnel, time required to effect repairs is also given. Recommendations are included for ways to reduce damage probability. In light of current uncertainties in EMP effects and in EBS reliability requirements recommendations for additional hardware have been avoided. Rather, procedures have been stressed which could reduce EMP damage or minimize its impact.

1.3 THE NUCLEAR ELECTROMAGNETIC PULSE

The detonation of a nuclear weapon produces intense transient electric and magnetic fields. These fields are called the electromagnetic pulse (EMP). Any electrical conductor which is exposed to the EMP will have induced on it transient voltages and currents. Whether or not these transients will cause damage or malfunction depends both upon their magnitude and upon the sensitivity of components connected to the conductor. These in turn depend upon the location of the detonation point with respect to the equipment in question, and upon the electrical and mechanical details of that equipment.

The body of research results which has been accumulated during the past few years concerning EMP effects on electrical and electronic equipment indicates that under a great many circumstances damage or malfunction can result. Further this damage can occur at distances from the explosion great enough to be completely free from blast or other effects (except possibly fallout), and the areas so affected by the EMP from a single detonation can encompass hundreds of thousands of square kilometers. In particular this is true for high altitude detonations - those at an altitude greater than about fifty kilometers.

The open literature concerning the nuclear electromagnetic pulse is somewhat circumscribed, but a number of introductory references are available.[1-4] These are listed approximately in order of increasing difficulty or specialization. They discuss the phenomenology of EMP production and propagation, coupling into electrical equipment, and countermeasures which may be used to avoid damage or malfunction. They provide useful background material for the understanding of this report.

The salient features of the EMP as it relates to the stations of the Emergency Broadcast System are that it is a short but intense pulse of radiofrequency fields, broadband with a frequency sprectrum extending from almost zero hertz to up to more than one hundred Megahertz. Peak electric field strength in zero overpressure regions can be in excess of 10^4 volts/meter. By way of comparison, field strength from the transmitted radio signal at a typical 50KW transmitter in close proximity to its transmitting antenna will be one to ten volts/meter. As with other radiofrequency interference, EMP effects are reduced by shielding, filtering, bypassing, good grounding and wiring practices, etc., many of these practices being already familiar to the broadcast engineer. However, the energy content at very high frequencies, which is primarily a result of the rapid rise time of the pulse (a few tens of nanoseconds), means that inductive effects mitigate against the full effectiveness of these measures.

When picked up by structures such as large antennas or long cables, EMP can cause effects similar to those from a direct lightning stroke including exploded capacitors, crushed coils, and punctured insulation. Lightning protective measures are expected to be partially effective against these effects, but the finite ionization time of devices such as spark gaps reduces the protection afforded by them against the fast rising EMP surges.

Another factor of some importance is that one must expect many pulses at a given location, each one from a different detonation. Cumulative effects may cause damage to equipment which might survive one pulse.

Knowledge about EMP effects is not yet complete enough that inexpensive yet reliable countermeasures are routinely available. In particular it is quite difficult to assess the likelihood of damage to an existing installation. However, enough is presently known to establish that for many systems, especially power and communications, EMP is a cause for concern. Further there are methods for reducing the chance of damage which, although not foolproof, have the dual advantage of low cost and reasonable increase in protection. Except for very critical installations they are to be recommended as a first step until better information about EMP effects is available.

1.4 THE EMERGENCY BROADCAST SYSTEM

"The Emergency Broadcast System (EBS) has been devised to provide the President and the Federal Government, as well as State and local government, with means of emergency communications with the general public through nongovernment broadcast stations during and following an Emergency Action Condition. Mass communications from such sources might include, but not be limited to, messages from the President or other Federal officials and National, Regional, State and Operational Area (local) authorities providing instructions, news, and information.

"The Basic Emergency Broadcast System (EBS) Plan provides for utilizing the facilities and personnel of the entire nongovernment communications industry on a voluntary organized basis to provide the Nation with a functional emergency system."[5] AM, FM, or TV broadcast station licensees participating in the EBS have been issued National Defense Emergency

Authorizations (NDEA) by the Federal Communications Commission which authorize operations in a controlled manner on a voluntary organized basis during a grave National crisis or war.

Under the EBS, primarily the AM broadcast stations are used for communications to the public with selected FM and TV stations assisting in forming backup communications facilities to the combined normal programming networks. OCD, under its Broadcast Station Protection Program, provided selected key EBS stations with minimum fallout protected operating space, emergency power facilities, and remote pickup units for programming from designated civil defense emergency operating centers (EOC's). For these reasons this study on the effects of EMP was aimed chiefly at AM broadcast stations, although findings applicable to FM and TV stations participating in the EBS are indicated in Section VI.

Although the EBS is not officially considered as a warning system, it is the only present means of issuing verbal statements to the general public that an attack is occuring. Since it is generally agreed[6] that siren warning is not sufficient by itself, the EBS is de facto an important component of the warning process. Accordingly it is of extreme importance that this system function satisfactorily before and during a nuclear attack.

Even with limited fallout shelter protection, the number of casualties depends sensitively on the amount of tactical warning time available. For every minute of delay in warning receipt the number of additional casualties grows rapidly because of the inability to take shelter in time. Further, unless the EBS functions quickly as a confirmation of siren warnings, the latter may be disregarded with an attendant loss of warning time.

Although reliable operation of the EBS is most critical during the tactical warning time, it serves important functions during and after an attack. Among these are information on fallout radiation levels, confirmation of end of attack or of additional attacking waves, mobilization of civil defense teams, etc. Because the AM transistor radio is so ubiquitous (and generally immune to EMP damage) maintenance of public communications is quite possible during and after a nuclear attack if the EBS survives.

1.5 NATURE OF THE THREAT

Although a strong electromagnetic pulse is produced by both low altitude and high altitude detonations, a number of factors combine to make the high altitude case the more serious for the EBS. Broadcast antennas and transmitter buildings are fairly soft to damage by blast and debris with extensive damage expected at the five p.s.i. level or greater. The EMP from a surface burst is reduced fairly quickly as distance from the detonation point increases. For all but very small weapons (few KT) the EM environment on the five p.s.i. contour is less severe than that produced by a high altitude detonation, for which there are negligible blast effects on the ground. If the station is heavily damaged by blast effects, whatever EMP damage occurs is inconsequential.

From a systems standpoint the difference in EMP area coverage between high and low altitude detonations is also important. For a low altitude or surface burst the area over which EMP damage could conceivably occur to an EBS broadcasting station, but blast damage would not occur, is an annulus with inner radius of a few kilometers and outer radius of a few tens of kilometers for a total area of a few hundred or thousand kilometers. But for a high altitude burst this area is a circle with a radius greater than one thousand kilometers: a total area of millions of square kilometers, or a large fraction of the U. S. For a high altitude detonation nearness to probable target is not a meaningful concept; most stations are at risk from most bursts.

High altitude bursts are no longer unlikely. The deployment of our Safeguard ABM system will include Spartan megaton-range warheads to be used at altitudes greater than one hundred kilometers. In addition, the high altitude detonation of offensive missiles to produce EMP effects on the ground should not be ruled out. The launch of one or a few FOBS missiles* just before the launch of the first heavy wave, timed so that detection of the FOBS missiles occurred not earlier than detection of the heavy wave, would incur no penalty to the attacker of increased warning time for the defender. If the FOBS missiles were detonated in orbit at a height of 150 to 300 kilometers, intense EMP could be produced over most of the U. S. after at most three to four minutes of warning time. This is

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*FOBS: Fractional Orbit Bombardment System.

less than the expected activation time, of about five minutes, for the EBS and at best would allow only one or two minutes of warning message broadcast before the first, or perhaps several, EMP pulses were produced.

In any realistic encounter the number of high altitude defensive and offensive bursts is likely to be many dozens or perhaps hundreds spread over a few minutes or hours. Because most stations will receive the pulse from most bursts, one must consider effects of many pulses in a short time. The simplest new effect is the increased probability of damage due to simple combination of independent single pulse damage probability. Even if the single pulse damage probability, p, is small, the probability that damage will occur during one of n pulses is $1 - (1 - p)^n$. For $p = .1$ and $n = 50$ the total damage probability is 0.995, or almost certain damage. The situation is usually more complicated because parts weakened during one pulse may be more susceptible to damage during succeeding pulses; also a circuit breaker which opened at one pulse may preclude damage at the next, etc.

The fields produced by a single high altitude detonation can have considerable variation of amplitude, time dependence, and direction, depending upon yield, height of burst, location of observer, and orientation with respect to the geomagnetic field. One can, however, define a typical field environment which will not exceeded by a significant amount, nor is it much greater than the average which might be expected; i.e., it is close to a worst case without being too far from the average. Figure 1.1 shows the electric and magnetic field strengths near the ground as functions of time for this typical environment. One graph suffices for both, because as a free space plane wave the ratio of electric to magnetic field strength is constant. Direction of the fields is arbitrary, except that the electric field, E, must be perpendicular to the magnetic field. The reason for this is that different orientations of observer and burst can produce any polarization of the fields.

The fields shown in Figure 1.1 are the incident fields, those which propagate towards the earth. The reflection of thse fields from the ground must in general be considered when determining the total (measured) fields at a given point. The total fields can be either larger or smaller than the incident fields depending upon polarization.

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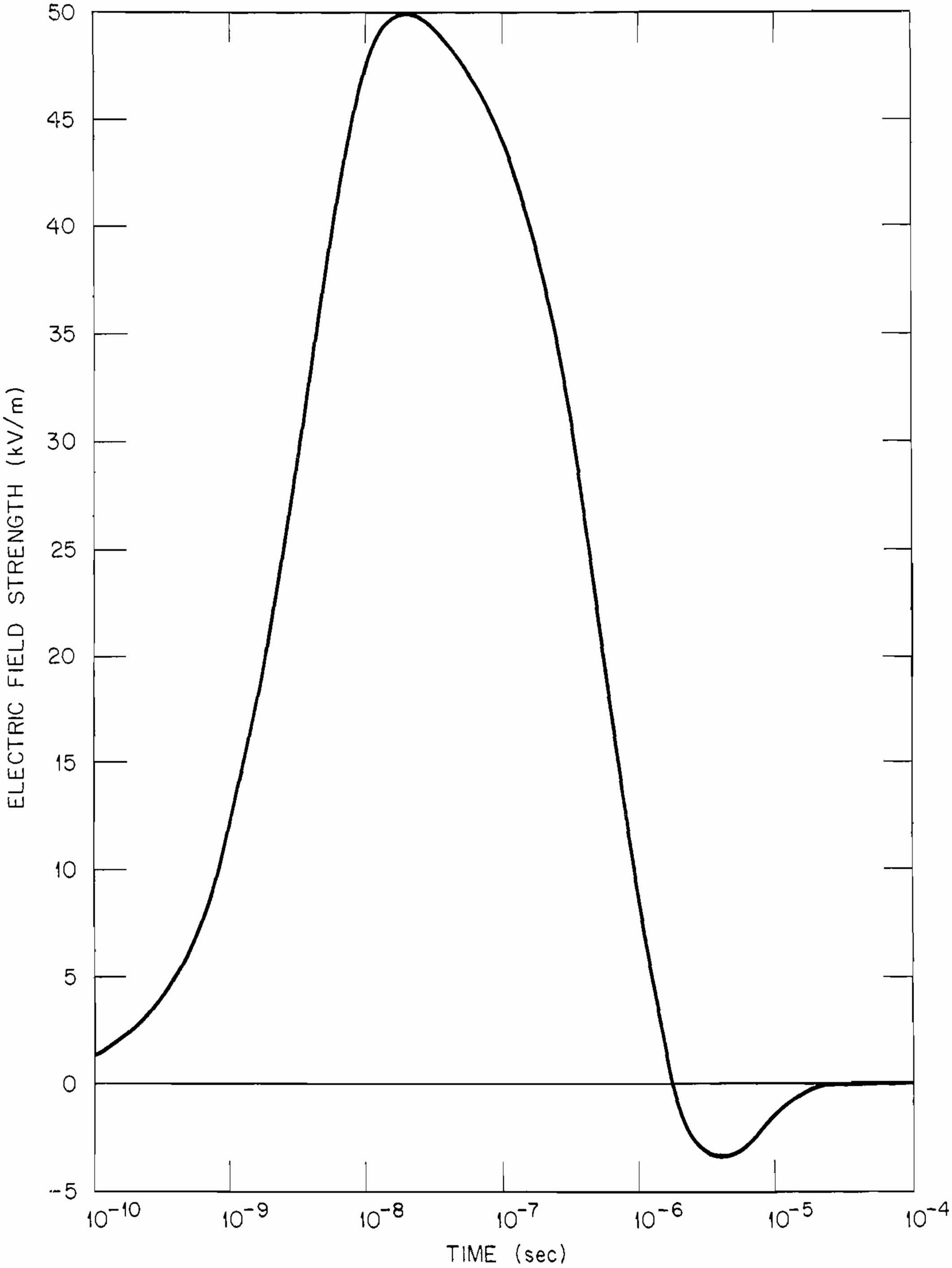

Figure 1.1. Electric Field Strength as a Function of Time for the Representative EMP.

The fields given in Figure 1.1 have an analytic representation in terms of exponentials: the incident electric field, E_i, is given by

$$E_i(t) = E_0 \left[e^{-\alpha t} - e^{-\beta t} - A(e^{-\gamma t} - e^{-\delta t}) \right] \qquad (1.1)$$

where t = time in seconds

$\alpha = 1.5 \times 10^6$

$\beta = 2.6 \times 10^8$

$\gamma = 2.0 \times 10^5$

$\delta = 5.0 \times 10^5$

$A = \dfrac{\alpha^{-1} - \beta^{-1}}{\gamma^{-1} - \delta^{-1}}$

$E_0 = 5 \times 10^4/.9646$ volts/meter

The first pair of exponentials (involving α and β) form a pulse with a rise time of two shakes and a width at half maximum of 45 shakes. The second pair produce a negative pulse which lasts about 25 microseconds. For many analyses the influence of this second pulse is negligible. The fact of its presence is known more on theoretical than experimental grounds; it serves to make the total time integral of the pulse vanish. The time for this to occur is approximately the relaxation time for the upper atmosphere.

The fields comprising the EMP induce currents in conductors in precisely the same fashion as any electromagnetic fields, e.g. radio waves. However, because EMP is a pulse, one cannot ascribe to it a single frequency, in contrast to radio waves. The energy content at different frequencies can be studied via the Fourier transform, which for $E_i(t)$ defined by (1.1) leads to the function $E_i(\omega)$:

$$E_i(\omega) = \frac{E_0}{\sqrt{2\pi}} \left[\frac{1}{\alpha + i\omega} - \frac{1}{\beta + i\omega} - \frac{A}{\gamma + i\omega} + \frac{A}{\delta + i\omega} \right]$$

The energy content is then proportional to $|E_i(\omega)|^2$, the energy spectral density. This is presented in Figure 1.2, normalized to the peak

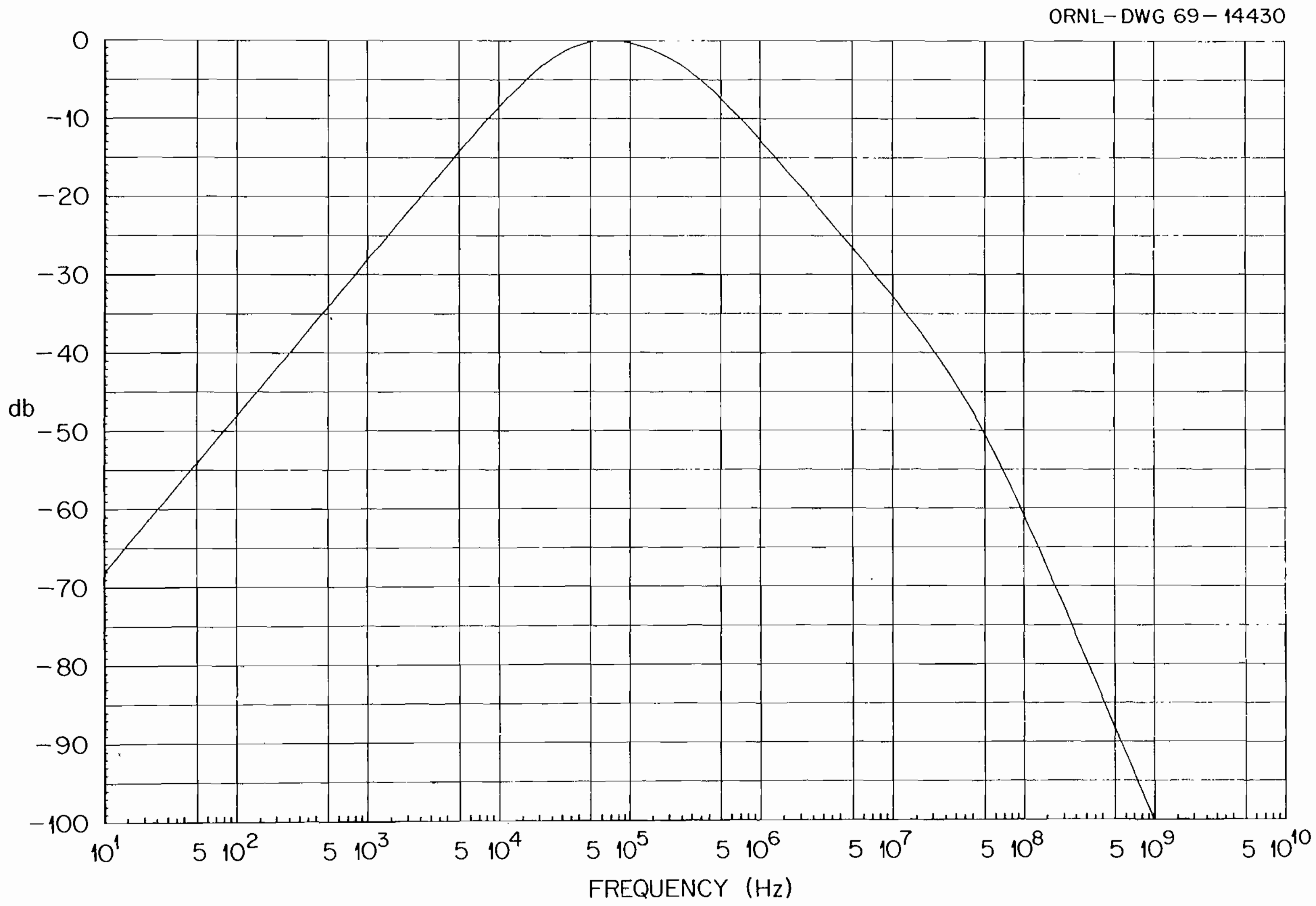

Fig. 1.2. Normalized Power Spectrum for the Representative EMP.

value of 0.075 volts/meter-hertz which occurs at ω_o = 700 kHz. The ordinate is in decibels:

$$10 \cdot \log \left[\frac{|E_i(\omega)|^2}{|E_i(\omega_o)|^2} \right]$$

Because the spectrum extends from a few hertz up to several hundred MHz (depending on how one defines the cutoff point), the EMP is quite broadband. From an equipment standpoint, this fact means that EMP is difficult to filter and can couple into circuits resonant at a wide range of frequencies. In particular for the broadcast band, we note that the energy density peaks in this band, and even at 1.5 MHz, it is down only about 15dB. This fact indicates that EMP should couple well to broadcast antennas and pass without significant attentuation through transmitter tuned circuits. We shall see that this is true.

CHAPTER II

EBS STATION CONSTRUCTION AND PRACTICE

2.1 INTRODUCTION

It is impossible to describe all the stations of the EBS, or even to outline typical features, without presenting some half truths or meeting numerous counterexamples. Nevertheless, most stations are similar in their broadest outlines, and when we consider only the factors relevant to EMP vulnerability some general observations do emerge.

2.2 GENERAL CHARACTERISTICS

Depending upon their engineering budgets and authorized power, stations can be quite primitive or extremely elaborate. From the EBS standpoint the basic elements are three:

1. Program source including outside links
2. Transmitter
3. Antenna

At the lowest level of sophistication, all elements are grouped in or adjacent to a single small building with an attendant engineer and announcer. Outside information enters via common carrier and may include network feed AP or UPI wire services, and normal telephone service. Telephone conversations can be broadcast directly using phone patches. Normal radio receivers can monitor other EBS stations, and even at this lowest level many stations have equipment for radio contact with civil defense or other public service communications networks.

At a higher, and more common, level, the program source is located at a studio remote from the transmitter location. The main reason for this is that AM antennas require much space and favorable broadcasting locations and hence are generally located outside the city they serve. The studios are better placed at a more suitable business site in the city. Program material is relayed by common carrier or infrequently by microwave links. Under attack conditions, some stations plan to relocate their studios at the transmitter; others are constrained by teletype locations or space limitations to maintain both their studio and transmitter operations.

Although some of these stations have an engineer continuously on duty at the transmitter, an increasingly common practice of remote operation leaves the transmitter unattended except for maintenance. All required checks on operation are made by remote control from the studio.

Key AM broadcast transmitter locations have been provided by OCD with a fallout shelter and a diesel generator capable of supplying full power required by the transmitter as well as normal auxiliary loads. Some stations with remote studios also provide fallout shelters and emergency generators for the studio. However, in at least two known instances the studio generator uses the natural gas utility for a fuel supply to meet fire insurance regulations prohibiting large amounts of stored fuel in a business district.

In general the stations are aware that the links between studio and transmitter are fragile. Often they have backup facilities which could provide the link in case of emergency. Examples include two-way radio cars normally used for news gathering and whose battery operated transreceivers could be used for direct program feed. Also AM and FM stations could relay programming from studio to FM transmitter to AM transmitter using an existing FM receiver at the AM transmitter site.

2.3 TRANSMITTERS

There are comparatively few manufacturers of AM broadcast transmitters; they include Collins, R.C.A., Gates, and Continental. Because all transmitters must be type-approved by the FCC and because broadcast transmitters are conservatively designed, there are many similarities between different types.

2.3.1 A Typical Transmitter

Figure 2.1 shows the simplified schematic for Gates BC-5B and BC-10B transmitters, five and ten kilowatts output respectively. No transistors are used, and the most sensitive tubes - the 6V6 and the 6J5 - would require several joules of energy to damage them. The smallest capacitors are 400 volt types. Operating voltage to the power amplifier plate is 5000 volts. Capacitors in this stage are Sangamo type G3 with mica dielictric rated up to 10,000 working volts. Overload protection in the form of circuit

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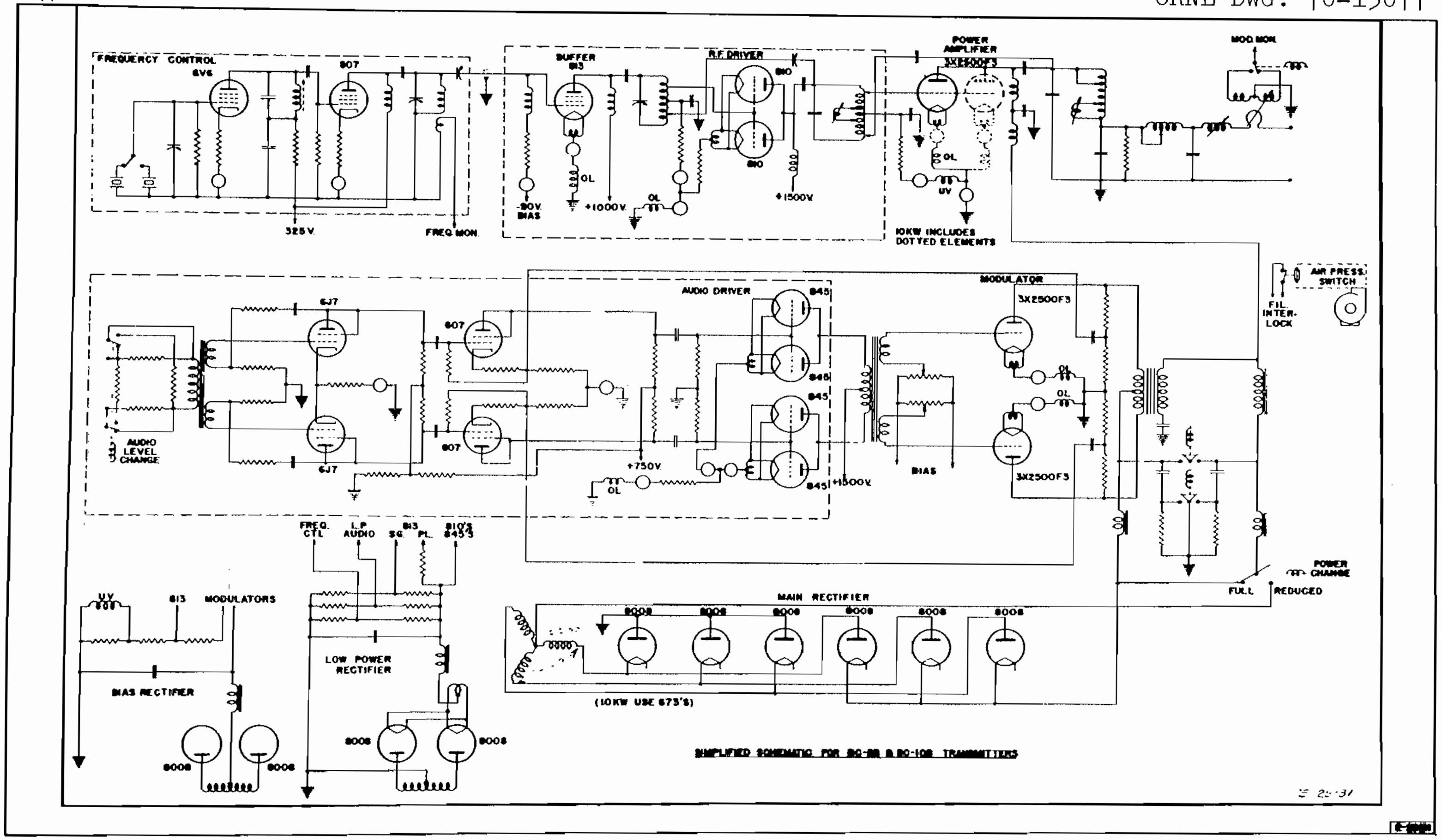


Figure 2.1. Simplified Schematic for Gates BC-5B Transmitter.

breakers is provided to every stage except the oscillator and first audio stages. These are designed to automatically reclose three times before locking out.

Audio levels required for input are +16 dBm at 600 ohms. Hence a microphone will not drive the transmitter directly. However, most stations have auxiliary amplifiers, including battery-operated portable ones, which could be used for this purpose.

The high voltage power supply uses a three-phase 230 volt transformer with a Y connected secondary. Low voltage supplies are single phase. All are protected with circuit breakers in the primary circuits.

The entire transmitter is housed in three enclosed relay racks as shown in Figures 2.2 and 2.3.

2.3.2 Other Transmitters

The most powerful AM broadcast stations use fifty kilowatt transmitters such as the RCA BTA50 or the Continential 317B. These are somewhat larger than the BC-10B and use final plate voltages of about 10KV to 15KV with capacitors rated up to 20KV working voltage. Otherwise they are very similar.

Many stations actually have two transmitters and either alternate regularly between them or maintain one on standby. Sometimes this situation arose because an old transmitter, being replaced, was kept in case anything happened to the new one. Or perhaps a second transmitter was purchased expressly for standby duty. In a business like broadcasting where time equals money, reliability is important. Usually the antenna feed can be changed almost instantaneously from one transmitter to the other using a changeover switch like the one shown in Figure 2.4. The present trend in transmitter design is toward solid state devices in lieu of vacuum tubes, at least for audio and lower power RF stages. Because of the much greater inherent sensitivity of transistors to damage by transients typical of EMP, such transmitters may be more susceptible to EMP effects than those discussed above.

2.4 ANTENNAS AND FEED LINES

Without exception AM broadcast station transmitting antennas are vertical monopoles, usually either one-quarter or one-half wavelength

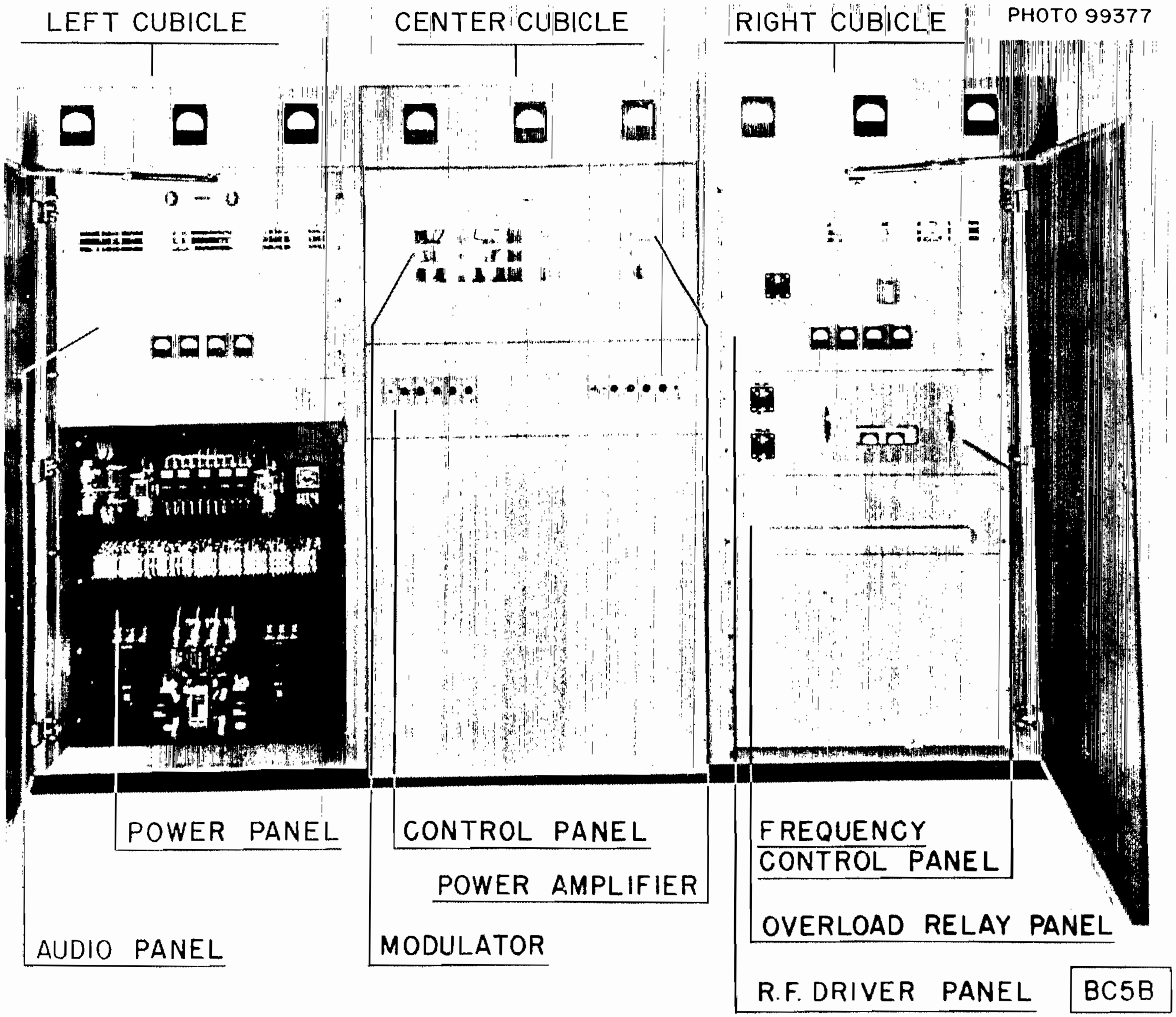


Figure 2.2. Front View of BC-5B.

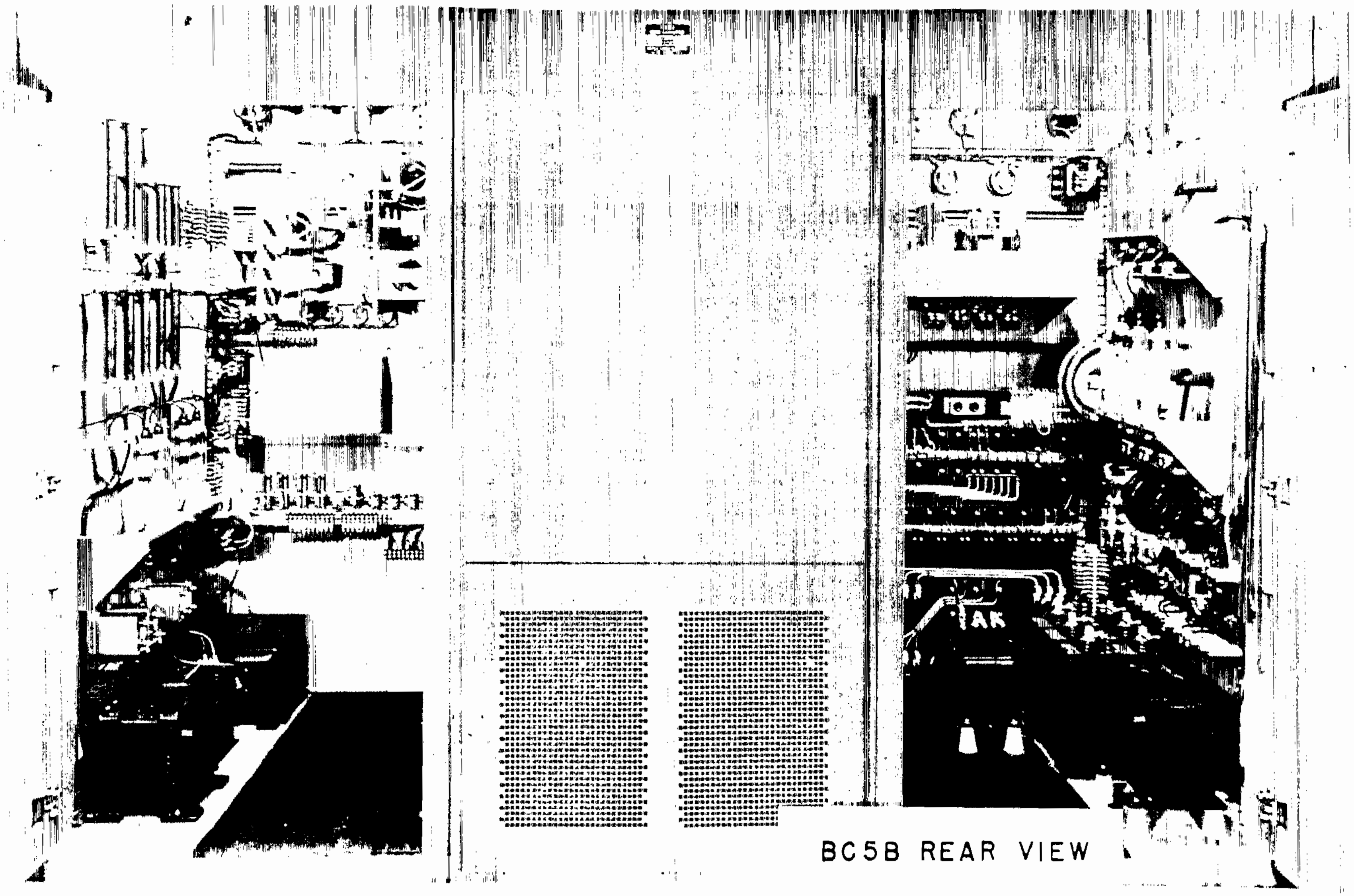


Figure 2.3. Rear View of BC-5B.

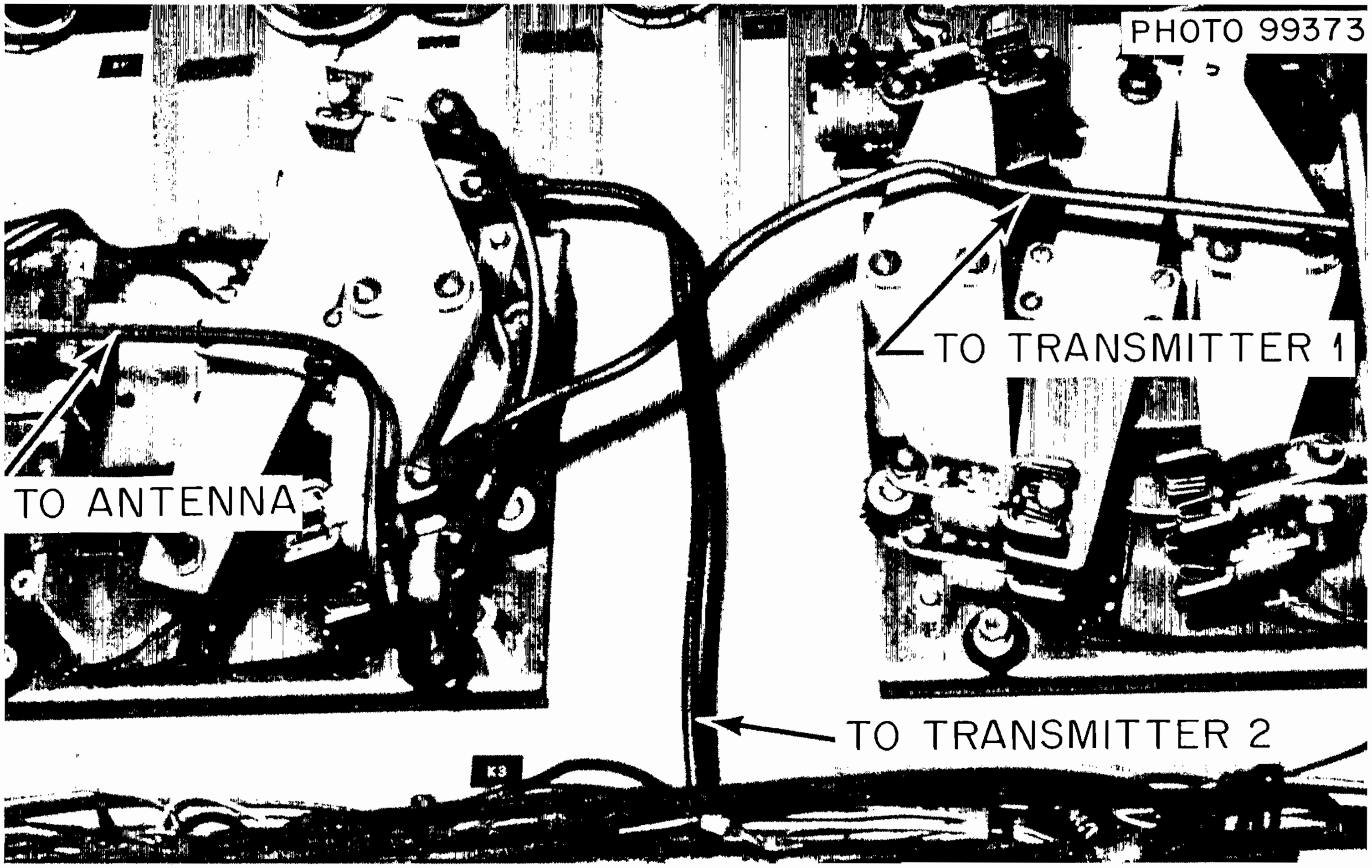


Figure 2.4. Transmitter Changeover Switch.

long but occasionally five-eighths wave lengths. This entails a vertical mast perhaps 100 to 200 meters high which is insulated at the base from the ground. Normal construction is a steel tower of the required height with massive ceramic insulators at the base of each leg. Examples of such insulators are shown in Figures 2.5 and 2.6.

The antenna feed line is normally a solid dielectric or nitrogen-filled coaxial cable, with a diameter of 1.75 in. or 3.25 in. depending on power and a characteristic impedance of about 50 ohms. This provides a good match to a one-quarter wavelength monopole, which has a resistance at resonance (the point of zero reactance) of 40 to 50 ohms. A one-half wavelength monopole has a resistance 300 to 400 ohms and is occasionally fed by an open wire line of the type shown in Figure 2.7 whose higher impedance simplies the matching network required. The antenna mast shown in this figure is actually five-eighths wavelengths long.

In practice the feed line does not perfectly match the antenna. To terminate the feed line in its characteristic impedance, preventing reflected waves and a high standing wave ratio, a matching L network of the type shown in Figure 2.8 is customarily introduced. The values of L and C are small. For example, if $R_a = 40\Omega$ and $R_o = 50\Omega$, then at one MHz. $L = 3$ μ henries and $C = .0016$ μ farads.

The FCC requires many stations to maintain a directional radiation pattern, i.e. suppress the radiation in certain directions, to avoid interfering with other stations. This requires the use of two or more masts, each fed with a signal of differing relative phase. The phase shifting circuit, called a phasor, is located just after the output circuit of the transmitter. The phase shifted signals are fed from it in individual feed lines to each antenna. Components in the phasor are capacitors and inductors, with working voltages at or below those of the final amplifier plate circuit.

In general it is possible to bypass the phasor and to disconnect any antenna in the event of damage. The time required would be a few hours

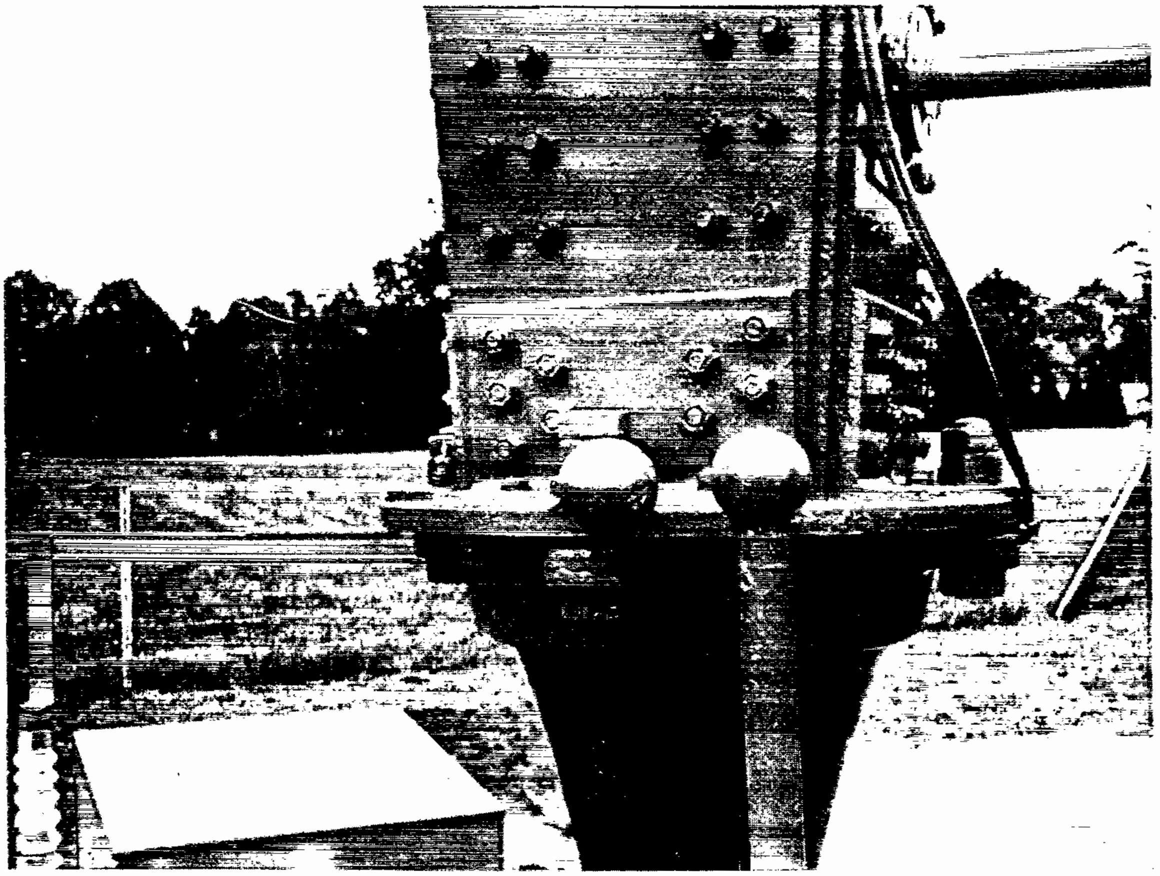


Figure 2.5. Tower Base Insulator and Spark Gap.

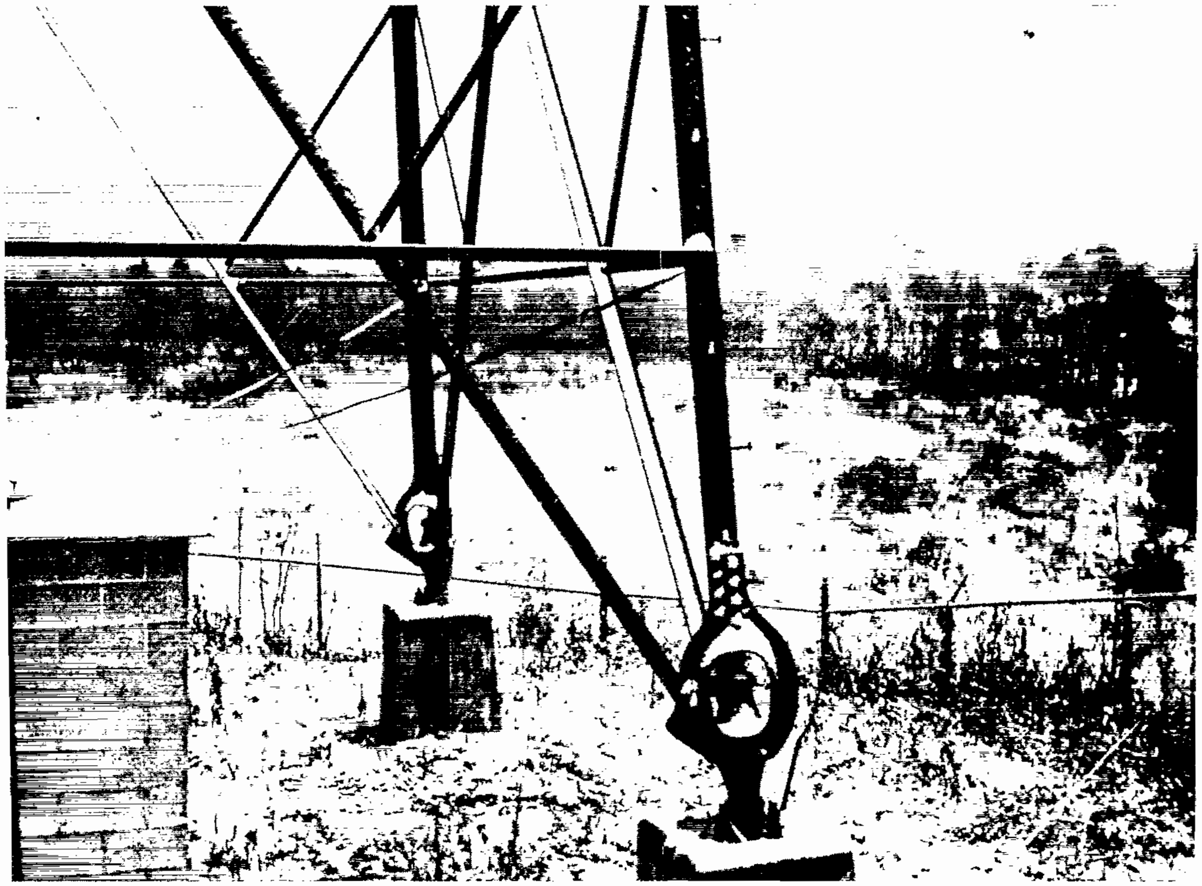


Figure 2.6. Tower Base Insulators.

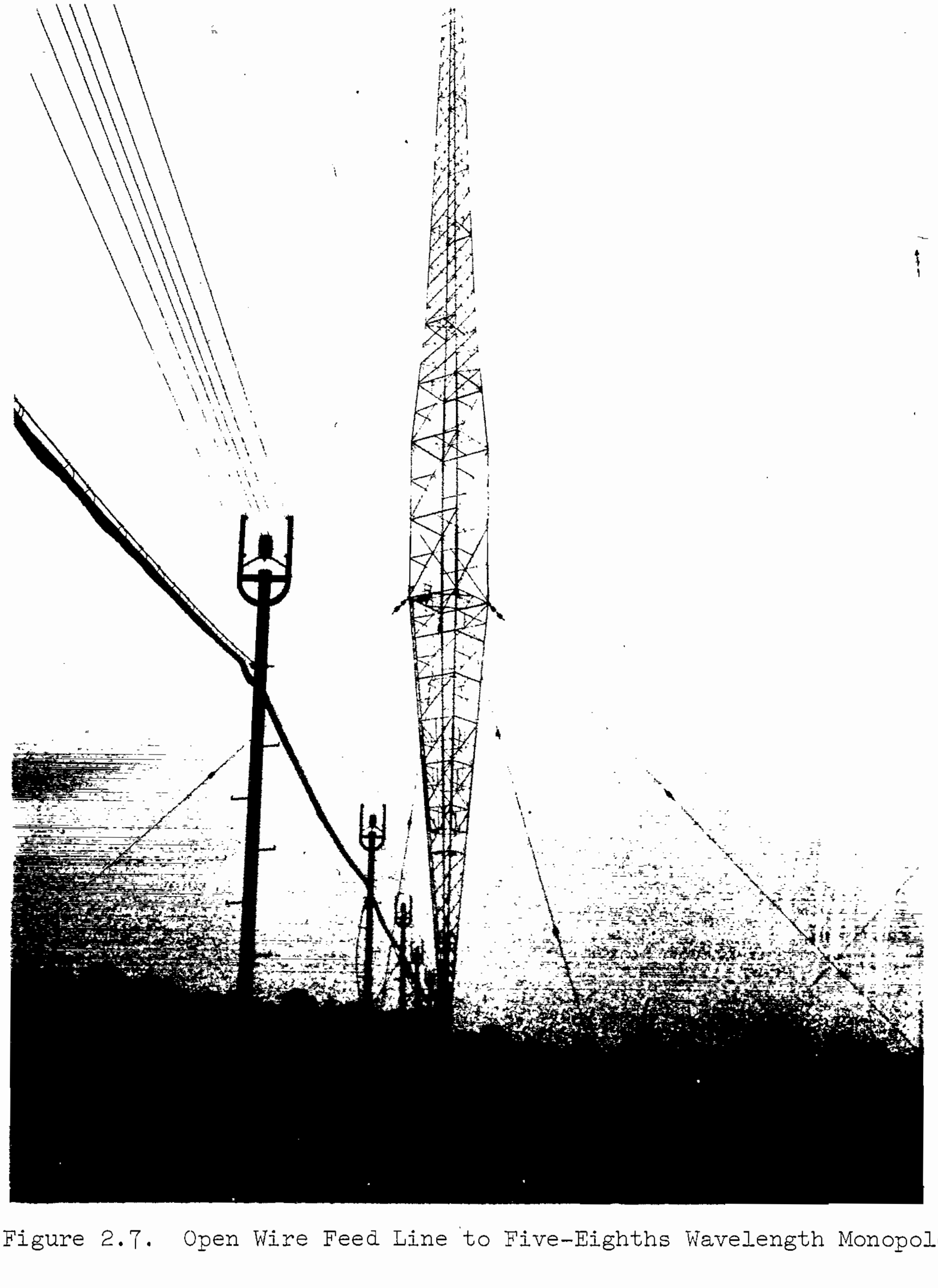
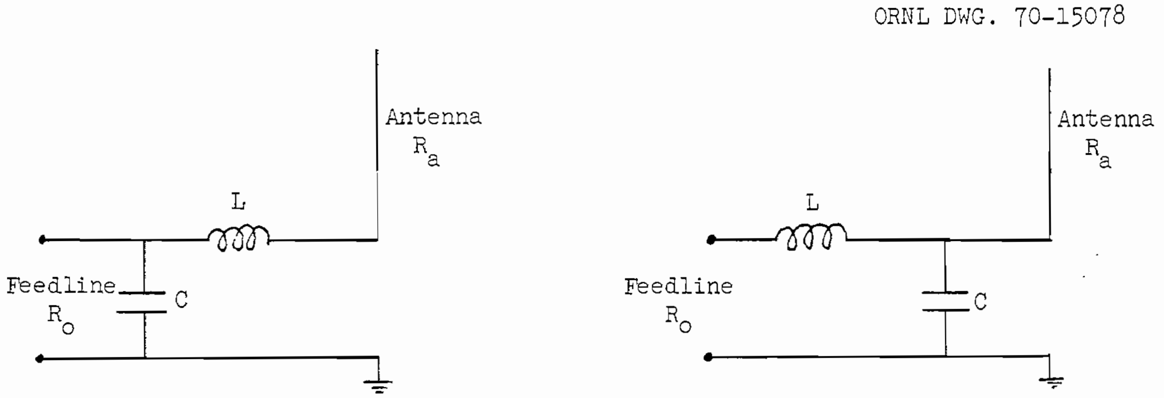


Figure 2.7. Open Wire Feed Line to Five-Eighths Wavelength Monopole.



(a) $R_o > R_a$

$$X_L^2 = R_a(R_o - R_a)$$

$$X_c = \frac{X_L^2 + R_a^2}{X_L}$$

(b) $R_o < R_a$

$$X_L^2 = R_o(R_a - R_o)$$

$$X_c = \frac{X_L^2 + R_o^2}{X_L}$$

Figure 2.8. Antenna Matching L. Network.

using parts on hand. This would generally be done only in an emergency because of the loss of directionality. One anecdote was related about a station which suffered damage to its antenna in a fire. The engineer made a half wavelength dipole out of wire, strung it between two trees, and the station was back on the air in a few hours.

2.5 GROUNDING, SHIELDING, AND WIRING PRACTICE

Many of the tenets held useful for avoiding EMP damage in electronic equipment are routinely adhered to by broadcast stations because of their need to avoid interference from their own signals. Normal field strengths inside transmitter buildings run from slightly under one v/m up to more than five v/m. The FCC requirements for 60 dB S/N ratio in the transmitted audio signal dictate fairly stringent RFI suppression measures. All audio wiring is shielded, single point grounding is used, and loops are scrupulously avoided. Low signal level components are sometimes shielded, and bypass capacitors may be used. In general wave traps (single frequency filters) are not employed.

Because satisfactory radiation from a vertical monopole requires a high conductivity ground plane, stations go to considerable pains to bury an extensive radial ground plane at the base of each antenna. These are usually well maintained because deterioration causes antenna loading problems. Under extreme conditions electrolytes may be added to the soil and a sprinkler system installed to improve ground conductivity.

2.6 LIGHTNING PROTECTION AND DAMAGE

The tall antenna masts located on flat land make attractive lightning targets, and they are apparently struck fairly often. It is customary to install spark gaps at the base of the tower, and less frequently also where the feedline emerges from the transmitter building. These can be ball gaps, points, or self extinguishing horn gaps. Examples of such gaps are given in Figures 2.5, 2.9, and 2.10.

Station practice on setting gap spacing is not uniform. One station indicated that it set the gaps so they would almost arc on maximum modulation; the others were less systematic. Gap spacing is usually somewhat more than an inch. Tower base arrestor ground leads are connected to the antenna ground system with short leads. Surge impedance should be very low.

Figure 2.9. Spark Gap at Base of Antenna. (This is an enlargement of part of Figure 2.6.)

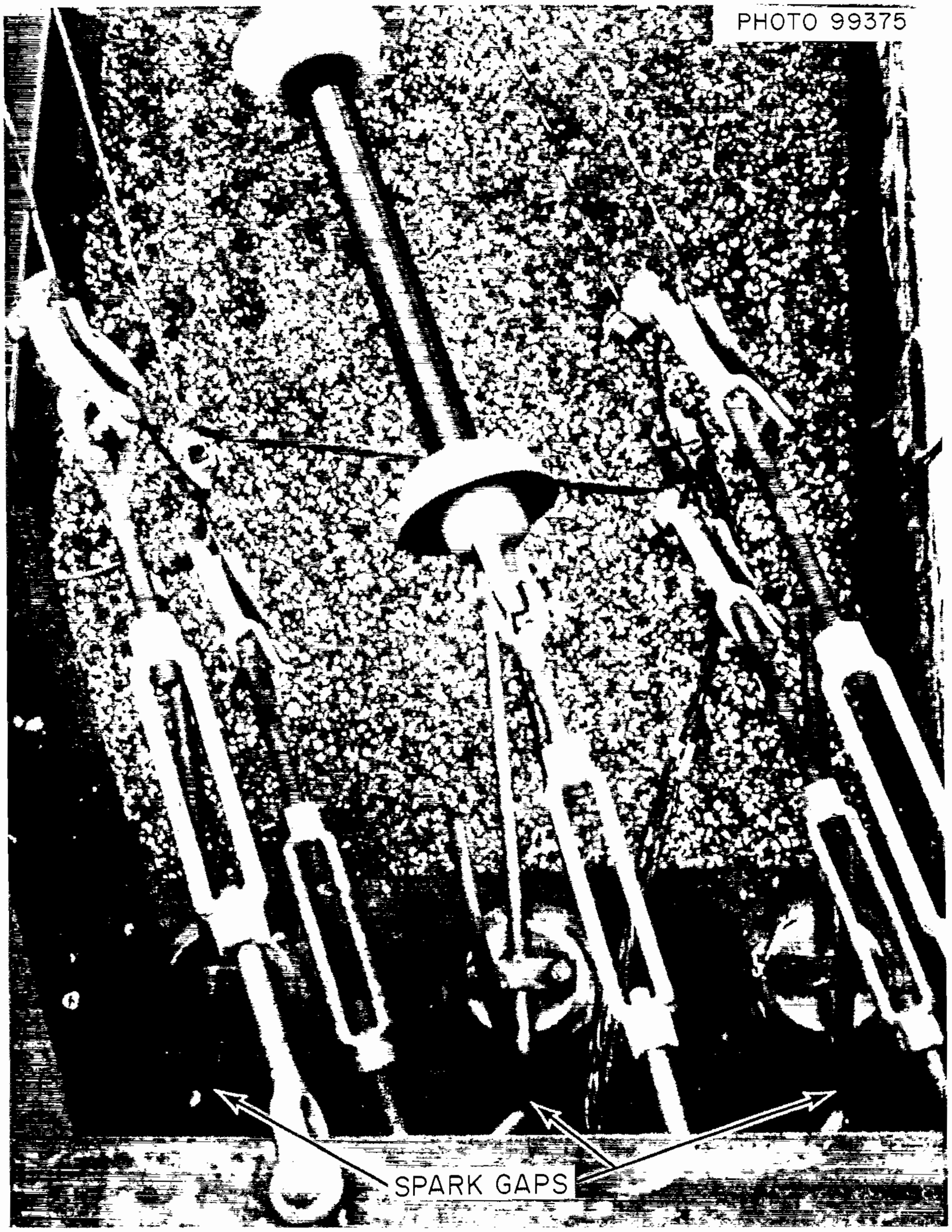


PHOTO 99375
SPARK GAPS

Observation of direct lightning strokes to antenna masts indicates that the tower guy wires, not the spark gap, may carry most of the lightning current to ground. These guy wires are interrupted by insulators at intervals along their length, and in numerous instances they have been seen to arc progressively when the tower is struck by lightning; occasionally the tower base insulator will also flash over. Some stations with open-wire feed lines introduce inductance to broaden lightning pulses by placing a small (a few μ henries) choke in series with the center conductor where it enters the transmitter building. Power system experience indicates this may be of questionable value.

When gaps arc to discharge a lightning stroke, the effective short circuit across the final amplifier opens the overload circuit breaker, preventing power follow. If automatic reclosing is provided and functioning properly, the interruption of transmitted signal is a fraction of a second. Lightning strokes seem to be infrequent enough that some stations do not use the automatic reclosing feature even when provided. It can be, and is, defeated by a "manual mode" switch.

Despite the lightning protection devices, damage from lightning is fairly frequent. The most commonly damaged component is the capacitor in the matching network at the base of the antenna. (See Figure 2.8). Usually it suffers dielectric failure, although instances of the capacitor exploding are also reported. Occasionally the inductor in this network is melted; one instance of the turns "welding" together was reported. Capacitors and inductors in the phasor circuit are also subject to damage. No instances of damage to the transmitter itself were reported, but for nondirectional stations lacking the phasor network damage, could probably occur to the final tank circuit of the transmitter.

No instances are reported of damage due to surges from the power line, although loss of power due to lightning damage of power system components occurs fairly frequently. It is unlikely that lightning would strike nearby power lines in preference to the much taller antenna.

2.7 REPAIRS AND SPARE PARTS

For commercial broadcast stations time off the air is advertising revenue and listeners lost. Accordingly there is a high premium placed on quick repair of damaged parts. Station engineers are expected to trouble shoot and correct any failure quickly and to be intimately familiar with all transmitting equipment. Most station engineers have a good practical engineering knowledge, and many of them have designed and built some of the station equipment.

Sufficient test equipment and spare parts are also stocked at most stations to repair damaged or defective parts. In addition station engineers in an area generally know each other and cooperate by lending parts and sometimes even help to find and repair trouble at another station.

CHAPTER III
ANTENNA ANALYSIS

3.1 INTRODUCTION

As mentioned in Section 2.4, AM broadcast transmitting antennas are vertical monopoles over a ground plane, usually either one quarter or one half wavelength long but occasionally five-eighths wavelengths long. Since a wavelength at 600 kHz. is 500 meters and at 1600 kHz. is 188 meters, these monopoles range from about 50 meters to perhaps 250 meters high. (In practice very few stations would use a half wavelength antenna at 600 kHz. EBS antennas over 200 meters high are very rare.) The standard construction for such a monopole is a steel tower of the required height insulated from the ground. That is, the large towers one sees at AM broadcast transmitting sites are the antennas. They are not supports for the antennas.

Transmitting antennas function well as receiving antennas. In this mode they can intercept some of the energy from the EMP and couple it back into the transmitter and associated circuits. For broadcast transmitters the antenna is one of the two principal means whereby sufficient energy can be picked up to cause damage.

3.2 MONOPOLE ANALYSIS

Determining the current and voltage pulses induced in the feed line and transmitter by EMP is not easy, even for a relatively simple antenna such as a vertical monopole. At present it is not possible to work directly in the time domain. The most successful attack has been made via the Fourier transform, using existing theories in the frequency domain for the antenna properties. The answer in the frequency domain is then transformed back to the time domain, giving the current and voltage as a function of time. Approximations which are made in replacing the transmitter and feed line by an equivalent load, and in describing the antenna properties, reduce the accuracy of the final result. However, unless one wished to study in detail a particular installation, the answers from the approximate analysis suffice to indicate the likelihood of damage.

Toulios et al.[8] at IITRI have carried through this analysis. In the frequency domain the equivalent circuit of the antenna and load is shown in Figure 3.1. The antenna is replaced by a voltage generator, with magnitude of $-2h_e(\omega)E_i(\omega)$, where $h_e(\omega)$ is the complex effective height at the angular frequency ω, and $E_i(\omega)$ is the Fourier transform of the incident electric field. The complex impedance of the antenna is $Z_a(\omega)$. The load impedance is $Z_L(\omega)$.

The antenna effective height and impedance in this analysis are determined for low and high frequencies by two well known theories. For low frequencies ($\beta h < 1$ where $\beta = \omega/c$ and h is antenna height) the expressions developed by King and co-workers[9,10] are used. For high frequencies ($\beta h > 1$) the Wu theory of the long antenna[11,12] is used. Reference 8 has extended these theories to the case where the impinging plane wave is not normal to the antenna. Variables entering into the calculation of h_e and Z_a are the antenna height h, the angular frequency ω, the angle from the normal of the propagation vector of the incident plane wave, and the shape factor Ω, defined by

$$\Omega = 2 \ln (2h/a)$$

where a is the antenna radius.

Referring to the equivalent circuit, one sees that the current $I(\omega)$ through the load $Z_L(\omega)$ is given by

$$I(\omega) = \frac{2h_e(\omega)E_i(\omega)}{Z_a(\omega) + Z_L(\omega)}$$

From $I(\omega)$ can be derived the current in the time domain $I(t)$, since the one is the Fourier transform of the other. Because of the complexity of h_e and Z_a the transform must be evaluated numerically. Toulios et.al. at IITRI have programmed this analysis for a digital computer and have supplied the author with a copy. Their assistance, especially that of J. C. Lambert, is gratefully acknowledged.

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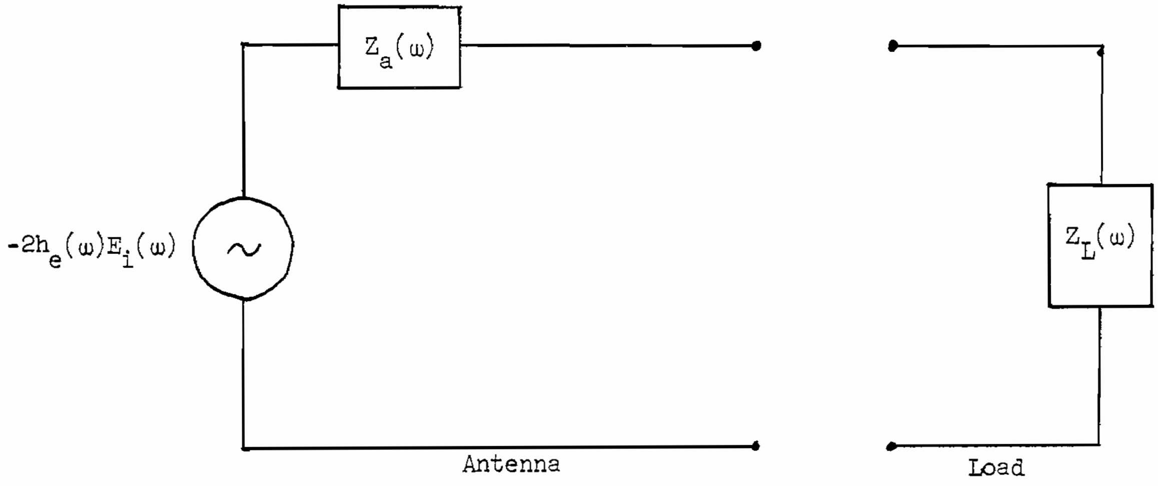

Figure 3.1. Equivalent Circuit of Antenna.

Figures 3.2 and 3.3 display as functions of frequency the real and imaginary parts of the impedance of a 75 meter high monopole (one quarter wavelength at one MHz.) with shape factor Ω equal to ten. For this antenna the radius a is therefore slightly greater than one meter. Figures 3.4 and 3.5 show the real and imaginary parts of the effective height of the same antenna for normal incidence of the electromagnetic field (θ equal to 90°).

3.3 CURRENT AND VOLTAGE SURGES PRODUCED BY EMP

3.3.1 Introduction

We are interested in the likelihood of damage when the transmitting antenna is illuminated by the representative EMP defined in section 1.4. Because of the many kinds of matching circuit, **feed line**, and phasor used in coupling transmitter to antenna as well as the many kinds of spark gap that may be encountered, we shall not be able to give a complete answer. However, calculations can give an idea of the magnitude of the problem and point to areas where experimental data would be useful.

We shall do two kinds of calculations in this section. First we calculate the antenna to ground current and voltage for a purely resistive load typical of a directly connected feed line. Second, we study the modifications due to the matching L network and focus directly on the matching capacitor, this usually representing the weakest component.

Since virtually all EBS antennas are protected by a spark gap, it is important to consider the action of the spark gap in calculating the currents and voltages to which components will be exposed. After doing this we can compare the resultant surges with lightning strokes to make use of available information on lightning caused damage.

3.3.2 Pulses Across a Purely Resistive Load Without Spark Gap

As a first baseline case we have calculated the current and voltage surges across Z_L, a pure resistance of 50 ohms, for a 75 meter high monopole with shape factor of ten. This corresponds to a one MHz. quarter wave antenna, two meters in diameter, fed by a coaxial cable without matching circuit.

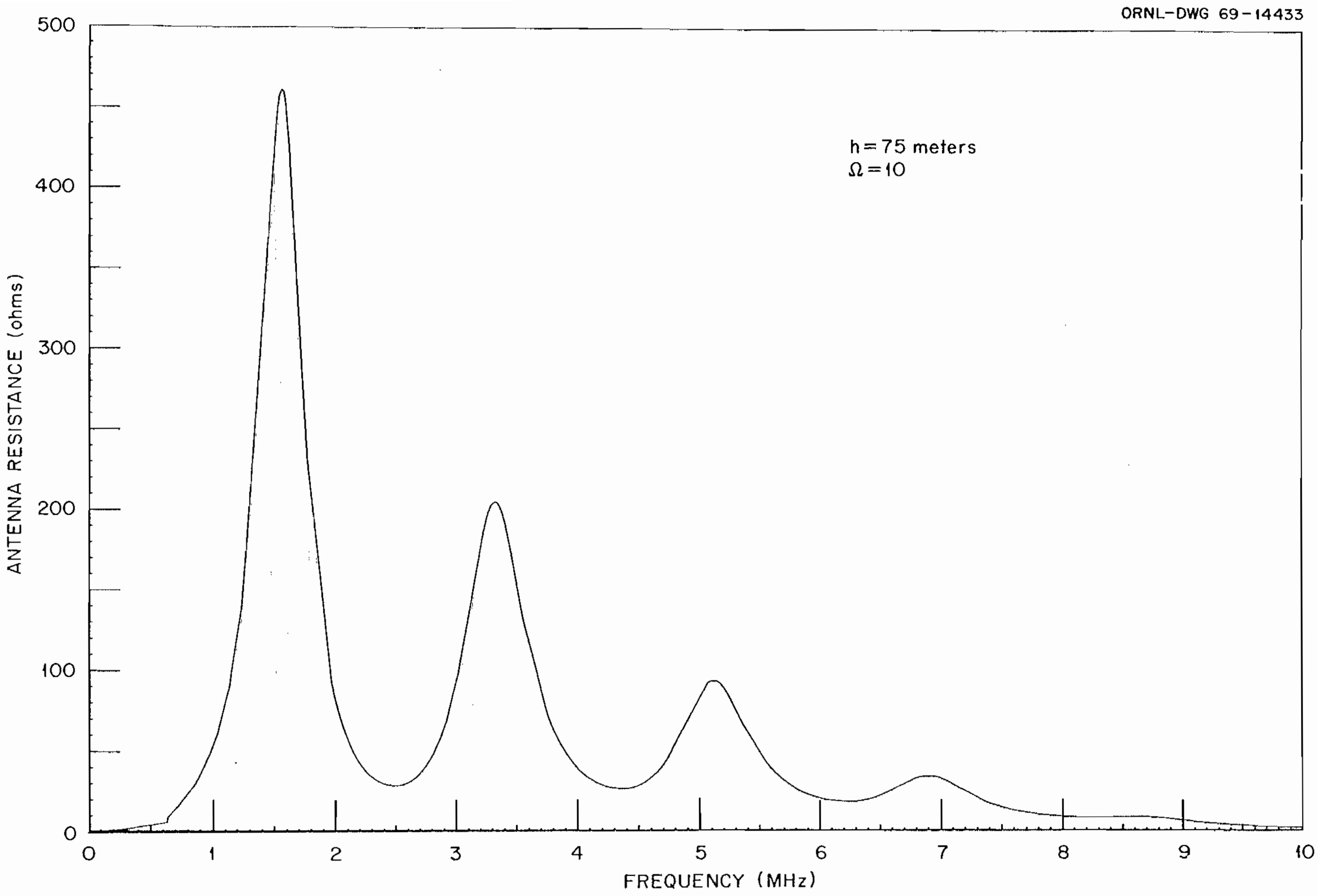

Figure 3.2. Antenna Resistance of 75 Meter Monopole.

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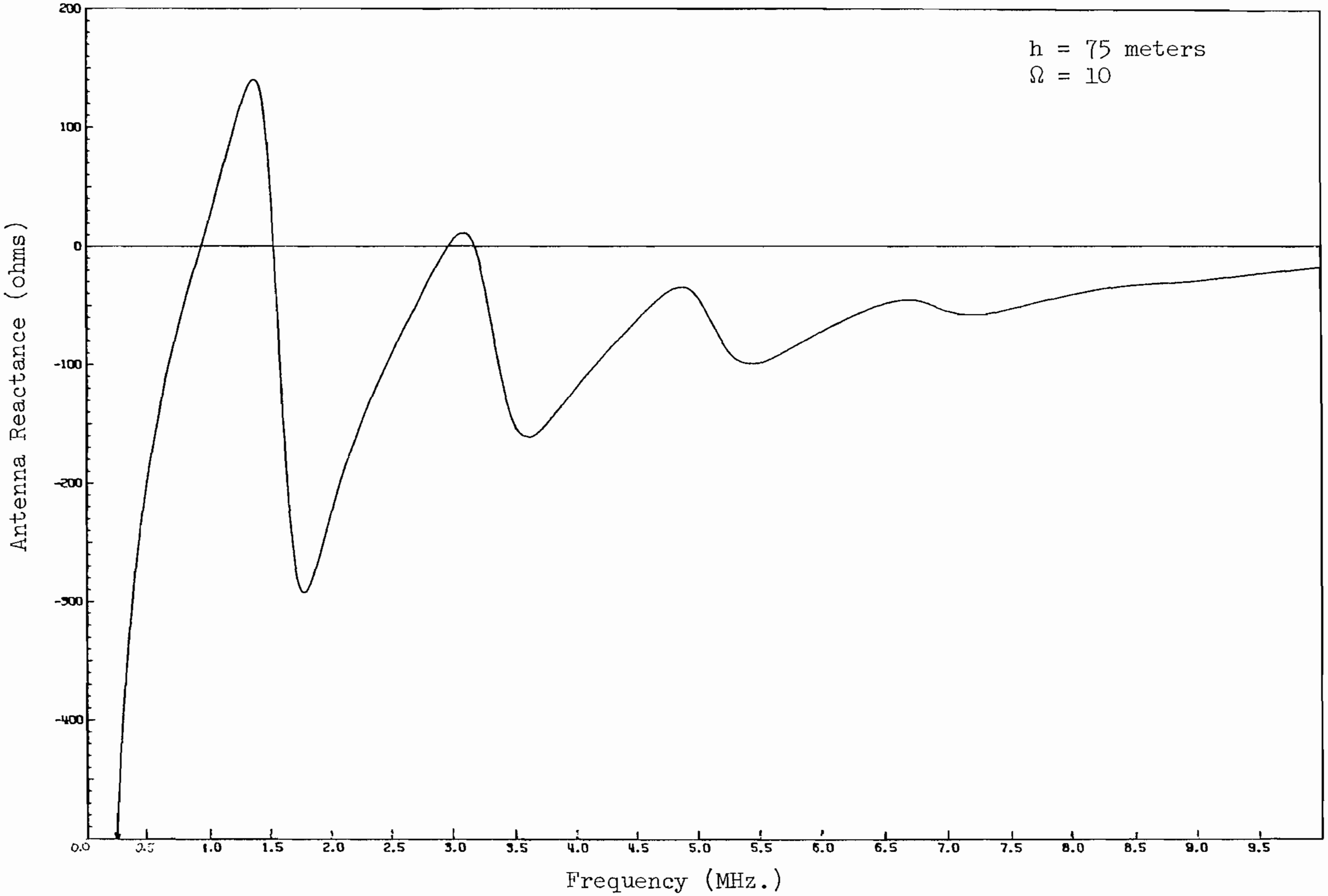

Figure 3.3. Antenna Reactance of 75 Meter Monopole.

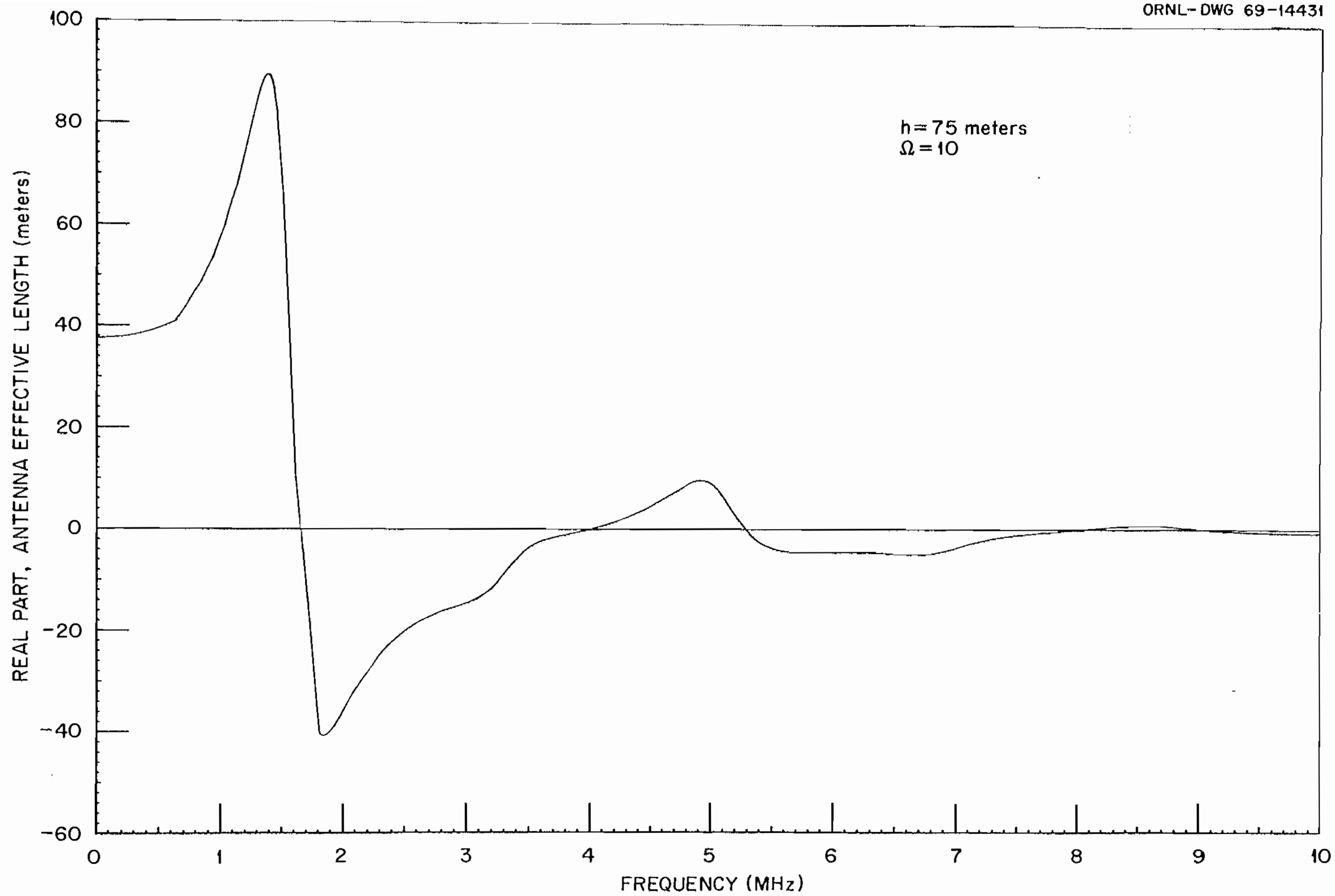

Figure 3.4. Real Part of Antenna Effective Length of 75 Meter Monopole.

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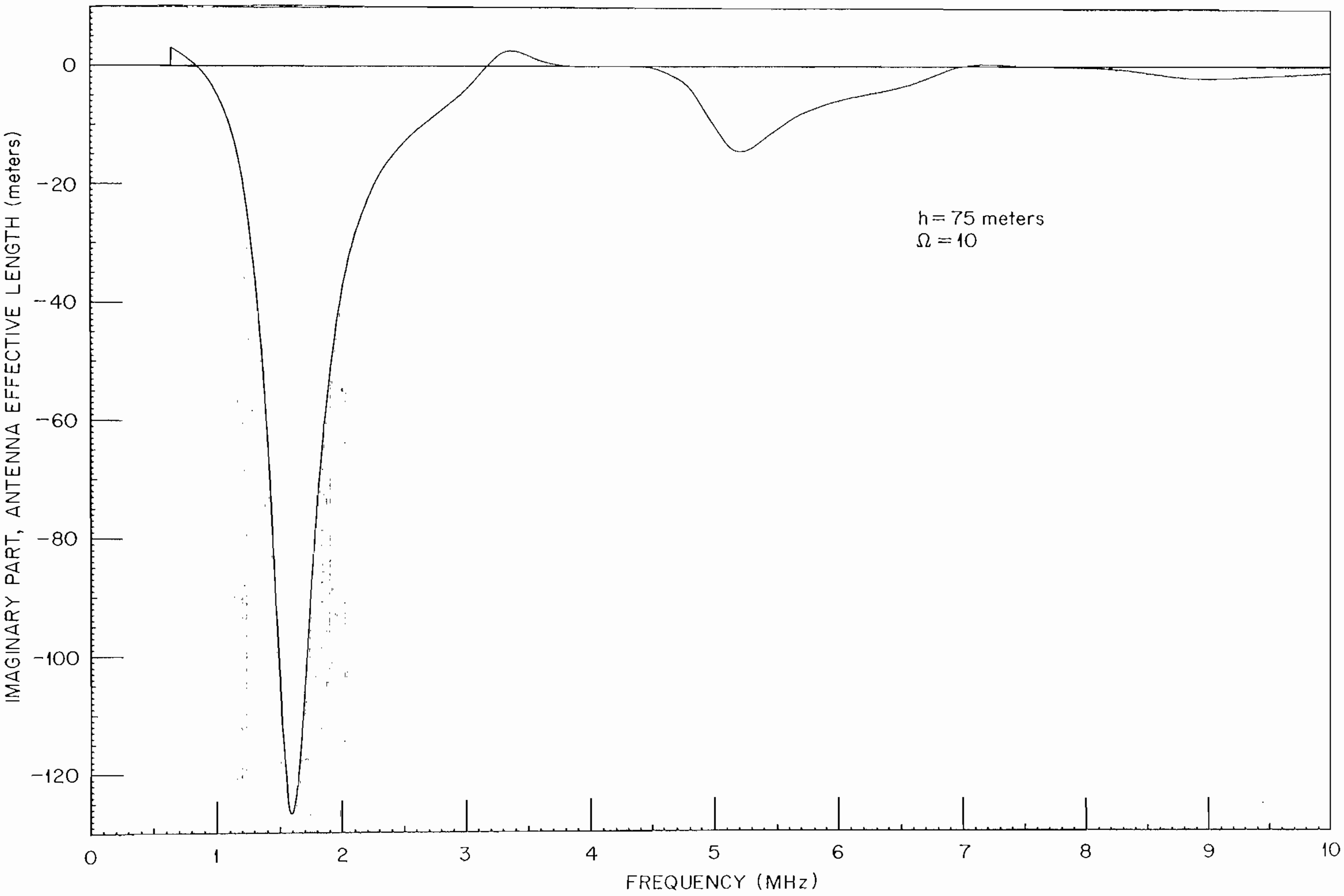

Figure 3.5. Imaginary Part of Antenna Effective Length of 75 Meter Monopole.

The current and voltage across Z_L are plotted in Figure 3.6. The antenna rings at its resonant frequency of one MHz. for about three cycles. Peak current is 20 kiloamperes; peak voltage is one megavolt. Oscillation ceases after about three μsec. Rate of rise of current and voltage on the first peak are 118 kiloamperes/μsec and 5.9 megavolts/μsec respectively.

A second baseline case is an antenna 200 meters high, shape factor of ten, with Z_L a pure resistance of 230 ohms. This corresponds to a half wavelength monopole at about 750 kHz., fed by an open wire line without matching circuit.

The current and voltage across Z_L are plotted in Figure 3.7. The antenna responds to the EMP with one heavily damped cycle at its resonant frequency (taken as a quarter wave antenna) of 375 kHz. Peak current is 23 kiloamperes, peak voltage is 5.3 megavolts. The pulse lasts about three μsec. Rate of current and voltage rise on the first peak are 53 kiloamperes/μsec. and 1.1 megavolts/μsec. respectively.

3.3.3 Effect of a Matching Network

A matching L network of the type shown in Figure 2.8 will change somewhat the shape and magnitude of the induced surges. For this case we are interested in the voltage across the spark gap (indicative of when the gap may fire) and across the coupling capacitor.

The 75 meter antenna is actually resonant at 933 khz. This is the point where the antenna reactance shown in Figure 3.3 vanishes. At this point the antenna impedance Z_a is a pure resistance of 40.4 ohms. To match a 50 ohm coaxial cable to this requires the L network shown in Figure 3.8a.

The voltage across the spark gap, designated V_1 in Figure 3.8a, has been calculated and is shown in Figure 3.9. The voltage V_o across the capacitor is also given in this Figure. It will be seen that they differ little from each other or from the voltage across the feed line in the absence of the matching network, shown in Figure 3.6. The current drawn from

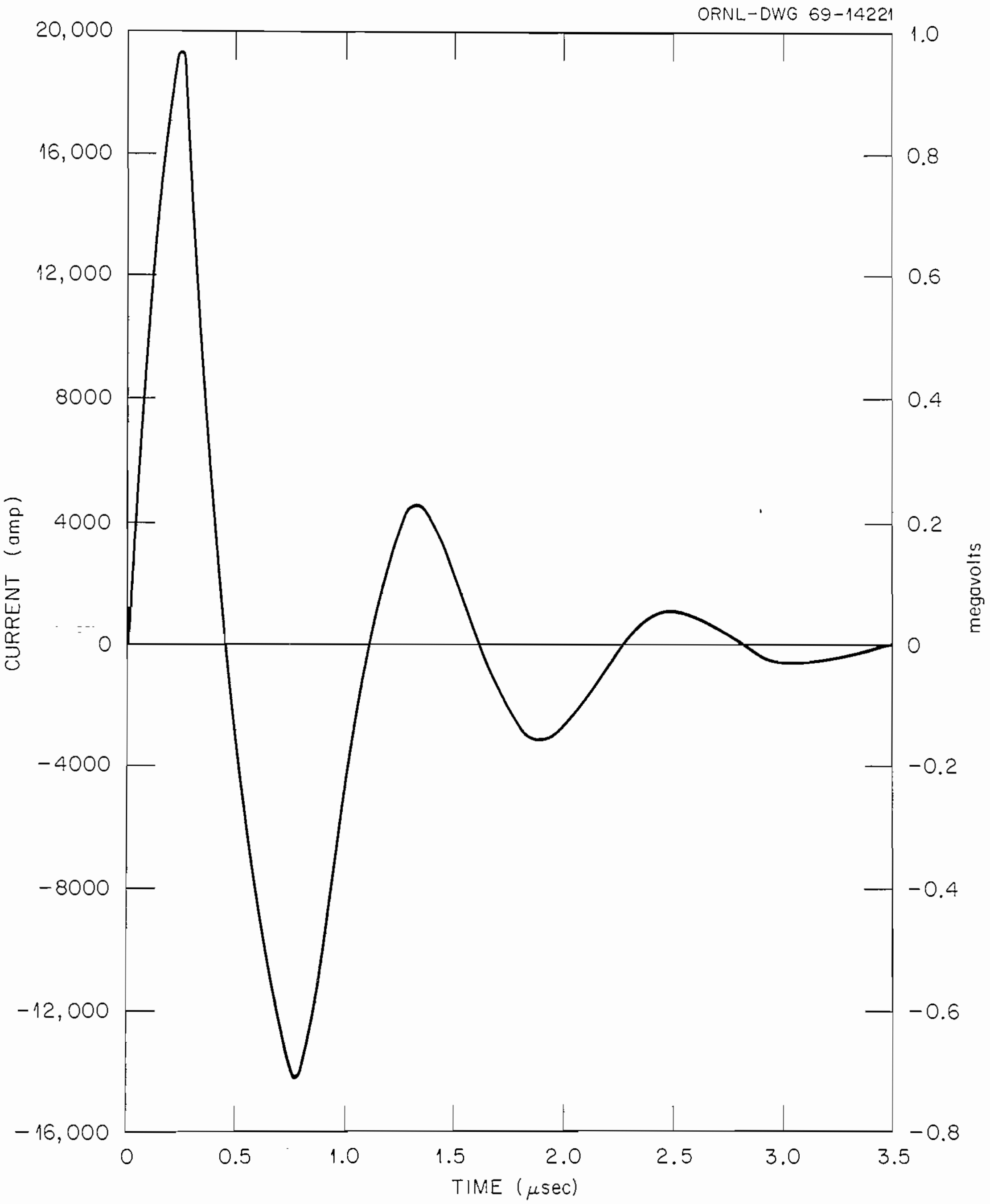

Figure 3.6. Current and Voltage Across 50 Ω Load When 75 Meter Monopole is Illuminated by Representative EMP.

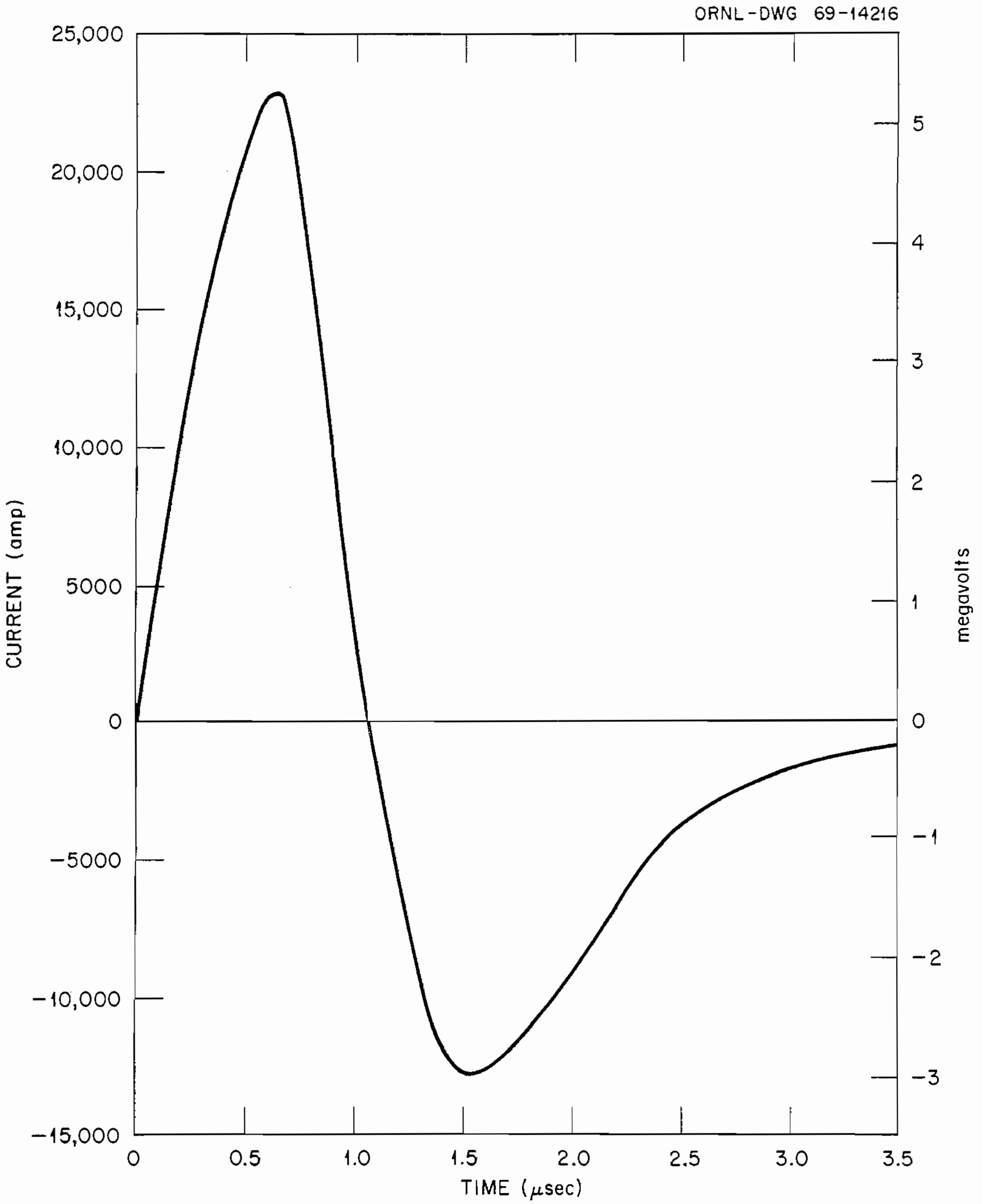

Figure 3.7. Current and Voltage Across 230 Ω Load When 200 Meter Monopole is Illuminated by Representative EMP.

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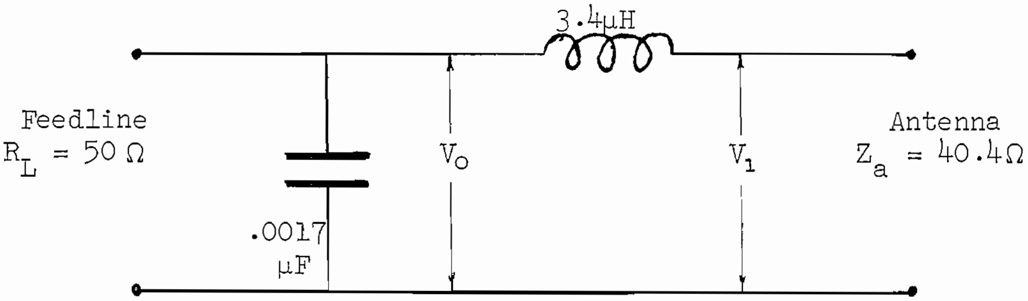

Figure 3.8a. L Network to Match 50 Ω Coaxial Cable to 75 Meter Monopole Resonant at 933 kHz.

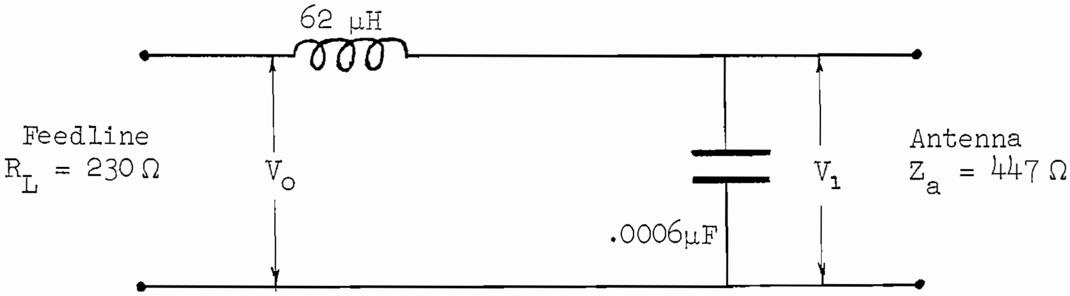

Figure 3.8b. L Network to Match 230 Ω Open Feed Line to 200 Meter Monopole Antiresont at 572 kHz.

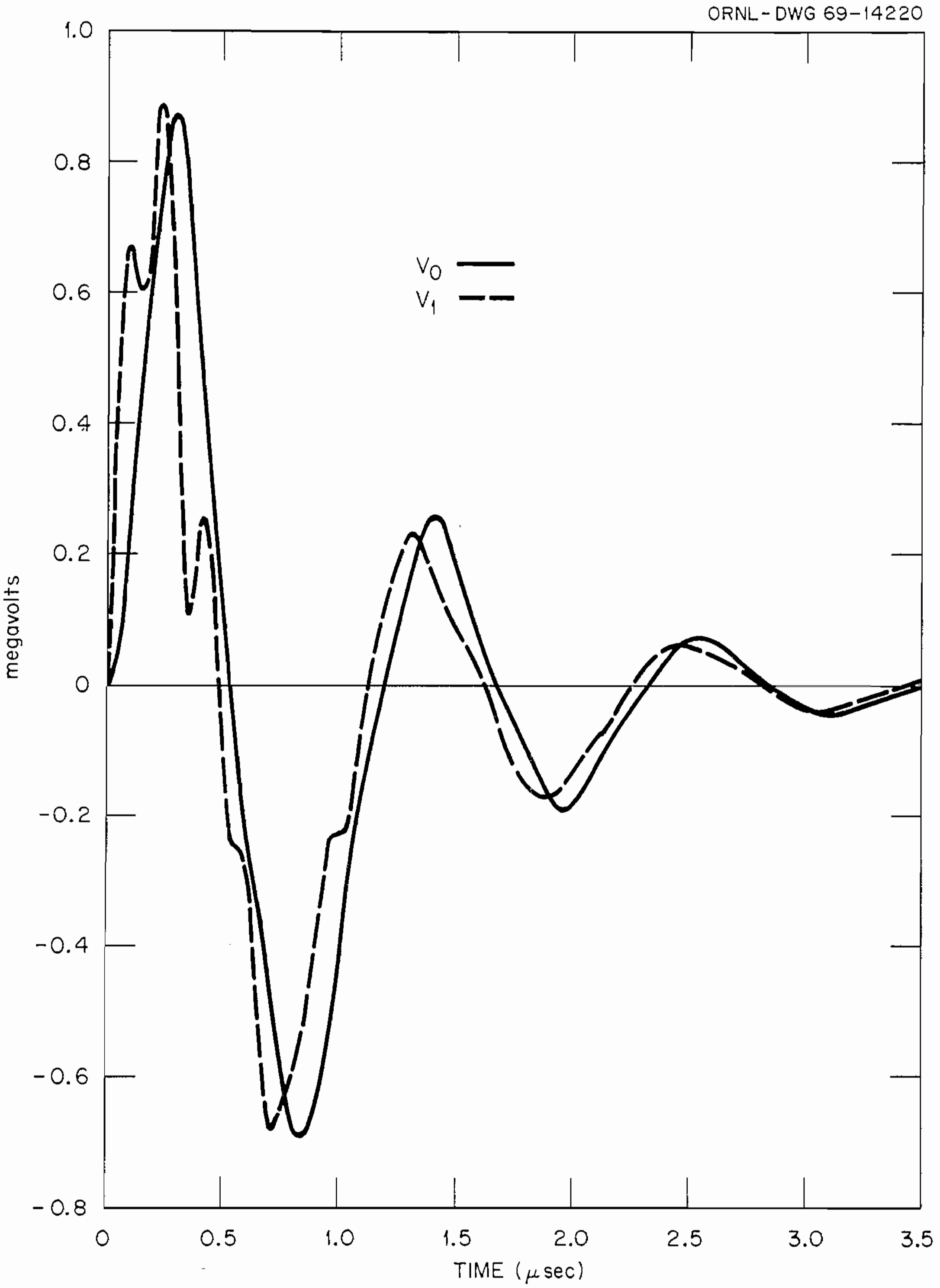

Figure 3.9. Voltage Across Spark Gap, V_1, and Across Capacitor, V_o, for 75 Meter Monopole with Matching Network.

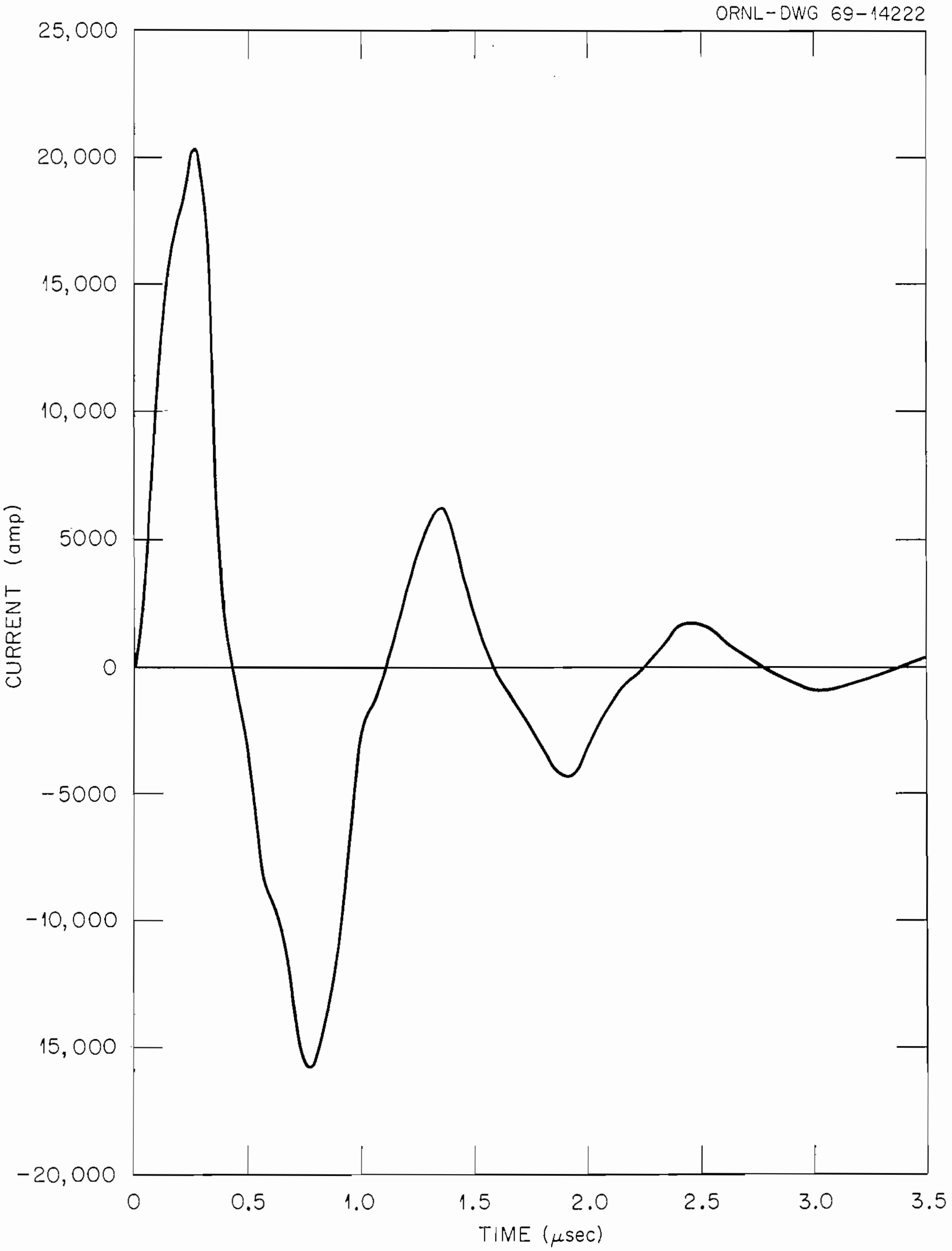

Figure 3.10. Current Drawn From 75 Meter Monopole With Matching Network.

the antenna has also been calculated for this case and is shown in Figure 3.10. Its peak value is 22 kiloamperes, slightly larger than when the matching network is absent, but qualitatively the two cases are indistinguishable.

Thus it may be concluded that the matching network for this antenna and feed line does essentially nothing to change the form of the induced pulse. It does, however, add a relatively vulnerable capacitor. This conclusion is not surprising; the antenna impedance and effective height plus the spectrum of the EMP are such that very little contribution to the induced waveform comes from frequencies above a few Megahertz. There the reactive impedances are unimportant compared to the resistive (more precisely the inductor's impedance is small and the capacitor's large compared to 50 ohms).

The 200 meter antenna is anti-resonant at 572 kHz; there its impedance is a pure resistance of 447 ohms. To match a 230 ohm open wire feed line to this requires the L network shown in Figure 3.8b.

For this case the voltage V_1 is across both the capacitor and the spark gap. Figure 3.11 is a graph of this voltage. Comparing this figure with Figure 3.7 shows that the rate of rise is slightly faster on the first half cycle and the peak of 5.8 megavolts is slightly larger when the matching network is present. V_o, the voltage pulse traveling down the feedline, is also given in this Figure. The current has been calculated for this case, and it exhibits almost identical behavior as shown in Figure 3.12. Again we may conclude that the matching network has little significant effect on the pulses.

3.3.4 Effect of the Spark Gap

Spark gaps are designed to protect the equipment across which they are connected against voltage impulses. They do this by arcing when the voltage across them exceeds a preset value (determined for a particular type of electrode by the gap spacing). The breakdown voltage normally is set less than the voltage required to damage the protected component but greater than the normal working voltage.

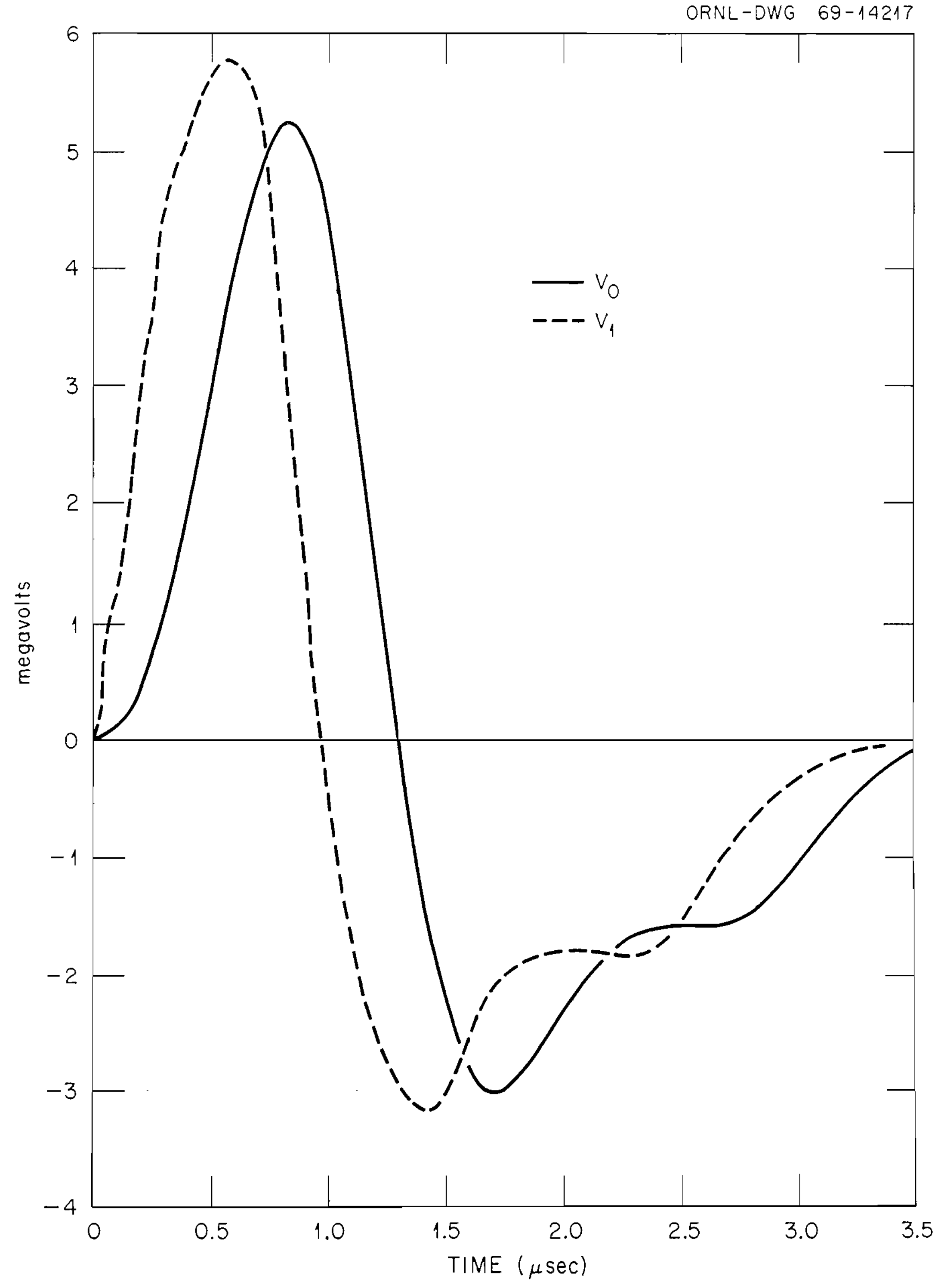

Figure 3.11. Voltage Across Spark Gap and Capacitor V_1, and Across Feed Line, V_o, for 200 Meter Monopole With Matching Network.

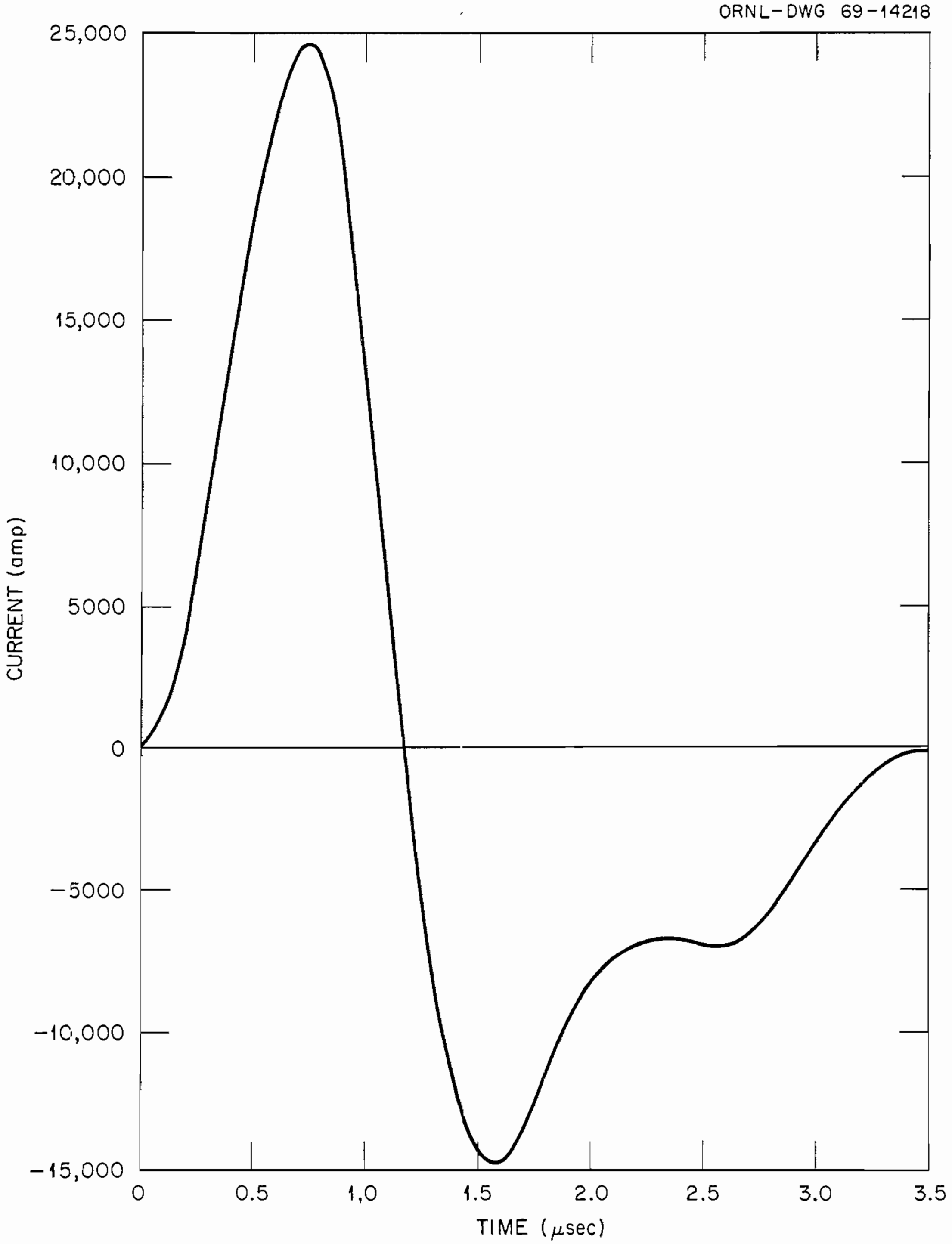

Figure 3.12. Current Drawn From 200 Meter Monopole With Matching Network.

Unfortunately the voltage at which the gap actually breaks down is strongly dependent upon the rate of voltage rise for impulses which reach the normal (or critical) breakdown voltage in a few microseconds or less. Figure 3.13 shows this dependence for a three inch rod gap (formed by two coaxial rods). The dashed curve gives the relationship between percent overvoltage above the critical breakdown voltage and the time of breakdown. The solid line, a hypothetical impulse, illustrates the application of the dashed line. For this impulse the gap breaks down at 200 percent overvoltage. A more rapidly rising impulse would cause breakdown at a higher voltage.

This effect, sometimes called voltage turn-up, is typical of all gaps. The amount of turn-up is dependent upon the electrode shape. Gaps formed by large spheres or planes exhibit less turn-up than do rod gaps. Turn-up can also be reduced by preionizing the gap, through the use of radioactive sources. Residual ions from a previous breakdown will also serve this function. Slower rising leaders preceding a lightning stroke may effect preionization which then lessens the turn-up for the main stroke.

Data on voltage turn-up and arc formation time lag in the submicrosecond region is not plentiful. Physics literature in this area is not very helpful since the usual method for studying the time lag in arc formation involves applying a constant voltage just below the critical sparkover voltage and then applying an additional voltage to make the overvoltage a few percent of the sparkover voltage.[13,14] There is some information in the power engineering literature, which even the physics literature recognizes as being the best currently available. For example, Meek and Craggs[15] cite the work of Hagenguth[16,17] and of Bellaschi and Teague[18] on this point. From references[15-18] the following conclusions may be drawn:

1. Electrodes with uniform field across the gap, such as parallel planes or large spheres, exhibit less overvoltage for short breakdown times than do electrodes with nonuniform field, such as rods.

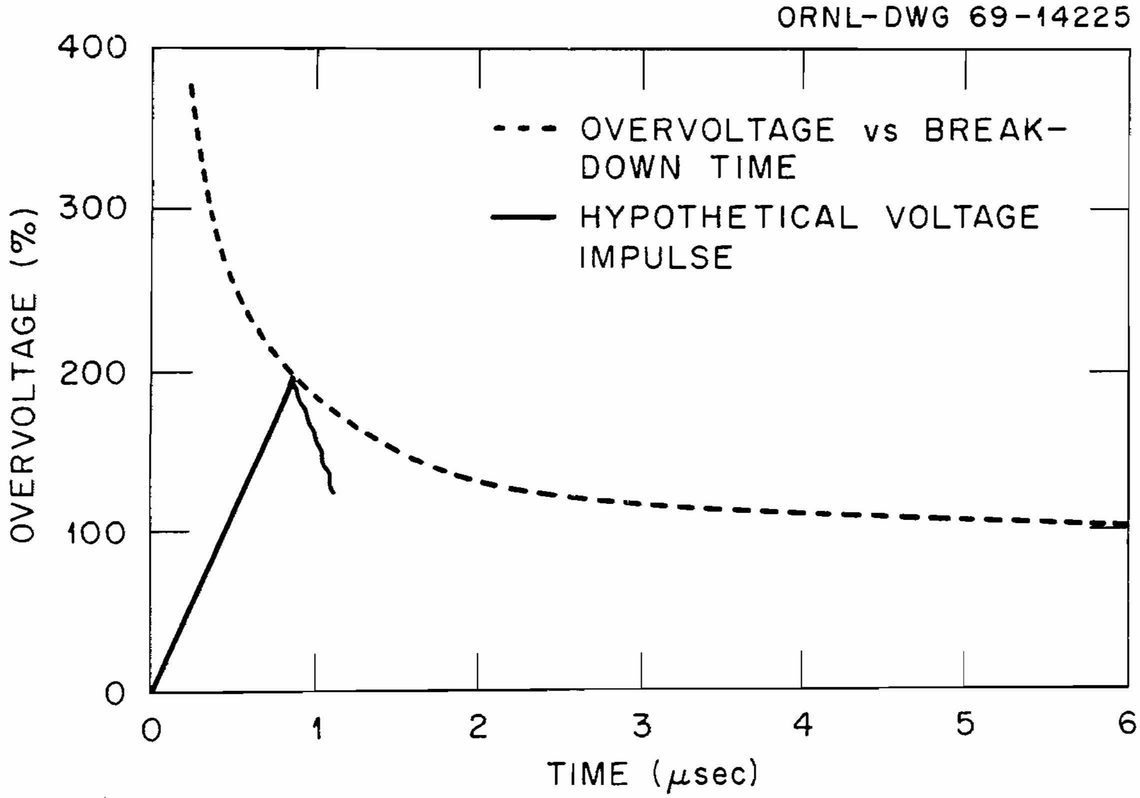

Figure 3.13. Gap Formation Time Lag, or Voltage Turn-Up, For a Three-Inch Rod Gap.

2. Because breakdown initiates slowly at one electrode and accelerates as it moves across the gap, gap spacing is of lesser importance in breakdown time than would be expected.
3. Overvoltage achieved is dependent on impulse time history up to breakdown time. It is greater for impulses which as functions of time are concave upwards or linear than for those which are convex upwards.
4. A plot of voltage turn-up for gaps typical of antenna lightning arrestors, with critical voltage of 30-50 KV and rod type or small diameter ball electrodes is tentatively suggested to to be as given in Figure 3.13.
5. Once the gap has fired, the voltage across it is reduced to at most a few hundred volts in a fraction of a microsecond.

The available data does not permit even an estimate of the voltage time curve across the capacitor because these voltage pulses rise so extremely fast. The lowest measurements are for about 0.25 μsec. They indicate an overvoltage of about 400 percent. For a 40 kilovolt critical voltage this is 160 kilovolts. Figures 3.9 and 3.11 indicate that the voltage exceeds 160 kilovolts in 0.01 μsec. The best one can say is that voltages considerably in excess of 200 kilovolts, and possibly as high as 500 to 700 kilovolts will exist across the capacitors for a fraction of a microsecond.

Unfortunately, we have no data on the time required to puncture the mica dielectric that is typically used in these capacitors. It will be appreciated that puncture voltage for these short impulses exhibits a turn-up phenomenon similar to that of spark gaps. For some types of insulation (oil is an example) the turn-up is less than for the spark gaps discussed here, i.e. the protected components are more vulnerable to fast rising impulses. Lacking this data on components typical of transmitters, we must rely on the comparison of EMP-induced surges with direct lightning strokes discussed in the next section.

3.4. COMPARISON BETWEEN EMP AND LIGHTNING SURGES

Direct lightning strokes are essentially constant current sources. The wave shape of lightning currents usually exhibits a steep rise, lasting a few microseconds, to a peak current of up to 100 kiloampheres or more. The current decays in tens of microseconds. Figures 3.14 to 3.16 taken from Feference 19 give respectively the percentage distribution of lightning stroke peak currents, rate of current rise on the front of the surge, and time to crest. The faster rising currents generally have a smaller crest value.

Comparing the peak current of 20 to 25 kiloamperes obtained from the EMP with Figure 3.14 reveals that in terms of this parameter EMP parallels a slightly stronger than average direct stroke. A more important measure for components protected by spark gaps is the rate of current rise, for this translates into peak voltage before the gap fires as explained in Section 3.3.4.

The values of 53 and 118 kiloamperes per μsec for the calculated EMP surges, compared with Figure 3.15, reveals a startlingly greater rate of rise for the EMP currents. As explained in Section 3.3.4, components will be subject to a greater overvoltage from these pulses. Because there is no leader associated with EMP, gap preionization as occurs with some lightning strokes will not take place, and the difference in overvoltage could be even greater than indicated here. Lower field strength EMP could duplicate the full range of current rate of rise experienced with lightning.

3.5 CONCLUSIONS

The chief verifiable finding of this chapter is that EMP will put as much strain on gap-protected transmitter, phasor, and matching networks as any direct lightning stroke, and in one parameter, the overvoltage attained before gap breakdown can be expected to considerably exceed lightning. The higher over-voltage is associated with a shorter voltage pulse duration, so the significance of this fact must be weighed by component tests.

The components most likely to be damaged, based on lightning experience, are high voltage capacitors. Since dielectric puncture is cumulative (partial puncture from one pulse renders puncture more likely for succeeding strokes) the numerous EMP pulses expected in an attack are likely to

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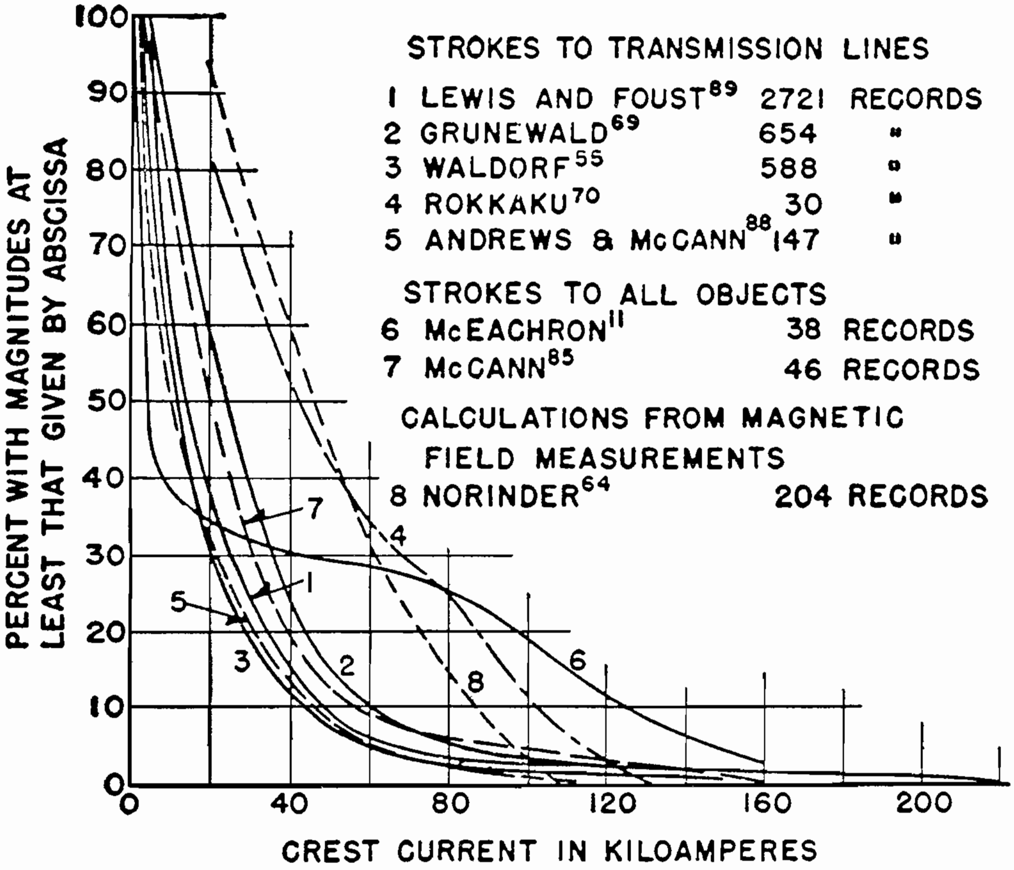

Figure 3.14. Peak Lightning Currents. Taken from Reference 19, q.v. for References shown here.

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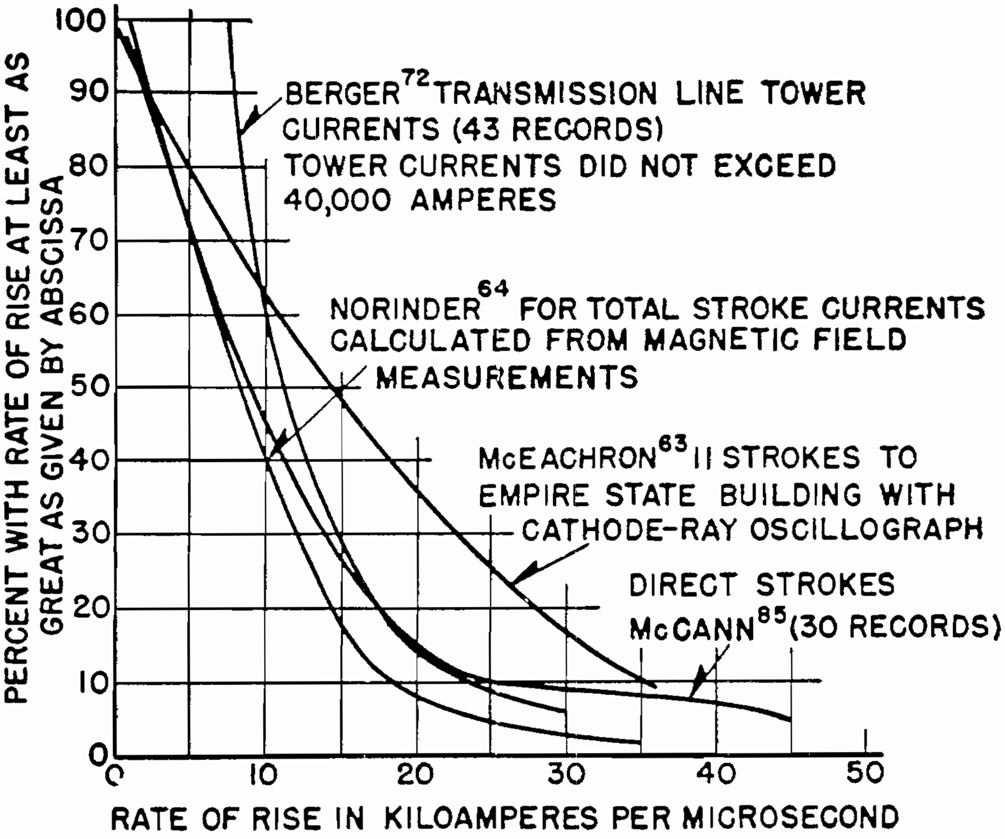

Figure 3.15. Rate of Current Rise for Direct Lightning Strokes. Taken from Reference 19, q.v. for References shown here.

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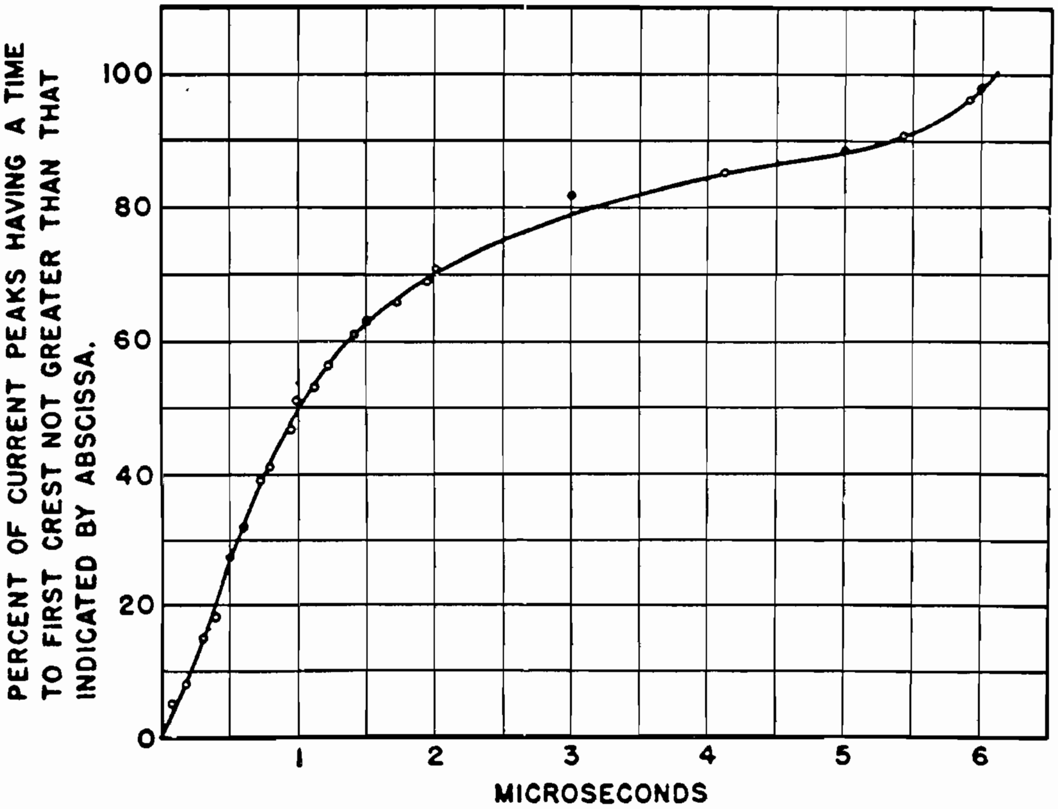

Figure 3.16. Time to Crest of Direct Lightning Strokes. Taken from Reference 19.

result in significantly more capacitor damage than reported for lightning. The most likely system result of this damage is a short from feed line to ground across the capacitor which will preclude transmission until repaired.

These fast rising surges go beyond present data on spark gap performance and on component damage modes such as dielectric puncture. Before more concrete statements can be given than those in the above paragraph, it is essential that such data be obtained.

Normal matching networks will have no significant effect on pulse shapes reaching transmitter components. However, the capacitor used in the matching network may be damaged.

Additional damage possibilities, based on lightning experience, include damaged antenna guy wire insulators and resulting short circuits to ground as well as coaxial transmission line damage due to dielectric flash-over. During lightning strokes, guy wire insulator flash-over dissipates much of the lightning currents, as discussed in Section 2.6, and hence can be a beneficial effect. On the other hand, EMP caused flashover will not dissipate energy. Hence, comparison of EMP with lightning caused damage, even as we have done here, could seriously understate the damage potential of EMP. This is so because lightning involves current injection, but EMP involves field induction. Lightning currents injected into the antenna will follow parallel paths down the guy wires and mast. But for EMP, even if most of the insulators short out, the configuration is merely changed from that of a dipole (mast plus its image) to that of a folded dipole (mast and guy wires plus their images).

Voltage across the spark gap induced by EMP is so great that arcing is virtually certain. Power follow will cause opening of transmitter circuit breakers. Those set in manual mode will require operator resetting. Multiple pulses (as will be expected) may cause lockout after three reclosings for circuit breakers in automatic mode. Again this would require operator resetting. If direct access can be gained to the transmitter, time required is very short, but if station personnel are confined by fallout or other weapons effects to the fallout shelter, time off the air could be hours or days.

CHAPTER IV
POWER LINE ANALYSIS

4.1 ANTICIPATED POWER LINE SURGES FROM EMP

Above ground power lines form excellent receiving antennas for EMP, and because of their length they can collect large amounts of energy, delivering it to an attached load and possibly causing damage. The most successful analyses of surges developed on power lines have considered them as transmission lines with the ground forming the return conductor. The currents developed in the three phases of the line are almost identical, and the voltages which exist across the load are with respect to ground; phase to phase voltages are comparatively small. Because of this, it suffices to consider for a model of a power line a single conductor terminating in a load connected to ground, as shown in Figure 4.1. When the EMP fields intercept the wire, current is induced. This current flows down the transmission line and through the load to ground. Part of the current may also be reflected and travel back away from the load. Across the load is a voltage drop given by the product of the current and the load impedance.

The magnitude of the current and voltage pulses depends strongly on the impedance of the load and less strongly on such details as the height above ground of the transmission line, the conductivity of ground and wire, and the angle of incidence of the pulse.

As representative examples, we have calculated the current and voltage in two loads: one with an impedance of 100 ohms (a moderate load for a power transmission line) the other an impedance of 450 ohms (a light load). Figures 4.2 and 4.3 show the results when the loads are connected to long (many kilometers) typical power lines which are illuminated by the representative EMP defined in Section 1.4. The early parts of the curves are valid for shorter lines as well. Because voltage and current are proportional, the figures have two scales but only one curve for each case.

In both cases the peak voltages and currents are attained in about 0.5 µsec. Peak voltage for the 100 ohm load is about 320 kilovolts; for the 450 ohm load it is 940 kilovolts.

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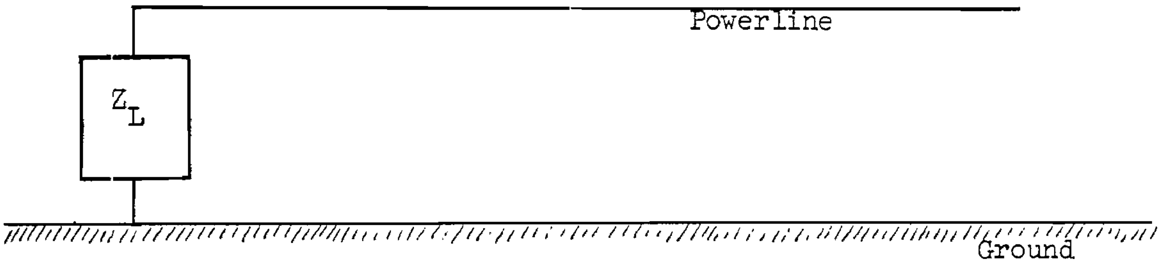

Figure 4.1. Schematic of Power Line with Load.

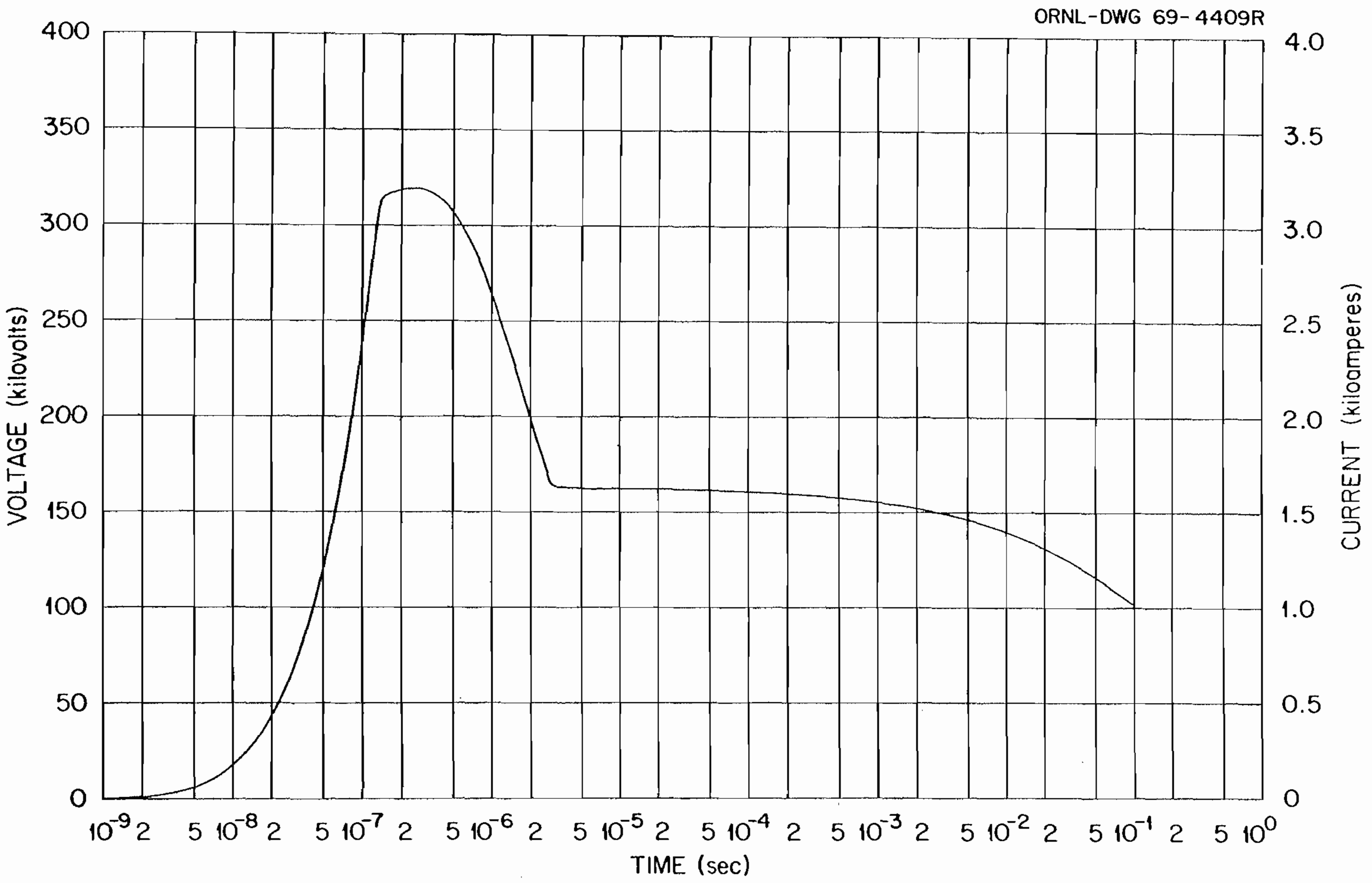

Figure 4.2. Voltage and Current Across 100 Ω Load Connected to Long Power Line When Illuminated by Representative EMP.

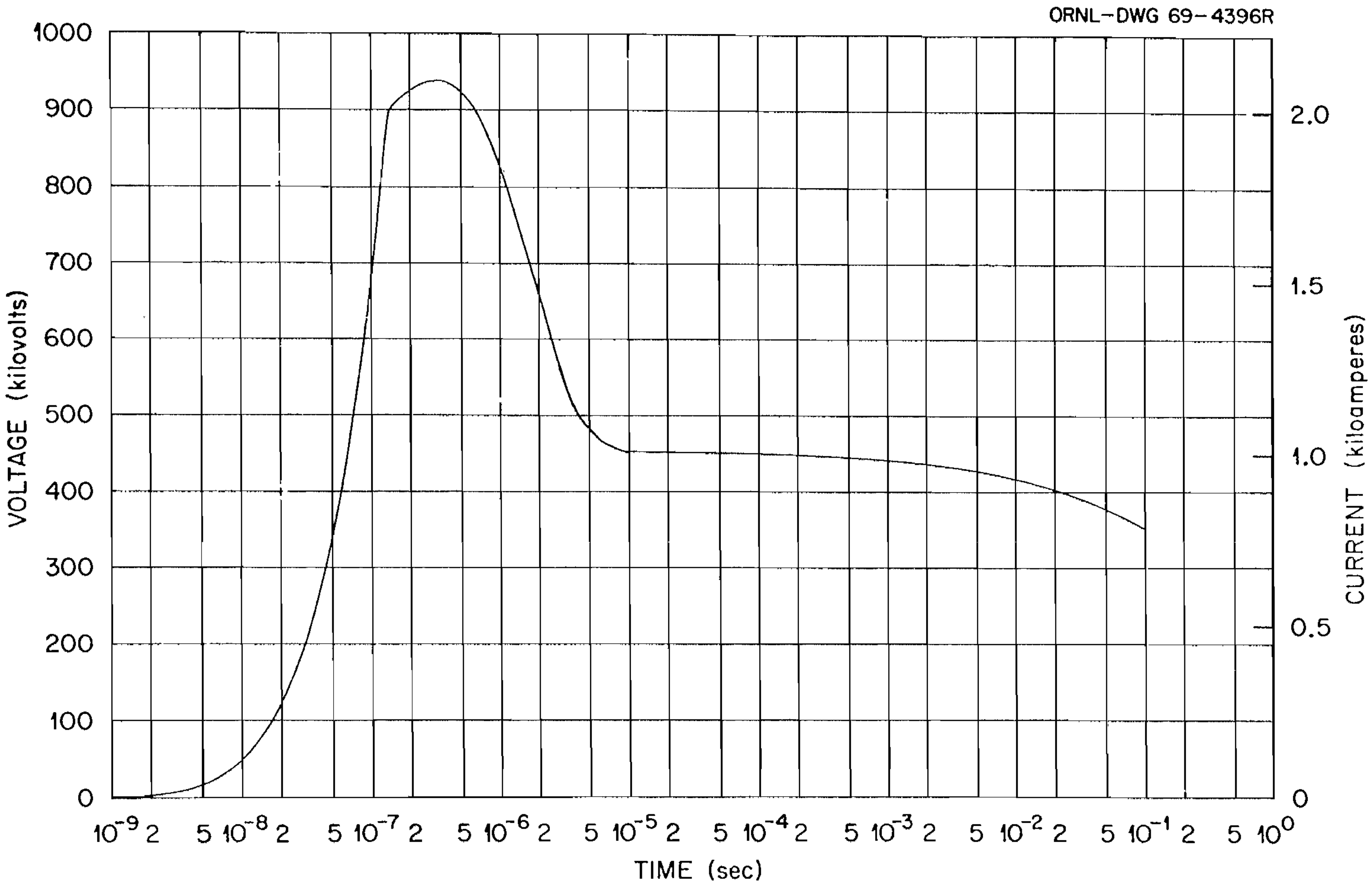

Figure 4.3. Voltage and Current Across 450 Ω Load Connected to Long Power Line When Illuminated by Representative EMP.

Although the analysis is reasonably accurate for the cases considered and includes such effects as the reflection of the EMP from the ground and dispersion in the transmission line due to finite conductivity of ground and wire, it cannot be considered as, for example, being representative of the pulse one would see across the terminals of a wall outlet. Unfortunately, power lines are much more complicated electromagnetically than are broadcast antennas; equivalent accuracy is very difficult to obtain. The chief flaws in this model of a power line are that the transformer which would be ahead of any load is omitted as is the power line lightning protection.

Efforts are currently underway to reduce these and other limitations of the model. Tentatively we believe that:

1. Capacitative coupling across the windings of normal transformers, those without special electrostatic shielding, will pass at least the early part of these pulses.

2. These voltages are with respect to ground and are approximately equal on all three phases (common mode). Thus the greater danger would exist in equipment connected from one phase to neutral rather than in equipment connected between phases.

3. Secondary lightning protection installed immediately adjacent to the station will be at least partly effective in shunting these pulses. Primary protection as well as secondary arrestors more than a few hundred feet from the station are of questionable value.

Accordingly one must expect large transients at equipment connected to the power line. These transients can cause damage ranging from burned out transistors to shorted capacitors, fused or vaporized coils and conductors, and possibly exploding transformers.

Power system equipment could also be damaged by transients coupled into power lines. If this damage were sufficiently severe, power service interruptions would result, lasting for hours to days.

The transients discussed in this section would be expected from overhead power lines. If all lines are below ground, the pickup is much reduced. However, few broadcast transmitters will be serviced by such lines because they are generally located in sparsely populated areas zoned for commercial use. High costs presently argue against underground power lines for such areas.

4.2 PROTECTIVE MEASURES

Fortunately many key AM broadcast stations have been supplied by OCD with emergency generators. In every case at the stations visited these generators could be reliably started and the load shifted to them within a few seconds. In one case there was automatic switchgear to accomplish this in the event of a power failure. Diesel oil is stored sufficient for two weeks continuous operation under load. Wiring from generator to equipment is generally encased in conduit and seldom are the runs longer than one hundred feet.

If the stations are disconnected from the power lines before the first detonation, the pulses picked up on these lines are effectively blocked from the station equipment. We therefore recommend highly that those stations possessing generators switch immediately to them upon receipt of tactical attack warning, or possibly even in advance of this, during a period of rapidly escalating crisis. The two weeks' fuel supply makes the penalty of a few hours or even days of generator operation relatively minor. This simple scheme would serve in place of extensive (and expensive) surge protection. If power is not disconnected, EMP pulses may well damage transmitter equipment.

One weakness of the changeover switch is that it generally leaves the power line unterminated. The gap between switch contacts in the open position is only an inch or two as shown in Figure 4.4. High voltages could arc across this gap and still deliver a strong pulse to station equipment. A simple scheme such as given in Figure 4.5 uses an additional switch to insure that any arc is conducted to ground.

Operationally, this protective scheme is not foolproof, since human action is required for the changeover. In addition, attack warning may not be given before the first detonations. But this scheme does represent a very positive first step to assure fairly good protection at essentially negligible cost. As better information is developed regarding power line surges from EMP it will be desirable to review these recommendations.

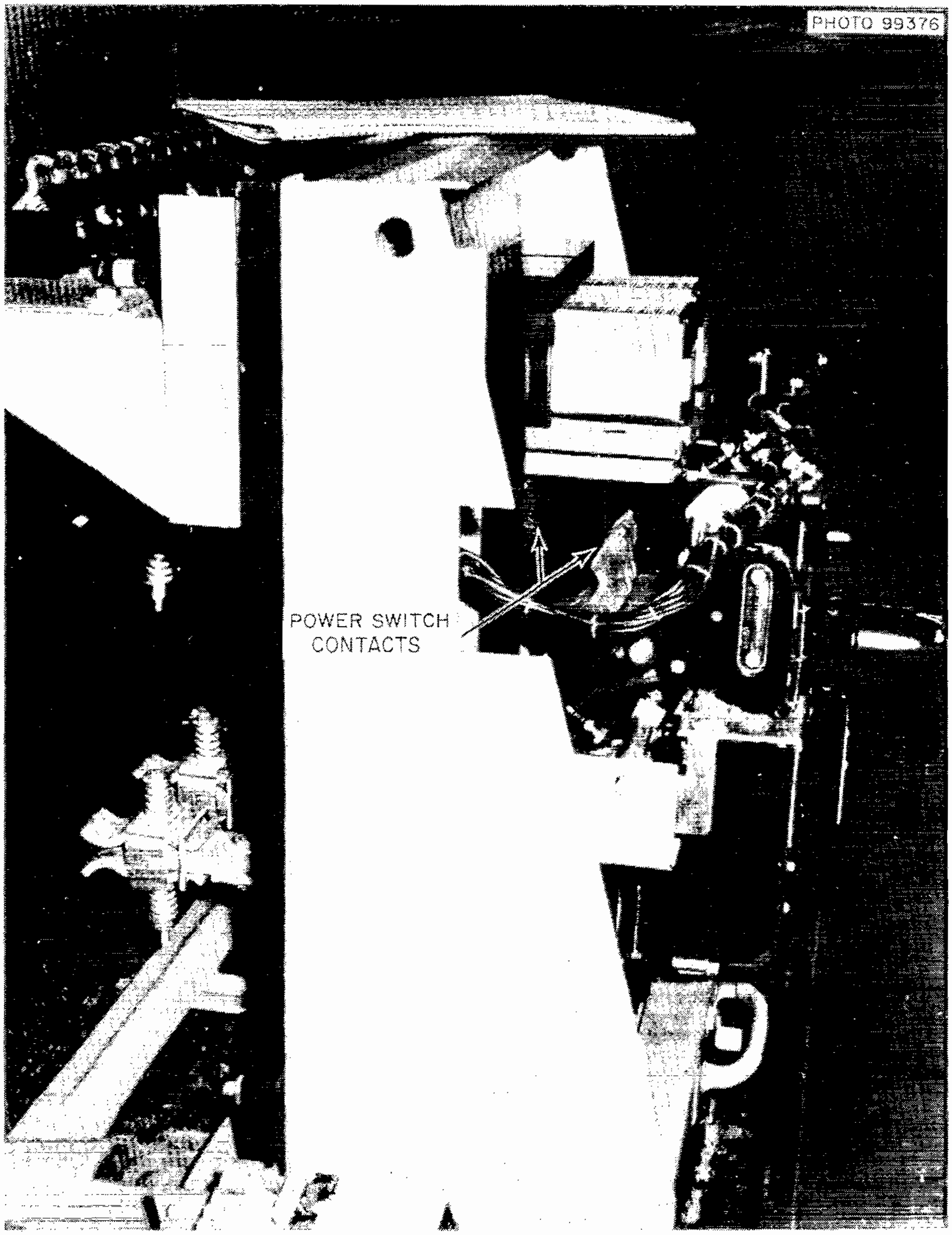

Figure 4.4. Side View of Main Power Switch Showing Contacts in Open Position.

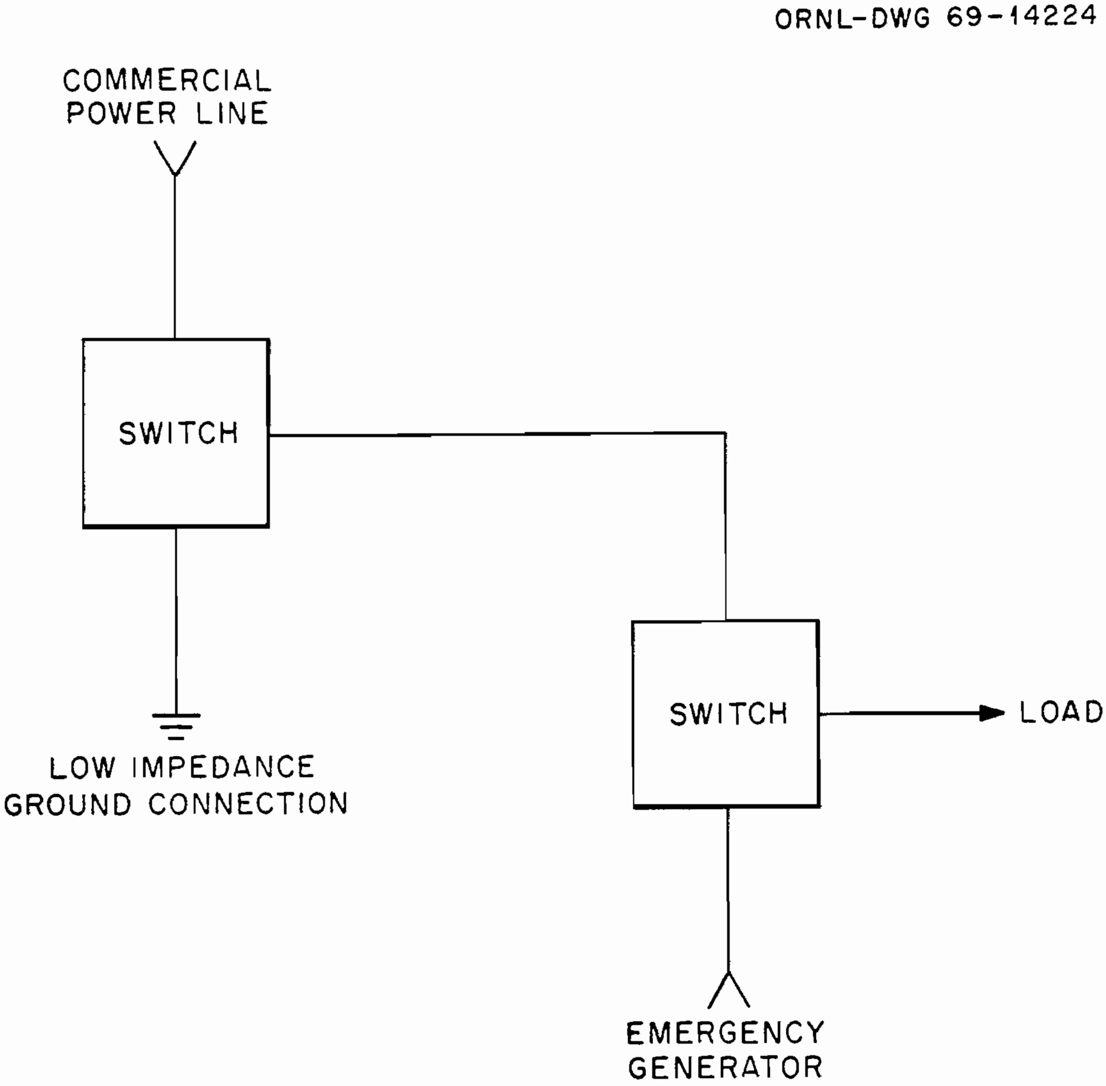

Figure 4.5. Switching Scheme to Avoid Arcing.

CHAPTER V

LINKS BETWEEN STUDIO AND TRANSMITTER

5.1 INTRODUCTION

At the lowest level of sophistication the studio and transmitter are housed in the same building, in close physical proximity. With this arrangement the only "links" are twisted pair or shielded cable connecting the audio console to the transmitter. Network and wire service feeds terminate in the same building. With such an arrangement there is slight danger of EMP damage severing the connection between studio and transmitter.

A more typical arrangement for modern stations is a studio separate from the transmitter. The most common link between the two is via telephone lines, although microwave may also be used. A few stations have the emergency alternative of using the VHF or UHF two-way radios normally used for their news cars.

Studio audio consoles, especially the increasing majority using transistorized equipment, may be subject to EMP damage, either from pulses conducted in on power lines or from currents induced directly on long audio cables. In particular, those studios remote from the transmitter, lacking a high level ambient RF field with its attendant hum problem, may be less exact in their grounding, shielding, and wiring practices than those near their transmitter. Other things being equal, this would tend to increase the probability of damage.

5.2 TELEPHONE LINKS

Present knowledge about EMP effects on metropolitan telephone circuits is too limited to permit estimates of damage probability. Areas of possible concern include damage to subscriber's or central office equipment from pulses induced on telephone wires, faulty dialing or loss of connection, and central office damage from surges induced on power lines. Since information is lacking, no recommendations can be given.

5.3 MICROWAVE LINKS

Microwave transmitting and receiving dish antennas will not pick up enough energy to damage most circuits. Long (few hundred feet) coaxial cables such as from a dish at the top of a tower down to the receiver may intercept enough EMP energy to damage sensitive front end circuits. In this regard, attention should be paid to transistor circuits which are inherently more sensitive to EMP damage than older, tube-type circuits. Of particular concern are field effect transistors (FET's) often used as RF amplifiers.

Pulses coupled through the power line may also be a cause for concern, as outlined in Chapter IV. Again, use of generator power would reduce the possibility of damage.

5.4 VHF AND UHF TWO WAY RADIO

The energy spectrum of the representative EMP falls rapidly above a few tens of MHz. Antennas resonant at frequencies higher than 100 MHz. will couple much less energy into associated circuits than the monopoles discussed in Chapter III. Still, even at these frequencies enough energy is received to be potentially damaging to RF transistors. To illustrate this we have calculated the voltage and current across a fifty ohm load attached to a vertical monopole over a ground plane with antenna height of 0.75m and shape factor of 12.5. This antenna could be a car roof mounted monopole for a mobile two way radio with an operating frequency of about 200 MHz. Figure 5.1 gives the results of this calculation. Although the voltage and current attain relatively high values compared with normal working parameters, they last only a few tens of nanoseconds. The energy delivered is about 10^{-4} joules, which is roughly ten times the amount required to burn out a FET if applied optimally. Since tuned circuits, parallel current paths, etc. will drain away some of this energy, damage probability cannot be predicted except on a case by case basis.

In general, especially in the 450 MHz. band, we would be cautiously optimistic about the survivability of mobile two way radio links. For the fixed station the same caveat about the commercial power lines applies as given elsewhere.

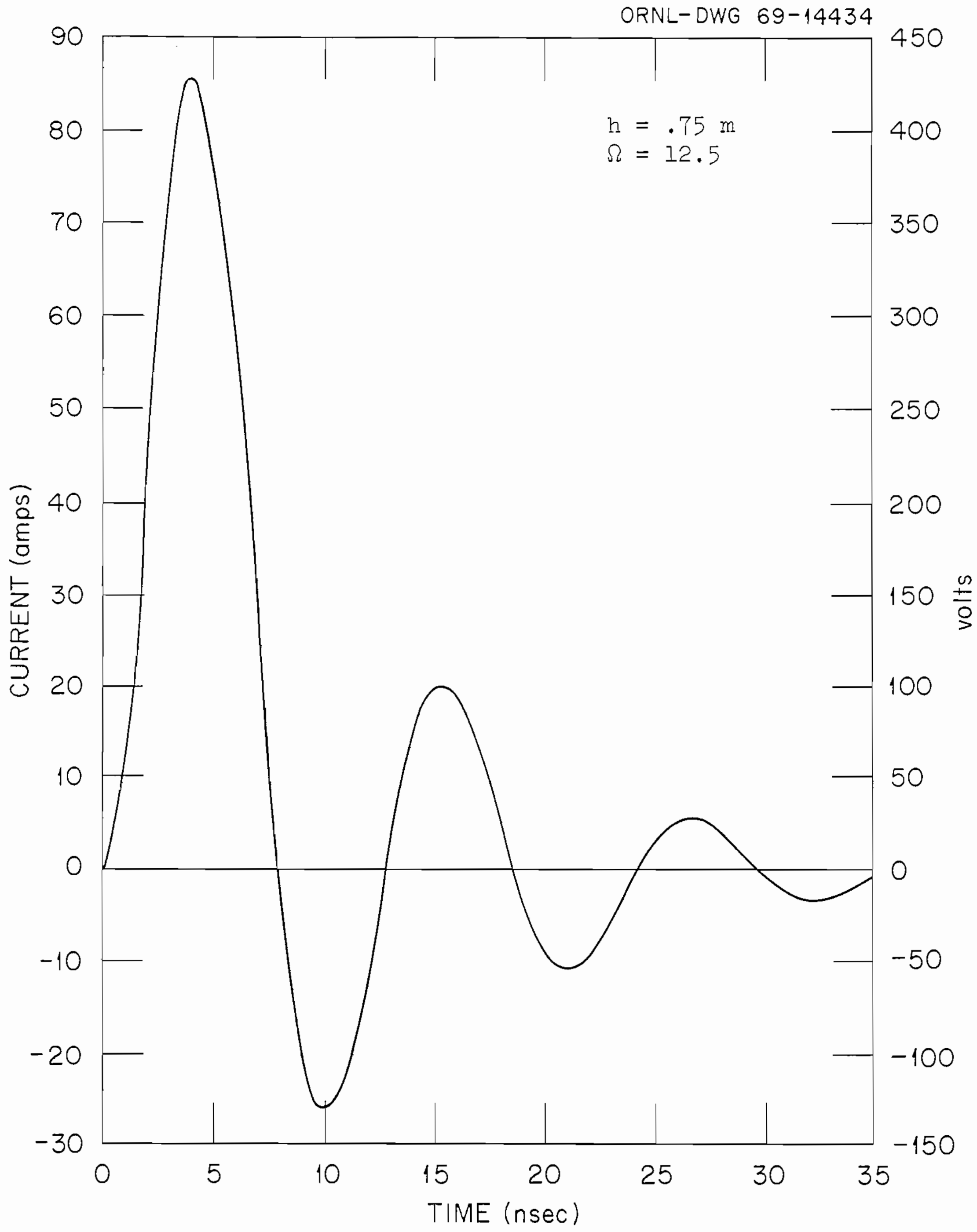

Figure 5.1. Current and Voltage Across 50 Ω Load When 0.75 Meter Monopole is Illuminated by Representative EMP.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

Because of financial exigencies and the uncertain reliability requirements of the EBS, it would be unwise at present to recommend massive station hardware modifications, even if these should be required. In addition, the lack of data on national and regional communications channels makes one uncertain whether the AM broadcast stations are the weakest link. If money were to be spent, it should go where most needed.

Accordingly, the conclusions and recommendations will concentrate on procedures which could measurably reduce station vulnerability at very low cost. Because of the tentative nature of some of the conclusions, it must be appreciated that not all recommendations may be important, or conceivably even correct. They represent the best that the state-of-the-art can offer and point the way to most probable improvement until the art and science of EMP analysis are further advanced.

6.2 MOST PROBABLE DAMAGE

We have isolated three areas of concern regarding EMP damage to station operation. Of these the most fully documented concerns energy coupled into the antenna. Although this energy is rather less than for an average direct lightning stroke, when the protective action of the spark gap is included the strain on transmitter, antenna insulators, transmission lines, phasor, and matching network components is fully equal to that of lightning and in some respects exceeds that of the latter by a considerable amount. Because high voltage capacitors are reported to be damaged fairly frequently by lightning, we conclude that EMP would also damage them. The damage probability cannot now be ascribed with confidence because of the current lack of experimental data. It could be quite high. Possibly other components could be damaged as well, but uncertainty regarding them is even higher.

Damage caused by coupling to the antenna should not be difficult for station engineering personnel to repair, and the spare parts required might well be on hand. Time required would probably be a few hours but the necessity for working in the open would preclude these repairs under heavy fallout conditions or threat of nearby detonations. Further, there may be an electrical hazard, if repairs are attempted during a period when EMP may reoccur.

There is some evidence that vacuum capacitors are less susceptible to EMP damage than are those using mica dielectric. Unless the glass envelope explodes, the dielectric in the former is self healing.

Currently, some interest is being given to the possibility of using materials such as thyrites for antenna insulators to give increased protection against lightning strokes. These would be of negligible aid for EMP protection, because of the differing mechanism of current production in the antenna structure as noted in Section 3.4.

The possibility of coaxial transmission line arc-over should not be completely discounted. If this should occur, it could take many hours to replace, and most stations do not stock spare sections of cable.

Stations whose directive radiation patterns require more than one antenna gain somewhat in the survival probability of at least one antenna and its coupling network. Station personnel report that a shorted antenna can be disconnected from the transmitter. Loading the remaining antennas requires retuning which would take some minutes to an hour. Depending upon relative phase, the impulses from the multiple antennas could add at the phasor to create a strain more severe than that of an individual antenna. Hence, it would be wise to disconnect all but one antenna at the first tactical warning.

Voltage across the antenna spark gap is so great that arcing is virtually certain. Transmitter circuit breakers will trip to prevent power follow. Multiple pulses could cause even automatically reclosing breakers to lock out as described in Chapter III. While this effect does not cause damage, if station personnel are unable to reach the transmitter because of heavy fallout or threat of detonations nearby, an indeterminate amount of time may elapse before the breakers are reclosed and transmission resumed. In no known instance is the transmitter itself located in the fallout shelter.

Antennas for FM broadcast transmitters will pick up less energy from EMP because of their smaller size. However, these transmitters use much more transistorized equipment so they are not necessarily less damage prone.

Damage from power line coupling is less well established. We do not yet know what fraction of the induced surges will propagate past transformers and other discontinuities. Damage from this mechanism could be more serious than from antenna coupling. The many entries of AC power into a transmitter might cause damage at several locations which would be hard to diagnose and rectify. Such damage could occur in studio as well as transmitter equipment and would affect FM stations as well.

Fortunately, the presence of a diesel generator obviates much of the need for further analysis in this area if the station can be disconnected from the power line before the first detonation. Since this must be done manually upon receipt of attack warning, rather stringent warning time requirements are imposed.

Damage to links between studio and transmitter is even more uncertain. Microwave transmitters and receivers should be fairly immune if not connected to the power lines, but they are used uncommonly compared with telephone lines. Information on metropolitan telephone system vulnerability is presently unavailable. The exigencies of emergency operation plus the greater chance that a studio located in the central city will suffer blast or fire damage makes one unhappy about studio-transmitter separation independent of EMP effects.

It is the requirement of a teletype terminal plus network feeds which usually dictates this separation under emergency conditions. Lack of space at the transmitter site may also be a factor. Where possible, serious thought should be given to consolidating emergency operations at the transmitter. In most cases, however, such a provision might be economically unfeasible. Fortunately every transmitter visited had at least a microphone and the possibility of getting an audio signal on the air. (Instances have been reported where this was impossible!) This plus the incoming phone line provides at least a rudimentary back-up (which again may be subject to damage). Two-way mobile radio provides another form of back-up which, although possibly damaged by EMP, may well remain unscathed. Particularly in the 450 MHz. band or higher, available energy is too small to damage all but the most sensitive of receiver RF amplifiers.

6.3 OTHER CONCLUSIONS

Broadcast transmitters are inherently rugged and conservatively designed. In addition, station engineering personnel are generally capable and ingenious. If not pinned down by direct weapons effects or by heavy fallout concentrations (and if they have radiation detection equipment to ascertain this) most damage caused by EMP should be reparable using station personnel and spare parts on hand.

Probably the most critical time interval for the EBS is the tactical warning period. Reliable operation during this interval is of extreme importance if the population is to be adequately sheltered. It appears from the conclusions of Section 6.2 that EMP damage might be inflicted during this period to AM broadcast transmitters over a large area which could not be repaired within the few minutes available. At present, redundancy in numbers of stations appears to be the best defense against this. Neither procedures nor inexpensive hardware are currently available to guarantee freedom from damage to a given station. This problem may be eliminated if the proposed nation-wide low frequency radio voice warning system DIDS (Decision Information Dissemination System) is installed. The small number of transmitters required would make EMP hardening fairly easy at sufficiently low cost. This possibility does not exist for the EBS.

Many stations maintain two transmitters with provision for rapid switching between them. This fact decreases somewhat the chance that a station would be knocked out by EMP. If one transmitter were completely isolated from the antenna and power line, including adequate gaps to prevent flash-over, the likelihood of damage to that transmitter is virtually zero. Of course the transmitter must remain disconnected until the last detonation. Ascertaining when this was might be difficult,and damage to the antenna matching capacitors might still preclude broadcasting.

6.4 RECOMMENDATIONS

6.4.1 For Proximate Implementation

The first requirement is that station engineering personnel be informed that EMP exists. They should expect possible damage to their transmitting equipment in a fashion sometimes similar to lightning. It should be explained that the most likely sources of damaging energy are the transmitting antenna and the power line. Current lightning arrestors may not function satisfactorily when confronted with EMP.

Second, attack warning should be expedited to EBS stations which would switch immediately to generator power, isolating themselves from the power line as completely as possible.

Third, radiation detectors should be provided to all EBS stations. Personnel will have to leave fallout shelters to make repairs.

Fourth, stations should maintain stocks of spare parts, particularly capacitors and possibly antenna coaxial cable feed lines, which might be damaged. Since this is already customary, the recommendation would ensure that stocks were not depleted.

Fifth, a microphone and basic audio console should be kept at the transmitter site of stations with a remote studio.

6.4.2 For Consideration and Possible Implementation

Stations with remote transmitters should consider whether it would be possible to consolidate emergency operations at the transmitter, including provision for wire service teletype, network feeds, Civil Defense radio, and required minimal audio console.

Stations with two transmitters might isolate one of them, during emergency operations, from power line and antenna. It would be available if the primary transmitter were damaged.

Spare feed lines might be installed for manual connection if needed. The necessity for going outside to repair damaged matching capacitors at the antenna base suggests that stations experiment with the possibility of dispensing with the matching circuit, at reduced transmitting efficiency, under crisis conditions.

Another alternative would be to erect an expedient horizontal wire dipole, cut to match a feed line into the transmitter building and fitted there with a lightning arrestor employing large spheres or planes instead of points to reduce the voltage turn up. Gap spacing should be set so that modulation peaks almost cause arcing. A horizontal antenna has the added attraction that ground reflection of EMP reduces the pulse delivered as compared with a vertical antenna. This antenna could be connected to the transmitter upon receipt of attack warning.

Consideration might be given to reserving some stations from the EBS until other stations are damaged or until conclusion of the attack. These stations, possibly the existing alternates, would isolate their transmitters from antennas and power lines to avoid damage. Since small AM receivers with ferite core antennas are virtually immune to EMP damage, unless placed near wires, pipes, or other conductors, these stations could monitor those broadcasting, ready to switch on in case of signal failure.

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APPENDIX

The following five stations of the EBS, selected by OCD and the FCC, were visited in connection with this study and station engineering personnel interviewed:

WDOD	Chattanooga, Tennessee
WSB	Atlanta, Georgia
WSOC	Charlotte, North Carolina
WBT	Charlotte, North Carolina
WJLS	Beckley, West Virginia

These interviews, plus observations of station details, provided the basis for much of Chapter II of this report.

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