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RADIO FREQUENCY EMISSION CHARACTERISTICS AND MEASUREMENT PROCEDURES OF INCIDENTAL RADIATION DEVICES AND INDUSTRIAL, SCIENTIFIC AND MEDICAL EQUIPMENT

H. Martin, et al

IIT Research Institute

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RADIO FREQUENCY EMISSION CHARACTERISTICS AND MEASUREMENT PROCEDURES OF INCIDENTAL RADIATION DEVICES AND INDUSTRIAL, SCIENTIFIC AND MEDICAL EQUIPMENT

H. Martin & F. Tabor
of
IIT Research Institute
Under Contract With
DEPARTMENT OF DEFENSE
Electromagnetic Compatibility Analysis Center
Annapolis, Maryland 21402

September 1972

FINAL REPORT

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16. Abstract

Descriptive information and measured radio frequency radiation characteristics are reported for radio frequency dielectric heaters, garage door openers (superregenerative receivers), a superregenerative converter, a radio frequency diathermy machine, a radio frequency stabilized arc welder and an automobile ignition system.

Procedures suitable for FAA use, for measuring the radiation characteristics of dielectric heaters and superregenerative receivers, are reported.

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PREFACE

The Electromagnetic Compatibility Analysis Center (ECAC) is a Department of Defense facility, established to provide advice and assistance on electromagnetic compatibility matters to the Secretary of Defense, the Joint Chiefs of Staff, the military department and other DOD components. The Center, located at North Severn, Annapolis, Maryland 21402, is under executive control of the Director of Defense Research and Engineering and the Chairman, Joints Chiefs of Staff or their designees who jointly provide policy guidance, assign projects, and establish priorities. ECAC functions under the direction of the Secretary of the Air Force, and the management and technical direction of the Center are provided by military and civil service personnel. The technical operations function is provided through an Air Force sponsored contract with the IIT Research Institute (IITRI).

This report was prepared for the Systems Research and Development Service of the Federal Aviation Administration in accordance with Interagency Agreement DOT-FA70WAI-175, as part of AF Project 649E under Contract F-19628-73-C-0031, by the staff of the IIT Research Institute at the Department of Defense Electromagnetic Compatibility Analysis Center.

To the extent possible, all abbreviations and symbols used in this report are taken from American Standard Y10.19 (1967) "Units Used in Electrical Science and Electrical Engineering" issued by the United States of America Standards Institute.

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SECTION 1

INTRODUCTION

BACKGROUND

The Federal Aviation Administration (FAA) has reported instances of harmful interference to the aeronautical communication and navigation services from two classes of generally unlicensed radio frequency emitters (Reference 1). The first class comprises those Industrial, Scientific and Medical (ISM) devices which employ radio frequency energy to perform their function. Arc welders, dielectric heaters and medical diathermy machines belong to this class. The second class is composed of those emitters whose radio frequency emissions are a byproduct of their operation. Automobile ignition systems, television receivers and superregenerative receivers are included in the second class.

The Electromagnetic Compatibility Analysis Center (ECAC) was tasked by the FAA to determine the nature and severity of interference to the communication and navigation services from these emitters and, when necessary, to formulate methods of mitigating the interference (Reference 2).

As a first step in the task, a measurement program was initiated to determine the radiation characteristics of limited samples of ISM and incidental radiation devices. This report documents the measurement program. Reference 3 reports on the balance of the task, that is, the effects of interference from dielectric heaters and superregenerative receivers to the aeronautical communication and navigation services.

OBJECTIVES

The objectives of this effort were to:

1. Measure the electromagnetic radiation from dielectric heaters, superregenerative receivers, diathermy machines, arc welders, and automobile ignition systems and provide quantitative and qualitative descriptions of their emissions.
2. Document measurement procedures which can be used by the FAA and other agencies to determine quantitatively the electromagnetic radiation from dielectric heaters and superregenerative receivers.

APPROACH

The information contained in this report has been obtained both by measurement and by reference to text books, manufacturers specifications and instruction books. Measurements were obtained employing narrow-band spectrum analyzers as well as wide-band field intensity meters (FIM).

Employing instrumentation provided by the FAA, field measurements were performed on the following emitters:

1. Radio Frequency Dielectric Heaters (5 samples)
2. Garage Door Openers (Superregenerative Receivers) (5 samples)
3. Superregenerative VHF Converter (2 samples)
4. Radio Frequency Diathermy Machine (1 sample)
5. Radio Frequency Stabilized Arc Welder (1 sample)
6. Automobile Ignition Systems (1 sample)

The parameters measured were the field strength, and the time- and frequency-domain characteristics of the radiated signals. Section 2 reports these measurements.

The measurement procedures developed for dielectric heaters and superregenerative receivers are presented in Section 3.

SECTION 2

EMITTER CHARACTERISTICS AND THEIR MEASUREMENT

DIELECTRIC HEATER

Description

A dielectric heater, sometimes referred to as a plastic welder or high frequency welder, is a machine that heats, dries, cooks, cures and/or binds dielectric material such as plastics, wood, food and glue. The heater applies a high frequency potential, approximating 10,000 volts, across the dielectric material to be treated. These heaters produce powers between 1,000 and 100,000 watts and operate in a frequency range between approximately 5 MHz and 100 MHz. Food heaters normally operate above 1,000 MHz and were not considered in this investigation.

The heart of the dielectric heater is a high power radio frequency transmitting tube. The tube plate voltage is supplied by a rectified single phase or three phase 60 Hz signal which unintentionally modulates the carrier frequency. From APPENDIX A, the expression for the instantaneous voltage at the plate of the tube is:

$$\text{for} -\frac{T}{2} \leqslant t \leqslant \frac{T}{2}$$

$$e = E\,(k \cos \omega_m t)\,(\cos \omega_o t) \qquad (2\text{-}1)$$

where e is periodic in time T

ω_m modulating frequency, in radians per second

E is the peak amplitude of the carrier, in volts

ω_o is the carrier frequency, in radians per second

k is a modulation constant depending upon the types
of modulation signals.

The Fourier series of Equation (2-1) (dielectric heater spectrum) is a symmetrical spectrum whose fall-off approximates 12 dB per octave with spectral line separation of 120 Hz, 180 Hz or 360 Hz, depending upon modulation type.

In addition to amplitude modulation, the dielectric heater carrier frequency varies with time. Carrier frequency variations are caused by:

1. The intentional change of frequency to search for maximum plate current.
2. Tube warm-up.
3. Dielectric load capacitance variation.

From measured observations, the carrier frequency may vary exponentially, sinusoidally or linearly with time. The carrier frequency variation is relatively slow as compared to the modulating frequency. Consequently, the spectrum of the dielectric heater looks like the Fourier series of Equation (2-1) with all of its spectral lines moving at an exponential, sinusoidal or linear rate.

The dielectric heater produces numerous significant harmonics. Usually, the radiated level of one of the harmonics is approximately equal to the radiated level of the fundamental. The harmonic spectrum is similar to the fundamental spectrum; however, the maximum frequency variation is directly proportional to the harmonic number.

Measurements

The emission characteristics of five dielectric heaters were measured. Four were INPAK model L14A serial numbers 331, 301, 342, and 349, the fifth was a THERMONIC model M-15.

INPAK. The INPAK heater produces 3.5 kW of power at 26 MHz and uses a single-phase full-wave rectified signal for a plate supply. The procedure that was used to measure the emission characteristics of the INPAK heater is similar to that written in Section 3. Specifically, a 54" whip antenna placed 14 feet from the heater was used to receive and deliver signals to an HP8555 spectrum analyzer. A Marconi TF2002 signal generator was used to calibrate the received signal levels. A Uher tape recorder was used to record detected signals, noise and interference.

Harmonic amplitudes, carrier frequency variations and carrier-on times were measured with the spectrum analyzer. The analyzer, adjusted as a 300 kHz bandwidth receiver, was used to measure the detected time wave form of the INPAK heater.

Received harmonic amplitudes are converted to electric field strength at 100 feet by using Equation (2-2) (derived in APPENDIX A):

$$E = P_R + L_c + AF + AF_L + 116 + F_d \tag{2-2}$$

where

E is in dB above one microvolt per meter (dB/μV/m)

P_R = received power dissipated into 50 ohms (dBm)

L_c = antenna-to-analyzer cable loss (dB)

AF = antenna factor, converts dBm to dBm/m^2 (dB)

AF_L = 0 dB, except when loop antenna is used in near field (dB)

116 = converts dBm/m^2 to dB above one microvolt per meter

F_d = converts field strength at measured distance "d" to field strength at 100 feet, includes near field effects (dB). See Equation (AII-11).

Explanations and derivations of the terms on the right hand side of Equation (2-2) are found in APPENDIX A.

For an example in using Equation (2-2), consider a $P_R = -49$ dBm at 104 MHz, cable loss = 2 dB, antenna factor for 54" whip = 10 dB, $AF_L = 0$ dB (since a whip is being used), $F_d = 20 \log (14/100)$ (for d = 14 feet the near field frequency-dependent portion of F_d is negligible).

$$E = -49 + 2 + 10 + 0 + 116 - 17$$

$$E = 62 \text{ dB}/\mu\text{V/m at 100 feet (or 1260 } \mu\text{V/m)}$$

This value of field strength at 100 feet is shown on Figure 2-1 with all other harmonic field strengths of serial number 301. Field strengths of INPAK heater harmonics at 100 feet are shown in Figures 2-2, 2-3, and 2-4 for serial numbers 342, 331 and 349 respectively.

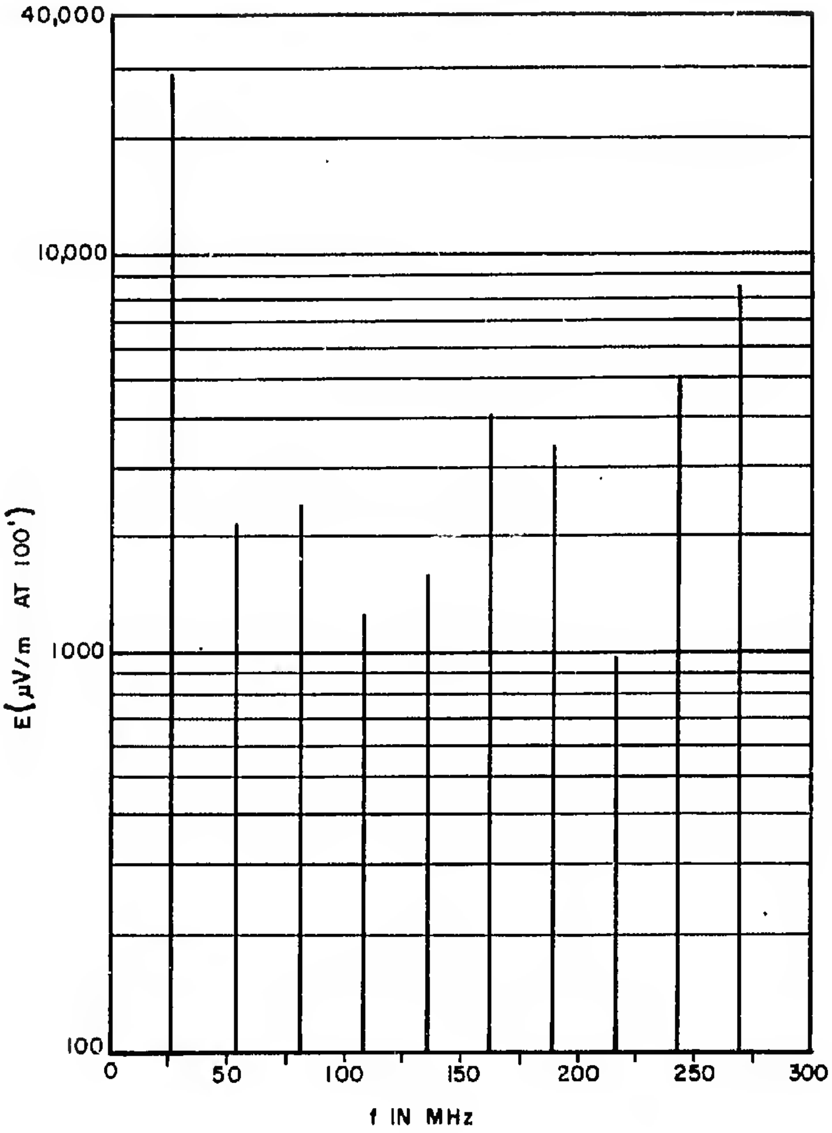


Figure 2-1. Radiated Field Strength of INPAK Dielectric Heater No. 301 (Receiving Antenna was 54" Broadband Whip 14 Feet from Heater. Receiver was HP8555 Spectrum Analyzer, BW = 300 kHz)

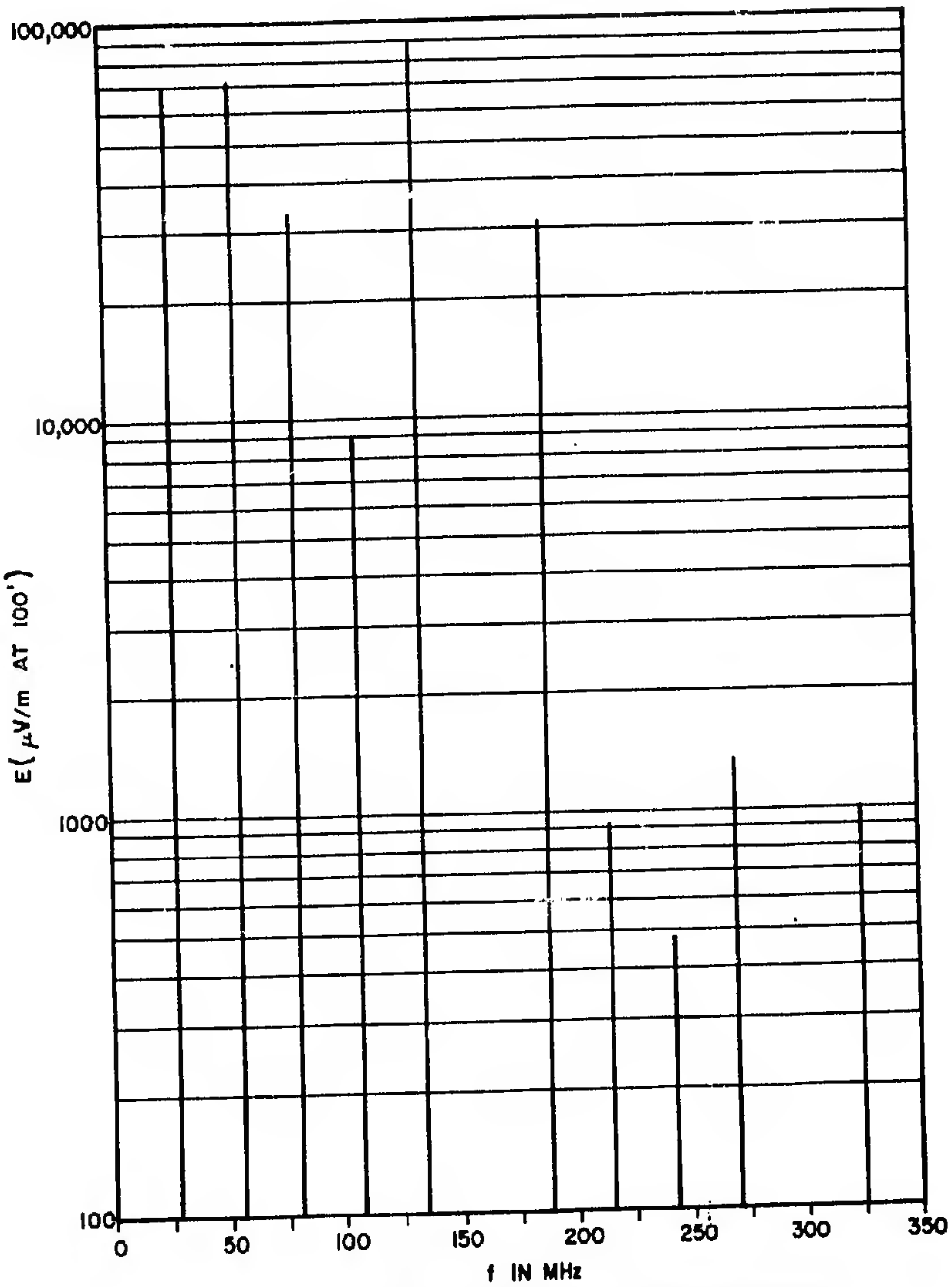


Figure 2-2. Radiated Field Strength of INPAK Dielectric Heater No. 342 (Receiving Antenna was 54" Broadband Whip 14 Feet from Heater. Receiver was HP8555 Spectrum Analyzer, BW = 300 kHz)

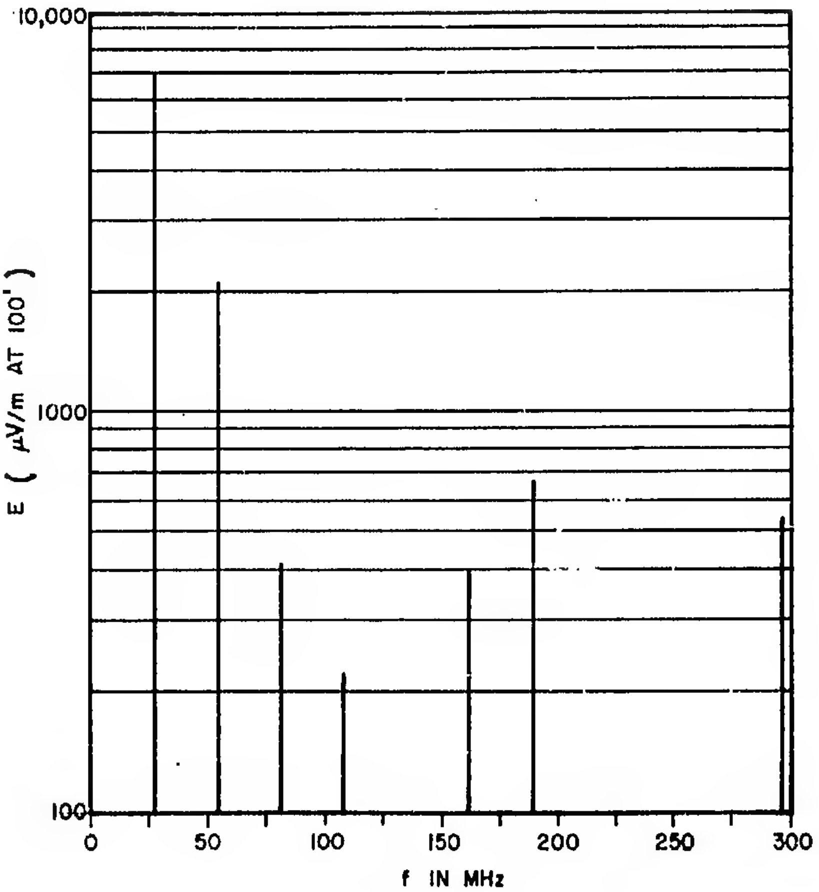


Figure 2-3. Radiated Field Strength of INPAK Dielectric Heater No. 331 (Receiving Antenna was 54" Broadband Whip 14 Feet from Heater. Receiver was HP8555 Spectrum Analyzer, BW = 300 kHz)

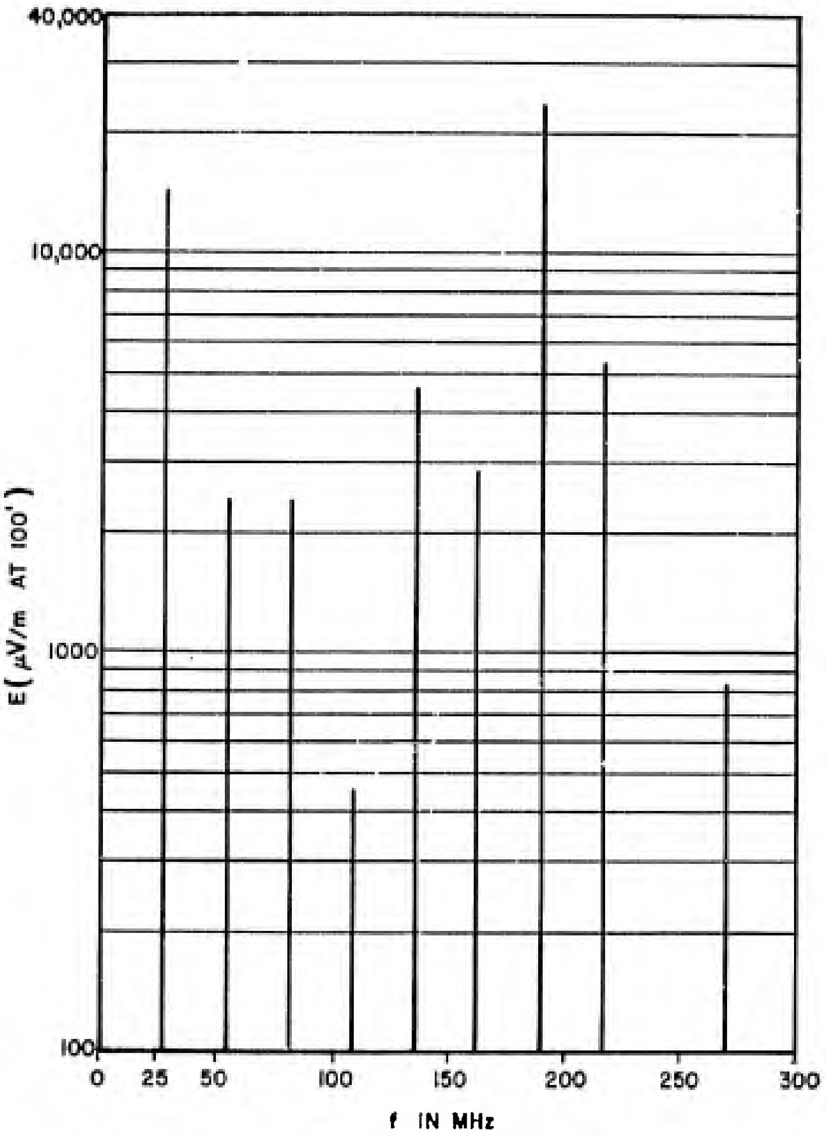


Figure 2-4. Radiated Field Strength of INPAK Dielectric Heater No. 349 (Receiving Antenna was 54" Broadband Whip 14 Feet from Heater. Receiver was HP8555 Spectrum Analyzer, BW = 300 kHz)

Measured frequency variations at the fundamental and sixth harmonic and carrier-on times are listed in TABLE 2-1 for the four serial numbers tested.

TABLE 2-1

FREQUENCY VARIATIONS AND ON TIMES OF INPAK MODEL L14A

Serial Number	Variation at f_o*	Variation at $6f_o$*	On-Time
331	200 kHz	1200 kHz	1.5 sec.
301	330 kHz	2000 kHz	1.5 sec.
342	300 kHz	1750 kHz	1.5 sec.
349	220 kHz	....	....

* Measured Values

Figures 2-5 and 2-6 are detected waveforms (See "Modulation Characteristics", pg 3-4) at f_o of serial numbers 301 and 331 respectively. Note that the waveforms are single-phase, full-wave, based on 60 Hz with a negative modulation factor (See Equation 2-3a, pg 2-13) of 1.0. Figure 2-7 is a spectral display of the carrier frequency variation for serial number 349.

Thermonic M-15. The Thermonic heater produces 15 kW of power at 16 MHz and uses a three-phase full-wave rectified signal for a plate supply. The Thermonic heater could be left on for pre-set periods of time up to 15 minutes. When the plate current was less than 0.5 ampere the oscillator frequency would vary at a rate of approximately 25 kHz/sec. When the plate current exceeded 0.5 ampere, the oscillator would "lock on" to the frequency that corresponded to the maximum plate current. The procedures used to measure the emission characteristics of the Thermonic heater are similar to those listed in Section 3. Specifically, a 12 inch loop antenna placed 10 feet from the heater and a half-wave dipole placed 30 feet and 100 feet from the heater were used to receive and deliver signals to an HP8553 spectrum anlyzer. For frequencies above 110 MHz the HP8555 was used. A Marconi TF2002 signal generator was used to calibrate measured levels and a Uher tape recorder was used to record detected interference. The physical dimensions at the test site are illustrated in Figure 2-8.

Harmonic amplitudes, emission spectra and carrier frequency variations were measured with the spectrum analyzer. The analyzer, adjusted to a 300 kHz bandwidth, was used to measure the detected waveform of the Thermonic heater. Using Equation (2-2), received harmonic amplitudes were calculated and plotted in Figure 2-9.

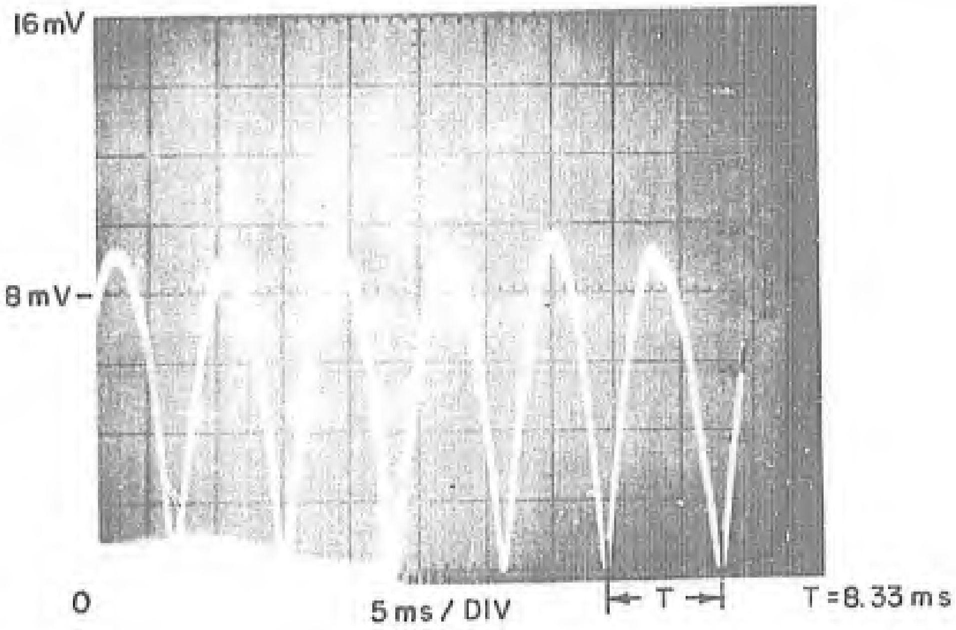


Figure 2-5. Detected Time Waveform of Single-phase, Full-wave Dielectric Heater No. 301

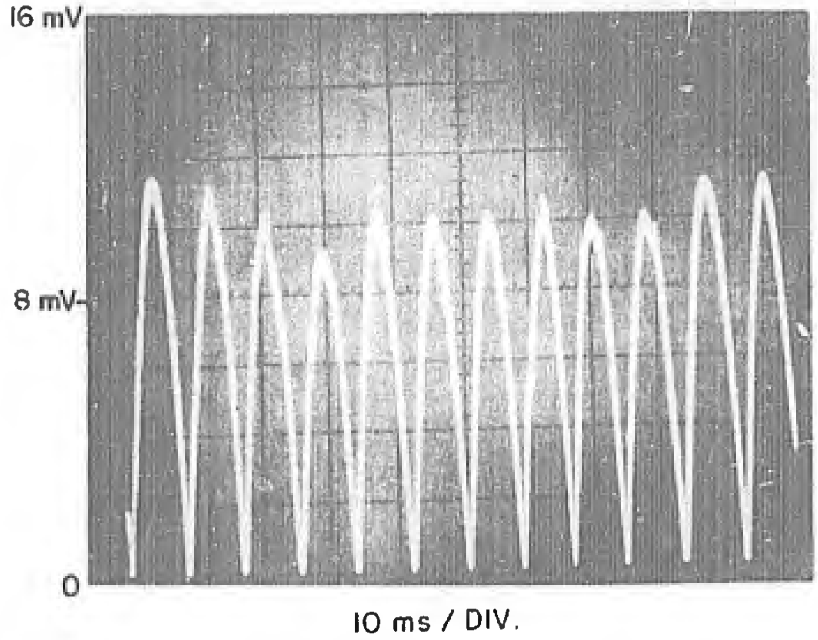


Figure 2-6. Detected Time Waveform of Single-phase, Full-wave Dielectric Heater No. 331

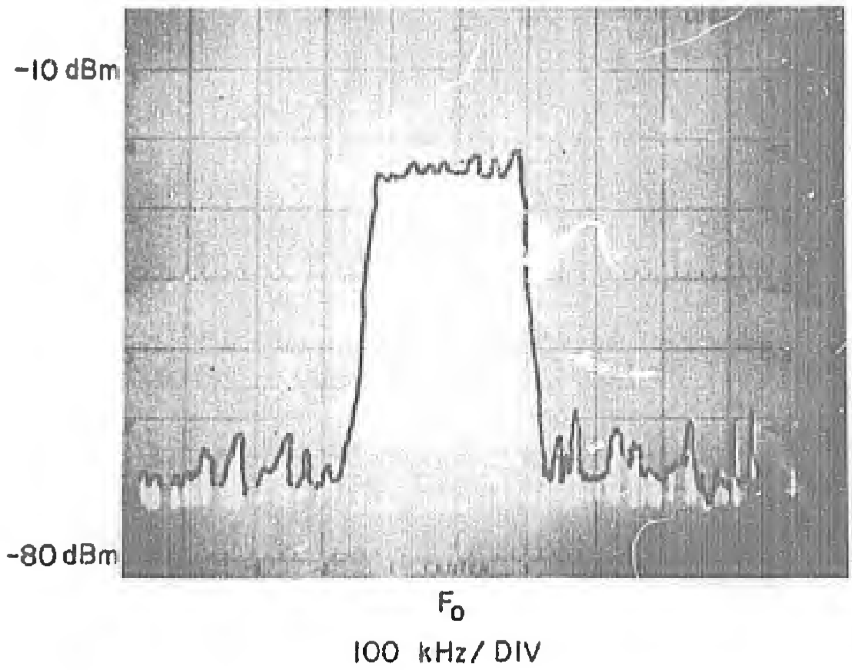


Figure 2-7. Spectrum of Dielectric Heater No. 349, Showing Carrier Frequency Variation

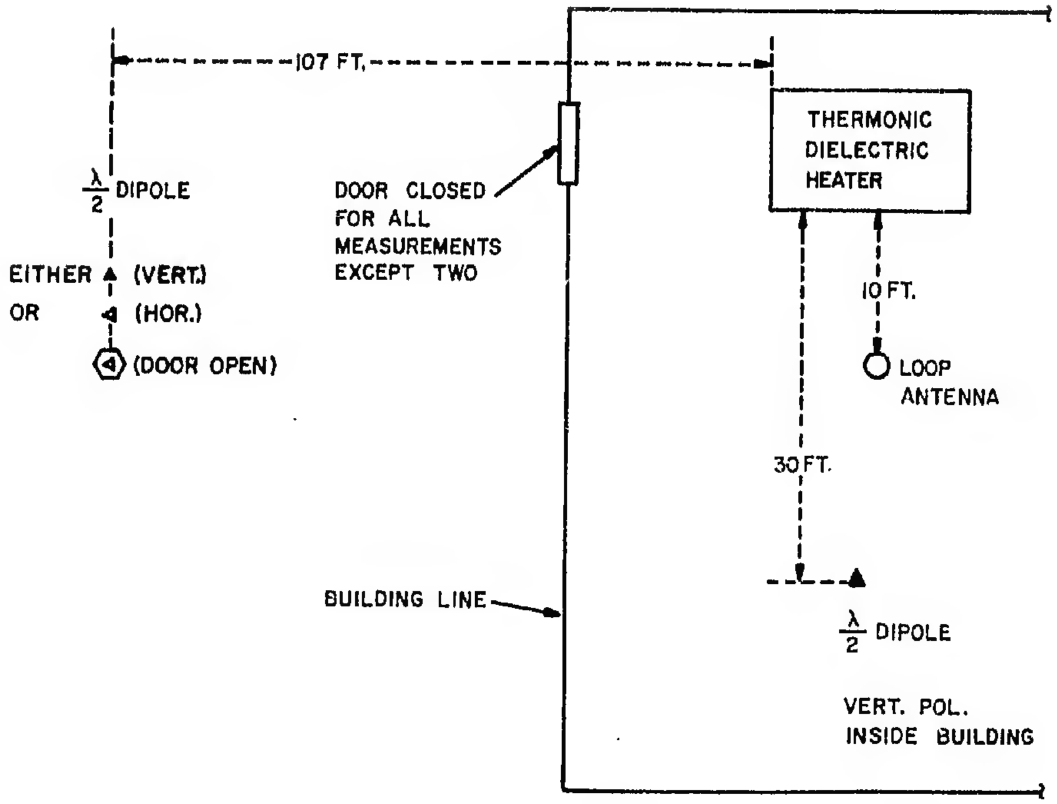


Figure 2-8. Antenna Locations for Thermonic Dielectric Heater Tests

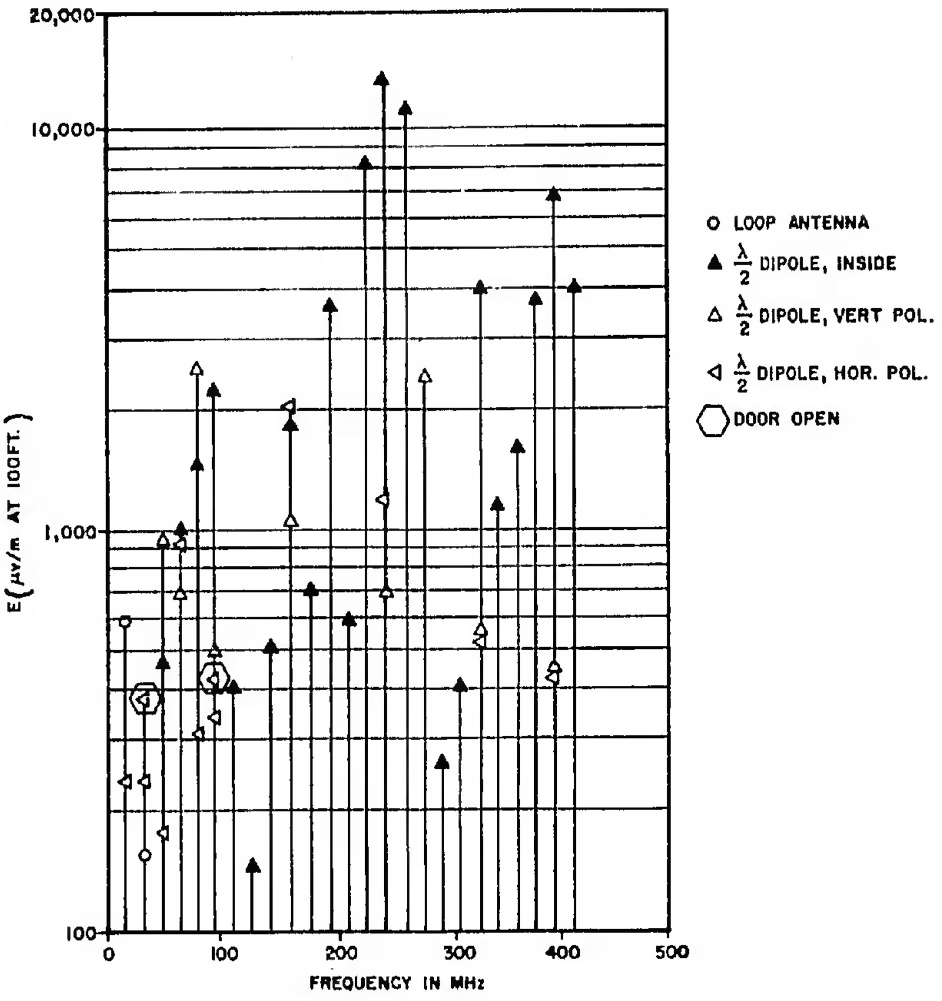


Figure 2-9. Calculated Harmonic Amplitudes 61.5 Feet from a Thermonic Dielectric Heater (f_o = 16 MHz)

Frequency excursions at various harmonics are tabulated in TABLE 2-2 for plate currents of 0.3 ampere and 1 ampere.

TABLE 2-2

FREQUENCY EXCURSIONS (IN kHz) FOR VARIOUS HARMONICS OF THE THERMONIC M-15 DIELECTRIC HEATER

Harmonic Number	Frequency Excursion for 0.3 AMPERE PLATE CURRENT	Frequency Excursion for 1 AMPERE PLATE CURRENT
1	48	9
2	90	20
3	155	30
4	190	30
5	225	30
6	285	35
7	340	no data
10	450	45

Detected waveforms of the carrier frequency, the fifth harmonic and the ninth harmonic are shown in Figures 2-10, 2-11 and 2-12, respectively. Note that the detected waveforms are three-phase full-wave, based on 60 Hz. The modulation factors may be found using Equation (2-3). (See page A-14).

$$m_p = \frac{V_{max} - V_{min}}{kV_{max} + V_{min}} \qquad (2\text{-}3)$$

$$m_n = km_p \qquad (2\text{-}3a)$$

where

V_{max} = the maximum detected voltage

V_{min} = the minimum detected voltage

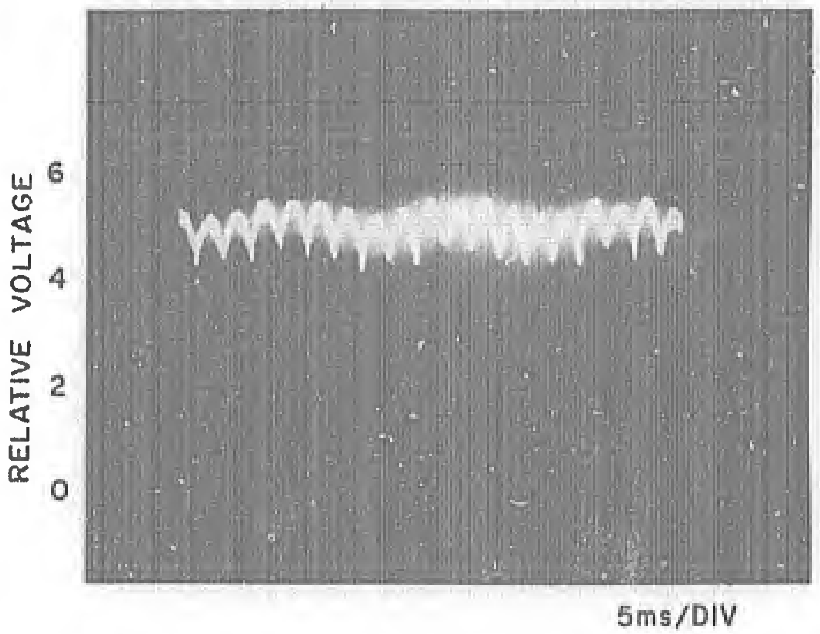


Figure 2-10. Detected Time Waveforms of a Three Phase, Dielectric Heater at 16 MHz

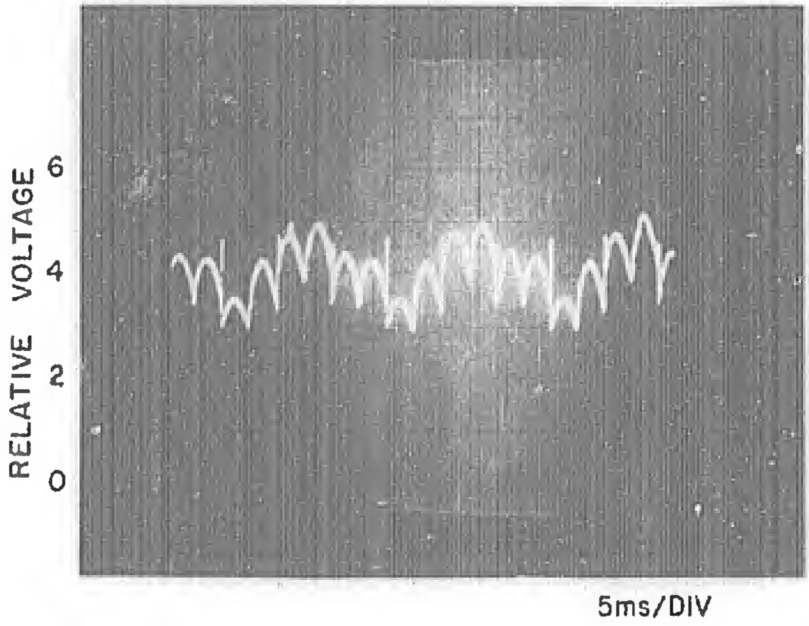


Figure 2-11. Detected Time Waveforms of a Three Phase, Dielectric Heater at 80 MHz

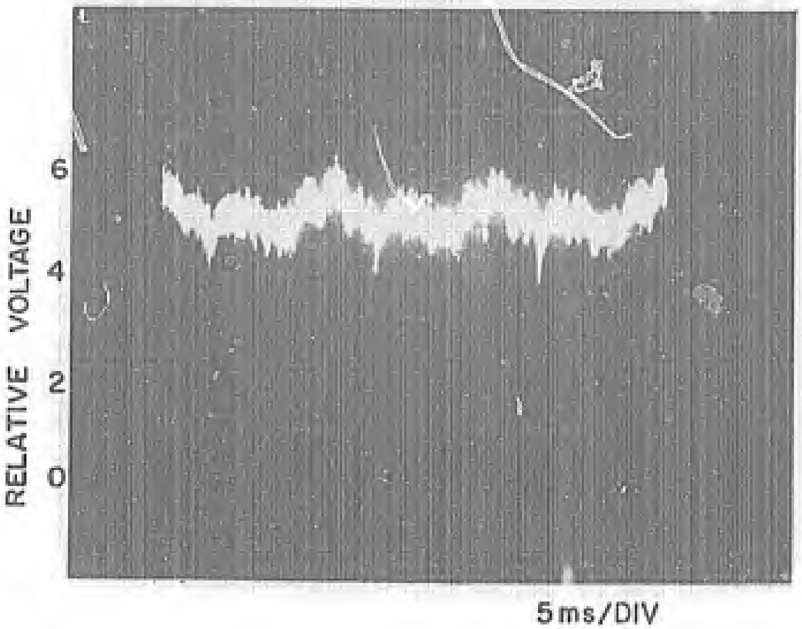


Figure 2-12. Detected Time Waveforms of a Three Phase, Dielectric Heater at 144 MHz

m_p = the positive modulation factor

m_n = the negative modulation factor

k = 1.75 for single-phase, full-wave

k = 1.88 for three-phase, half-wave

k = 2.06 for three-phase, full-wave

The modulation factors are +.075 and −.08 for f_o, and +.099 and −.104 for 5 f_o. The modulation factors were determined by averaging the six values of V_{max} and six values of V_{min} over one period. (See example on pg 2-19).

DIATHERMY MACHINE

Description

The diathermy machine is a special type of dielectric heater in that the dielectric load to be heated is body tissue. Diathermy machines produce powers between 100 watts and 1,000 watts and usually operate on the assigned ISM frequencies of 13.56 and 27.12 MHz. Diathermy machines are designed to operate in either a continuous mode or a pulsed mode. In the continuous mode the machine may be left on for periods up to one half hour. One pulsed machine that was examined had a pulse width of 70 microseconds, a pulse repetition rate adjustable between 80 and 2,600 pulses per second, and produced a peak power of 1,060 watts.

Measurements

The test program for diathermy machines consisted of measuring the emission characteristics of one Birtcher Corporation Model 800. This machine is crystal-controlled, operates at 13.56 MHz, has full-wave single-phase 60 Hz modulation on its carrier, and requires 750 watts of 60 Hz input power.

The procedures used to measure the interference characteristics of the Birtcher Corporation diathermy machine are similar to those written in Section 3. Specifically a 54 inch whip antenna placed 33 feet from the diathermy machine was used to receive and deliver signals to an HP8555 spectrum analyzer. A Marconi TF2002 signal generator was used to calibrate the received levels. A Uher tape recorder was used to record detected signals, noise and interference.

Harmonic amplitudes of the diathermy machine were measured with the analyzer. The analyzer was then adjusted as a 300 kHz bandwidth receiver tuned to 13.56 MHz, and the detected time waveform of the diathermy signal was measured.

Received harmonic amplitudes are converted to electric field strengths at 100 feet using Equation (2-2) and the results are plotted on Figure 2-13. Figure 2-14 displays the detected time waveform of the diathermy signal at 13.56 MHz. The modulation factors are +.475 and −.83 as determined from Equation (2-3).

AUTOMOBILE IGNITION SYSTEM

Description

Automobile ignition systems radiate narrow pulses at a pulse repetition rate proportional to the engine speed. These narrow pulses have very small rise times and produce broadband spectral energy in a range from low frequencies to beyond 1,000 MHz. Many articles have been written on the subject of automobile ignition interference; consequently, the only item that will be discussed here will be the ignition noise interference tests performed during this task.

Measurements

The test program for automobile ignition interference consisted of measuring the radiated emission characteristics of a four cylinder Volkswagen. Received ignition levels were calibrated by equating the peak of detected pulsed signals with a continuous sine wave signal. The peak of the detected pulsed signal was measured at various receiver bandwidths.

The equipment arrangement was similar to that shown in Section 3. A quarter-wave ground plane monopole antenna elevated 31 inches off the ground and placed ten feet from the rear bumper of a Volkswagen was used to receive and supply signals to an HP8555 spectrum analyzer. The monopole was adjusted for a quarter-wave at the center frequencies listed in TABLE 2-3. A frequency band about the center frequency was searched and peak levels were obtained by allowing the analyzer to remain at a particular frequency for 10 seconds. The analyzer was set to its widest bandwidth – 300 kHz.

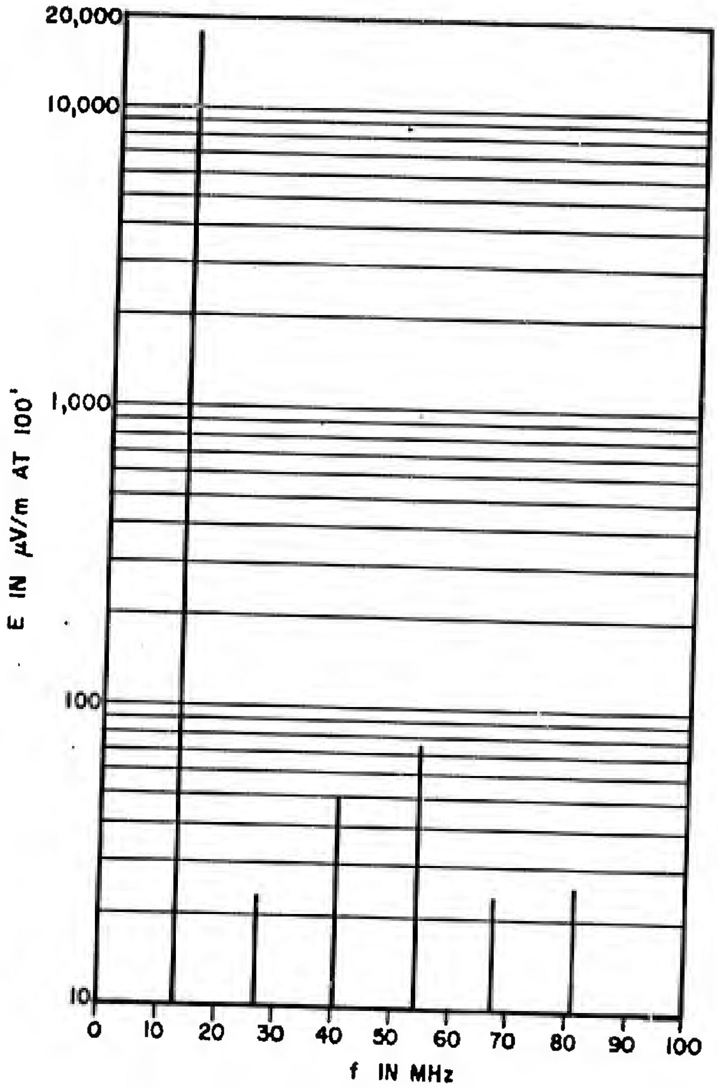
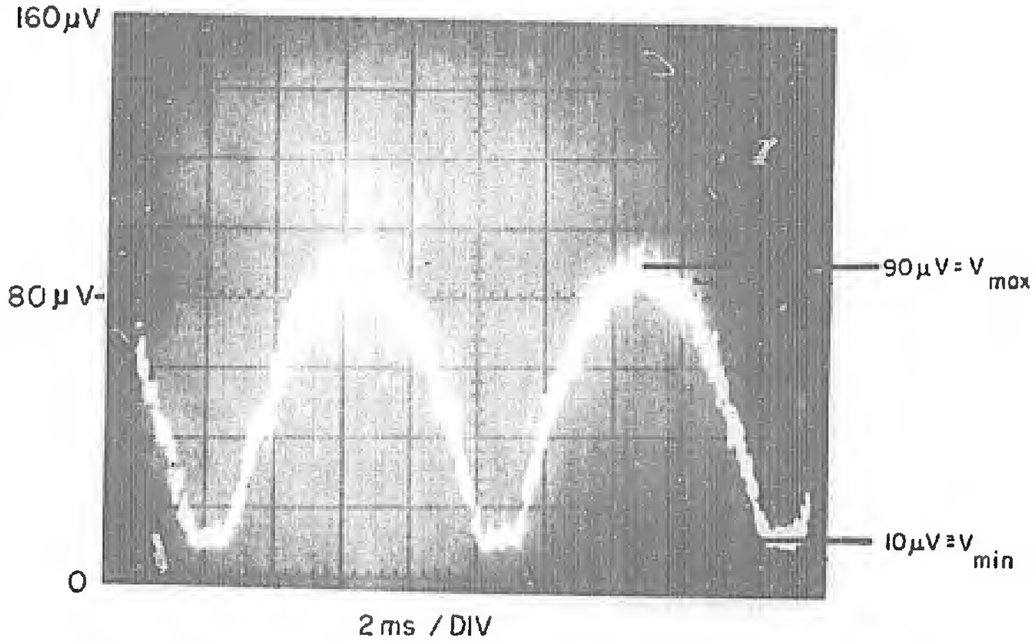


Figure 2-13. Radiated Field Strength from Birtcher Corp. Diathermy Machine Received by a 54" Whip Antenna 33 feet from Source



Example of Modulation Factor Calculation:

$$m_p = \frac{V_{max} - V_{min}}{kV_{max} + V_{min}} = \frac{90 - 10}{1.75\,(90) + 10} = 0.48$$

$$m_n = km_p = 1.75\,(0.48) = 0.84$$

Figure 2-14. Detected Time Waveform of Diathermy Signal

TABLE 2-3

QUARTER-WAVE MONOPOLE FREQUENCIES IN MHz FOR SAMPLING IGNITION INTERFERENCE

Center Frequencies	Frequency Band
40*	30-50
50	40-60
70	60-80
90	80-100
100	90-110
120	110-130
140	130-150
160	150-170
180	170-190
200	175-225
250	225-275
300	275-325
350	325-375
400	375-425

* Monopole height equal 5 feet for 40 MHz only.

Field intensities were calculated using Equation (2-2). However, field intensities in units of volts per meter can be misleading since the level of the receiver output is dependent on the receiver bandwidth. Therefore, a test was performed to determine how the peak output level of a receiver varied as the bandwidth was varied in decade steps from 100 Hz and 300 Hz to 100 kHz and 300 kHz respectively. The results of this test are shown on Figure 2-15. The test results show that the peak output level is directly proportional to the receiver 3 dB bandwidth.

Field intensities from a single automobile ignition system are distributed in frequency and properly stated in terms of microvolts per meter per kilohertz of bandwidth or μV/m/kHz. Distributed field intensities are calculated using Equation (2-4).

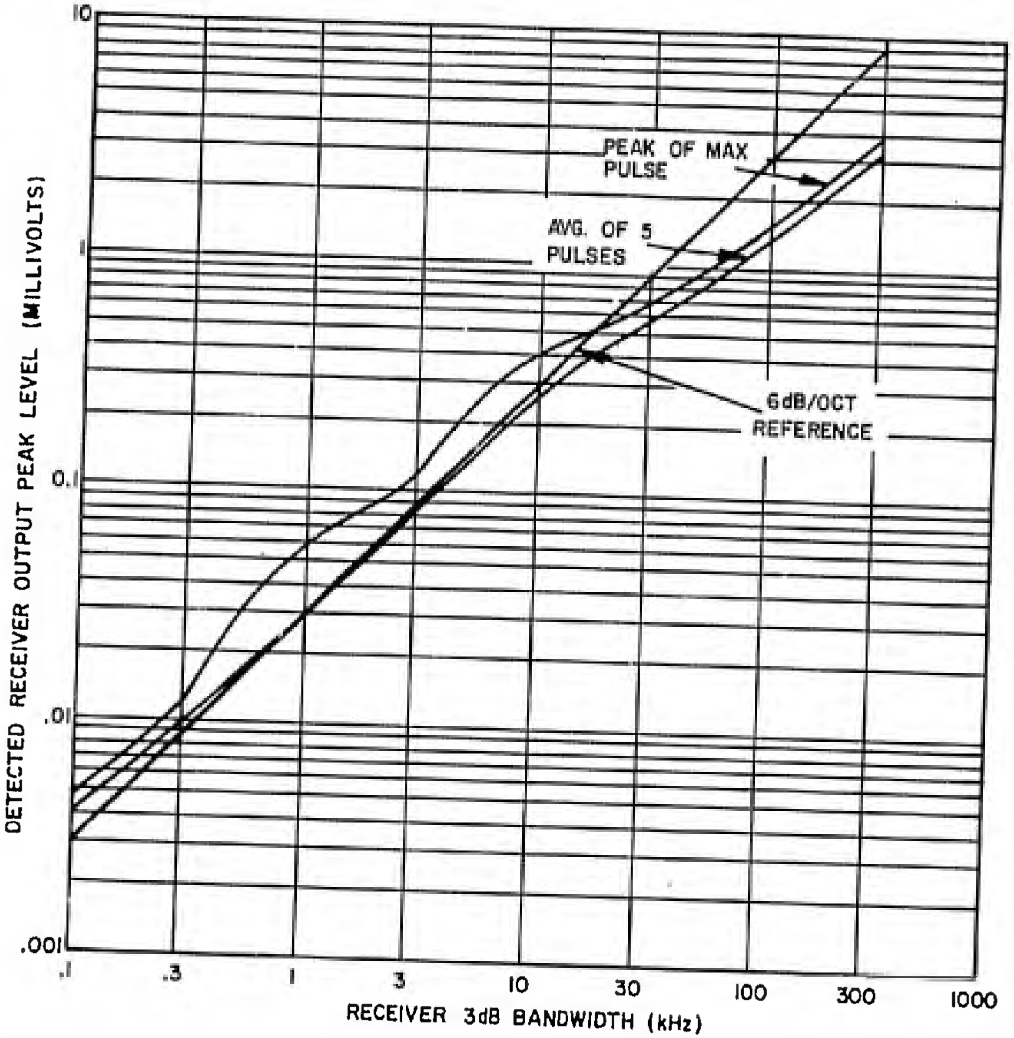


Figure 2-15. Detected Peak Output Level from VW Ignition versus Receiver Bandwidth ($f_o > 1$ MHz)

$$E_d = \frac{E \text{ at } 300 \text{ kHz}}{300} \quad \text{in } \mu V/m/kHz \tag{2-4}$$

where

E = the field strength in $\mu V/m$ related to a 300 kHz bandwidth.

Distributed field intensities versus frequency are shown in Figure 2-16. Equation (2-4) indicates that the peak output level can be determined by multiplying the distributed level by the receiver bandwidth. There is a limit to this manipulation as described in Equation (2-5).(See page A-17).

$$V_o = \frac{aV_I}{Q} \tag{2-5}$$

where

V_I = maximum amplitude of pulse input to receiver

V_o = maximum amplitude of pulse out of receiver

Q = receiver tuned frequency divided by 3 dB bandwidth

a = receiver gain

Equation (2-5) is stated for two reasons.

1. As a reminder that levels exceeding V_I cannot be obtained by multiplying a given distributed voltage level by a bandwidth.
2. To determine what V_I is, so that a determination can be made to assure that the receiver is not being saturated.

Figure 2-17 shows the detected time waveform of the automobile ignition system that was measured.

RADIO FREQUENCY STABILIZED ARC WELDER

Description

The arc welder is a device that establishes an electric arc that can sustain currents from several amperes to thousands of amperes. Welding cables carry the current from the welder

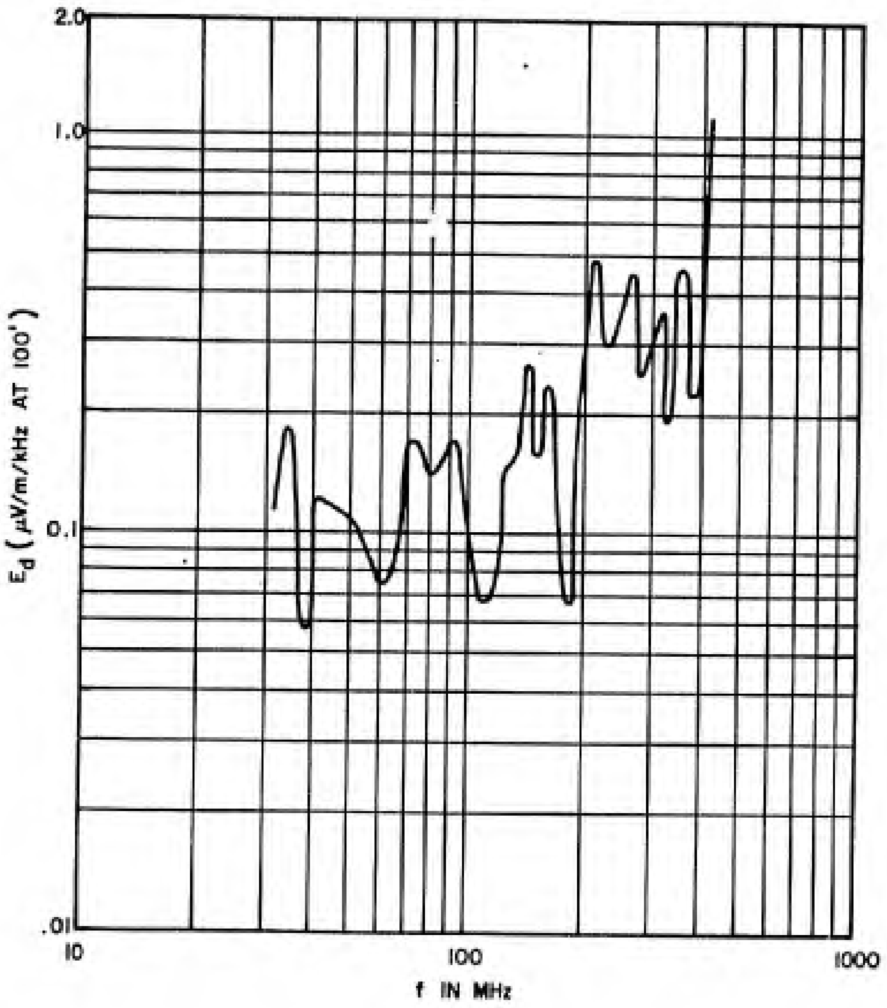


Figure 2-16. Distributed Field Intensity from the Ignition of a 4 Cylinder VW (Antenna was a ¼-wave Monopole 10 Feet from Source. Receiver was an HP8555 Spectrum Analyzer, BW 300 kHz)

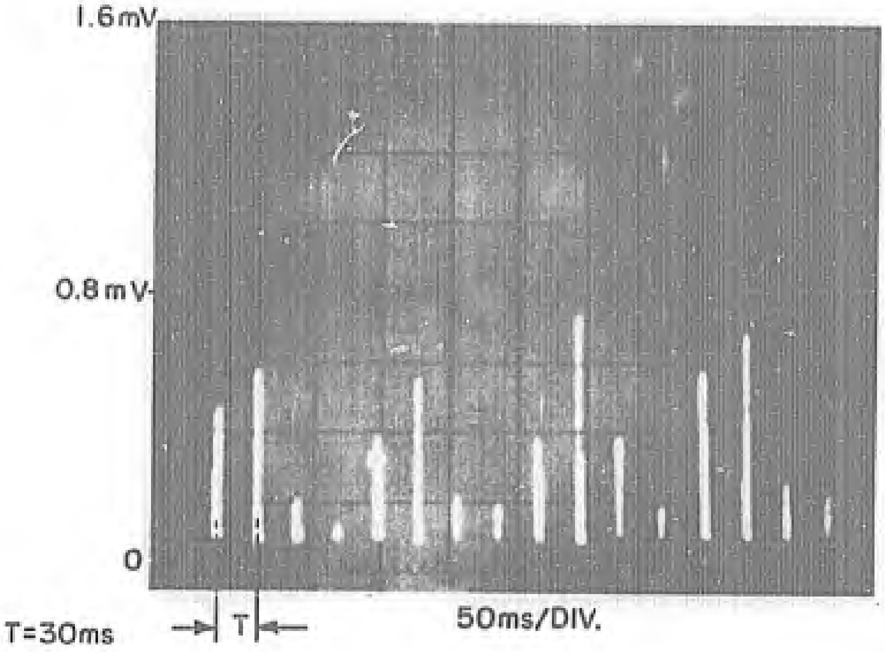


Figure 2-17. Detected Time Waveform of Automobile Ignition (4 cylinder VW) (Receiver BW=300 kHz)

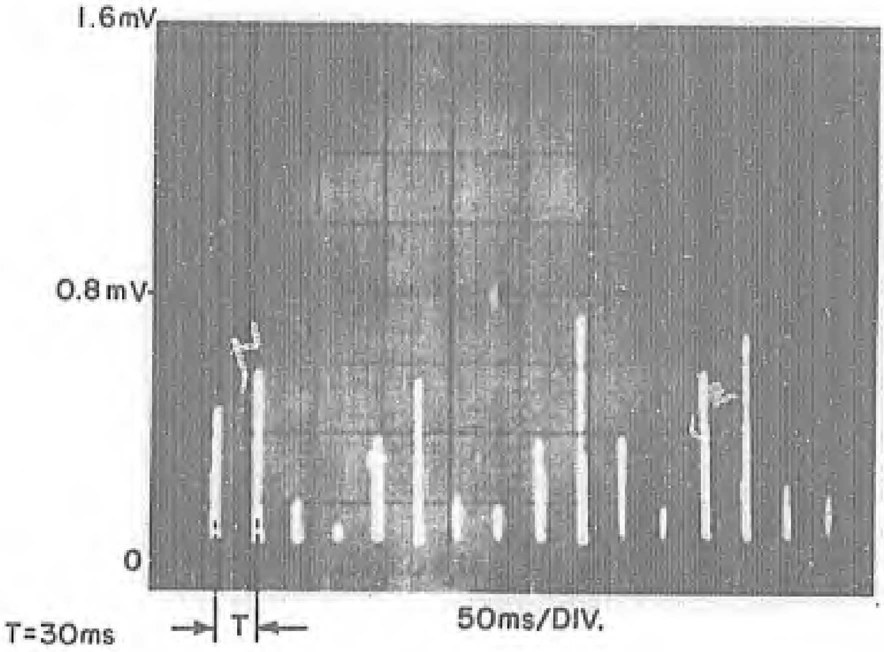


Figure 2-17. Detected Time Waveform of Automobile Ignition (4 cylinder VW) (Receiver BW=300 kHz)

to the work load. High frequency stabilized arc welders electrically consist of an ac (60 Hz) or dc welder plus a high frequency unit. The high frequency unit is placed in series with, and inductively coupled to, the welding cables. The high frequency unit may be left on for the duration of the welding time, or all the time (even when the main welding unit is off). A typical high frequency circuit is shown in Figure 2-18.

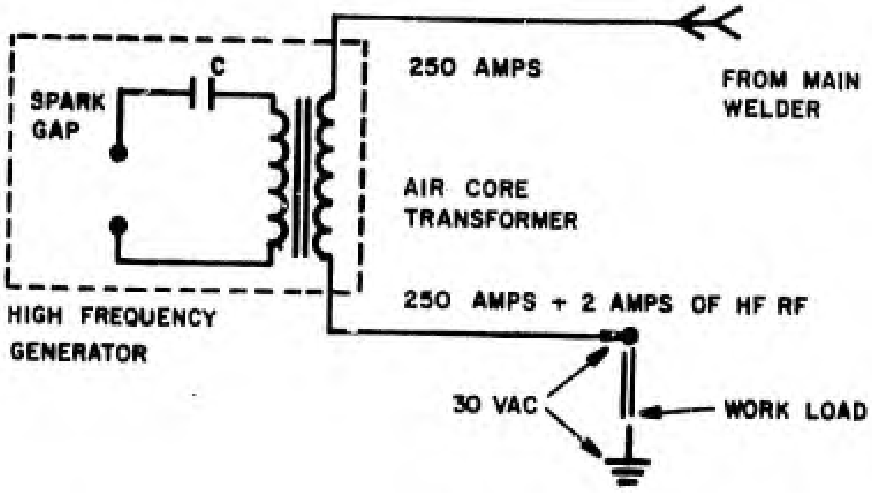


Figure 2-18. Typical High Frequency Circuit Coupled to Welder and Work Load

Measurements

The test program for high frequency stabilized arc welders consisted of measuring one Linde High Frequency Generator. The test equipment arrangement was similar to that described in Section 3. A loop antenna and a half-wave dipole were used to receive and deliver signals to a spectrum analyzer. The antennas were placed twenty feet from the welder. Below 30 MHz the loop was used; above 30 MHz the dipole was used. The HP8553 analyzer was used below 110 MHz and the HP8555 was used above 110 MHz.

The spectrum of the welder was measured from 1 MHz to 400 MHz in the discrete frequency band steps listed in TABLE 2-4.

TABLE 2-4

FREQUENCY BANDS AT WHICH WELDER SPECTRUM WAS MEASURED

Center Frequency (MHz)	Frequency Interval (MHz)	Antenna	Spectrum Analyzer	Analyzer Bandwidth (kHz)
1.5	± 1	Loop	HP8553	1.0
3.6	± 2.5	Loop	HP8553	↓
9.0	± 5	Loop	HP8553	↓
21.0	± 10	Loop	HP8553	1 & 10
40	± 10	Dipole	HP8553	10
50	± 10	Dipole	HP8553	↓
70	± 10	Dipole	HP8553	↓
90	± 10	Dipole	HP8553	↓
100	± 10	Dipole	HP8553	↓
120	± 10	Dipole	HP8555	↓
140	± 10	Dipole	HP8555	↓
160	± 10	Dipole	HP8555	↓
180	± 10	Dipole	HP8555	↓
200	± 25	Dipole	HP8555	↓
250	± 25	Dipole	HP8555	↓
300	± 25	Dipole	HP8555	↓
350	± 25	Dipole	HP8555	↓
400	± 25	Dipole	HP8555	10

Spectral photographs were taken at each center frequency listed in TABLE 2-4. Using Equation (2-2) the field intensities were determined in microvolts per meter. Since the spectrum is distributed, the field intensity in microvolts/meter is correct for only the bandwidth that was used to measure the welder emission. A test was performed to determine the relationship between the received peak output level and the receiver bandwidth. The receiver bandwidth was varied in decade steps from 10 Hz to 100 kHz and from 30 Hz to 300 kHz. The peak output level was recorded at each step. The test was performed at 1.7, 58, 100, 400 and 1,000 MHz. At 58 MHz, 10 dB and 50 dB of attenuation were placed between the antenna and the analyzerto illustrate possible receiver saturation effects.

Figure 2-19 shows the receiver peak output power (referenced to the receiver input) versus bandwidth. The measured results indicate that the receiver noise followed a 3 dB per octave slope, as expected. The welder emission followed a 3 dB per octave slope from 10 Hz to approximately 5 kHz and a 6 dB/per octave slope from approximately 5 kHz to 300 kHz. The phenomenon held true for all five test frequencies. As a result the distributed field intensities assume the units of microvolts per meter per kHz bandwidth for receiver bandwidths greater than 5 kHz and microvolts per meter per square root of bandwidth for receiver bandwidths less than 5 kHz.

Equations (2-6) and (2-7) are used to calculate distributed field intensities from field intensities stated in microvolts per meter.

$$E_d = \frac{E}{\sqrt{BW}} \quad \text{for BW} < 5\text{ kHz (units are } \mu\text{V/m/}\sqrt{BW}\text{)} \tag{2-6}$$

$$E_d = \frac{E}{BW} \quad \text{for BW} > 5\text{ kHz (units are } \mu\text{V/m/BW)} \tag{2-7}$$

where

BW = the bandwidth of the measuring receiver

Distributed field intensities versus frequency for the HF stabilized arc welder are shown in Figure 2-20.

Figures 2-21, 2-22 and 2-23 show the welder emission at 120 MHz ± 10 MHz. The three figures correspond to the main welder off, the main welder producing 100 amperes intermittently and the main welder producing 380 amperes continuously. The high frequency unit was always on. The line at approximately 110.4 MHz comes from a source other than the welder.

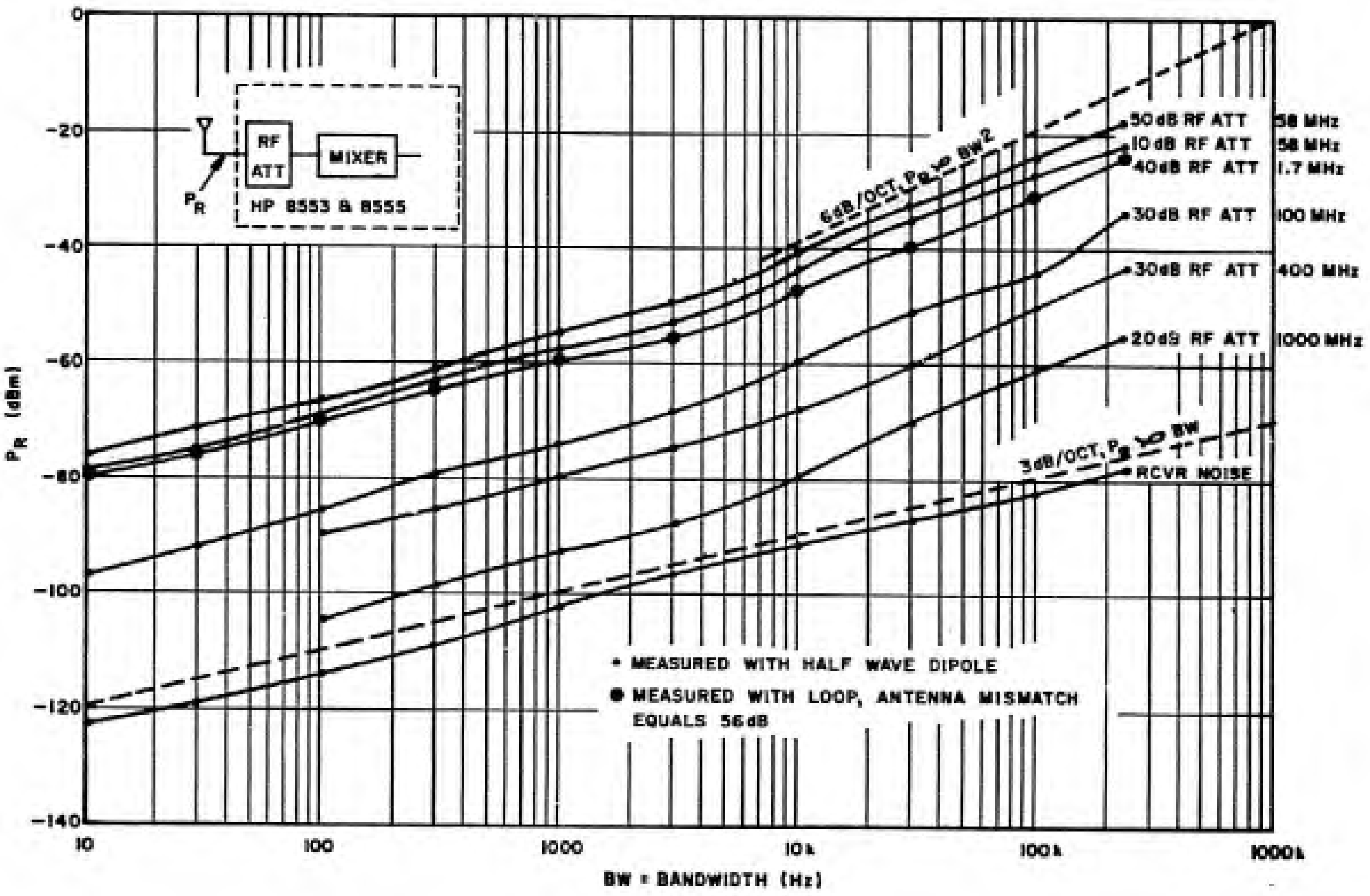


Figure 2-19. Peak Power at Receiver Output (Referenced to Receiver Input) versus Receiver Bandwidth for an RF Stabilized Arc Welder at NSRDL

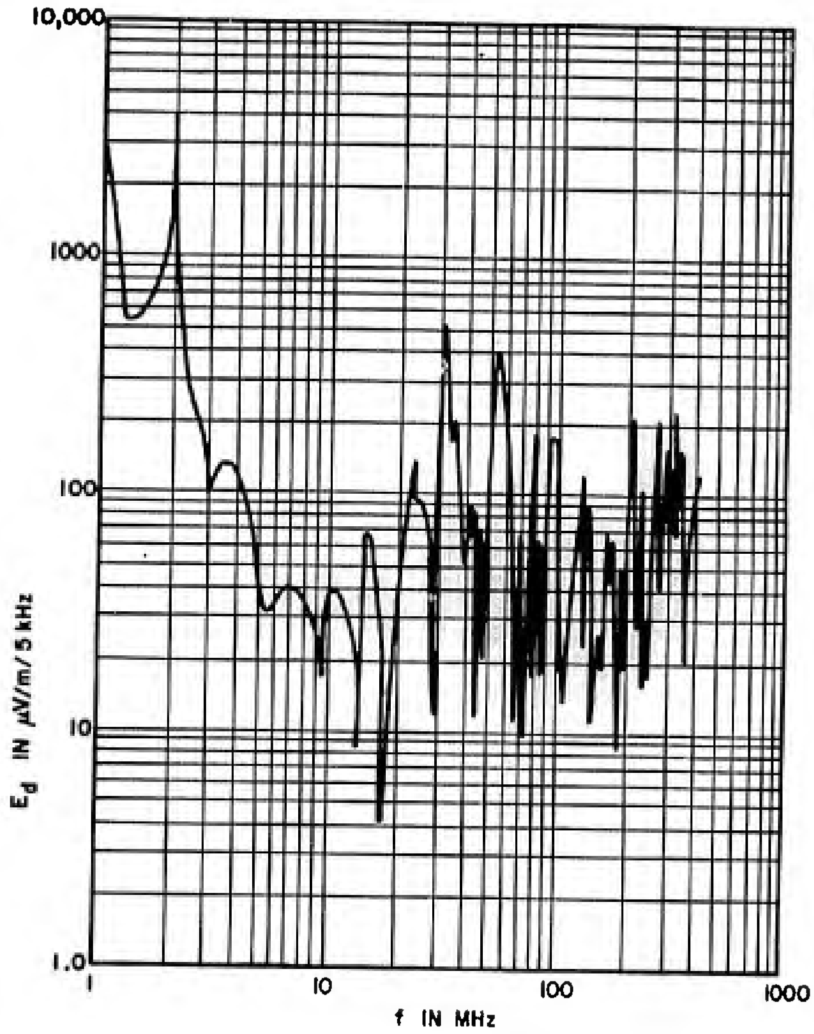


Figure 2-20. Distributed Field Intensities of Impulsive or Random Noise from an RF Stabilized Arc Welder (Measured at a Distance of 100′)

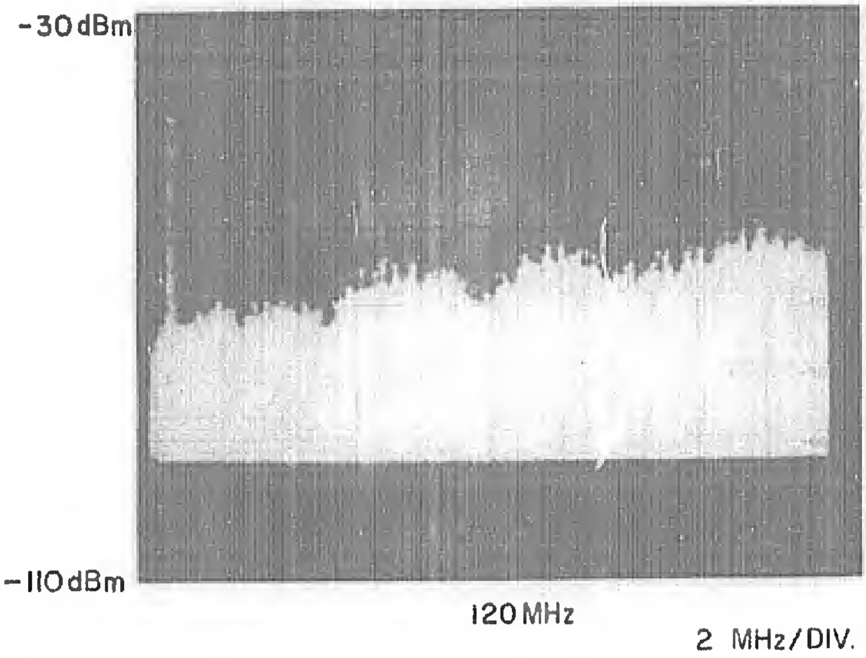


Figure 2-21. Welder RF Emissions (Main Welder Off)(BW = 10 kHz)

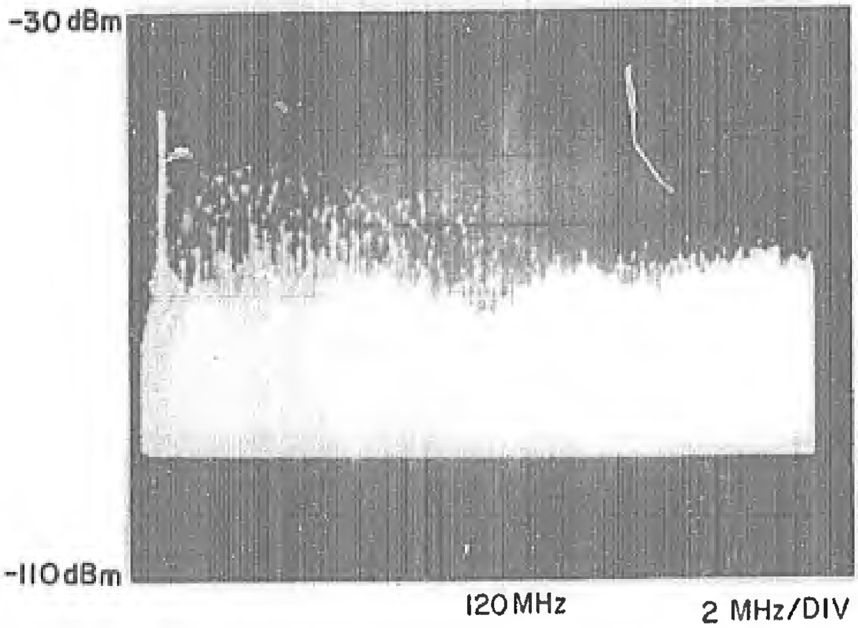


Figure 2-22. Welder RF Emissions (Main Welder at 100 Amps Intermittent) (BW = 10 kHz)

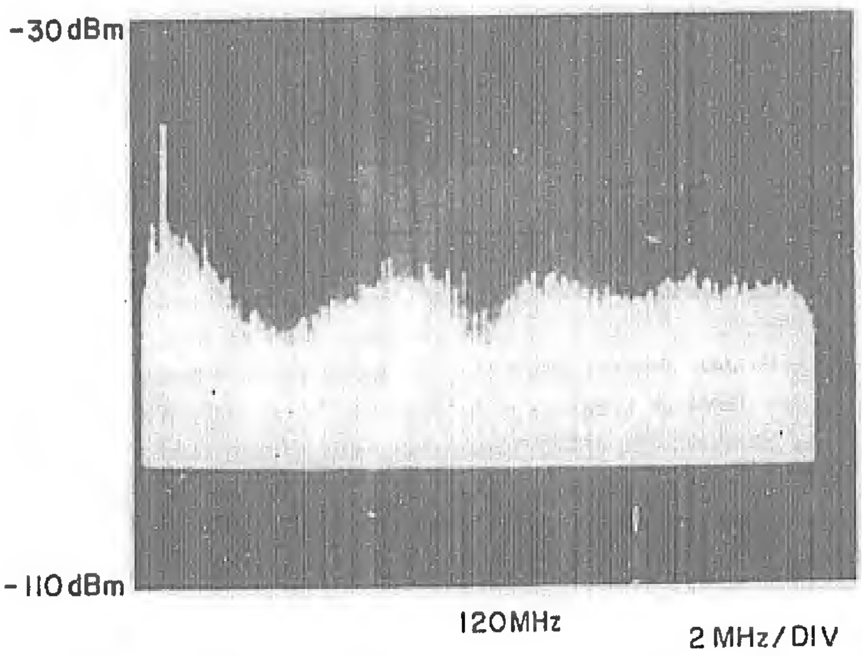


Figure 2-23. Welder RF Emissions (Main Welder at 380 Amps Continuous) (BW = 10 kHz)

Figures 2-24, 2-25 and 2-26 are detected time waveforms at 1,000 MHz, 100 MHz and 1.7 MHz, respectively. The receiver bandwidth was 300 kHz for all three waveforms. 120 Hz modulation is present at all frequencies.

SUPERREGENERATIVE RECEIVER

Description

A regenerative receiver contains an active stage that employs positive feedback which causes the stage to oscillate. If a threshold level is set at the active grid or base, and a signal (whose frequency is much less than the received frequency and much greater than the audio frequency) is applied to the grid or base, the stage will oscillate periodically. This type of operation is referred to as superregeneration.

The signal applied to the grid or base is the quench signal which exceeds the threshold for a predetermined portion of its period, causing the active stage to oscillate at the receiver frequency. The frequency of the bursts of oscillations is referred to as the quench frequency. When the threshold is exceeded long enough to allow the receiver oscillations to reach a maximum, the receiver operates in a "logarithmic mode". When the threshold is exceeded for a short time and the oscillations reach only a fraction of their maximum, the receiver operates in a "linear mode".

If a quench signal is not used and a resistive/capacitative network is placed at the grid or base, the stage will oscillate periodically at a rate determined by the resistor/capacitor time constant and the strength of the input signal. This type of superregeneration is referred to as "self-quenched".

Since the antenna of a simple superregenerative receiver is connected directly to the input grid or base of the active stage and the quench signal is also connected to the input grid or base; the quenched oscillations of the active stage are radiated by the antenna.

Measurements

Five garage door openers and two VHF converters were investigated. All seven units were self-quenched, logarithmic mode superregenerative receivers. Radiations from two door openers were not detectable. The emission characteristics of the two VHF converters were similar to each other, except for amplitude. Consequently, only the stronger (10 dB) of the two was measured. TABLE 2-5 contains information concerning the equipments measured.

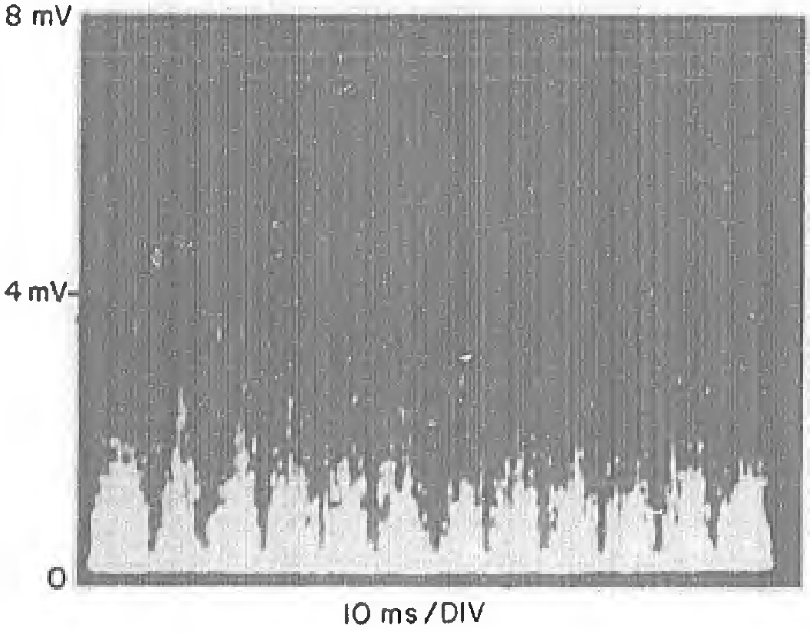


Figure 2-24. Welder Detected Time Waveform at 1000 MHz

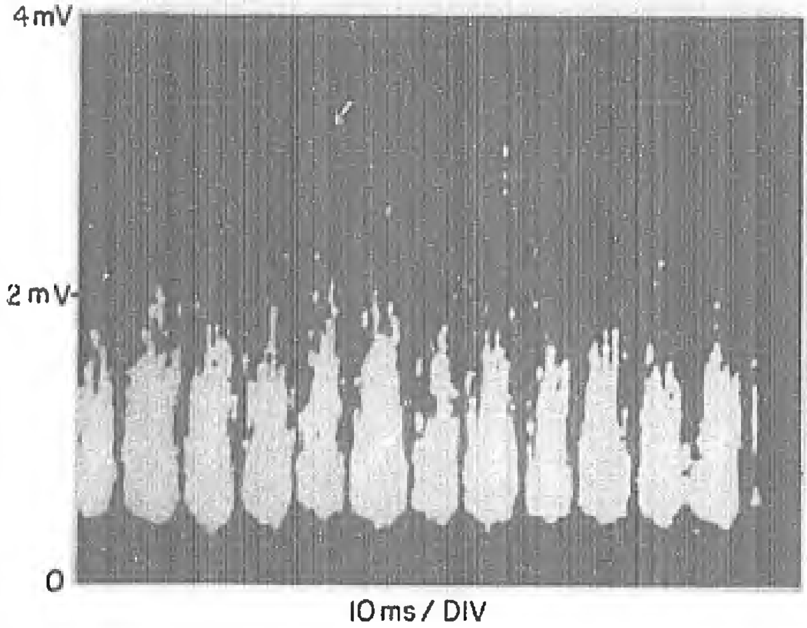


Figure 2-25. Welder Detected Time Waveform at 100 MHz

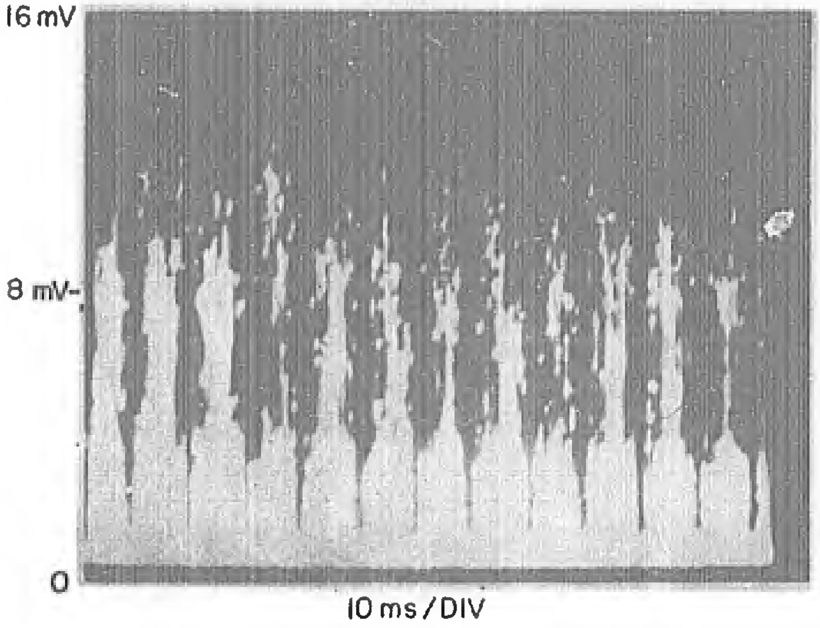


Figure 2-26. Welder Detected Time Waveform at 1.7 MHz

TABLE 2-5

SUPERREGENERATIVE RECEIVER FREQUENCIES AND MEASUREMENT DISTANCES

Model	Frequency (MHz)	Emitter-to-Antenna Distance (feet)
	Garage Door Openers	
VEMCO ET-4	225.174	20 (no radiation detected)
Linear Corp. 903	250	15 (no radiation detected)
Overhead Door R80Z	273	2.5
Telectron R-40	295.22	3
Wards 903	234	2.5, 30
	VHF Converter	
SKYWAVE	109	30

The test procedures used for all superregenerative units were similar to those outlined in Section 3. Field strengths are calculated using Equation (2-2). Distributed field strengths and power densities are summarized later in TABLE 2-6, for the units measured.

SKYWAVE Converter. A dipole antenna placed 30 feet from the converter was used to receive and deliver signals to the HP8555 spectrum analyzer and NF105 field intensity meters. The peak amplitude of the received signal was calibrated using an HP608 signal generator. The emission spectrum was photographed and the results are shown in Figure 2-27.

Overhead Door. A quarter-wave monopole antenna was placed 2.5 feet from the door opener and received signals were measured and calibrated using an HP8555 spectrum analyzer and an HP608 signal generator, respectively. The emission spectrum is shown in Figure 2-28. Field strengths are calculated using Equation (2-2) and distributed field strengths and power densities are listed in TABLE 2-6.

TABLE 2-6

DISTRIBUTED POWER DENSITIES OF SUPERREGENERATIVE RECEIVERS AT 100 FEET

Model	Instrument Bandwidth (kHz)	Distance (feet)	Instrument	Antenna	P_{davg} dBm/m^2/kHz	E_{drms} $\mu V/m/\sqrt{kHz}$
Skyway	100	30	HP8555	Dipole	−132.9	.143
Skyway	300	30	HP8555	Dipole	−133.7	.130
Skyway	120	30	NF105	Dipole	−132.2	.174
Overhead Door	3	2.5	HP8555	Monopole	−119.5	.675
Telectron	1	3	HP8555	Monopole	−120.4	.60
Wards	30	30	HP8555	Dipole	−119.2	.69
Wards	100	30	HP8555	Dipole	−118.4	.76
Wards	300	30	HP8555	Dipole	−117.2	.87
Wards	185	30	HP8555	Dipole	−117.1	.88
Wards	185	30	NF105	Monopole	−115.6	1.05
Wards	1	2.5	HP8555	Monopole	−117.9	.80

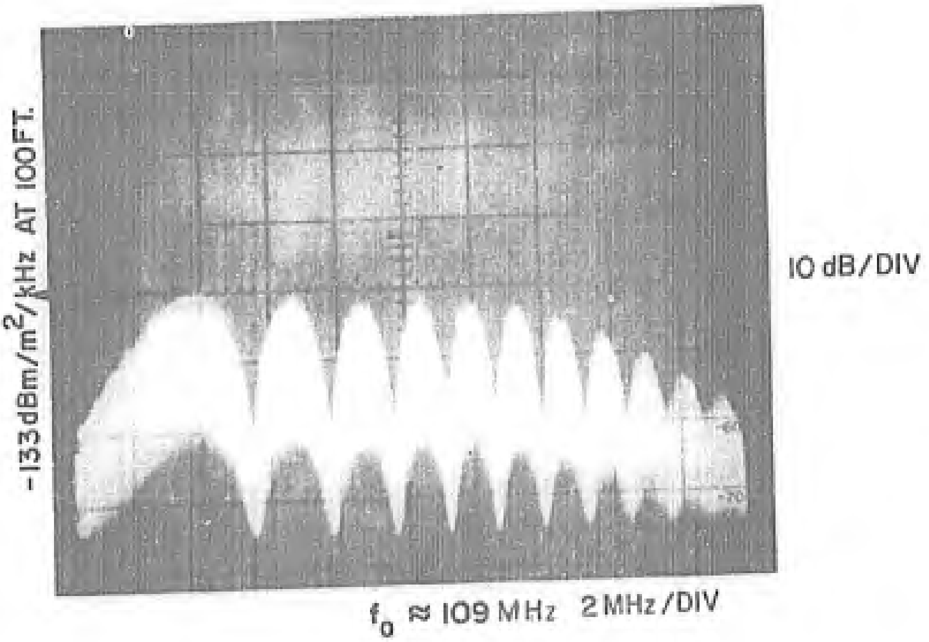


Figure 2-27. Emission Spectrum of Skywave Converter

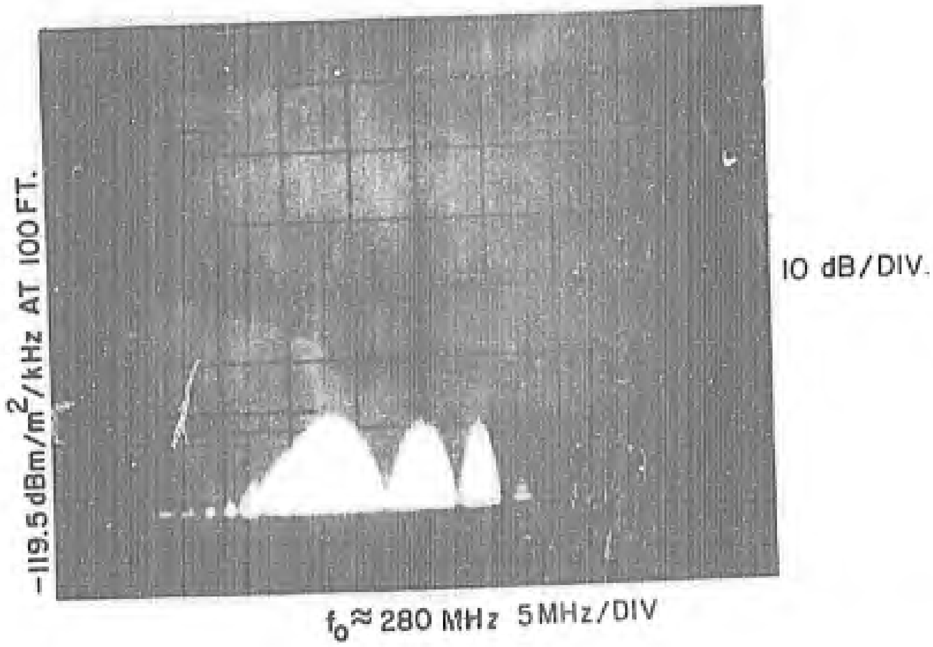


Figure 2-28. Emission Spectrum of Overhead-Door Garage Door Opener

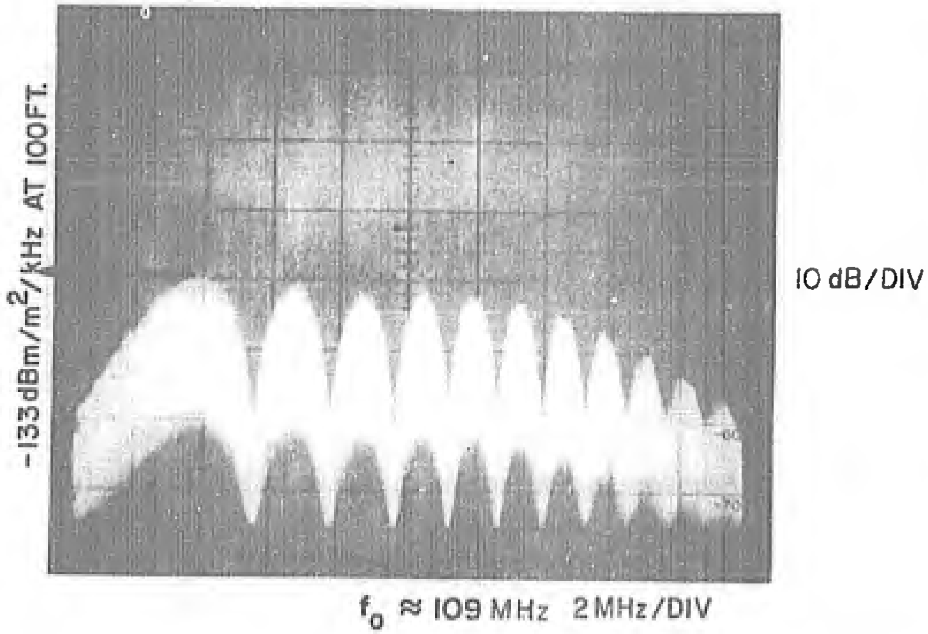


Figure 2-27. Emission Spectrum of Skywave Converter

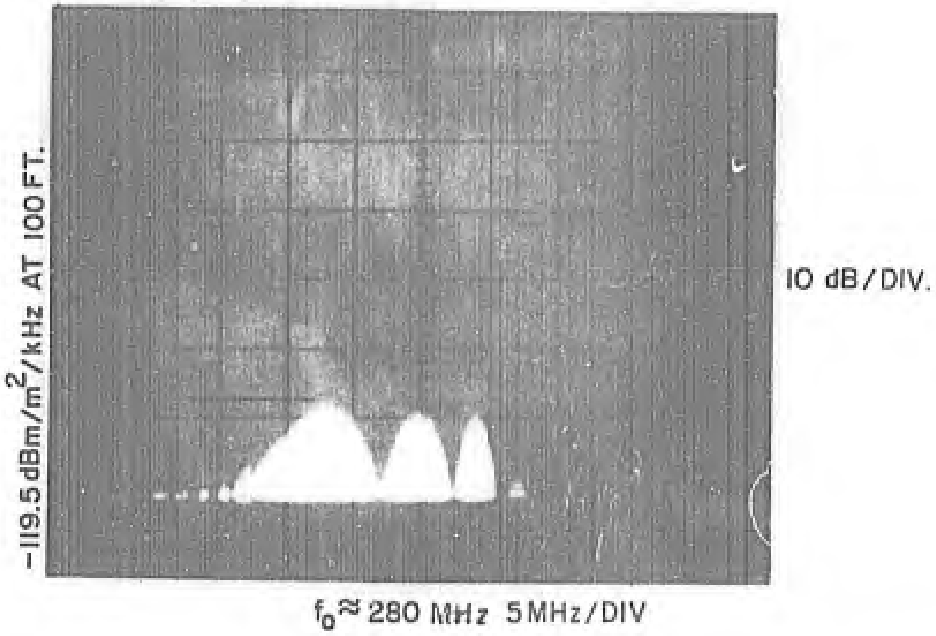


Figure 2-28. Emission Spectrum of Overhead-Door Garage Door Opener

Telectron. A quarter-wave monopole was placed 3 feet from the door opener and received signals were measured and calibrated with an HP8555 spectrum analyzer and an HP608 signal generator, respectively. The emission spectrum is shown in Figure 2-29. Figure 2-30 shows the simultaneous recording of the receiver emission spectrum and the emission of the door opener transmitter.

Wards. The Wards Model 903 was measured at 30 feet and 2.5 feet with a half-wave dipole and quarter-wave monopole. The received signals were measured and calibrated using the HP8555 spectrum analyzer, an NF105 field intensity meter and an HP608 signal generator. The measured emission spectrum is shown on Figure 2-31. Figure 2-32 shows the door opener's spectrum and the emission from the transmitter. Notice the quench frequency occurring at approximately 450 kHz.

Distributed Field Intensities and Power Densities. The field intensities in microvolts per meter calculated from Equation (2-2) are correct only at the bandwidth at which the measurement was made. As the bandwidth is increased the measured power increases in direct proportion. Tests were made of all the measured receivers to confirm this fact.

Since the measured average power output of a random noise signal varies in direct proportion to the receiver bandwidth, all field intensities calculated using Equation (2-2) were converted into distributed power densities in milliwatts per square meter per bandwidth. A problem arose in that the peak amplitude was measured and the average power per bandwidth was desired; consequently, a conversion factor was needed to relate peak amplitude to average power for random noise. Measurement results indicate that the crest factor (peak voltage to rms voltage ratio) for random noise amplitudes is approximately 5 to 1 (14 dB). Therefore, the peak power, as measured with the HP608 generator, is related to the average power using the following expression:

$$p_{peak} = 25\, p_{avg} \text{ for random noise,} \qquad (2\text{-}8)$$

or in logarithmic form:

$$P_{avg} = P_{peak} - 14 \text{ dB, where } P_{peak} \text{ is in dBm.}$$

The distributed average power density is calculated using Equation (2-9a).

$$P_{davg} = P_D - 14 - 10 \log (BW), \text{ in dBm/m}^2\text{/kHz} \qquad (2\text{-}9a)$$

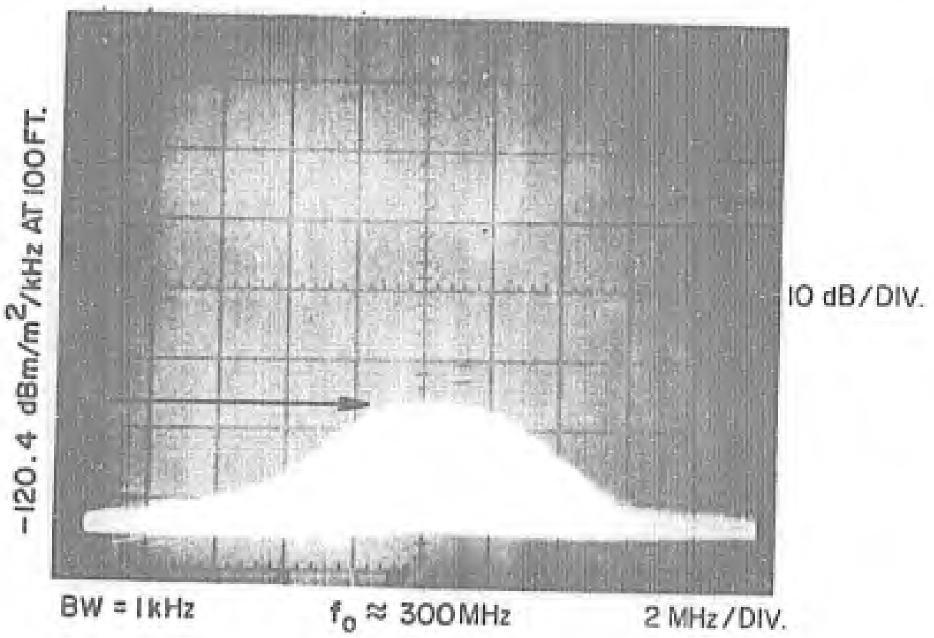


Figure 2-29. Emission Spectrum of Telectron Garage Door Opener Receiver

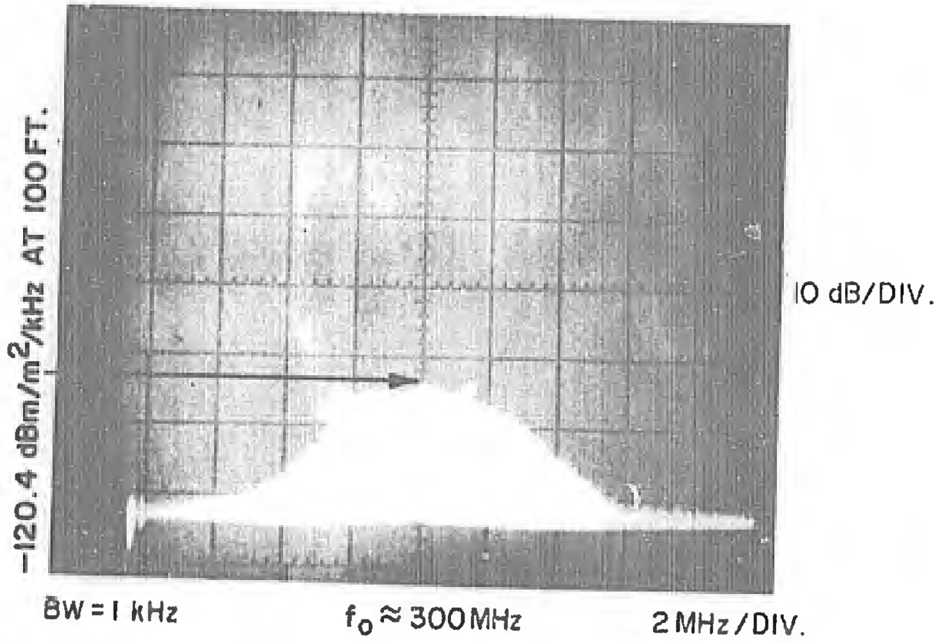


Figure 2-30. Combined Emission Spectrum and Transmitter, of Telectron Garage Door Opener Receiver

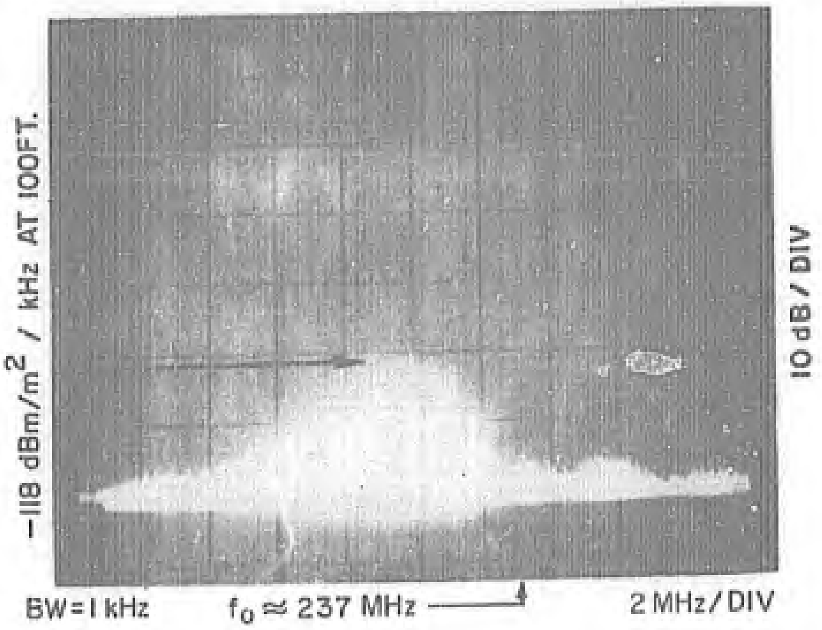


Figure 2-31. Emission Spectrum of Wards Garage Door Opener Receiver

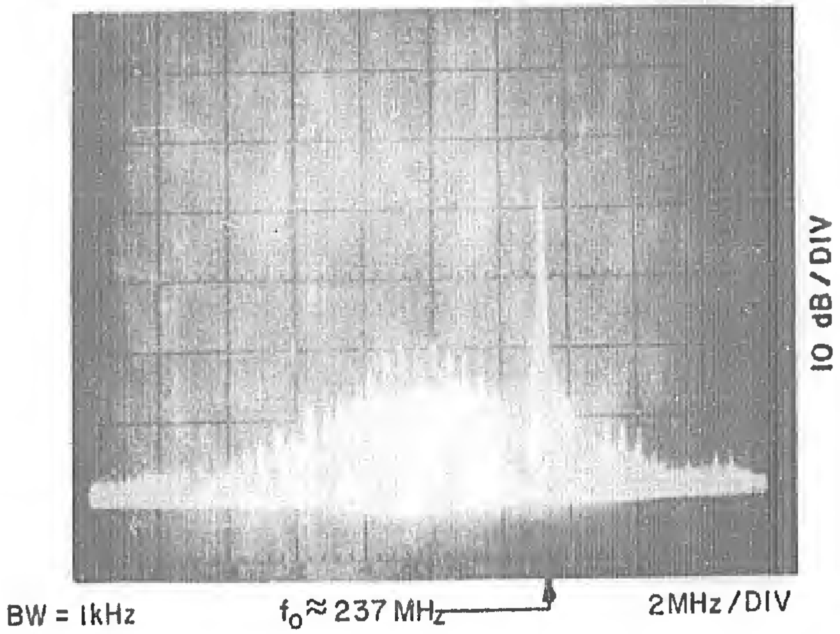


Figure 2-32. Combined Emission Spectrum of Wards Garage Door Opener Receiver and Transmitter

The distributed electric field intensity is calculated using Equation (2-9b).

$$E_{drms} = 10^{6} \sqrt{0.377 \log^{-1} \frac{P_{davg}}{10}} \text{ ,in } \mu V/m/\sqrt{kHz} \qquad (2\text{-}9b)$$

where

BW = the analyzer bandwidth in kHz.

P_D = the peak power density in dBm/m².

The distributed power densities and field intensities are listed in TABLE 2-6.

SECTION 3

MEASUREMENT PROCEDURES

The procedures in this section were developed by ECAC in the process of performing the field measurements described in Section 2. The radiation from a dielectric heater is considered to be narrow-band since its spectrum is narrower than the bandwidth of most field intensity meters (FIM). Radiation from a superregenerative receiver, on the other hand, is broadband by comparison with the bandwidth of the FIM. A separate measurement procedure for each type of signal is furnished.

Of special interest is Figure 3-1 which shows basic transmission loss versus distance for a family of frequencies. The dark portions of the curves delineate the range of distances over which the measurements must be made in order to insure accuracy.

EMISSION MEASUREMENT PROCEDURE FOR DIELECTRIC HEATERS

1. Determine the approximate operating frequency and harmonic frequencies of the dielectric generator and consult the basic transmission loss versus distance chart (Figure 3-1) to ascertain over what range of distances the test half-wave dipole may be placed from the dielectric heater. Distances less than those indicated by the dark portions of the curves will result in near field problems and distances greater than those indicated will result in ground-wave attenuation. No attempt was made to account for the multipath problem at frequencies higher than 170 MHz.

2. Refer to Figure 3-2 and connect the half-wave dipole to the broadband radio frequency voltmeter. Determine the maximum received power of the dielectric generator.

3. Determine and insert the amout of attenuation necessary to protect the spectrum analyzer. Insert at least 6 dB.

4. The sensitivity of the receiving system referenced at the attenuator input should be at least -60 dBm + 20 log $(F_{MHz}/100)$. For example, a system sensitivity of -80 dBm would be satisfactory for frequencies greater than 10 MHz.

5. *Harmonic Energy*

   a. Set the analyzer bandwidth to maximum, but not to exceed 1 MHz.

   b. Set the analyzer sweep width and tuning to display the operating frequency.

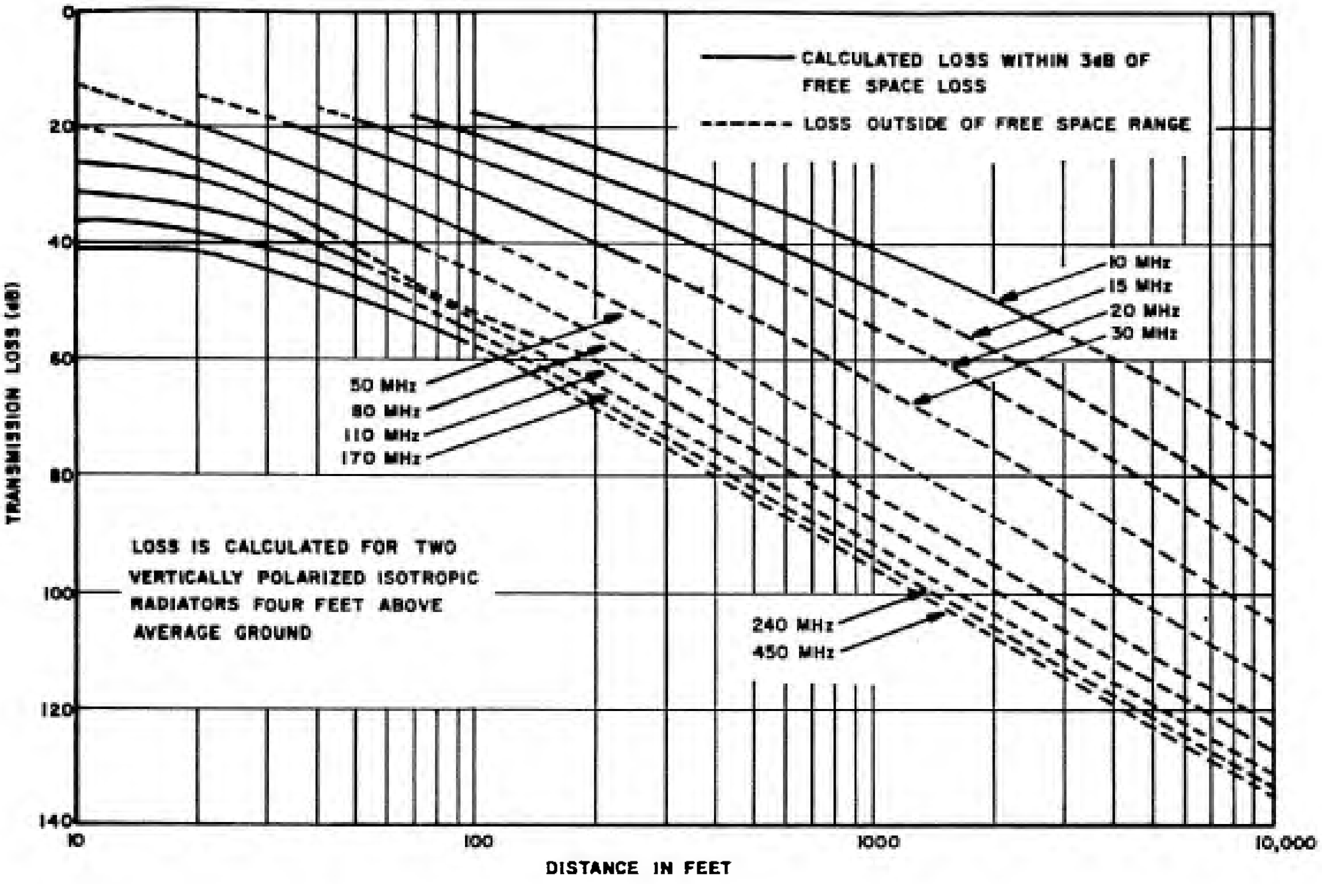


Figure 3-1. Basic Transmission Loss versus Distance for a Family of Frequencies

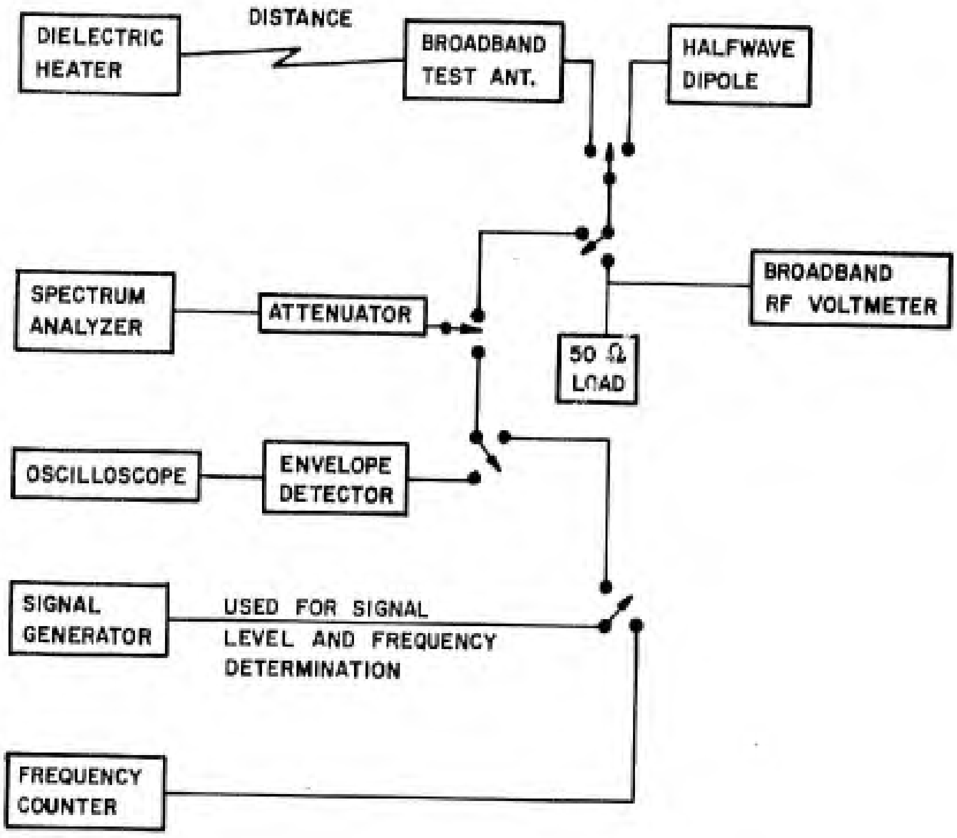


Figure 3-2. Equipment Arrangement for Measuring Emissions from Dielectric Heaters

c. Adjust the half-wave dipole to the operating frequency.

d. Decrease the sweep time in steps until the displayed amplitude decreases, then increase the sweep time one step; or increase the sweep time in steps until the amplitude no longer increases.

e. Measure the level and frequency using signal substitution.

f. Repeat steps a. through e. for each harmonic and spurious emission that exceeds $-60 + 20 \log (F_{MHz}/100)$ dBm.

6. *Carrier Frequency Sweep Limits*

a. Tune the analyzer to the dielectric heater fundamental frequency and adjust the sweep width to display the emission spectrum. Let the sweeping carrier of the dielectric heater be displayed so that the display appears on approximately 80% of the screen.

b. Choose a convenient sweep time (approximately 3 milliseconds per division).

c. Set the bandwidth to 1 kHz or a frequency that is less than one tenth of the sweep width (whichever is the lesser).

d. Record the result displayed on the analyzer and determine the difference between the maximum and minimum frequencies.

7. *Carrier On-Time*

a. If the difference between the maximum and minimum frequencies (step 6.d.) is greater than the widest analyzer bandwidth position, use the envelope detector and oscilloscope and proceed to step 7.d.; if not, use the analyzer and continue with step 7.b.

b. Set the analyzer bandwidth to maximum.

c. Set the sweep width to zero.

d. Set the sweep time to 1 second per division (this should provide a reading accuracy of 0.2 seconds).

e. Count the time the carrier is on.

8. *Modulation Characteristics*

a. If the difference between the maximum and minimum frequencies (step 6.d.) is greater than the widest analyzer bandwidth position use the envelope detector and oscilloscope and proceed to step 8.d.; if not, use the anlayzer and continue with step 8.b.

b. Set the analyzer bandwidth to maximum.

c. Set the sweep width to zero.

d. Set the vertical display to linear and adjust the gain and sweep time to obtain a convenient display.

e. Photograph the displayed . information. Record the vertical (volts/division) and horizontal (seconds/division) scales.

f. Determine the type of modulation (single-phase full-wave, three-phase half-wave, or three-phase full-wave).

9. Instead of using a half-wave dipole antenna, a broadband antenna (with its associated antenna factor versus frequency curve) may be used and numerous harmonic amplitudes may be displayed on the spectrum analyzer in one sweep. Using a broadband antenna will shorten the measurement time for step 5.

10. The power density or field strength of each harmonic may now be calculated and expressed in terms of dBm/m^2 or dB above one microvolt per meter at the distance separating the dielectric heater from the half-wave dipole.

11. *Measurement at Large Distances.* When it becomes impractical to comply with the distances specified in step 1., use the following steps to obtain the correct field strength in dB above one microvolt per meter.

a. Set up the half-wave dipole at a convenient distance and move the antenna around in an attempt to locate the *source* of interference. The source may be the dielectric heater or possibly power cables extending from the dielectric heater or the building in which the dielectric heater is housed.

b. Determine the distance between the *source* and the half-wave dipole.

c. The field strength measured at this distance should be extrapolated to a convenient point within the range of distances shown on the transmission loss versus distance chart where ground-wave attenuation is negligible.

d. Example: If 20 dB above one microvolt per meter is measured at one mile (5280 feet) at 20 MHz, the field strength at 100 feet would be 20 + 58 = 78 dB above one microvolt per meter. The 58 dB is obtained from Figure 3-1 by subtracting the loss at 100 feet from the loss at 5280 feet.

EMISSION MEASUREMENT PROCEDURE FOR SUPERREGENERATIVE RECEIVERS

1. Determine the approximate operating frequency of the source to be measured and consult the transmission loss versus distance chart (Figure 3-1) to ascertain over what

range of distances from the source the half-wave dipole may be placed. Distances less than those indicated by the dark portions of the curves will result in near field problems and distances greater than those indicated will result in ground-wave attenuation.

2. Referring to Figure 3-3, connect the half-wave dipole to the spectrum analyzer or field intensity meter (FIM), keeping at least 6 dB of attenuation in the attenuator. Tune the analyzer or FIM to the source frequency. The FIM in the quasi-peak mode may be used to locate weak signals.

3. Move the half-wave dipole vertically to obtain a maximum field strength.

4. The displayed signal will be either broadband random noise or broadband random noise with a combination of narrow-band signals.

5. *Broadband Random Noise Power with Spectrum Analyzer*

a. Adjust the analyzer sweep width and tuning so that the significant components of the source are displayed. This usually corresponds to a sweep width of approximately 2 MHz per division or 20 MHz total.

b. Set the analyzer bandwidth equal to or less than one tenth of the measured spectrum. Bandwidths of approximately 10 kHz are usually sufficient.

c. Adjust the sweep time to satisfy the following inequality.

$$\text{sweep time} > \frac{50\ (\text{sweep width})}{(\text{bandwidth})^2}\ , \tag{3-1}$$

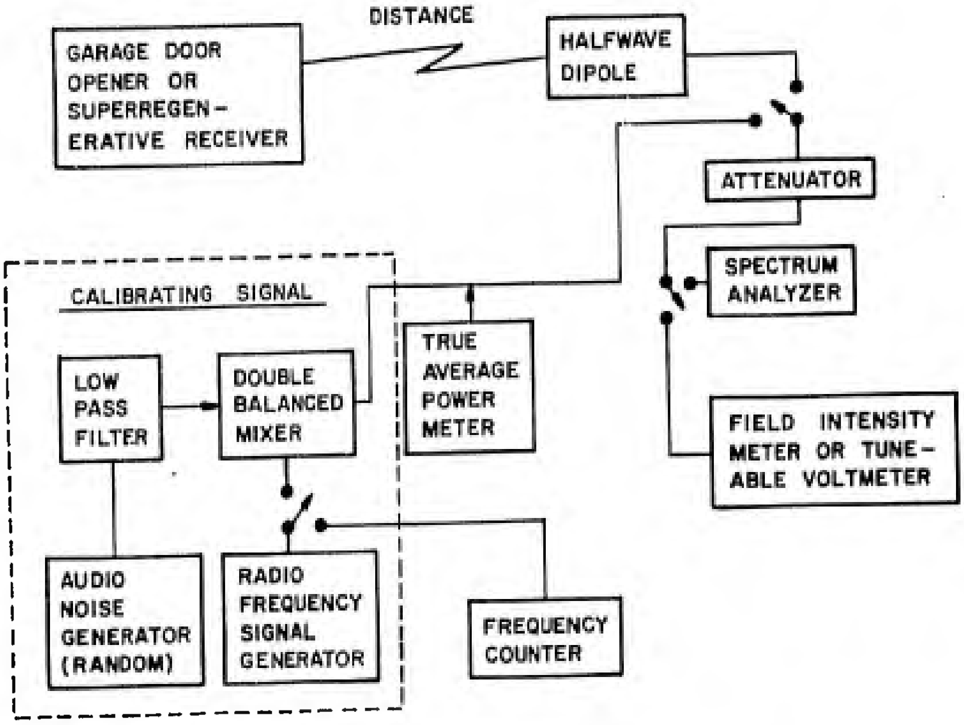
all units are in seconds and hertz.

d. Photograph the resulting display.

e. Insert the calibrating signal into the analyzer and duplicate the amplitude of the source. The bandwidth of the random noise calibrating signal must be greater than the analyzer bandwidth (preferably ten times greater).

f. Record the average power in milliwatts going into the analyzer and the calibrating signal bandwidth in kHz so that the distributed power may be determined in milliwatts per kHz.

g. The distributed power density and distributed field intensity may be calculated and expressed in terms of milliwatts per square meter per kHz bandwidth and dB above one microvolt per meter per square root of kHz bandwidth.



USED TO DETERMINE THE DISTRIBUTED POWER IN dBm/kHz AND RADIO FREQUENCY

Figure 3-3. Equipment Arrangement for Measuring Garage Door Openers and Superregenerative Receivers

6. *Broadband Random Noise with Field Intensity Meter.* Step 5. was written for use with a spectrum analyzer. The following steps should be used for an FIM.

a. Set the FIM detector function to the quasi-peak position and adjust the tuning to the signal frequency of the superregenerative receiver.

b. Adjust the tuning over a range of approximately 20 MHz about the superregenerative receiver frequency and note minima and maxima.

c. Tune the FIM to the strongest maximum and obtain a convenient reading.

d. Insert the calibrating signal of Figure 3-3 and duplicate the reading obtained in step c. The bandwidth of the calibrating signal must be greater than the FIM bandwidth.

e. Follow steps 5.f. and 5.g.

f. If narrow-band signals are suspected, follow the procedures set forth in step 7.

7. *Broadband Random Noise with Narrow-band Signals*

a. Perform steps 5.a. through 5.d. for the analyzer or 6.a. through 6.c. for the FIM.

b. Insert a CW signal into the analyzer or FIM and adjust the level to duplicate the amplitude of the largest narrow-band signal.

c. Record this level in dBm or dB above one microvolt.

d. Record the frequency difference between the narrow-band signals. This is the superregenerative receiver's "quench" frequency.

e. The power density and field intensity of the narrow-band signal may be calculated and expressed in terms of dBm per square meter and dB above one microvolt per meter.

8. If the calibrating signal shown in Figure 3-3 cannot be obtained, insert a CW signal and adjust the level to duplicate the random noise signal amplitude. Record the CW signal level in dBm, subtract 14 dB to obtain the average random noise power in dBm, convert to milliwatts and divide by the analyzer or FIM 3 dB bandwidth to express the distributed power in milliwatts per kHz bandwidth.

Example: If the analyzer or FIM bandwidth is 10 kHz and the substituted CW level is −86 dBm, the average power will be approximately $-86 - 14 = -100$ dBm in a 10 kHz bandwidth or 10^{-10} milliwatts per 10 kHz which is equal to 10^{-11} milliwatts per kHz which is equal to −110 dBm per kHz bandwidth.

SECTION 4

CONCLUSIONS

An examination of the measured data reveals that the radiations from superregenerative receivers, radio frequency stabilized arc welders and automobile ignition systems are broadband in nature; that is, their radio frequency spectra are much wider than the bandwidth of the measuring instrument. As a consequence, the measuring receiver only samples a portion of these broadband radiated spectra.

Therefore, it is not possible to express the measured radiation strength from these broadband signal sources in the traditional units of volts per meter or watts per square meter. Instead, the bandwidth of the measuring instrument must be included and the terms defined in this report (*distributed* field intensity or *distributed* power density) should be used. The basic units of these expressions are volts per meter per hertz and watts per square meter per hertz, respectively. This is because of the basic physical fact (Reference 10) that the peak of the detected output voltage envelope of a receiver when processing impulsive noise varies directly with its bandwidth, and when processing random noise, varies directly with the square root of its bandwidth.

It is further concluded that:

1. The radiation from a superregenerative receiver is a broadband *random noise* signal, and measured radiation levels from it must be expressed in basic units of watts per square meter per hertz.
2. The radiation from an automobile ignition system is a broadband *impulse* signal, and measured radiation levels from it must be expressed in basic units of volts per meter per hertz.
3. The radiation from a radio frequency stabilized arc welder is a combination *broadband* random noise and broadband *impulse* noise signal. The measured radiation level must be expressed in basic units of watts per square meter per hertz for small measurement bandwidths and volts per meter per hertz for large measurement bandwidths (Figure 2-19). A bandwidth must be determined below which the units of watts per square meter per hertz are used and above which the units of volts per meter per hertz are used. In this investigation, that bandwidth was 5 kHz.
4. The radiations from dielectric heaters (except for microwave ovens which were not investigated) and medical diathermy machines are *narrow-band* in nature, and the measured radiation levels are expressed in the traditional units of volts per meter or watts per square meter.
5. The measurement procedures provided in Section 3 will result in the type of data needed to describe quantitatively the electromagnetic radiations from dielectric heaters and superregenerative receivers.

APPENDIX A

DERIVATION OF EQUATIONS

DEVELOPMENT OF DIELECTRIC HEATER TIME WAVEFORM AND SPECTRAL EQUATIONS

Consider a carrier frequency expression,

$$e = E \cos \omega_o t, \qquad \text{(AI-1)}$$

where

E = the peak amplitude of the carrier frequency ω_o.

If amplitude e is allowed to vary sinusoidally about E for a finite period of time the following equation results,

$$e = E\,(k \cos \omega_m t)\,(\cos \omega_o t) \text{ where } -\frac{T'}{2} \leqslant t \leqslant \frac{T'}{2} \qquad \text{(AI-2)}$$

Figure A-1 illustrates the basic waveform.

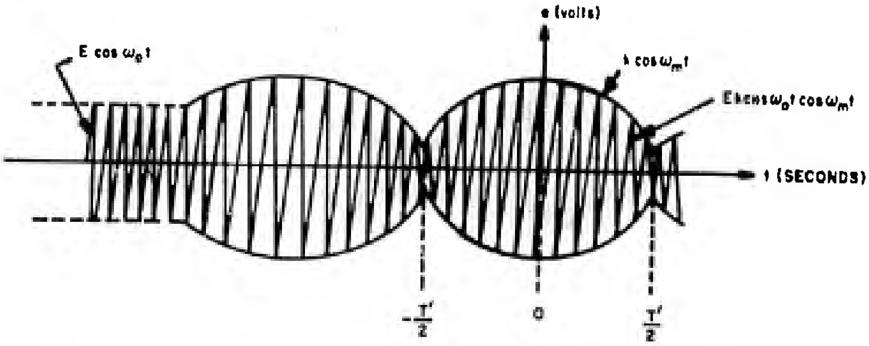


Figure A-1.

The frequency ω_m, in radians, is a slowly varying modulating frequency such that $\omega_o >> \omega_m$. For the 60 Hz dielectric heater power supply $\omega_m = 2\pi f = 377$ radians/second and $T = 1/f = 1/60$ seconds.

Time waveforms and spectra of three cases of Equation (AI-2) will be determined for

1. Single-phase full-wave $\frac{T'}{2} = T/4$ (AI-3)
2. Three-phase half-wave $\frac{T'}{2} = T/6$ (AI-4)
3. Three-phase full-wave $\frac{T'}{2} = T/12$ (AI-5)

The average value of the modulating envelope is equal to the peak value of the unmodulated carrier, (Reference 4). The constant k in Equation (AI-2) becomes,

$$k = \frac{e_{peak}}{E} \qquad \text{(AI-6)}$$

The average value of the modulating envelope is,

$$E = \frac{1}{T'} \int_{-T'/2}^{T'/2} e_{peak} \cos\omega_m t \, dt \qquad \text{(AI-7)}$$

When Equations (AI-3), (AI-4) and (AI-5) are substituted into Equation (AI-7) the ratio of e_{peak}/E may be solved for the three cases.

1. Single-phase full-wave k = 1.57.
2. Three-phase half-wave k = 1.21.
3. Three-phase full-wave k = 1.046.

Substituting into Equation (AI-2)

1. Single-phase full-wave

$$e_1 = 1.57\, E \cos \omega_m t \cos \omega_o t, \quad -\frac{T}{4} \leqslant t \leqslant \frac{T}{4} \qquad \text{(AI-8)}$$

2. Three-phase half-wave

$$e_2 = 1.21\,E \cos \omega_m t \cos \omega_o t, \quad -\frac{T}{6} \leqslant t \leqslant \frac{T}{6} \qquad \text{(AI-9)}$$

3. Three-phase full-wave

$$e_3 = 1.046\,E \cos \omega_m t \cos \omega_o t, \quad -\frac{T}{12} \leqslant t \leqslant \frac{T}{12} \qquad \text{(AI-10)}$$

The Fourier series of equations (Reference 5) may be found by using

$$C_n = \int_{-T'/2}^{T'/2} e(t)\, e^{-j\omega_n t}\, dt \qquad \text{(AI-11)}$$

and

$$e(t) = \sum_{-\infty}^{\infty} C_n e^{j\omega_n t} = \frac{2}{T'} \sum_{1}^{\infty} |C_n| \cos \omega_n t \qquad \text{(AI-12)}$$

The right hand side of Equation (AI-12) is valid when the function e(t) has zero average value.

When Equation (AI-2) is substituted into Equation (AI-11) and the assumption is made that $\omega_o >> \omega_m$,

$$C_n = \frac{Ek}{2}\left[\frac{\sin(\omega_o + \omega_m - \omega_n)\frac{T'}{2}}{\omega_o + \omega_m - \omega_n} + \frac{\sin(\omega_o - \omega_m - \omega_n)\frac{T'}{2}}{\omega_o - \omega_m - \omega_n}\right] \qquad \text{(AI-13)}$$

Inserting the solutions for three cases of C_n into Equation (AI-12) results in

1. Single-phase full-wave

$$e_1 = E\cos\omega_o t + \frac{E}{3}\cos(\omega_o \pm 2\omega_m)\,t - \frac{E}{15}\cos(\omega_o \pm 4\omega_m)\,t + \frac{E}{35}\cos(\omega_o \pm 6\,\omega_m)\,t - \ldots.. \qquad \text{(AI-14)}$$

2. Three-phase half-wave

$$e_2 = E\cos\omega_o\,t + \frac{E}{8}\cos(\omega_o \pm 3\,\omega_m)\,t - \frac{E}{35}\cos(\omega_o \pm 6\,\omega_m)\,t + \frac{E}{80}\cos(\omega_o \pm 9\,\omega_m)\,t - \ldots.. \qquad \text{(AI-15)}$$

3. Three-phase full-wave

$$e_3 = E\cos\omega_o t + \frac{E}{35}\cos(\omega_o \pm 6\,\omega_m)\,t - \frac{E}{143}\cos(\omega_o \pm 12\,\omega_m)\,t + \frac{E}{323}\cos(\omega_o \pm 18\,\omega_m)\,t - \ldots.. \qquad \text{(AI-16)}$$

DERIVATION OF FIELD STRENGTH (EQUATION 2-2)

The Whip Antenna

Electric field strength at 100 feet can be calculated (Equation 2-2) when the received power dissipated into 50 ohms is known. The field strength is assumed to be a function of the distance (d) separating the receiving antenna from the radiation source, the cable loss between the receiving antenna and the 50 ohm termination, and the type of receiving antenna; transmission losses other than free space are not considered here but are treated separately (see Figure 3-1).

As shown in Reference 4, the relationship between the electric field strength at a receiving antenna and the maximum power dissipated in an antenna terminating load resistance is,

$$P_{Rmax} = \frac{G\lambda^2}{480\pi^2} \mathcal{E}_m^2 \text{ in watts} \qquad \text{(AII-1)}$$

where

G = antenna power gain based upon an isotropic gain of unity.

λ = wavelength in meters

$\mathcal{E}_m$ = field strength in volts/meter

P_{Rmax} = maximum power the antenna can dissipate in a terminating resistor.

Since an impedance mismatch usually occurs between the receiving antenna and the terminating resistor, the power dissipated in the terminating resistor is,

$$P_R = \frac{P_{Rmax}}{MM} = \frac{G\lambda^2 \mathcal{E}_m^2}{480\pi^2 \, MM} \qquad \text{(AII-2)}$$

where

MM = mismatch factor

Solving Equation (AII-2) for $\mathcal{E}_m$ one obtains,

$$\mathcal{E}_m = \sqrt{\frac{480\pi^2 \, MM \, P_R}{G\lambda^2}} \quad \text{in volts/meter} \qquad \text{(AII-3)}$$

It is desired to calculate $\mathcal{E}_m$ at distance d_m from the source of radiation and extrapolate $\mathcal{E}_m$ to $\mathcal{E}_1$ at another distance, d_1. In the far field the extrapolation becomes simply,

$$\mathcal{E}_1 = \frac{\mathcal{E}_m d_m}{d_1} \qquad \text{(AII-4)}$$

Since several measurements were made in the near field, it is necessary to determine a more complete expression for $\mathcal{E}$ as a function of d.

For an elementary dipole, or an antenna whose length is small compared to a wavelength, the electric field component perpendicular to a plane normal to the radiating element is given by (Reference 6):

$$\mathcal{E} = K\left(j\frac{2\pi}{\lambda d} + \frac{1}{d^2} + \frac{\lambda}{j2\pi d^3}\right) \qquad \text{(AII-5)}$$

In extrapolating from d_m to d_1, λ is a constant and

$$\mathcal{E} = jK_1\,(x - x^3 - j\,x^2) \qquad \text{(AII-6)}$$

where

$$x = \lambda/2\pi d$$

Since the magnitude of $\mathcal{E}$ is desired

$$|\mathcal{E}| = K_1\sqrt{x^2 - x^4 + x^6} \qquad \text{(AII-7)}$$

at distances d_m and d_1

$$\mathcal{E}_m = \frac{\mathcal{E}_1\sqrt{x_m^{\,2} - x_m^{\,4} + x_m^{\,6}}}{\sqrt{x_1^{\,2} - x_1^4 + x_1^6}} \qquad \text{(AII-8)}$$

When the right hand sides of Equations (AII-8) and (AII-3) are equated,

$$\mathcal{E}_1 = \sqrt{\frac{480\pi^2 MM\,P_R\,(x_1^{\,2} - x_1^{\,4} + x_1^{\,6})}{G\lambda^2\,(x_m^{\,2} - x_m^{\,4} + x_m^{\,6})}} \qquad \text{(AII-9)}$$

where

$$x_1 = \lambda/2\pi\, d_1$$

and

$$x_m = \lambda/2\pi\, d_m$$

Squaring both sides and rearranging the right hand side into four factors

$$\left[\mathcal{E}_1\ (\mu V/m)\right]^2 = \left(\frac{120\pi \times 10^{12}}{1000}\right)\left(\frac{4\pi\, MM}{G\lambda^2}\right)\left(P_{R\ (mW)}\right)\left(\frac{x_1^{\ 2} - x_1^{\ 4} + x_1^{\ 6}}{x_m^{\ 2} - x_m^{\ 4} + x_m^{\ 6}}\right) \qquad \text{(AII-10)}$$

The factor of 1000 is used to convert P_R from watts to milliwatts, and the factor 10^{12} is used to convert $\mathcal{E}_1^{\ 2}$ from $(V/m)^2$ to $(\mu V/m)^2$. Taking 10 $\log_{10}$ of both sides of Equation (AII-10) yields,

$$10 \log \left[\mathcal{E}_1\ (\mu V/m)\right]^2 = \mathcal{E}_1\ (dB/\mu V/m) = 115.76 + AF + P_R + F_d \qquad \text{(AII-11)}$$

where

$$AF = 10 \log \frac{4\pi\, MM}{G\lambda^2} \text{ in dB}$$

$$F_d = 10 \log \left(\frac{x_1^{\ 2} - x_1^{\ 4} + x_1^{\ 6}}{x_m^{\ 2} - x_m^{\ 4} + x_m^{\ 6}}\right) \text{ in dB}$$

For far-field calculations use:

$$F_d = 20 \log d_m/d_1$$

The antenna mismatch factor of the "AF" term in Equation (AII-11) is calculated using the following expression:

$$MM = \frac{|50 + ZA|^2}{200\ RA} = \frac{P_{R\,max}}{P_R} \qquad \text{(AII-12)}$$

where

ZA = complex antenna impedance (ohms)

RA = antenna radiation resistance (ohms)

Equation (AII-12) assumes a 50 ohm antenna terminating resistance.

Whip antennas used for field measurements were a monopole, a dipole and a 54 inch whip. Impedances (ZA and RA) of the monopole and dipole were determined from Reference 7, Section 3, pages 3 through 7. Mismatch loss was then calculated as a function of antenna length to wavelength ratio using Equation (AII-12). The results are plotted in Figure A-2. Received power (P_R) delivered by the 54 inch whip was measured and compared to P_R delivered by a matched quarter-wave monopole as a function of frequency. The results are plotted in Figure A-3.

Equation (AII-11) and Figures A-2 and A-3 were used to compute all electric field strengths in dB/μV/meter at distance d_1 when the received power was measured at distance d_m. Antenna gains of 2 dB and 5 dB were used for the half-wave dipole and quarter-wave monopole, respectively.

The Loop Antenna

Lenz's law states that the voltage induced in a loop is,

$$V_I = N\, d\phi/dt = \left(\frac{240N\pi^3 a^2}{\lambda Z}\right) \mathcal{E}_m \qquad \text{(AII-13)}$$

where

N = number of turns

$\frac{d\phi}{dt}$ = $2\pi^2 f \mu \mathcal{H}_m a^2$

Z = $\mathcal{E}_m/\mathcal{H}_m$ (ohms)

a = radius of loop (meters)

f = c/λ (Hz)

c = velocity of light 3×10^8 m/sec.

μ = $4\pi \times 10^{-7}$

$\mathcal{H}_m$ = magnetic field intensity (amps/meter)

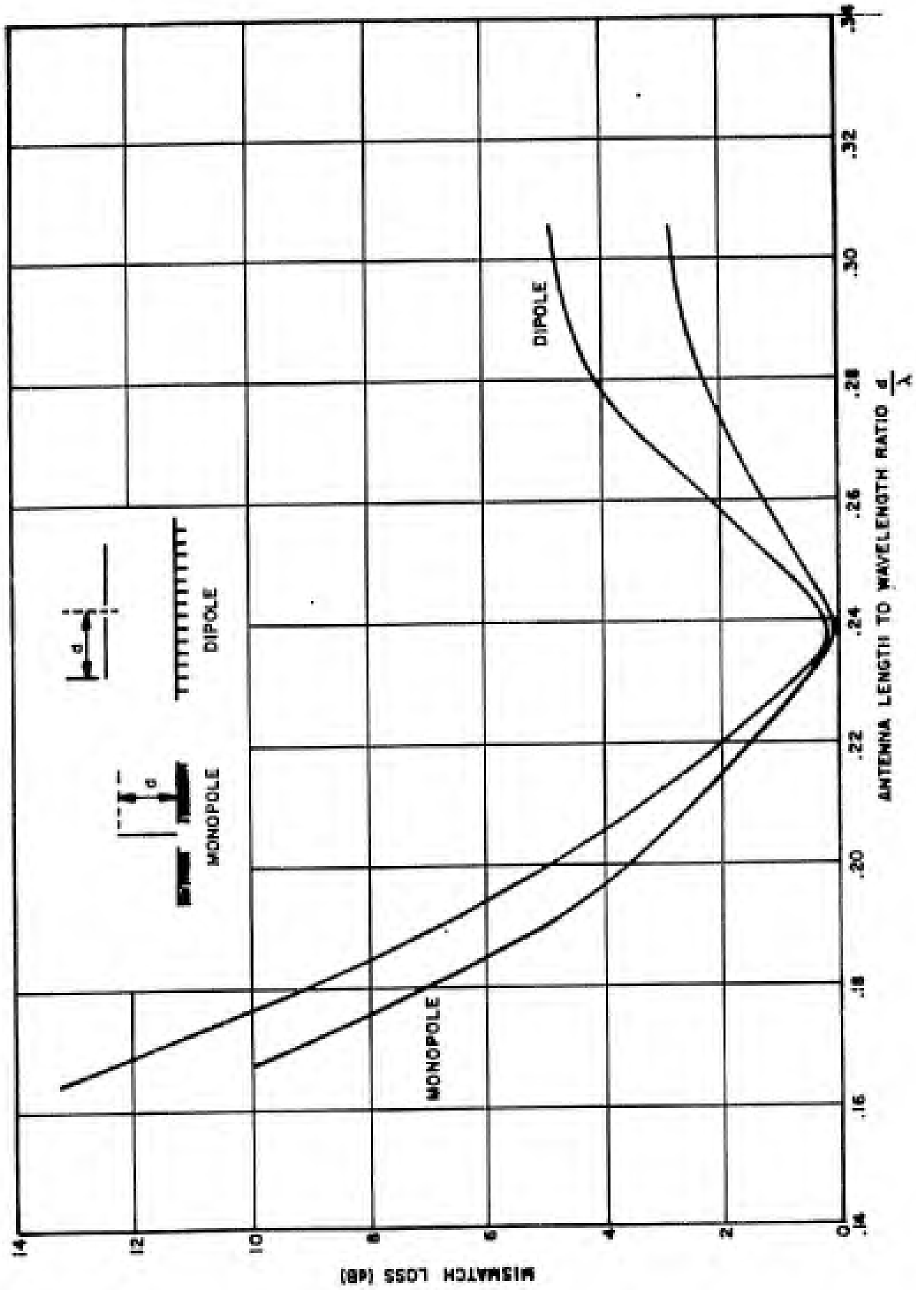


Figure A-2. Dipole and Monopole Antenna Mismatch (Antenna Length to Diameter Ratio = 100)

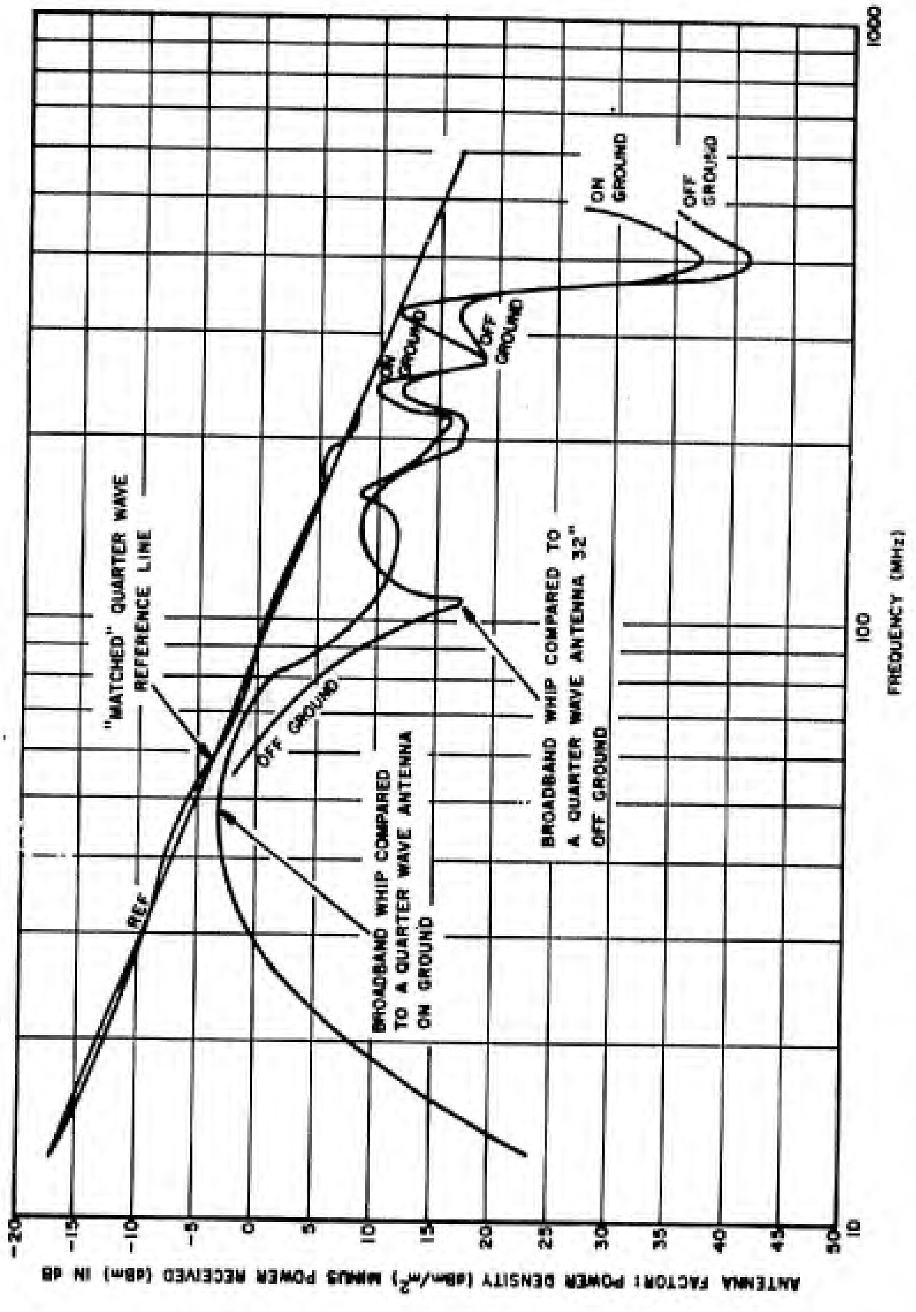


Figure A-3. Antenna Factor of 54" Broadband Whip and Quarter Wave Ground Plane Antennas

The field impedance (Z) at a distance d on a plane normal to an electrically short radiator is (Reference 6)

$$Z = \frac{\mathcal{E}_m}{\mathcal{H}_m} = 120\pi \left(\frac{j2\pi/\lambda d + 1/d^2 - j\lambda/2\pi d^3}{j2\pi/\lambda d + 1/d^2} \right) \qquad \text{(AII-14)}$$

Since the magnitude of Z is desired

$$|Z| = 120\pi \sqrt{y^6 + 1} \Big/ (y^3 + y) = 120\pi\ Z' \qquad \text{(AII-15)}$$

where

$$y = 2\pi d/\lambda$$

$$Z' = \sqrt{y^6 + 1} \Big/ (y^3 + y)$$

Substituting,

$$V_i = (2N\pi^2\, a^2/\lambda\, Z')\mathcal{E}_m \qquad \text{(AII-16)}$$

The maximum power the loop can deliver to a terminating resistance is,

$$P_{Rmax} = \frac{V_i^2}{4RA} \qquad \text{(AII-17)}$$

where

$$RA = \text{loop radiation resistance.}$$

The radiation resistance for an electrically small loop is, (from Reference 8):

$$RA = 20\pi^2 \left(\frac{2\pi a}{\lambda} \right)^4 \text{ ohms} \qquad \text{AII-18)}$$

Substituting Equations (AII-16) and (AII-18) into Equation (AII-17) yields,

$$P_{Rmax} = \left(\frac{1.5\lambda^2}{480\pi^2} \right) \left(\mathcal{E}_m^{\ 2} \right) \left(\frac{N^2}{Z'^2} \right) \qquad \text{(AII-19)}$$

When comparing Equation (AII-19) to Equation (AII-1) (for the whip) one can see that the gain of the elementary dipole is equal to the gain of the elementary loop which is 1.5. The remaining factor of Equation (AII-19) is N^2/Z^2. When $N = 1$ and the near field correction factor, Z', approaches unity (this occurs when $d \geqslant \lambda$); the loop Equation (AII-19) is identical to the whip Equation (AII-1). Using a procedure similar to that used for the whip antenna, the electric field intensity as measured with a loop antenna is

$$\mathcal{E}_1 \text{ (dB}/\mu\text{V/m)} = 115.76 + AF + P_R + F_d + AF_L \tag{AII-20}$$

where

$$AF_L = 20 \log Z'$$

and AF, P_R and F_d are defined as in Equation (AII-11).

The mismatch factor for the loop antenna is the ratio of the matched power (P_{Rmax}) to the power dissipated in a 50 ohm terminating resistance (P_R). P_{Rmax} is given in Equation (AII-17) and

$$P_R = \frac{(V_l k)^2}{50} \tag{AII-21}$$

The k factor is the ratio of the voltage across a 50 ohm resister to the open circuit induced loop voltage. The k factor has been measured by the National Bureau of Standards for the NF105 loop antenna that was used (Reference 9).

The mismatch factor for the NF105 single turn loop is

$$\frac{P_{Rmax}}{P_R} = MM = \frac{4.06 \times 10^{-5} (\lambda/a)^4}{k^2} \tag{AII-22}$$

Equation (AII-22) is plotted in Figure A-4 for four tuning bands of the NF105 loop antenna.

Equation (AII-20) and Figure A-4 were used to compute all electric field strengths in dB/µV/meter at distance d_1 when the received power was measured at distance d_m. An antenna gain of 2 dB was used for the loop antenna.

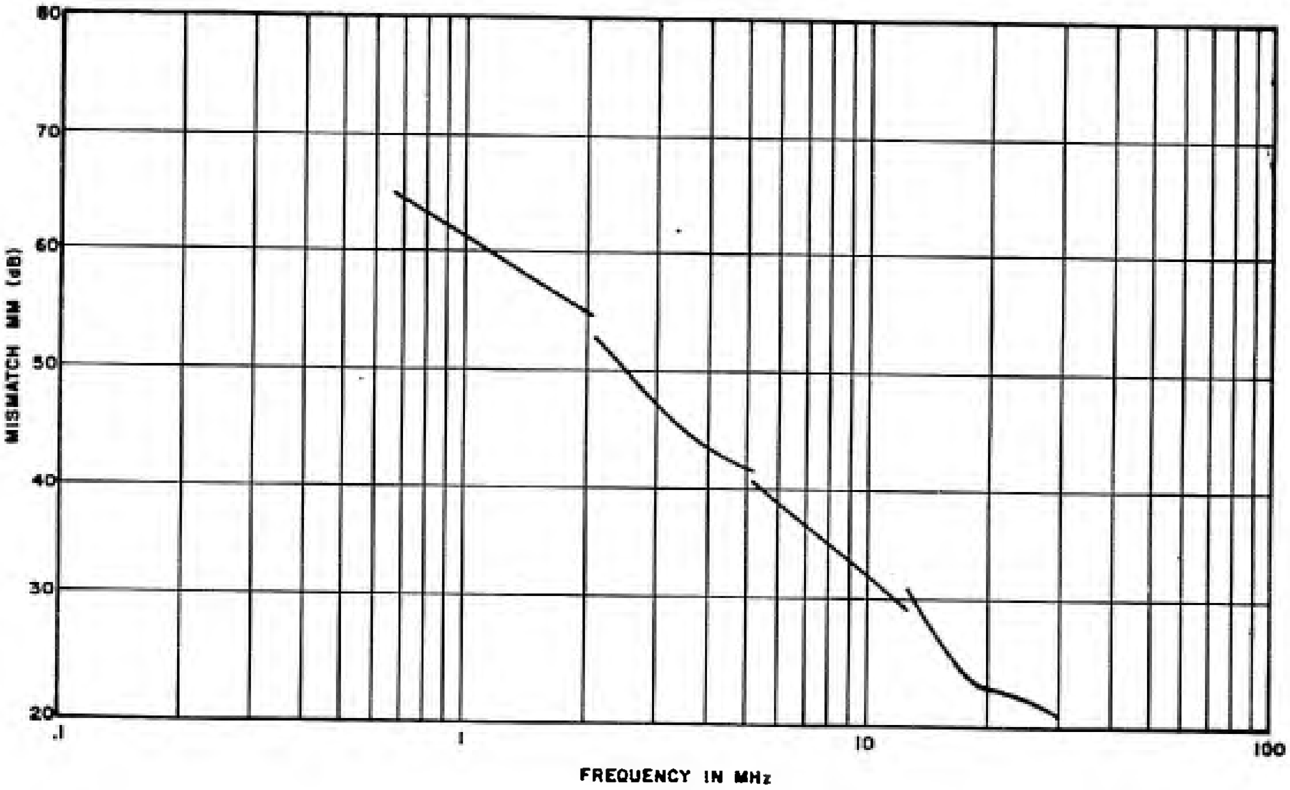


Figure A-4. Mismatch Factor for NF-105 12″ Diameter Loop Antenna

Cable Losses

Cables 25 feet, 50 feet, and 125 feet in length were used at various times to connect the antenna to the 50 ohm terminating resistance. The measured losses of these cables as a function of frequency are shown in Figures A-5, A-6 and A-7.

The cable loss factor, L_C (in dB), is added to Equation (AII-20) to form Equation (AII-23).

$$\mathcal{E}_1 \; (\mathrm{dB}/\mu\mathrm{V/m}) \quad = \quad 116 + AF + AF_L + P_R + L_C + F_d \qquad \text{(AII-23)} \; \text{(2-2)}$$

DERIVATION OF MODULATION (EQUATION 2-3)

When a detected modulated waveform is unsymmetrical about its average value, two modulation factors (one positive and one negative) are used to describe the amplitude modulation.

Equations relating the modulation factors and maximum, minimum and average values of the waveform are,

$$V_{min} \quad = \quad V_{avg} - (m_n)\, V_{avg} \qquad \text{(AIII-1)}$$

$$V_{max} \quad = \quad V_{avg} + (m_p)\, V_{avg} \qquad \text{(AIII-2)}$$

where V_{min}, V_{max} and V_{avg} are the minimum, maximum and average voltages of the detected waveform; and (m_n) and (m_p) are the negative and positive modulation factors respectively. Dividing Equation (AIII-2) by Equation (AIII-1) results in

$$V_{max}\,[1 - a\,(m_p)] \quad = \quad V_{min}\,[1 + (m_p)] \qquad \text{(AIII-3)}$$

where

$$a \quad = \quad (m_n)/(m_p) \qquad \text{(AIII-4)}$$

Solving Equation (AIII-3) for m_p yields

$$(m_p) \quad = \quad \frac{V_{max} - V_{min}}{aV_{max} + V_{min}}, \; (m_n) = a(m_p) \qquad \text{(AIII-5)} \; \text{(2-3)}$$

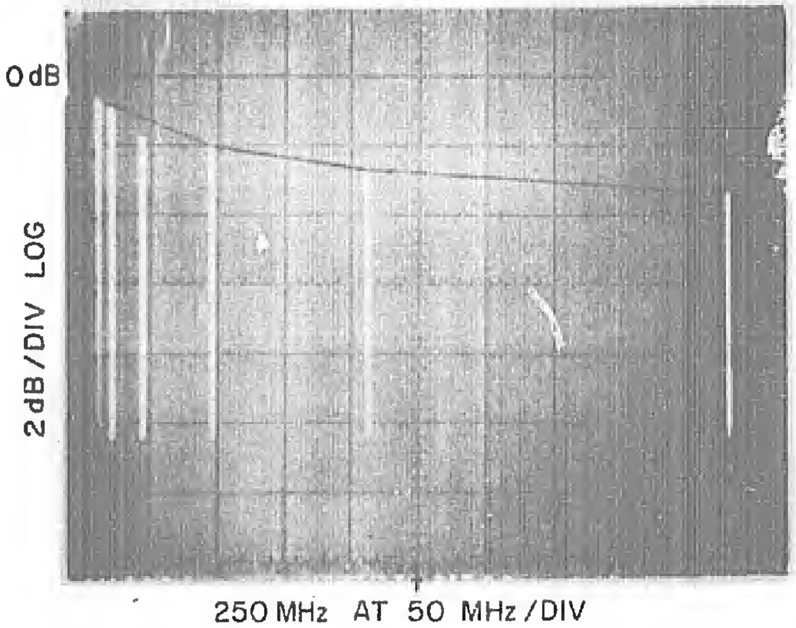


Figure A-5. Measured Loss for 25 Feet of RG-58 Cable (dB)

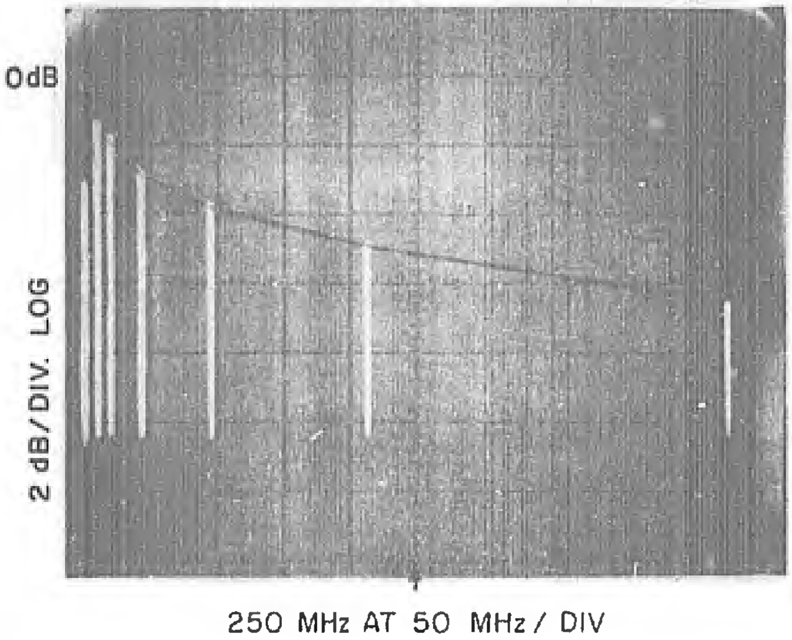


Figure A-6. Measured Loss for 50 Feet of RG-58 Cable (dB)

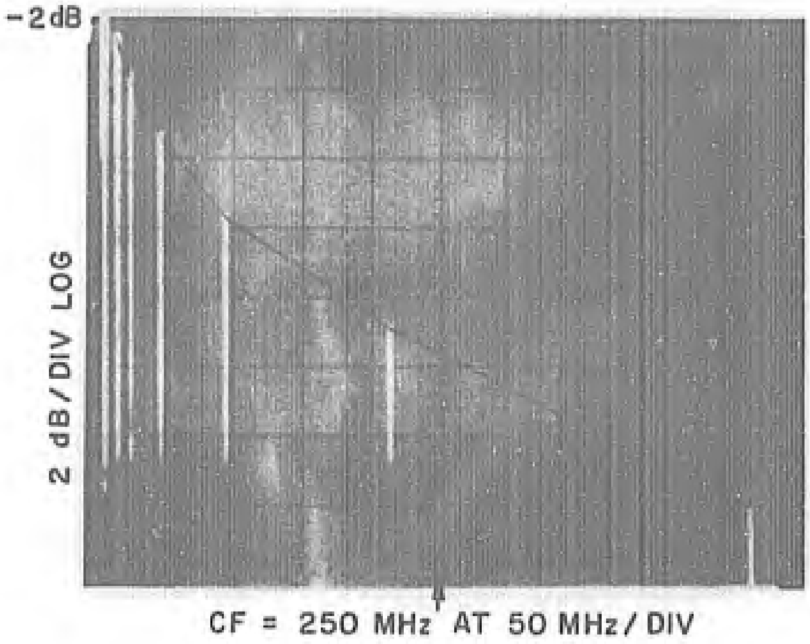


Figure A-7. Measured Loss for 125 Feet of RG-58 Cable (dB)

V_{max} and V_{min} for single-phase full-wave, three-phase half-wave and three-phase full-wave can be determined from Equations (AI-8), (AI-9), and (AI-10). Inserting V_{max} and V_{min} into Equation (AIII-1) and (AIII-2) will determine (m_p) and (m_n), from which a is found.

a = 1.75 for single-phase full-wave

a = 1.88 for three-phase half-wave

a = 2.06 for three-phase full-wave

DEVELOPMENT OF PEAK PULSE (EQUATION 2-5)

The amplitude of a dc pulse at the input of a bandpass filter is related to the peak voltage at the filter output when the Q of the filter is known and the input pulse width is greater than one fourth of the inverse of the filter resonant frequency. The following circuit is used,

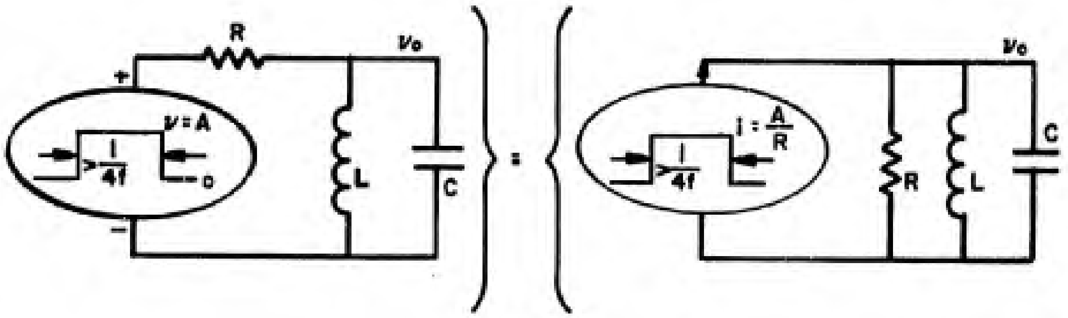


Figure A-8.

The output voltage is: (for $t \leqslant 1/4f$)

$$V_o = \left(\frac{A/RC}{\sqrt{(1/RC) - (1/4R^2C^2)}} \right) \left(e^{-t/2RC} \right) \left(\sin \sqrt{(1/LC) - (1/4R^2C^2)}\; t \right) \quad \text{(AIV-1)}$$

The symbols are explained in Figure A-8.

when

$$Q = \omega RC > 10, \text{ (}\omega\text{ is the natural radian frequency)}$$

$$Q = \omega / \Delta\omega, \ RC = 1/\Delta\omega, \ \omega = \sqrt{1/LC}$$

where $\Delta\omega$ corresponds to the 3 dB bandwidth

when $Q > 10$ Equation (AIV-1) becomes

$$V_o = \frac{A}{Q} e^{-t\Delta\omega/2} \sin \omega t \qquad \text{(AIV-2)}$$

The first maximum of V_o occurs when

$$t \approx \frac{\pi}{2\omega} = \frac{1}{4f} \qquad \text{(AIV-3)}$$

Substituting this value of time into Equation (A-2)

$$V_{omax} \approx \frac{A}{Q} \qquad \text{(AIV-4)}$$

When $Q = 10$, $V_{omax} = .925A/Q$ and V_{omax} approaches A/Q as Q increases. If an amplifier of voltage gain "a" is placed between the input and output

$$V_{omax} = \frac{aA}{Q} \qquad \text{(AIV-5)}$$

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