IEEE Standards

IEEE Std C95.4™-2002

C95.4™

IEEE Recommended Practice for Determining Safe Distances from Radio Frequency Transmitting Antennas When Using Electric Blasting Caps During Explosive Operations

IEEE Standards Coordinating Committee 28

Sponsored by the
IEEE International Committee on Electromagnetic Safety

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(Standards Coordinating Committee 28)

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The equations in 8.4 and 8.5 are from the Franklin Institute Research Laboratories Publication F-B2256-1 [B9], Franklin Institute Research Laboratories Publication F-C1951-1 [B10], and Franklin Institute Research Laboratories Publication M-C2210-1 [B12].[a]

Abstract: This project provides recommended practices for the prediction and practical determination of safe distances from radio and radar transmitting antennas when using electric blasting caps to remotely detonate an explosive charge. Specifically, this document includes mathematical formulas, tables, and charts that allow the user to determine safe distances from RF transmitters with spectrum bands from 0.5 MHz to 300 GHz, including VHF, UHF television antennas, FM, AM radio transmitting antennas, radar, navigation beacons, and portable communication devices.

Keywords: blasting caps, detonation, explosive charge, RF transmitters, transmitting antennas, safe distance

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[a] The numbers in brackets correspond to those in the bibliography in Annex A.

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Introduction

(This introduction is not part of IEEE Std C95.4-2002, IEEE Recommended Practice for Determining Safe Distances From Radio Frequency Transmitting Antennas When Using Electric Blasting Caps During Explosive Operations.)

In 1960, the American Standards Association approved the initiation of the Radiation Hazards Standards project under the co-sponsorship of the Department of the Navy and the Institute of Electrical and Electronics Engineers.

In 1965 and 1966, the Institute of Makers of Explosives (IME), a trade group with headquarters in Washington, DC, sponsored research on RF hazards to electric blasting caps. Laboratory tests and analyses were performed at the Franklin Institute, Philadelphia, Pennsylvania. Tables of safe distances were included in this early work. Since 1966, the IME has published updated tables of safe distances from time to time. Standards committees have included technical people from the IME and from the Franklin Institute.

Prior to 1988, C95 standards were developed by an accredited standards committee C95, and submitted to ANSI for approval and issuance as ANSI C95 standards. Between 1988 and 1990, the committee was converted to Standards Coordinating Committee 28 (SCC 28) under the sponsorship of the IEEE Standards Board. In 2001, the IEEE SA-Standards Board approved the title "International Committee on Electromagnetic Safety" (ICES) for the SCC 28. In accordance with policies of the IEEE, C95 standards will be issued and developed as IEEE standards, and will be submitted to ANSI for recognition.

The present scope of IEEE SCC 28 is "Development of standards for the safe use of electromagnetic energy in the range of 0 Hz to 300 GHz relative to the potential hazards of exposure of man, volatile materials, and explosive devices to such energy. It is not intended to include infrared, visible, ultraviolet, or ionizing radiation. The committee will coordinate with other committees whose scopes are contiguous with ICES SCC 28."

The IEEE International Committee on Electromagnetic Safety is responsible for this recommended practice. There are five subcommittees concerned with

a) Techniques, Procedures, Instrumentation, and Computation

b) Terminology, Units of Measurements and Hazard Communication

c) Safety Levels with Respect to Human Exposure, 0–3 kHz

d) Safety Levels with Respect to Human Exposure, 3 kHz–300 GHz

e) Safety Levels with Respect to Elector-Explosive Devices

Two standards, two guides, and two recommended practices have been issued. Current versions are as follows:

IEEE Std C95.1™, 1999 Edition, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz.[b]

IEEE C95.2™-1999, IEEE Standard for Radio Frequency Energy and Current Flow Symbols.

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[b] Information on references can be found in Clause 2.

IEEE Std C95.3™-2002, IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields with Respect to Human Exposure to Such Fields, 100 kHz to 300 GHz.

ANSI C95.4-1978, American National Standard Safety Guide for the Prevention of Radio-Frequency Radiation Hazards in the Use of Electric Blasting Caps.

IEEE 1460™-1996, IEEE Guide for the Measurement of Quasi-Static Magnetic and Electric Fields.

Disclaimer

As an IEEE recommended practice, this document provides procedures preferred by IEEE. Following the procedures in this recommended practice does not guarantee absolute safety, and users should take all the reasonable, independent steps necessary to minimize risks to safety.

Participants

IEEE Std C95.4-2002 was prepared by the Working Group of Subcommittee V, Safety Levels with Respect to Elector-Explosive Devices, of Standards Coordinating Committee 28 (SCC 28). The Working Group had the following membership at the time this standard was prepared:

John Defrank, *Co-chair*
George Andrew Koban, *Co-chair*
Brad Roberts*, Secretary*

T. Babij
Q. Balzano
J. Bean
F. Colville
W. Hammer
R. Harmon
J. Hatfield
K. Joyner
D. Leidel
J. Leonowich
R. Petersen
J. Stuart
R. Thompson
A. Varanelli

Standards Coordinating Committee 28, which also participated in the preparation of IEEE Std C95.4-2002 had the following membership at the time this standard was prepared:

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Eric van Rongen
Arthur G. Varanelli
Femme-Michelle Wagenaar
Robert T. Watkins
Christian B. Wenger
Louis A. Williams, Jr.
Donald W. Zipse
Marvin C. Ziskin

The following members of the balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention.

Eleanor R. Adair
Quirino Balzano
David Chou
Robert F. Cleveland
Jules Cohen
John DeFrank
Stewart M. Fastman
Gregory M. Gorsuch
Jerry Hatfield
George A. Koban
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Maurice Murphy
John M. Osepchuk
Ron Petersen
Carl Roberts
Mays L. Swicord
Arthur G. Varanelli
H. N. Williams
Donald W. Zipse

Contents

IEEE Recommended Practice for Determining Safe Distances from Radio Frequency Transmitting Antennas When Using Electric Blasting Caps During Explosive Operations

1. Overview

This recommended practice provides an analysis of electromagnetic radiation phenomena that could present a potential hazard to the transportation, handling, or use of electric blasting caps or detonators by commercial or military personnel. It discusses the transfer of electromagnetic energy from a radiation source to the receiving antenna formed by electric blasting cap wires or circuit wiring, techniques for determining whether an electromagnetic radiation hazard is likely to exist, and operating procedures that can be used to minimize the possibility of accidental initiation.

The safety methods outlined here are for blasting caps with a 40 mW no-fire threshold, or for types whose radio frequency (RF) sensitivity has been tested. This recommended practice is not intended for use with blasting caps of unknown sensitivity.

1.1 Scope

This document is concerned with the fact that an electric blasting cap (initiator) might explode unexpectedly when a nearby radio transmitter is turned on. A cap can absorb electrical energy from a free-space electromagnetic field of the type produced by radio and radar transmitters. This document provides recommendations for limiting the amount of electrical energy absorbed and recommended methods for determining safe distances from radio and radar transmitting antennas when one is using electric blasting caps. Safety is determined by comparing the RF power pickup to the blasting cap's no-fire power level. This criterion is valid over the frequency range 3 kHz to 300 GHz that is commonly discussed in connection with RF safety. Radio frequency transmitters that a blaster might encounter occupy only a small portion of this frequency range. Specifically, this document explains how to determine safe distances from RF transmitters with spectrum bands from 10 kHz to 12 GHz, including VHF and UHF television antennas, FM and AM radio transmitting antennas, radar, navigation beacons, and portable communication devices.

This document excludes criteria for the use of electro-explosive devices (EEDs) with electrically conductive enclosures or weapons containers, and it does not include sufficient information on hazards deriving from electrostatics or from electromagnetic fields generated by other sources of energy, such as electrical storms, electromechanical equipment, electrical power plants, or power transmission lines. This document does not apply to the use of non-electric detonators.

1.2 Responsibility for safety

Both the operators of RF transmitting equipment and the users of electric blasting caps have a responsibility for preventing the hazard of inadvertent detonation. Fixed transmitting antennas should not be installed at locations where they could present a hazard to existing operations that utilize electric blasting caps, and users of mobile radio equipment should not transmit near sites where electric blasting caps are used. Before beginning operations at new locations, electric blasting cap users should survey the surrounding area using the recommended practices provided in Clause 6 for existing fixed transmitting antennas that could present a hazard. They should also establish restricted areas around their blasting sites where transmission by mobile transmitters is banned. If necessary, expert technical assistance should be called in to determine whether a hazard exists. Ideally, expert technical assistance is used in all situations to best ensure safety.

1.3 Background

Regulations exist, and other documents have been published, which cover various aspects of this hazard, but these are not generally available, nor do they specifically address electric blasting caps (see AMC R 385-100 [B1][1], Bureau of Explosives [B3], DOD 4145.26M [B6], DOD 6055.9 STD [B7], IME Safety Library Publication No. 20 [B14], IME [B15], MIL-STD-449D [B18], MIL-STD-464 [B19], and NAVSEA OD [B21]).[2] This document provides recommended practices for theoretical and practical assessment of this hazard. Research on RF hazards to electric blasting caps sponsored by the Institute of Makers of Explosives (IME) in Washington, DC in the 1960s led to IME Safety Library Publication No. 20 [B14], which contains tables of safe distances for blasting near RF transmitters. Further work by IME to improve the calculations led to an update of this document [B15]. These efforts have been aided by other organizations, principally the National Aeronautics and Space Agency (NASA) and the U.S. Bureau of Mines.

2. References

This recommended practice shall be used in conjunction with the following publications. When the following specifications are superseded by an approved revision, the revision shall apply.

IEEE Std C95.1™, 1999 Edition, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz.[3, 4]

IEEE Std C95.3™-2002, IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields with Respect to Human Exposure to Such Fields, 100 kHz to 300 GHz.

IEEE Std 211™-1990, IEEE Standard Definitions of Terms for Radio Wave Propagation.

IEEE Std 291™-1991, IEEE Standard Methods for Measuring Electromagnetic Field Strength of Sinusoidal Continuous Waves, 30 Hz to 30 GHz.

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[1] The numbers in brackets correspond to those in the bibliography in Annex A.

[2] Safety associated with blasting caps used by the armed services is governed by Department of Defense regulations.

[3] The IEEE standards or products referred to in Clause 2 are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.

[4] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

3. Definitions

For the purposes of this recommended practice, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition [B13], should be referenced for terms not defined in this clause.

3.1 amateur radio: *See:* **radio services.**

3.2 antenna: A means for radiating (transmitting) or receiving electromagnetic waves.

3.3 antenna regions: The electromagnetic field surrounding a transmitting antenna is separated into regions that are characterized by the predominant effects. Two regions are defined as follows: **(A) near-field (Fresnel) region:** For land-mobile communications transmitters, field measurement is limited to the region external to the induction field and extending to the outer boundary of the reactive field that is commonly taken to exist at a distance of 0.16 wavelength. Either the electric or magnetic component of the radiated energy may be used to determine the magnitude of power present.

NOTE—If the antenna has a well-defined aperture in a given aspect, then the Fresnel region in that direction is commonly taken to extend a distance (r) of twice the square of the largest linear aperture dimension (D) divided by the wavelength (λ), i.e.,

$$r \le \frac{2D^2}{\lambda}$$

(B) far-field (Fraunhofer) region: That region of the field in which the energy flow from an antenna proceeds essentially as though coming from a point source located in the vicinity of the antenna. For land-mobile communications transmitters, field measurement is performed at or beyond a distance of three wavelengths, but not less than 1 m.

NOTE—If the antenna has a well-defined aperture in a given aspect, then the Fraunhofer region in that direction is commonly taken to exist at distances (r) greater than twice the square of the largest linear aperture dimension (D) divided by the wavelength (λ), i.e.,

$$r > \frac{2D^2}{\lambda}$$

3.4 antenna factor: Quantity relating the strength of the field in which the antenna is immersed to the output voltage across the load connected to the antenna. A factor that, when properly applied to the meter reading of the measuring instrument, yields the electric field strength in volts per meter (V/m) or the magnetic field strength in amperes per meter (A/m).

3.5 aperture (of an antenna): A surface, near or on, an antenna, on which it is convenient to make assumptions regarding the field values for the purpose of computing fields at external points.

NOTE—The aperture is often taken as that portion of a plane surface near the antenna, perpendicular to the direction of maximum radiation, through which the major part of the radiation passes.

3.6 attenuation: A general term used to denote a decrease in magnitude of signal level from one point to another.

3.7 base station: *See:* **radio stations**.

3.8 blast area: The area of a blast within the influence of flying rock missiles, gases, and concussion.

3.9 blasting cap: A cylindrical detonator containing one or more highly sensitive explosives at the base end that can be initiated either electrically or from a spit of flame (nonelectric).

3.10 bridgewire: A small resistive element. When the electric blasting cap is intentionally fired, a current pulse is passed through the bridgewire, causing heating and resultant detonation of the explosive charge.

3.11 Bruceton test: A general statistical method for determining probability of one-shot type events. This method assumes that the logarithm of incremental probability is distributed normally with respect to the stimulus strength. In the context of this document, the Bruceton test is a method for determining firing probability of electric blasting caps. (See Dixon and Mood [B5] and Franklin Institute Research Laboratories Publication F-C3102 [B11].)

3.12 citizens radio bands: Frequency bands allocated for short-distance personal or business radio communication, radio signaling, and control of remote devices by radio.

NOTE—The frequency bands may differ from country to country. The bands presently in use in the United States are 26.965–27.405 MHz, 72–76 MHz, and 462.550–467.425 MHz.

3.13 dipole antenna: A straight radiator, usually fed in the center, producing a maximum of radiation in the plane normal to its axis. The length specified is the overall length.

NOTE—Common usage considers a dipole to be a metal radiating structure that supports a line-current distribution similar to that of a thin straight wire, a half-wavelength long, so energized that the current has two nodes, one at each of the far ends.

3.14 directivity (of an antenna): The value of the gain of an antenna in the direction of its maximum value, ignoring loss. The ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions.

NOTE— The average radiation intensity is equal to the total power radiated by the antenna divided by 4π.

3.15 double-sideband transmission: Transmission containing both the upper and lower sidebands (or a portion thereof) resulting from the modulation of a carrier.

3.16 duty factor: For a transmission composed of pulses that occur at regular intervals, the product of the pulse duration in seconds and the pulse repetition frequency in hertz.

3.17 effective area (of an antenna): In a given direction, the ratio of the power available at the terminals of an antenna to the incident power density of a plane wave from that direction polarized coincident with the polarization that the antenna would radiate.

3.18 effective radiated power: In a given direction, the relative gain of a transmitting antenna with respect to the maximum gain of a half-wave dipole multiplied by the net power accepted by the antenna from the connected transmitter.

3.19 electric blasting cap: A device that contains a base charge of a high explosive, a primer charge, and an ignition charge. A firing element consisting of two leg wires connected by a bridgewire is embedded in the igniter. The cap is fired when an electric current is applied to heat the bridgewire.

3.20 electric blasting cap firing mode: With respect to the detonation of an electric blasting cap by electromagnetic energy, two firing modes are defined: **(1) pin-to-pin:** The RF energy is converted to heat in a bridgewire connected between the ends of two conductor pins (leg wires). **(2) pin-to-case:** The RF energy is converted to heat in the region between one or both pins and the metal case (cap shell). Firing may also occur due to an arc discharge.

3.21 electromagnetic field: The electric and magnetic fields produced by a transmitting antenna.

3.22 electromagnetic spectrum: The range of frequencies associated with electromagnetic waves.

3.23 electromagnetic wave: Waves characterized by variations of electric and magnetic fields.

NOTE—Electromagnetic waves are known as radio waves, heat rays, light rays, etc., depending on the frequency.

3.24 far field: *See:* **antenna regions**.

3.25 field strength: Electromagnetic waves comprise two field components: electric fields and magnetic fields. These two fields are related in a complicated way. Whenever "field strength" is mentioned, it must be made clear which field is meant.

3.25.1 electric field strength: At a given point, the magnitude of the vector limit of the quotient of the force that a small stationary charge at that point will experience, by virtue of its charge, to the charge as the charge approaches zero in a macroscopic sense. The SI unit of electric field strength is volts per meter (V/m).

3.25.2 magnetic field strength (*H*): The magnitude of the magnetic field vector. For time harmonic fields in a medium with linear and isotropic magnetic properties, H is equal to the ratio of the magnetic flux density B to the magnetic permeability of the medium μ, i.e., $H = B/\mu$. The SI unit of magnetic field strength is amperes per meter (A/m).

3.26 Fraunhofer region: *See:* **antenna regions** and **far field**.

3.27 Fresnel region: *See:* **antenna regions** and **near field**.

3.28 frequency: Of a periodic function, the reciprocal of the time required for one complete cycle.

NOTE—The SI unit of frequency is hertz.

3.29 Friis' transmission equation: The ratio of received power (P_r) to transmitted power (P_t), which is equal to the product of the effective maximum receiving-antenna aperture area (A_{er}) and the effective maximum transmitting antenna aperture area (A_{et}), divided by the square of the product of separation (r) in meters and wavelength (λ) in meters, i.e.,

$$\frac{P_r}{P_t} = \frac{A_{er}A_{et}}{r^2\lambda^2}$$

This assumes that the two antennas are pointed at each other. If the two are identical antennas with gain (G), the ratio is given by

$$\frac{P_r}{P_t} = \left(\frac{G\lambda}{4\pi r}\right)^2$$

3.30 gain (of an antenna): The ratio of the power density at a given point in space to the power density that would occur at the same point if the transmitting antenna was a point source radiating the same power isotropically. The gain of an antenna is usually quoted as the maximum value (the value determined at the point where the power density is greatest).

3.31 impedance: (A) wave impedance: The ratio of electric field strength to magnetic field strength. **(B) circuit impedance:** The ratio of voltage (between two points in a circuit) to the current between the same points. **(C) free space impedance:** *See:* **wave impedance.** For plane waves in vacuum, the numerical value of impedance is approximately 377 ohms.

3.32 incident wave: A wave that impinges on a discontinuity in refractive index or a medium of different propagation characteristics. The incident wave is the total field in the absence of the discontinuity.

3.33 isotropic antenna: A hypothetical antenna radiating or receiving equally in all directions.

3.34 lobe: A portion of the antenna directional pattern bounded by one or two cones of nulls. **(A) main lobe:** The radiation lobe containing the direction of maximum radiation.

NOTE—In certain antennas, such as multilobed or split-beam antennas, there may exist more than one major lobe.

(B) side lobe: A radiation lobe in any direction other than that of the major lobe.

3.35 microwaves: The region of the electromagnetic spectrum with frequencies between 300 MHz and 30 GHz, with corresponding wavelengths of 1 m to 1 cm.

3.36 modulation: The process of changing or regulating the characteristics of a carrier that is vibrating at a certain amplitude and frequency so that the variations represent meaningful information.

3.37 no-fire level (of an electric blasting (EB) cap): The maximum “no-fire” power level is the maximum DC or RF power at which a blasting cap or detonator will not fire with a probability of 0.999 at a confidence level of 95%, as determined by test and computer simulation. (See IME [B15].)

3.38 omnidirectional antenna: An antenna designed so the maximum radiation in any horizontal direction is within 3 dB of the minimum radiation in any other horizontal direction.

3.39 parabolic antenna: An antenna consisting of a parabolic reflector and a source at or near its focus.

3.40 peak power: The output power, averaged over a carrier cycle, at the maximum amplitude that can occur with any combination of signals to be transmitted.

3.41 peak pulse amplitude: The maximum absolute peak value of the pulse excluding those portions considered to be unwanted, such as spikes.

3.42 peak power—delivered to receiving antenna (load): The power that goes into the receiving antenna load—in this context, the EB cap.

3.43 peak power—delivered to transmitting antenna: The power that is radiated as plane electromagnetic waves.

3.44 power flux density (power density): Emitted power per unit cross-sectional area normal to the direction of propagation. The SI unit for power density is watts per square meter (W/m^2).

3.45 radar: A device for transmitting electromagnetic signals and receiving echoes from objects of interest (targets) within its volume of coverage. (An acronym for radio detection and ranging.)

3.46 radiation intensity: The radiation intensity in a given direction is the power radiated from an antenna per unit solid angle in that direction.

3.47 radiation pattern (of an antenna): The spatial distribution of a quantity that characterizes the electromagnetic field generated by an antenna.

NOTE—The distribution can be expressed as a mathematical function or as a graphical representation. The quantities that are most often used to characterize the radiation from an antenna are proportional to, or equal to, power flux density, radiation intensity, gain, phase, polarization, and field strength.

3.48 radiator: Any antenna or radiating element that is a discrete physical and functional entity.

3.49 radio services: Types of radio transmitting stations such as amateur, citizens' band, military, and commercial (AM and FM radio stations, TV stations, and short-wave broadcast).

3.50 radio station: A place where there is a transmitter. This may be a fixed location (base station), or it may be in a vehicle (mobile station).

3.51 radio wave: *See:* **electromagnetic wave.**

3.52 receiver: A device for demodulating (extracting information from) radio frequency currents induced in an antenna by electromagnetic waves.

3.53 wavelength: The distance between points of corresponding phase of two consecutive cycles of a sinusoidal wave. The wavelength, λ, is related to the phase velocity, v, and the frequency, f, by $\lambda = v/f$.

4. General

4.1 Hazard zones

Hazards to electrical blasting operations are likely to arise in relatively close proximity to transmitting antennas; actual distances are considered later in this recommended practice. However, it should be noted that these hazards can exist where the electromagnetic field strength is substantially less than that which is normally considered to create a hazard to human health. Hazard zones may be defined for both fixed and mobile transmitters, and unless it can be shown otherwise, the effect of two or more transmitter fields must be taken as additive.

4.2 Contributing factors

There are three interrelated elements, all of which must be present to produce a hazard from electromagnetic energy;

a) An electromagnetic field above some critical minimum level
b) Means of extracting energy from the electromagnetic field, e.g., any piece of metal that can act as an antenna
c) Electric blasting cap in a situation such that it can accept sufficient energy from the energy-extracting means in item b) to cause it to detonate.

4.3 Hazard level

The level of radiation [4.2 item a)] at which the hazard becomes real depends on the energy required to detonate the blasting cap [4.2 item c)] under existing environmental conditions and the efficiency of the energy extracting means [4.2 item b)].

4.4 Measurements

Ideally, it should always be possible to define a maximum safe value of electric field strength that would permit only a negligible probability of the worst combination of:

a) Localized and positive fluctuations in field strength
b) Maximum energy extraction and delivery
c) Maximum sensitivity of blasting caps

However, no inexpensive general method of electromagnetic field measurement can be recommended. Omnidirectional instruments that measure electromagnetic field strength are commercially available, but these instruments are expensive and require competent users because they yield readings that can easily be misinterpreted. Therefore, it is recommended that blasting personnel seek professional, expert assistance to ascertain electromagnetic field strength at the blasting area.

4.5 Theoretical determination of the hazard

To determine if a hazard exists, the following approach is recommended:

a) Establish the no-fire level of the electric blasting cap to be used, in terms of maximum energy or power that can be applied to the device without its initiation. In a realistic sense, this will be the energy or power level at which a negligible probability of initiation exists. The no-fire level is precisely defined in Clause 3. Refer to Clause 6 for procedures to calculate no-fire levels for blasting caps.
b) Calculate the overall theoretical electromagnetic field strength at the blasting site. This requires knowledge of the field source characteristics and the locations of all transmitting antennas near the site. Refer to Clause 7 for procedures to calculate field strength from any mobile (air, sea, or land vehicle) transmitters.
c) Using the data derived from item b), calculate the theoretical maximum possible energy or power that could be extracted from the field that can be delivered to the blasting cap. Refer to Clause 8 for procedures to calculate this energy.
d) Compare the energy or power levels obtained from item a) and item c). If item c) is greater than item a), then a hazard can exist.

4.6 Practical evaluation of the hazard

Apply any appropriate safety regulations existing for the blasting location. If, however, no regulation covers the specific conditions, or if use within the proscribed distances is unavoidable, then experimental tests can determine the presence or absence of an unsafe radio frequency environment at the site where the blasting cap is required to be used. Experimental determination should not be undertaken without expert advice and precise knowledge of the electromagnetic field environment. Whenever exceptional circumstances are thought to exist or whenever there is the slightest doubt, technical advice should be sought from the manufacturers or suppliers of the electric blasting caps. Until such advice is obtained, the device or material should not be exposed to the potential hazard.

5. Safety precautions when using blasting caps

5.1 General

To minimize the hazards associated with the use of electric blasting caps, the following safety precautions should be observed:

a) Blasting caps are extremely sensitive and may explode unless handled carefully. They must be protected from shock and extreme heat, and they must not be tampered with. They are never to be stored with other explosives.
b) Batteries alone can fire electric blasting caps. Keep batteries away from blasting circuits.
c) Do not connect the blasting machine to the firing wire until all pre-firing tests have been completed and until ready in all respects to fire the charge.
d) When testing a blasting cap, place the cap and any persons as far away as practicable behind a suitable barrier (if possible).
e) When testing blasting circuits, use only blasting galvanometers or other instruments specifically designed for this purpose. Do not mistake an ohmmeter or any other instrument for the circuit tester.
f) Misfired blasting caps may be more sensitive to detonation. When necessary and under the direction of the blaster, misfired electric blasting caps should be handled with extreme care following a suitable waiting time.
g) During the approach and progress of an electrical storm, all explosive handling should be suspended and personnel withdrawn to a safe location.
h) Minimize the potential for electrostatic discharge while handling electric blasting caps. For example, static electricity producing clothing (nylon, silk, synthetic hair, etc.) should not be worn while working with electric blasting caps. Also, electric blasting cap lead wires should not be passed from one person to another without prior grounding of both personnel.
i) Keep the lead wires shunted during the wiring of electric blasting caps.
j) Electric blasting caps should not be exposed to excessive direct sunlight or other sources of extreme heat, i.e., greater than 67 °C, unless the manufacturer recommends their use or provides procedures for their use in such environments.[5]
k) Firing lines should not be dragged.
l) Lead wires of electric blasting caps should not be connected to an electrical source until ready to fire and all personnel in the hazard (blast) area are under cover.
m) If possible, turn off radio frequency transmitters and post signs in the area surrounding the hazard area.
n) An electric blasting cap should not be removed from its transit box until it is required for insertion into the explosive or firing circuit.
o) Shunts will not be removed from cap or lead-in wires until it is time to connect them.
p) A blasting cap, or any lead connected to it, should not be allowed to come into contact with any extraneous energized metal object, especially an antenna.
q) Firing lines and all blasting wires should be placed as close to the ground as possible; e.g., make all connections without lifting them far off the ground.
r) The two wires connecting the firing power source to the blasting cap(s) should be placed as close together as possible. This also applies to any other wires; i.e., minimize the included area of the firing circuit. Insulation quality of the wires must be maintained to preclude short-circuits.
s) The firing line should be placed (if practical) as nearly as possible along a line perpendicular to that joining the site and the nearest or most powerful transmitting antenna.
t) The firing line should not be grounded at any time, and the blasting circuit should not be grounded. This requires good insulation of all parts of the circuit and particularly those likely to come into contact with the ground or objects at ground potential. The blasting machine end of the firing line should be kept shunted and insulated from earth until ready for firing.

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[5] (150 °F)

6. Practical hazards identification and elimination

6.1 Hazard origin

Electric blasting caps in common use are of the bridgewire type, which normally fire as the result of the bridgewire being heated by an electric current to the critical temperature of the primary explosive. In the case of accidental initiation by RF fields, current is induced by the RF field either in the bridgewire (pin-to-pin mode) or in the explosive material (pin-to-case). When characterizing electric blasting cap performance for hazard evaluation, one is normally interested in the "no-fire" conditions. When discussing the RF susceptibility of blasting caps, it is convenient to use the "no-fire" power. This parameter is applicable even when discussing pulsed transmitters. An exact definition of the "no-fire" level is given in Clause 3.

6.2 Hazard levels

When evaluating the "no-fire" condition in terms of RF power, it is found that the "no-fire" values vary with frequency and with mode, i.e., pin to pin and pin to case (see 4.1). At present, these characteristics must be determined statistically by experiment. Complete data of this type are not yet available for all commonly used electric blasting caps at all frequencies. In lieu of specific data, present studies by Dixon and Mood [B5], Franklin Research Laboratories Publication F-C3102 [B11], and MIL-STD 1576 [B20] indicate that a "no-fire" average power value of 40 mW is an appropriate level on which to base calculations. This value can be converted to a "no-fire" current or a "no-fire" voltage by the standard equations, although it must be kept in mind that the resistance of the cap may change during exposure and that the impedance of the circuit is a function of frequency and of the cap construction.

6.3 Assessment of hazard levels

The assessment of a possible hazard in the handling or use of blasting caps in an RF environment is considered in two stages:

a) From theoretical considerations outlined in Clause 8, safe distances can be calculated for various types of transmitters, beyond which hazards associated with the blasting cap due to the transmitters are minimized.
b) Theoretical calculations may be made in specific circumstances showing that a particular site is still safe although lying within these safe distances. Alternatively, a field test may be carried out to determine whether a hazard exists in a circuit equivalent to the most unfavorable layout of the blasting cap circuit to be used.

When evaluating a hazard, the safety characteristics of the blasting cap should be obtained from its manufacturer with a statement of the statistically derived firing characteristics. A further safety factor may be applied, if considered desirable.

NOTE—Blasting operations with electric blasting caps should not be undertaken at distances less than the safe distances referred to in 6.6 and 6.7 without a good theoretical and practical knowledge of the electromagnetic field environment, the characteristics of the blasting caps to be used, and the limitations of electromagnetic field measuring or sensing devices used (see Clause 4). The manufacturers of commercial blasting caps will normally give advice and assistance if this is requested. It is also recommended to seek expert advice.

6.4 Potential sources of radiofrequency energy

Possible radiofrequency energy sources in the context of this subclause are as follows:

a) Mobile and fixed radio communication and radio services
b) Radar transmitters

c) Navigational aid transmitters

d) Geophysical survey equipment

Low flying aircraft having the equipment in item a) through item d) of this subclause (6.4) could also pose an unforeseen hazard.

6.5 Safety in transit

Any hazard from radiation to blasting caps in transit can be minimized by following a simple code of practice, which is to leave the leg wires of the blasting cap wound, or folded and shunted, as supplied by the manufacturer until they are connected in the firing circuit. Blasting caps that are not in their original shipping containers should be transported and stored in a closed metal container.

6.6 Safe distance assumptions

The safe distance tables in 6.7 (Table 2 through Table 8) were generated using the mathematical expressions from 8.3 and 8.4 [Equation (3) through Equation (8)] and are based on the following assumptions and conditions. Additional assumptions for specific tables are sited in the appropriate table. If assumptions deviate from the actual situation, then a qualified engineer should perform an assessment.

a) In the United States, horizontally polarized TV and FM antennas are used on towers up to approximately 600 m tall.

b) For AM broadcasting stations, between 540 kHz and 1600 kHz, a maximum broadcast antenna gain of 10 is used.

c) For AM broadcast antennas, the maximum antenna input power allowed by the FCC is 50 000 W.

d) For fixed vertical radiators other than AM broadcast stations, a maximum gain of 10 is assumed.

e) For mobile transmitters, the maximum gain is assumed to be 3.

f) For VHF TV and FM broadcasting stations, the FCC limits the maximum effective radiated power (ERP) as follows: 100 kilowatts for channels 1 to 6, 316 kilowatts for channels 7 to 13, and 550 kilowatts for FM broadcast.

g) For UHF TV stations, the maximum ERP allowed by the FCC is 5000 kilowatts.

h) The bridgewire resistance of a blasting cap is 1.0 ohm.

i) The leg wires of a blasting cap are AWG #20 copper.

j) The “no-fire” RF power level of commercial blasting caps is 40 mW, (see 6.2).

k) For both horizontally and vertically polarized sources, the worst-case configuration of the blasting wiring simulates a matched loop antenna.

l) Radio navigation beacons have antennas with gains of 3.

6.7 Safe distances (tables of recommended distances)

Various kinds of radio transmitters are listed in Table 1, which is a directory showing which of following seven tables should be used to find safe distance for each particular case. The following tables of distances (Table 2 through Table 8) are for the commercial blaster. The selected groupings include all of the obvious types of RF transmitters that might be encountered around blasting sites. Actual field tests have shown that these tables are conservative. Because of the uncertainties involved in the efficiency of RF energy pickup and its delivery to the blasting cap, it is strongly recommend that these tables be followed. If these tables present distances that are operationally inconvenient to use, then field tests must be made by experts. Also the procedures detailed in Clause 5 for providing minimum RF pickup should be strictly adhered to.

Table 1—Characteristics of radio transmitting services (partial list)

Type of service	Frequency (MHz)	Reference table for safe distances
Commercial		
Standard broadcast (AM)	0.54–1.705	2
Standard broadcast (FM)	88–108	5
Television (channels 2–6)	54–88	5
Television (channels 7–13)	174–216	5
Television (channels above 13)	470–806	6
Amateur[a]		
160-Meter band	1.8–2.0	3
80-Meter band	3.5–4.0	3
40-Meter band	7.0–7.3	3
30-Meter band	10.1–10.15	3
20-Meter band	14.0–14.4	3
17-Meter band	18.068–18.168	3
15-Meter band	21.0–21.45	3
Citizens' band	26.96–27.23	4
10-Meter band (mobile only)	28.0–29.7	4
10-Meter band (fixed)	28.0–29.7	3
6-Meter band	50.0–54.0	4
2-Meter band	144–148	4
1.25-Meter band	222–225	4
Automobile telephone		
VHF fixed station	150–160	4
VHF mobile station	158	4
UHF fixed station	450–465	4
UHF mobile station, cellular	455–470 > 800	4

Table 1—Characteristics of radio transmitting services (partial list) ***(continued)***

Type of service	Frequency (MHz)	Reference table for safe distances
Two-way communications		
HF range fixed station	25–50	3
(Mobile unit)	25–50	4
VHF range fixed station	148–174	4
(Mobile unit)	148–174	4
UHF range fixed station	450–470	4
(Mobile unit)	450–470	4
LF range (aviation)	0.2–0.4	
HF range (aviation)	4–23	3
VHF range (aviation)	118.0–135.9	4
UHF range (aviation)	225–500	4
Radio telegraph	6–23	3
Microwave relay	2000–12 000	– [a]
Navigational aids		
Loran-C	0.1	8
Radio range beacon (A–N)	0.2–0.415	8
Loran	1.8–2.0	8
VOR	110	8
Localizer	110	8
Shoran	290–320	8
Glide slope	315	8
Radar		
Long-range (non-military)	1300–1350	7
10-cm (non-military)	2700–2900	7
3-cm (non-military)	10 000	7

[a] The likelihood of exposure to the main beam is improbable, because these antennas are deployed to prevent the main beam from striking the ground or any structure.

Table 2—Recommended minimum distances from commercial AM broadcast transmitting antennas 0.54 to 1.7 MHz[a]

Transmitted power (W)[b]	Minimum distance (m)
up to 1000	110
4000	220
5000	245
10 000	345
25 000	550
50 000	770
100 000	1090
500 000	2500

[a] This table is based on the configuration shown in Figure 2 (b) using Equation (9) at 1.6 MHz. Other assumptions are a transmitter gain of 1, loop length of 7.35 m, and loop area of 2.32 m^2. This table should be applied to International Broadcast Transmitters in the 6–28 MHz range.

[b] Power delivered to antenna. Present maximum for International Broadcast is 500 000 W.

Table 3—Recommended minimum distances from transmitting antennas up to 50 MHz (excluding AM broadcast) calculated for a specific loop pickup configuration[a]

Transmitted power (W) [b]	Minimum distance (m)
100	240
500	540
1000	760
5000	1700
50 000	5390
500 000	17 000

[a] This table is based on the configuration shown in Figure 2 (b) using Equation (9) at 22.8 MHz, which is the most sensitive frequency. Other assumptions are a transmitter gain of 1, loop length of 6.1 m, and loop area of 2.32 m^2. This table should be applied to International Broadcast Transmitters in the 6–28 MHz range.

[b] Power delivered to antenna. Present maximum for International Broadcast is 500 000 W.

Table 4—Recommended minimum distances from mobile and hand-held transmitters, including amateur, citizens' band, and cellular phones. Minimum distance is in meters

Transmit power (W)[1]	Frequency range				
	MF[a] (MHz)	HF[b] (MHz)	VHF-low[c] (MHz)	VHF-high[d] (MHz)	UHF[e] (MHz)
	Minimum distance (m)				
5	10	32	25	8	5.3
10	14	45	35	11	7.5
50	31	100	79	25	17
100	44	140	110	36	24
180[2]	59	190	150	48	32
250	69	230	180	57	37
500[3]	98	320	250	80	53
600[4]	107	350	270	88	58
1500[5]	170	550	430	140	92
10 000[6]	439	1400	1100	360	240

NOTES

1—Recommended distance from portable communication devices (less than 4 W) is at least 1.5 m.

2—Additional assumptions for Table 4 calculations:
- Equation (5) used for HF, VHF, and UHF; and Equation (7) used for MF.
- Transmit antenna gain is 1.60.
- Loop length for Equation (9) is 7.35 m (isosceles triangle with 3 m base and 1.5 m height).
- Wire radius is 0.4 mm (1/64 inch), and wire length for Equation (5) is 7.35 m.
- Frequencies are 3 MHz (MF), 27 MHz (HF), 35 MHz (VHF-Lo), 140 MHz (VHF-Hi), and 450 MHz (UHF).

[a] Calculated at 3 MHz.
[b] Calculated at 27 MHz,.
[c] Calculated at 35 MHz.
[d] Calculated at 140 MHz.
[e] Calculated at 450 MHz.
[1] Power delivered to antenna.
[2] Maximum power for VHF two-way mobile units in the 150.8 MHz or 161.6 MHz range and for two-way mobile and fixed station units in the 450–460 MHz range.
[3] Maximum power for major VHF two-way mobile and fixed station units in 35–44 MHz range.
[4] Maximum power for VHF two-way fixed station units in the 150.8–161.6 MHz range.
[5] Maximum power for amateur radio mobile units.
[6] Maximum power for some base stations in 42–44 MHz range and 1.6–1.8 MHz range.

Table 5—Recommended minimum distance from VHF TV and FM radio broadcast transmitting antennas

Effective radiated power (W)	**Minimum distance (m)**		
	Channels 2 to 6 54–88 MHz	**FM broadcast 88–108 MHz**	**Channels 7 to 13 174–216 MHz**
150 000	870	710	540
316 000	1050	860	650
400 000	1110	910	680
1 000 000	1400	1150	860
1 500 000	1550	1270	950
6 000 000	2190	1790	1340
10 000 000	2500	2040	1530
25 000 000	3130	2560	1900

Assumptions:

All bands use Equation (8) for half-wave dipole and mast height of 61 m.

For VHF Channels 2–6, the frequency used is 54 MHz and $r = 44.2 \times \sqrt[4]{P}$ m.

For FM Radio, the frequency used is 88 MHz and $r = 36.2 \times \sqrt[4]{P}$ m.

For VHF Channels 7–13, the frequency used is 174 MHz and $r = 27.15 \times \sqrt[4]{P}$ m.

Table 6—Recommended minimum distances from UHF (channels above 13) TV transmitting antennas

Effective radiated power (W)	**Minimum distance (m)**
600 000	485
2 500 000	693
5 000 000	825

Assumptions: Equation (8) for a half-wave dipole is used: Mast height = 610 m; frequency = 470 MHz; reflection coefficient = unity and $r = 17.44 \times \sqrt[4]{P}$ m.

Table 7—Recommended minimum distances from maritime radio navigational radar

Service	Wavelength (cm)	Effective radiated power (W)	Minimum distance (m)
Small pleasure craft	3	500	6
Harbor craft, river boat	3	5000	15
Commercial shipping	3 and 10	50 000	100

NOTES

1—The above table should be used only if the exact nature of the radar hazard is understood. In cases where an uncertainty exists as to the nature of the radar signal as well as ground scatter and reflection of the radar signal, a recommended minimum distance of 300 m should be maintained from the radar antenna.

2—Long-range radar (non-military), at frequencies between 1.3–1.35 GHz (wavelength 0.2 m) can have 1 000 000 W peak power (100 000 W average). This is hazardous within 1 mile. Consult local authority.

3—High-power military radar at frequencies of 0.4–4.0 GHz can have up to several million W peak power. This is hazardous within three miles. For off-shore blasting operations, navy ships with high-power radars constitute a possible threat if ships approach within 3 miles.

4—If tests are to be carried out, a technical knowledge of electromagnetic radiation fields and the limitations of measuring devices and the experimental method used is essential. Tests should not be undertaken without expert assistance. Apparatus used for measurement of ambient electromagnetic field strength should only be used by an expert. It is very easy to get a deceptive answer in a field test.

Table 8—Recommended minimum distances from radio navigation beacons

Type of beacon	Power (kW)	Frequency (MHz)	Minimum distance (m)
Loran-C	1000	0.1	200
VOR	0.1	110	35
Localizer	0.1	110	35
Glide slope	0.015	315	8

6.7.1 Radar

Occasionally 10 cm (3000 MHz) and 3 cm (9000 MHz) Maritime Radio Navigation Radar will be encountered at blasting sites. This radio frequency source may be characterized by a high average effective radiated power, in some cases exceeding 50 000 W. There will be no hazard from the radar beam if the blasting site is well outside of the confines of the beam. If water surface craft can be seen using radar, assume personnel are within the radar beam and discontinue blasting operations (IME [B14], IME [B15]). Generally, the strength and potential hazard of the radar source will depend on the type of boat or ship it is on. Table 7 provides some guidelines as to what may be encountered at river, harbor or ocean blasting sites (IME [B14], IME [B15]).

6.8 Unsafe distances

If the safety distances referred to in the preceding paragraphs cannot be met, and if it is impractical to arrange for the closing down of any suspected transmitters while the firing circuit is being laid out and during operation, then expert help should be sought. Calculations in accordance with the principles enumerated earlier in this clause may be carried out to determine theoretical safety with due regard to the overall safety factor desired. It will be necessary to ascertain the characteristics of the equipment in terms of wavelength, transmitted power (mean, peak, pulse width, duty cycle, as appropriate) and antenna characteristics. Field tests may be necessary.

6.9 Basic area hazard assessment

6.9.1 General

The assessment of possible hazards in the handling or use of electric blasting caps in a radiation environment requires a knowledge of two basic parameters; the maximum tolerable RF field strength and the closest distance of safe approach to given transmitters. These parameters are addressed in the tables of this recommended practice.

6.9.2 Area assessment

An area assessment for the risk of initiation at a proposed firing site due to RF radiation should be performed as follows:

a) Establish the characteristics of the blasting cap to be used.
b) Inspect the area within approximately 20 km of the limits of possible firing circuit configurations for the presence of any transmitting antennas. Advice from all government, civil, commercial, and private transmitter operators should supplement the physical survey. These organizations should be able to provide specific frequencies and power output to apply the recommendations of this recommended practice.
c) Transmitters on board fixed or rotary wing civil or military aircraft should be treated as stationary at the minimum anticipated flying height. Relevant information (transmitter details and minimum height) should be obtained from the appropriate authority.
d) Where appropriate, consider the presence of transmitters on vehicles using nearby public highways.
e) In the absence of any transmitting antennas within the area as described in item b), item c), or item d), the assessment need to proceed no further. If transmitters are found, select the distance and power output from the appropriate table. If the details of the transmitter are not identical to one of those shown in the table, the transmitter selected should be the nearest equivalent given the larger safe distance.

6.10 Alternate method of blasting

An expert in RF field measurements should monitor the RF field strengths at the blast site when encountering special cases not included in the proceeding guidance or when in doubt regarding the safety of the blasting operation. The expert should have credentials, such as electromagnetic compatibility (EMC) certification by the National Association of Radio and Telecommunications Engineers. Indeed, use of such an on-site expert is always preferred. As an alternative to electric blasting caps, a nonelectric blasting system may be used or devices less sensitive to unplanned initiation such as exploding wire detonators, exploding foil initiators, electronic detonators, and deflagration-to-detonation detonating devices. These are designed to minimize susceptibility to RF fields.

7. Radiated electromagnetic fields

7.1 Nature of the radiation field

Frequencies with which this clause is concerned may range from about 3 kHz (wavelength of 100 km) to about 300 GHz (wavelength of 1 mm). The electromagnetic field radiated from a transmitting antenna consists of magnetic and electric components mutually perpendicular to each other and to the direction of propagation. Each of these field components decrease in magnitude inversely as the distance from the antenna; e.g., if at 25 m, the field strength is 50 V/m; then at 50 m, the field strength would be 25 V/m. Close to an antenna, i.e., within distances comparable to the wavelength (or the maximum dimension of the antenna, whichever is larger), the radiation field is accompanied by an induction field whose magnetic and electric components decrease rapidly with distance from the antenna. This induction field does not normally carry energy away from the antenna, but energy can be extracted from it through a suitable coupling medium.

Standard methods for calculating and measuring electromagnetic fields are covered in IEEE Std C95.3-1991.[6] This publication should be consulted before attempting to conduct field calculations and measurements.

7.2 Hazard from multiple frequency superposed fields

Fields from multiple transmitters may combine to create a hazard that would not otherwise exist from any single (individual) transmitter. A reasonable way to determine if superimposed fields could be hazardous to electric blasting caps or circuits would be to proceed as follows:

a) For each radar transmitter, determine the ratio (E_{mr} /E_c), where E_{mr} is the greatest measured or calculated electric field strength produced by all radar transmitters for the situation and distance in question (in V/m) and E_c is the critical or potentially hazardous electric field strength for the particular blasting cap in question (in V/m).[7]

b) For each communication transmitter determine the ratio (E_{mc} /E_c), where E_{mc} is the measured or calculated electric field strength produced by each transmitter for the situation and distances in question, (in V/m). If it is known that each transmitter acting alone is not hazardous, the ratio will always be a fraction less than one. The ratio for the radar transmitter is E_{mr} /E_c and the ratio for the first communications receiver $E_{mc1}/E_{c1,}$ etc.

c) Square the ratios found above for each transmitter and add them together. If the sum of the squares $(E_{mr} /E_c)^2 + (E_{mc1} /E_{c1})^2 + \ldots$ is equal or greater than 1, a potential hazard exists.

d) If a potential hazard exists, at least one transmitter must be silenced and the above process repeated to determine if a safe condition has been obtained. If the sum of the squares of the remaining ratios is still greater than 1, this process must be repeated until a combination of transmitters is found for which the sum of the squared ratios is not greater than 1.

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[6] Information on references can be found in Clause 2.

[7] For radar transmitters, the illumination is generally momentary, due to the antenna rotation or electronic beam steering. As a result, the blasting caps are only illuminated for short period of time (e.g., 200 milliseconds or less, every 5–10 seconds). The probability of simultaneous illumination at a specified location from multiple radars during such illumination “windows” is thus negligible. From a practical standpoint, the hazard is therefore based on the radar that generates the highest level of energy at the location of the blasting cap operation.

8. Extraction of energy from the radiated field

8.1 General

When considering extraction of energy from a radiated RF field, the concept of aperture is useful. In the far-field of an antenna, basic antenna formulas can be applied and the power delivered to a receiving antenna, in terms of the effective aperture area (A_e) of the receiving antenna, can be determined from Equation (1).

$$S = P_R/A_e \tag{1}$$

where

S is the power density of the field (W/m^2),
P_R is the power dissipated in the receiving antenna load, an electric blasting cap (W),
A_e is the effective aperture area of the receiving antenna (m^2).

The maximum effective aperture area (A_{em}) of any antenna is given by Equation (2) (see Balanis [B2], Collin and Zucker [B4], Jasik et al. [B16], Kraus [B17], Schelkunoff and Friis [B22], Stutzman and Thiele [B23], and Terman [B24]).

$$A_{em} = \frac{G\lambda^2}{4\pi} \tag{2}$$

where

A_{em} is the maximum effective aperture area (m^2),
G is the gain or directivity of the antenna,
λ is the wavelength (m).

8.2 Antenna characteristics of electric blasting wiring

Consideration of the normal uses of blasting caps and their related circuits shows that the matched half-wave dipole and the matched loop antenna are good models because of the close physical resemblance to possible blasting wiring configurations and the fact that one or the other of them responds to either of the two possible field configurations one would expect close to the earth. Any evaluation of blasting cap wiring-configurations must consider both the receiving antennas connected to the cap's bridgewire circuit (pin-to-pin) and to any circuit connected to the electrical load represented by the region between the bridgewire and the case (pin-to-case).

8.3 The horizontal dipole model

For the case in which antenna dimensions are large compared with wavelength, the horizontal dipole model is appropriate for determining stand off distances from transmitters. In this model, the antenna is the blasting cap wire (see Figure 1).

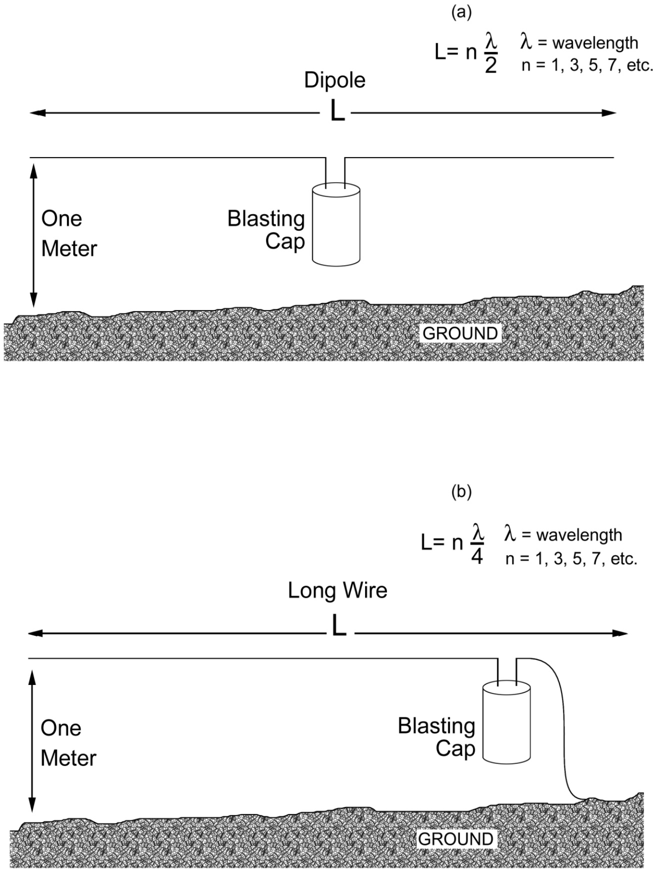


Figure 1—Dipole and longwire pickup circuits

To begin, we want to know the highest gain obtainable if a given length of wire is used as a receiving antenna. The gain obtained will depend on the length of the wire and on the pattern in which it is laid out. Any chance layout of the EED wires will have gain less than that predicted by Equation (3).

$$G = 1.5 + 0.1322\left(\frac{L}{\lambda}\right) + 0.0775\left(\frac{L}{\lambda}\right)^2 \tag{3}$$

where

G is the maximum gain obtainable

L is the wire length in m

NOTE—This length is NOT the total length of the wire. Rather, it is the length of the wire portion suspended above ground. Any wire in contact with the ground will not extract sufficient energy from the RF field to be of any consequence.

λ is the wavelength (m).

Combining Equation (2) and Equation (3) yields Equation (4), an expression for the effective aperture of a wire whose length is not small in relation to a wavelength. Equation (4) gives the worst-case effective aperture area as a function of frequency for cases in which the wire length is larger than the wavelength.

$$A_e = \frac{1}{4\pi}\left[1.5\left(\frac{c}{f}\right)^2 + 0.1322 \times L\left(\frac{c}{f}\right) + 0.0775 \times L^2\right. \tag{4}$$

where

c	is the velocity of light,
A_e	is the effective aperture area in square m.

Combining Equation (4) with the far field equation [Equation (2)] yields Equation (5), the expression for the safe distance (*r*) from a long wire of length *L*.

$$r = \frac{1}{4\pi}\sqrt{\left(\frac{P_t}{P_r}\right) \times G_t \times \left[1.5 \times \left(\frac{c}{f}\right)^2 + 0.1322 \times L \times \left(\frac{c}{f}\right) + 0.0775 \times L^2\right]} \qquad (5)$$

where

P_r	is the no-fire power at the blasting cap in W,
P_t	is the power of the transmitting device in W,
G_t	is the gain of the transmitting device,
r	is the safe distance in m.

The maximum electric field strength parallel to the ground near blasting wiring (see Figure 1) for a horizontally polarized incident field may be expressed by Equation (6) from Appendix 1 of Franklin Research Laboratories Publication F-B2256 [B8]. Both the incident and reflected waves are considered.

$$E_b \le (h/(r))E_i \text{ , } h \le r/2 \text{ , and } f_z > 0.036 \text{ MHz} \qquad (6)$$

where

E_b	is the magnitude of the total electric field at the earth's surface ("boundary") (V/m),
h	is the height of the transmitting antenna (m),
r	is the radial distance from the antenna base to the point in question (m),
E_i	is the magnitude of the incident electric field (from the antenna), considered to be in free space, (V/m),
f	is the frequency of the transmitted wave (MHz).

A half-wave dipole antenna laid out on the ground or near the ground will be sensitive to the horizontal electric field from a nearby radio transmitter. The amount of RF pickup power will be affected by reflection from nearby metal surfaces, and by refraction at the surface of the earth. Equation (7) is an expression for the effective aperture A_e for a half-wave dipole; *G* is the gain of a half-wave dipole, i.e., 1.65 and λ is the wavelength. The electric field can be enhanced by reflection from nearby metal surfaces; the reflection coefficient ρ quantifies this enhancement. The effect of refraction at the surface of the earth is γ. The permeability and conductivity of the wire is μ and σ, respectively. The speed of light is *c*, and the frequency is *f*. The radius of the wire is r_0. The resistance of the load (blasting cap) is *R*.

$$R_L = \frac{L}{ro}\sqrt{\frac{f\mu}{\sigma}}$$

for $L = \lambda/2$,

$$R_L = \frac{1}{2r_0}\sqrt{\frac{\mu}{f\sigma}}, \quad A_e = \frac{G\lambda^2}{4\pi} \times \frac{R}{R_L + R}(1+\rho)^2(1+\gamma)^2 \text{ , and}$$

$$A_e = \frac{1.65c^2}{4(\pi f^2)} \times \frac{R}{R + \frac{1}{2r_o\sqrt{\frac{\mu}{f\sigma}}}} \times (1+\rho)^2(1+\gamma)^2 \qquad (7)$$

Combining Equation (6) and Equation (7) provides the expression for safe distance shown as Equation (8). Thus,

$$P_r = \frac{PG_t}{4\pi r^2}A_e \quad \text{for: } r \geq 2h,\ r^2 = \frac{P}{P_r}\frac{G_t}{4\pi}\frac{1.65\,c^2}{4\pi f^2} \times \frac{R}{R + \frac{1}{2r_0}\sqrt{\frac{\mu}{f\sigma}}}(1+\rho)^2\left(\frac{h}{r}\right)^2 \text{, and}$$

$$r = \left[\frac{P}{P_r} \times \frac{1.65 G_t c^2 h^2}{16\pi^2 f^2} \times \frac{R}{R + \frac{1}{2r_0}\sqrt{\frac{\mu}{f\sigma}}}(1+\rho)^2\right]^{1/4} \tag{8}$$

Equation (8) is for blasting-cap wires that are not connected together, near a radio transmitter with horizontally-polarized radiation. P_r is the no-fire power level of the cap, and G_t is the gain of the transmitting antenna. The height of the transmitting antenna mast is h. P is the transmitter power. The safe distance between the transmitting antenna and the cap wires is r.

NOTE—This equation is only valid for distances greater than twice the mast height.

8.4 The vertical loop model

The vertical polarization model (see Figure 2) is of the closed loop style and should be more sensitive (for dimensions small in relation to wavelength) to the time rate of change of flux within the loop's area. Equation (9) gives the safe distance (r) between the device and the RF source. The following is assumed:

a) The receiving antenna is a portion of the blasting wire making a small loop of area A, perimeter length L, and effective area A_e. It is also assumed that the antenna is reactively matched, and the radiation resistance is zero.

b) Effective aperture area (A_e) is used until the wavelength is equal to $2L$, where L is the perimeter of the loop. At higher frequencies, the maximum effective aperture area (A_{em}) in Equation (2) should be used under the assumption that the blasting cap lead configuration will be no more directive than a long wire, unterminated rhombic, or circular-loop antenna of equal linear dimensions.

c) The wire that makes up the small loop has a total resistance R_L, radius r_0, permeability μ, and conductivity σ.

d) The RF transmitting device operates at a frequency (f) and power P_t.

e) The received power, equal to the no-fire power of the electro-explosive device, is P_r.

f) The gain of the transmitting antenna is G_t.

g) The speed of light is c. The resistance of the explosive device bridgewire is R. It was also assumed that the terminating bridgewire resistance is no less than the dc resistance. The bridgewire (pin-to-pin) loop was used as the worst-case condition.

$$P_r = P_t \times \frac{G_t}{4\pi r^2} \times A_e,\ A_e = 4\pi^2\frac{A^2}{\lambda^2}\left(\frac{4\pi}{c}\right)\frac{R}{(R+R_L)^2},\quad R_L = \frac{L}{r_0 c}\sqrt{\frac{\mu f}{\sigma}} \text{, and}$$

$$r = \frac{2\pi A f}{c}\sqrt{\frac{G_t P_t}{P_r}\left(\frac{1}{c}\right)\frac{R}{\left[R + \left(\frac{L}{r_0 c}\right)\sqrt{\frac{\mu f}{\sigma}}\right]^2}} \tag{9}$$

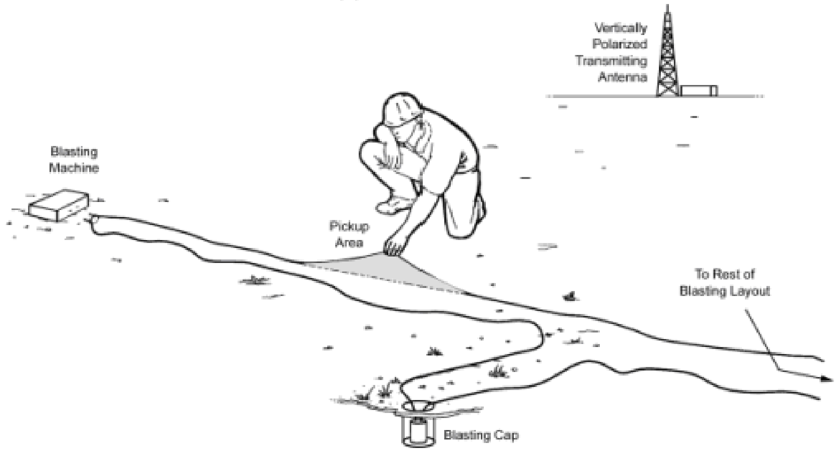
NOTE—The equations in 8.4 and 8.5 are taken with permission from the Franklin Institute Research Laboratories Publication F-B2256-1 [B9], Franklin Institute Research Laboratories Publication F-C1951-1 [B10], and Franklin Institute Research Laboratories Publication M-C2210-1 [B12].

8.5 Frequency for maximum pickup of wideband transmissions

If the radio transmission band is very wide, including both high and low frequencies, and if the exact frequency of the transmitter in use cannot be determined, then as a worst case, one should calculate the safe distance using the maximum aperture value obtainable, i.e., at the intersection of the low-frequency model and the high-frequency model. At this frequency, RF pickup power is maximum. Combining the expressions for A_e in Equation (4) and Equation (9), we obtain Equation (10), which can be solved for frequency. We take as a worst case the triangular loop of blasting wire, and we find that the frequency is 22.8 MHz.

$$A_e = \frac{16\pi^3 A^2 f^2}{c^3} \frac{R}{\left[R + \frac{L}{r_0 c}\sqrt{\frac{\mu f}{\sigma}}\right]^2} = \frac{1}{4\pi}\left[1.5\left(\frac{c}{f}\right)^2 + 0.1322\left(\frac{c}{f}\right) + 0.0775L^2\right] \tag{10}$$

(a) Preferred Case



(b) Acceptable but less desirable

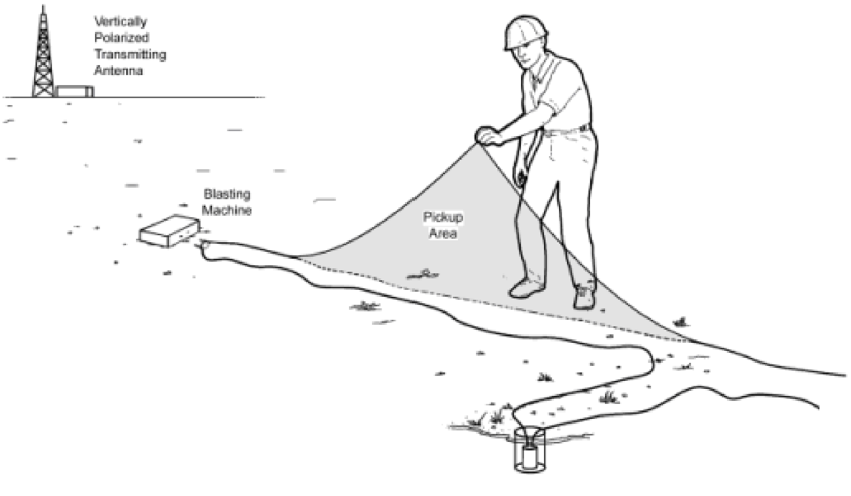


Figure 2—Loop pickup circuits

Annex A

(informative)

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