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VOLUME 1 **REVISION 7**

NAVSEA TECHNICAL PUBLICATION

ELECTROMAGNETIC RADIATION HAZARDS (HAZARDS TO PERSONNEL AND FUEL)

Supersedure Notice: This manual supersedes NAVSEA OP 3565/NAVAIR 16-1-529 Volume 1 Sixth Revision dated 1 February 2003.

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RECORD OF REVISIONS

REVISION NO.	DATE	TITLE OR BRIEF DESCRIPTION/PREPARING ACTIVITY
4	15 SEP 1971	Radio Frequency Hazards to Ordnance, Personnel, and Fuel (U)
5	15 DEC 1979	Electromagnetic Radiation Hazards (U) (Hazards to Personnel, Fuel, and Other Flammable Material) (U) W/Chgs 1 and 2
6	01 FEB 2003	Electromagnetic Radiation Hazards; Hazards to Personnel, Fuel, and Other Flammable Material, Volume 1 (U)
7	30 MAR 2022	This revision incorporates exposure limits based on IEEE C95.1-2345 per the 2021 issuance of DoDI 6055.11, incorporates changes in terminology used by the RADHAZ engineering community, removes the HERP standoff distance tables which now reside online, removes commonly-known engineering principles (such as decibel tables) from the appendices, removes discussion of test instrumentation from the appendices, and divests of NAVAIR specific content.

FOREWORD

The purpose of this volume is to prescribe operating procedures and precautions to prevent injury to personnel and ignition of volatile vapors from exposure to environmental electromagnetic radiation (EMR). The sources of this EMR include communications transmitters, radar, and other transmitters.

This manual provides data and information concerning non-ionizing EMR hazards to personnel and fuel.

This manual cancels and supersedes NAVSEA OP 3565/NAVAIR 16-1-529 Volume 1 Sixth Revision of 1 February 2003, which should be destroyed.

This manual provides technical guidance to assist commanding officers (CO) in carrying out their responsibilities for EMR safety. The procedures and precautions prescribed herein apply in every instance within the naval establishment where a person or a flammable vapor mixture is exposed to EMR of potentially hazardous intensity. Operational Commanders may waive compliance with any provision when essential under emergency conditions. When noncompliance with restrictions contained herein is essential, emergency procedures are suggested and background information is provided in order to explain and minimize the risks involved.

The concept of word usage and intended meaning that has been adhered to in preparing this manual is as follows:

"Must" has been used only when a specified action or procedure is mandatory.

"Should" has been used only when a specified action or procedure is recommended.

"May" and "need not" have been used only when a specified action or procedure is optional.

"Will" has been used only to indicate futurity. No requirement for compliance is implied.

Changes and revisions to this publication will be promulgated by Naval Sea Systems Command (NAVSEA) in a timely manner following coordination with the other cognizant commanders. Interim changes will be made by letter or message as advisories, which will be forwarded to the commanders directly concerned. Formal changes will be forwarded to all addresses on the distribution list of this manual, and, subsequently, will be included in formal revisions. Comments or suggestions relative to material to be included in such changes should be forwarded as specified in chapter 1.

Assistance in evaluating specific electromagnetic or other radiation hazards (RADHAZ) or interpreting provisions of this manual can be obtained by contacting the NAVSEA 05W Technical Warrant Holder for Electromagnetic Environmental Effects (E3) and Spectrum Supportability.

TMDER INSTRUCTIONS

Ships, training activities, supply points, depots, Naval Shipyards, and Supervisors of Shipbuilding are requested to arrange for the maximum practical use and evaluation of NAVSEA and NAVWAR TMs. All errors, omissions, discrepancies, and suggestions for improvement to NAVSEA and NAVWAR TMs shall be submitted as a Technical Manual Deficiency/Evaluation Report (TMDER). All feedback comments shall be thoroughly investigated and originators will be advised of action resulting therefrom.

The NAVSEA/NAVWAR TMDER form, NAVSEA 4160/1, is included at the back of the TM.

The following methods are available for generation and submission of TMDERs against unclassified TMs:

For those with a Technical Data Management Information System (TDMIS) account, the most expedient and preferred method of TMDER generation and submission is via the TDMIS website at https://mercury.tdmis.navy.mil/.

For those without a TDMIS account, generate and submit a TMDER via the Naval Systems Data Support Activity (NSDSA) website at https://mercury.tdmis.navy.mil/def_external/pubsearch.cfm. (TDMIS accounts may be requested at the NSDSA website at https://nsdsa.dc3n.navy.mil/ by submitting a Customer Service Request [CSR].)

When internet access is not available, submit TMDER via hardcopy to:

COMMANDER NAVAL SURFACE WARFARE CENTER
NAVAL SYSTEMS DATA SUPPORT ACTIVITY
4363 MISSILE WAY
ATTN: CODE 310 BLDG 1389 TMDERS
PORT HUENEME, CA 93043-4307

Additional copies of the TMDER form may also be downloaded from the NSDSA website at https://nsdsa.dc3n.navy.mil/ by clicking on the blue tab labeled “Reference Docs/Forms”.

TMDERs against classified/restricted TMs (includes all NOFORN) must be submitted using the hardcopy method cited above.

Urgent priority TM deficiencies shall be reported by naval message with transmission to Port Hueneme Division, Naval Surface Warfare Center (Code 310), Port Hueneme, CA. Local message handling procedures shall be used. The message shall identify each TM deficiency by Technical Manual Identification Number (TMIN) and title. This method shall be used in those instances where a TM deficiency constitutes an urgent problem (i.e., involves a condition, which if not corrected, could result in injury to personnel, damage to the equipment, or jeopardy to the safety or success of the mission).

Complete instructions for TMDER generation and submission are detailed on the NSDSA website at https://nsdsa.dc3n.navy.mil/ by clicking on the blue tab labeled “TMDER/ACN” and then clicking on the gray button labeled “TMDERs”.

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INTRODUCTION

1-1 INTRODUCTION.

1-1.1 GENERAL. DoDI 6055.11, OPNAVINST 5100.19, and OPNAVINST 5100.23 establish the principal Department of Defense (DoD) and Department of Navy (DON) non-ionizing radiation safety policies. This publication summarizes policy for radiation hazards (RADHAZ) and the prevention of hazards of electromagnetic radiation (EMR) to personnel and fuel. If a conflict exists between this publication and DoD or DON instructions, the instructions take precedence. For conflicts between this publication and any other technical instructions and procedures, the provisions specified in this manual take precedence.

1-1.2 PURPOSE. The purpose of this volume is to amplify pertinent information for Navy RADHAZ safety into a consolidated technical publication.

1-1.3 SCOPE. This manual is applicable to all naval ships and shore facilities, during all naval activities, in the presence of (EMR) between 0 hertz (Hz) and 300 gigahertz (GHz).

1-2 BACKGROUND.

1-2.1 ELECTROMAGNETIC RADIATION (EMR). EMR is the transmission of energy though electric and magnetic fields. EMR can be either intentionally or unintentionally generated by electrical, electronic, or electromechanical equipment. Intentional EMR sources include communication, radar, and other transmitters using the electromagnetic spectrum. Unintentional EMR sources are typically high-power density electrical equipment such as power generation, electrical transmission, and pulsed-power equipment. All EMR is non-ionizing, meaning that it does not have sufficient energy to cause ionization of atoms or molecules, but it can result in other hazards.

1-2.2 RADIATION HAZARDS (RADHAZ). RADHAZ is defined to include Hazards of Electromagnetic Radiation to Personnel (HERP), Hazards of Electromagnetic Radiation to Fuel (HERF), and Hazards of Electromagnetic Radiation to Ordnance (HERO).

1-2.2.1 HERP. The potential for EMR hazards to personnel is present in the 0 Hz to 300 GHz frequency range. Below 5 megahertz (MHz), certain magnetic and electric fields can result in adverse non-thermal effects. The effects resulting from exposure to EMR below 5 MHz can include painful stimulation sensory or motor nerves, inadvertent muscle excitation resulting from potentially hazardous activity, alteration of synaptic activity within the brain, cardiac excitation, and adverse effects associated with blood flow. Above 100 kHz, exposure to EMR can results in adverse thermal effects. The effects resulting from exposure to EMR above 100 kHz can include modified behavior, tissue burns, and, in extreme cases, death. Depending on the frequency and strength of the EMR, these effects may not produce a noticeable sensation of pain or discomfort to give warning that injury may be occurring. EMR can also result in high levels of induced and contact current through the body. EMR hazards to personnel, exposure limits, and an explanation of induced and contact currents are contained in chapter 2. EMR-related burns are discussed in chapter 3.

1-2.2.2 HERF. Arcs induced by EMR during fuel-handling operations can cause fuel vapors to ignite under certain conditions. The probability of an ignition varies with factors such as the electromagnetic power density, the type of fuel, the manner and locations in which the fuel is handled, and the size of the vehicle being refueled. Safe handling distances and procedures to eliminate arc-conducive conditions during fuel-handling operations are provided in chapter 4.

1-2.2.3 HERO. The possibility of inadvertent ignition or duding of electrically initiated devices and other ordnance items may occur when exposed to EMR. The probability depends on the strength of the EMR, the type of explosive device, the design of the ordnance item, and the location of the explosive device within the ordnance item. NAVSEA OP 3565 Volume 2 addresses EMR effects on Navy and Marine Corps ordnance items.

1-2.3 EMR EXPOSURE LIMITS. The Institute of Electrical and Electronics Engineers (IEEE) expresses EMR exposure limits in terms of Dosimetric Reference Limits (DRL) and Exposure Reference Levels (ERL). DRLs are exposure limits associated with in situ electric field strengths, specific absorption rates (SAR), and epithelial power densities. Compliance with DRLs requires the measurement of internal fields or specific absorption rates of exposed personnel, which is difficult and complicated. ERLs are exposure limits associated with external electric and magnetic fields, induced and contact currents, and voltages. ERLs are derived from DRLs and are more convenient to measure and assess compliance than DRLs. The ERL can be exceeded if it can be shown that the corresponding DRL is not exceeded. Adequate safety margins have already been included in DRLs and ERLs, even under repeated or long-term exposure conditions. In earlier publications, ERLs are called reference levels, derived limits, permissible exposure limits (PEL), maximum permissible exposure (MPE) values, action levels, or investigation levels. Additional discussion on exposure limits is in chapter 2.

1-3 RESPONSIBILITIES.

1-3.1 NAVAL SEA SYSTEMS COMMAND (NAVSEA). Per OPNAVINST 5100.23, NAVSEA is the lead agent for shipboard HERP and HERF. This includes all associated analysis, assessments, and certifications. Per OPNAVINST 5100.19, NAVSEA is the lead agent for coordinating EMR safety programs for naval ships. Independent technical authority for RADHAZ has been delegated by NAVSEA's Chief Engineer to the NAVSEA 05W Technical Warrant Holder (TWH) for Electromagnetic Environmental Effects (E3) and Spectrum Supportability.

1-3.1.1 Naval Ordnance Safety and Security Activity (NOSSA). Per OPNAVINST 5100.23, NOSSA is the lead agent for HERO as well as ashore HERP and HERF.

1-3.1.2 Naval Surface Warfare Center Dahlgren Division (NSWCDD). NSWCDD is responsible for determining hazardous areas and ensuring that hazards to personnel from EMR are mitigated or eliminated. NSWCDD is the authorized activity to perform shipboard RADHAZ surveys. NSWCDD is also the single engineering agent for shore facility RADHAZ safety and analysis.

1-3.2 NAVAL FACILITIES ENGINEERING SYSTEMS COMMAND (NAVFAC). NAVFAC handles site approval requests for projects with EMR safety implications at naval installations.

1-3.3 BUREAU OF MEDICINE AND SURGERY (BUMED). BUMED is responsible for adopting scientifically established personnel exposure levels for EMR, reviewing personnel overexposures, and providing appropriate medical recommendations.

1-3.4 COMMANDING OFFICER (CO). The CO must initiate policy to enforce compliance with this manual. COs have the authority to impose and enforce more stringent safety rules than those imposed by higher authority. However, where no existing safety rule or regulation applies, or where a deviation from an established mandatory safety regulation is desired, the CO must submit full particulars and detailed plans for approval to NAVSEA – except in emergency situations. The CO must:

a. Establish a RADHAZ safety program or EMR personnel protection program per DoDI 6055.11.

b. Ensure that standard operating procedures are established whereby equipment that transmits EMR is positively controlled and coordinated with personnel working near antennas, handling ordnance, and conducting fueling operations.

c. Ensure that RADHAZ associated with the operation of equipment (in both restricted and unrestricted environments) are known to all personnel and that the necessary safety precautions are implemented.

d. Ensure that RADHAZ surveys are conducted in accordance with OPNAVINST 5100.19, OPNAVINST 5100.23, and NAVSEAINST 2400.20 to determine the appropriate safety precautions for personnel and fuel handling.

1-3.5 SHIP AND SHORE SAFETY OFFICER. The safety officer should be the central point of contact for the HERP and HERF program on the ship or shore station. The safety officer must:

a. Execute and enforce the HERP and HERF aspects of the RADHAZ safety program.

b. Implement the RADHAZ control measures contained in the ship or shore HERP and HERF survey report(s).

c. Inspect and replace damaged RADHAZ control measures.

d. Disseminate HERP and HERF related RADHAZ safety program documentation to all departments and tenant commands.

e. Ensure that all personnel who operate transmitter systems are familiar with and comply with the RADHAZ control measures and recommendations when operating transmitter systems.

f. Provide general RADHAZ awareness training to all personnel within their organization and specific training to personnel who routinely operate or work in close proximity to equipment generating EMR.

g. Request HERP and HERF surveys at their designated periodicities. Survey periodicities have been determined to be 5 years for ships and 5, 7, or 10 years for shore, depending on the density of transmitters. If any changes occur to the electromagnetic environment (EME) – including, but not limited to, new transmit system installations, transmit system modifications, antenna relocations, or shipboard topside superstructure changes – then a survey or analysis may be required sooner than the scheduled periodicity date.

h. Investigate and document all HERP and HERF suspected overexposures and report those results to the CO.

i. For shore activities: Request and obtain certification for new emitter system installs or relocation of existing systems prior to installation or use.

1-3.6 SHIP AND SHORE SUPERVISORY PERSONNEL. Supervisors should be thoroughly familiar with the provisions of this publication. Supervisors have no authority to waive or alter NAVSEA or NAVFAC safety regulations, nor should they permit the violation of such safety regulations by others. They should act positively to eliminate any potential accident hazards existing in operations under their jurisdiction. Each supervisor must also:

a. Develop and promulgate standard operating procedures for activities that have the potential for HERP and HERF incidents.

b. Investigate or assist in the investigation of all HERP and HERF related incidents – including possible HERP overexposures involving operations, equipment, or personnel under their supervision – and report or assist in the preparation of the report on the investigation’s results to higher authority for appropriate action.

1-3.7 SHIP AND SHORE PERSONNEL. All personnel are responsible for understanding and strictly observing all safety standards, requirements, and precautions applicable to their work or duty. In addition, each individual will:

a. Report to their supervisor all HERP and HERF related incidents, including possible HERP overexposures.

b. Comply with all RADHAZ control measures and warn others who might be violating safety precautions.

c. For personnel with medical devices:

(1) Obtain a description of the EME as a function of frequency and electromagnetic field in and around their work area.

(2) Discuss the potential impacts of this EME on device performance with their physician and device manufacturer.

(3) Inform their supervisor of potential concerns with the use of their medical device in the work EME.

1-4 TRAINING.

All personnel assigned to work in EMR environments must receive radio frequency (RF) safety training that addresses RADHAZ and ERL limits. Afloat personnel must also receive annual refresher training. Resources for training are offered by the Enterprise Safety Applications Management System (ESAMS), Navy e-learning (NEL), Electromagnetic Environmental Effects (E3) Team Online, and other DoD organizations (such as the Defense Information Systems Agency's Joint Spectrum Center).

Personnel engaged in operations involving the use of RF transmitting equipment should be familiar with all phases of work that they will be required to perform. The following topics should be included:

a. RF RADHAZ.

b. Sources of RF burns.

c. Detection of faulty transmitters or related equipment.

d. RADHAZ warning signs, devices, and controls.

e. Electrical characteristics of metallic objects.

f. Sources of RF hazards.

g. The characteristics of modified or new RF transmitting equipment.

h. Use of protective equipment.

i. Use of OPNAVINST 5100.23, OPNAVINST 5100.19, and this manual.

1-5 SITE APPROVALS AND CERTIFICATIONS.

The NAVFAC site approval request process for Navy-controlled shore installations is implemented through NAVFACINST 11010.45, CNICINST 11010.3, NAVFAC Business Management Systems B-25.3.3, and B-25.3.2. All shore site RF emitter systems must be submitted for HERP/HERF review and certification utilizing NAVFAC Form 11010/31 Parts I and II (Request for Project Site Approval/Explosive Safety Certification). When a site approval request is initiated for RF emitter systems (such as mobile radios, fixed base stations, repeaters, drones, radars, intrusion detection systems, communication equipment, etc.), details of the system and proposed installation location should be assessed by the site's spectrum manager and NSWCDD for a RADHAZ impact assessment.

Shipboard system certification requirements can be found in NAVSEA S9040-AA-GTP-010/SSCR. Ship RADHAZ certification involves a survey to validate the shipboard EME via instrumented testing and verification of required control measures. Certification is issued upon confirmation of proper placement of required control measures and is effective for five years unless topside alterations are made that alter the baseline EME. Ship changes involving RF emitter systems will be assessed in accordance with COMUSFLTFORCOMINST/COMPACFLTINST 4720.3 and NAVSEAINST 9700.2.

Requests for RADHAZ surveys and information can be obtained by contacting NSWCDD or visiting https://e3.nswc.navy.mil for online assistance. Host nation personnel who do not have access to E3 Team Online can also contact the NAVSEA 05W TWH for E3 and Spectrum Supportability for assistance.

1-6 HERP OVEREXPOSURE INVESTIGATION AND REPORTING REQUIREMENTS.

All suspected potential overexposures must be investigated and documented. All instances of overexposure that exceed five times the ERL level or require medical attention must be reported to BUMED in accordance with the requirements of OPNAVINST 5100.19 for ship personnel and OPNAVINST 5100.23 for shore personnel.

1-7 DEFINITIONS AND ABBREVIATIONS.

The definitions of the terms and the meaning of the abbreviations used are listed in appendix A.

1-8 REFERENCES.

A list of reference documents applicable to this volume is presented in appendix B. RADHAZ survey reports, reference documents, control measures, tools, and other useful information can be found on the E3 Team Online Knowledge Management System at https://e3.nswc.navy.mil.

1-9 CALCULATIONS AND MEASUREMENTS OF ELECTROMAGNETIC FIELDS.

The EME, the method for calculating power density in an electromagnetic field, and calculation aids for use in predicting EMR RADHAZ are described in appendix C.

CHAPTER 2
HAZARDS OF ELECTROMAGNETIC RADIATION TO PERSONNEL (HERP)

2-1 INTRODUCTION.

2-1.1 GENERAL. This chapter discusses HERP and the means by which such hazards may be mitigated.

The biological hazards associated with electromagnetic radiation (EMR) have been established by the Institute of Electrical and Electronics Engineers (IEEE) International Committee on Electromagnetic Safety. These hazards have been adopted by the Tri-Service Electromagnetic Radiation Protection working group per DoDI 6055.11. Limits in this chapter are primarily extracted from IEEE C95.1-2345.

2-1.2 BIOLOGICAL EFFECTS.

IEEE exposure limits are defined from 0 hertz (Hz) to 300 gigahertz (GHz). Between 0 Hz and 5 megahertz (MHz), the Dosimetric Reference Limits (DRL), and Exposure Reference Levels (ERL) are defined to protect against painful electrostimulation of nerves and muscles. Between 100 kilohertz (kHz) and 300 GHz, the DRLs and ERLs are based on thermal effects. In the transition region of 100 kHz to 5 MHz, both effects apply. The limits vary as a function of frequency and provide limits for power density, electric field, magnetic field, transient fields, and body currents.

2-1.3 RESTRICTED AND UNRESTRICTED ENVIRONMENTS. Environments are categorized as either restricted or unrestricted based on a person's awareness of EMR hazards and access to EMR generating equipment. An unrestricted environment is one in which exposure does not result in exceeding the DRL that marks the safety program initiation level, and which serves as an exposure limit for the general public. In some documents, the unrestricted environment is referred to as a "lower tier", or an "uncontrolled environment", or a "general public exposure." A restricted environment is one in which exposure can result in exceeding the unrestricted environment (lower tier) DRL. In some documents, exposure in restricted environments is referred to as "upper tier", or "controlled environment", or "occupational exposure." For US Navy vessels, all exterior and interior spaces should be considered restricted environments. For shore installations/activities, accessible areas beyond the stations' perimeter fence lines (at a minimum) should be considered unrestricted environments.

2-1.4 SPECIFIC ABSORPTION RATE (SAR).

The basic dosimetric parameter for radio frequency (RF) exposure is the (whole-body) SAR. The SAR is defined as the amount of energy, absorbed over an exposure time period, divided by the total mass of the body. The SAR is expressed in units of Watts per kilogram (W/kg). The SAR for human exposure is set at a threshold of 0.4 W/kg for restricted environments and 0.08 W/kg for unrestricted environments. These levels represent a safety factor of 10 and 50, respectively. At 4 W/kg and above, the chances for adverse biological effects increase, but below this threshold, there is no established evidence of harm to humans.

The whole-body SAR is frequency-dependent, and the resonance frequency is about 70 MHz. This resonance occurs at frequencies for which the length of the body is approximately one-half of the free-space wavelength. The average SAR is highest when the incident electric field (E field) is nearly parallel to the human body. When a person is standing on a perfect ground plane, the electrical length appears twice as tall compared to free space, thus, lowering the resonant frequency to one-half of free space. For incident magnetic fields (H fields), the SAR is greater when the cross section of the body is perpendicular to the incident H field.

Because the SAR is not a field measurement and can be measured only with laboratory-type equipment, derived equivalent limits that are measurable with commercially available instruments are used to determine the ERL.

2-1.5 SPECIAL CONSIDERATIONS.

No special limits or additional RF exposure restrictions are imposed in the case of pregnancy.

Currently there are no EMR immunity standards invoked by the Food and Drug Administration or the Federal Communications Commission on medical devices. The sensitivity of medical devices to EMR-induced electromagnetic interference (EMI) is a function of the electrical components, signal levels, device construction, and modulation of the EMR signal. It has been repeatedly demonstrated through testing that commercial electronics can experience EMI at EMR levels well below the ERL limits.

2-2 ERL FOR ELECTROSTIMULATION EFFECTS.

Electrostimulation is the basis for safety limits in the 0 Hz to 5 MHz frequency range. This effect is short-term, resulting in reactions to electric and magnetic fields that are usually a fraction of a second in duration. These short-term adverse effects include the following:

a. Painful stimulation of sensory or motor neurons.

b. Muscle excitation that may lead to injury while performing hazardous activity.

c. Excitation of synaptic activity within the brain.

d. Cardiac excitation.

e. Effects associated with moving charges within the body, such as blood flow.

Measurable ERL magnetic field limits established to comply with the basic restrictions are listed in table 2-1 for the head and torso and in table 2-2 for limbs. The averaging time for root mean square (rms) current measurements should be 0.2 second for frequencies above 25 Hz. For lower frequencies, the averaging time should include at least five cycles, with a maximum of 10 seconds. The limits for peak exposure refer to instantaneous values measured through a bandwidth from zero to the highest frequency of interest.

ERLs for restricted and unrestricted environments are specified in tables 2-1 through 2-3 and graphically in figures 2-1 and 2-2. Compliance with table 2-1 (or table 2-2) and table 2-3 should be considered separately and not additively.

Table 2-1. Magnetic Field ERLs for Exposure of Head and Torso

Frequency (Hz)	Persons in Unrestricted Environments		Persons Permitted in Restricted Environments	
	Magnetic Flux Density (B_{rms}) (mT)	Magnetic Field (H_{rms}) (A/m)	Magnetic Flux Density (B_{rms}) (mT)	Magnetic Field (H_{rms}) (A/m)
<0.153	118	9.39×10^4	353	2.81×10^5
0.153 to 20	$18.1/f_{Hz}$	$1.44 \times 10^4/f_{Hz}$	$54.3/f_{Hz}$	$4.32 \times 10^4/f_{Hz}$
20 to 751	0.904	719	2.71	2.16×10^3
751 to 3,350	$687/f_{Hz}$	$5.47 \times 10^5/f_{Hz}$	$2060/f_{Hz}$	$1.64 \times 10^6/f_{Hz}$
3,350 to 5×10^6	0.205	163	0.615	490

Table 2-2. Magnetic Field ERLs for Exposure of Limbs

Frequency (Hz)	Persons in Unrestricted Environments		Persons Permitted in Restricted Environments	
	Magnetic Flux Density (B_{rms}) (mT)	Magnetic Field (H_{rms}) (A/m)	Magnetic Flux Density (B_{rms}) (mT)	Magnetic Field (H_{rms}) (A/m)
<10.7	353	2.81×10^5	353	2.81×10^5
10.7 to 3,350	$3{,}790/f_{Hz}$	$3.02 \times 10^6/f_{Hz}$	$3{,}790/f_{Hz}$	$3.02 \times 10^6/f_{Hz}$
3,350 to 3×10^6	1.13	900	1.13	900

Table 2-3. Electric Field ERLs for Whole-Body Exposure

Persons in Unrestricted Environments		Persons Permitted in Restricted Environments	
Frequency Range (Hz)	Electric Field (E_{rms}) (V/m)	Frequency Range (Hz)	Electric Field (E_{rms}) (V/m)
0 to 368 [1/]	5,000 [1/, 2/]	0 to 276	20,000 [3/,4/]
368 to 3,000	$1.84 \times 10^6/f_{Hz}$	276 to 3,000	$5.53 \times 10^6/f_{Hz}$
3,000 to 100,000	614	3,000 to 100,000	1842

NOTES:

1/ Within power line right-of-ways, the ERL for general public is 10 kV/m.

2/ At 5 kV/m, induced spark discharge will be painful to approximately 7 percent of adults (well-insulated individual touching ground).

3/ Painful discharges are readily encountered at 20 kV/m and are possible at 5-10 kV/m without protective measures.

4/ The limit of 20 ,000 V/m may be exceeded in the restricted environment when a worker is not within reach of a ground conducting object.

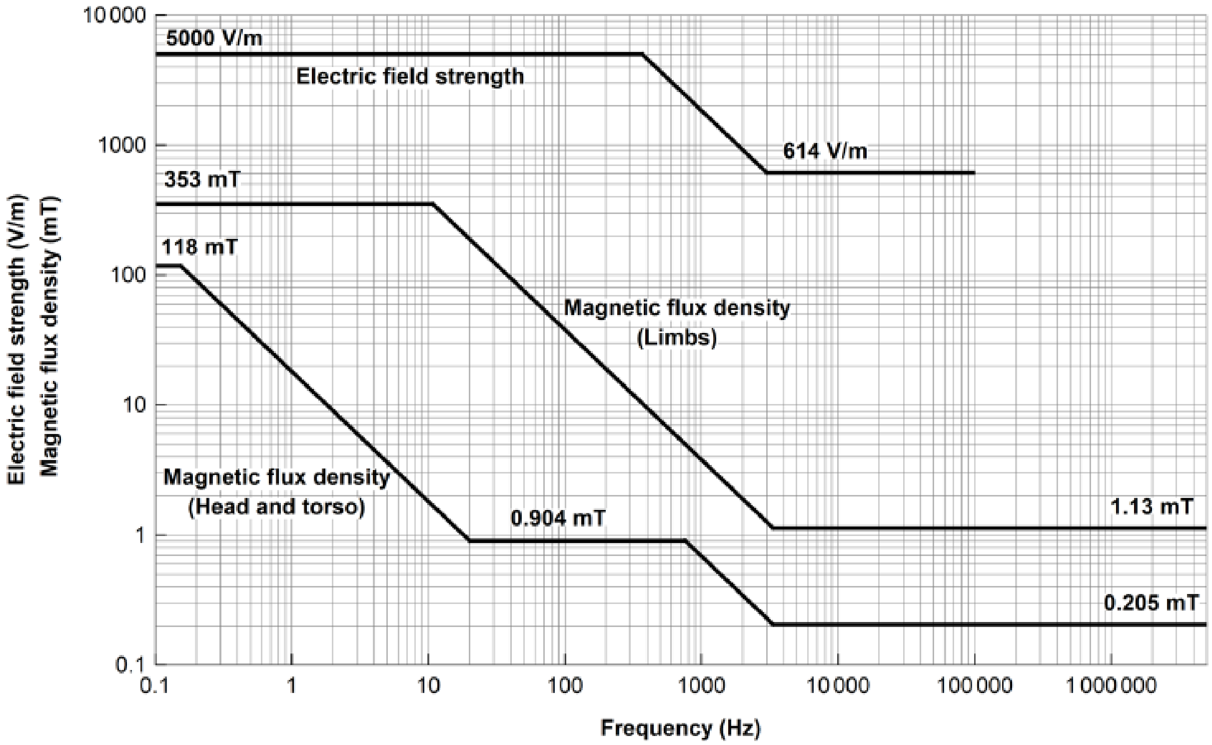

Figure 2-1. Graphical Representations of the ERLs (0 Hz to 5 MHz) for Persons in Unrestricted Environments

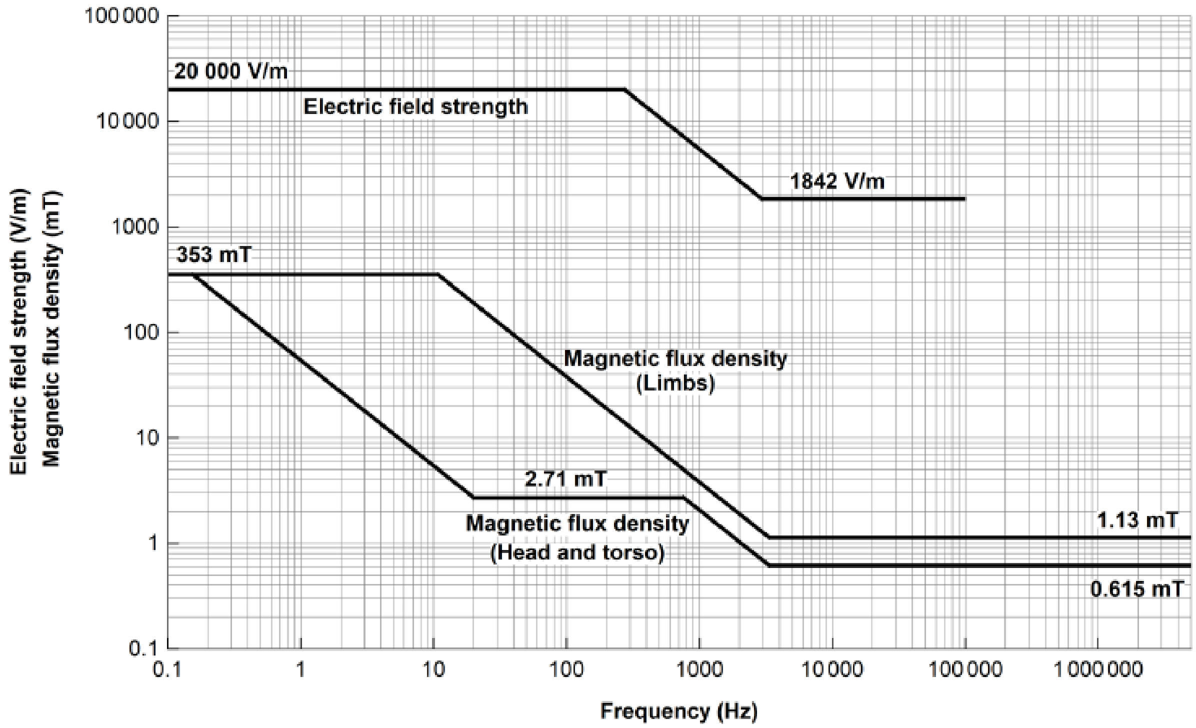

Figure 2-2. Graphical Representations of the ERLs (0 Hz to 5 MHz) for Persons in Restricted Environments

2-3 ERL FOR THERMAL EFFECTS.

Biological tissue exposed to EMR is heated by means of molecular agitation. Dielectric heating of biological tissue by the absorption of EMR is the fundamental principle of the microwave oven. If the body cannot dissipate this heat energy as fast as it is produced, the internal temperature of the body will rise. Under extreme EMR exposure conditions, this may result in damage to the tissue and possible death. It is this potential for heat generation, as well as the possibility for tissue damage, that prompted the development of EMR exposure limits.

The depth of penetration and coincident heating effects of EMR on the human tissue are frequency dependent. A transition region exists between 1 and 3 GHz. Below 1 GHz, EMR penetrates to the deep body tissues; above 3 GHz, the heating effect occurs closer to the surface. At the higher frequencies, the body has an inherent warning system in the sensory elements located in the skin. At frequencies between 1 and 3 GHz, the thermal effects are subjected to varying degrees of penetration.

The body's ability to dissipate heat successfully depends upon many related factors, such as environmental air circulation rate, clothing, power density, and duration of exposure (time). Temperature regulation in the human body is accomplished primarily through the action of sweat glands (cooling through evaporation) and by heat exchange resulting from peripheral circulation of blood. If EMR exposure is not prolonged and within the time exposure limits, the internal core temperature of the body will remain normal. Where areas of the body are cooled by an adequate flow of blood through the vascular system, there is less likelihood of tissue damage resulting from abnormal temperatures. ERLs for EMR above 100 KHz must be time-averaged because of the aforementioned factors.

ERLs for restricted and unrestricted environments are specified in tables 2-4 through 2-5 and graphically as figures 2-3 and 2-4.

Table 2-4. ERLs (100 kHz to 300 GHz) for Whole Body Exposure of Persons Permitted in Restricted Environments

Frequency Range (MHz)	Electric Field Strength (E_{rms}) (V/m) 1/	Magnetic Field Strength (H_{rms}) (A/m) 1/	E-Field Power Density (S_E) (W/m^2) 2/	H-Field Power Density (S_H) (W/m^2) 2/	Averaging Time (Minutes)
0.1 to 1.0	1,842	$16.3/f_{MHz}$	9,000	$100{,}000/f_{MHz}^2$	6
1 to 30	$1{,}842/f_{MHz}$	$16.3/f_{MHz}$	$9{,}000/f_{MHz}^2$	$100{,}000/f_{MHz}^2$	6
30 to 100	61.4	$16.3/f_{MHz}$	10	$100{,}000/f_{MHz}^2$	6
100 to 300	61.4	0.163	10		6
300 to 3,000	--	--	$f_{MHz}/30$		6
3,000 to 30,000	--	--	100		$19.63/f_{GHz}^{1.079}$
30,000 to 300,000	--	--	100		$2.524/f_{GHz}^{0.476}$

NOTES:

1/ For exposures that are uniform over the dimensions of the body, such as certain far-field plane-wave exposures, the exposure field strengths and power densities are compared with the ERLs in the table. For non-uniform exposures, the mean values of the exposure fields, as obtained by spatially averaging the squares of the field strengths or averaging the power densities over an area equivalent to the vertical cross section of the human body (projected area) or a smaller area depending on the frequency, are compared with the ERLs in this table.

2/ These plane-wave equivalent power density values are commonly used as a convenient comparison with ERLs at higher frequencies and are displayed on some instruments in use.

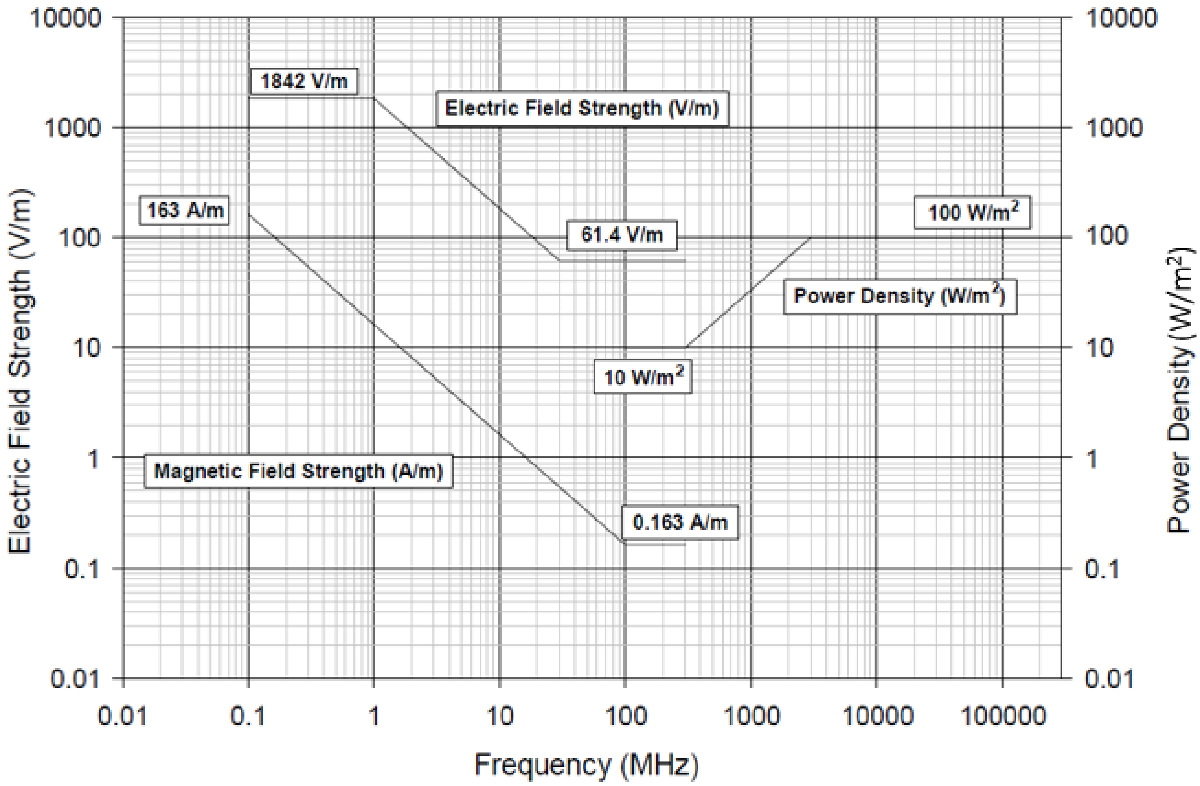

Figure 2-3. Graphical Representations of the ERLs (100 kHz to 300 GHz) for Persons in Restricted Environments

Table 2-5. ERLs (100 kHz to 300 GHz) for Whole Body Exposure of Persons in Unrestricted Environments

Frequency Range (MHz)	Electric Field Strength (E_{rms}) (V/m) [1/]	Magnetic Field Strength (H_{rms}) (A/m) [1/]	E-Field Power Density (S_E) (W/m^2) [3/]	H-Field Power Density (S_H) (W/m^2) [3/]	Averaging Time [2/] (Minutes)	
0.1 to 1.34	614	$16.3/f_{MHz}$	1,000	$100{,}000/f_{MHz}^2$	6	6
1.34 to 3	$823.8/f_{MHz}$	$16.3/f_{MHz}$	$1{,}800/f_{MHz}^2$	$100{,}000/f_{MHz}^2$	$f_{MHz}^2/0.3$	6
3 to 30	$823.8/f_{MHz}$	$16.3/f_{MHz}$	$1{,}800/f_{MHz}^2$	$100{,}000/f_{MHz}^2$	30	6
30 to 100	27.5	$158.3/f_{MHz}^{1.668}$	2	$9{,}400{,}000/f_{MHz}^{3.336}$	30	$0.0636\ f_{MHz}^{1.337}$
100 to 400	27.5	0.0729	2		30	30
400 to 2,000	--	--	$f_{MHz}/200$		30	
2,000 to 5,000	--	--	10		30	
5,000 to 30,000	--	--	10		$150/f_{GHz}$	
30,000 to 100,000	--	--	10		$25.24/f_{GHz}^{0.476}$	
100,000 to 300,000	--	--	$6.43\text{x}10^{-4}\ f_{GHz}^{2.096}$		$3.925\text{x}10^5/f_{GHz}^{2.572}$	

NOTES:

[1/] For exposures that are uniform over the dimensions of the body, such as certain far-field plane-wave exposures, the exposure field strengths, and power densities are compared with the ERLs in this table. For nonuniform exposures, the mean values of the exposure fields, as obtained by spatially averaging the squares of the field strengths or averaging the power densities over an area equivalent to the vertical cross section of the human body (projected area) or a smaller area depending on the frequency, are compared with the ERLs in this table.

[2/] The left column is the averaging time for $|E|^2$, the right column is the averaging time for $|H|^2$. For frequencies greater than 400 MHz, the averaging time is for power density S.

[3/] These plane-wave equivalent power density values are commonly used as a convenient comparison with ERLs at higher frequencies and are displayed on some instruments in use.

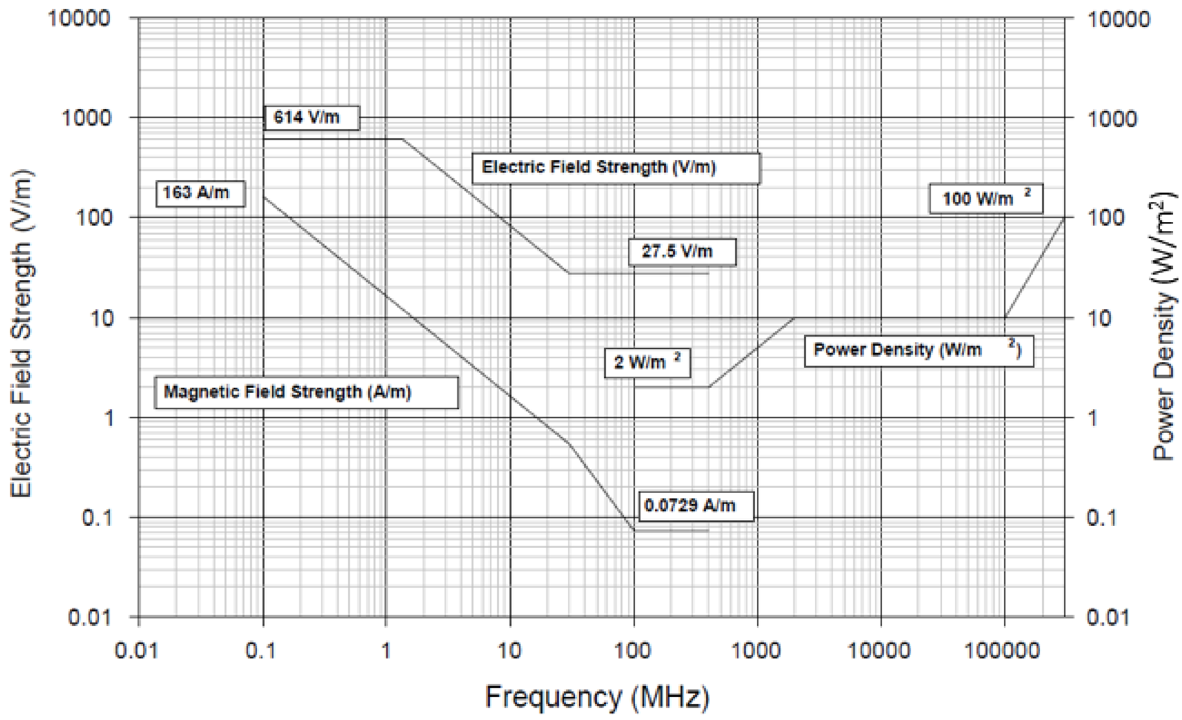

Figure 2-4. Graphical Representations of the ERLs (100 kHz to 300 GHz) for Persons in Unrestricted Environments

The following example, representative of a common workplace safety concern, is provided to help understand the concept of time-averaged EMR exposure limits, as well as the method by which such limits are calculated.

A worker wishes to conduct maintenance in a restricted area nearby a transmitting antenna operating at 200 MHz. The radiated power density in the desired work area has been surveyed to be 20 W/m^2. The transmitter cannot be silenced, nor can the transmitted power be reduced. Given the following conditions, determine if maintenance personnel can safely enter the area and, if so, for how long. Assume whole body illumination.

From table 2-4, at 200 MHz the ERL = 10 W/m^2 and the averaging time = 6 minutes.

Safe duration	=	ERL/measured power density × averaging time
	=	10 W/m^2 / 20 W/m^2 × 6 minutes
	=	3 minutes
Cool-down	=	averaging time – safe duration
	=	6 minutes – 3 minutes
	=	3 minutes

Based upon the above calculation, workers are permitted to conduct maintenance operations in the RF hazard area for 3 minutes, after which they must leave the area for a minimum of 3 additional minutes before returning.

2-4 ERL FOR INDUCED AND CONTACT CURRENT.

When a person is freely standing (not grasping or touching a conductive object) in a radiated field, RF currents are induced into the body. As those induced currents flow between the human body and ground, heat is produced, particularly in the constricted area of the ankles. Contact current is the current which flows through the wrist(s) when a person grasps a conductive object while in a radiated field. IEEE C95.1-2345 has specified a contact current limit with a touch area defined as 1 cm^2 and grasp area defined as 15 cm^2. For personnel trained and authorized to work in Navy controlled environments (i.e., restricted experts only), a touch current limit has not been specified. In most cases, personnel are required to maintain contact with RF energized metal objects over a much larger area, therefore, a “grasping contact” current ERL is the only one specified. Limits for induced and contact currents are specified in table 2-6.

Table 2-6. RMS Induced and Contact Current ERLs for Continuous Sinusoidal Waveforms

Frequency	Persons in unrestricted environments Current (mA)			Persons permitted in restricted environments Current (mA)			Restricted experts only Current (mA)
	Induced, each foot	**Contact, grasp [1/]**	**Contact, touch**	**Induced, each foot**	**Contact, grasp [1/]**	**Contact, touch**	**Contact, grasp [1/]**
0 Hz to 3 kHz	1.35		0.5	3.0	3.0	1.5	
3 kHz to 100 kHz	0.45 f_{kHz}		0.167 f_{kHz}	1.0 f_{kHz}	1.0 f_{kHz}	0.5 f_{kHz}	
100 kHz to 3 MHz	45	--	16.7	100	100	50	250
3 MHz to 30 MHz	45	--	16.7 $(f_{MHz}/3)^{0.3}$	100	100 $(f_{MHz}/3)^{0.3}$	50 $(f_{MHz}/3)^{0.3}$	250
30 MHz to 110 MHz	45	--	33.4	100	200	100	250

FOOTNOTE:

[1/] The grasping contact limit pertains to persons in restricted environments where personnel are trained to make rapid grasping contact and to avoid touch contacts with conductive objects that present the possibility of painful contact.

NOTES:

1. Tabulated values are rms values.
2. Limits apply to current flowing between the body and a grounded object that may be contacted by the person.
3. The averaging time for determination of compliance is 6 minutes (Restricted) and 30 minutes (Unrestricted) for induced currents, 1 second for touch contact current, and 6 minutes for grasp contact current.
4. Light “brush” contact may result in arcs and shock and burn even at 50 mA and should be avoided, especially with long objects such as cranes or cables.
5. Restricted expert only access may be established only when mission essential and only when all personnel who are allowed access are expert on the particular system and informed that fingertip touch contact is to be avoided. Grasp is the appropriate method of contact.
6. The ceiling values (temporal peak values as measured with accepted instruments) for induced current are 220 mA for unrestricted environments (for a maximum duration of 75.3 seconds) and 500 mA for restricted environments (for a maximum exposure duration of 14.4 seconds).

2-5 LOCAL EXPOSURE ERL.

The ERLs presented in this document are based on whole body SAR, as discussed in 2-1.4. IEEE C95.1-2345 describes additional ERLs for local exposure – when only part of the body is exposed to EMR. Local exposure ERLs are not listed in this publication because of their unusual occurrences in Navy environments. Specific circumstances can be addressed by subject matter experts on an as needed basis.

2-6 LOW POWER DEVICES.

The HERP standoff distance calculations are based upon the transmitter and antenna specifications. This data can be found in transmitter/antenna databases, manufacturers' data sheets, technical manuals, Hazards of Electromagnetic Radiation to Ordnance (HERO) reports, and Hazards of Electromagnetic Radiation to Personnel/Hazards of Radiation to Fuel (HERP/HERF) reports.

Based upon guidance provided in IEEE Standard C95.1-2345 and Federal Communications Commission Office of Engineering and Technology Bulletin 65 of August 1997 commercially available RF communication equipment that will be used in restricted environments does not require a formal review because it meets all HERP requirements.. This communication equipment includes mobile radios with an effective isotropic radiated power (EIRP) less than 28 watts, 802.11 wireless devices, cellular telephones, and handheld radios. HERP control measures are not required for these low-power devices.

CHAPTER 3
RADIO FREQUENCY BURNS

3-1 INTRODUCTION.

This chapter discusses radio frequency (RF) burns, why they can occur, and the procedures for minimizing RF burn hazards. An RF burn hazard will exist if there is a sufficiently high induced RF voltage on a metallic object to cause pain, visible skin damage, or involuntary reaction to a person who comes in contact with the object. The RF burn phenomenon is distinct from hazards of electromagnetic radiation (EMR) to personnel and electrical shock.

3-2 RF BURNS ABOARD SHIPS.

3-2.1 GENERAL. The use of high-frequency (HF) transmitters and the complicated structure and rigging aboard ship, especially cargo ships, have increased the probability of RF voltages being induced on various objects. On numerous occasions, RF voltages have been encountered on items such as crane hooks, running rigging, metallic cargo lines, booms, missile launchers, and parked aircraft. These voltages, which may be sufficient to cause injury, are induced on the metallic items by radiation from nearby transmitting antennas.

3-2.2 RF BURN EFFECTS. An RF burn is the result of RF current flow through that portion of the body in direct contact with a conductive object (in which an RF voltage has been induced) or at the site of a spark discharge (no direct contact with a conductive object). Any burn injury that occurs is entirely the result of heat produced by current flow through the resistance of the skin. Current flow through a resistance produces heat regardless of the nature of the circuit. The effect of the heat on a person ranges from warmth to painful burns. The specific level at which contact with RF voltage should be classified as an RF burn hazard is not distinct. Hazardous, for the purpose of this section, is defined as the RF voltage that will cause a person pain, visible skin damage, or will cause an involuntary reaction. An empirically determined value of 140 V root mean square (rms) open circuit voltage as measured between any two points of contact with the body is used by the U.S. Navy as a protective limit for RF burns for frequencies between 100 kilohertz (kHz) and 100 megahertz (MHz). Contact voltages above the empirically determined value of 140 V rms can be induced on large objects, even when the RF field is in compliance with the Exposure Reference Levels (ERL) for power density.

3-2.3 ELECTRICAL CHARACTERISTICS OF METALLIC OBJECTS.

All metallic items, regardless of intended use, have electrical properties of resistance, inductance, and capacitance. These properties depend upon the material, the size and shape of the objects, and the proximity of the objects to each other. The effect of the inductance and capacitance is frequency dependent and coupling to these metallic objects is maximized when the inductance and capacitance form a resonant circuit. An antenna is an example of an object that is designed to be resonant at selected frequencies.

Metallic objects having the physical and electrical characteristics of an antenna are commonplace aboard ships. Large metallic objects are particularly efficient interceptors of RF energy between 100 kHz and 100 MHz An open circuit voltage that exists on objects exposed to EMR is the factor most likely to lead to an electrical arc between the object and a person approaching contact, and hence an RF burn of the skin. The amplitude of the induced RF voltage depends on the following:

a. The length of the line with respect to the wavelength of the exciting electromagnetic field.
b. The proximity of the object to a radiating antenna.
c. The power being radiated by the transmitting antenna.
d. The orientation of the object with respect to the transmitting antenna.

As a practical matter, whether an induced voltage creates an RF burn hazard also depends upon whether personnel will come into contact with the object. Generally, only the voltage between an object and the deck is important.

When conditions conducive to RF burn hazards exist aboard ship, proper measurements are necessary to determine the extent of the hazard. Valid data from comprehensive tests will lead to recommendations to ensure maximum personnel safety with a minimum of operational limitations.

Figure 3-1 shows a demonstration of RF burn potential with a shipboard cargo hook.

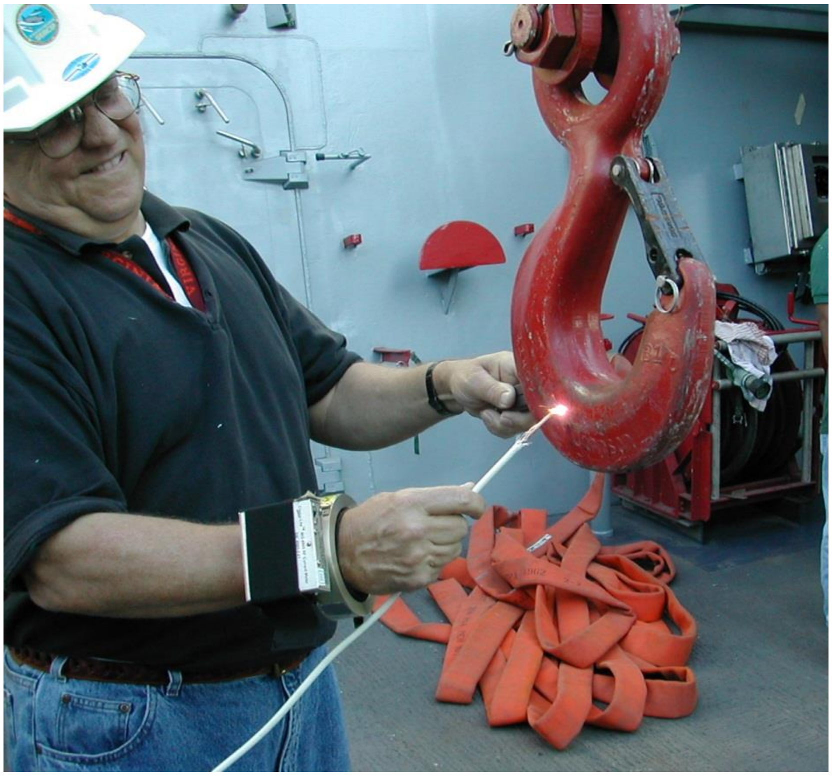

Figure 3-1. Electrical Equivalent of Cargo-Handling Equipment

3-3 RF BURN HAZARD CONTROLS.

While there is no universally applicable method to completely eliminate RF burn hazards, there are several approaches to eliminating the problem in some cases or, in other cases, reducing it to manageable proportions.

3-3.1 HOOK INSULATORS. One method of eliminating the RF burn hazard on boom whip and downhaul hooks is to install an insulator link between the rigging and the hook. Tests have shown that these insulators are effective in the prevention of RF burns to the extent that contact with the hook itself will not injure anyone; however, the RF voltage and potential burn hazard above the insulator remains unaffected. Unfortunately, numerous pieces of equipment involved in the RF burn problem are not amenable to the use of an insulating link.

3-3.2 NONMETALLIC MATERIALS. Another approach being pursued is the use of nonmetallic materials for applications where the RF burn hazard is a problem. Objects that can be made of nonconducting material will not be susceptible to induced voltages. At the present, though, there is no suitable nonmetallic substitute for the wire rope used on cargo equipment.

3-3.3 ANTENNA RELOCATION Eliminating RF burn hazards by relocating antennas is often tempting but seldom practical. Because so many factors are involved in designing a shipboard antenna system, antenna relocation is not a feasible general solution to the RF burn hazard problem. Nevertheless, antenna relocation should not be dismissed as a method to eliminate RF burn hazards.

3-3.4 OPERATIONAL PROCEDURES In some cases, the RF burn hazard can be eliminated only through the use of restrictive operating procedures that govern the simultaneous use of transmitters and cargo equipment. These procedures incorporate the use of techniques such as operation of transmitters at reduced power and the prohibition of simultaneous use of certain combinations of antennas, frequencies, and cargo-handling equipment. The use of operational limitations will reduce the effectiveness of all equipment involved; therefore, these limitations must not be excessively restrictive. Effective operational procedures can be developed only after a radiation hazard (RADHAZ) survey has been conducted. Following this survey, specific operational procedures must be developed by persons who have a thorough knowledge of the operational requirements of the ship and have the authority to designate which operations and equipment have priority over others.

CHAPTER 4
HAZARDS OF ELECTROMAGNETIC RADIATION TO FUEL

4-1 INTRODUCTION TO HAZARDS OF ELECTROMAGNETIC RADIATION TO FUEL (HERF).

The potential for HERF exists whenever exposed fuel vapors are present. This includes, but is not limited to, fueling aircraft, vehicles, or equipment from a pump or a portable container; transferring fuel from a storage container to a fuel truck; and transferring fuel from a pump to a portable container.

The possibility of accidentally igniting fuel vapors by radio frequency (RF)-induced arcs during fuel-handling operations in proximity to high-powered communication and radar transmitting antennas has been the subject of extensive study and research. Tests aboard ships and in laboratories have shown that, while it is possible to ignite volatile fuel-vapor mixtures by induced RF energy, the probability of ignition during normal fueling procedures is remote., given the number of conditions that need to exist simultaneously in order to support combustion.

The probability of accidental ignition has been reduced in recent years by the following:

a. Location of transmitting antennas away from fueling stations and vents.

b. Introduction of pressurized fueling systems on aircraft.

c. The move to almost exclusive use of JP-5 aircraft fuels aboard ships.

Even though the potential fuel hazard from electromagnetic radiation has been reduced by the foregoing measures, it is still present when handling the more volatile JP-4 fuel, motor gasoline (MOGAS), aviation gasoline (AVGAS), and possibly JP-8 fuel. JP-5 and marine diesel fuels have no HERF issues since their vapor pressures are low enough that, under ordinary temperatures, there is no chance of fire from an RF-induced arc. Personnel handling fuels afloat and ashore should be aware of all potential hazards, which are more fully described herein.

Operations involving the transfer of fuel from a portable container to a vehicle or equipment should not occur within the prescribed safe separation distances for transmitters if main beam illumination of the area is possible. In addition, mobile and handheld transmitters should not be operated within the minimum safe separation distance from any fuel handling operation.

4-2 PHYSICAL NATURE OF COMBUSTION.

The probability of ignition of fuel vapors by RF-induced arcs is small, since the following conditions must occur simultaneously for ignition to take place:

a. A flammable fuel-air mixture must be present within range of the induced arcing.

b. The arc must contain a sufficient amount of energy to cause ignition.

c. The gap across which the arc occurs must be a certain minimum distance.

For fuel vapors to ignite, the fuel-air mixture needs to be within limits to support combustion. For example, the limits of flammability of MOGAS are between 1.25 percent and 7.6 percent by volume of gasoline vapor in the air. Handling of gasoline under normal operating conditions does not produce a flammable atmosphere except close to fuel vents, open fuel inlets, or spilled gasoline. With no ventilation, flammable gasoline vapors, being heavier than air, may travel or spill down an inclined surface, such as that provided by a wing or fuselage of an aircraft, before becoming diluted. However, if air movement (wind) is present, the gasoline vapor is diluted and dispersed rapidly, reducing the zone of possible ignition. Additionally, the flammability of hydrocarbon fuels can be influenced by temperature. Changes in temperature affect the hydrocarbon vapor levels, which indirectly affect the fuel vapor-air mixture.

Volatile materials (gases, fuels, liquids) with flash point temperature below 60 °C (140 °F) are considered potentially hazardous when exposed to RF electromagnetic radiation. If a volatile material is heated to its flash point temperature or higher, it will be considered hazardous in presence of RF electromagnetic radiation. If the flash point temperature of a liquid or a fuel is unknown, it should be assumed to be less than 60 °C (140 °F).

Flammable/combustible materials in hermetically sealed containers are considered non-hazardous. However, if the containers are open or leaking, they can become hazardous.

Figure 4-1 shows the temperature-flammability regions for different types of commonly used fuels.

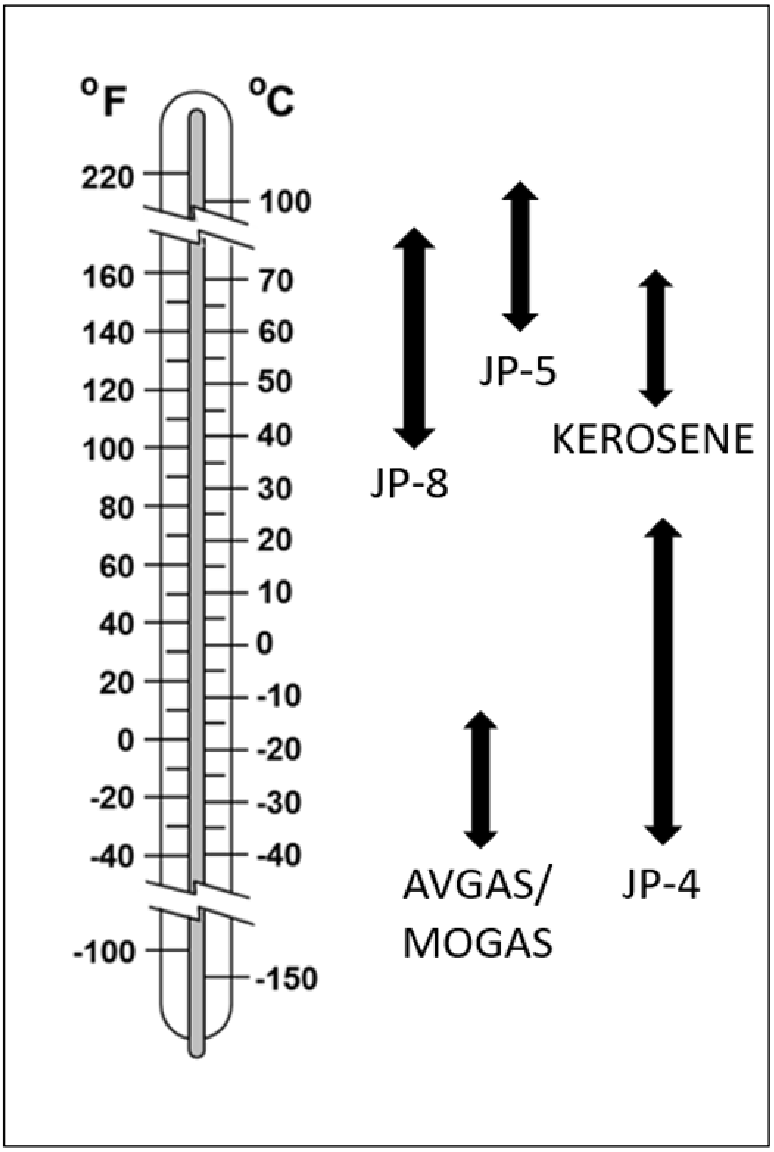

Figure 4-1. Temperature-Flammability Ranges for Fuels

The presence of an odor of gasoline is not a reliable indicator of flammability since the effect of odorous substances varies among observers. However, in comparative tests of individual response, it was found that the odor of gasoline was quite perceptible at concentrations of less than 1 percent of the lower flammability limit. At 100 percent, a very strong odor existed; at 125 percent, the gas-air mixture was noticeably irritating to the eyes and nasal passages.

A minimum spark gap of approximately 0.5 millimeter (0.02 inch) is required for ignition of a fuel-air mixture. In terms of fueling operations, this generally requires a metal-to-metal contact and subsequent withdrawal to produce a drawn arc of sufficient length to ignite a fuel-air mixture. Ensuring that the static ground wires, tie-down cables, and other metallic connections to the aircraft or motor vehicle are properly made before fueling or defueling operations commence and are not disturbed until after the operation is finished, will greatly reduce the possibility of accidental ignition.

4-3 HANDLING PRECAUTIONS FOR FUELS IN AN RF ENVIRONMENT.

Three hydrocarbon-based fuels are currently used throughout the Navy: marine diesel, aviation jet fuel (JP-5 and JP-8), and MOGAS. Of these, only MOGAS and JP-8 are considered to present a HERF concern during fuel-handling operations.

4-3.1 FUELING PRECAUTIONS. The total elimination of RF-induced arc hazards to fuels probably cannot be achieved, particularly aboard ship, without placing unacceptable restrictions on flight and ship operations. Although precise criteria have not been fully developed, the following guidance, applicable to fueling operations both afloat and ashore, will minimize the risk of accidental ignition. This guidance must govern in the event of conflict with other directives.

a. Do not energize any transmitter (radar or communications) on the aircraft or motor vehicle being fueled or on adjacent aircraft or motor vehicles.

b. Do not make or break any electrical, static ground wire, tie-down connection, or any other metallic connection to the aircraft or motor vehicle while it is being fueled. Make the connections before fueling commences; break them afterwards.

4-3.2 LIMITS. The HERF limit for frequencies below 225 megahertz (MHz) is 0.009 milliwatts per square centimeter (mW/cm^2). The HERF limit for frequencies of 225 MHz and above is 5 watts per square centimeter (W/cm^2). To calculate distances, use of the E3 Team Online calculator is recommended. The calculator can be accessed from https://e3.nswc.navy.mil.

4-3.3 TRANSMITTER RESTRICTIONS.

The following RF transmitter restrictions are required during fuel-handling operations involving fuels of concern.

a. RF transmitter systems that operate at or above 225 MHz with a peak transmitter power less than or equal to 250 watts Effective Isotropic Radiated Power (EIRP) must be installed at least 10 feet from fueling operations/fuel handling areas.

b. RF transmitter systems that operate below 225 MHz with a peak transmitter power less than or equal to 250 watts EIRP must be installed no less than 50 feet from fueling operations/fuel-handling areas.

c. For handheld transmitters, antennas radiating 10 watts EIRP or less should remain at least 10 feet away from fueling/fuel-handling operations.

d. See section 4-3.2 if the above are not applicable.

CHAPTER 5
ADMINISTRATIVE CONTROLS

5-1 RADIATION HAZARDS (RADHAZ) WARNING SIGNS.

RADHAZ warning signs have been developed to advise personnel of the hazards of Electromagnetic Radiation (EMR). The format of these signs conforms with national and international standards, such as IEEE C95.2. The RADHAZ warning sign formats are provided, along with the National Stock Numbers, in figure 5-1.

STANAG 1379 provides requirements to mark or control areas where hazards to personnel, munitions and ordnance, and flammable materials exist due to the presence of EMR, and provides signs for participating North Atlantic Treaty Organization (NATO) nations. STANAG 1380, Allied Environmental Conditions Publication (AECP-2), provides procedures for managing Hazards of Electronic Radiation to Personnel (HERP), Hazards of Electronic Radiation to Fuel (HERF), and Hazards of Electronic Radiation to Ordnance during the conduct of NATO operations.

Type 1		Radio Frequency Hazard Warning **KEEP MOVING** NSN: 7690-01-377-5893 (5" per side) NSN: 7690-01-377-5894 (12" per side)
Type 2		Radio Frequency Hazard Warning **BEYOND THIS POINT** NSN: 7690-01-377-5895 (5" per side) NSN: 7690-01-377-5082 (12" per side)
Type 3		Radio Frequency Hazard Warning **BURN HAZARD** NSN: 7690-01-377-5896 (5" per side) NSN: 7 690-01-377-5898 (12" per side)
Type 4		Radio Frequency Hazard Warning **FUELING OPERATIONS** NSN: 7690-01-377-5899 (5" per side) NSN: 7690-01-377-5900 (12" per side)
Type 5		Radio Frequency Hazard Warning **(BLANK)** NSN: 7690-01-377-5374 (5" per side) NSN: 7690-01-377-5375 (12" per side)

Figure 5-1. RADHAZ Warning Sign Formats

Variations – such as subdued and camouflage signs for tactical reasons, or to provide improved visibility under certain lighting conditions – are authorized, provided the general layout of the sign remains the same. When required by military operational considerations, commanders may waive the requirement for signs, provided personnel are informed of possible hazards by other means.

5-1.1 TYPE 1 WARNING SIGN. The Type 1 warning sign advises personnel of an RF hazard and must be posted at the boundary of an area, designated by a Personnel Exposure Limit (PEL) line, beyond which the Exposure Reference Levels (ERL) may be exceeded. Personnel may pass through this area but should not linger. If personnel are required to remain in the area, they must contact the cognizant command authority, who will ensure that procedures are implemented to limit RF exposure to a level below the ERL. Type 1 warning signs should never be posted in an area without a PEL line.

5-1.2 TYPE 2 WARNING SIGN. The Type 2 warning sign excludes personnel from proceeding past a designated point. The sign informs personnel to check with command authority before proceeding beyond this point. This sign is normally posted at access points to RADHAZ restricted zones, such as masts and high-power antenna platforms, and in the vicinity of normally occupied areas which have RADHAZ barriers or personnel barriers to restrict access.

5-1.3 TYPE 3 WARNING SIGN. The Type 3 warning sign informs personnel that contact current or RF burn hazards may exist on metallic objects in this area. The Type 3 sign is used to denote RF hazards due to contact with metallic objects in the area and is normally posted on the metallic object that presents the worst hazard. The present procedure for measuring this limit of contact or "grasping contact" current for the shipboard and shore RADHAZ survey is to measure only those items that may be grasped during their normal operation or use, such as lifelines or rails. Personnel should be aware that this hazard may also exist on other metallic objects in the area. An RF burn hazard may exist when either the RF voltage or contact current ERL is exceeded. Additional RADHAZ control measures (i.e., Type 5 RADHAZ sign) may be required to ensure that this hazard is limited to levels that do not exceed the ERL on metallic objects that personnel must grasp, such as signal lights and binoculars.

5-1.4 TYPE 4 WARNING SIGN. The Type 4 warning sign informs personnel that an RF hazard exists and to check with command authority prior to fueling operations. Further instructions are then provided that may include limitation on transmitter power or silence of specific transmitting antennas. This sign is usually placed next to a fuel storage or refueling station.

5-1.5 TYPE 5 WARNING SIGN. The Type 5 warning sign provides a blank area in which special instructions necessary for safe operations can be specified. Often, the sign provides operators and maintenance personnel with specific frequency or power limitation information for the safe operation of the antenna systems associated with the RF transmitting equipment. The Type 5 sign may also be used to inform personnel to contact command authority prior to operation of equipment in order to prevent an RF hazard to the operator or other personnel. The Type 5 sign should be posted in clear view of system operators.

5-2 PEL LINE.

A PEL line is used to mark a deck area where precautionary measures are required to minimize the possibility of personnel exposure to EMR in excess of the ERL. The PEL line is a 4-inch-wide red line (usually a circle or semicircle) painted on the deck to mark the boundary of an area surrounding an antenna where the ERL can be exceeded. When a PEL line is used, a Type 1 RADHAZ warning sign is posted on the PEL line to advise personnel that a hazard may exist and that they must keep moving. Personnel outside the PEL line need not take precautionary measures; however, when it is necessary for personnel to be within the marked areas, they must contact appropriate personnel who will ensure that operational procedures are implemented to limit RF exposure to a level below the ERL.

5-3 RED WARNING BANDS.

A red warning band is used to mark a safety rail or life rail where precautionary measures are required in order to minimize the possibility of exposure to contact currents in excess of the ERL. The red warning band is a 4-inch-wide red line painted on the top of the safety rail to mark the boundary of an area in proximity to an antenna where the ERL can be exceeded. Where a red warning band is used, a Type 3 RADHAZ warning sign is posted to advise personnel that an RF burn hazard may exist. In those cases where further information or clarification is required, a Type 5 RADHAZ sign should be used.

5-4 PERSONNEL BARRIERS.

In areas where access to levels greater than 10 times the exposure limits for controlled environments may exist, warning signs alone do not provide sufficient protection. Devices such as flashing lights, audible signals, barriers, or interlocks must be installed to prevent inadvertent access. The specific device(s) employed will be determined by the certifying authority based on the potential for exposure.

Personnel barriers are devices that restrict personnel access to an antenna or area where the ERL can be exceeded. The personnel barrier may be a fixed one, such as a permanent fenced area around an antenna. If no access to the antenna is provided, personnel barriers are not required. If there is an access opening, a temporary barrier (i.e., nylon rope) may be used to restrict personnel access. In this case, a Type 2 warning sign is also posted on a placard, which is normally attached to the nylon rope.

5-5 FREQUENCY OR POWER MANAGEMENT.

Frequency or power management restrictions may be employed to ensure that personnel are not exposed to RF energy in excess of the authorized ERL. Such restrictions may be imposed to limit RF exposure within a RADHAZ area defined by PEL lines, or to limit RF contact current on items that personnel are required to grasp while performing their assigned task. The HERP/HERF Technical Report (prepared following a HERP/HERF survey) provides specific guidance and recommended operating procedures to manage potential RF hazards. These procedures may include one or more of the following:

a. Refrain from using the antenna.

b. Reduce power for the frequencies at which the ERL is exceeded.

c. Refrain from using frequencies at which the ERL is exceeded.

d. Restrict access to the antenna unless authorized.

Type 5 warning signs are used to provide operator or maintenance personnel with the frequency or power management requirements.

APPENDIX A
DEFINITIONS, ABBREVIATIONS, AND SYMBOLS

A-1 INTRODUCTION.

This appendix contains definitions of terms, abbreviations, and symbols related to radio frequency (RF) radiation hazards to personnel, volatile flammable liquids, and ordnance.

A-2 DEFINITIONS.

TERM	DEFINITION
Antenna	The part of a transmitting or receiving system that is designed to radiate or receive electromagnetic waves.
Antenna Directivity	The ratio of the maximum radiation intensity to the average radiation intensity produced at a given distance from a given transmitting antenna. The directivity of an antenna is the same whether the antenna is used as a receiving antenna or a transmitting antenna.
Antenna Gain, Relative	The ratio of the power gain of an antenna relative to a standard reference antenna. The relative gain may be in dB or it may be numeric. The standard antenna is usually a half-wave dipole or an isotropic antenna. The latter is preferred even though such an antenna does not exist.
Antenna Illumination	Variation in amplitude across an antenna. Tapered illumination occurs naturally in reflector antennas due to the feed radiation pattern and the variation in distance from the feed to different portions of the reflector.
Arc	An electrical discharge of relatively long duration that may be brought about by separating current-carrying electrodes or may result from a spark discharge between initially separated electrodes, provided that the energy source is sufficient to maintain the arc.
Averaging Time (T_{avg})	The appropriate time period over which exposure is averaged for purposes of determining compliance with a permissible exposure limit.
Beamwidth	The angular width between half-power points on the major lobe of an antenna radiation pattern for a specified plane.
Contact Current	Current flowing through a person touching a charged conducting object.
Continuous Exposure	Exposure for durations exceeding the corresponding averaging time. Exposure for less than the averaging time is called short-term exposure.
Continuous Wave	Unmodulated radio frequency energy, the successive oscillations of which are identical under steady state conditions.
Depth of Penetration	For a plane electromagnetic wave incident on the boundary of a medium, the distance from the boundary into the medium along the direction of propagation in the medium, at which the field strengths of the wave have been reduced to 1/e (e=2.7183) of the boundary values.

TERM	DEFINITION
Dosimetric Reference Limits (DRL)	Limits relative to dosimetric thresholds for established adverse health effects that incorporate appropriate safety factors. DRLs are expressed in terms of the *in situ* electric field strength (0 hertz to 5 megahertz), specific absorption rate (100 kilohertz to 3 gigahertz), or incident power density (3 gigahertz to 300 gigahertz) with the associated averaging times. DRLs are equivalent to the quantity previously referred to as basic restrictions.
Duty Cycle	The ratio of pulse duration to the pulse period of a periodic pulse train. A duty factor of 1.0 corresponds to continuous-wave operation.
Effective Area	The effective area of an antenna in any specified direction is equal to the square of the wavelength multiplied by the power gain (or directive gain) in that direction and divided by 4π.
Effective Isotropic Radiation Power (EIRP)	The hypothetical power that would have to be radiated by an isotropic antenna to give the equivalent signal strength as the actual source antenna in the direction of the antenna's strongest beam.
Electric Field (E)	A state of the region in which stationary charged bodies are subject to forces by virtue of their charges.
Electric Field Strength (E)	The magnitude of the electric field vector. The electric field strength represents the magnitude of the electric force (F) on a positive test charge (q) at a point divided by the charge. Electric field strength is expressed in units of V/m.
Electromagnetic Environment (EME)	The composite electromagnetic field generated by natural and manmade sources.
Electromagnetic Radiation (EMR)	Emission of energy in the form of electromagnetic waves in any portion of the electromagnetic spectrum.
Electronic Equipment	Equipment that produces useful internal signals, or serves functionally by generating, transmitting, receiving, storing, processing, or using information in the broadest sense. Examples are communications, radar, sonar, countermeasures, navigation, computers, test equipment, etc.
Exposure	The subjection of a person to electric, magnetic, or electromagnetic fields or to contact currents other than those originating from physiological processes in the body and other natural phenomena.
Exposure Reference Level (ERL)	The highest level of an electric field, magnetic field, electromagnetic field, induced current or contact current, or voltage to which the standard permits exposure, and which provides an adequate margin of safety against established adverse health effects. The ERL is expressed as the metric appropriate to the frequency and temporal characteristics of the exposure under consideration. The ERL is measured, estimated, or derived from the DRL (*in situ* electric field, SAR, or power density). In other documents, ERLs are sometimes called reference levels, derived limits, permissible exposure limits, maximum permissible exposure values, or investigation levels.

TERM	DEFINITION
Far-Field Region	That region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna. In this region (also called the freespace region), the field has a predominantly plane-wave character; i.e., locally uniform distributions of electric field strength and magnetic field strength in planes transverse to the direction of propagation which decay inversely (1/r) with distance r from the antenna. For aperture antennas, the far-field region is also referred to as the Fraunhofer region.
Field Intensity	The measure of the magnitude of an electromagnetic field. For communication frequencies (200 kilohertz to 1.0 gigahertz), field intensity is a measurement of the electrical field component expressed in V/m. For radar frequencies (200 megahertz to 100 gigahertz), field intensity is a measurement of the average power density expressed in mW/cm^2.
Flammable	A relative term that applies to liquids, gases, and solids, indicating that they are easily ignited in air.
Flammable Limits	The minimum and maximum concentration of a vaporized material in air that will propagate flame if ignited. The difference between the upper and lower flammability limit is known as the flammable or explosive range. The limits are usually expressed in terms of percentage of vapor by volume in air.
Frequency Spectrum	Range of frequencies of electromagnetic energy from both natural phenomena and manmade sources. The radio frequency spectrum is, loosely, that portion of the total spectrum used for information communication.
Ionizing Radiation	Electromagnetic waves with sufficient energy to produce ions; usually x-ray frequencies and higher.
Isotropic Antenna	A hypothetical (lossless) antenna having equal radiation intensity in all directions. Isotropic antennas do not exist physically but represent a convenient means of expressing directional properties of actual antennas.
Magnetic Field Strength (H)	A field vector that is equal to the magnetic flux density divided by the permeability of the medium. Magnetic field strength is expressed in units ampere per meter (A/m).
Magnetic Flux Density (B)	A field vector quantity that results in a force (F) acting on a charge(s) (q) moving with velocity (v). Magnetic flux density is expressed in units of tesla (T). One tesla is equal to 10^4 gauss (G).
Main Beam of Radar	The “main beam” as used herein refers to the solid angular arc describing the maximum radiation lobe of the radar, outside of which the power level is at least 20 dB below the maximum power level radiated.

TERM	DEFINITION
Near-Field Region	A region generally in proximity to an antenna or other radiating structure in which the electric and magnetic fields do not have a substantially plane-wave character but vary considerably from point to point. The near-field region is further subdivided into the reactive near-field region, which is closest to the radiating structure and contains most or nearly all of the stored energy, and the radiating near-field region, where the radiation field predominates over the reactive field but lacks substantial plane-wave character and is complicated in structure. For aperture antennas, the near-field region is also referred to as the Fresnel region. Refer to appendix C. For most antennas, the outer boundary of the reactive near-field region is commonly taken to exist at a distance of one-half wavelength from the antenna surface.
Power Density (S)	Power per unit area normal to the direction of propagation, usually expressed in units of watts per square meter (W/m^2) or, for convenience, units such as milliwatts per square centimeter (mW/cm^2) or microwatts per square centimeter ($\mu W/cm^2$). For plane waves, power density, electric field strength (E), and magnetic field strength (H) are related by the impedance of free space; i.e., 377 (ohms) Ω.
Power Density, Peak	The maximum instantaneous power density occurring when power is transmitted.
Radiated Field	That portion of the total electromagnetic field produced by a current carrying conductor or aperture, the magnitude of whose electric or magnetic vector varies inversely as the distance from the conductor, and the energy of which is propagated away from the conductor. This region is made up of two distinct parts: the *Fresnel* or *near-field region* and the *Fraunhofer* or *far-field region*. The distinction between near-field and far-field regions has no practical meaning for small radiators but is extremely important for large antennas.
Radiation Hazards (RADHAZ)	Radio frequency electromagnetic fields of sufficient intensity to produce harmful biological effects in humans, cause spark ignition of volatile combustibles, or actuate electroexplosive devices.
Radio Frequency (RF)	A frequency between 3 kHz and 300 GHz used for radio and radar transmission.
Restricted Environment	Locations where EMR exposure can exceeding the DRL that marks the safety program initiation level. Restricted environments are where personnel access is controlled, where high level of EMR may be present, and where personnel should be aware of the hazards. The restricted environment has also been referred to as 'Zone 1' or 'controlled.'
RF Burn	A radio frequency (RF) burn hazard exists if there is sufficient induced RF voltage on a metallic object to cause pain, visible skin damage, or involuntary reaction to a person who comes in contact with the object. The RF burn phenomenon is distinct from electrical shock and is the result of heating of the skin by RF currents and is usually accompanied by an involuntary withdrawal. The radio frequency burn mechanism is different from general RF heating.

TERM	DEFINITION
Root Mean Square (rms)	The effective value, or the value associated with joule heating, of a periodic electromagnetic wave. The rms value is obtained by taking the square root of the mean of the squared value of a function.
Scanning	The process or action of directing a radar beam through a space search pattern for the purpose of locating a target.
Spark	An electrical discharge of relatively short duration between initially separate electrodes; the discharge may be repetitive.
Spatial Average	The root mean square of the field over an area equivalent to the vertical cross section of the adult human body, as applied to the measurement of electric or magnetic fields in the assessment of whole-body exposure. The spatial average is measured by scanning (with a suitable measurement probe) a planar area equivalent to the area occupied by a standing adult human (projected area). In most instances, a simple vertical, linear scan of the fields over a 2-meter height (approximately 6 feet), through the center of the projected area, will be sufficient for determining compliance with the permissible exposure limits.
Specific Absorption Rate (SAR)	A measure of the rate at which energy is absorbed per unit mass by a human body when exposed to a radio frequency electromagnetic field.
Thermal Effect	Generally refers to the heating effects of electromagnetic radiation on materials and people.
Unrestricted Environment	Locations where EMR exposure does not result in exceeding the DRL that marks the safety program initiation level. Unrestricted environments are where personnel access is uncontrolled and where high level of EMR are not present. Exposure limits are suitable for the general public. The unrestricted environment has also been referred to as ‘Zone 0’ or ‘uncontrolled.’
Volatile	A relative term which indicates the tendency of a liquid or solid to assume the vapor state (evaporate).
Wavelength (**λ**)	Of a monochromatic wave, the distance between two points of corresponding phase of two consecutive cycles in the direction of propagation. The wavelength (λ) of an electromagnetic wave is related to the frequency (f) and velocity (v) by the expression $\lambda=v/f$. In free space, the velocity of an electromagnetic wave is equal to the speed of light; i.e., approximately $3x10^8$ m/s.

A-3 ABBREVIATIONS.

ABBREVIATION	TITLE
A/m	Amperes per meter
AECP	Allied Environmental Conditions Publication
AM	Amplitude modulation
avg	Average
AVGAS	Aviation gasoline
Az	Azimuth (beamwidth)
BUMED	Bureau of Medicine and Surgery
BMS	Business Management Systems
Cm	Centimeter
cm^2	Square centimeters
CNICINST	Commander, Navy Installations Command Instruction
COMPACFLTINST	Commander, Pacific Fleet Instruction
COMUSFLTFORCOMINST	Commander, United States Fleet Forces Command Instruction
dB	Decibel
DoD	Department of Defense
DoDI	Department of Defense Instruction
DON	Department of the Navy
DRL	Dosimetric reference level
E3	Electromagnetic environmental effects
el	Elevation (beamwidth)
EME	Electromagnetic environment
EMI	Electromagnetic interference
EMR	Electromagnetic radiation
ERL	Exposure reference level
f	Frequency
FCC	Federal Communications Commission
FM	Frequency modulation
ft	Feet

ABBREVIATION	TITLE
GHz	Gigahertz (1,000 MHz or 10^9 Hz)
HERF	Hazards of Electromagnetic Radiation to Fuel
HERO	Hazards of Electromagnetic Radiation to Ordnance
HERP	Hazards of Electromagnetic Radiation to Personnel
HF	High frequency (3 to 30 MHz)
H-field	Magnetic field
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
kHz	Kilohertz (10^3 Hz)
kW	Kilowatt (10^3 watts)
m	Meter(s)
m/s	Meters per second
mA	Milliampere (10^{-3} ampere)
MHz	Megahertz (10^6 Hz)
mm	Millimeter
MOGAS	Motor gasoline (i.e., automotive gasoline)
MPE	Maximum permissible exposure
MW	Megawatt (10^6 watts)
mW	Milliwatt (10^{-3} watt)
mW/cm^2	Milliwatts per square centimeter
NATO	North Atlantic Treaty Organization
NAVAIR	Naval Air Systems Command
NAVFAC	Naval Facilities Engineering Systems Command
NAVFACINST	NAVFAC instruction
NAVSEA	Naval Sea Systems Command
NAVSEAINST	NAVSEA Instruction
NOSSA	Naval Ordnance Safety and Security Activity
NSN	National stock number

ABBREVIATION	TITLE
OP	Ordnance publication
OPNAVINST	Chief of Naval Operations Instruction
PEL	Personnel exposure limit
PCM	Pulse Code Modulation
Pk	Peak
Radar	Radio detection and ranging
RADHAZ	Radiation hazards
Rev	Revolutions
RF	Radio frequency
Rms	Root mean square
S	Power density
SAR	Specific absorption rate
Sec	Second(s)
SS	Spectrum supportability
STANAG	Standardization agreement
TWH	Technical Warrant Holder
V/m	Volts per meter
W	Watt
W/cm^2	Watts per square centimeter
W/kg	Watts per kilogram
W/m^2	Watts per square meter
µs	Microsecond
µW	Microwatt
µW/cm^2	Microwatts per square centimeter

APPENDIX B
REFERENCE DOCUMENTS

B-1 GOVERNMENT DOCUMENTS.

COMMANDER, NAVY INSTALLATIONS COMMAND (CNIC) INSTRUCTION

CNICINST 11010.3 - Site Approval Request Process

(Copies of this document are available online at https://www.cnic.navy.mil/.)

DEPARTMENT OF DEFENSE ISSUANCE

DoDINST 6055.11 - Protecting Personnel from Electromagnetic Fields

(Copies of this document are available online at www.esd.whs.mil/DD/.)

FEDERAL COMMUNICATIONS COMMISSION OFFICE OF ENGINEERING & TECHNOLOGY

FCC OET Bulletin 65 - Evaluating Compliance with FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields

(Copies of this document are available online at https://www.fcc.gov/general/oet-bulletins-line.)

NATO STANDARDIZATION AGREEMENT

STANAG 1379 - NATO RADHAZ Warning Sign

STANAG 1380 - NATO Naval Radio and Radar Radiation Hazards Manual

(Copies of these documents are available online at https://nso.nato.int/nso/nsdd/main/standards/.)

NAVFAC BUSINESS MANAGEMENT SYSTEMS

B-25.3.3 - EMR Safety

B-25.3.2 - Explosives Safety

(Copies of these documents are available at www.navfac.navy.mil.)

NAVFAC INSTRUCTION

NAVFACTINST 11010.45 - Regional Planning Instruction Site Approval Process

(Copies of this document are available online at https://www.navfac.navy.mil/.)

NAVSEA INSTRUCTIONS

NAVSEAINST 2400.20 - Electromagnetic Environmental Effects (E3) and Spectrum Supportability (SS) Program and Procedures

NAVSEAINST 9700.2 - Integrated Topside Safety and Certification Program for Surface Ships

(Copies of these documents are available online at www.navsea.navy.mil.)

NAVSEA TECHNICAL PUBLICATIONS

NAVSEA OP 3565 Volume 2	-	Electromagnetic Radiation Hazards; (Hazards to Ordnance)
S9040-AA-GTP-010/SSCR	-	Shipboard Systems Certification Requirements for Surface Ships

(Copies of these documents are available online via Technical Data Management Information System (TDMIS) at https://mercury.tdmis.navy.mil/ by searching for the document number without the suffix. Refer questions, inquiries, or problems to: DSN 296-0669, Commercial (805) 228-0669. These documents are available for ordering (hard copy) via the Naval Logistics Library (NLL) at https://nll.navsup.navy.mil. For questions regarding the NLL, contact the NLL Customer Service at nllhelpdesk@navy.mil, (866) 817-3130, or (215) 697-2626/DSN 442-2626).

OPNAV INSTRUCTIONS

OPNAVINST 5100.19	-	Navy Safety and Occupational Health Program Manual for Forces Afloat
OPNAVINST 5100.23	-	Safety and Occupational Health Program

(Copies of these documents are available online at https://www.secnav.navy.mil/doni/default.aspx.)

U.S. FLEET FORCES COMMAND INSTRUCTION

COMUSFLTORCOMINST/COMPACFLTINST 4720.3 - C5ISR Modernization Policy

(Copies of this document are available online at https://usff.navy.deps.mil.)

B-2 NON-GOVERNMENT DOCUMENTS.

ALLIED ENVIRONMENTAL CONDITIONS PUBLICATION

AECP-2 - NATO Naval Radio and Radar Radiation Hazards Manual

(Copies of this document are available at https://webstore.ansi.org/.)

IEEE

IEEE C95.1-2345	-	IEEE Standard for Military Workplaces—Force Health Protection Regarding Personnel Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz
IEEE C95.2	-	IEEE Standard for Radio-Frequency Energy and Current-Flow Symbols

(Copies of these documents are available online at www.ieee.org.)

APPENDIX C
CALCULATIONS OF ELECTROMAGNETIC FIELDS

C-1 INTRODUCTION.

Electromagnetic radiation (EMR) is the emission of energy from a source in the form of an electromagnetic wave. EMR is not visible nor is it detected reliably by any biological response. EMR intensity must be measured by instruments or approximated by calculation. This section provides procedures and tabular material which aid in calculating the power density radiated from large-aperture antennas.

These computations enable the supervisor or any other designated personnel to derive power density as power flow per unit area expressed in watts per square meter (W/m^2) or field strength in volts per meter (V/m). From these calculations, safe distances can be determined to reduce the possibilities of personnel exposure to excessive EMR or accidental ignition of ordnance materials or fuels.

Calculations may be conducted in either the metric or English system of units as long as consistency is maintained; however, metric is more commonly used to calculate power density in mW/cm^2 or W/m^2. The correction factor graphs are presented with distance in wavelengths, which gives a dimensionless number that can be used with all units.

C-2 NEAR-FIELD AND FAR-FIELD DETERMINATION

The spatial regions of radiation associated with any arbitrary antenna are known as the near-field region (which generally contains two subregions: the reactive near-field region and radiating near-field region) and the far-field region. There is also a third region of radiation, the intermediate region, which is a region of transition between the near- and far-field regions. The fields in the intermediate region are generally complex and are, therefore, difficult to determine. However, the spatial extent of the intermediate radiation region is generally small compared to the extent of the near- and far-field regions; therefore, the intermediate region is generally ignored in determining electromagnetic field quantities, or it is included as part of the near field. The approximations of the boundaries for these field regions are defined in equations (C.1) through (C.3):

$$d_r \leq 0.62\sqrt{\frac{L^3}{\lambda}}$$ Reactive near-field boundary (C.1)

$$0.62 \times \sqrt{\frac{L^3}{\lambda}} \leq d_{rad} \leq \frac{2L^2}{\lambda}$$ Radiating near-field boundaries (C.2)

$$d_{ff} \approx \frac{2L^2}{\lambda}$$ Far-field boundary (C.3)

λ = the wavelength of the radiation

d_r = the reactive near-field region

d_{rad} = the radiating near-field region

d_{ff} = the far-field region

L = for an aperture antenna, the largest linear dimension of the aperture

for wire, monopole, and dipole antennas, the electrical length of the antenna (e.g., for a monopole or a half-wavelength dipoles, $L = \boldsymbol{\lambda}/2$).

Note: For a wire antenna where the antenna dimension is small compared to the wavelength ($\lambda > 10L$), the radiating near-field does not exist.

C-3 FAR-FIELD CALCULATIONS

C-3.1 FAR-FIELD GAIN. The gain, G, is generally known for an antenna since the parameter is specified in the documentation provided by the antenna manufacturer or calibration lab. However, if the gain of an antenna is not known, it can be calculated to an accepted degree of accuracy by the following, provided the antenna azimuth and elevation beamwidths are known or measured:

$$G \approx \frac{4\pi}{\phi_{az}\Theta_{el}} \tag{C.4}$$

where:

ϕ_{az} = azimuth angle beamwidth, in radians

Θ_{el} = elevation angle beamwidth, in radians

1 radian = $\frac{180°}{\pi}$

C-3.2 FAR-FIELD POWER DENSITY

In the far-field region of the antenna, the magnitudes of the electric and magnetic fields vary inversely with the distance from the antenna ($E, H \propto 1/r$). Furthermore, the ratio of the electric field magnitude to the magnetic field magnitude (E/H), also called the wave impedance, has a constant value of 377 ohms (Ω).

Because of the inverse relation between the electric and magnetic field magnitudes with the distance from the antenna, the power radiated from the antenna can be envisioned as being distributed over a spherical shell at that distance and can be calculated using the Friis transmission equation:

$$S = \frac{GP}{4\pi r^2} \tag{C.5}$$

where:

S = power density of the radiation (in W/m^2 or mW/cm^2)

P = total power transmitted from the antenna (in watts [W] or milliwatts [mW])

G = far-field gain (power ratio) of the antenna

r = distance from the antenna (meters or cm)

C-3.3 ELECTRIC AND MAGNETIC FIELDS

With the power density S known, it becomes a relatively simple matter (in the far field) to determine the magnitudes of the electric and magnetic fields. The power density, electric field, and magnetic field are related by:

$$S = EH \sin\alpha \tag{C.6}$$

where:

α = angle between the electric and magnetic field amplitude directions.

In the far-field, EMR propagates as a transverse wave (α=90º or π/2 radians), and since the magnetic and electric fields are related to each other by the wave impedance, we have:

$$S = \frac{E^2}{Z}\ \mathrm{W/m^2} = ZH^2\ W/m^2 \tag{C.7}$$

where:

E = electric field intensity in V/m

H = magnetic field intensity in A/m

Z = intrinsic wave impedance of free space = 377Ω

C-4 NEAR-FIELD CORRECTIONS

In the near-field region of an antenna (also known as the Fresnel region for aperture antennas), determination of electromagnetic field characteristics is more complicated. The electric and magnetic fields are generally dependent on the source of the radiation and can vary with both angular position and distance around an antenna. Furthermore, the wave impedance of the radiation is no longer a constant value, as it was in the far-field region. In general, a source antenna that has a high terminal voltage, high impedance, and low driver current will generate a high electric field in the near field which varies as $1/r^3$ (r being the distance between the antenna and measurement point), while the magnetic field varies as $1/r^2$; the wave impedance of such an antenna will be much greater than 377Ω, on the order of thousands of ohms. However, a source antenna that has low terminal voltage, low impedance, and high driver current will generate a higher magnetic field in the near-field region which varies as $1/r^3$, while the electric field varies as $1/r^2$. The wave impedance of an antenna where the magnetic field is the dominant radiation component will typically be one to two orders of magnitude below the far-field wave impedance. Note that, as the distance from an antenna is increased, the variation of the electric and magnetic fields with distance will approach the characteristic 1/r dependence associated with the far-field region. Furthermore, as distance from the antenna is increased, the wave impedance will asymptotically approach the constant value of 377Ω.

In the near-field, a correction factor, N, must be used. N is dependent on several parameters:

a. Mismatch (Voltage Standing Wave Ratio) loss derived from the reflection at the antenna feed port because of impedance mismatch.

b. RF losses between the antenna and the antenna feed point or measurement point.

c. Spillover loss, which takes into account energy spillover beyond the edge of a reflector antenna into the backlobes of the antenna.

d. Illumination efficiency, which is the ratio of the directivity of an antenna to the directivity of a uniformly illuminated antenna of the same aperture size.

e. Phase error loss, or loss resulting from the fact that the antenna aperture is not a uniform phase surface.

Parameters a and b above are generally applicable to all antennas and are usually determined by measurement. Parameter c is applicable to reflector antennas and is also usually determined by measurement. Parameters d and e are generally applicable to aperture antennas and can be calculated, to a reasonable approximation, using the methods outlined in the following paragraphs.

C-4.1 ANTENNA ILLUMINATION

For aperture antennas, the near-field correction factor depends on the type of antenna illumination and the distance from the antenna. If the antenna illumination is unknown, it can be estimated by calculating the illumination constant (R) and then referencing table C-1 or table C-2. Calculate the illumination constant using equation (C.8):

$$R = 5.817 \times 10^{-5} \times (f) \times (BW) \times (L \text{ or } D) \qquad (C.8)$$

where:

f = Frequency in megahertz (MHz)

BW = Beamwidth in degrees (horizontal or vertical) at 3 dB points

L = Horizontal or vertical dimension of a rectangular aperture antenna (meters)

D = Diameter of circular antenna in meters (meters)

After calculating R, the illumination type can be estimated from tables C-1 and C-2. Illuminations above $\cos^4$ or $(1\text{-}r^2)^4$ are purposely omitted, since the gain reduction in the Fresnel region would be almost negligible.

A numerical factor (F), which will be used later, is also tabulated in tables C-1 and C-2 adjacent to the type of antenna illumination. For rectangular apertures, F is the product of the horizontal factor and vertical factor.

$$F = F_h \times F_v \qquad (C.9)$$

Table C-1. Rectangular Apertures

Limits of R	Estimated Illumination	F_h or F_v
0.88 to 1.20	Uniform	1.000
1.20 to 1.45	cos	0.810
1.45 to 1.66	$\cos^2$	0.667
1.66 to 1.93	$\cos^3$	0.575
1.93 to 2.03	$\cos^4$	0.515

Table C-2. Circulator Apertures with $(1\text{-}r^2)^\rho$ Illumination

Limits of R	Estimated Illumination	F
1.02 to 1.27	Uniform	1.00
1.27 to 1.47	$(1\text{-}r^2)$ Taper	0.75
1.47 to 1.65	$(1\text{-}r^2)^2$ Taper	0.56
1.65 to 1.81	$(1\text{-}r^3)^3$ Taper	0.44
>1.81	$(1\text{-}r^2)^4$ Taper	0.36

This estimate is then checked by calculating the antenna efficiency. When the constant (R) is found to be borderline between two orders of illumination, the higher order should be checked for antenna efficiency first, because the power density in the Fresnel region will be greater and, therefore, more hazardous to personnel. If the choice of the higher illumination causes the efficiency to be too high, then the next lower order can be tried. The antenna efficiency (K) can be checked by the equation:

$$K = \frac{G(\lambda)^2}{4\pi(A)F} \qquad \text{(C.10)}$$

where:

A = Physical area of the aperture (same units as λ)

F = Factor depending on antenna illumination

An efficiency (K) within the limits of 0.0017 to 1.0 is reasonable for rectangular apertures. An antenna efficiency (K) within the limits of 0.3 and 0.9 is considered reasonable for circular apertures.

C-4.2 NEAR-FIELD GAIN REDUCTION (RECTANGULAR APERTURES)

After the illumination has been determined, the Fresnel gain correction factors for both the horizontal and vertical planes can be found using the appropriate aperture dimension. For rectangular aperture antennas, the near-field gain correction factor (N) is the sum of the vertical and horizontal gain correction factors in decibels (dB).

Graphic curves of gain versus distance have been provided for finding the gain correction factors within the Fresnel region of antennas, depending on the type of illumination of the antenna. Graphs showing uniform, cos, $\cos^2$, $\cos^3$, and $\cos^4$ illumination are given by figures C-1 through C-5. On each of these graphs, the abscissa is the distance from the antenna in wavelengths, and the ordinate is the gain reduction in dB within the Fresnel region. The aperture dimension, L, on the graphs is in wavelengths. The Fresnel gain is always less than the far-field gain and is determined by subtracting the appropriate gain reduction for both horizontal and vertical planes from the far-field gain (in dB). For a linear calculation, G is divided by the antilog of N. Therefore, by the use of this reduced gain in the far-field equation, the power density in the Fresnel region, at a distance r from the antenna, can be calculated.

$$S = \frac{G\,P}{4\pi r^2}\left(\frac{1}{antilog(N)}\right) \tag{C.11}$$

C-4.3 NEAR-FIELD CORRECTION FACTOR (CIRCULAR APERTURES)

After the illumination has been determined, the Fresnel gain correction factor can be applied to calculations. The following provides the details for calculating the near-field correction factors (N) for the Fresnel region of a circular aperture antenna. As stated above, the near-field correction factor depends on the type of antenna illumination and the distance from the antenna.

Calculate the normalized distance from the antenna using equation (C.12). For a given distance (r), the normalized distance (x) is a percentage of the far field distance.

$$x = \frac{r}{2 \times D^2/\lambda} \tag{C.12}$$

Using the normalized distance and the illumination type (ρ = 0,1,2,3,4), look up the appropriate correction factor from figure C-6. The near-field power density level (S) at distance (r) is determined by computing the power density at the far-field distance and multiplying this value by N.

$$S = \frac{G\,P}{4\pi\left(\frac{2D^2}{\lambda}\right)^2} N \tag{C.13}$$

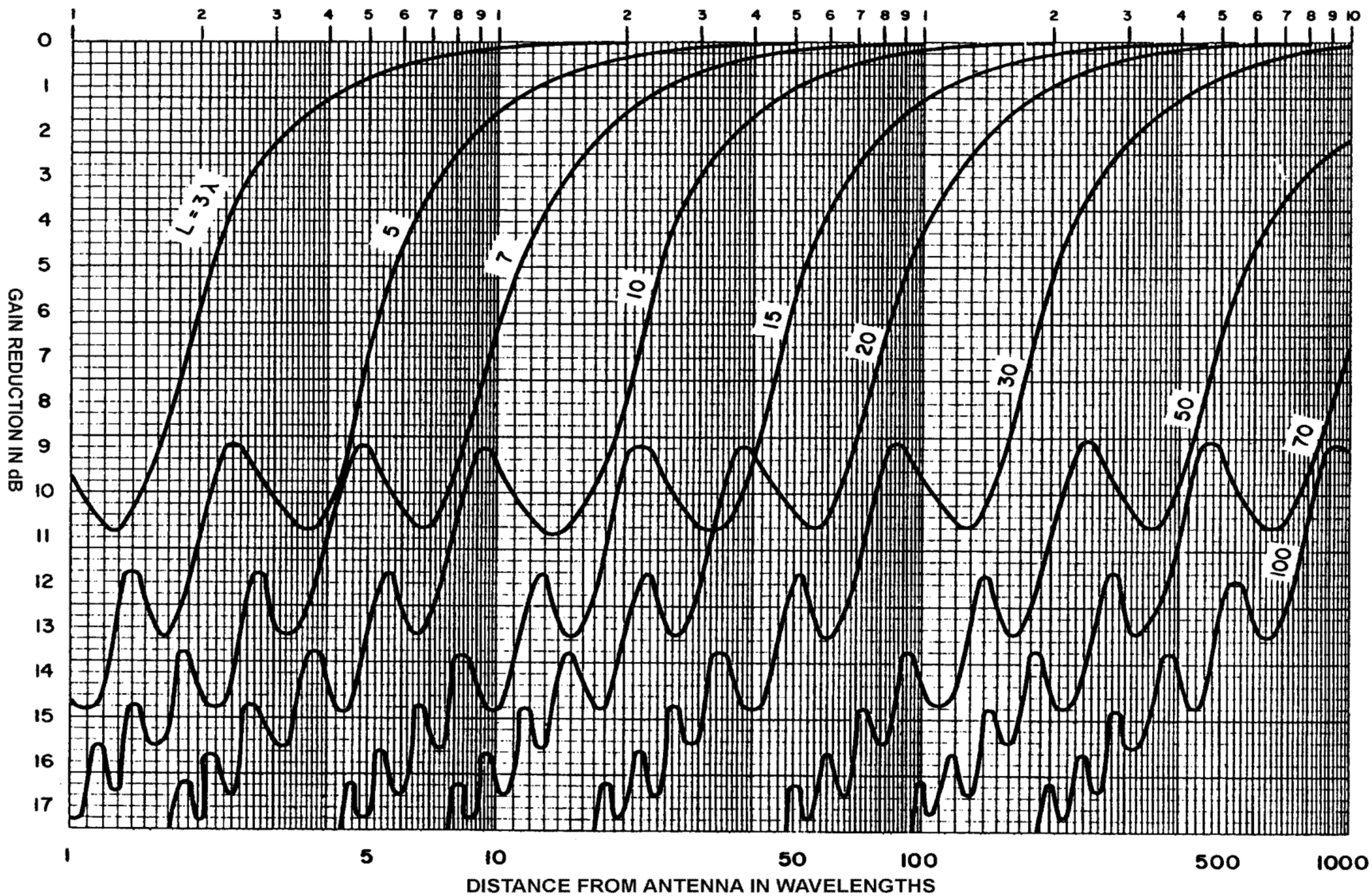

Figure C-1. Fresnel Region Gain Correction for Uniform Illumination (Rectangular Aperture)

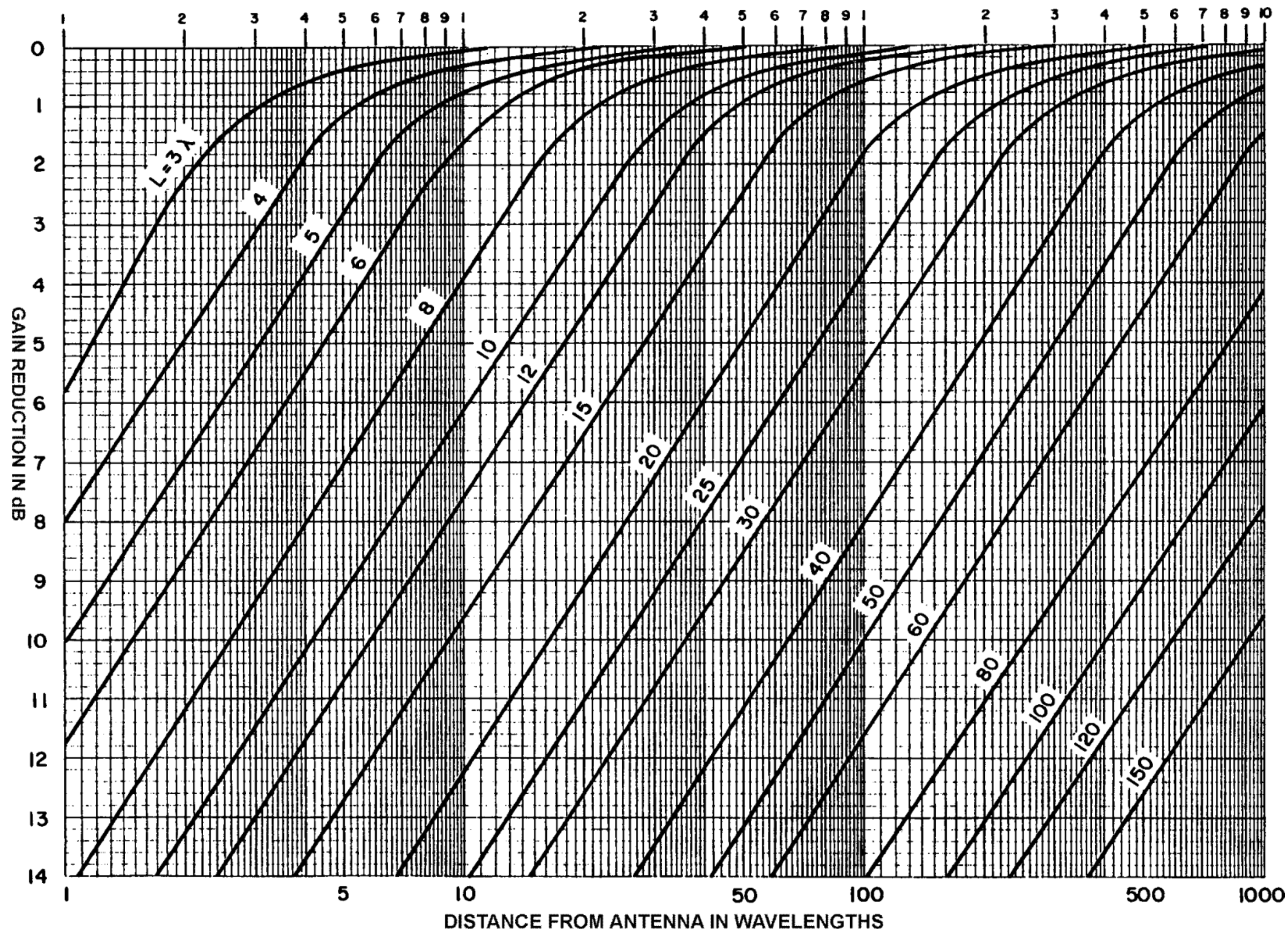

Figure C-2. Fresnel Region Gain Correction for Cosine Illumination (Rectangular Aperture)

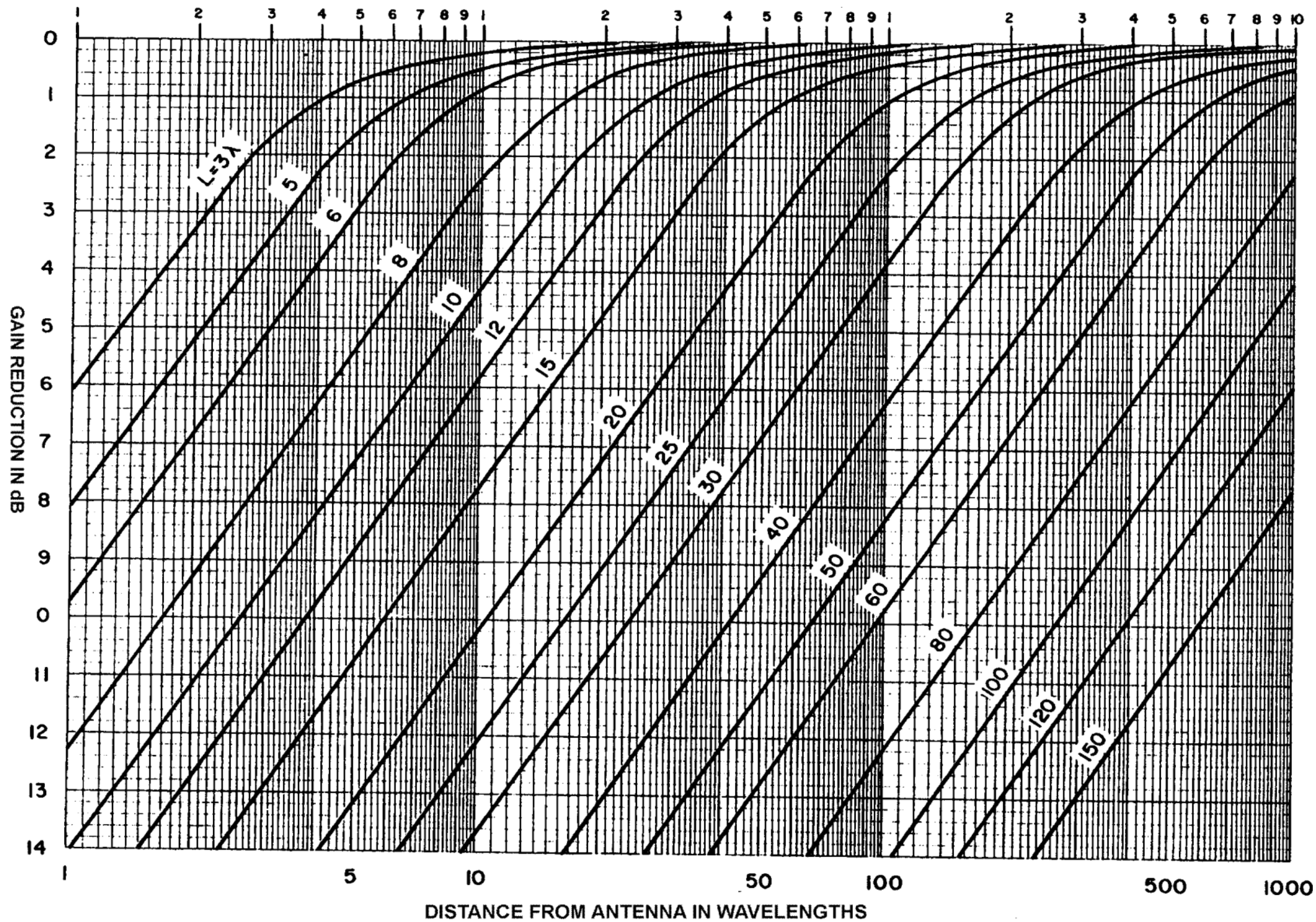

Figure C-3. Fresnel Region Gain Correction for Cosine Square Illumination (Rectangular Aperture)

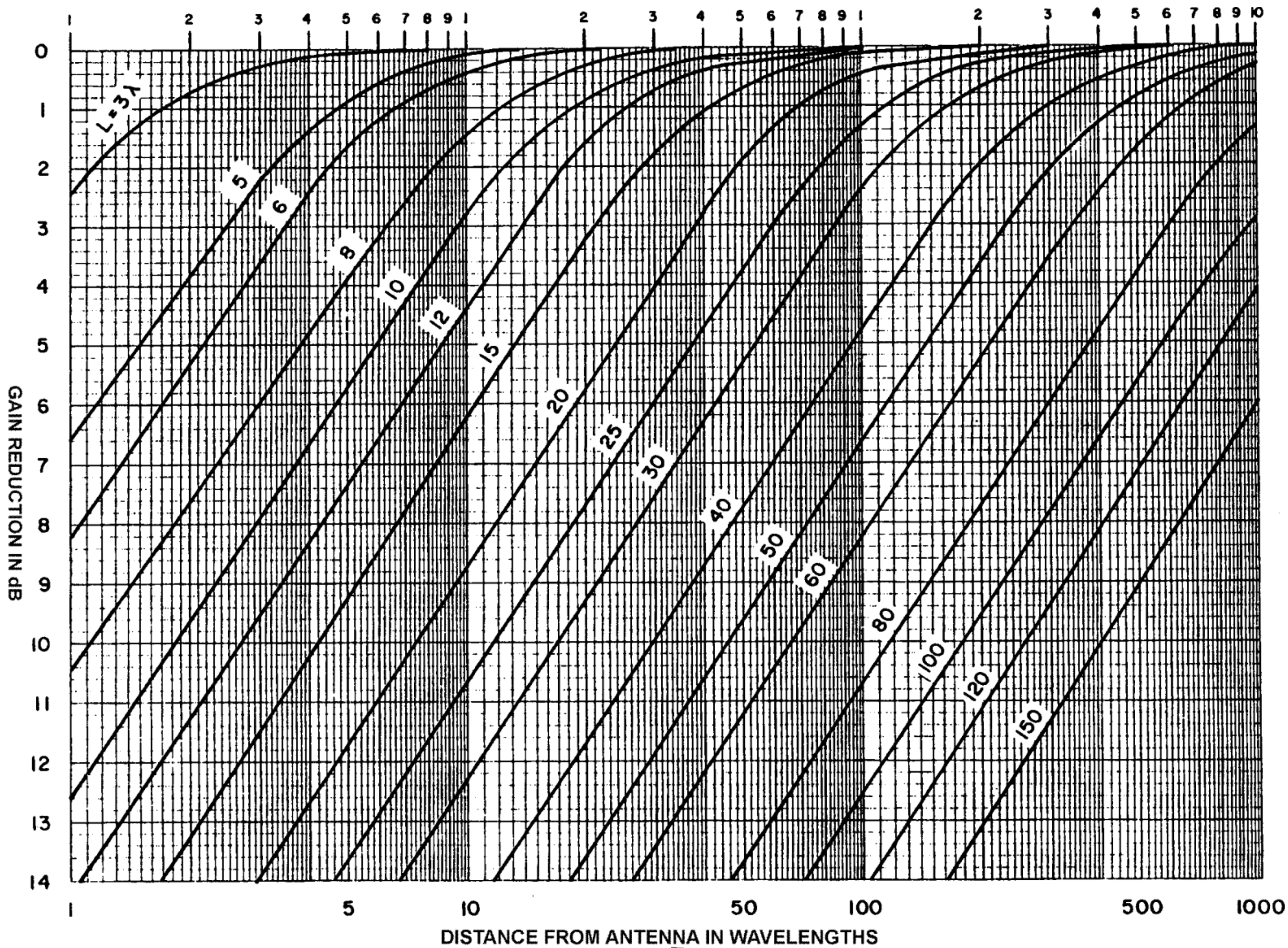

Figure C-4. Fresnel Region Gain Correction for Cosine Cubed Illumination (Rectangular Aperture)

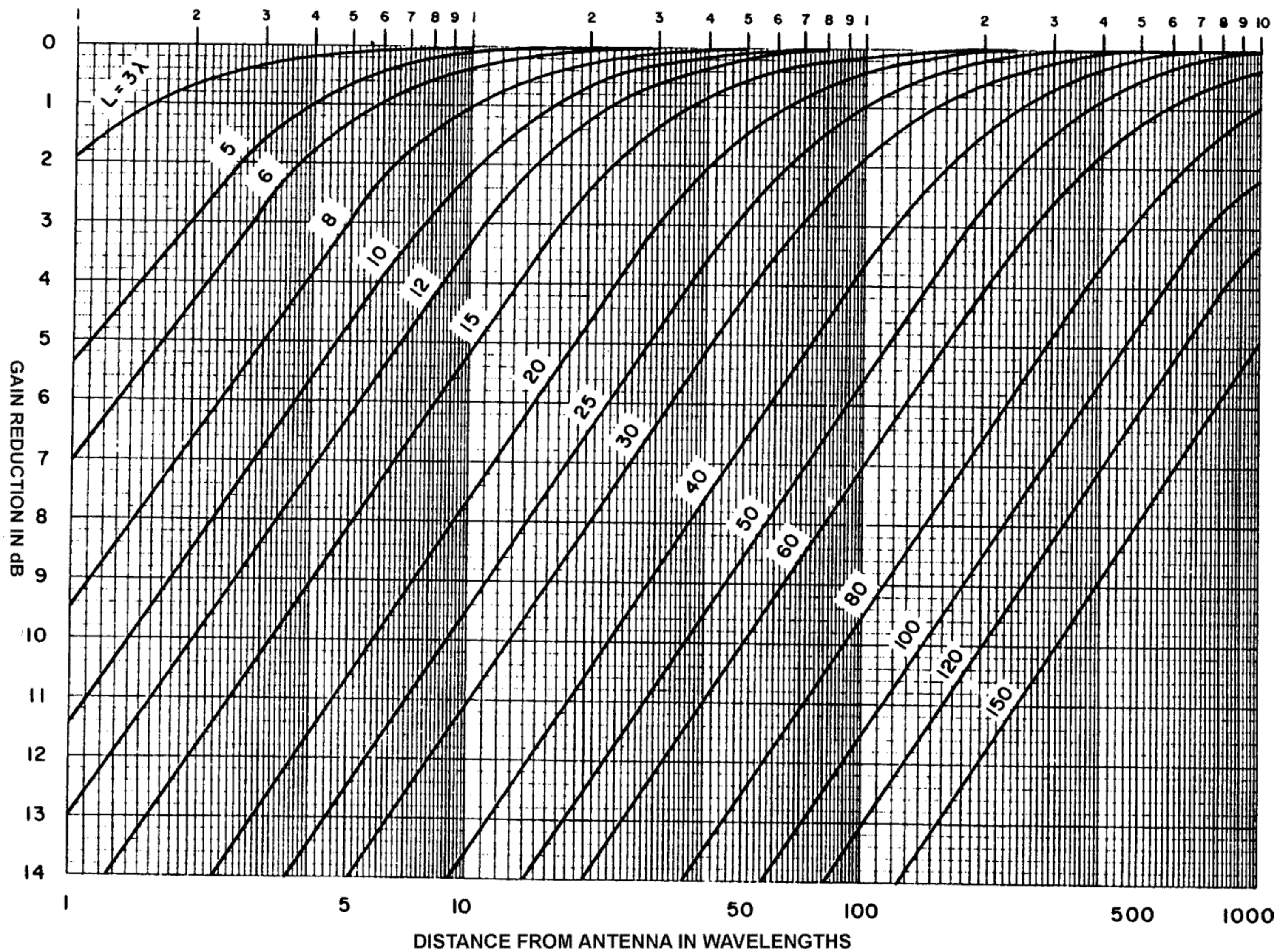

Figure C-5. Fresnel Region Gain Correction for Cosine Fourth Illumination (Rectangular Aperture)

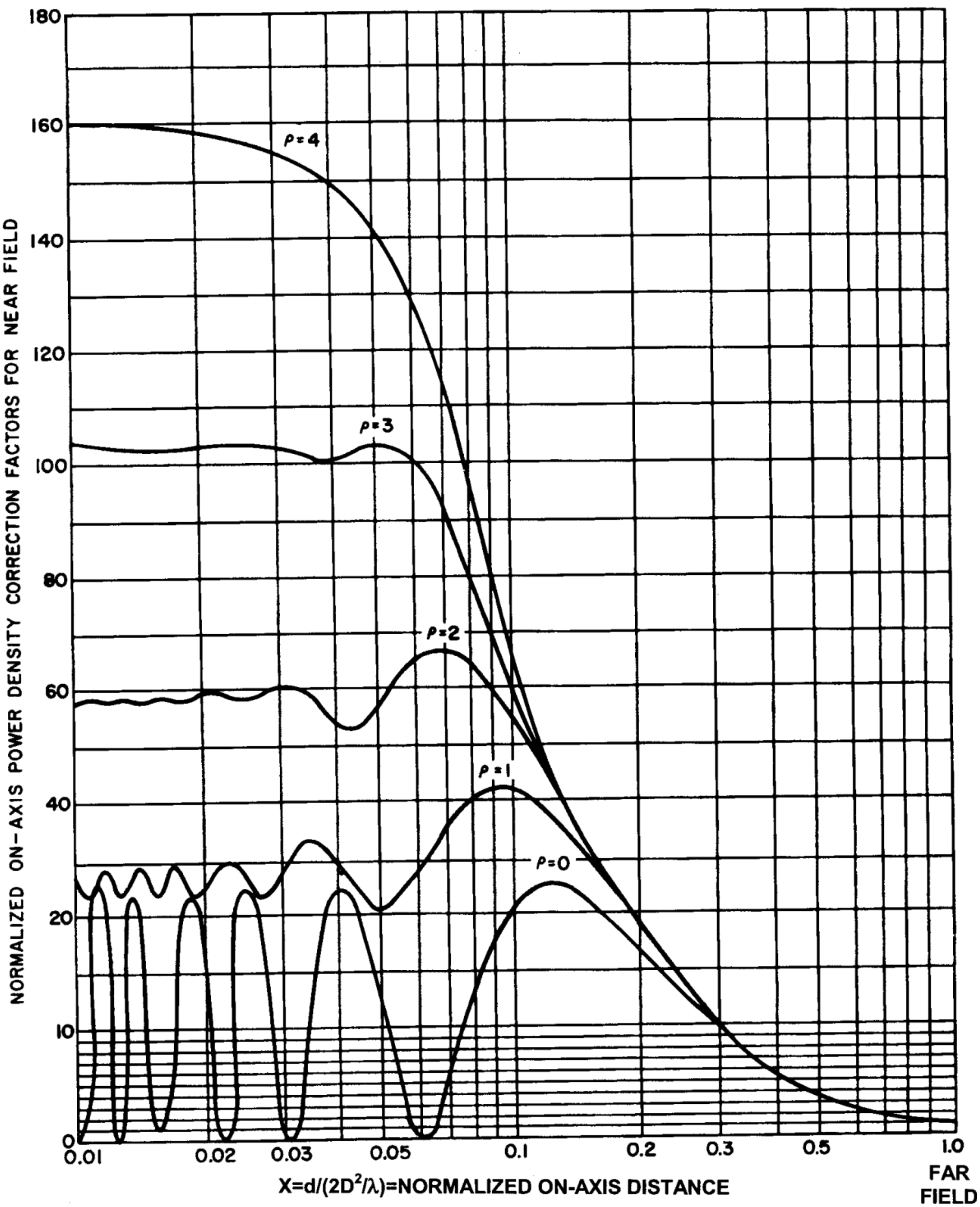

Figure C-6. Normalized On-Axis Power Density Curves Circular Aperture ($1-r^2$)

C-5 POWER DENSITY OF SIDELOBES

Under certain circumstances, it may be necessary to calculate the power density at a location to the side of a radar antenna main beam. If the antenna in question does not have its aperture distribution defined in its fundamental characteristics, the aperture distribution parameters can be established by using tables C-3 and C-4. Table C-3 defines the directivity patterns for circular aperture from $(1\text{-}r^2)^0$ through $(1\text{-}r^2)^2$ illumination, while table C-4 defines the directivity patterns of rectangular aperture from uniform through $\cos^2$ illumination. The angular displacement in degrees of the first sidelobes is also listed in tables C-3 and C-4. Because the sidelobe is less than the main beam, the power density is given as:

$$S = \frac{PG}{4\pi(d)^2}\left(\frac{1}{antilog(SL)}\right) \qquad (C.14)$$

where:

SL = gain degradation of the first sidelobes (in dB)

Table C-3. Circular Aperture Distribution

Type of Illumination	Half-Power Beamwidth in Degrees	Angular Displacement to First Zero in Degrees	Intensity of First Sidelobe dB Below Maximum	Angular Displacement to First Sidelobe in Degrees
$(1 - r^2)^0$	$58.9\frac{\lambda}{D}$	$69.8\frac{\lambda}{D}$	17.6	$97.4\frac{\lambda}{D}$
$(1 - r^2)^1$	$72.7\frac{\lambda}{D}$	$93.6\frac{\lambda}{D}$	24.6	$119.8\frac{\lambda}{D}$
$(1 - r^2)^2$	$84.3\frac{\lambda}{D}$	$116.2\frac{\lambda}{D}$	30.6	$139.3\frac{\lambda}{D}$
NOTE: D = Aperture diameter in the same units as λ.				

Table C-4. Rectangular Aperture Distribution

Type of Illumination	Half-Power Beamwidth in Degrees	Angular Displacement to First Zero in Degrees	Intensity of First Sidelobe dB Below Maximum	Angular Displacement to First Sidelobe in Degrees
Uniform	$50.8\frac{\lambda}{L}$	$57.3\frac{\lambda}{L}$	13.2	$83.8\frac{\lambda}{L}$
Cosine	$68.8\frac{\lambda}{L}$	$85.9\frac{\lambda}{L}$	23	$113.5\frac{\lambda}{L}$
Cosine Squared	$83.2\frac{\lambda}{L}$	$114.6\frac{\lambda}{L}$	32	$137.3\frac{\lambda}{L}$
NOTE: L = Vertical or horizontal length of aperture in the same units as λ.				

C-6 ROTATING OR SCANNING BEAMS

Although the on-axis power density of a radar beam may exceed the ERLs, there may be no hazard if the beam is being rotated or scanned. Duration of exposure, as well as power density, is a factor in determining the hazard.

C-6.1 ROTATING BEAM. The time factor is recognized by specifying the ERL in two ways: for example, 10 mW/cm^2 for continuous exposure, and 1 mW-hr/cm^2 in any given 0.1-hour interval. Since a continuous 10 mW/cm^2 for 0.1 hour produces energy of 1 mW-hr/cm^2, these limits are identical for the case of continuous exposure. The latter limit, though, expresses the fact that higher power densities up to 100 mW/cm^2 are permissible for intermittent exposure. To illustrate the use of this criterion for a rotating antenna, assume the following radiation characteristics:

Maximum power density on axis = 50 mW/cm^2

Beamwidth = 10 degrees

Rotation speed = 6 rpm

If this antenna was not rotating while transmitting, the permissible exposure time in a continuous power density of 50 mW/cm^2 is:

$$T_{hours} = \frac{1}{S(mW/cm^2)} = \frac{1}{50} = 0.02 \text{ hour} = 1.2 \text{ minutes}$$

About 1 minute out of each 6 minutes would be permitted in the beam.

When the antenna is rotating at 6 rpm, it will make one revolution each 10 seconds (0.167 minute), and a point will be exposed to the beam throughout the beamwidth of each period. The actual exposure time for each revolution is (10°/360°)(0.167 minute) = 0.0046 minute. In 6 minutes, there will be 36 revolutions (6 rev/minute x 6 minutes), so that, the total exposure time is 0.167 minute (0.0046 minute x 36). The total energy/cm^2 is thus (50 mW/cm^2)(0.167 minute) (1 hr/60 minutes) or 0.139 mW-hr/cm^2. This is below the permissible intermittent exposure level of 1.0 mW-hr/cm^2; thus, the radar is not hazardous as long as it is rotating, even though the on-axis power density exceeds the safe limit for continuous exposure.

C-6.2 SCANNING BEAM. Power density from a scanning antenna can be approximated by a method similar to that for the rotating antenna. As a rule of thumb, the fixed-beam power density of a scanning antenna can be reduced by a factor of twice the beamwidth divided by the scan angle. That is:

$$S_{scanning} = \frac{2 \times BW}{SA} \times S_{fixed} \quad \text{(C.15)}$$

where:

$S_{scanning}$ = power density while scanning

S_{fixed} = fixed power density

BW = beamwidth in degrees

SA = scan angle in degrees

C-7 PEAK AND AVERAGE POWER CALCULATIONS.

Typically, communication systems are capable of modulation techniques such as amplitude modulation (AM), frequency modulation (FM), and either pulse-code modulation (PCM) or continuous wave (CW). To determine the root mean squared (rms) peak power for FM and PCM, a worst-case approach is used where the peak power is equal to the unmodulated carrier peak power. However, the peak envelope power of a 100 percent modulated AM signal is twice the carrier peak power and, therefore, is used to provide the worst-case scenario from AM signals. In addition, the duty cycle of a CW signal equals unity, and the average and peak rms power are the same. The aforementioned rationale was used because of the randomly changing nature of true peak power over a specific interval.

Pulse-modulated signals, typically from radar transmitters, have significant differences between peak and average power. The average power is determined by the ratio of pulse width (PW) to pulse repetition interval (PRI). This ratio is the duty cycle and can be calculated using equation (C.16). The average power can be calculated by the product of peak power and duty cycle as shown in equation (C.17).

$$DC = \frac{PW}{PRI} = (PW)(PRF) \qquad \text{(C.16)}$$

$$P_{avg} = (P_{pk})(DC) \qquad \text{(C.17)}$$

where:

DC	=	duty cycle (unitless)
PW	=	pulse width (sec)
PRI	=	pulse repetition rate interval (sec)
PRF	=	pulse repetition rate frequency (hertz)
P_{avg}	=	average power (watts)
P_{pk}	=	peak power (watts)

C-8 EXAMPLE CALCULATIONS.

C-8.1 RECTANGULAR APERTURE.

For rectangular aperture antennas, the preceding procedures are illustrated by the calculation of near-field power density at 1 m. The assumed characteristics of the system are as follows:

a.	Antenna width	=	0.991 meters
b.	Antenna height	=	0.177 meters
c.	Far-field Gain (G)	=	29.3 dB or 851
d.	Frequency (f)	=	8825 MHz
e.	Beamwidth (BW)	=	3.0° horizontal and 13° vertical
f.	Peak Power (P_{pk})	=	13.1 kW
g.	Pulse width (PW)	=	0.5 µsec
h.	Pulse repetition frequency (PRF)	=	2 kilohertz (kHz)

Calculations are as follows:

Wavelength (λ) = $\frac{300}{f}$ = $\frac{300}{8825}$ = 0.034 meter

Antenna width (wavelengths) = $\frac{0.991}{0.034}$ = 29

Antenna height (wavelengths) = $\frac{0.177}{0.034}$ = 5.2

Average Power (P) = $(P_{pk})(PW)(PRF)$ = $(13.1x10^3)(0.5x10^{-6})(2x10^3)$ = 13.1 W

Far field distance = $\frac{2L^2}{\lambda}$ = $\frac{2(0.991)^2}{0.034}$ = 57.8 meters

Illumination constant (R) = $5.84x10^{-5}$ (f) (BW) (L)

Horizontal R = $5.84x10^{-5}$ (8825) (3.0) (0.991) = 1.53

(From table C-1, R of 1.53 → $\cos^2$ illumination and F_h = 0.667)

Vertical R = $5.84x10^{-5}$ (8825) (13) (0.177) = 1.19

(From table C-1, R of 1.19 → uniform illumination and F_v = 1.0)

N is the sum of the horizontal and vertical correction factors obtained from figure C-3 for $\cos^2$ and figure C-1 for uniform illumination using the aperture dimension normalized to wavelength (29λ and 5.2λ). At 1 meter (approximately 29λ), the horizontal gain reduction is approximately 9.0 dB and the vertical gain reduction is 0.1 dB.

N = 9.0 dB + 0.1 dB = 9.1 dB = 8.1

$$S = \frac{G\,P}{4\pi(r)^2(antilog(N))} = \frac{(851)(13.1)}{4\pi(1)^2(8.1)} = 109.5\ W/m^2$$

C-8.2 CIRCULAR APERTURE.

For circular aperture antennas, the calculation of near-field power density illustrated for a hypothetical antenna with a circular aperture. The assumed characteristics of a hypothetical circular aperture antenna are as follows:

a. Aperture diameter (D) = 2 meters
b. Gain (far-field) (G) = 21 dB = 126
c. Center frequency (f) = 5000 MHz
d. Beamwidth = 3°
e. Average Power (P) = 50 W
f. Rotation speed = 6 rpm
g. ERL = 50 mW/cm^2

Calculations are as follows:

Wavelength (λ) = $\frac{300}{f}$ = 0.06 meter

Far-field distance = $\frac{2D^2}{\lambda}$ = 133.33 meters

Illumination constant (R) = 5.84×10^{-5} $(f)(BW)(D)$ = 1.752

Using table C-2, the value of R, 1.752, indicates a circular aperture antenna with an estimated $(1\text{-}r^2)^3$ taper illumination. The corresponding antenna illumination factor (F), also from table C-2, is equal to 0.44.

$$\text{Antenna Efficiency (K)} = \frac{G\lambda^2}{4\pi AF} = \frac{126(0.06)^2}{4\pi(\pi D^2/4)(0.44)} = \frac{126(0.0036)}{\pi^2(2)^2(0.44)} = 0.026$$

N is the circular aperture gain correction obtained from figure C-6. Since our hypothetical antenna was found to have a $(1\text{-}r^2)^3$ taper illumination, the curve specified for ρ=3 would be applicable. Therefore, the power density at a point 5 meters away from the antenna would be as follows:

With r=5m, the normalized distance (with respect to the far-field distance) is calculated as:

$$X = r/\left(\frac{2D^2}{\lambda}\right) = \frac{5}{133.3} = 0.0375.$$

From figure C-6, N is found to have a value of 100 for the ρ=3 curve at x = 0.0375.

Therefore, at a distance of 5 meters, the power density is given by:

$$S = N \times \frac{G\,P}{4\pi(\frac{2D^2}{\lambda})^2} = 100 \times \frac{(126)(50)}{4\pi(133.3)^2} = 2.82\ \text{W}/m^2 \text{ or } 0.282\ \text{mW/cm}^2$$

C-9 CALCULATIONS FROM RECEIVER MEASUREMENTS

In the real world, measurements of radiation from an emitting antenna source are conducted using another antenna with its own characteristics. If Gr is the gain of the measurement antenna, then the total power (Pr) received by the measurement antenna, at a distance r away from the transmitting antenna, is:

$$P_r = \frac{G_t G_r P_t\,\lambda^2}{(4\pi r)^2} \tag{C.18}$$

where:

G_t = gain of the transmitting antenna

P_t = total power transmitted from transmitting antenna

The power density is then:

$$S = \frac{4\pi P_r}{G_r\lambda^2} \tag{C.19}$$

The possibility exists that fields from a radiating source could be measured in the near-field region of the receiving antenna used for the measurements. Therefore, a correction factor for the measurement antenna may have to be used such that:

$$P_r = \frac{G_t G_r P_t \lambda^2}{(4\pi r)^2} N_t\, N_r \tag{C.20}$$

and

$$S = \frac{4\pi P_r}{N_r\, G_r \lambda^2} \tag{C.21}$$

where:

N_t = near-field correction factor for the source antenna

N_r = near-field correction factor for the measurement antenna

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