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TECHNICAL MANUAL

ELECTROMAGNETIC RADIATION HAZARDS

25 MAY 1989

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INTRODUCTION

PURPOSE OF MANUAL. The purpose of this manual is to: (1) Familiarize personnel involved in the operation and maintenance of communications-electronic equipment with the types of electromagnetic radiation hazards and the hazard control program, and (2) Provide technical information and guidance for those personnel who are involved in the prediction and/or measurement of electromagnetic radiation hazards.

SCOPE OF MANUAL. The contents of this manual are divided into six chapters and four appendices as follows:

Chapter 1, General Information, provides general information relative to radiation hazards and their control.

Chapter 2, EMRH Control, contains information on establishing a local electromagnetic radiation hazards control program. It also outlines the responsibilities of support activities.

Chapter 3, RF Hazards, discusses various types of rf hazards, i.e., personnel, fuel, and electroexplosive device hazards; their effects; and safety measures that must be taken to prevent their occurrence.

Chapter 4, X-Ray Hazards, deals with the sources, detection, and biological effects of, and protection from, X-radiation.

Chapter 5, Associated Hazards, provides data on other forms of hazards such as infrared, laser, radioactive material, and toxicity hazards which may be encountered in the operation and maintenance of communications-electronic equipment.

Chapter 6, RF Power Density/Hazard Distance, discusses rf propagation in considerable detail, and shows how to calculate power density and hazard distance. Sample calculations are also shown.

Appendix A shows an example of an electromagnetic radiation hazards control Operating Instruction (OI) that can be used as a guide when preparing Unit OIs.

Appendix B presents a guide by which AFCC accomplishes an rf radiation hazard study.

Appendix C presents a guide by which AFCC accomplishes an rf radiation hazard survey.

Appendix D contains various mathematical tables, conversion tables, graphs, and monograms that can be used in the calculation or prediction of rf radiation hazards. It also contains explanations regarding their use.

RECOMMENDING CHANGES TO MANUAL. Users of this manual are encouraged to report errors and omissions and to make recommendations for improving its content. For this purpose, U.S. Air Force personnel should submit their recommendations on an AFTO Form 22 (Technical Order System Publication Improvement Report and Reply) in accordance with Section VI of TO 00-5-1. U.S. Army personnel should use DA Form 2028 (Recommended Changes to Publications) and forward it to HQ USAESEIA, Attn: ASC-E-ES, Fort Huachuca, AZ 85613-5300.

CHAPTER 1

GENERAL INFORMATION

1-1. RADIATION HAZARDS.

a. A hazard exists when electromagnetic or particulate radiation has sufficient power to cause biological damage to personnel and/or create the possibility of igniting fuel or electroexplosive devices (EEDs). USAF has established hazard criteria for personnel, fuel and EEDs. Although this energy is radiated throughout a wide frequency range (radio/radar, infrared, visible light, ultraviolet and X-ray) the radiated hazards of major concern in the operation of communications-electronic (C-E) equipment are radio frequency (rf) and X-ray.

b. Rf and X-ray are to be treated as separate and different hazards. Rf energy is non-ionizing while X-rays are ionizing. Exposure to rf energy raises the body temperatures while exposure to X-rays may cause ionization within the cells or tissues of the body. The equipment used to measure these hazards, the units of power, and the method of protection are different.

c. Both X-ray and rf energy are hazardous to personnel and the criteria for these hazards are published in AFR 161-8 and AFOSH Standard 161-9. Rf energy is also hazardous to fuel and EEDs and the criteria for these hazards are published in AFOSH Standard 127-38 and AFR 127-100, respectively. This manual also provides general information and safety precautions for several other related hazards (radioactive material, infrared, laser and toxicity) which may be encountered in the operation maintenance (O&M) of C-E equipment.

1-2. HAZARDS CONTROL RESPONSIBILITIES. AFR 700-13 states the AF policy and assigns major command responsbilities for the electromagnetic radiation hazards (EMRH) control program. In accordance with AFR 700-13 each major command will establish and maintain procedural guidance to control EMRH and ensure that O&M activities implement these measures. AFOSH Standard 161-9 provides a further breakdown of major command responsibilities and delineates commanders responsibilities. Without question, the EMRH control effected at each C-E facility is the most important part of the program. Therefore, the commanders' responsibilities (per AFOSH Standard 161-9) are restated as follows:

a. Appoints a Radiation Protection Officer (RPO) for rf radiation. Notifies the Bioenvironmental Engineering Section (BES) and the Environmental Health Section (EHS) of this appointment and any subsequent changes. This individual should be a person from the unit who is the most knowledgeable on operational characteristics of the emitters used by the unit and the hazards to personnel from rf radiation. The term "Radiation Protection Officer" is a functional title and is not intended to denote a commissioned status or a job classification.

b. Makes sure that unit operating instructions (OIs) are published which identify the location of all fixed emitters of rf radiation, approved areas where mobile rf radiation emitters (such as aircraft and communications systems) can be operated and maintained, and control procedures to limit personnel access to potentially hazardous areas.

c. Makes sure that incidents involving potential overexposure of personnel are reported and investigated as required by AFOSH Standard 161-9 and AFR 127-4.

d. Makes sure that periodic training is given workers about unit rf radiation sources, safety procedures, and actions to be taken in the event of an accidental overexposure. Advice and assistance on health effects can be obtained from the Environmental Health Section (EHS) of the supporting medical facility.

e. Tells BES personnel of changes which could alter the existing rf radiation environment.

f. Makes sure that BES personnel are given the technical support needed to investigate suspected or alleged rf radiation overexposures from emitters within his or her organization.

CHAPTER 2

EMRH CONTROL

2-1. GENERAL. A systematic approach to EMRH control is essential due to the nature of the hazard. Personnel can expose themselves, fuel, or EEDs to electromagnetic energy exceeding the safe level without being aware that the energy is present. Therefore, a local program must be developed which will ensure that all hazards are identified and their boundaries defined; guidance must be provided on the safe operation of equipment, the safe handling of fuel/EEDs, and personnel access to hazardous areas. The primary responsibility for this program lies with the base or site commander.

2-2. LOCAL EMRH CONTROL PROGRAM. To have an effective control program a focal point at each unit is required to:

a. Ascertain which, if any, of the unit's transmitters are a potential hazard to personnel, fuel and/or EEDs. (Contact local BEE and/or other support activities for this information.)

b. Make contact with the support activities for consultation, studies, surveys, radiation hazard drawings, etc.

c. Develop an Operating Instruction (OI) for the Unit.

d. Ensure that the areas designated hazardous to personnel are properly posted.

e. Ensure adherence to the recommended operational restrictions and maintenance procedures.

f. Disseminate information to O&M personnel.

g. Coordinate training through briefings, training films, etc.

h. Ensure that Communications-Electronics Facility Records (CEFR) contain current data.

The base or site commander shall officially task each unit operating rf transmitters to designate a radiation protection officer (RPO) to act as this focal point. At bases having several unit RPOs, a lead individual should be appointed. This would allow standardization, coordination of support requests, consolidated training, etc.

2-3. PROGRAM IMPLEMENTATION. It is the responsibility of supervisors and field personnel to implement the control program. This will require close coordination with the RPO and BEE and adherence to all applicable guidance (OI, AFOSH Standard 161-9, AFOSH Standard 127-38, AFR 127-100, AFR 127-101, etc). In general, supervisors and field personnel will:

a. Follow health and safety guidance. Rf protective garments will not be worn by individuals working in rf radiation fields without specific approval of the Air Force Medical Service Center, Director of Professional Services (AFMSC/SGPA).

b. Ascertain that interlock mechanisms are properly maintained and operated.

c. Ensure that personnel know the location of all areas that contain rf energy in excess of permissable exposure levels (PEL).

d. Ensure that sufficient warning signs are posted to delineate rf hazard areas.

e. Maintain written, up-to-date accident reporting and operating procedures that provide acceptable personnel protection.

f. Before energizing aircraft radar systems on the flight line for maintenance:

(1) Delineate the perimeter of the radiation area exceeding the PEL by placing appropriate rf warning signs at points where they will be conspicuous from any direction of approach.

(2) Make sure all personnel are clear of the hazardous radiation pattern. During activation of the system, the radiation area must be under constant visual observation. Activation must be immediately terminated when any individual enters the controlled radiation area. The hazardous radiation pattern must not encompass inhabited structures or other positions containing personnel unless monitors are positioned at each access point to prevent entry during operation of the transmitter or unless surveys indicate these positions are not in excess of the PEL. For nighttime operations, the radiation area must be sufficiently illuminated to insure full visual observation and control of the hazardous area.

(3) Activation of aircraft radar systems during routine checkout procedures will be accomplished only when the entire radiation area containing power densities exceeding the PEL is under visual observation by an aircrew member and no personnel are located within this area. Activation must be immediately terminated when any individual enters the radiation area. Equipment technical manuals should be consulted for determination of the extent of the radiation area.

g. Ensure that personnel engaged in fuel or EED handling are aware of the potential rf hazards and that proper safety precautions are observed.

h. Maintain effective controls to prevent rf overexposure from rf emitters in avionic repair and test facilities. Rf emitters shall be operated into dummy loads unless testing requires actual radiation through an antenna. (Dummy loads are devices designed to absorb most of the emitted power thus the immediate areas are free from significant rf power levels.) Their effectiveness should be evaluated by medical personnel observing their use and surveying the area with an appropriate instrument. When the system requires radiation through an antenna, the evaluation should be similar to that of the aircraft mounted system and must include a careful evaluation for possible reflections and scattering within the shop area. Also, an inspection is necessary to make certain that the area in front of any radiating antenna that contains rf levels in excess of the PELs is restricted to personnel and vehicles.

i. Technical Manuals for each emitter being used should be reviewed for the presence and adequacy of warning to personnel regarding radio frequency hazards. If they are found to be inadequate, Air Force personnel shall submit their recommendations on an AFTO Form 22 (Technical Order System Publication Improvement Report and Reply) in accordance with Section VI of T.O. 00-5-1. Army personnel should use DA Form 2028 (Recommended Changes to Publications) and forward it to Commander, U.S. Army Communications Command, Attn: CC-OPS-PP, Fort Huachuca, AZ 85613.

2-4. SUPPORT ACTIVITIES AND RESPONSIBILITIES. Safe operation of electronic equipment depends on accurate information on EMRH. O&M personnel must know if and where safe power density levels are exceeded. This can be determined by theoretical calculations and by actual measurements. The need for accuracy dictates that both prediction and measurement of EMRH be accomplished by trained, experienced personnel. AFR 100-6 assigns supporting roles to several organizations to ensure that the O&M personnel have ready access to the information/assistance required to develop and maintain an effective EMRH control program. The appropriate organization to contact depends on the specific need. Table 2-1 categorizes the type support required and indicates the organization to be contacted. Field personnel are encouraged to contact any of these organizations for information on EMRH.

a. The Air Force Communications Command (AFCC) provides a consultive and measurement service for rf hazards to personnel, fuel and EEDs. They also provide radiation hazard C-E facility drawings. Specific responsibilities within AFCC are specified in AFCC Supplement 1 to AFR 700-13.

b. The USAF Occupational and Environmental Health Laboratory (OEHL) provides consultative and measurement service for rf and X-ray hazards to personnel. These services are extended to the field through the base Bioenvironmental Engineer (BEE). (See AFOSH Standard 161-9 for more detailed information.)

c. The Aeronautical System Division (ASD) of the Air Force Systems Command (AFSC) provides a consultative service for rf hazards to fuel and EEDs.

2-5. OPERATING INSTRUCTION (OI). An OI is required to ensure that no oversight occurs in implementing the local EMRH control program. The OI must contain basic information that pertains to all situations. Assistance in developing the OI is available (see Table 2-1). The format must comply with AFR 5-8 requirements for Air Force units. See Appendix A for an example of a Radiation Hazard Control OI.

a. The following is essential information that must be in the unit OI:

(1) Guidance on visitor control.

(2) Instructions on reporting suspected personnel overexposures or accidents.

(3) List of documents for EMRH information/guidance including: AFR 700-13, AFR 127-100, AFOSH Standard 161-9, AFOSH Standard 127-38, and T.O. 31Z-10-4.

(4) O&M training requirements.

(5) The requirements for posting hazardous areas.

(6) The current name and phone numbers of RPO, BEE, etc. If these are subject to frequent change then a separate attachment may be used to simplify changes to the OI.

(7) The requirements for rf hazard drawings (CEFR).

b. Attachments should be made to the OI to outline those facilities that have rf emitters that have been identified by the BEE to be hazardous or potentially hazardous. The attachment should contain the following minimum information:

(1) The name of the applicable facility.

(2) The transmitters and/or equipment ascertained to be hazardous or potentially hazardous must be identified. That equipment which has been determined to be non-hazardous can be listed on a separate attachment in an abbreviated format.

(3) The types of hazards, e.g., x-ray to personnel, rf to personnel, fuel, or EEDs, etc.

(4) Special O&M procedures/restrictions.

2-6. REQUIRED ATTACHMENT TO THE OPERATING INSTRUCTION. An example of an attachment to an OI for a hypothetical radar facility is contained in Appendix A and is intended as a guide in the preparation of the required attachment. Some facilities (such as mobile transmitters, maintenance shops, flight lines, etc.) may present unique problems.

2-7. CEFR DOCUMENTATION OF RADIATION HAZARDS.

a. The existence or non-existence of EMRH at a facility shall be documented in the C-E facility records. This documentation can be obtained from either the local BEE or OEHL (for rf & X-ray hazards to personnel) or AFCC (for rf hazards to personnel, fuel and EEDs). The non-existence of a hazard may be documented by letter from the BEE, OEHL, or AFCC. The existence of a hazard shall be documented by either a study or survey.

b. An "RF HAZARD STUDY" (theoretical hazard distance obtained by calculations based on equipment parameters) provides the information required for siting new equipment and safe operation of new or existing equipment. AFOSH Standard 161-9 requires that an "RF HAZARD SURVEY" (field measurements of hazards) be accomplished on all emitters which have been catagorized as being potentially hazardous to personnel. However, if the safe operating conditions provided by the study do not cause significant operational restrictions or inconvenience for fuel/EED handling, then a survey for these hazards may not be required. The hazard predictions depend soley on the equipment parameters used for calculations and any siting anomolies taken into consideration. The customer should provide the equipment parameters (power, frequency, antenna gain, etc) and any pertinent siting information (antenna height above ground, proximity of other structures, etc). The report will then show the hazards during normal operation as well as the "worst case" hazards. Otherwise only the parameters creating the worst case hazard situation can be used. The distances/restrictions of a study may be reduced or eliminated by a survey. A guide by which AFCC accomplishes an rf radiation hazard study is provided as Appendix B to this manual.

c. An "RF HAZARD SURVEY" (field measurements of hazards) provides the information required for safe operation of equipment. Measurements provide the most accurate information possible to define hazardous areas and allow minimal operational restrictions. The results of an EMRH survey are published in a report. The hazard distances are first calculated from equipment parameters to allow formulation of a safe procedure to accomplish the measurements. Close cooperation between O&M personnel and the survey team is required to accomplish the task with minimal impact on operations and to insure accuracy and completeness of the survey. A guide by which AFCC accomplishes an rf radiation hazard survey is provided as Appendix C.

d. In accomplishing either a study or survey a decision must be made on the requirement for an "RF HAZARD DRAWING." If required, these drawings will be furnished by AFCC and will be retained in the C-E facility records.

e. Studies, surveys and RF HAZARD DRAWINGS shall be reviewed upon any change to hazard criteria and when any change is made to the facility/site which might affect hazard control. If the current criteria/site conditions are not reflected then a request for reaccomplishment should be submitted.

Table 2-1. Hazards Support Activities

TYPE OF SUPPORT REQUIRED	AFCC					OEHL	BEE	ASD
	EID	1842 EEG	485 EIG	1843 EIG	1839 EIG			
Assistance in Developing OI	X	X	X	X	X	X	X	
Obtaining RF Hazard Drawings	X		X	X				
Consultation/Studies/Measurements for RF Hazards to Personnel, Fuel, and EEDs	X	X	X	X	X			
Consultation/Studies/Measurements for RF, X-ray, and Radioactive Hazards to Personnel						X	X	
Consultation on RF Hazards to Fuel and EEDs								X

Addresses and Phone Numbers:

EID/EIEUS, Oklahoma AFS, OK 73145, AV 884-9564

1842 EEG/EEITE, Scott AFB, IL 62225, AV 576-5596

485 EIG/EIEUS, Griffiss AFB, NY 13441, AV 587-3514

1843 EIG/EIEM, Hickam AFB, HI 96853, AV 449-5671

1839 EIG/EIEE, Keesler AFB, MS 39534, AV 868-3920

OEHL/RZ, Brooks AFB, TX 78235, AV 240-3486

BEE - Contact Medical Facility at nearest Support Base.

ASD/ENACE, Wright-Patterson AFB, OH 45433, AV 785-5078

Note: Office symbols and telephone numbers should be frequently verified.

CHAPTER 3

RF HAZARDS

SECTION I - PERSONNEL HAZARDS

3-1. GENERAL.

a. The ever increasing application of higher powered systems that generate rf (10 kHz to 300 GHz) radiation requires continuous vigilance and study so that personnel exposure criteria and limits remain consistent with, and reflect current knowledge of, the biological effects of rf radiation. Personnel exposure levels (PELs) for average size adults and small size humans are established in AFOSH Standard 161-9 which contains guidelines for the protection of personnel working with, or in the vicinity of rf radiation emitters. These PELs, along with guidelines for their use, are shown in table 3-1.

b. Ongoing rf bioeffects studies may suggest changes in personnel exposure criteria and will form the basis for subsequent revisions of AFOSH Standard 161-9. Such studies include investigation of the effect of frequency, exposure geometry, hot spots, and subject aperture on energy transfer and distribution; defining more meaningful biological indicators for assessing the state of health of individuals exposed to rf (other than temperature rise); development and validation of suitable models to extrapolate animal data to man; as well as scaling exposure frequencies and power densities to account for size differences between animal and man.

c. The fact that heating is associated with absorption of rf power was known nearly 50 years ago and led to the introduction of rf diathermy. The assumption is made that heat from rf field interactions simply adds to metabolic heat load and is dissipated by thermal transfer to blood and lymph, circulation through the skin and respiratory tract, evaporation of sweat from the skin or, in the case of lower mammals, by bronchial secretions. The biologic factors of increased temperature are mainly those related to the ability of the body to rid itself of excess heat. If heat gain exceeds heat loss, the body temperature rises, when heat loss predominates, normal temperature is restored. Therefore, if significant rf power is absorbed one could expect an increase in body temperature which could have a competing effect on metabolic processes with potentially deleterious effects.

d. Radio frequency radiation photons typically present in the environment are low in energy and therefore incapable of causing ionization as in classical radio biological experiments with X-rays or gamma rays.

3-2. ABSORPTION OF RADIO FREQUENCY RADIATION.

a. Most of the effects in biological systems are produced by changes in the vibrational energies of components in solution. Since living organisms are made up of 60 to 80 percent water, the energy transfer to water and ions probably accounts for most of the energy absorbed in biological systems. The electric field is attenuated by the high dielectric of the biological media resulting in lower internal E-fields. The magnetic fields, on the other hand, penetrate essentially without attenuation, so that E/H ratios internally may vary widely depending on the magnitude of magnetically induced electric fields and eddy currents.

b. Energy deposition in tissue is principally frequency dependent, and because of multiple interactions within different body structures in man, become very complex. Higher frequencies cause larger thermal deposition per unit penetration length and have shorter distances of penetration. At frequencies where man is much smaller than a wave-length (for example, in the hf band), a quasistatic approximation can be used to predict fields in man and predict total power deposited. In spheres or ellipsoid models of man, it has been demonstrated that the magnetic component of the incident field can be important in power deposition. Magnetic interactions at low frequencies are almost completely from eddy currents.

3-3. BIOLOGICAL EFFECTS.

a. The thermal burden of an rf field requires the same physiological adjustments to heat as any other thermal burden. Since the rf-induced burden adds to other thermal burdens, the precise response of the person depends on the temperature and the effective heat capacity of the surrounding environment (wind velocity and relative humidity), thermal conductivity of clothing, and infrared radiance in the immediate surroundings.

WARNING

Although overexposure causes a thermal burden you cannot rely on a "sense of warmth" to warn that the safe rf energy level has been exceeded.

b. As stated in paragragh 3-1b many other aspects of exposure to rf energy are under study. The long-term exposure to low-level rf energy is also under investigation. This section will be updated to reflect any biological effect substantiated by research.

3-4. OPTHALMOLOGICAL CONSIDERATIONS. Population surveys and other research indicate that where the current permissible exposure level is not exceeded, cataracts are not a major problem. The eyes are less able to cope with a thermal burden due to the relatively small blood circulation. Avoid looking into the open end of a waveguide or exposing the eyes to other sources of rf energy exceeding the safe criteria.

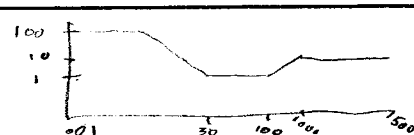
3-5. INDIRECT BIOLOGICAL EFFECTS. The interaction of any radio frequency radiation field and electronic medical prosthetic device such as a cardiac pacemaker can result in an adverse biological effect and should be avoided where possible. In the specific case of the cardiac pacemaker, extensive tests have been conducted to establish the types and extent of rf interference possible from a multitude of sources. Current technology allows production of pacemakers with thresholds above 200 V/m and most manufacturers have voluntarily produced such electromagnetic interference (EMI) insensitive pacemakers. The voluntary nature of this hardening continues to justify the need for statuatory requirements such as those the Air Force has recommended to the Department of Health and Human Services/Food and Drug Administration (DHHS/FDA) — that manufacturers design and test all such prosthetic devices to operate safely up to a pulsed E-field level of 200 V/m (rms). Very few Air Force systems exceed this level for sufficient time to adversely affect pacemakers in areas normally accessible to the general public. Refer to AFOSH Standard 161-9 for risk distance application.

3-6. ELECTROMAGNETIC PULSE. Nuclear explosions generally produce a short, intense electromagnetic pulse (EMP) which, depending on altitude can radiate over hundreds of miles. Large voltages and currents can be induced into conductors exposed to EMP. The Air Force

EMP medical surveillance program has not demonstrated that human exposure to EMP results in any adverse effects. All available data indicates that no acute or chronic biological effects can be assigned to EMP exposure. Tentative limits are established in AFOSH Standard 161-9 as a precautionary measure.

Table 3-1. Maximum Permissible Exposure Levels (PELs) for Human Exposure to Radio Frequency Radiation (Averaged over any Six-Minute Period)

Frequency From (MHz)	TO (MHz)	PEL for Average Size Adult (mW/cm^2)	PEL for Small Size Human (mW/cm^2)
.01	3	100	100
3	30	$900/f^2$	$900/f^2$
30	100	1	1
100	300	f/100	1
300	1000	f/100	f/300
1000	1500	10	f/300
1500	300000	10	5



Notes:

1. All exposures must be limited to a maximum (peak) electric field intensity of 100 kilovolts per meter (kV/m).

2. In the equations for PELs, "f" is the operating frequency of the emitter in megahertz.

3. Use the PELs under the heading 'Average Size Adult' for Air Force workers and workplaces. Use the more restrictive PELs under the heading 'Small Size Human' when assessing potential hazards in areas where the public has unrestricted access.

4. A small size human is an individual less than 55 inches tall.

5. When exposure is to multiple-frequency radiation, the sum of the fractions of the PELs at the separate frequencies must not exceed unity.

6. When an rf emitter operates over a band of frequencies in which the PEL varies such as between 3 and 30 MHz, the lowest PEL shall apply.

SECTION II - FUEL HAZARDS

3-7. GENERAL. Fuel vapors can be ignited by an arc induced by a strong rf field: therefore, the potential hazard of any fuel handling operation near an rf source must be addressed. The existance and extent of a fuel hazard is determined by comparing the actual rf energy level to the safety criteria. Precautionary measures must be taken to preclude any fuel handling within the area that has been determined hazardous.

3-8. FACTORS NECESSARY FOR COMBUSTION. In order for fuel vapor to be ignited by a spark, the following conditions are necessary:

a. The presence of a fuel vapor-air mixture which is between the upper and lower limits of flammability.

b. A spark of sufficient energy across a gap having a certain minimum spacing called the "minimum quenching distance."

3-9. IGNITION OF FUEL BY RADIATED RF ENERGY.

a. Rf energy can induce currents into any metal object. The amount of current and thus the strength of a spark across a gap between two conductors depends on both the field intensity of the rf energy and how well the conductors act as a "receiving antenna." Many parts of an aircraft, refueling vehicle and/or the static grounding conductors can act as receiving antennas. The induced current depends mainly on the conductor length, in relation to the wavelength of the rf energy and the orientation in the radiated field. It is not feasible to predict nor control these factors. The hazard criteria must then be based on the assumption that an ideal receiving antenna could be inadvertently created with the required spark gap.

b. Personnel should be constantly alert to the fact that electronic transmitting equipment can cause hazardous voltages to be induced in various fuel-handling equipments, metal structures, and aircraft which are in the same plane as the radiating source. For maximum safety, the recommended safe minimum separation distances for fuel handling operations, as obtained from published data should be observed at all times.

WARNING

T.O. 00-25-172 provides safety guidance to control other hazards encountered in operating a transmitter near fuel.

3-10. FUEL HAZARD CRITERION.

a. Areas in which the peak power density exceeds 5 watts/cm^2 (Refer to AFOSH Standard 127-38 for current criteria) shall be considered hazardous areas for refueling operations regardless of the source of rf energy. Hazards could result from the installation of higher-powered equipment at operational facilities that were previously considered safe. They could also arise when a mobile version of a radar set is sited near refueling facilities, or when airborne radar equipment is energized during ground checks in proximity to refueling operations. Moreover, the use of radar sets equipped with antennas to provide lower beam angles for approach and guidance control will also present problems not normally encountered with tower-mounted ground radar systems.

NOTE

For a given transmitter the fuel hazard criteron can be expressed in terms of average power. See paragraph 6-5.

b. The use of theoretical calculations together with a consideration of antenna radiation patterns may be sufficient to determine fuel hazard areas. However, the final decision should be based on actual field measurements which take into consideration the possible existence of reflections. If measured data is not available, then theoretical "far field" calculations corrected for "near field" effect (as outlined in Chapter 6) should be used as an interim measure to determine hazardous areas in which a peak power density of 5 watts/cm^2 can occur.

3-11. FUEL HAZARD PREVENTION.

a. The location of facilities for personnel housing, fuel storage and handling, ordnance storage and handling (including missiles) with respect to nearby communications-electronic equipment and the associated rf propagation should be given extensive study during the site planning phase. Planned utilization of shielding offered by natural terrain features often eliminates the need for large tracts of expensive real estate which would otherwise be required in order to obtain satisfactory separation of facilities. The minimum separation distances can be less when the terrain features "shade" the facilities from direct illumination by the radar beam or when the facilities lie below the beam.

b. Siting criteria for various types of communications-electronic facilities may be found by reference to Air Force T.O.'s 31-1-16 and 31R-10-3.

3-12. SAFETY MEASURES. Strict safety control measures must be observed when operating a radar capable of producing a fuel hazard to an adjacent or nearby fuel handling area. Each operational facility will require individual study to determine the operational procedures that should be used and the safety devices that should be installed to permit fuel handling in complete safety. Some typical situations and precautions are:

a. Where sufficient seperation allows normal operation of the transmitter, some precautions are still required.

(1) Transmitter power shall not be increased above normal without considering the increased hazard distance.

(2) The transmitter shall not be operated when the antenna is below normal tilt without considering the change in hazard area.

(3) No refueling of lawn mowers, vehicles, etc, shall be permitted within the hazard area.

b. Where restrictions on the transmitter operation (sector blanking or limiting, antenna elevation limiting, reduced power, etc) are required this information must be in an OI and all concerned shall be made aware of it.

c. Where the transmitter is not allowed to operate during fuel handling and vice versa there must be a checklist type procedure and close coordination.

d. Flight line operations require strict control to ensure that all fuel handling operations are completely safe. Both fuel handlers and transmitter operators must be aware of the restrictions.

WARNING

There is a special case where a fuel or weapon rf hazard can exist even though the rf levels are within the safe limits specified. This special case is for both the hand-held (1-5 watts) and mobile 5-50 watts) transceivers. The antennas on these equipments can generate hazardous situations when they are allowed to accidentally touch the aircraft, weapon, or support equipment. To avoid this hazard, transceivers should not be operated any closer than 10 feet from weapons, fuel vents, etc. Local procedures should be established to control the operation of transceivers in hazardous areas (Refer to T.O. 00-25-172 for information on approved explosion proof transceivers for use in refueling operations), and to provide guidance to personnel. The 10-foot distance is based on an average 6-foot individual with a walkie-talkie in his hand who might accidentally stumble. The recommended 10-foot separation distance could be tailored to fit local situations.

SECTION III - ELECTROEXPLOSIVE DEVICE (EED) HAZARDS

3-13. GENERAL. EEDs are small-size pyrotechnic or explosive devices designed to function by the passage of an electric current through them which detonates an explosive charge. Explosives derive their usefulness from the fact that they liberate chemical energy in the form of heat which raises the gaseous products of decomposition to high pressure and temperature. This provides systems which are capable of doing considerable quantities of work by expansion. Among such devices are: primers, detonators, squibs, blasting caps, igniters, initiators, dimple motors, etc. At present, and in the envisaged future, four types of EEDs are employed: Bridgewire (BW), Conducting Composition (CC), Exploding Bridgewire (EBW), and Carbon Bridge (CB). The basic EED is the squib, and this is the term which will be used throughout this section as a general term to include all types of EEDs, without regard to its technical application to ordnance items.

3-14. TYPICAL ELECTRIC SQUIB. The squib is the medium by which an electrical signal causes a flammable material to ignite. A typical electric squib is illustrated in figure 3-1. It is a simple device consisting of the flammable material in contact with an electrical tranducer. It comes in numerous shapes and sizes, but all consist of four main components: the electrical leads, a filament or bridge across the leads, the explosive material, and, the cylinder of metal in which these are enclosed. Generally, a heat-sensitive initiating bead located on the filament or between the ends of the two leadwires constitutes the bridge. The heat-sensitive bead is generally a matchhead composition of potassium chlorate, antimony sulfide, and dextrin. The designer of a system using such devices is bound by certain limitations. He must provide that the squib will not be activated prematurely or unintentionally, especially by stray or spurious currents. On the other hand, the system cannot be so stable that it will make intentional activation difficult, impossible, or lengthy. A recent tendency has been to minimize the use of the term "squib" and to use "primer" instead, for the basic electroexplosive activating device. The reason for this is that almost all EEDs contain some primer or booster charge.

3-15. FIRING CURRENT.

a. The current sensitivity of the squib is related to the resistance (per unit length and cross-section) of the bridgewire, the voltage and the ignition temperature of the matchhead composition ignition bead. These variables will differ even when squibs are of the same design and composition. The bridgewire is usually an alloy of two or more metals combined to produce the desired resistance and thermal characteristics. Metals commonly used for this purpose are nickel, chromium, iron, platinum, iridium, and copper. The resistance of a typical bridgewire designed for ordnance application may be only a fraction of an ohm to several ohms. The resistance of the filament or bridge changes the electrical energy to heat, causing the heat-sensitive bead to ignite. The whole process takes milliseconds to complete.

b. Another consideration is the characteristics of the ingredients chosen to form the ignition bead relative to the temperature at which ignition of the powder grains will occur. The thermal action of the resistance wire forming the bridgewire introduces a time delay in the ignition process. In general, the time delay decreases as the firing current is increased above the minimum firing value. For example, if a firing current of 0.5 ampere is applied to a certain type of squib at an ambient temperature of 70°F, the time delay before an explosion occurs is approximately 27 microseconds, whereas the same squib at a firing current of 1.0 amperes has a time delay of only 9 microseconds.

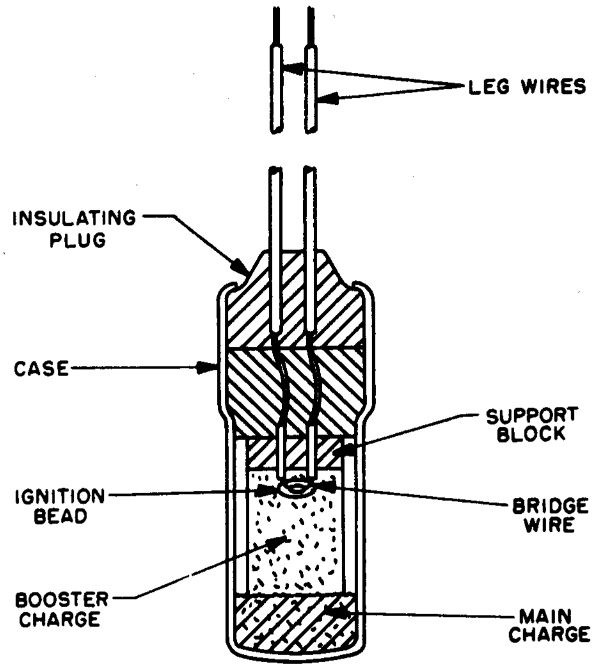


Figure 3-1. Typical Electric Squib.

c. Values of minimum firing current may vary as much as ± 10 percent for a given type of squib. Also, a current which is below the minimum firing value may be passed through the bridgewire for several minutes before sufficient heat is developed to fire the ignition bead, if it fires at all. The highest amperage at which none of the squibs is activated is called the "no-fire" current; the lowest amperage which will energize all the squibs is the "all-fire" current. In practice, the current sensitivity of a squib is decreased by placing a "shunt" in parallel with the bridgewire between the external leg wire of the squib. The shunt may merely consist of a piece of metal foil wrapped around bared sections of the leg wires. The addition of the shunt makes it necessary to use a higher firing current to detonate the squib. Also, since the shunt is in parallel with the bridgewire, the effects of static electricity are almost completely offset because static discharge currents are shunted around the bridgewire. However, the placement of the shunt in the leg wires of the firing circuit may be critical with respect to the higher radio frequencies, therefore, the use of a shunt does not rule out the possibility that rf energy may fire the squib.

3-16. BASIC FIRING CIRCUIT. The basic firing circuit for a squib consists of a firing switch in series with the voltage source used to supply the necessary current to the bridgewire. The firing circuit includes all electrical circuits and components between the trigger circuit initiation power source and the electroexplosive element of the squib. It is the wiring of the external firing circuit that presents the greatest problem with regard to a possible rf radiation hazard. To deny access of stray energy to squibs, and for a sound electroexplosive subsystem, the following is necessary:

a. Firing circuits should be isolated from other circuits and from each other, by means of individual shields. Individually shielded firing circuits may be routed together in a common secondary shield.

b. Trigger-circuit-firing shields should be grounded to the vehicle only at the initiator casing. The shield should have no discontinuities or gaps, and good electrical contact of the initiator case with the vehicle into which it is assembled should be insured.

c. Static discharge resistors may be connected in parallel across the firing circuit as close to the bridgewire as possible. Such a resistor provides a path of high resistance to firing-currents, through which any accumulation of static charges can be dissipated.

d. Firing-circuit wiring should be kept to a minimum.

e. All conductors that connect the firing circuit with other weapon components, should be shielded.

f. Carefully designed and tested rf attenuating filter elements should be used to protect against nearby sources of rf energy, such as airborne radar beacons, telemetry transmitters, very high power ground radars, etc. Temperature rise of the filter due to dissipation of rf energy should be isolated from the squib.

g. The firing-circuit wiring should be twisted in order to maintain electrical balance and reduce induction.

h. The trigger circuit should be in a completely shielded case and located as close to the initiator as possible.

i. The trigger-circuit interface should be designed to preclude actuation by a false signal from internal or external stray electrical energy. Extreme care must be exercised on any electroexplosive subsystem that does not meet the criteria listed above.

3-17. RF IGNITION OF SQUIBS.

a. Military and commercial electric squibs are susceptible to detonation by rf currents. The accidental firing of electroexplosive devices by rf energy is not a new problem. Commercial manufacturers of blasting caps have warned their customers for many years about the potential hazard involved in using electrically fired blasting caps in the vicinity of radio transmitters.

b. The response of a squib to an rf energy field and the possibility of detonation depend on many factors, such as the average power output and frequency of radiation from communications-electronic equipment in the vicinity, the polarization of the rf energy field with respect to the plane of the firing circuit leads, antenna propagation characteristics, physical separation distance between antenna and firing circuit lead wires, type and configuration of firing circuits (as they may affect resonance and govern induced currents), shielding of the squib, and the thermal time-constant of the bridgewire. The typical squib tends to become less sensitive to rf energy as the frequency increases.

c. Sufficient rf energy can be induced to raise the temperature of the explosive in contact with the wire to a point where its physical conditions are modified. It is also possible to burn out the bridgewire with power insufficient to initiate the device. This phenomenon, known as "dudding" is generally restricted to the exploding bridgewire type device and is undesirable from a reliability standpoint.

d. Because of the tactical uses and nature of ordnance items in which the squib is a necessary part, an accidental firing due to rf ignition could have serious consequences. Therefore, until such time as thorough investigation of the problem reveals otherwise, it must be assumed that a hazardous condition exists whenever a squib device is exposed to a high-intensity rf field. To insure against inadvertent activation, stray current checks must be made of circuits into which EEDs are to be inserted, immediately before such installation.

3-18. EED HAZARD CRITERION AND SAFETY PRECAUTIONS.

a. The safe power density for EEDs is dependent upon the exposure, frequency, and maximum no-fire sensitivity of the squib involved. Refer to AFR 127-100, Explosives Safety Standards, Chapter 6, for current criteria information.

b. The following safety rules shall be followed when working with squibs:

(1) Only qualified and authorized personnel shall handle, install, remove, or dispose of squibs.

(2) Squibs shall not be stored, handled, or installed without proper electromagnetic shielding. Squibs shall be left in their containers until ready for installation. The criteria given in Chapter 6 of AFR 127-100 shall be used as a guide in maintaining safe distance between the squib and a transmitting antenna.

(3) Squib leads shall be twisted, shielded wire, with the shield grounded. Leads shall not be untwisted into a loop, resonant dipole, or other effective type of antenna configuration.

(4) Firing leads shall be routed separately and isolated from electric power cables and rf transmission lines. During storage and handling, lead wires shall be shorted together.

(5) Filament shunts, clips, or other short-circuiting devices in use, shall not be removed except for continuity testing or when the squib is ready for immediate installation.

(6) Squibs shall be left in their containers until immediately before they are to be installed. They shall be stored in accordance with AFR 127-100. Only approved containers shall be used for transporting, storing, and testing these devices.

(7) Immediately before installation, a stray current check shall be made of the circuit into which the squib is to be inserted.

(8) Squib parts shall not be rubbed or polished. Lightning protection devices and grounding equipment should be used to eliminate static electricity. Outdoor activities shall be curtailed during an electrical storm or when one is eminent.

(9) Only prescribed testing devices and procedures shall be used on squibs or circuits in which they are installed. They should be tested only in designated areas by trained, authorized personnel using prescribed equipment.

(10) Electrical connections shall not be made to a squib in a system using an indicator-type safe and arm unless the indicator shows the device is in the safe position.

(11) Squibs should not be dropped, thrown about, or handled in any manner that will damage them or cause their accidental activation. They shall not be carried in pockets, tool boxes, or similar unprotected places.

(12) Squibs shall be kept away from open flame, prolonged direct sunlight, and heating and electrical equipment.

(13) Nonessential personnel shall not be permitted in areas where a squib is being installed.

(14) Deteriorated or expended squibs shall be disposed of as prescribed in applicable regulations and directives.

WARNING

There is a special case where a fuel or weapon rf hazard can exist even though the rf levels are within the safe limits specified. This special case is for both the hand-held (1-5 watts) and mobile (5-50 watts) transceivers. The antennas on these equipments can generate hazardous situations when they are allowed to accidentally touch the aircraft, weapon, or support equipment. To avoid this hazard, transceivers should not be operated any closer than 10 feet from weapons, fuel vents, etc. Local procedures should be established to control the operation of transceivers in hazardous areas (Refer to T.O. 00-25-172 for information on approved explosion proof transceivers for use in refueling operations), and to provide guidance to personnel. The 10-foot distance is based on an average 6-foot individual with a walkie-talkie in his hand who might accidentally stumble. The recommended 10-foot separation distance could be tailored to fit local situations.

CHAPTER 4

X-RAY HAZARDS

4-1. GENERAL. Some C-E equipment does produce X-rays and this potential hazard must be controlled. When invisible X-radiation penetrates the body, it gives no sensation to warn of its presence or to indicate the biological damage which is occurring. Therefore, it is important for the individual to understand how X-rays are generated, to know something about their behavior, to be familiar with the X-ray shielding problem, and to know the dangers of overexposure. Armed with this knowledge, the individual can avoid unsafe situations.

4-2. ELECTROMAGNETIC SPECTRUM.

a. Electromagnetic waves include Hertzian waves (long waves to microwaves) in the low-frequency (long-wavelength) portion of the electromagnetic spectrum and X-rays and gamma rays in the extremely high-frequency (short-wavelength) portion of the spectrum. These electromagnetic radiations are all basically the same in that they travel at the same speed as light.

b. Figure 4-1 illustrates a portion of the electromagnetic spectrum to establish the spectral relationship of X-radiations to other electromagnetic radiations. As the illustration suggests, the frequency and wavelength regions occupied by the various kinds of electromagnetic radiation are not clearly defined, but rather overlap one another to provide a gradual transition from waves of one type to those of another. Thus, the X-ray higher frequencies (shorter wavelengths) overlap and are not easily distinguished from the gamma-ray lower frequencies (longer wavelengths).

c. The electromagnetic spectrum includes a great number of frequencies, or wavelengths. Therefore, it is natural that several convenient units are used to measure wavelength. Wavelength in the radio-frequency spectrum is measured in meters, centimeters, or millimeters; wavelength in the regions near visible light is measured in microns (1 micron equals 10^{-4} centimeter) or angstroms. The angstrom unit (A) is used almost exclusively to express wavelength in the X-ray and gamma-ray regions; 1 angstrom unit is equal to 10^{-8} centimeter.

4-3. PROPERTIES OF X-RAYS.

a. X-rays are electromagnetic waves which are produced in a vacuum tube when high-velocity electrons strike a metal target. The slowing-down process of the electrons is accompanied by a loss of energy, which is given up in the form of heat and a relatively wide band of electromagnetic radiations. These radiations or waves travel at the speed of light, are unaffected by electric or magnetic fields, can be reflected, refracted, and polarized, and can produce fluorescence and phosphorescence.

b. X-rays have an extremely short wavelength, as indicated by the portion of the electromagnetic spectrum illustrated in figure 4-1. The terms "soft" and "hard" are used to designate the penetrating power of an X-ray beam. The harder the radiation (shorter wavelength), the greater its penetrating power. Since electromagnetic waves are classified according to their source or to the method of producing them, the wavelengths of X-rays overlap those of other rays such as gamma radiation. (X-rays are produced by bombarding a metallic target with high-velocity electrons; gamma rays are radiations which originate in the nuclei of atoms.) However, an X-ray and a gamma ray of the same wavelength have identical properties.

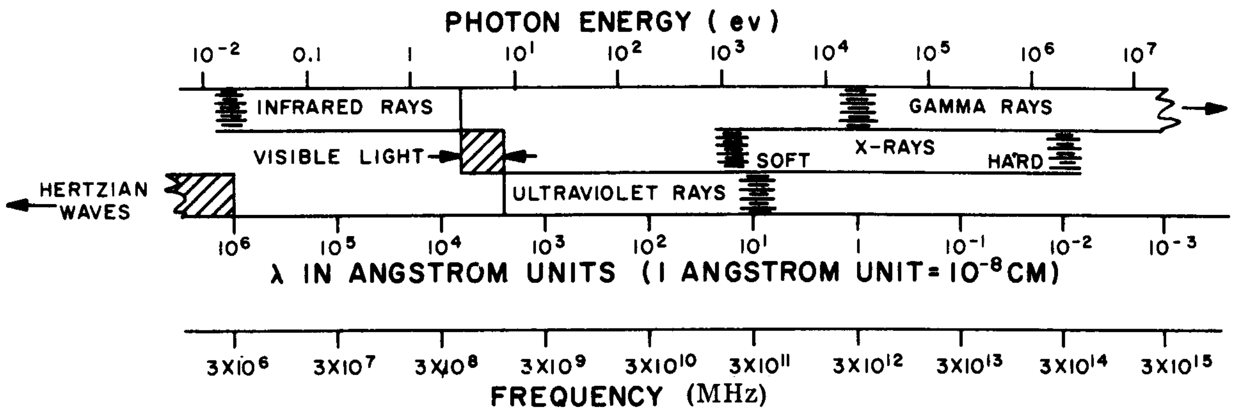


Figure 4-1. Portion of Electromagnetic Spectrum, Showing Relationship of X-Radiation to Other Electromagnetic Radiations

c. Like all electromagnetic radiations, X-rays obey the inverse square law; that is, their intensity decreases as the square of the distance from a point source. One of their most unusual properties is the ability to penetrate solid matter, and this property is commonly used in radiography to reveal the internal structure of normally opaque objects. Another important property of X-rays is their ability to modify, damage, and destroy living tissue; this property makes X-rays useful for medical treatments, but also makes them a hazard when not controlled.

4-4. HIGH-VOLTAGE ELECTRON TUBES AS A SOURCE OF X-RADIATION. X-ray tubes are built for the specific purpose of generating X-rays; however, other types of electron tubes operating under similar conditions can also produce these radiations. Some of these types of tubes, under normal and/or abnormal operating conditions, can and do generate a dangerous amount of X-radiation.

WARNING

In practice, the shielding is designed to attenuate the X-radiation to a level which is well within the permissible levels established by AFR 161-8. Without the radiation shields in place, the intensity of the radiation emitted is extremely dangerous to personnel.

a. Klystron.

(1) A typical high-power klystron is illustrated in figure 4-2. This type of klystron power amplifier operates with anode potentials up to 250 kV and higher. X-radiation occurs with greatest intensity in the region of the collector assembly. The shaded areas shown in figure 4-2 illustrate the general distribution of X-radiation around a typical high-power klystron when it is in operation. Note that the greatest intensity is near the collector assembly, the output cavity, and the elbow bend of the output waveguide. Radiation of lesser intensity occurs along the body of the tube approaching the output cavity and also from the electron gun itself.

(2) X-radiation from the klystron occurs under two conditions: when the tube is in operation and delivering rf power to the load, and when high voltage is present but rf drive is not applied. In the latter condition, the electron beam travels through the tube to the collector, and X-radiation is produced predominantly in the collector region. However, when rf drive is applied to the tube and velocity modulation of the electron beam takes place, some dispersion of the electron beam causes emission from the body cavities of the tube. The increased acceleration of electrons near the output cavity region, caused by the higher-effective voltage developed as a result of the applied dc potential and rf fields, gives rise to the generation of X-radiation of even greater intensity and penetrating power. Under normal operating conditions, the X-radiation measured in the immediate vicinity of the collector assembly may average 800 milliroentgens per hour for a typical klystron. Thus, as can be seen from the illustration in figure 4-2, the klystron must be equipped with radiation shielding made of lead or other suitable material(s) installed over the collector, output cavity and main rf body, and electron gun assembly.

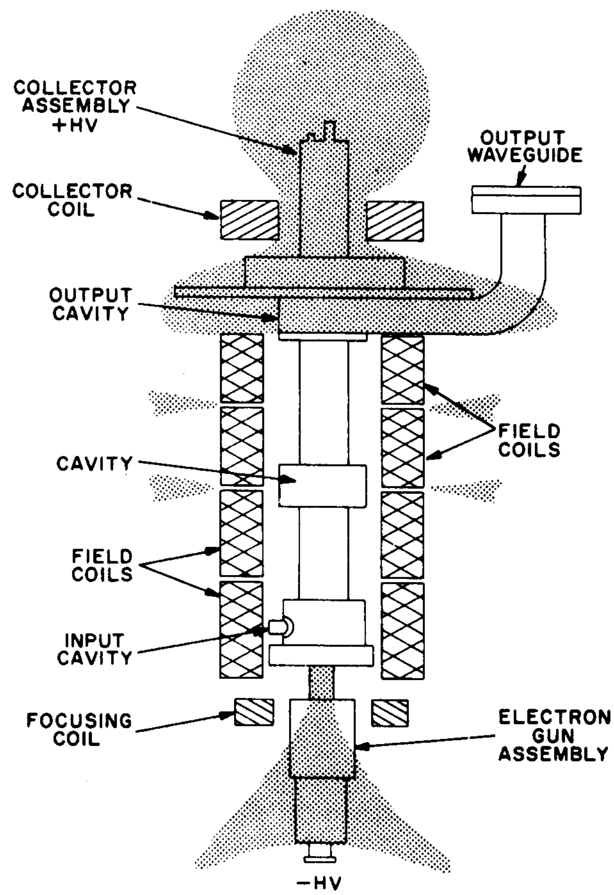


Figure 4-2. X-Radiation Distribution for Typical High-Power Klystron

b. Thyratrons.

(1) Hydrogen thyratrons operating with high anode potentials may also emit X-rays. When thyratrons are used for high-voltage switching applications, as in radar pulse-modulator circuits, they may produce a considerable amount of X-radiation at the beginning of a pulse before the anode voltage drops, and a smaller amount of radiation between pulses. Radiation between pulses is caused, not by cathode electron emission, but by grid emission. The anode is surrounded by the grid structure in a thyratron tube, so that most of the radiation completely surrounds the tube in the form of a very narrow beam, extending outward from the grid-anode region as shown in figure 4-3. It is important to note that with such a narrow radiation beam, as illustrated in figure 4-3, irradiation of personnel could occur at head level and not be detected by a film badge or dosimeter worn at chest level, depending upon the equipment configuration. The intensity of the X-radiation is closely related to the amount of grid emission; therefore, a tube with excessive grid emission may generate X-rays of a much higher intensity than those of a normal tube with little or no grid emission.

(2) A series of investigations has been made concerning the production of ionizing radiation from a number of thyratron tube types. X-radiation from one type hydrogen thyratron, operated with a plate voltage of 30 kV and at a prf of 100 pps, has been measured to be approximately 20 milliroentgens per hour. For the same set of operating conditions, when the prf was increased to 250 pps, the radiation level increased to 360 milliroentgens per hour. Increasing the prf to a still higher rate of 500 pps caused a sharp increase in the measured radiation level to approximately 1200 milliroentgens per hour and, in some cases, to as high as 4800 milliroentgens per hour. Thus, it is seen that for a given set of operating conditions, an increase in prf increases the amount of X-radiation generated by the tube.

(3) Thyratrons can be shielded to prevent radiation from reaching dangerous levels. Equipment cabinets designed with solid steel panels at least 1/16 inch thick, or similar panels with inspection windows of 1/4 inch leaded glass, will attenuate radiation from the typical hydrogen thyratron to an acceptable level as defined by AFR 161-8.

c. Magnetrons, Traveling-Wave Tubes and Other. Magnetrons and traveling-wave tubes operating with high electron-accelerating potentials will also emit X-rays. The internal rf voltage, as well as the dc potential, affects the velocities of the electrons. Like the klystron, most of the radiation occurs near the output of the tube and its associated waveguide. Again, as for klystrons, there is an almost linear relationship between the value of the applied high-voltage potential and the production of X-radiation. Other types of tubes operating above approximately 15 kV, such as high-voltage rectifiers (diode) and cathode-ray tubes, may also emit X-radiation.

4-5. DETECTION OF X-RADIATION.

a. Various devices are used to ascertain the presence of the different types of radiation to which personnel may be exposed and to measure the intensity over a given period of time. However, to date there is no single device which is capable of measuring all types of radiation; as a result, many kinds of devices using several different methods of detection, identification, and measurement have been developed.

b. Almost all radiation detectors are based on one of three basic principles; the exposure of undeveloped photographic film, the ionization of gas within an enclosed chamber, or the liberation of light by certain crystals when excited by radiation. Radiation detectors form an integral part of all radiation monitoring systems devised for either personnel or area monitoring. Several types of portable equipment are available for area monitoring or for testing for the presence of radiation generated by communications-electronic equipment; these include ionization chambers, proportional counters, Geiger-Mueller counters, scintillation detectors, large photographic films, and electroscopes. The Bioenvironmental Engineer (BEE) has the equipment and responsibility for X-ray monitoring.

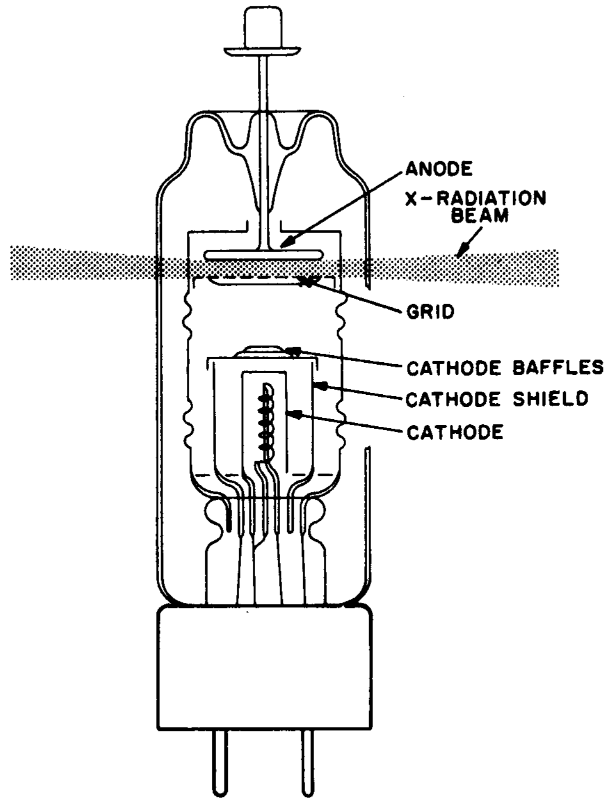


Figure 4-3. X-Radiation Distribution for Typical Hydrogen Thyratron

c. Radiation detectors used for personnel monitoring fall into two general classifications: those which require additional processing to determine the level of exposure and those which are direct reading. The film badge is an example of a detector which requires further processing; the pocket dosimeter (electroscope) is read directly. Neither of these devices are recommended for C-E personnel.

4-6. UNITS OF MEASUREMENT. The roentgen is the basic unit commonly used to indicate a measured quantity of X-rays and gamma rays. Milliroentgen (mR), which is one-thousandth of the basic unit, is frequently used for convenience in expressing small values of ionizing radiation.

4-7. BIOLOGICAL EFFECTS OF IONIZING RADIATION.

a. General.

(1) All X-rays except those of very low photon energy will penetrate human tissue and form positive and negative ions. Depending upon the dosage, these ions may cause tissue damage of either a temporary or permanent nature. The absorption of X-rays gives up energy to matter by the process of ionization. Unless the dosage is extremely high, there will be no noticeable effects for days or weeks or, in some cases, years after the exposure. This delay in the effect is no doubt the most important reason for cases of overdoses of X-rays, since the damage has been done long before the symptoms begin.

(2) Each cell of the body comprising the various tissues and organs is a very small living structural and functional unit, which has a definite life span. The parent cell must grow and divide, producing "daughter" cells, which in turn grow and divide. Radiation produces structural and functional changes in the cells and tissues, depending upon the amount of ionization which has taken place. After exposure of a cell to ionizing radiation, the cell functions may eventually return to normal, just as a normal recovery is made from disease or infection, in which case the biological effects of radiation are said to be "reversible." When the damage results in permanent injury to the cell, the effects are said to be "irreversible."

(3) The effects of ionizing radiation upon the cells may be either direct or indirect, and may be immediate or delayed. Because of the nature of the cell structure of the body, the biological effects may be limited to those cells that receive radiation directly, or because of normal body processes, the effects may be transmitted to other locations within the body. For this reason, elapsed time is a factor and accounts for the fact that biological effects are not immediately apparent.

b. Symptoms of Overexposure.

(1) Ionizing radiation produces biological effects by damaging the cell structure. Many illnesses cause similar cell damage and the body reacts the same regardless of the cause. As indicated in table 4-1 the symptoms vary with the extent of exposure.

(2) Radiation exposure can be described in terms of the part of the body exposed, the total dose received, the dose rate, and the time duration of the exposure. A single exposure to radiation or a series of exposures in a short period of time is considered to be an "acute" exposure, whereas minute continuous exposure over a long period of time is considered to be a "chronic" exposure.

(3) Acute exposure to radiation can cause immediate and delayed biological effects. Chronic exposure usually produces only delayed effects. Delayed effects from radiation exposure are considered to be either "genetic" effects or "somatic" effects. Genetic effects are those effects that control the inherited characteristics of succeeding generations; somatic effects are those effects that pertain to the individual human body, its tissues, organs, and parts, and for the most part are similar to pathological conditions such as leukemia, skin changes, cataracts, sterility, and changes in life span, which can result from other causes. The delayed effects produced by either acute or chronic exposure are similar, but the ability of the human body to repair the damage is usually greater for chronic exposure than for acute exposure. A controlled exposure of 1000 roentgens may be safely applied to a small part of the body for radiation therapy purposes, but 450 roentgens applied to the whole body would most likely produce the symptoms noted in table 4-1, and the individual could have a 50-50 chance of survival. Therefore, the term "radiation dose" must be qualified to indicate whether the whole body or only part of the body was exposed.

Table 4-1. Symptoms and Effects Resulting from Acute Whole-Body Exposure to Radiation

EXPOSURE (ROENTGEN)	SYMPTOMS AND EFFECTS
0–25	No observable reactions. Delayed effects may occur.
25–100	Changes in blood detectable by clinical tests. Disabling sickness not common; individual should be able to continue usual duties. Delayed effects possible, but serious effects on average individual unlikely.
100–200	Produces nausea and fatigue, with possible vomiting above 125 roentgens. Changes in blood detectable by clinical tests. Delayed effects may shorten life expectancy of exposed individual on the order of one percent.
200–300	Produces nausea and vomiting on first day following exposure. Latent period up to 2 weeks or longer, then other symptoms appear, but are not severe. Symptoms are loss of appetite, general illness or discomfort, sore throat, pallor, petechiae (crimson spots in skin or mucous membrane), diarrhea, and moderate emaciation. Recovery is expected in about 3 months unless complicated by poor previous health, additional injuries or infections.
300–600	Produces nausea, vomiting, and diarrhea in first few hours following exposure. Latent period, perhaps as long as 7 days, with no definite symptoms. Symptoms are epilation (loss of hair), loss of appetite, general illness or discomfort, and fever during second week, followed by hemorrhage, petechiae, inflammation of mouth and throat, diarrhea, and emaciation in the third week. Some deaths in 2 to 6 weeks. Possible eventual death of up to 50 percent of the exposed individuals for exposures of 450 roentgens.
600 and over	Produces nausea, vomiting, and diarrhea in first few hours following exposure. Short latent period with no definite symptoms in some cases during first week. Diarrhea, hemorrhage, inflammation of mouth and throat, and fever toward end of first week. Rapid emaciation and death as early as the second week with possible eventual death of up to 100 percent of the exposed individuals.

4-8. MAXIMUM PERMISSIBLE DOSE. The National Committee on Radiation Protection has developed a set of protection rules which define maximum permissible levels of radiation exposure. The term "permissible dose" is generally defined as the dose of ionizing radiation which, in the light of present knowledge, is not expected to cause appreciable injury to an average individual at any time during his normal life span. AFR 161-8 provides information regarding occupational exposure to ionizing radiation. Consult the local BEE for specific guidance.

4-9. X-RAY PROTECTION.

a. X-ray survey data is supplied with all new equipment capable of X-ray production. X-ray measurements are made on the equipment to determine the amount of radiation produced and to verify the adequacy of shielding provided. The latter measurements are repeated periodically in the field by base Bioenvironmental Engineers and should also be conducted anytime a change or modification occurs which could increase or introduce a hazard.

WARNING

In the event that any component used to safeguard personnel from X-radiation (leaded glass inspection windows, shielding, interlocks, etc) is damaged or becomes defective during the installation or operation phase, it shall be replaced with an exact replacement. Following replacement, X-radiation measurements shall be made by qualified personnel, to make certain that the radiation level does not exceed an acceptable level as defined in AFR 161-8. Disregard of this warning may result in a serious accident.

b. Personnel working with high-voltage electron tubes capable of generating X-rays should make certain that the radiation has been checked by qualified medical personnel. Under normal operating conditions, there will very likely be proper shielding for these tubes, but the technician should be aware of the fact that radiation intensity may increase under unusual operating conditions. Personnel should not be permitted to operate any electronic device or tube employing a peak plate voltage of 15 kV or higher with any of the shielding removed from the equipment, except where such operation is conducted following approved health procedures specifically required by a technical manual or following procedures approved by the local BEE.

CHAPTER 5

ASSOCIATED HAZARDS

SECTION I - INFRARED HAZARDS

5-1. INFRARED SPECTRUM.

a. Infrared radiation is a form of electromagnetic radiation. Its spectrum lies between the microwave portion of the electromagnetic spectrum and visible light. The infrared spectrum is frequently divided into three arbitrary bands: near infrared (near visible light), middle infrared, and far infrared.

b. Wavelength in the radio-frequency spectrum is measured in meters, centimeters, or millimeters; and in the regions near visible light, as microns (1 micron equals 10^{-4} centimeter) or angstroms. It is generally found more convenient to express wavelength in the infrared region in terms of the micron. The near infrared band wavelengths are 0.75 to 3 microns, the middle infrared band wavelengths are from 30 to approximately 1000 microns.

c. Figure 5-1 illustrates a portion of the electromagnetic spectrum to establish the spectral relationship of infrared radiation to other electromagnetic radiations. As the illustration suggests, the far infrared region is not clearly defined, but in recent years the development of improved infrared detectors has enabled measurements to be extended into the longer wavelength far infrared region of 900 to 1100 microns.

d. A characteristic of the infrared portion of the electromagnetic spectrum permits the waves to be readily absorbed and the energy converted into heat. It behaves as do radio or light waves and is transmitted in the same manner through air or vacuum. Infrared radiation can be refracted and reflected according to the laws of optics, since infrared and visible light are of the same nature. The fact that infrared radiation is readily converted into thermal energy when it strikes an object distinguishes it from other types of electromagnetic radiation.

5-2. PASSIVE AND ACTIVE INFRARED SYSTEMS.

a. Passive infrared systems are systems that function to detect infrared radiation emitted by objects (targets). Active infrared systems function in a manner similar to radar, in that an infrared source generates and radiates energy which is reflected from objects and is then detected. The active infrared system represents the greatest hazard to personnel, since the infrared source generally produces a searchlight type of beam, which is filtered to remove any radiation in the form of visible light.

b. Passive and active infrared systems are employed for tactical communications, beacons, reconnaissance, surveillance, recognition, navigation, airborne proximity warning, direction finding, tracking, homing, fire control, bombing, and missile guidance, to name a few of the military applications. Infrared is also used in the fields of photography, chemistry, astronomy, criminology, physiotherapy, and has many industrial applications.

5-3. RADIATION HAZARDS TO PERSONNEL. The human eye is susceptible to damage by infrared energy, since the energy may cause the development of cataracts or opacities. Infrared is invisible and it is therefore possible that personnel may interrupt an infrared beam (from an active system) without being aware of the fact. This danger does not exist where only passive systems are in operation. Usually, the danger is not too great because personnel will sense the heating effects of infrared and thus be alerted before damage occurs, assuming they have knowledge of the presence of a nearby active infrared system. However, it is possible for the eyes to be damaged before the heating effects provide sufficient warning. It is not advisable to stare into a source of intense infrared radiation, even though the source is equipped with a filter and all visible light is removed. Special problems related to personnel exposure should be referred to the support medical facility (Bioenvironmental Engineer/ Environmental Health).

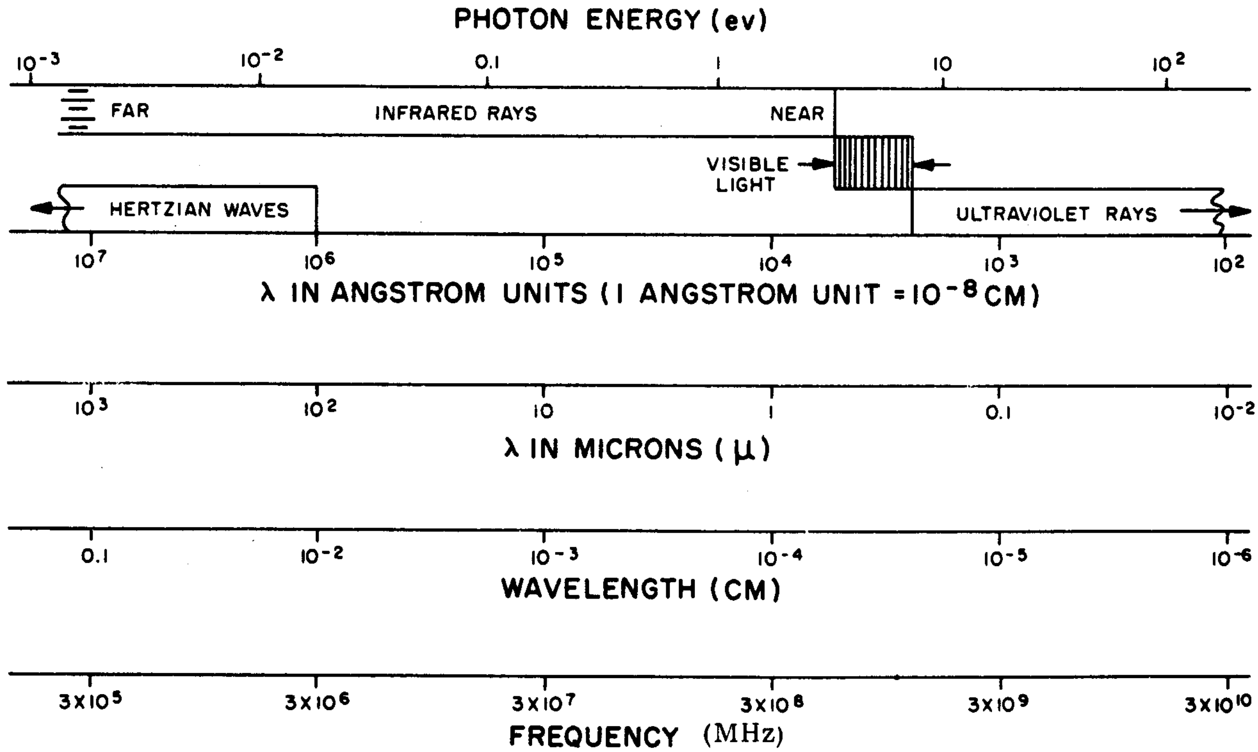


Figure 5-1. Portion of Electromagnetic Spectrum, Showing Relationship of Infrared Radiation to Other Electromagnetic Radiations

SECTION II - LASER HAZARDS

5-4. GENERAL. In this section the reader is acquainted with the hazards of laser devices. Comprehensive discussions of these hazards are contained in AFOSH Standard 161-10. Lasers generate or amplify electromagnetic energy. Electromagnetic energy, as discussed earlier, can be harmful to the human organism. In this respect, lasers are identical to conventional rf generators. There are, however, at least two important differences: First, there is the matter of power level. Such devices can generate peak power levels far exceeding those ever before generated. Secondly, the laser operates in the visible or near-visible region of the electromagnetic spectrum. (Many lasers operate at infrared wavelengths.) This, then, constitutes a special hazard to the human eye. Consider that the eye functions at light frequencies. It collects and focuses such energy. Consequently, it can further concentrate sub-hazard levels of power to levels hazardous to the internal structure of the eye.

5-5. SAFETY PRECAUTIONS. The following safety precautions must be observed with laser devices:

a. Prior to placing a laser device in operation become familiar with, and adhere to, the safety guidance provided in AFOSH Standard 161-10. Maintain a close liaison with the base medical services (Bioenvironmental Engineer/Environmental Health).

b. Never knowingly look into the beams of such devices, regardless of their power level or how distant they may be. Consult the Bioenvironmental Engineer for safe skin and eye distances.

c. Keep reflective surfaces out of laser beams.

d. Keep covers and shields in place when working on such devices.

e. Be aware of the dangers of electrical shock due to the use of high voltage.

f. The most important precaution of all is tc seek the guidance of the base Bioenvironmental Engineer. He is kept up-to-date on the hazards involved. For additional assistance, contact the USAF Occupational and Environmental Health Laboratory at Brooks AFB, Texas (see table 2-1 for office symbol and telephone number).

SECTION III - RADIOACTIVE MATERIAL HAZARDS

5-6. GENERAL. The purpose of the information contained in this section is to provide the reader with a knowledge of the potential hazard which exists in the form of radioactive materials used in components of electronic equipments. One primary source of potentially harmful ionizing radiation is the radioactive electron tubes which are commonly employed in modern microwave and radar equipments. It is, therefore, important for personnel working with such equipments to be aware of the possible dangers associated with radioactive electron tubes and to exercise caution when handling such tubes.

5-7. TYPES OF IONIZING RADIATION. Ionizing radiation exists in two forms: electromagnetic radiation (consisting of photons) or particulate radiation (sometimes call corpuscular radiation) consisting of electrons, positrons, neutrons, etc. Radioactive substances are sources of ionizing radiation. These substances undergo a disintegration process which is accompanied by the emission of radiation. Most naturally occurring radioactive elements radiate either alpha or beta particles. In some cases, gamma rays accompany the alpha or beta particles. The specific properties of the radiations, such as the velocities of the alpha or beta particles, their penetrability and power of ionization, and the wavelengths of the gamma rays, depend on the particular radioactive element from which they originate.

a. Alpha Rays. Alpha rays (or particles) are particulate ionizing radiation consisting of helium nuclei carrying a positive charge traveling at moderately high speeds (approximately 7 percent of the speed of light). Alpha particles have a short range, dissipate their energy quickly, and have a very strong ionizing power. However, these particles have weak penetrating power and are easily stopped by a thin sheet of paper, such as this printed page.

b. Beta Rays. Beta rays (or particles) are particulate ionizing radiation consisting of electrons or positrons traveling at extremely high speeds (up to 95 percent of the speed of light). Beta particles have strong ionizing power and moderate penetrating power. Beta particles do not ionize gases as readily as alpha particles, but beta particles can penetrate shields 100 times as thick as that required to stop alpha particles. Metallic shields are very effective against beta particles; a sheet of aluminum 0.04 inch thick will stop a beta particle.

c. Gamma Rays. Gamma rays are electromagnetic radiations which originate in the nuclei of atoms. Gamma rays are similar to X-rays, but extend into the shorter-wavelength region of the electromagnetic spectrum. However, X-rays and gamma rays of the same wavelength have identical properties. Gamma rays are more penetrating than either alpha or beta particles and can be detected after passing through as much as 12 inches of steel.

5-8. INTERNAL EXPOSURE HAZARD.

a. General. Exposure of the human body to ionizing radiation can be either external or internal. External exposure, originating from sources of ionizing radiation outside the body, can be dealt with by providing proper shielding, by increasing the distance from the source, or by decreasing the exposure time. However, internal exposure results from radioactive substances within the body; therefore, the problem of internal exposure resolves itself into preventing the entry of radioactive material into the body. If significant radioactive material is taken into the body, the effects can be quite serious and equally as dangerous as the external exposure effects described in the previous section in connection with X-radiation. When a radioactive substance is taken into the body, it may tend to concentrate in certain parts of the body, or it may disperse itself throughout the body. Wherever it is located, the substance irradiates nearby cells and tissues; this irradiation process continues until the substance is excreted through normal body processes or until it decreases in radioactivity to a level which ceases to be biologically significant. The biological damage caused by such internal emitters depends upon many factors, such as the concentration and distribution of material within the body, the sensitivity of tissues and organs, the route of material entry, the material solubility, and the route and rate of elimination from the body. The effect of ionizing radiation upon body cells and tissues is the same regardless of whether the radiation exposure is internal or external.

b. Intake of Radioactive Material. Biological effects in man occurring as a result of the intake of radioactive material are not as common as those occurring as a result of external exposures; nevertheless, internal exposure to radiation can be quite dangerous and precautionary measures must be taken by those who may be occupationally exposed to potential sources of internal radiation to avoid the intake of radioactive materials. The processes by which radioactive material can be taken into the body in the order of likelihood are: inhalation, ingestion, or absorption.

(1) Inhalation. Airborne particles of radioactive material gain access to the body through the process of inhalation, or breathing. As air containing radioactive dust or vapor is drawn into the lungs and exhaled, some filtering takes place and the larger radioactive particles are removed from the air and deposited in the nose. Other particles may come in contact with, and be deposited in, the mucous coating of tissues lining the nasal and upper lung respiratory passages. Particles which are trapped in the upper respiratory passages may eventually be swallowed and enter the digestive system. Only a small amount of the radioactive material inhaled will reach the small air sacs of the lungs. Any of this material that is soluble will pass throught the air sac membranes and enter the blood stream to cause damage elsewhere in the body. Insoluble materials will remain in the air sacs to cause continuous damage to the surrounding tissues and will likely result in the formation of tumors.

(2) Ingestion. Particles of radioactive material can enter the body through the process of ingestion, wherein contaminated food or drink is taken into the stomach for digestion. If the radioactive materials are capable of being dissolved in the digestive system, they will be absorbed in the same manner as food and carried to various parts of the body. These soluble materials may eventually be eliminated from the body by means of urine and excrement. Materials which do not dissolve will pass through the digestive system and will be ejected with the body excrement.

(3) Absorption. Particles of radioactive material can enter the body through the process of absorption. Access to the body interior is mostly through open sores, skin punctures, cuts, scratches, or other surface wounds which lay open to the entry of small particles. The absorption process depends upon the dissolving of the material in body fluids and entrance via these fluids into the blood stream, to be distributed throughout the body. Insoluble material entering surface wounds may remain beneath the skin tissues to cause damage.

c. Internal Emitters.

(1) The hazards associated with internal emitters arise primarily from alpha and beta particles, since these are completely absorbed in the body, while only a fraction of the gamma-ray energy given off by an internal emitter is absorbed by body tissues before the gamma rays leave the body.

(2) The alpha particle does not represent a danger to the body from an external source because of its weak penetrating power, but if inside the body it becomes extremely injurious.

If alpha-emitting materials gain access to the body, the alpha particle will expend a large portion of its ionizing energy at short range and concentrate on a few nearby cells causing a higher degree of cell damage. For this reason, alpha radiation is considered to be a greater hazard than beta or gamma radiation.

(3) The beta particle is dangerous to the body as either an external or internal source. Beta radiation from an external source is capable of penetrating skin tissues as much as one centimeter thick, and if beta-emitting materials are present within the body, the hazard is greatly increased because all the energy will be given up directly to internal body tissues. An additional hazard results when beta radiation decelerates in the tissues, since rapid deceleration causes the production of X-radiation.

(4) Gamma radiation is emitted when an unstable nucleus rids itself of excess energy. Gamma radiation destroys tissues in much the same manner as does X-radiation, that is, through ionization by the photoelectric effect, Compton effect, and pair production. Since gamma radiation can penetrate tissues, it represents a hazard to the body as an external source. However, if gamma-emitting materials are present within the body, only a small portion of the gamma radiation energy is absorbed by tissues before the radiation leaves the body; therefore, gamma radiation from an internal emitter does not represent as great a hazard to the body as alpha or beta radiation from an internal emitter.

5-9. RADIOACTIVE ELECTRON TUBES AND SPARK GAPS:

a. Materials Used in Tubes.

(1) Many different types of tubes are used in electronic equipment. Some of these contain as much as five microcuries of radioactive material although most contain much less than one microcurie. The radioactive material used includes but is not limited to carbon (C-14), cobalt (Co-60), cesium (Cs-137), nickel (Ni-63) and radium (Ra-226). Radioactive material is intentionally added in the production of tubes to assure reliable performance at a given operating voltage throughout their useful life. Since the radioactive material will outlast the tube, it is a potential hazard at all times until the tube is properly disposed of.

(2) As long as a tube containing radioactive material remains unbroken, it does not pose any hazard to personnel. Even if broken, the tube still poses no hazard to personnel provided the radioactive material is not inhaled, ingested, or taken into the body through an opening in the skin such as a cut (injected).

It is unlikely that breakage of a single, or even several tubes would create a potential airborne hazard because of the limited quantities of radioactive materials involved and their forms. This route of entry becomes a concern only when large numbers of tubes may be involved in a catastrophic event such as a major fire in a central tube storage area. Injection can be avoided by not handling broken tubes, or if pieces must be picked up by hand, wearing protective gloves. It is preferable to sweep the pieces into some container and avoid physical contact. To prevent ingestion, individuals cleaning up broken tubes must not smoke, eat, or drink until clean-up is complete and they have thoroughly washed their hands. Thus, insuring personnel health and safety is simply a matter of preventing broken tubes or preventing entry of the radioactive material into the body by avoiding cuts and washing after contact.

b. Radioactive Tube Identification.

(1) Manufacturers of electron tubes which contain radioactive materials are required by the US Nuclear Regulatory Commission (USNRC) to provide an identification label on each tube indicating that it contains radioactive material. If an electron tube does not have a label there is no requirement to provide such a label either on the tube itself or on the container in which it is packaged.

(2) If tubes which have a manufacturer's label indicating the presence of radioactive material are stored in some location such as a bin, work drawer or storage cabinet, a label should be placed on the outside of the storage area (i.e. on the outside of the bin, work drawer or storage cabinet) to advise personnel that this is a location where radioactive material is stored. A small AFTO Form 9B as described in TO 00-110N-3, paragraph 14c (2), may be used.

c. Handling and Disposition. See TO 00-110N-7 for specifics. For CONUS bases, unserviceable electron tubes and spark gaps containing radioactive material shall be disposed of as normal waste by using activity as they are removed from service. Place unbroken tubes in their original cartons or equipment container and seal with tape prior to placement in bulk waste containers. Place accidently broken tubes in a heavy-duty plastic bag or small cardboard box which will not allow the pieces to escape and seal with tape. Dispose in same manner as unbroken tubes. In order to avoid concentration of radioactive material in waste disposal sites, do not discard more than five marked tubes per day.
TO 00-110-N-7 provides specific guidance for overseas bases and equipment salvage operations.

SECTION IV - TOXICITY HAZARDS

5-10. GENERAL. The introduction of new chemicals in the workplace should be coordinated with the local medical service (Bioenvironmental Engineer) to insure that necessary health controls are formulated. AFR 161-18 establishes channels for coordinating toxicological studies and AFOSH Standard 161-8, Permissible Exposure Levels, provides guidance on many common industrial chemicals.

5-11. USE OF GASEOUS DIELECTRIC FOR WAVEGUIDES.

a. The development of high-power microwave transmitting equipment has reached the point where the power levels available for radiation exceed the power-handling capabilities of ordinary waveguide transmission lines. Therefore, it has been necessary to devise means by which the power-handling capability of waveguides can be increased.

b. Waveguides for use with moderate power equipments employ dry air as the dielectric medium. The power-handling capability of this type of waveguide can be increased by increasing the pressure of the gas (air) within the waveguide. However, there is a practical limit to this approach, because the increased internal pressure of a waveguide may require considerable strengthening of the guide, and the use of pressurizing seals and windows. When thick, solid dielectric materials are used to withstand the increased pressure in the waveguide, there are electrical problems of impedance matching, possible dielectric losses, and narrowed transmission bandwidth. Therefore, increasing the pressure in the waveguide system is not always an answer to increasing the power-handling capabilities of the transmission line.

c. One solution to the problem has been the use of a gas, other than dry air, which has a dielectric strength greater than air. The dielectric strength of a gas is influenced by the nature and purity of the gas, and by its density. The dielectric strength is subject to large variation as the result of the introduction of impurities. Small amounts of foreign gases may either decrease or increase the dielectric strength of the predominant gas by as much as 50 percent.

d. Nitrogen, which has a relative dielectric strength slightly greater than dry air, and Freon, which has a relative dielectric strength several times that of dry air, have been used as gas dielectric media in waveguides. Freon has a greater relative dielectric strength than does dry air or nitrogen; however, its vapor pressure varies considerably with changes in temperature and, if an arc-over or breakdown occurs in the waveguide, its decomposition products are highly toxic and corrosive, and undesirable carbon tracks remain on the waveguide inner surfaces.

e. A gas presently used with much success as a dielectric medium in waveguides is sulfur hexafluroide (SF_6). This gas has high dielectric strength, is essentially inert chemically and biologically, possesses a wide operating temperature range, does not leave carbon tracks on waveguide surfaces after breakdown, and permits almost 8 to 10 times the power to be transmitted through the waveguide at microwave frequencies as compared to that of similar dry air-filled waveguides.

f. In many applications, microwave transmission lines are quite long and subject to leakage when pressurized. The waveguide originating at a transmitter usually passes through areas accessible to, and possibly occupied by, personnel; therefore, the toxicity factor of the gas used to pressurize the waveguide must be known to safeguard personnel against toxic effects arising from leaks in the waveguide, especially should the leak occur in closed spaces. Adequate ventilation, provided by exhaust fans, may be required to keep the concentration of escaping gas well below a tolerable percentage in closed spaces occupied by personnel.

g. The use of either Freon or sulfur hexafluoride as a dielectric medium to pressurize waveguide systems does permit increasing the power-handling capability of the waveguide system. However, in the event of arc-over or breakdown, both gases are subject to decomposition. Freon is not likely to be used in low-temperature applications because of its comparatively high condensation temperature (a Freon-filled system operated under low-temperature conditions requires special treatment to keep the temperature of the gas above the condensation temperature).

h. Sulfur hexafluoride in its pure state is essentially inert and nontoxic, and has found use in medical applications as a therapeutic measure to rehabilitate damaged lungs. In tests on humans, the gas in its pure state has been found to be nontoxic when inhaled in gas-oxygen mixtures containing as much as 80 percent sulfer hexafluoride. However, when arc-over occurs in a waveguide filled with this gas, the decomposition products that are produced constitute a dangerous personnel hazard in the form of several toxic gases, including fluorine. See AFOSH Standard 161-8 for current acceptable exposure levels, presently 1000 parts per million as eight-hour time weighted average concentration.

5-12. RECOMMENDED SAFETY PRECAUTIONS.

a. When a breakdown occurs within a waveguide system, the standing-wave ratio in the transmission line will likely increase. Depending upon the individual radar system, the increase in standing-wave ratio may cause arcing in the magnetron transmitter, and this in turn may actuate power "run-down" control circuits to stop the transmitter until the arc is extinguished. However, arcing may take place periodically until the system fails completely, or at least until the system performance drops below an acceptable minimum. Thus, if a maintenance technician should open the waveguide while repairing the system, he may release highly toxic gases (resulting from dielectric breakdown) into the area in which he is working.

b. The possibility of inhaling a concentrated mixture in proximity to the waveguide as the pressure in the system is released and as the system is opened represents a serious hazard to personnel, especially in closed work spaces. Since the results of tests indicate that the decomposition products of sulfur hexafluoride are definitely hazardous to personnel, the following safety precautions are recommended in installations where this gas is used to pressurize waveguide systems:

(1) The portion of the waveguide system which originates at the transmitter and passes through confined areas should be well sealed and made as gas-tight as is possible.

(2) Adequate room ventilation should be provided in confined areas where leakage from the waveguide is possible.

(3) Consideration should be given to the incorporation of an escape valve in the waveguide system, at a point external to any closed area or equipment shelter, to allow continuous leaking of the gas to the open atmosphere. The purpose of such a pressure leak is to keep the gases moving through the system and to expel decomposition products resulting from electrical breakdown to the open atmosphere, where the gases will be diluted and dissipated harmlessly. The rate of flow through the escape valve would require adjustment to a rate which is economically feasible. A flow rate of 2.25 liters per hour has been suggested; at this rate a 100-lb tank of sulfur hexafluoride connected to a typical waveguide system would maintain system pressurization continuously for approximately 5 months.

(4) An alternative to the recommendation given in the previous subparagraph is to provide a gas recirculating system to circulate the gases from the waveguide through a scrubbing column of soda lime for absorption of the toxic gases and to return the purified gas back to the wavegiude. (If found necessary, an absorption column containing activated alumina may be used in series with the soda lime scrubber.) The scrubbing agent requires replacement after losing its effectiveness; therefore, the scrubbing columns of such a system must be opened periodically to remove the spent absorbing agent and to recharge them with fresh absorbing agent.

(5) Infrared spectrograms have been made to obtain information on the nature of the toxic by-products resulting from the decomposition of sulfur hexafluoride. Based upon this data, respiratory protective devices may be used by maintenance personnel when working on pressurized waveguides employing sulfur hexafluoride. However, the use of such respiratory devices should be confined to emergency or intermittent exposure conditions and should not be relied upon as the sole safety measure for controlling the personnel toxicity hazard. Use of any respiratory protective devices must be based on recommendations of the Bioenvironmental Engineers and use must be in strict accordance with AFOSH Standard 161-1, Respiratory Protection.

WARNING

Sulfur hexafluoride and Freon must be controlled in accordance with AFOSH Standard 161-8, Permissible Exposure Levels. Consult the local Bioenvironmental Engineer for specific guidance. In addition, in confined spaces such chemicals could displace the oxygen and cause asphyxiation. In an oxygen deficient atmosphere cartridge type respirators offer no protection and are not approved for use.

CHAPTER 6

RF POWER DENSITY/HAZARD DISTANCE

SECTION I - RF PROPAGATION

6-1. GENERAL.

a. Hertzian, or radio, waves propagated into space are considered to be a radiant form of energy, similar to light and heat. The waves travel at a speed of approximately 300,000,000 meters per second, or 186,000 miles per second. The radio-frequency portion of the electromagnetic spectrum is theoretically considered to include all frequencies from 0.01 megahertz to 3,000,000 megahertz. This theoretical concept includes a portion of the infrared band, as shown in figure 6-1. However, from the practical standpoint, the radio-frequency spectrum is assumed to extend from 0.01 megahertz (very low frequency) to 300,000 meghertz (extremely high frequency).

b. The wavelength of any radio wave in free space can be determined by using the equation:

$$\lambda = \frac{v}{f}$$

where λ is the wavelength in meters, f is the frequency of the radiation in hertz, and v is the velocity (speed) in meters per second (300,000,000). Thus, a 3-MHz radio wave has a wavelength of 100 meters, while a 30,000-MHz radio wave has a wavelength of 0.01 meter, or 1 centimeter.

c. The radio-frequency spectrum includes frequencies with other designations such as radar, microwave, infrared, etc.

d. The term "microwave" applies to a somewhat arbitrary range or band of frequencies, but is generally intended to mean a band of frequencies between 300 MHz (1 meter in wavelength) and 300,000 MHz (0.1 cm in wavelength), and includes frequencies normally used by radar. The fact that the shorter wavelengths of the microwave band approach the wavelengths of infrared rays is important. It suggests that the biological effects which result from exposure to microwaves are related to the thermal effects associated with the infrared spectrum.

6-2. PROPAGATION OF ELECTROMAGNETIC ENERGY.

a. Wave Theory. Assume that an alternating current is applied to a closed loop of wire of infinite length, i.e., an infinite line. At the instant the current begins to flow, a magnetic field builds up around the conductor, with its lines of force circling the conductor and traveling in the direction given by the right-hand rule (assuming conventional current flow). The magnetic field continues to build up, until maximum strength is reached when the current reaches its maximum value. The field then begins to decrease as the current decreases to zero. As the current begins to increase in the negative direction during the second half cycle of the alternating current, the magnetic field again builds up about the conductor, but with the lines of force traveling in the reverse direction. Thus, the lines of force expand and collapse along the conductor, in phase with the current flowing through it. This is illustrated in (a) and (b) of figure 6-2.

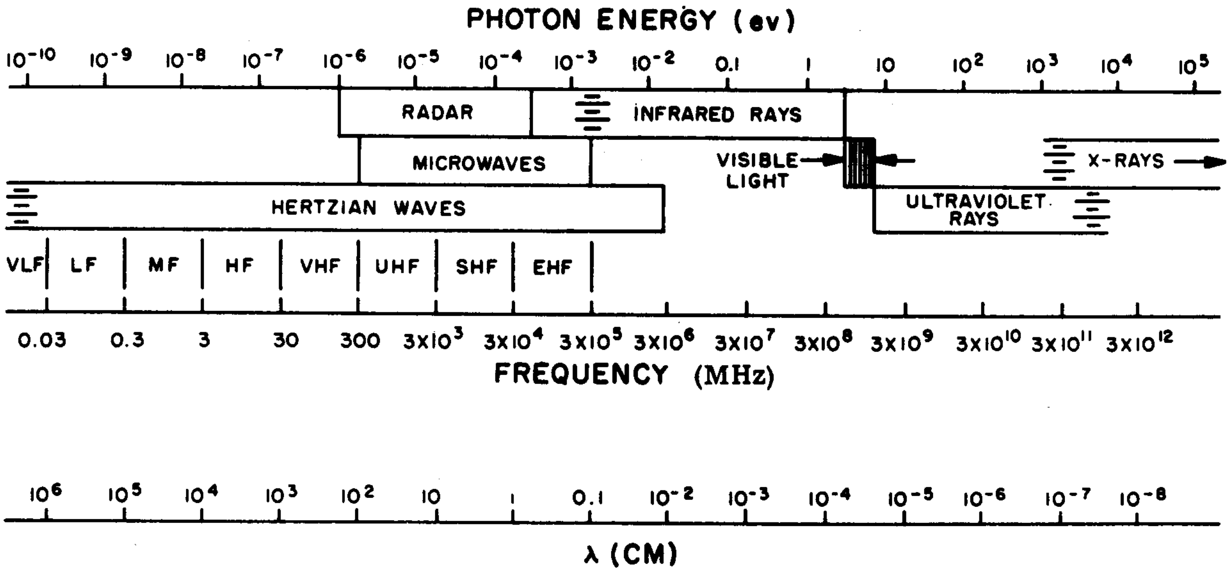


Figure 6-1. Portion of Electromagnetic Spectrum, Showing Relationship of Microwave Radiations to Other Electromagnetic Radiations

b. Induction and Radiation Fields.

(1) It would be expected that, when the lines of force had reached a maximum value, all of them would begin to collapse toward a zero value as the current decreases to zero at the end of the half cycle. For some unknown reason, however, not all of the lines of force collapse. Instead, a small percentage of the lines of force, or magnetic field, continues outward from the conductor, into space. The percentage of the field which does not return to the conductor is extremely small at low frequencies of the alternating current, but as the frequency is increased, the percentage increases to a point where, at extremely high frequencies nearly all of the field continues outward from the conductor.

(2) The percentage of the field which returns to the conductor at the end of each half cycle is known as the "induction field," while the remainder of the field which does not return is termed the "radiation field."

c. Electric and Magnetic Fields.

(1) Although nothing has been said about the characterisitcs of a particular antenna, it is obvious that this element should be used in describing the principles of radiation. When power is applied to an antenna, two fields are set up by the applied energy; the induction field, which is associated with the stored energy, as described in paragraph 6-2b(2), and the radiation field, which moves through space at approximately the speed of light. At the antenna the intensities of these fields are large, and are proportional to the amount of power being delivered to the antenna. At a short distance from the antenna, and beyond, only the radiation field prevails. The radiation field is made up of an electric component, known as the "electric

field" (E field), and a magnetic component, which is termed the "magnetic field" (H field). These two fields (E and H) vary together in intensity, but their directions are at right angles to each other in space, and both are at right angles to the antenna from which they were radiated. The relative directions of the E and H fields, and their relation to the alternating current in an antenna of infinite length, are shown in (b) and (c) of figure 6-2. It should be kept in mind that the illustration shows the fields which exist about the antenna at a single instant of time. As time progresses, from the left side to the right side of the illustration, the applied current will fall to a negative value, with corresponding changes in the polarity of the magnetic and electric fields along the antenna.

(2) As time passes, the lines of force, or flux lines, shown in (b) and (c) of figure 6-2, expand radially with the velocity of light, and new flux lines are generated at the antenna to replace those that travel outward, as in (d) and (e) of figure 6-2. In this manner oscillating electric and magnetic fields are produced along the path of travel. The variations in the magnitude of the electric component (E field) and those of the magnetic component (H field) are in time phase, so that at every point in space the time-varying magnetic field induces a difference in voltage, which is the electric field. The electric field also varies with time, and its variation is equivalent to a current which is called the "displacement current." This displacement current establishes a magnetic field in precisely the way that a conduction current does. In summary, the varying magnetic field produces a varying electric field, and the varying electric field, through its associated displacment current, sustains the varying magnetic field. Each field supports the other, and neither can exist by itself, without setting up the other. Together, they are termed the "electromagnetic field."

d. Polarization.

(1) At a distance from the radiating antenna, the circular pattern of the lines of force of the electric field becomes less apparent, and the lines appear to be straight lines, as in (e) of figure 6-2. It should be noted that these lines of the electric field (E lines) are in effect parallel to the radiating antenna. When these lines are in a horizontal plane, being radiated from an antenna which is horizontal in space, the electric wave is said to horizontally polarized, as are the lines in (e) of figure 6-2. If the antenna is vertical in space, and the E lines of the electric field are in a vertical plane, the electric wave emitted from the antenna is said to be vertically polarized. The reference in both cases is taken from the earth's surface.

(2) Another type of polarization, which has found application in many radar equipments, is known as "circular polarization." In electronic countermeasures and telemetry systems, circularly polarized antennas are used to permit equal reception of signals without regard to their plane of polarization. They are used in ground radar systems for the reduction of rain and snow return. A circularly polarized wave has two components which are simultaneously at right angles in space and in phase quadrature. At a given instant of time, when the vertically polarized component is at +E max, the horizontally polarized component is at zero and rising in a positive direction. The electric field produced at points along the axis of propagation is the vector sum of the two waves. Since the vertical component leads the horizontal component, the resultant field rotates in a clockwise direction, and since both fields vary at the same frequency, the resultant field rotates at one complete revolution per cycle.

(3) When the vertical and horizontal components are equal in amplitude, the resultant field vector describes a perfect circle, and the resultant wave is said to be circularly polarized. If the vertical and horizontal components are not equal in amplitude, the resultant rotating field vector will describe an ellipse, and the resultant wave is said to be elliptically

polarized. In spite of its apparent rotation, the circularly polarized field consists of, not one wave, but rather two waves. Because of their phase and frequency requirements, both waves must obviously be developed by the same generator.

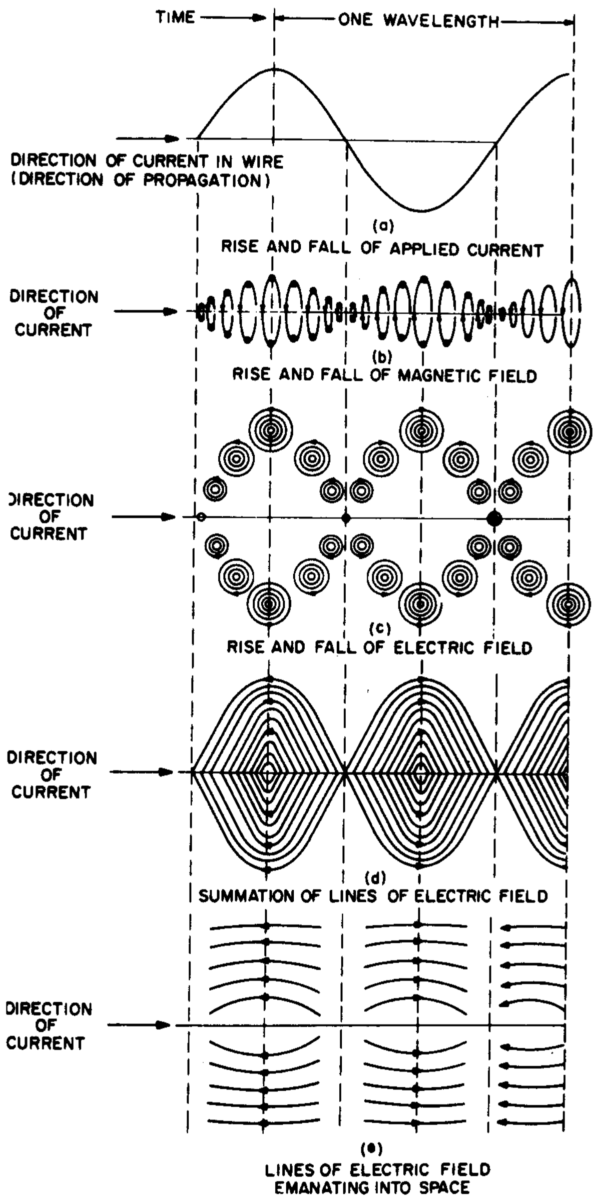


Figure 6-2. Creation of Electric and Magnetic Fields About a Conductor Carrying an Electric Current

(4) Four common methods are used to develop a circularly polarized wave. First, vertical and horizontal dipoles are spaced a quarter wavelength apart and fed, in phase, from the same source. Second, vertical and horizontal dipoles are crossed at the same point, and one is fed directly while the other is fed through a 90-degree phase-shifting network. Third, a circular waveguide flared into a feedhorn is fed by two probes located at right angles in phase quadrature. Fourth, a 45-degree lens is used to divide the incident wave into two perpendicular components while advancing the phase of one component by 90 degrees.

(5) It is important to note that, in discussing circular polarization, a circularly polarized antenna which radiates a clockwise rotating field will not receive a counterclockwise rotating field. Circularly polarized reflections from conducting surfaces retain the direction of rotation of the transmitted signal, but those from dielectric boundaries such as precipitation have their direction of rotation reversed.

(6) Occasionally it is desired to measure circular polarization. This may be done using either a conical horn or a conventional dipole antenna to pick up the signal. If a conical horn is used, no regard need be paid to horizontal or vertical polarization. The horn is directed toward the radiating source so that maximum power is picked up, and the power is indicated directly by the meter in the conventional manner. If a conventional dipole antenna is used, the vertical polarization component and the horizontal polarization component must be measured separately, and the total power calculated. The dipole should be held with its axis parallel with the ground, and its elements should be slowly rotated while the meter is carefully observed. If the wave is truly circular, the meter indication will remain constant throughout the full 360 degrees of dipole rotation, and equal powers in both horizontal and vertical polarization may be read. If the wave is elliptical then maximum and minimum readings will be noted, displaced at 90-degree intervals. The maximum and minimum may not necessarily occur when the dipole elements are exactly horizontal or vertical with respect to the earth, because the ellipse may be tilted. This is the reason for rotating the antenna slowly, so that the highest and lowest readings may be noted and recorded.

(7) The meter readings obtained in the preceding paragraph may be used to calculate the total power in the following manner: Assume that a circularly polarized wave is indicated, by obtaining a constant reading of 0.02 watt per square centimeter as the antenna is rotated. The reading is 0.02 watt/cm^2 with the dipole held in a horizontal plane; it remains at 0.02 watt/cm^2 with the dipole in a vertical plane. Solving for total power:

$$P_t = 0.02 + 0.02 = 0.04 \text{ watt/cm}^2$$

The total power in the circularly polarized wave is therefore 0.04 watt/cm^2. It should be noted that the accuracy of this measurement is based on the assumption that the field density meter (densiometer) used in taking the measurements is calibrated for use with the dipole.

(8) If an elliptically polarized wave is indicated by maximum and minimum meter readings as the antenna is rotated, the total power may be calculated in the same manner as that used for circular polarization in the preceding paragraph. For example:

Assume maximum reading = 0.04 watt/cm^2

Assume minimum reading = 0.015 watt/cm^2

$$P_t = 0.04 + 0.015 = 0.055 \text{ watt/cm}^2$$

e. Field Intensity.

(1) The conventional measure of the field intensity of a radiated wave is a measure of the intensity of the electric field. This intensity usually is expressed in microvolts per meter, and is a measure of the dielectric stress produced by the electric field, or the voltage induced in a conductor 1 meter long when positioned so that it lies in the direction of the electric field and at right angles to both the direction of the magnetic field and to the direction of propagation. For example, assume that a conductor which is 100 feet long and has constant conductivity throughout its length is energized with a battery of 100 volts. If the leads of a voltmeter are touched to the conductor at points exactly 1 foot apart, the meter will indicate 1 volt. Therefore, the voltage drop along the conductor is 1 volt per foot. This is in accordance with Kirchhoff's law, which states that the sum of the voltage drops around any closed circuit is equal to the applied voltage.

(2) In a similar manner, suppose that a transmitter excites a dipole antenna, and that another dipole 1 meter long is placed some distance away to receive the transmitted energy. If a voltmeter is used to measure the voltage drop across the receiving dipole and the voltage reads 1 volt, the field intensity at this point in space is 1 volt per meter.

(3) The relationship of voltage, current, and power to area may be seen as follows: If two very sharp metallic points are used as a spark gap, a potential of 40,000 volts will easily leap across a 1.5 inch gap. If however, two brass balls 1.5 inches in diameter are used as the spark gap electrodes, the spacing will have to be reduced to approximately 1/2 inch before 40,000 volts will jump across the gap. The reason for this is that the increase in the surface area of the electrodes reduces the voltage per square inch of surface. Considering the aspect of power, a figure of 1000 amperes per square inch of cross-sectional area is sometimes used in selecting the size of copper bus bars for power distribution. On the basis of this figure, a bus bar which measures 2 inches wide by 2 inches thick, or has a cross-sectional area of 4 square inches, can carry a current of 4000 amperes.

(4) Now that the relationship between voltage, current, or power and the length or area of a conductor has been shown, the power in an rf field may be considered. Suppose that a horn antenna which has an aperture of 5 centimeters by 10 centimeters is 100 percent efficient and that the physical and effective apertures are identical. The area is then 50 square centimeters. If 50 watts of power is fed to the horn, the power may be considered to distribute itself evenly across the aperture (this may not be absolutely true in practice, but is assumed to be true in this case for a theoretical explanation), and the power density across the aperture will be 1 watt per square centimeter. If a person should inadvertently stand directly in front of this horn, he would be exposed to a power density of 1 watt per square centimeter, which is an extremely high and hazardous power level.

(5) The field intensity of a radiated wave falls off in direct proportion to distance between the transmitting and receiving antennas. For example, if the received field intensity of a signal is 50 microvolts per meter at a distance of 25 miles, then at 50 miles, or twice the distance, the field intensity is one-half as much, or 25 microvolts per meter. Thus, electric field intensity (when measured in terms of voltage, e.g., microvolts per meter) varies inversely with the distance from the transmitting antenna.

(6) In order to understand this variation of the field intensity of a radiated wave, it is essential to consider the relationship between the power radiated and the field intensity. The power of a radiated wave, such as a light wave, falls off as the square of the distance between the source of light and the point of measurement. A sheet of paper held perpendicular to the

rays of a candle at a certain distance from it will be lighted four times as brightly as one held at twice this same distance, because the given amount of light must spread out to cover four times as great an area on the paper which is only twice as far from the candle as the first one. This law is expressed by the formula:

$$A = 4 \pi r^2$$

where A is the area of the portion of the surface of a sphere of radius r, having its center at the source of the light. This same law holds for the field intensity of electromagnetic waves when the power intercepted per unit area is considered. However, since electric power expressed in terms of the voltage present is propotional to E^2 (because $P = E^2/R$), then the square of the voltage falls off as the square of the distance, or the voltage itself falls off directly as the distance.

(7) The power flow through a unit area at a distance D from an isotropic antenna is found by dividing the total radiated power by $4 \pi D^2$. However, if a directive antenna is used, the energy is concentrated in certain directions, and the distribution over the sphere is not uniform. In this case, the power flow through a unit area at a given distance differs by a factor, G, from that which would be produced by an isotropic antenna. This factor G is called the "gain" of the antenna. The greater the concentration of energy in a given direction, the greater the gain will be in that direction. By definition, an isotropic antenna has a gain of 1 in all directions. A directive antenna has a gain greater than 1 in some directions and less than 1 in other directions. However, the average of the sum of the gains in all directions, or the total gain taken over the entire sphere, must be equal to 1.

(8) Antenna gain may be calculated from the formula $G = 4\pi A/\lambda^2$, where A is the area of the antenna aperture, and λ is the wavelength of the transmitted signal. The units for A and λ must be the same. This formula is derived as follows: Using an aperture with dimension L in both directions, the angular width of the beam determined by diffraction is approximately λ/L radians. The radiated power is then concentrated in a solid angle beam of λ^2/L^2. An isotropic antenna should spread the same power over a solid angle of 4π. Therefore, the gain in concentration of energy is equal to:

$$\frac{4\pi}{\lambda^2/L^2} = \frac{4\pi L^2}{\lambda^2}.$$

Since L^2 equals the area of aperture A, then the gain $G = \frac{4\pi A}{\lambda^2}$.

(9) Before an equation for the attenuation of radio waves in free space can be derived, one other factor, known as the effective receiving cross-section of the antenna, must be defined. The effective cross-section is equal to the total signal power available at the antenna terminals divided by the power density (power per unit area) of the incident wave. In most cases, this cross-section is different from the actual physical area of the antenna. The effective cross-section is a quantity which tells the effectiveness of the antenna in capturing the power in the incident wave. If all of the energy incident on aperture A is absorbed, then the effective cross-section is equal to the area of the aperture. The formula for effective cross section is:

$$A_R = \frac{G\lambda^2}{4\pi}$$

(10) All of the discussion so far concerning free-space propagation can be summarized by providing the equation for power received over a free-space circuit. This equation is:

$$P_R = P_T \left[\frac{G_T A_R}{4 \pi D^2} \right]$$

where: P_R = total power at the output terminals of the receiver antenna
P_T = power input to the transmitter antenna
A_R = effective cross-section of the receiver antenna
G_T = gain of the transmitter antenna
D = distance between antennas

This equation shows the inverse relationship between the received power and the distance. It also shows that the received power is directly dependent upon the amount of power transmitted, the gain of the transmitter antenna, and the effective cross-section of the receiving antenna. Assuming that isotropic antennas are used, G_T is equal to 1 and A_R is equal to $\lambda^2/4\pi$.

f. Transmission in Free Space.

(1) There is a certain amount of attenuation, or loss, of energy for radio signals transmitted in free space. This loss is due to the spreading of energy over a greater area as the transmission distance is increased. The loss is directly related to the frequency and transmission distance. The formula for free-space loss is:

$$L_{FS} = 37 + 20 \log F + 20 \log D$$

where: L_{FS} = ratio of transmitter power to receiver power, in dB
F = frequency, in MHz
D = transmitted distance, in miles (statute)

An understanding of the above formula is necessary in order to understand all other propagation losses. This important formula is developed and explained in the following paragraphs.

(2) Theoretically, free space transmission can be realized only if the transmitting and receiving antennas are isolated in unbounded, empty space. For practical purposes, however, it is realized if the following conditions are fulfilled: No large obstacles intervene between the two antennas along an optical line of sight; no alternate transmission path can be followed by a substantial fraction of the radiated energy; the intervening atmosphere has a constant index of refraction, so that no bending of the wave occurs at the particular frequency used; the intervening atmosphere does not absorb energy from the wave at the frequency used. If these conditions are fulfilled, the transmitted wave will have spherical wavefronts, and these wavefronts will spread out so that the intensity of radiated energy varies inversely as the square of the distance. The intensity of energy is the power per unit of area on the spherical wavefront.

(3) The relationship between intensity of energy and distance is illustrated in figure 6-3, which shows part of the pattern of radiated energy from an isotropic antenna in free space. An isotropic antenna both radiates energy uniformly in all directions and receives energy uniformly from all directions. In figure 6-3, let A be a given unit of area on the surface of a sphere at a distance D_1 from the isotropic antenna. The total area of the entire sphere at this distance is $4\pi D_1^2$. Since power is distributed uniformly over the entire area of the sphere, the fraction of the total power which falls on area A is equal to $A/4\pi D_1^2$. Now increase the distance D_2 and consider the intensity of energy on the same area A on the sphere has increased, the area A has now become a smaller fraction of the total area. Thus, the fraction of total power incident to A decreases with increased distance from the free-space circuit, the total received power is calculated according to the formula:

$$P_R = P_T \left[\frac{\lambda^2/4\pi}{4\pi D^2} \right] = P_T \left[\frac{\lambda^2}{4\pi} \right] \left[\frac{1}{4\pi D^2} \right] = P_T \left[\frac{\lambda^2}{16\pi^2 D^2} \right]$$

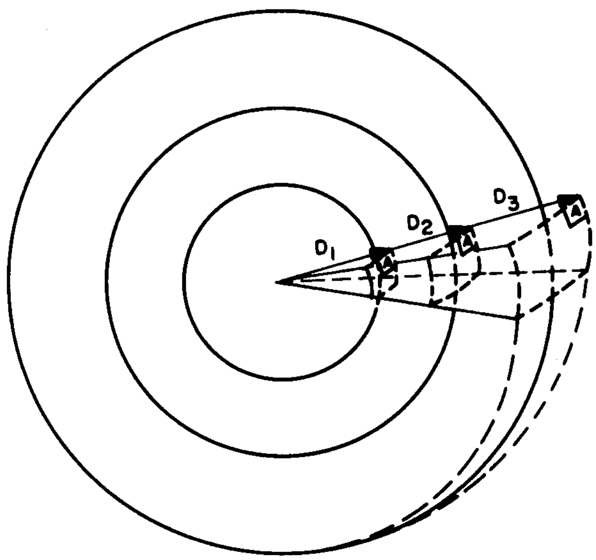


Figure 6-3. Change in Intensity of Radiated Energy with Distance in Free Space Over a Given Area

(4) Free-space loss, or attenuation, is the difference between the input power to the transmitting antenna and the output from the receiving antenna, or $P_T - P_R$, assuming isotropic antennas in both cases. This free-space loss in decibels is equal to $10 \log \frac{P_T}{P_R}$. Using the expression developed in the preceding paragraph for received power with isotropic antennas, the formula for free-space loss is developed as follows:

$$\frac{P_T}{P_R} = \frac{16\pi^2 D^2}{\lambda^2}$$

If the frequency, F, is expressed in megahertz, and the speed of radio waves, C, in miles per second, then:

$$\lambda = \frac{C}{F} = \frac{186000 \times 10^{-6}}{F} = \frac{0.186}{F}$$

Therefore:

$$\frac{P_T}{P_R} = \frac{16\pi^2 D^2}{\left[\frac{0.186}{F}\right]^2} = \frac{16\pi^2 D^2 F^2}{0.186^2}$$

In decibels, free-space loss is given by the following formula:

$$L_{FS} = 10 \log \left[\frac{16\pi^2 D^2 F^2}{0.186^2}\right]$$

$$= 10 \log 16 + 20 \log \pi + 20 \log D + 20 \log F - 20 \log 0.186$$

Removing the constants 10 log 16 + 20 log π - 20 log 0.186, which equals 37, the final expression for free-space loss in dB, with F in megahertz and D in miles (statute), is:

$$L_{FS} = 37 + 20 \log D + 20 \log F$$

NOTE

This is only applicable in the far field of an antenna. Refer to paragraphs 6-3h and 6-7 for information on near field, far field and near-field gain reduction.

(5) To illustrate the usage of the above formula, consider the following example:

Find the free-space loss over a circuit covering a distance of 100 miles between the transmitting and receiving antennas, using a transmitting frequency of 1000 megahertz.

$$L_{FS} = 37 + 20 \log 100 + 20 \log 1000$$

$$= 37 + (20 \times 2) + (20 \times 3)$$

$$= 37 + 40 + 60 = 137 \text{ dB}$$

> This means that the output from the receiving antenna will be down 137 dB from the power input to the transmitting antenna because of free-space loss alone, assuming isotropic antennas. Expressed in another way, the received power is approximately 0.00000000000001 of the transmitter power input.

It can be seen from this example that free-space loss introduces a substantial attenuation to the transmitted signal. This is the basic loss which occurs for all types of radio transmissions. For line-of-sight circuits where the conditions for propagation in free space are closely approximated, the total loss can be considered to be free-space loss. However, for long-distance transmission, where either ground wave, sky wave, or scatter propagation is used, other losses are introduced by the effects of the earth and the atmosphere. Each of these losses must be added to the free-space loss, to find the total loss or attenuation to the transmitted signal.

6-3. TRANSMISSION OF RF ENERGY.

a. General. The radiated waves from an antenna travel through space in all directions. Some of the waves travel along the surface of the earth, and are greatly affected by the earth and its terrain. These waves are collectively called "ground waves." Other waves travel upward and away from the earth's surface, and may or may not return depending upon the conditions in the upper atmosphere and beyond. These waves are called "sky waves."

b. Ground-Wave Propagation. Generally, ground wave propagation refers to the transmission of energy which does not make use of reflections from the ionosphere. Ground waves may take a direct or reflected course from the transmitter to the receiver, or they may be conducted by the surface of the earth or reflected in the troposphere. The resulting ground wave, therefore, may be composed of one or more of the following components: the direct wave, the ground- reflected wave, the surface wave, and the tropospheric wave.

(1) Direct-Wave Component. The direct wave is that component of the entire wave front which travels directly from the transmitting antenna to the receiving antenna. It is limited only by the distance from the transmitter to the horizon, or line-of-sight, plus the small additional distance due to atmospheric diffraction of the wave around the curvature of the earth. The intensity of the electric field of the direct wave varies inversely with the distance. The direct wave is not affected by the ground or by the earth's surface, but it is subject to refraction in the tropospheric air between the transmitter and receiver.

(2) Ground-Reflected Component. The ground-reflected wave is that component of the entire wave that reaches the receiving antenna after being reflected from the ground or from the sea. Upon reflection from the earth's surface, the reflected wave is reversed 180 degrees in phase; this fact is important in determining the resultant effect when the reflected wave combines with the direct wave at the point of reception. Since the ground reflected wave travels a longer time in reaching its destination than does the direct wave, its phase is displaced an additional amount over and above the 180-degree shift caused by reflection.

(3) Surface-Wave Component. The surface wave is that component of the entire wave that is affected primarily by the conductivity and dielectric constant of the earth, and is able to follow the curvature of the earth. When both the transmitting and receiving antennas are either on, or close to, the ground, the direct wave and the ground-reflected wave tend to cancel each other, and the remaining field intensity is principally that of the surface wave. The surface wave extends to considerable heights above the earth's surface, diminishing in

field strength with increased height. Part of its energy is absorbed by the ground, resulting in a greater rate of attenuation than the rate due to the inverse of the distance. The surface-wave component generally is transmitted as a vertically polarized wave, retaining this polarization at appreciable distances from the antenna. This polarization is chosen because the earth has a short-circuiting effect on the electric intensity of a horizontally polarized wave, but offers resistance to the electric component of a vertical wave. The ground currents of the vertically polarized surface wave do not short-circuit a given electric field, but rather serve to return part of the stored energy to the following field. The better the conducting surface, the more energy returned and the less energy absorbed.

(4) Tropospheric-Wave Component. The tropospheric wave is that component of the entire wave which is refracted in the lower atmosphere by relatively rapid changes in humidity with respect to height, and sometimes by rapid changes in the density and temperature with respect to height. At heights between a few thousand feet and approximately one mile, huge masses of warm and cold air exist near each other, causing abrupt temperature differences and changes in density. As a result, reflection and refraction in the troposphere make possible the propagation of the ground wave over distances far greater than can be covered by the ordinary ground wave.

c. The Ionosphere. The earth's atmosphere extends up to a distance of over 200 miles. Since the density of the gases which compose the atmosphere decreases with height, the air particles at a height of 250 miles are so rare as to be almost nonexistent. The atmosphere is in a constant state of bombardment by radiation and particle showers from the sun, and by cosmic rays from an unknown source. The radiation from the sun includes the components of the entire spectrum, ranging from infrared rays to ultraviolet rays, and and particle showers composed of positrons and electrons moving at nearly the speed of light. As these different forms of radiation approach the earth's atmosphere, they reach certain critical levels where the gases are of such density as to be particularly susceptible to ionization, and at these levels ionized layers are formed. It has been found that there are four distinct layers of the ionosphere, which are called, in order of increasing heights and intensities, the D, E, F_1, and F_2 layers. The four layers are present only during daylight hours, when the sun is directed toward that portion of the atmosphere. During the night, F_1 and F_2 layers seem to merge into a single F layer, while the D and E layers fade out, due to the recombination of the ions composing them. It has been found, in addition, that the actual number of layers, their heights above the earth, and the relative intensity of ionization present in them vary from hour to hour, from day to day, from month to month, from season to season, and from year to year. These layers in the ionosphere are commonly referred to as the Kennelly-Heaviside layers, in honor of the two men who were first to propose the idea of the existence of the ionosphere.

d. Sky-Wave Propagation.

(1) Sky-wave propagation generally refers to the transmission of electromagnetic energy which depends upon, and makes use of, reflections from the layers in the ionosphere. The principal ionosphere characteristics which control the reflection of electromagnetic waves back toward the earth are the height and the ionization density of each of the layers. The higher the frequency, the greater the density of ionization required to reflect waves back to earth. In other words, the shorter the length of the waves, the denser, or more closely compacted, must be the medium to refract them. Therefore, the upper layers, which are the most highly ionized, reflect the highest frequencies, whereas the D layer, being the least ionized does not reflect frequencies above approximately 500 kHz. Thus, at any given time for each layer there is a value of highest frequency, called the "critical frequency," at which

waves sent vertically upward are reflected directly back to earth. Waves of frequencies higher than the critical frequency pass on through the ionized layer and are not reflected back to earth, unless they are reflected from an upper layer. Waves of frequencies lower than the critical frequency are reflected back to earth, unless they are absorbed by, or have been reflected from, a lower layer.

(2) Although the critical frequency, when determined by vertical propagation as explained in the preceding paragraph, marks a boundary condition in that all frequencies at or below the critical frequency will be returned to earth, it is to be noted that other frequencies above the critical frequency also will be returned to earth if they are propagated at certain angles of incidence. At angles of incidence near the vertical, a given frequency may pass on through the ionosphere. But as the angle of incidence is decreased, an angle is reached at which the wave is reflected back to earth. This angle is called the "critical angle." The distance, on the earth's surface, to the point at which the wave returns is called the "skip distance;" as the angle of incidence decreases, the wave returns at greater and greater distances, or, in other words, the skip distance increases.

(3) The distance at which the wave returns to the earth depends on the height of the ionized layer and the amount of bending of the path while traversing the layer, the latter depending on the frequency of the wave as compared to the ion density of the layer required to refract or bend the wave. Upon return to the earth's surface, part of the energy enters the earth and is rapidly dissipated, while part is reflected back into the ionosphere again, where it may be reflected downward again at a still greater distance from the transmitter.

e. Directed Radiation.

(1) In present day radio transmission, utilizing frequencies that are extremely high, it is necessary to concentrate the transmitted energy into a narrow beam and to direct this beam toward the desired receiver, much like the headlamp of an automobile focuses a light beam. This is necessary for two reasons: to realize a greater signal at the receiving antenna, and to avoid transmission of the signal in undesired directions where unfriendly receivers may be loacted. At extremely high frequencies, single-wire antennas, or arrays, become less efficient because of the small physical size for a half wavelength and consequently high radiation resistance. Since the radiation properties of extremely high, or microwave, frequencies approach those of light waves, their propagation can be directed by reflecting surfaces placed in their path. These reflecting surfaces can be properly spaced elements acting in parasitic fashion, additional driven elements properly spaced or oriented, or a parabolic-shaped reflecting device.

(2) A reflecting surface in the shape of a parabola, having at its focal point the source of rf energy, will focus most of the radiated power in more or less parallel lines, forming a relatively narrow beam in which the rf energy is of high concentration. Some of the energy, however, does escape from the main beam and is dispersed at various angles in the immediate vicinity of the reflector.

f. Power Densities in a Typical Radar System.

(1) Significantly different levels of electromagnetic energy exist in each radar system. In the typical radar system shown in figure 6-4, the highest power density exists within the transmission line, which normally is closed and therefore not readily accessible. Power density, expressed in terms of average watts per square centimeter, is given approximately by the equation:

$$W = \frac{P_t}{A_{tl}}$$

where: W = power density, in average watts per cm^2

P_t = average power output of transmitter, in watts

A_{tl} = cross-sectional area of transmission line, in cm^2

It should be noted that the power is not distributed uniformly over the entire area of the transmission line, as implied by the equation above, but the equation gives a close approximation.

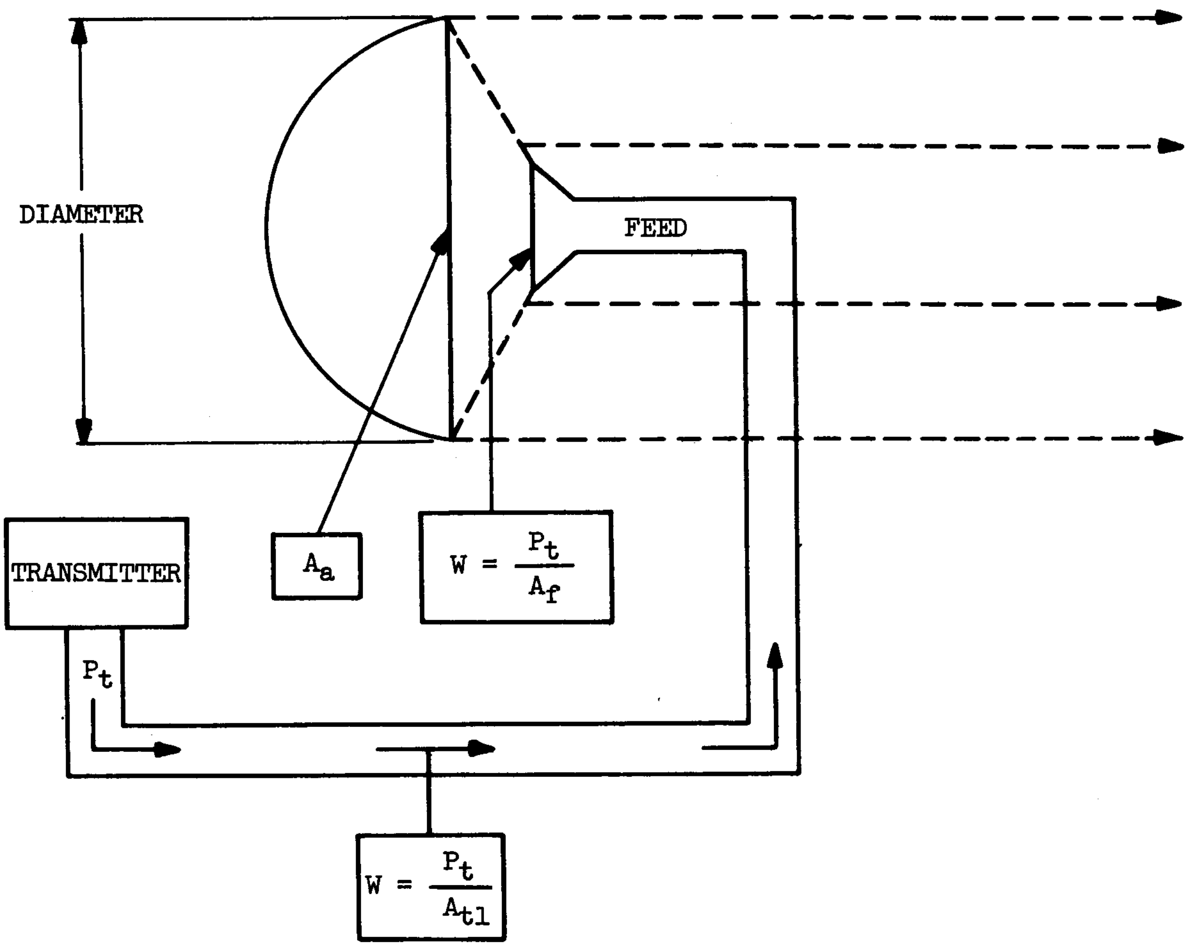


Figure 6-4. Power Densities in a Typical Radar System

(2) The transmission line conveys the power to an antenna feed, which in turn feeds the energy on to the antenna. Before reaching the antenna, the energy from the feed is propagated through space which ordinarily is not enclosed, and is therefore more accessible to personnel than is the inside of the transmission line. The power density in the aperture of the feed is given, again approximately, by the equation in the preceding paragraph, except that the feed aperture A_f is now used instead of A_{tl}. Since the feed aperture, A_f, is usually larger than the cross-sectional area of the transmission line, A_{tl}, the power density in the feed aperture is usually less than that in the line.

(3) From the antenna, the electromagnetic energy is radiated into free space, to enable the system to perform its function. While the energy is traveling through space, it cannot be controlled; this fact constitutes one of the biggest problems in combatting the possible hazards due to this radiation.

(4) The manner in which a parabolic antenna radiates its energy is somewhat complicated and is subject to many variations. For purposes of simplicity and generalization, this process may be depicted as shown in figure 6-4. The available power, P, furnished by the transmitter through the transmission line and the antenna feed to the antenna itself, is radiated outward from the antenna in a direction normal to the antenna aperture in most cases (but with very important exceptions in other cases). In order to obtain useful beams with low side lobes, the energy is "tapered" across the aperture in a manner illustrated in figure 6-5 for different type antennas. The taper decreases the applied energy smoothly from a maximum at the center of the aperture to a typical value of 10 dB (one-tenth) down from maximum at the aperture extremities. This distribution of energy across the antenna aperture is commonly called the antenna illumination. Paragraph g below provides the general space distribution of the transmitted power leaving the antenna for the more common antenna illuminations of cosine or $(1-r^2)$ with a typical taper of 10 dB.

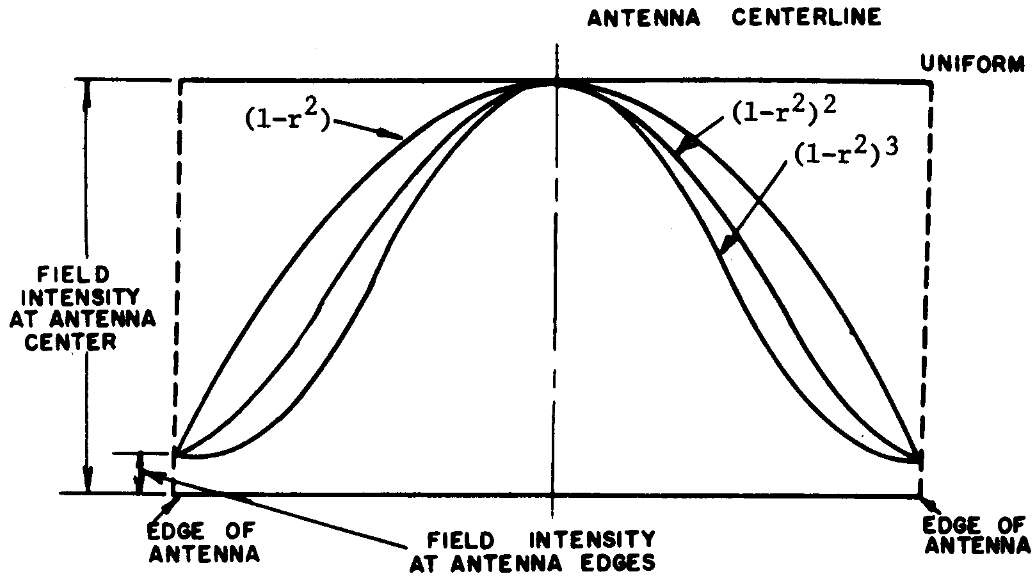
g. The Fresnel Region, or Near Field. After the electromagnetc energy leaves the aperture, its intensity varies with distance from the antenna as shown in figure 6-6. At distances relatively close to the antenna, in the area known as the "Fresnel" (or near field) region as given approximately by the equation below, the power remains fairly constant with distance, and is collimated in a beam of about the same size as the projected area of the aperture.

$$D_{Fresnel} = D < \frac{1}{4}\left[\frac{L^2}{\lambda}\right]$$

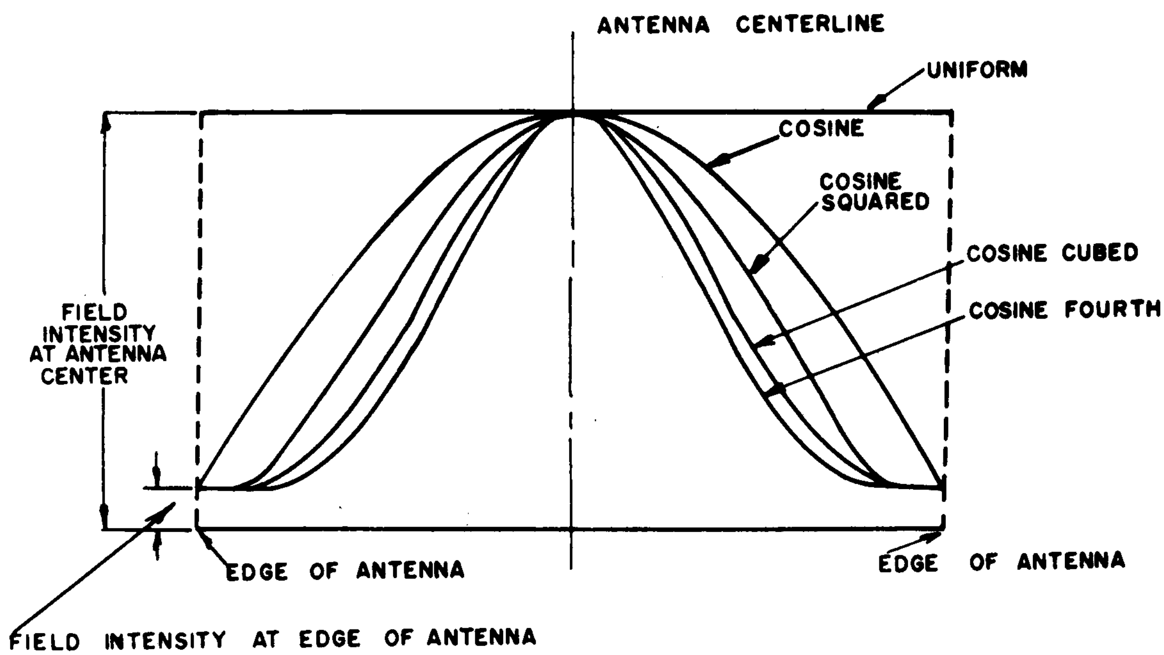
where: D = distance from antenna, in feet

L = antenna aperture dimension, in feet

λ = wavelength, in feet



(A)
ILLUMINATION OF ANTENNAS WITH CIRCULAR APERTURES



(B)
ILLUMINATION OF ANTENNAS WITH ELLIPTICAL OR RECTANGULAR APERTURES

Figure 6-5. Field Intensity Distribution Across an Antenna

As indicated in figure 6-6, the energy is not distributed uniformly across the beam because of the taper described in the paragraph above. The approximate power densities at the beam center and beam edges are:

$$W_{\text{beam center}} \approx \frac{3P_t}{A_a}$$

$$W_{\text{beam edges}} \approx \frac{P_t}{3A_a}$$

(inside Fresnel region)

where: A_a = antenna aperture projected area

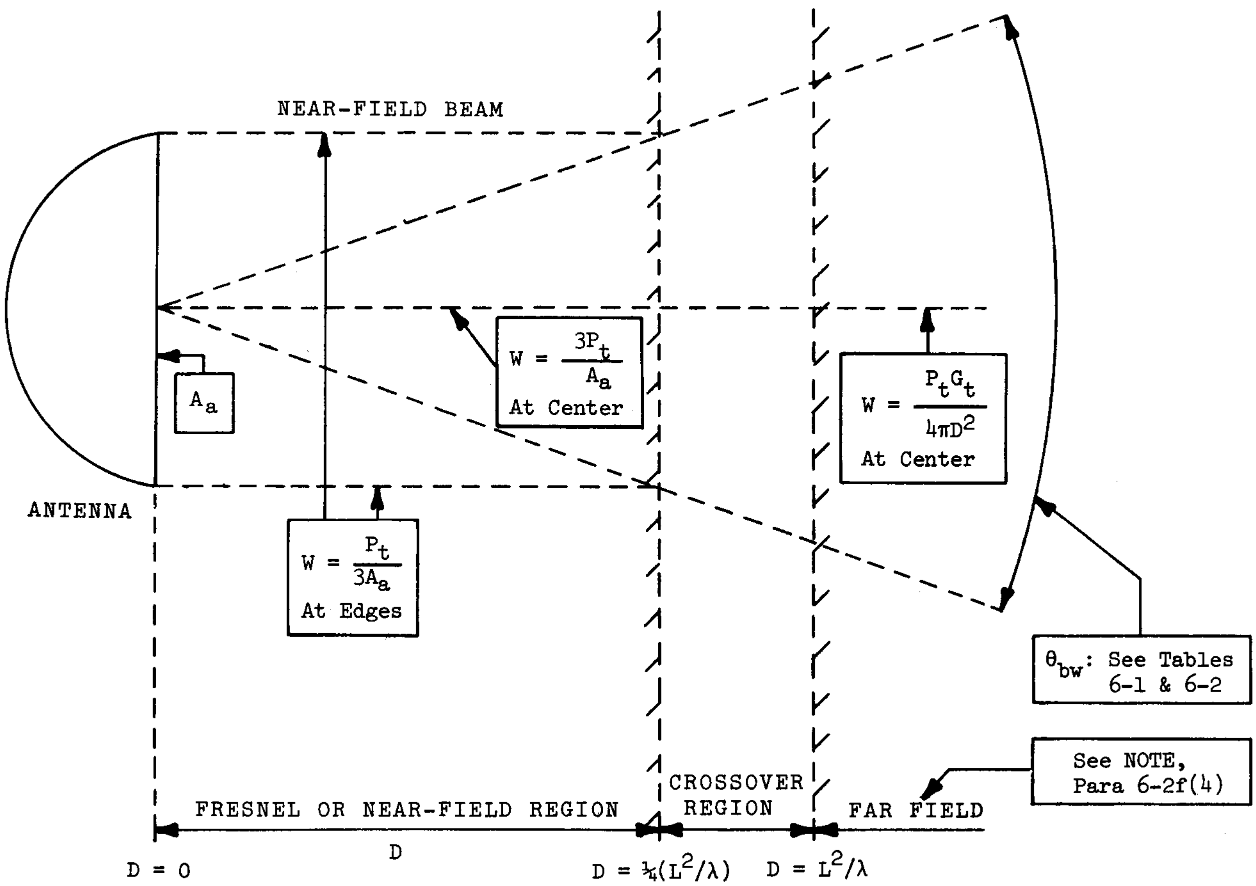


Figure 6-6. Distribution of Energy in Transmitted Beam

h. The Fraunhofer Zone, or Far Field. Beyond the Fresnel region, the radiated beam begins to spread out and the power density along the beam axis decreases with distance. At some distance the antenna appears to be a point source and the power density obeys the inverse square law. This is where the "Fraunhofer Zone," or far field begins. The distance to the far-field boundry (D_f) can be designated as:

$$D_f = \frac{2L^2}{\lambda}$$

where the actual on-axis power has reached 99% of the value obtained from the inverse square formula, or:

$$D_f = \frac{L^2}{\lambda}$$

where the actual on-axis power has reached 94% of the value obtained from the inverse square formula.

NOTE

D_f is limited to a minimum of 3 λ

A region of transition exists between the Fresnel and Fraunhofer fields, as shown in figure 6-6, this is known as the "quasi-Fresnel," or cross-over region. In the Fraunhofer region, the radiation is in a diverging beam shape, where the intensity is maximum at the beam center, and decreases away from the beam center as the angle of divergence increases. If the antenna is made larger or the antenna illumination is made more uniform, the radiated beam is made narrower and the beam center power density is made higher. Tables 6-1 and 6-2 express the half-power beamwidths for the different antenna illuminations in terms of the antenna diameter and the wavelength of the radiated wave. Another way of expressing the concentrating action of an antenna is by "its gain." Thus, a large antenna with a narrow beam has a large gain. The effects of the beam broadening due to antenna illumination is a Fraunhofer gain reduction. This "gain factor" is listed in tables 6-1 and 6-2 and normalizes the gain of ideal antennas with the different illuminations to the gain of an ideal uniformly illuminated antenna. In terms of gain, which is a pure number and can be furnished for each antenna, the power density at the beam center in the Fraunhofer region is given by the equation:

$$W_f = P_t G_t / 4\pi D^2$$

where: G_t = antenna power gain

W_f = Far-field power density

Table 6-1. Beamwidths, Gain Factors, and Side lobes of Rectangular and Elliptical Antennas with Various Illuminations

ILLUMINATION	GAIN FACTOR	HALF-POWER BEAMWIDTH θ (DEGREES)	FIRST SIDELOBE DB BELOW MAIN BEAM INTENSITY
Uniform	1.00	$\frac{50.4\lambda}{L}$ to $\frac{68.7\lambda}{L}$	13.2
Cosine	0.81	$\frac{68.7\lambda}{L}$ to $\frac{83\lambda}{L}$	23
Cosine Squared	0.667	$\frac{83\lambda}{L}$ to $\frac{95\lambda}{L}$	32
Cosine Cubed	0.575	$\frac{95\lambda}{L}$ to $\frac{110\lambda}{L}$	40
Cosine Fourth	0.515	$\frac{110\lambda}{L}$ to $\frac{116\lambda}{L}$	48

Table 6-2. Beamwidths, Gain Factors, and Side Lobes of Circular Antennas with Various Illuminations

ILLUMINATION	GAIN FACTOR	HALF-POWER BEAMWIDTH θ (DEGREES)	FIRST SIDELOBE DB BELOW MAIN BEAM INTENSITY
Uniform	1.00	$\frac{58.5\lambda}{L}$ to $\frac{72.8\lambda}{L}$	17.6
$(1-r^2)$	0.75	$\frac{72.8\lambda}{L}$ to $\frac{84.2\lambda}{L}$	24.6
$(1-r^2)^2$	0.56	$\frac{84.2\lambda}{L}$ to $\frac{94.5\lambda}{L}$	30.6
$(1-r^2)^3$	0.44	$\frac{94.5\lambda}{L}$ to $\frac{103.5\lambda}{L}$	—

i. Power Level on the Main Beam Axis.

(1) Some of the information given in previous paragraphs of this section may be summarized as follows: First, the power level radiated by a typical beam-forming antenna remains in a beam of approximately the same area as the projected area of the aperture, as far as the limit of the Fresnel, or near-field region. Within this region, the power along the axis of the beam is highly concentrated, having a power density of approximately three times the power density measured across the aperture of the antenna, expressed in average watts per

square centimeter, due to the concentrating effects of the reflector. Beyond the Fresnel region and as far as the limit of the quasi-Fresnel region, or between the distances of $1/4(L^2/\lambda)$ and L^2/λ (antenna aperture diameter squared divided by wavelength, both in feet), the beam spreads out and the concentration of power along the axis of the beam begins to decrease from the value given above. The power density decreases until it reaches a value, at the beginning of the Fraunhofer zone (which is at a distance of L^2/λ), where the power density is approximately equal to the total average power P_t multiplied by the power gain G_t of the antenna, divided by the quantity 4π times the square of the distance from the antenna. This is given by the formula:

$$W_f = P_t G_t / 4\pi D^2$$

At greater distances, it can be seen that the power level, or density, along the main beam axis, continues to fall off in proportion to the square of the distance.

(2) Figure 6-6 provides a convenient picture of the near field and cross-over region beam power distribution. In practice the transfer from collimated beam radiation to linear beam divergence would not be so abrupt. The beam cross-section would start spreading slowly at a point at a distance of $1/6(L^2/\lambda)$ to $1/4(L^2/\lambda)$ and would gradually diverge at a larger angle until linear divergence is nearly reached at L^2/λ. Therefore, in the near-field and cross-over region, the transmitter power is distributed over a greater area than that presented by a discrete antenna center point radiating at the divergent angle present in the Fraunhofer region. The beam is less concentrated than indicated by the formula $W_f = P_t G_t / 4\pi D^2$. The antenna gain is then less than in the Fraunhofer region and a gain reduction factor must be applied to the antenna Fraunhofer gain.

j. Power Level off the Main Beam Axis.

(1) The power level, or density, off the main beam axis depends upon a number of variables, so that only an approximation can be given by calculations. For the different illuminations of the type antennas noted in tables 6-1 and 6-2, the narrowest beamwidth of the beamwidth range would apply to an ideal antenna. The beamwidth of the actual antenna will be broadened from that of an ideal one, due to imperfect illumination, imperfect reflector surface, and aperture illumination phase errors. Centered about the main beam are separate and individual beams of energy of lesser amplitude called "side lobes." The forward side lobes can be attributed to illuminated energy in proximity to the antenna edge discontinuity. Note the relation of the side-lobe levels to the energy in the area near the antenna edge as shown for different illuminations of tables 6-1 and 6-2 (reference can be made to figure 6-5 for energy near the antenna edge for the different illuminations). The diffraction of the spill-over energy at the antenna edge and the energy transmission through the imperfect reflector contribute to like back lobes from the antenna. The result of the above combined effects is a loss of a portion of the transmitter power in directions other than that of the main beam axis. The relation of the main beam axial power concentration (antenna gain) to the theoretical antenna gain is referred to as the "antenna efficiency." The antenna efficiency varies from 50% to 90% for antennas designed to concentrate all the transmitter power within a narrow beam along the vertical and the horizontal axis. For antennas where reflector shape is made to form a cosecant-squared pattern along the vertical axis, this antenna efficiency varies from 35% to 60%. The theoretical antenna gain will vary with the type illumination employed. The theoretical antenna gain will be greatest for uniformly illuminated antennas where the

narrowest beamwidth is developed. The "antenna gain factor" is the factor by which the theoretical antenna gain of a uniformly illuminated antenna must be multiplied to obtain the theoretical antenna gain of an antenna with an illumination other than uniform along an axis. This gain factor must be separately applied for each axis illumination when applied to elliptical or rectangular antennas. The gain factors for different antenna illuminations are shown in tables 6-1 and 6-2.

(2) Due to the effects of paragraph (1) above further clarification of figure 6-6 is necessary. Since the illumination energy in the vicinity of the antenna edge is diffused, diffracted, and radiated in a direction governed by the antenna edge discontinuity, energy along the edge of the collimated radiation region cross-section decreases to a very low figure in a short distance from the antenna. Decrease of the antenna illumination level becomes less in the near field when progressing from the collimated area edge toward the center of the area. More specific calculations for finding the approximate power density at the center and at various distances off the center of the main beam axis within the close-in region are given in Section II of this chapter.

k. Reflection, Refraction, and Scattering.

(1) As previously pointed out in this chapter, the two principal ways in which radio waves radiated from a transmitter travel to a receiver are by means of ground waves and sky waves. The propagation of the ground wave is affected by the electrical characteristics of the earth (soil or sea), and by diffraction, or bending, of the wave with the curvature of the earth. Although these characteristics differ in different localities, they remain practically constant with time in any one given locality under most conditions. Skywave propagation, on the other hand, is variable, since the state of the ionosphere is always changing and, therefore, affects both the reflection and refraction of the sky wave.

(2) A radio wave may be reflected in a manner similar to that of any other type of wave. For instance, when a beam of light falls on the surface of a mirror, nearly all of it is reflected. In a similar manner, the efficiency with which reflection of radio waves occurs depends on the material of the reflecting medium. Large, smooth metal surfaces of good electrical conductivity, such as copper, are very efficient reflectors of radio waves, reflecting nearly all of the energy carried by the incident waves. The surface of the earth itself is a fairly good reflector of radio waves, particularly for waves that are incident at small angles from the horizontal. The ionosphere, even though it does not have a surface like that of a mirror, is also a fairly good reflector of radio waves.

(3) Reflection of waves is of importance in several ways. First, it provides a way of measuring the properties of material. A study of the constitutive properties of matter is often made by studying the fractional reflection and transmission of electromagnetic waves through matter. The reflectivity depends on the angle at which the wave strikes the boundary between the two media.

(4) The second important aspect of reflection is the standing-wave pattern in which the field intensity is greater or less than that in either separate traveling wave. A field with an intensity just at the threshold of safety (with respect to human exposure) in the absence of reflections can become hazardous at certain points when reflection occurs. Reflection is associated with dimensional resonance phenomena where the field amplitude builds up because the dimensions are such that successive reflections from walls or boundaries just overlay one another properly in space and time. Such dimensional resonances can occur in structures like the eyeball; the determining factor is the ratio of the wavelength (in the medium constituting

the eyeball) to the dimensions of the eyeball. The seriousness of the effect depends on the reflecting properties of the walls.

(5) The third important aspect of reflection is its bearing on any discussion of dosage. Consider a body, say a mouse, placed in a field whose intensity is known in the absence of the mouse. The free-space value may have little relevance to establishing a tolerance level for other animals, for what is important is the field within the mouse. To determine the latter, it is necessary to determine the reflectivity of the hair and skin.

(6) In addition to its ability to be reflected, a radio wave may also be refracted, in a manner similar to a beam of light. When a beam of light shines on a smooth surface of water, some of the light is reflected, and the remaining portion penetrates the water. The direction of travel of that portion which penetrates the water is different from that of the light beam incident to the surface of the water. This is so because the light passes from a less dense medium (air) to a more dense medium (water). In a similar manner, a radio beam is refracted when it passes through media of different densities. The amount that a wave is refracted as it passes from one medium to another, expressed by the ratio of the velocity of an electromagnetic wave through a perfect vacuum to its velocity through the denser medium, is called the "index of refraction."

(7) In somewhat recent years, extensive experiments have indicated that radio waves not only are reflected and/or refracted, but also are scattered, under certain conditions in the troposphere and in the lower ionosphere. The exact reason for, or the mechanism which causes, this scattering is not yet fully known. "Scattering" is the term given to the dispersing of the radio waves in various directions, in a sense similar to the manner in which the lens on the tail light of an automobile directs the light in all directions.

(8) Fluctuations in the humidity of the air are believed to play an important part in scattering, because of the large index of refraction of water vapor. Fluctuations in temperature at various altitudes may also contribute to the scattering phenomena. In the atmosphere there are layers in which the index of refraction changes as much as 30×10^{-6} over a distance of 100 meters, and rates of change of 10^{-2} to 10^{-3} per meter are quite common.

l. Absorption of RF Energy.

(1) In traveling through space, radio waves may be reflected, refracted, or scattered, as pointed out in previous paragraphs. Whenever the radio waves are so affected, some of the energy is absorbed at the point where the change of direction occurs. If conditions are favorable to the particular wavelength of the radio wave, it may happen that most, if not all, of the rf energy may be absorbed.

(2) When rf energy is absorbed by a body, using the term "body" in its broad sense to include any obstruction to the transmitted wave, the rf energy is converted into heat. The total amount of heat developed depends upon the field intensity of the rf energy and upon the area of the surface receiving the energy. The heat developed per unit area may, or may not, be in direct proportion to the actual size of the unit area. This is especially so when the unit becomes so small that it approaches the size of one wavelength. To explain this, it is necessary to consider how the electromagnetic field interacts with matter. Atoms and molecules are complexes of charge, and when placed in an electric field, their charge distribution becomes polarized. Some molecular systems, such as many molecules in living

tissue, already have charge distributions which are polar; that is, the center of gravity of the negative charge is displaced from that of the positive charge. All membranes have polar structure. In a time-varying field the polarization vibrates and, by virtue of interaction between different elements of the molecular system, the electrical energy is transformed into heat. This is the dominant phenomenon in what may be termed the low-amplitude region. The hazard of radiation in this region is purely thermal. The destruction of tissue is a secondary process resulting from the generation of heat. If the intensity of radiation is low so that the rate of generation of heat can be handled by the distribution processes in the organism, the result is only discomfort. When the intensity of radiation increases, not only does heat generation increase, but also another effect comes into play. The enforced redistribution of electric charge under the applied field can be so great that a complete reorganization results. This is the so-called process of field-induced transitions.

(3) Man, a biped, when in the erect position is potentially a long cylindrical antenna. Quadruped mammals, such as dogs, likewise may be expected to act more or less like antennas depending upon their size, length of head, tail, and body, and the manner in which they stretch out in a polarized electromagnetic field. Results of experiments indicate that when the longitudinal axis of the body corresponds, in its position, more or less to the plane of polarization, heating occurs more rapidly and more extensively than when the longitudinal axis is 90° away from the plane of polarization. Since more heat is developed within the body, it is apparent that more rf energy is absorbed.

(4) Sometimes it is necessary to intentionally absorb rf energy, in order to shield an area from radiation. Commercial materials such as impregnated hair, absorbent foam, and resistive cloth are available for this purpose.

(5) There are occasions when it is desirable to know to what degree electromagnetic energy will be attenuated in passing through various materials. Tests have been performed at Rome Air Development Center on some representative materials to determine such attenuation. Results of some of these tests are listed in the following paragraphs, along with the test conditions.

(a) Wood Frame Building. Tests were made on a portion of a wood frame building, of the following construction:

5-1/2" x 3/4" tongue-and-groove inner siding

5-1/2" x 7/8" clapboard outer siding (no tar paper between layers)

Inner wall unfinished

2" x 4" studding, spaced on 16" centers

At three test frequencies, power absorption was found to be as follows:

Frequency (MHz)	dB Down (Power)
1300	2.0
2800	3.1
9200	1.3

Since the inner wall of this building was unfinished, and since no tar paper was used between the two layers of wood siding, additional tests were made at one frequency (9200 MHz) on several interior finishing materials, as follows:

Material	dB Down (Power)
Plain tar paper (lightweight) 0.074" thick	2.5
Pressed cardboard 0.351" thick	2.8
Plaster board 0.362" thick	1.0

(b) Cinder-Block Wall. Power absorption tests were made on a wall built of cinder blocks which individually measured 16 inches long, 8 inches high, and 7-1/2 inches thick. The tests were made at three frequencies, with the following results:

Frequency (MHz)	dB Down (Power)
1300	11.4
2800	14.5
9200	20.5

(c) Microwave Absorbent Material. Power absorption tests were made at two frequencies on microwave absorbent material (Hairflex-Sponge Rubber Product), 2' x 2' x 4" thick. The power absorption was found to be as follows:

Frequency (MHz)	dB Down (Power)	
	(wet)	(dry)
1300	13.6	13.8
9200	25.0	25.0

(d) Copper Wire Screen. Tests were made at two frequencies on the power absorption of copper wire screen, having 19 wires (0.018" diameter) per inch. Absorption was found to be as follows:

Frequency (MHz)	dB Down (Power)
1300	20
9200	24

m. Transmission Through Waveguides.

(1) Transmission of electromagnetic waves by reflection from layers in the ionosphere was discussed previously, in paragraph 6-3d. After reflection in the ionosphere, the wave, returning to earth, may again be reflected back to the ionosphere. This process may continue, under ideal conditions, until the wave completely encircles the earth. This can be visualized by considering that the wave is guided by two conducting layers --- the earth and the

ionosphere --- in its travel. Instead of the earth and the ionosphere, two flat metal plates separated by only an inch or so may be used as conducting layers to guide an electromagnetic wave. If an electromagnetic wave of very short wavelength is fed between the plates by means of a very small dipole antenna, the wave will be confined and will be reflected back and forth between the plates in its travel. If two more metal plates are added to make a long, rectangular tube which completely confines the wave and prevents it from moving sideways out of the confines of the two original plates, the result is an efficient conductor of very short electromagnetic waves. This tube, which can also be of cylindrical cross-section instead of rectangular, is called a "waveguide."

(2) It is necessary that the wavelength of the electromagnetic wave applied to the waveguide be sufficiently short in order to be conducted through the guide. For a waveguide of given internal cross-sectional dimensions, a particular value of wavelength called the "cutoff wavelength" may be calculated. Any wavelength shorter than the cutoff wavelength will pass through the waveguide, while any longer wavelength will not pass through. This value of cutoff wavelength, for a rectangular waveguide, is approximately equal to twice the internal width dimension of the waveguide.

(3) The transmission of electromagnetic waves may be accomplished in either of two ways: by radiating them from an antenna or by conducting them through a waveguide or similar type of transmission line. When radiated from an antenna, the waves are unguided in that they spread out after leaving the antenna, because the rays of the beam are not parallel. Even though the waves may be concentrated into a narrow beam by means of a directional antenna, the energy is distributed over an increasingly large cross-sectional area as the distance from the antenna increases. When conducted through a waveguide, on the other hand, the energy is restricted to the constant cross-sectional area within the waveguide. Except for the attenuation of the energy due to copper loss along the walls of the waveguide, nearly all of the transmitted energy reaches its destination.

n. Standing Waves.

(1) When radio waves are fed to a wire conductor of infinite length, the rf waves of electromagnetic energy move along the wire. Because of the electrical resistance of the wire, the amplitude of the waves gradually diminishes, but the waves continue to travel as long as the wire does not come to an end. These waves of energy are called "traveling waves."

(2) In practice, however, a wire conductor (such as an antenna) has a finite length. Therefore, the traveling waves stop abruptly when they reach the end of the wire. At this point, since the current has stopped flowing, the magnetic field surrounding the wire collapses, and in doing so, the collapsing lines of force cut across the wire and induce a voltage in the wire, according to Lenz's law. This voltage causes a current to flow back toward the initial source. If a continuous succession of waves is fed to the wire, they will be continually reflected back toward the source. The waves moving from the transmitter toward the end of the wire are called "incident waves," while those which are reflected back are called "reflected waves."

(3) With a continuous flow of incident waves away from the transmitter and a continuous flow of reflected waves returning toward the transmitter, it is obvious that these waves, traveling in the same conductor, must pass each other. At certain points along the conductor both the incident and reflected waves will reach their maximum positive (or negative) values, at the same instant. At these points they reinforce each other. At certain other points along the conductor both of the waves reach a zero value at the same time; here

the resultant wave is zero. In a conductor, such as an antenna, which has a finite length, the points at which the resultant wave reaches its maximum (positive or negative) and its zero values are stationary. This is so, even though both the incident and reflected waves are moving. Since the resultant wave, in effect, stands still on the line, with only its amplitude changing from maximum positive, through zero, to maximum negative values, the wave is referred to as a "standing wave."

(4) When electromagnetic energy is transferred from a transmitter to an antenna, especially when they are located some distance apart, a transmission line of some form is used to conduct the energy. At the input end of the transmission line, the ratio of voltage to current is termed the "input impedance." At the output end of the line the ratio of voltage to current is termed the "output impedance." If the transmission line is of infinite length, the input impedance is called the "characteristic impedance" of the line. If the infinite line is now shortened to some finite length, and the line terminated by a load whose impedance is equal to the characteristic impedance of the line, the same impedance will appear at the input end of the line, or, in other words, the input impedance will remain the same. No matter how short the line is made, provided the line is terminated by its characteristic impedance, the input impedance will remain the same as if the line were an infinite line. Since an infinite line cannot contain standing waves, neither can a line of any length contain standing waves if the line is terminated by its characteristic impedance.

(5) When a line of a given length is terminated in its characteristic impedance, with the result that no standing waves appear on the line, and either the line or the termination is changed, then standing waves will again appear on the line, because the impedance has been changed. This may happen if a joint or point of coupling in a waveguide becomes loose. The loosened joint causes the impedance at this point to increase, giving an effect similar to a change in termination. The line impedance no longer matches the load (termination) impedance, and the result is a mismatch in impedance, and standing waves on the line.

o. Directional Antennas.

(1) Electromagnetic energy can be reflected in a similar manner to light energy, and under the same condition in that the physical dimensions of the reflector must be large compared to the wavelength of the energy to be reflected. Metallic reflecting surfaces in the shape of a parabola may be used to beam the energy in a manner similar to the beaming of light rays by the headlamp of an automobile. This type of beam transmission finds most use at the ultrahigh frequencies, where the physical dimensions of the radiating elements are small. By the use of two or more antennas properly spaced and phased, directional transmission may also be realized, by causing the radiated signals from the antennas to add in the preferred direction and to subtract, or cancel, in other directions.

(2) Two-Element Array. If two antennas A and B, such as dipoles, positioned vertically and parallel to each other, and spaced a half-wavelength apart, are excited in phase, the radiation from them is concentrated along a line passing between them at right angles to their plane. This is so because the radiation from each dipole will add, in phase, in the directions at right angles to their plane. The radiation in the plane of the two antennas, however, is negligible, because the energy from dipole A, in traveling the half-wavelength to dipole B, arrives at dipole B exactly reversed in phase by 180 degrees (a half-wavelength), and the two fields cancel each other.

(3) If the two antennas A and B, still positioned vertically and parallel to each other, are now spaced one-quarter wavelength apart and excited with equal currents which differ in phase by 90 degrees, the radiation from them will be concentrated in one direction along a line

in the plane of the antennas. If antenna A radiates toward antenna B a current which, instantaneously, is at zero degrees in phase, the current will reach antenna B a quarter-wavelength, or 90 degrees, later. If, at this instant, antenna B is fed and radiates a current which is 90 degrees later in phase than the current fed to antenna A, the two radiated currents will be in phase in this direction from A to B, and the fields will add to each other. In the reverse direction, however, if antenna B radiates its current, which is 90 degrees later in phase, in the direction toward antenna A, the current from antenna B will reach antenna A delayed another quarter-wavelength or 90 degrees, which means it will be exactly 180 degrees out of phase with the current from antenna A, and thus will cancel any radiation in the direction from B to A. At other angles the waves will add vectorially to give intermediate values of radiation.

(4) Broadside Array. If two, or multiples of two, horizontal antennas, each a half-wave long, are located in line and fed in phase at the point between each pair, with additional groups of these antennas stacked a half-wavelength apart above and below the first group, the result is called a "broadside array." Without a reflector this antenna would radiate a narrow beam of energy in the two directions at right angles to the plane of the antennas. If a similar array of parasitic reflectors, or a metal sheet or metal screen reflector, is located between one-tenth and one-quarter wavelength behind the antenna elements, the radiation will be confined in a narrow beam approximately 20 degrees wide in the single direction away from the reflector. The pattern of the radiated energy will become narrower in the horizontal plane as the number of pairs of elements alongside each other is increased. The radiated pattern will become narrower in the vertical plane as the number of stacks, one above the other, is increased. Arrays of sixteen elements, arranged in four rows of four each, have been commonly used in the past in heavy ground radar equipments, and much larger arrays are being used at the present time, radiating tremendous amounts of power, often at very low angles above the horizon.

p. Transmission from Microwave Antennas.

(1) When electromagnetic energy of frequencies in the microwave region is to be transmitted, the waveguide becomes the principal means of transmission. Waveguides are used, basically, in three applications, namely, to transmit energy, to radiate energy, and to obtain resonance under certain conditions. The transmission of energy through waveguides has already been discussed in a previous paragraph. In addition to transmitting the energy from the source to the load, a waveguide which is being fed electromagnetic energy will radiate energy if the end of the waveguide is left open. However, the termination is seldom of the proper impedance, resulting in mismatch and the creation of standing waves; therefore, a waveguide has low efficiency as an antenna.

(2) Waveguide Antennas. Electromagnetic energy may be put into, or may be removed from, waveguides by the same means. In the case of waveguides which are transmitting energy, the output end may be left open. Some of the energy is radiated into space, but a considerable portion of the energy is reflected because of the mismatch of impedances between the open end of the waveguide and the space beyond, causing standing waves to be set up within the waveguide. In order to eliminate the reflections and terminate the waveguide properly for maximum transfer of energy, the opening at the end of the guide may be flared in the shape of a horn. If the flaring is of the proper shape and dimensions, it will effectively match the impedance of the waveguide to the impedance of free space.

(3) Electromagnetic Horns. Horn radiators are often used to obtain directive radiation when the wavelength is in the microwave region. At this range of frequencies they are very practical because the physical dimensions, which must be large compared to the operating

wavelength, are not unduly large. Since horn radiators do not contain resonant elements, they are usable over a wide frequency band. In operation as a means of directing electromagnetic waves, an electromagnetic horn is similar to an acoustical horn. They differ in one respect, however, in that the physical dimensions of the throat of an acoustic horn are usually much smaller than the sound wavelengths for which it is used, while the dimensions of the throat of an electromagnetic horn are comparable to the wavelength being transmitted. The application of horn radiators is not confined to waveguide operation, although they are readily adapted for use with waveguides. A horn radiator serves not only to match the impedance of the waveguide to that of the external space, but also to produce directed radiation. The shape of the horn, along with the dimensions of the mouth, measured in wavelengths, determines the shape of the radiated field pattern for a given magnitude and distribution of phase across the mouth of the horn. In general, as the opening of the horn is increased in size, the more directive is the resulting field pattern. With an aperture of approximately five wavelengths, a radiated major lobe of approximately 30 degrees is produced. The flare angle, which is the included angle across the sides of the horn, determines in large part the major lobe of the radiated field pattern. With a rectangular waveguide and horn, a very narrow lobe, or highly directive pattern, is produced when the flare angle is 60 degrees. Reducing the angle to 20 degrees approximately doubles the width of the lobe, while at zero degrees (which is the open-ended waveguide) the lobe is approximately four times the width at 60 degrees.

(4) Lenses. In the same manner as a lens made of glass is used to focus a beam of light, so can a lens made of plastic be used to focus a beam of electromagnetic energy. A lens made of metal may also be utilized for this purpose. The metal lens is actually composed of a large number of small waveguides, arranged symmetrically in concentric circles, to give the general over-all shape of a convex lens. At the focal point a dipole with reflector, or a horn, is located. The rays of electromagnetic energy that are emitted from the dipole or horns, diverge toward the lens, where the waveguides composing the lens act to refract the rays to form a highly directional, concentrated beam in which the rays are essentially parallel. This action is similar to that of a convex lens, which when placed at a distance equal to its focal length from a point source of light, refracts the divergent light rays from the source to form a beam of light in which the rays are parallel.

(5) Pencil-Beam Antennas. Very directive, or pencil, beams of radiated energy, in which the radiation is restricted to small angles in both elevation and azimuth, may be produced by building up arrays of pairs of dipole elements (broadside arrays). When properly phased and equipped with reflectors and, in some cases, director elements, considerably narrower radiated beams may be obtained. Limitations to the directivity result from mechanical problems brought about in meeting the requirement of physical dimension versus wavelength ratio.

(6) To produce pencil beams when the wavelength is in the microwave region, the simplest and most practical method is to locate a point source of electromagnetic energy at the focal point of a symmetrical reflector (or lens). In the microwave region, the over-all size of the reflector (or lens) and the distance between the reflector (or lens) and the feed point can be made physically large enough so that the feed operates essentially as a point source.

(7) Fanned-Beam Antennas. While a pencil-beam antenna has the advantage of concentrating its radiated energy in a very narrow beam, this fact may become a disadvantage in an application such as radar target interception, because the beam covers a very limited area in space at a given instant. For use in the latter application it is often necessary to sacrifice some of the advantage in directivity, usually in a vertical plane, but still retain the directivity of the narrow beam in the horizontal plane. This is achieved by flaring, or

broadening, the beam vertically, by the use of a fanned-beam antenna. By maintaining a narrow beam in the horizontal plane, resolution of the target on the scope presentation is retained, while flaring the beam vertically increases the possibility of intercepting a target return in a random search scan. The resultant beam may be a simple fanned beam, with the original symmetrically circular beam "distorted" into a symmetrically elliptical beam, or it may take a form which is highly "distorted" from circular. The latter types are called "shaped-beam" antennas.

(8) Fanned-beam antennas may appear in several forms: a point source feeding an oval section of a parabolic reflector at its focal point; a line source from a rectangular aperture feeding a parabolic cylindrical reflector or portion of a cylinder; a point source between parallel plates to produce a rectangular aperture which is located at the focal point of, and feeds, a parabolic cylindrical reflector.

(9) Shaped-Beam Antennas. In order to reduce to a single scan the amount of scanning time required to completely cover, or explore, a region covering a wide angle in elevation, while at the same time holding to a narrow angle in azimuth, and to accomplish these requirements without wasting the transmitted power, a shaped-beam is necessary. Shaped-beam antennas are used on shipboard for surface scanning in azimuth; they provide a broad elevation pattern, to allow for the roll and pitch of the beam due to an unstabilized antenna. The beam must spread slightly downward from the antenna to the surface of the water, but then should follow the surface rather than continue in a fanshape toward a position beneath the water's surface, in order to conserve the power that would be wasted should the beam tend to penetrate the water. In azimuth the beam must be sharp, for accurate target location. This type of beam may be called a "sector-shaped beam."

(10) Shaped-beam antennas are also used on ground or aboard ship for height-finding. In this case the azimuth pattern of the beam must be relatively broad, so that the target will remain in the beam long enough to obtain elevation information. In elevation the beam must be sharp, for accurate height measurement. In order to allow relatively close targets traveling across the path of the beam to remain within the beam for the necessary period of time, a close-in broadening of the azimuth beam, equally on both sides of center, is required. This type of beam is called a beavertail-shaped, or double-cosecant theta, beam.

(11) Cylindrical Reflector Antennas. The cylindrical reflector antenna is a type of fanned-beam antenna, utilizing a line source to produce a rectangular aperture which feeds a parabolic cylinder. The beam from this type of antenna is broad in one plane and narrow in the other. When used in the conventional position with the axis of the cylinder in a horizontal plane, the beam is broad in that plane and narrow in the vertical plane. The reflector is in the form of a cylindrical parabola, with either open or closed ends. Cylindrical parabolic reflectors have a parabolic curvature in one plane, usually the horizontal plane, with no curvature in any plane perpendicular to this horizontal plane. The antenna which excites the parabola is normally placed parallel to the cylindrical surface, and located at the axis of the parabola. The focus should lie well within the mouth of the parabola, so that most of the energy radiated by the antenna will be intercepted by the reflecting surface, to produce the desired spread of the radiated beam.

(12) Spherical Reflector Antennas. The spherical reflector antenna is a type of pencil-beam antenna; when fed with a point source of electromagnetic energy located at the focal point of the reflector, it will produce a very directive or pencil-shaped beam in which the radiated energy is highly concentrated. The spherical reflector is often "shaped" to purposely broaden the radiated beam in a particular plane, as previously described in the discussion of shaped-beam antennas.

(13) Phased Array Antennas. The phased array antenna has an aperture that is constructed from many individual radiating elements such as horns, dipoles, slots, etc. The energy emitted from each element adds or subtracts according to the relative phase and amplitude to form the overall radiated pattern. The characteristics of the antenna are determined by the geometric position of the elements in the array and by the relative phase and amplitude of their exitation. The development of electronically controlled phase shifters and switches which can be controlled by a computer allows precise beam positioning without movement of the array. In addition to beam steering the radiation pattern can be controlled. Electronically controlling both beam position and pattern allows the phased array to perform multifunctions (tracking several targets while it continues to search).

(14) The fixed phase array allows the rf generator(s) to be physically located adjacent to the radiating element. Having multiple rf generators located at the radiator allows efficient radiation of very high power without the problems encountered in a single transmitter system with extensive waveguides and rotating joints.

(15) Some general characteristics of the phased array with the elements in a single plane (planar-array) are:

(a) The beam can be steered approximately 60 degrees from broadside in both azimuth and elevation.

(b) The number of radiating elements (N) which can be used in the array is limited by the maximum 3-dB bandwidth to be utilized.

(c) The maximum antenna gain (G) is in the broadside direction and is related to the number of radiating elements (N).

(d) The gain is reduced in relation to the angle (θ) by which the beam is steered away from broadside. "G" is approximately equal to broadside gain (cos θ).

(e) The 3-dB beamwidth increases in relation to the angle (θ) by which the beam is steered away from broadside. The 3-dB beamwidth is approximately equal to the broadside beamwidth/cos θ.

SECTION II

CALCULATING POWER DENSITY AND HAZARD DISTANCE

6-4. GENERAL. Hazard power density levels are usually exceeded only by systems with high gain antennas. The maximum power density at a given distance or maximum distance to a given power density can easily be determined by the far-field equation. However, since these high gain antennas are usually the aperture type and often the hazard level is only exceeded in the near field (where power distribution is a function of illumination taper) power densities and distances obtained with the far-field formula are often excessive. A mathematical process to obtain more realistic values is presented here. This process determines the antenna illumination taper and from illumination graphs determines the near-field gain reduction. This process can be used to predict the power density on-axis and off-axis in the main beam. Mathematical prediction is only a tool. Reasonable estimates of power density and hazard distance should be obtained if the input data is accurate.

6-5. PULSE SYSTEM CHARACTERISTICS. Figure 6-7 depicts the relationship of peak and average power versus pulse repetition time, etc. This may be found helpful when working on systems using pulse technique. From the figure:

$$(P_{pk})(d) = (P_{avg})(P_{rt})$$

where: P_{pk} = peak power, in watts
d = pulse width, in microseconds
P_{avg} = average power, in watts
P_{rt} = pulse repetition time, in seconds

To find Average Power:

$$P_{avg} = \frac{(P_{pk})(d)}{P_{rt}} = (P_{pk})(d)(P_{rf}) = (P_{pk})(d.c.)$$

where: P_{rf} = pulse repetition frequency in Hz
d.c. = duty cycle

To find Peak Power:

$$P_{pk} = \frac{(P_{avg})(P_{rt})}{d} = \frac{P_{avg}}{(d)(P_{rf})} = \frac{P_{avg}}{d.c.}$$

To find Pulse Width:

$$d = \frac{(P_{avg})(P_{rt})}{P_{pk}} = \frac{P_{avg}}{(P_{pk})(P_{rf})} = \frac{d.c.}{P_{rf}}$$

To find Pulse Repetition Time:

$$P_{rt} = \frac{(P_{pk})(d)}{P_{avg}} = \frac{1}{P_{rf}}$$

To find Duty Cycle:

$$d.c. = (d)(P_{rf}) = \frac{P_{avg}}{P_{pk}} = \frac{d}{P_{rt}}$$

To find Duty Cycle Figure:

$$D = \frac{1}{(d)(P_{rf})} = \frac{1}{d.c.}$$

6-6. FAR-FIELD EQUATION.

a. The far-field equation, so called because it produces realistic values only in the far field when applied to aperture antennas, is used to predict the maximum power density at a given distance or the maximum distance to a given power density. When applied to an aperture antenna a check should be made to determine if the point of interest is within the near field where a correction factor should be used.

b. To predict the maximum power density (W) at a given distance (D) the basic formula is used:

$$W = \frac{PG}{4\pi D^2} \qquad (1)$$

where: W = power density

P = transmitter power

G = antenna gain ratio

D = distance from antenna

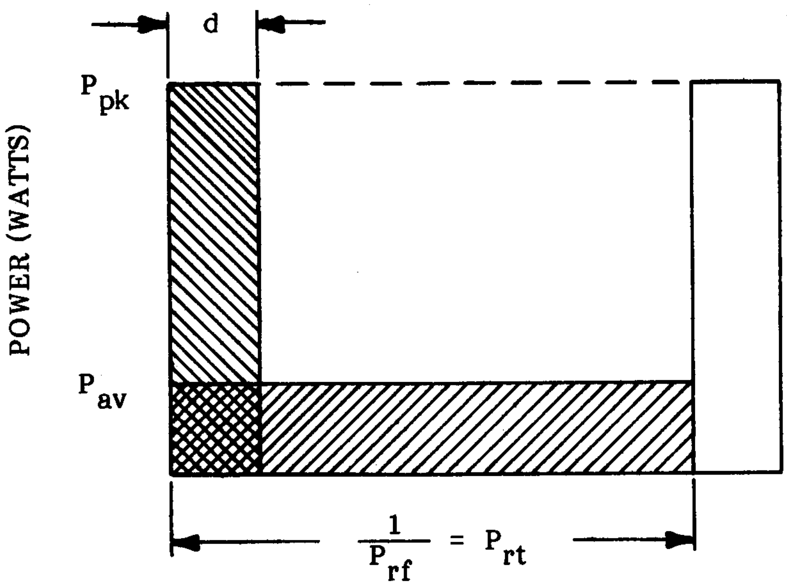


Figure 6-7. Pulse Power Versus Time, Characteristics

The power density can be expressed in watts/square meter (W/m^2), milliwatts/square meter (mW/m^2) or milliwatts/square centimeter (mW/cm^2) depending on the units used for P (watts or milliwatts) and D (meters or centimeters).

c. To predict the maximum distance (D) to a given power density (W) the basic formula becomes:

$$D = \sqrt{\frac{PG}{4 \pi W}} \qquad (2)$$

To obtain D in meters, express P in watts and W in watts/square meter (W/m^2). D may be converted to feet by using table D-2 (Appendix D) or by the conversion, 3.28 ft/meter.

d. The maximum hazard distance (D_h) for personnel, fuel, and EEDs may be determined by replacing W in equation (2) with the appropriate hazard criteria (W_h);

$$D_h = \sqrt{\frac{PG}{4 \pi W_h}} \qquad (3)$$

where: D_h = distance from antenna to hazard level
P = transmitter power
G = antenna gain ratio
W_h = power density deemed hazardous

6-7. EXAMPLE OF FAR-FIELD CALCULATIONS.

a. As an example of the use of equation (3) the personnel, fuel and EED hazard distances are calculated for a system operating with:

P_p (peak power) = 1 megawatt

P_a (average power) = 1080 watts

G (antenna gain) = 30.5 dB (1122 gain ratio)

F (frequency) = 1300 MHz

(1) Personnel Hazard Distance. AFOSH Standard 161-9 criteria for permissible exposure levels (PELs) at 1300 MHz for average size adults is 10 mW/cm^2 (average power density). For ease of calculation this is converted to 100 W/m^2. Therefore, from equation (3):

$$D_h = \sqrt{\frac{(1080)(1122)}{4\pi(100)}}$$

$$= 31.05 \text{ meters or } 102 \text{ feet}$$

(2) Fuel Hazard Distance. Chapter 3, Section II of this manual states the criteria for fuel hazard as 5W/cm^2 (peak power). Refer to AFOSH Standard 127-38 for current criteria. For ease of calculation this is converted to 50,000 W/m^2. Therefore, from equation (3):

$$D_h = \sqrt{\frac{(1 \times 10^6)(1122)}{4\pi(50{,}000)}}$$

$$= 42.25 \text{ meters or } 139 \text{ feet}$$

(3) EED Hazard Distance. AFR 127-100 provides criteria for EEDs in the exposed condition and five limited exposure situations. For this example we calculate the hazard distance for EEDs in the exposed condition. Using figure 6-7 of AFR 127-100 the exposure criteria at 1300 MHz is 7.2W/m^2 (average). Therefore, from equation (3):

$$= \sqrt{\frac{(1080)(1122)}{4\pi(7.2)}}$$

$$= 115.7 \text{ meters or } 380 \text{ feet}$$

NOTE

The above calculated distances, are maximum hazard distances and if they are less than the distance to the far field of aperture antennas the "Near-field Gain Reduction" should be applied. This will result in a more realistic hazard distance.

b. A multiple operation nomogram is provided in Appendix D (figure D-5) from which power density at a given distance, or distance to a given power density can be estimated.

6-8. NEAR-FIELD GAIN REDUCTION.

a. The purpose of the following paragraphs is to explain and illustrate the application of antenna gain reduction in the near-field region of rectangular, elliptical, and circular aperture antennas.

b. As was indicated in paragraph 6-6a, the maximum possible power density may be predicted by the use of equation (1) and the maximum possible hazard distance by the use of equation (3). However, the areas in which radiation hazards exist are most commonly within the near-field region. When the separation distance is less than the distance to the far field a near-field gain reduction should be applied. For this purpose the distance to the far field (D_f) is designated as:

$$D_f = \frac{L^2}{\lambda} \quad \text{or} \quad 3\,\lambda \text{ (whichever value is larger)} \qquad (4)$$

where: L is the largest dimension of the transmitting antenna.

NOTE

For circular parabolic antennas the maximum power density (W_m) in the near-field is:

$$W_m = \frac{4P}{A}$$

This maximum occurs at a distance $D = 0.2L^2/\lambda$ and can be used as a quick check to see if the system is capable of producing hazardous power densities.

Gain reduction is a function of antenna illumination taper. Graphs have been developed for several of the most common illumination tapers and are utilized to determine on-axis and off-axis power density. The following paragraphs illustrate the use of these graphs and show how illumination is determined.

6-9. NEAR-FIELD GAIN REDUCTION FOR ELLIPTICAL OR RECTANGULAR APERTURE ANTENNAS.

a. For elliptical and rectangular aperture antennas the vertical and horizontal axis may not have the same illumination taper (see figure 6-8). Therefore, the illumination for each axis must be estimated and the gain reduction for each axis summed (in dB) to determine the total gain reduction (C). The illumination for each axis is first estimated by calculating the value of $\theta L/\lambda$ and referring to table 6-3. The beam width for each axis (θ_v = vertical beamwidth, θ_h = horizontal beamwidth) and the antenna dimension on each axis (L_v & L_h) are used for the separate calculations. These estimates are reasonable if the antenna efficiency (K) falls within $0.5 < K < 0.9$.

$$K = \frac{G\lambda^2}{4\pi(AF_vF_h)} \qquad (5)$$

where: G = antenna gain

A = antenna area

F_v = gain factor from table 6-3 (vertical illumination)

F_h = gain factor from table 6-3 (horizontal illumination)

The sample calculations that follow illustrate the required adjustments to illumination estimates if K is not within tolerance.

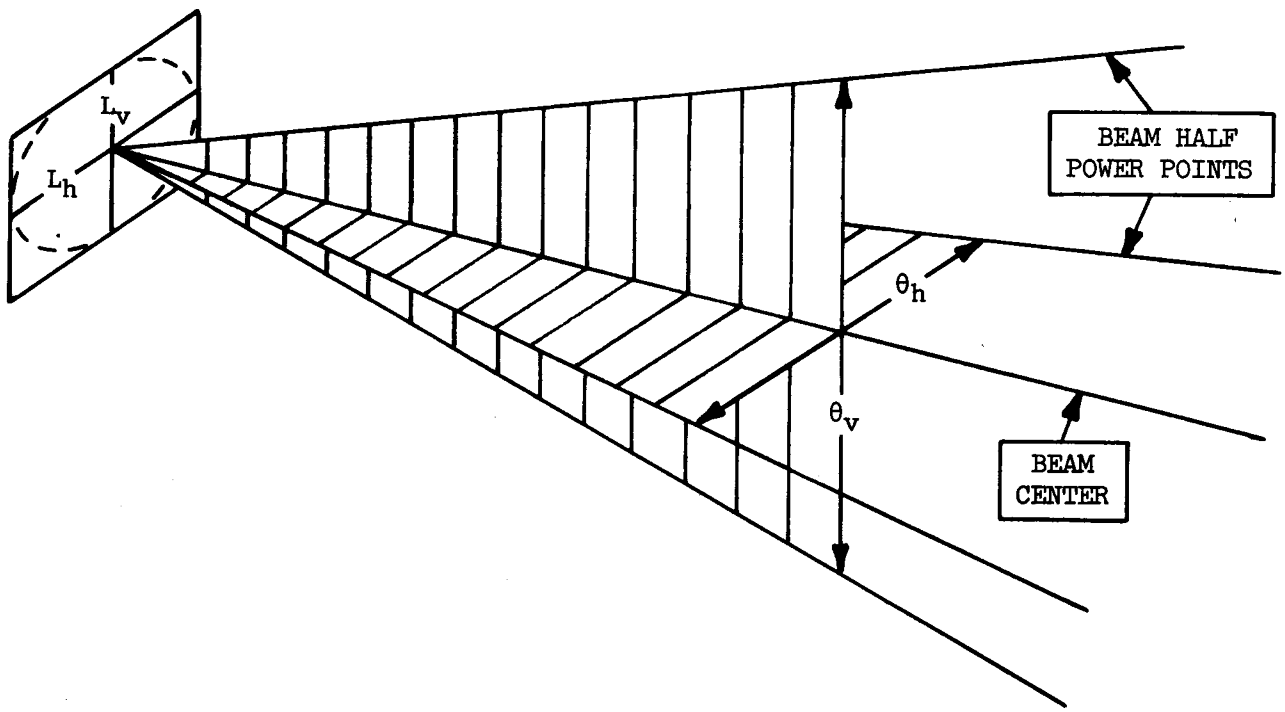


Figure 6-8. Rectangular or Elliptical Antenna Axes and Radiated Beamwidths

Table 6-3. Gain Factors and Axial Illuminations for Magnitudes of $\theta L/\lambda$

$\theta L/\lambda$	GAIN FACTOR	ILLUMINATION
50.4 to 68.7	1.0	uniform
68.7 to 83	0.81	cosine
83 to 95	0.667	cosine squared
95 to 110	0.575	cosine cubed
110 to 116	0.515	cosine fourth

b. For antennas having a cosecant-squared vertical radiation pattern some manipulation of the vertical beamwidth (θ_v) is required to utilize the above procedure. θ_v must be assigned a value equal to twice the angle between the beam axis and the 3-dB point below the axis. For example, from figure 6-9 the assigned value of θ_v = 2(3.2 degrees) = 6.4 degrees.

(1) For cosecant squared antennas not using multi-horn feed the efficiency check should yield $0.35 < K < 0.6$. If a pattern or information is not available to determine θ an illumination estimate can still be made by assuming a reasonably pessimistic value for K (let K = 0.45) and solving for F_v by:

$$F_v = \frac{G\lambda^2}{4\pi(AF_hK)} \quad (6)$$

(2) For cosecant-squared antennas using multi-horn feed the efficiency check should yield $0.5 < K < 0.9$ as determined by:

$$K = \frac{G\lambda^2 P_b}{4\pi(AF_vF_hP_t)} \quad (7)$$

where: P_b = total power of those horns contributing to the main beam

P_t = transmitter power

c. After the antenna axial illuminations have been estimated, the main beam axis near-field gain reduction for a selected distance (D) from the antenna may be determined in the following manner:

(1) Normalize the selected distance (normalized to unity at L^2/λ). This normalized distance is designated P and is the ratio of D to D_f.

For the horizontal axis:

$$P_h = D/(L_h^2/\lambda) \quad (8)$$

For the vertical axis:

$$P_v = D/(L_v^2/\lambda) \quad (9)$$

(2) From figure 6-10, read the near-field gain reduction C, for each axis using the axis illumination and "P" value. The total near-field gain reduction (C) is the sum of the gain reduction for the horizontal axis (C_h) and the vertical axis (C_v), all in decibels.

6-10. SAMPLE CALCULATIONS OF ILLUMINATION TAPER, ON-AXIS POWER DENSITY AND OFF-AXIS POWER DENSITY.

a. Illumination Taper. To illustrate the preceding procedures, the calculations involved in estimating the aperture illumination of Radar Set AN/FPS-6 will be made. Parameters are as follows:

Frequency: 2700 MHz (wavelength, 0.364 ft)

Peak power: 5 megawatts

Average power: 5400 watts

Antenna absolute gain: 7400

Vertical beamwidth: 0.93 degrees

Horizontal beamwidth: 3.26 degrees

Antenna dimensions: 7.5 ft h x 30 ft v

Pulse width: 3 microseconds

PRF: 360 pps

(1) The antenna axial illuminations are estimated from the magnitude $\theta L/\lambda$.

For the horizontal axis:

$$\theta_h L_h/\lambda = (3.26)(7.5)/0.364 = 67$$

From table 6-3, uniform illumination is indicated.

For the vertical axis:

$$\theta_v L_v/\lambda = (0.93)(30)/0.364 = 76.7$$

From table 6-3, cosine illumination is indicated.

(2) The antenna efficiency check is made with equation (5) using F_h and F_v (gain factors) from table 6-3 for the estimated axial illuminations:

$$K = \frac{G_o\lambda^2}{4\pi A F_v F_h}$$

$$= \frac{G_o\lambda^2}{4\pi L_h L_v F_h F_v}$$

$$= \frac{(7400)(0.364)^2}{(12.56)(7.5)(30)(1.0)(0.81)}$$

$$= 0.429$$

The antenna efficiency determined above is outside the limits ($0.5 < K < 0.9$). Hence, we look at the original values of $\theta_h L_h/\lambda$ and $\theta_v L_v/\lambda$. Since $\theta_h L_h/\lambda$ approached the upper limit for uniform illumination, we change its estimated illumination to cosine. Again referring to table 6-3 we now have:

Horizontal (cosine illumination): $F_h = 0.81$

Vertical (cosine illumination): $F_v = 0.81$

Substituting these values in equation (5) results in $K = 0.53$. This value lies within the limits, $0.5 < K < 0.9$. Hence, cosine illumination is more reasonable for the horizontal axis.

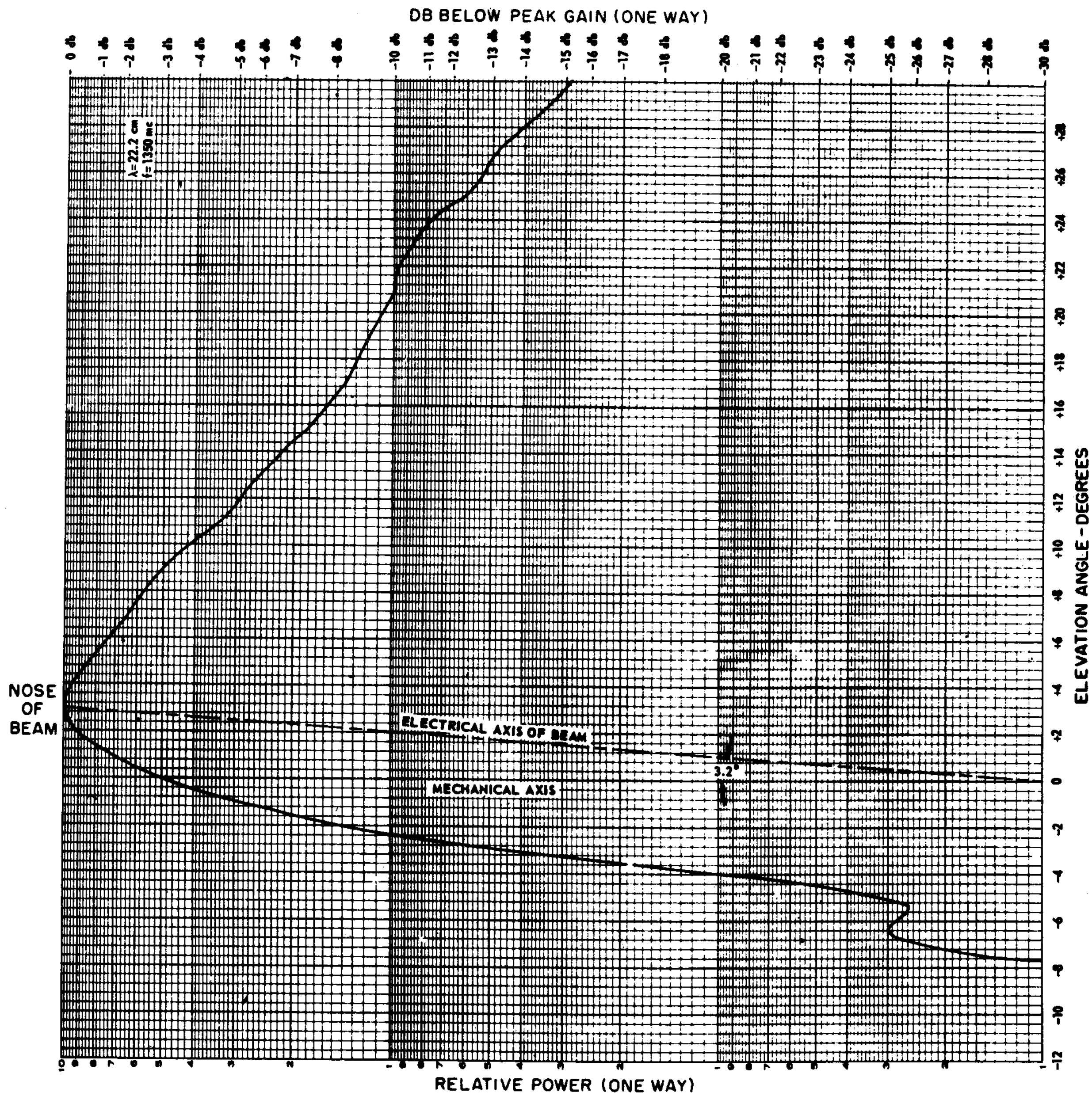


Figure 6-9. Typical Antenna Vertical Radiation Pattern for Radar Sets AN/FPS-8 and AN/MPS-11

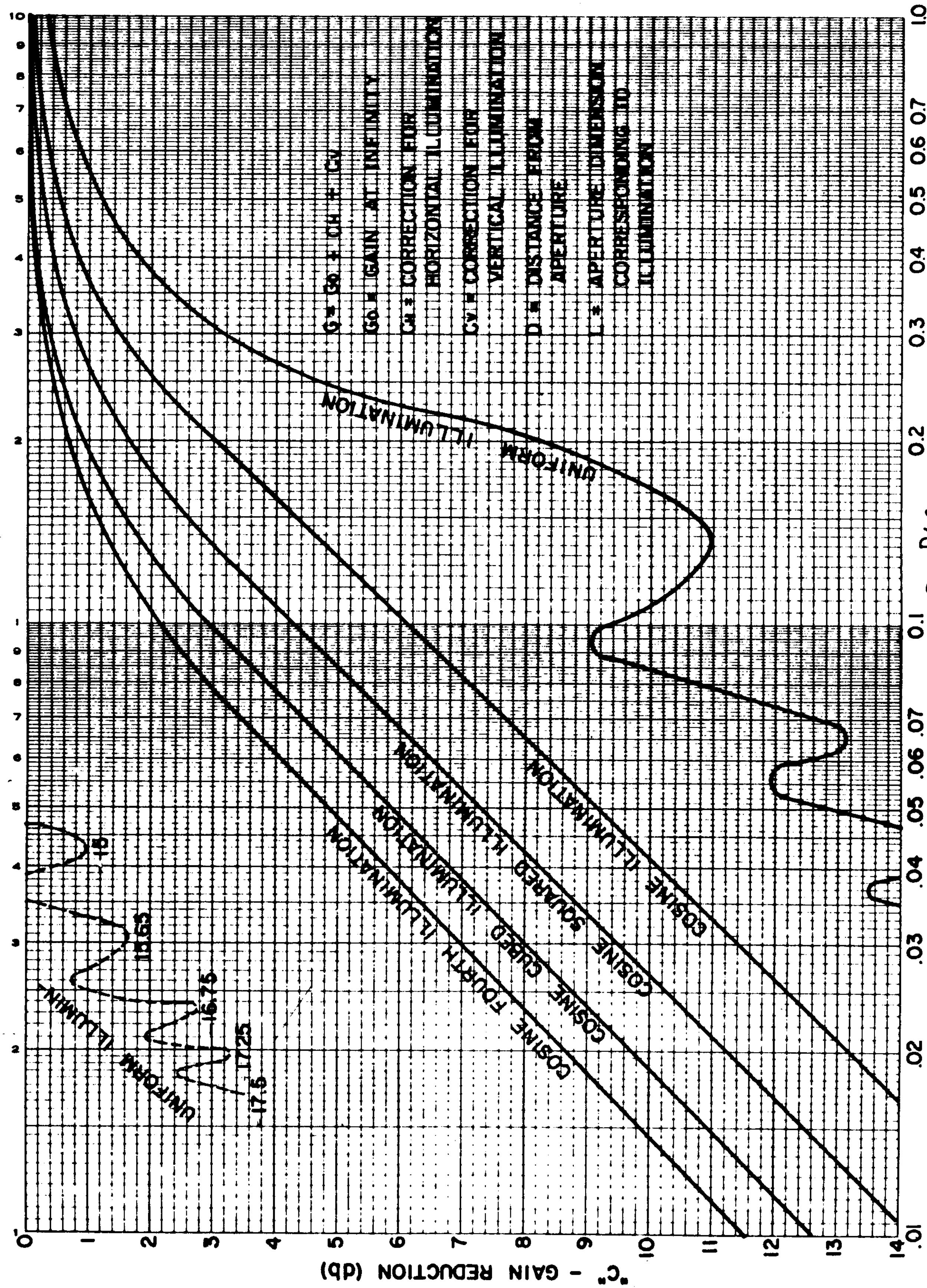


Figure 6-10. Near-Field Gain Reduction of Rectangular Aperture with Separable Illumination

b. On-Axis Power Density. The on-axis power density in the near field (W_n) will have to be calculated at several distances to determine where W_n equals the hazardous power density (W_h). These values will also be used in calculating the off-axis power density. Figure 6-11 illustrates a sample format of tabulating the calculated data. Using the AN/FPS-6 parameters given in paragraph 6-10a, the W_n at a distance of 300 ft is calculated as follows:

(1) Determine the near-field correction factors from figure 6-10 using the normalized distance (P) for each axis as follows:

For the horizontal axis:

$$P_h = D\lambda/L_h^2 = (300)(0.364)/(7.5)^2 = 1.94$$

This distance, P_h, is beyond the range of figure 6-10 and, thus, in the far field. No near-field correction is required and $C_h = 0$ dB

For the vertical axis:

$$P_v = D\lambda/L_v^2 = (300)(0.364)/(30)^2 = 0.1213$$

From figure 6-10 where P = 0.1213 and illumination is cosine, $C_v = 5.2$ dB.

Total near-field correction factor (C):

$$C = C_h + C_v = 0 + (-5.2) = -5.2 \text{ dB} = 0.302$$

(2) The far-field formula, equation (1), is modified by the total gain reduction (C).

$$W_n = \frac{P\,G\,C}{4\pi D^2} \qquad (10)$$

$$= \frac{(5400)(7400)(0.302)}{4\pi(300 \times 30.5)^2} \quad \text{with D in cm}$$

$$= 0.01147 \text{ watts/cm}^2$$

c. Off-Axis Power Density. The information and graphs provided here can be used to determine the power density at any off-axis point but we are interested here in profiling the beam containing power density exceeding the permissible exposure level (PEL) criteria. The beamwidth and depth can be determined from figures 6-12 through 6-16 for each set of W_n, P_h and P_v previously calculated. Again, using D = 300 ft for illustration, we have previously calculated:

$$W_n = 0.01147 \text{ watts/cm}^2$$

$$P_h = 1.94$$

$$P_v = 0.1213$$

(1) Normalize the PEL criteria for average size adults (0.01 watt/cm^2) by dividing the PEL by W_n. This value is designated "$|E_n|^2$."

$$|E_n|^2 = \frac{0.01}{0.01147}$$

$$= 0.872$$

(2) Read $\bar{x}$ values from figure 6-13 since cosine illumination was estimated along both antenna axes. The $\bar{x}$ value is read at the intersection of $E_n{}^2$ with P_h or P_v. From the graph it can be seen that interpolation is necessary, since the values of P_h fall between P = 1 and P = 2, and the values of P_v fall between P = 0.1 and P = 0.3. Interpolation is done as follows:

Horizontal $\bar{x}$:

For $|E_n|^2 = 0.872$ and $P_h = 1.0$; $\bar{x} = 0.54$

For $|E_n|^2 = 0.872$ and $P_h = 2.0$; $\bar{x} = 1.07$

Interpolating for $P_h = 1.943$

$$\bar{x} = 0.54 + \left[\frac{1.07 - 0.54}{2 - 1}\right] (1.943 - 1.0) = 1.04$$

Vertical $\bar{x}$:

For $|E_n|^2 = 0.872$ and $P_v = 0.1$; $\bar{x} = 0.27$

For $|E_n|^2 = 0.872$ and $P_v = 0.3$; $\bar{x} = 0.18$

Interpolating for $P_v = 0.1215$

$$\bar{x} = 0.27 + \left[\frac{0.18 - 0.27}{0.3 - 0.1}\right] (0.1215 - 0.1) = 0.26$$

(3) The personnel rf hazard width and depth across the main beam at a distance of 300 ft is calculated as follows:

$$\text{Hazard width} = (L_h)(\bar{x}) = (7.5)(1.04) = 7.8 \text{ ft}$$

$$\text{Hazard depth} = (L_v)(\bar{x}) = (30)(0.26) = 7.8 \text{ ft}$$

6-11. NEAR-FIELD GAIN REDUCTION FOR CIRCULAR APERTURE ANTENNAS.

a. Axial power density of circular aperture antennas may be determined by using figures 6-17 through 6-24. To select the appropriate figure, the illumination of the circular aperture must be estimated. For this purpose, the form of the data of table 6-2 is changed to associate magnitudes of $\theta L/\lambda$ with specified illumination types. Table 6-4 provides this information. An antenna efficiency check must be made to insure that the estimated illumination is reasonable. The factor of efficiency (K) should lie within the limits $0.5 < K < 0.9$ as determined from the equation:

$$K = \frac{G_t \lambda^2}{\pi^2 L^2 F} \qquad (11)$$

where: L = antenna diameter

F = gain factor (see table 6-4)

b. When the antenna illumination is known, the axial power density at a given distance, D, from the antenna may be determined as follows:

(1) Calculate the reference power density W_o at $2L^2/\lambda$ distance by the following equation:

$$W_o = \frac{P\ G\ \lambda^2}{16\ \pi\ L^4} \qquad (12)$$

(2) Convert distance, D, to normalized distance, P, by the equation:

$$P = \frac{D\lambda}{2\ L^2} \qquad (13)$$

(3) Choose the applicable figure (figures 6-17 through 6-24) for the known antenna illumination. For the calculated P read off the $\bar{x} = 0$ curve, the factor ($\bar{w}$) by which the reference power density W_o must be multiplied to obtain the power density (W_n) at the distance D.

$$W_n = \bar{w} W_o \qquad (14)$$

c. Should the personnel rf radiation hazard distance be desired:

(1) Determine the factor ($\bar{w}$) by which W_o must be multiplied to equal the hazardous power density (W_h) which in this case is the permissible exposure level (PEL):

$$\bar{w} = \frac{W_h}{W_o} \qquad (15)$$

(2) From the appropriate figure for the illumination involved, read the P value associated with the $\bar{w}$ determined off the $\bar{x} = 0$ curve.

(3) Convert P to personnel rf radiation hazard distance from the equation:

$$D_h = \frac{2L^2 P}{\lambda} \qquad (16)$$

where D_h = rf radiation hazard distance.

6-12. SAMPLE CALCULATIONS OF ILLUMINATION TAPER, ON-AXIS POWER DENSITY AND OFF-AXIS POWER DENSITY.

a. Illumination Taper. To illustrate the preceding procedures, the calculations involved in estimating the aperture illumination, personnel rf radiation hazard distance, and power density at 300 feet of Radar Set AN/FPS-16 will be made. Parameters are as follows:

Frequency : 5450 MHz

Wavelength (λ) : 0.181 ft

Average power (P) : 1707 watts

Antenna absolute gain (G) : 28,200

Beamwidth (θ) : 1.1 degrees

Antenna diameter (L) : 12 ft

(1) Estimate the antenna aperture illumination from the magnitude of $\theta L/\lambda$:

$$\frac{\theta L}{\lambda} = \frac{(1.1)(12)}{0.181}$$

$$= 73$$

from table 6-4 antenna illumination is $(1-r^2)$

(2) Make an antenna efficiency check by equation (11):

$$K = \frac{G_t \lambda^2}{\pi^2 L^2 F}$$

$$= \frac{(28{,}200)(0.181)^2}{(3.14)^2(12)^2(0.75)}$$

$$= 0.867$$

where F = 0.75 is obtained from table 6-4

This factor of antenna efficiency is within the range of $0.5 < K < 0.9$ so that estimated antenna illumination is reasonable.

Table 6-4. Gain Factors and Circular Aperture Illuminations for Magnitudes of $\theta L/\lambda$

$\theta L/\lambda$	GAIN FACTOR (F)	ILLUMINATION
58.5 to 72.8	1.00	Uniform
72.8 to 84.2	0.75	$(1-r^2)$
84.2 to 94.5	0.56	$(1-r^2)2$
94.5 to 103.5	0.44	$(1-r^2)3$

b. On-Axis Power Density. With the graphs provided, either the power density at a given distance or the distance to a given power density can be determined (figures 6-17 through 6-24).

(1) To determine the personnel rf radiation hazard distance for average size adults (D_h):

(a) Determine reference power density, (W_o), from equation (12):

$$W_o = \frac{P_t G_t \lambda^2}{16\pi L^4}$$

$$= \frac{(1707)(28,200)\left[(0.181)(30.5)\right]^2}{(16)(3.14)\left[(12)(30.5)\right]^4}$$

$$= 0.001625 \text{ watt/cm}^2$$

where: feet is converted to centimeters by the conversion factor 30.5

(b) Determine $\bar{w}$ from equation (15):

$$\bar{w} = \frac{W_h}{W_o}$$

$$= \frac{0.01}{0.001625}$$

$$= 6.15$$

(c) From figure 6-19 read the P value associated with $\bar{w} = 6.15$ on the curve labeled $\bar{x} = 0$. In this case, $P = 0.4$.

(d) Determine the personnel rf radiation hazard distance for average size adults from equation (16):

$$D_h = \frac{2L^2 P}{\lambda}$$

$$= \frac{(2)(12)^2(0.4)}{0.181}$$

$$= 637 \text{ ft}$$

(2) To find the power density 300 ft from the radar antenna:

(a) Determine the P value represented by 300 feet, from equation (13):

$$P = \frac{D\lambda}{2L^2}$$

$$= \frac{(300)(0.181)}{(2)(12)^2}$$

$$= 0.1885$$

(b) From figure 6-19 ($\bar{x}$ = 0 curve) read $\bar{w}$ value associated with P = 0.1885. In this case $\bar{w}$ = 21.3.

(c) Determine the near-field power density (W_n) at 300 feet, from equation (13):

$$W_n = \bar{w}W_o$$

$$= (21.3)(0.001625)$$

$$= 0.0346 \text{ watt/cm}^2$$

c. Off-Axis Power Density. Figures 6-17 through 6-24 are also used to determine the power density at an off-axis point at a given distance or the hazard width at a given distance. The off-axis reference power densities ($\bar{w}$) are plotted for various $\bar{x}$ distances off the center axis where $\bar{x}$ is normalized to unity at the antenna radius. That is:

$$\bar{x} = \frac{2 \text{ (off-axis distance)}}{L} \qquad (17)$$

(1) Power density four feet off beam axis 300 feet from the antenna is calculated as follows:

(a) Determine $\bar{x}$ by equation (17):

$$\bar{x} = \frac{2 \text{ (off-axis distance)}}{L}$$

$$= \frac{2 \text{ (4 feet)}}{12 \text{ feet}}$$

$$= 0.667$$

(b) Determine P by equation (13):

$$P = \frac{D\lambda}{2L^2}$$

$$= \frac{(300)(0.181)}{(2)(12)^2}$$

$$= 0.1885$$

(c) Find $\bar{w}$ from figure 6-19 by interpolating between $\bar{x}$ = 0.6 and $\bar{x}$ = 0.7:

when $\bar{x}$ = 0.6 and P = 0.1885, $\bar{w}$ = 7 when $\bar{x}$ = 0.7 and P = 0.1885, $\bar{w}$ = 5.3

$$\text{for } \bar{x} = 0.667,\ \bar{w} = 7 - \left[\left(\frac{0.667 - 0.6}{0.7 - 0.6}\right)\right](7 - 5.3)$$

$$= 7 - 1.14$$

$$= 5.86$$

(d) Find W_o by equation (12):

$$W_o = \frac{P_t G_t \lambda^2}{16\pi L^4}$$

$$= \frac{(1707)(28{,}200)\left[(0.181)(30.5)\right]^2}{(16)(3.14)\left[(12)(30.5)\right]^4}$$

$$= 0.001625 \text{ watt/cm}^2$$

(e) Find W_n by equation (14):

$$W_n = \bar{w} W_o$$

$$= (5.86)\,(0.001625 \text{ watt/cm}^2)$$

$$= 0.00953 \text{ watt/cm}^2$$

(2) To find the personnel rf radiation hazard width at 300 feet from the AN/FPS-16 antenna, proceed as follows:

(a) Determine P using equation (13):

$$P = \frac{D\lambda}{2L^2}$$

$$= \frac{(300)(0.181)}{(2)(12)^2}$$

$$= 0.1885$$

(b) Find W_o by equation (12):

$$W_o = \frac{P_t G_t \lambda^2}{16\pi L^4}$$

$$= \frac{(1707)(28{,}200)\left[(0.181)(30.5)\right]^2}{(16)(3.14)\left[(12)(30.5)\right]^4}$$

$$= 0.001625 \text{ watt/cm}^2$$

(c) Find $\bar{w}$ using equation (15) with W_h = 0.01 watt/cm^2

$$\bar{w} = \frac{W_h}{W_o}$$

$$= \frac{0.01}{0.001625}$$

$$= 6.15$$

(d) Find $\bar{x}$ which has $\bar{w}$ value of 6.15 at P = 0.1885. From figure 6-19, where P = 0.1385, the desired value of $\bar{x}$ is bracketed by $\bar{x}$ = 0.6 ($\bar{w}$ = 7) and $\bar{x}$ = 0.7 ($\bar{w}$ = 5.3). Thus, when $\bar{w}$ = 6.15:

$$\bar{x} = 0.7 - \left[\left(\frac{6.15 - 5.3}{7 - 5.3}\right) \quad (0.7 - 0.6)\right]$$

$$= 0.65$$

(e) Find hazard width using the following equation:

$$\text{Hazard width} = \bar{x}L$$

$$= (0.65)\,(12\text{ ft})$$

$$= 7.8\text{ ft}$$

6-13. ON-AXIS POWER DENSITY CALCULATIONS FOR CIRCULAR APERTURE ANTENNAS WITH UNACCEPTABLE ANTENNA EFFICIENCIES.

In some instances on-axis power densities for circular aperture antennas cannot be calculated because the estimated antenna aperture illumination determined by $\frac{\theta L}{\lambda}$ does not result in an acceptable antenna efficiency (K). If an acceptable antenna efficiency cannot be calculated, support can be obtained from the hazards support activities responsible for consultations/studies/measurements for RF, X-ray, and radioactive hazards to personnel. Hazards support activities are listed in Table 2-1 of this manual. Before contacting these offices, obtain the system's operating parameters as listed below:

a. Operating Frequency

b. Antenna Diameter

c. Gain

d. Average Transmitted Power

e. Sidelobe Ratio (this is the ration of the first sidelobe to the mainlobe and is give in decibels)

EQUIPMENT NOMENCLATURE: AN/FPS-6 Radar

PEAK POWER: 5.0 MW	ANTENNA POWER GAIN: 7400
PRF: 360	ANTENNA DIMENSIONS:
PULSE WIDTH: 3 μsec	Horizontal 7.5 ft
DUTY CYCLE: 0.00108	Vertical: 30 ft
AVG POWER: 5400 W	ANTENNA BEAMWIDTH:
FREQUENCY: 2700 MHz	Horizontal: 3.26 deg
WAVELENGTH: 0.364 ft	Vertical: 0.93 deg

DISTANCE (D)		W_f (w/cm^2)	L_v^2/λ (ft)	L_h^2/λ (ft)	P_v	P_h	C_v (dB)	C_h (dB)	C_t	W_n (W/cm^2)	$\|E_n\|^2$	VERT $\ddot{x}$	HORZ $\bar{x}$	HAZARD DEPTH (ft)	HAZARD WIDTH (ft)
(ft)	(m)														
30	9.15	3.8	2470	154.5	0.01213	0.194	-15.15	-3.15	0.0148	0.0565	0.177	0.72	0.725	21.6	5.44
45	13.7	1.69			0.0182	0.291	-13.4	-1.55	0.032	0.0542	0.184	0.71	0.73	21.3	5.47
100	30.5	0.343			0.0405	0.648	-9.95	-0.35	0.0933	0.032	0.312	0.61	1.02	18.3	7.65
150	45.8	0.152			0.0608	0.972	-8.2	-0.1	0.1479	0.0225	0.444	0.525	1.245	15.75	9.35
200	61.0	0.0857			0.081	1.295	-7.0	0	0.1995	0.0171	0.585	0.445	1.37	13.35	10.26
250	76.2	0.0547			0.1011	1.62	-6.05	0	0.2483	0.0136	0.735	0.37	1.31	11.1	9.83
300	91.5	0.038			0.1215	1.94	-5.2	0	0.302	0.01147	0.872	0.26	1.04	7.8	7.8
344	104.9	0.0288			0.1392	2.225	-4.6	0	0.3467	0.00999	1.00	0	0	0	0

Figure 6-11. Illustration of Suggested Radiation Hazard Calculation Table

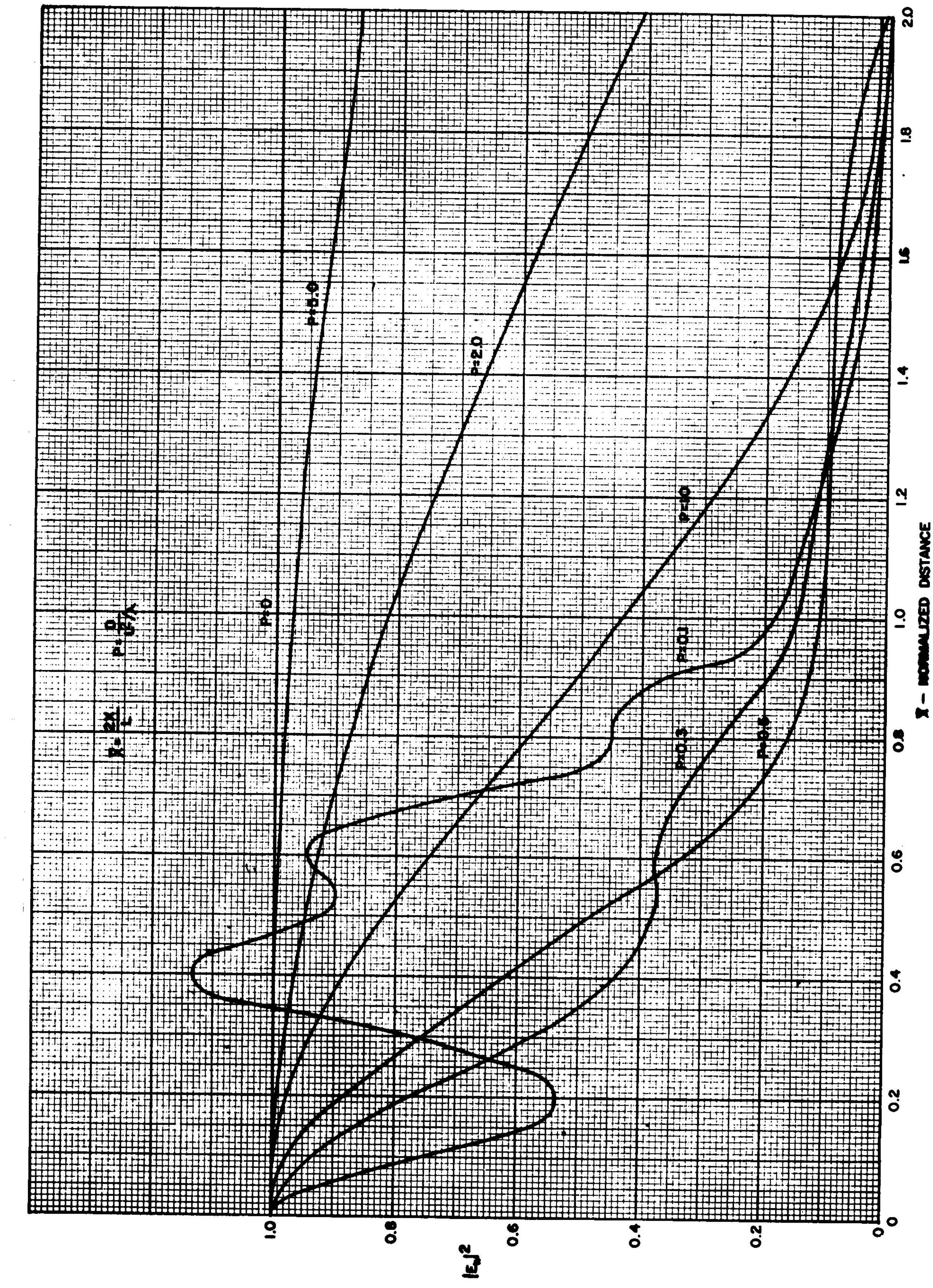


Figure 6-12. Fresnel Region Patterns for Rectangular Aperture with Uniform Illumination

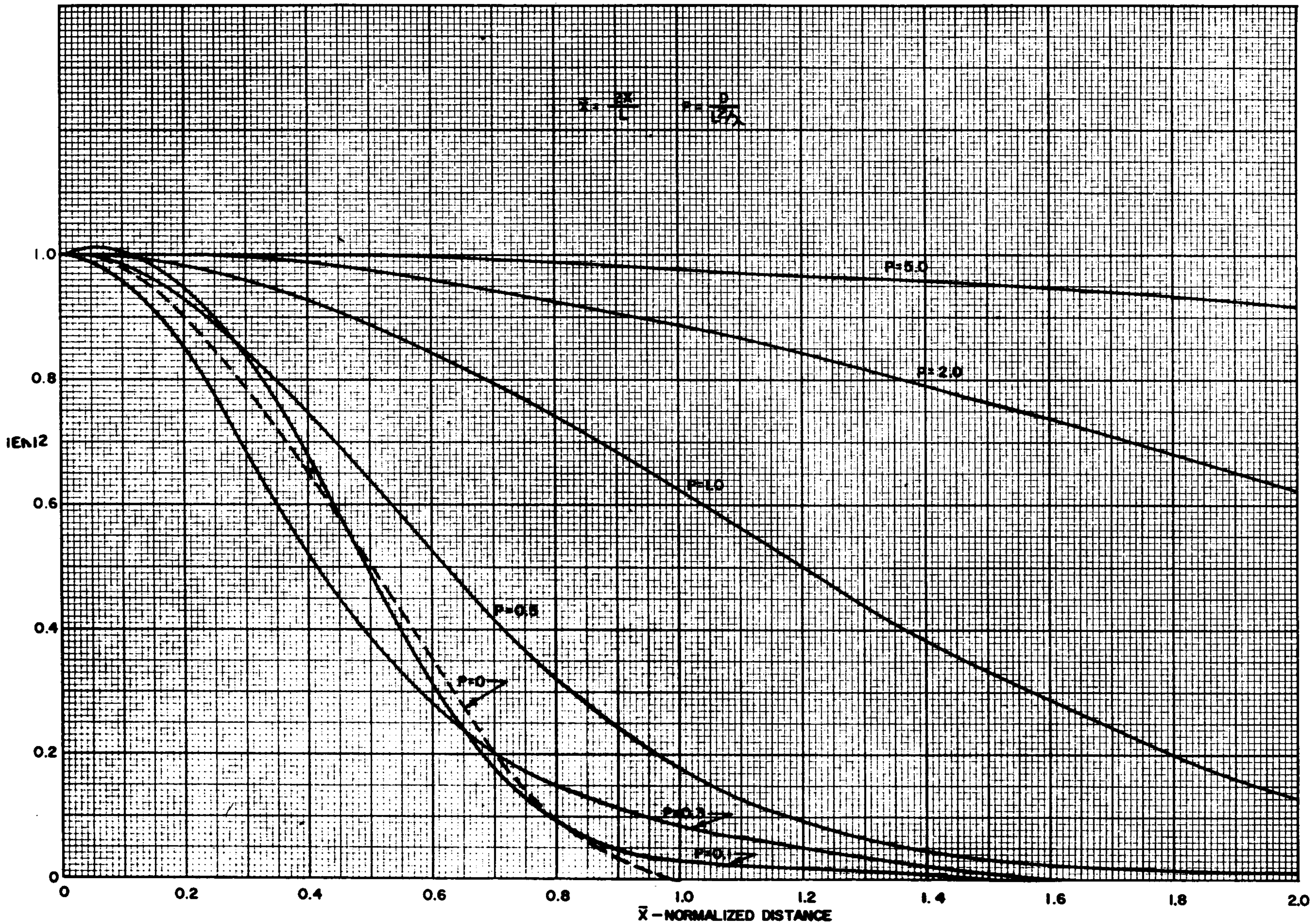


Figure 6-13. Fresnel Region Patterns for Rectangular Aperture with Cosine Illumination

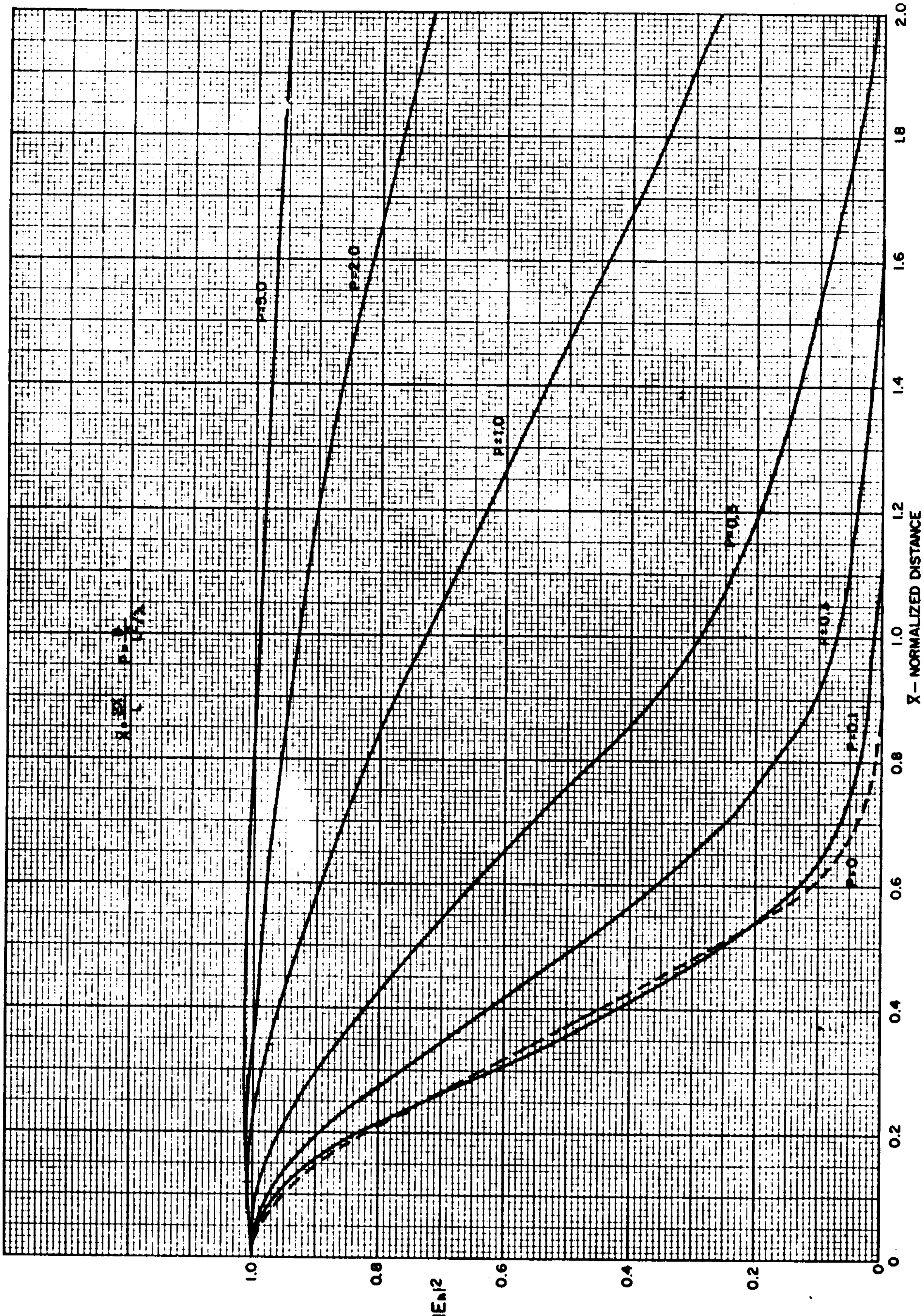


Figure 6-14. Fresnel Region Patterns for Rectangular Aperture with Cosine-Squared Illumination

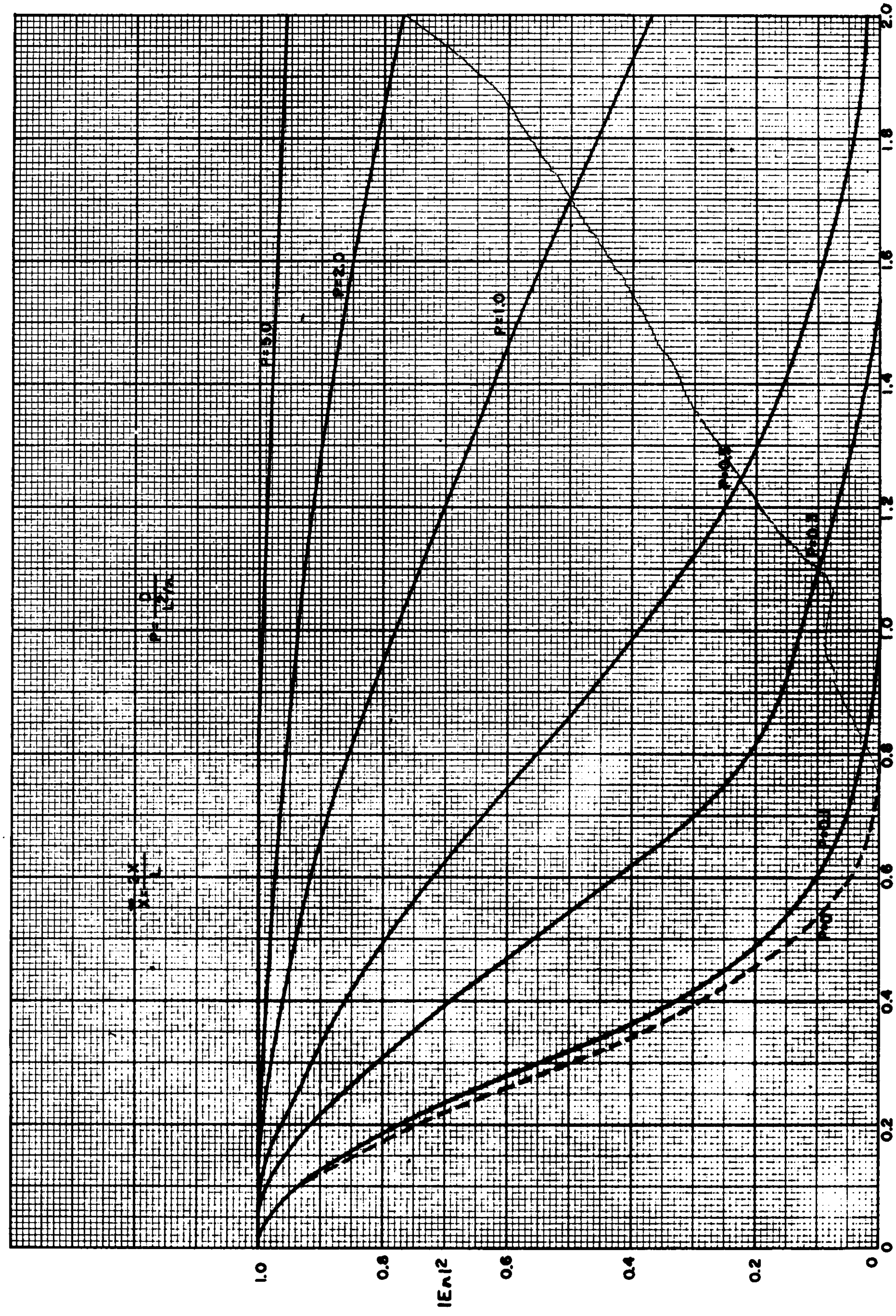


Figure 6-15. Fresnel Region Patterns for Rectangular Aperture with Cosine-Cubed Illumination

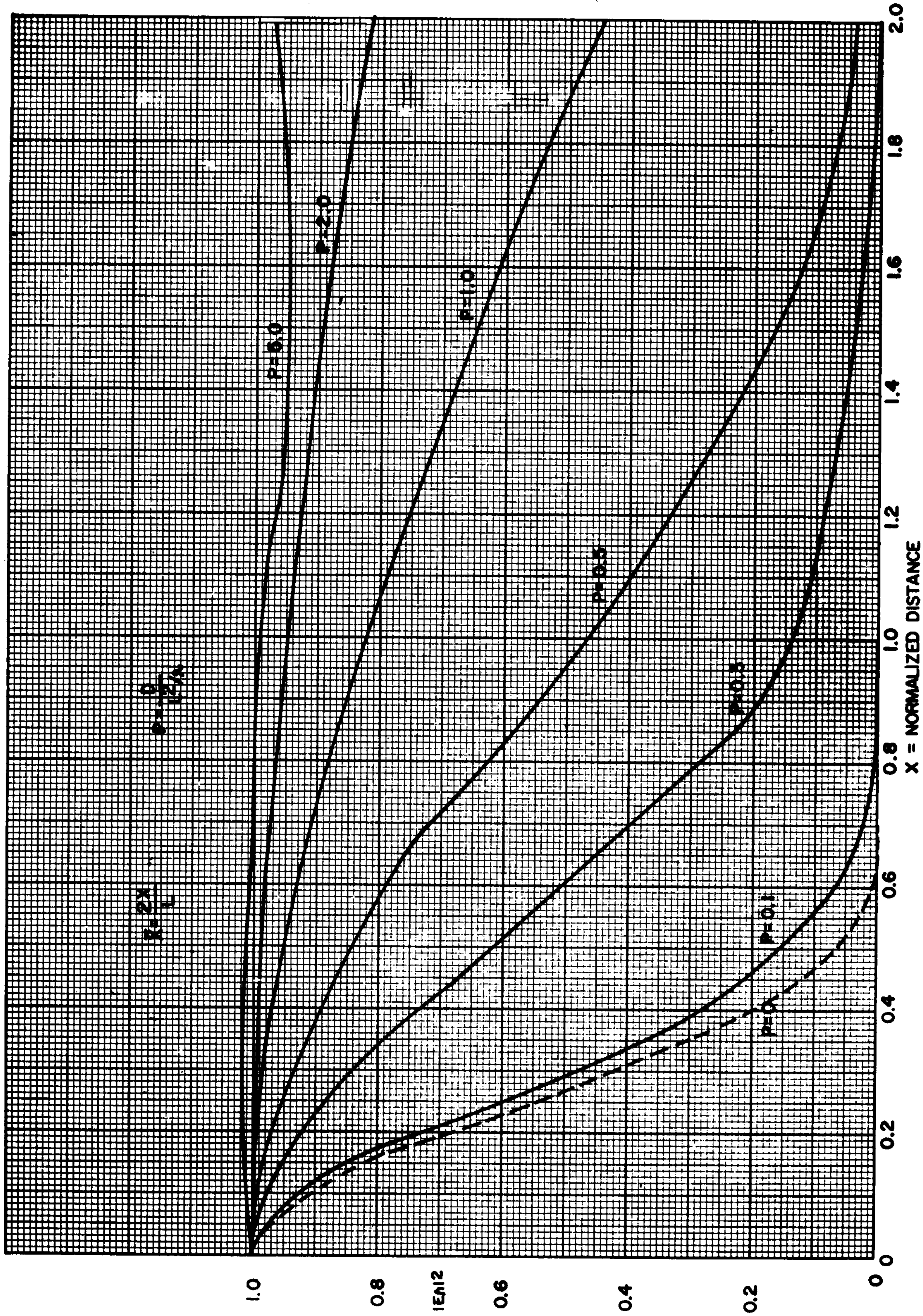


Figure 6-16. Fresnel Region Patterns for Rectangular Aperture with Cosine-Fourth Illumination

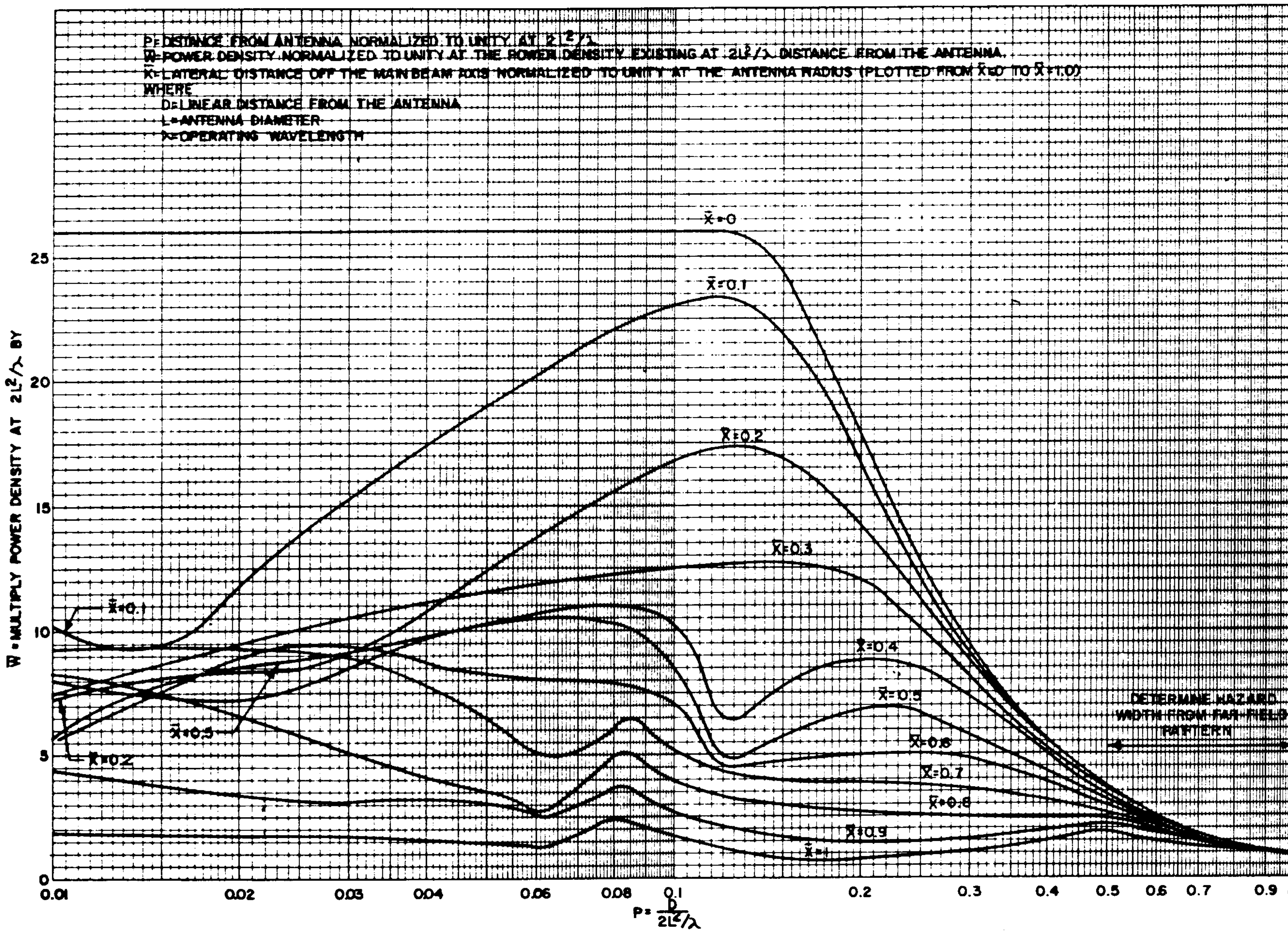


Figure 6-17. Power Density Dispersion from a Circular Aperture Antenna with Uniform Illumination ($\bar{x}$ = 0 to 1)

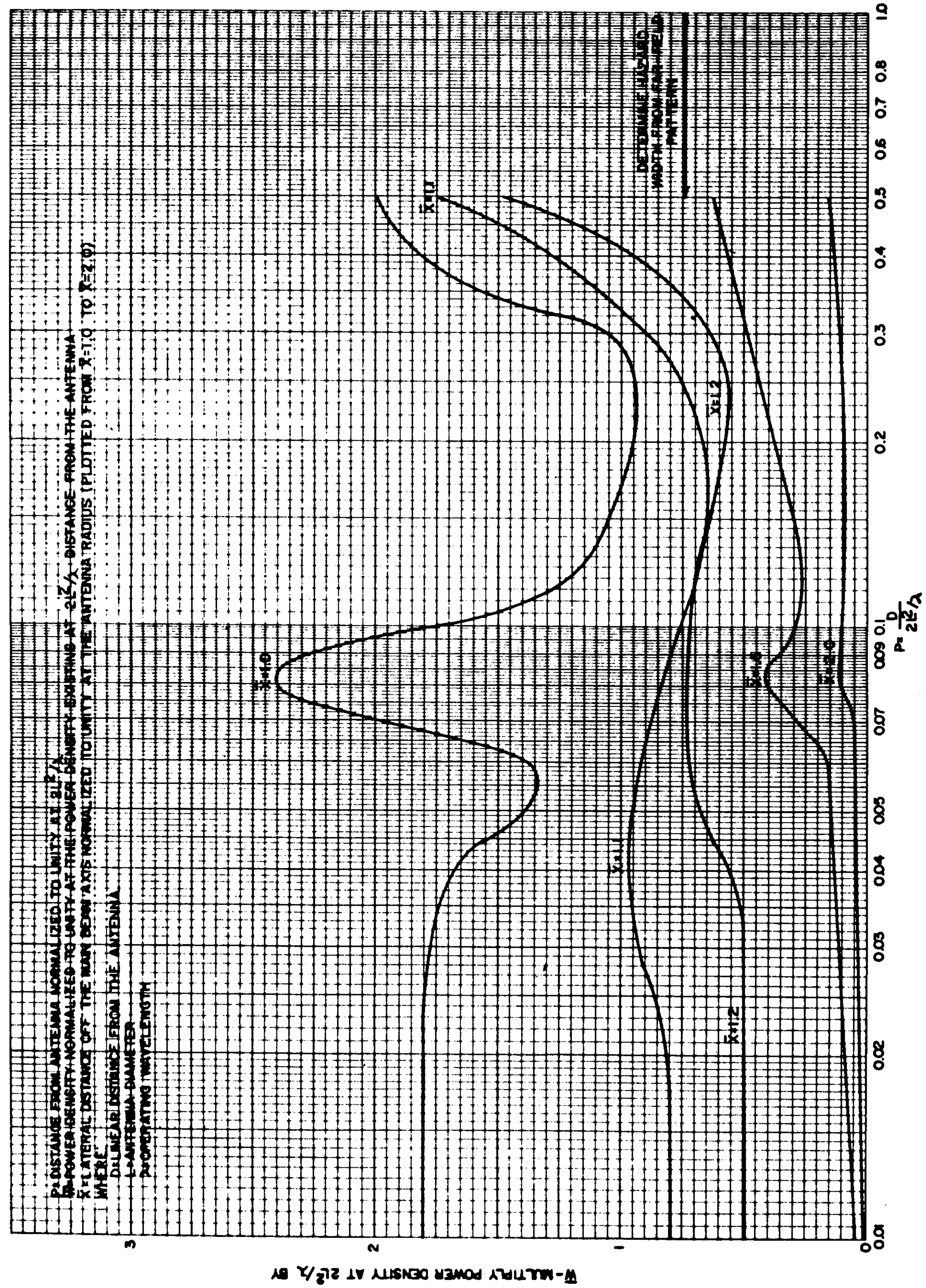


Figure 6-18. Power Density Dispersion from a Circular Aperture Antenna with Uniform Illumination ($\bar{x}$ = 1 to 2)

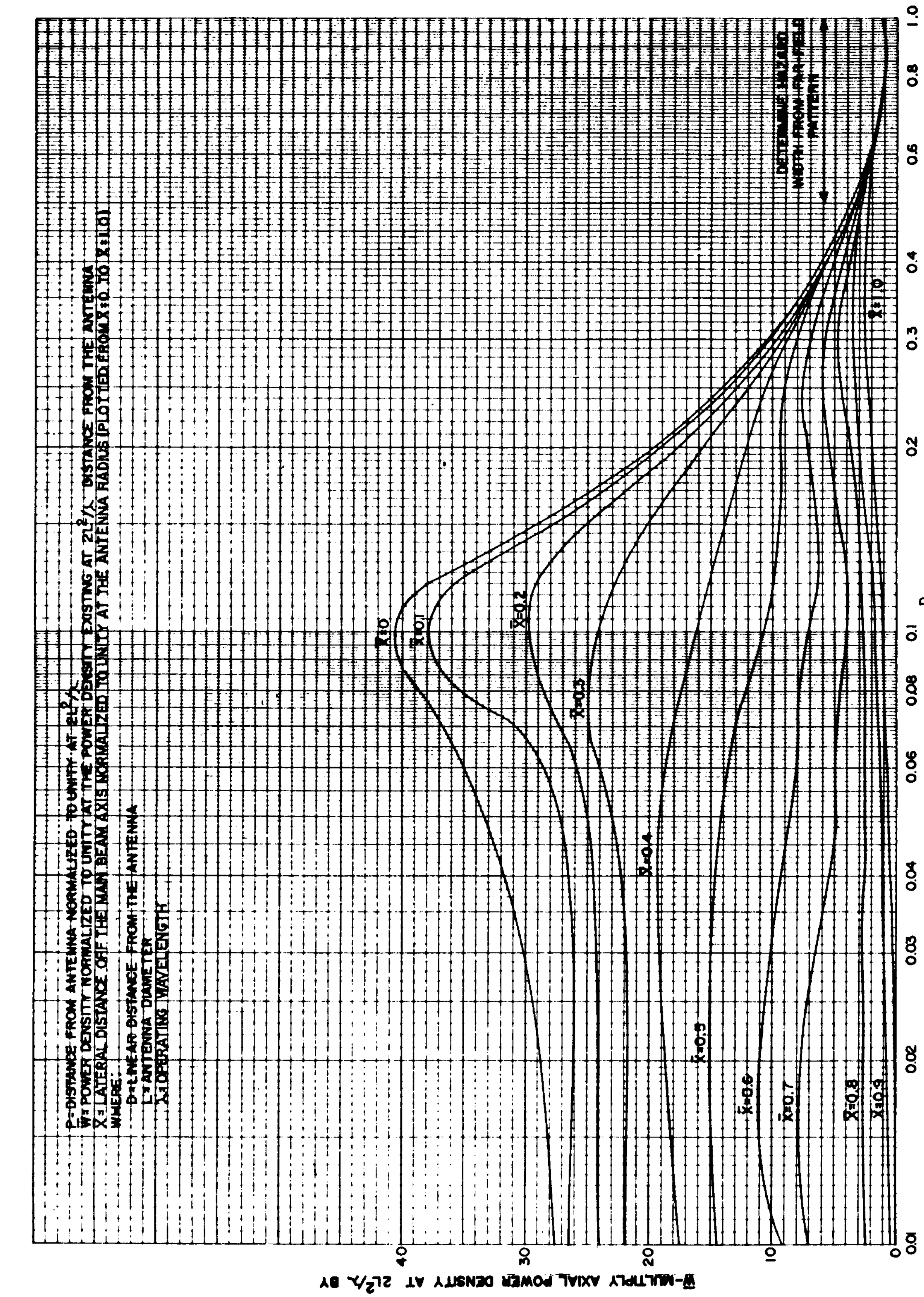


Figure 6-19. Power Density Dispersion from a Circular Aperture Antenna with $(1 - r^2)$ Illumination ($\bar{x}$ = 0 to 1)

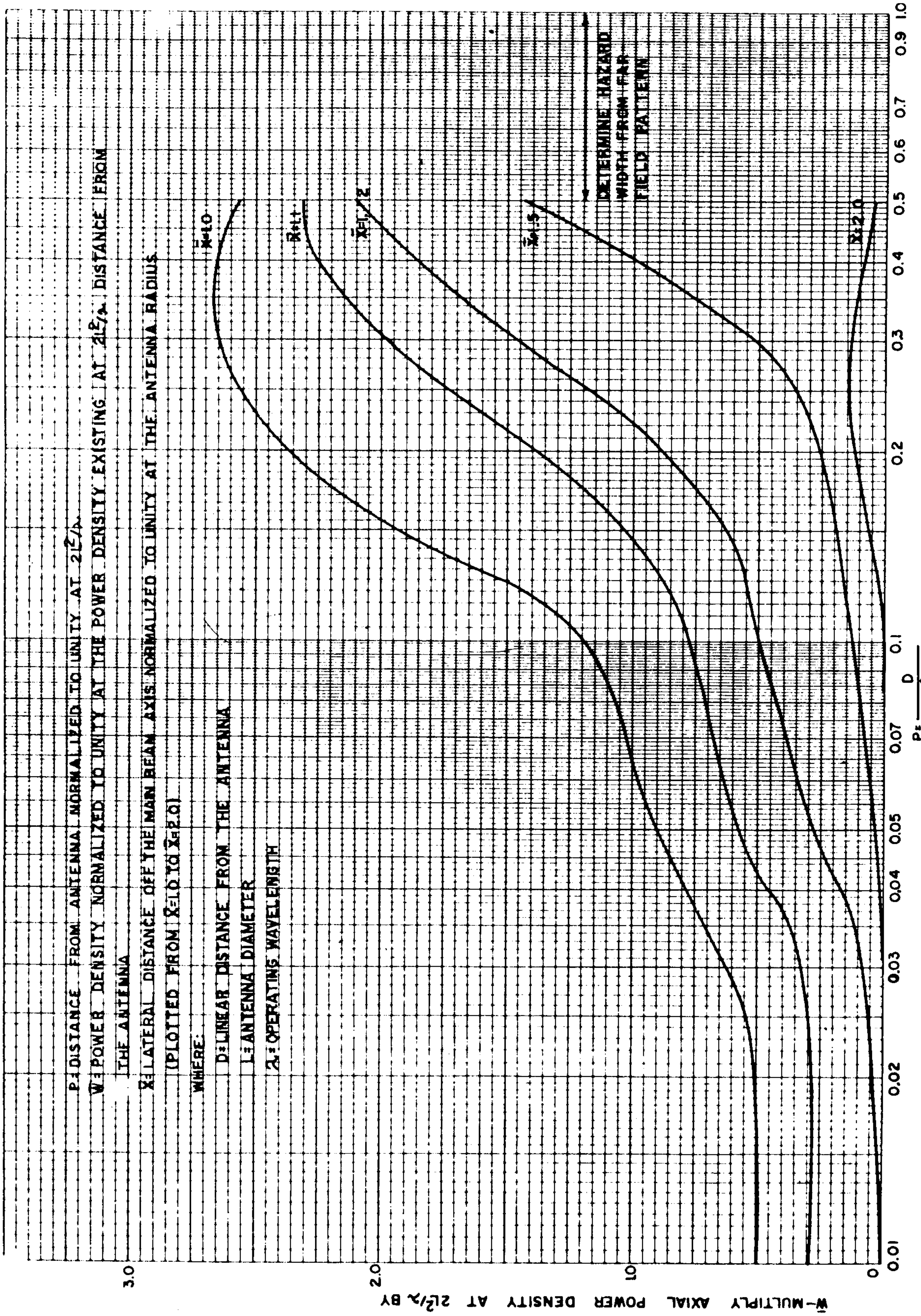


Figure 6-20. Power Density Dispersion from a Circular Aperture Antenna
$(1 - r^2)$ Illumination ($\bar{x}$ = 1 to 2)

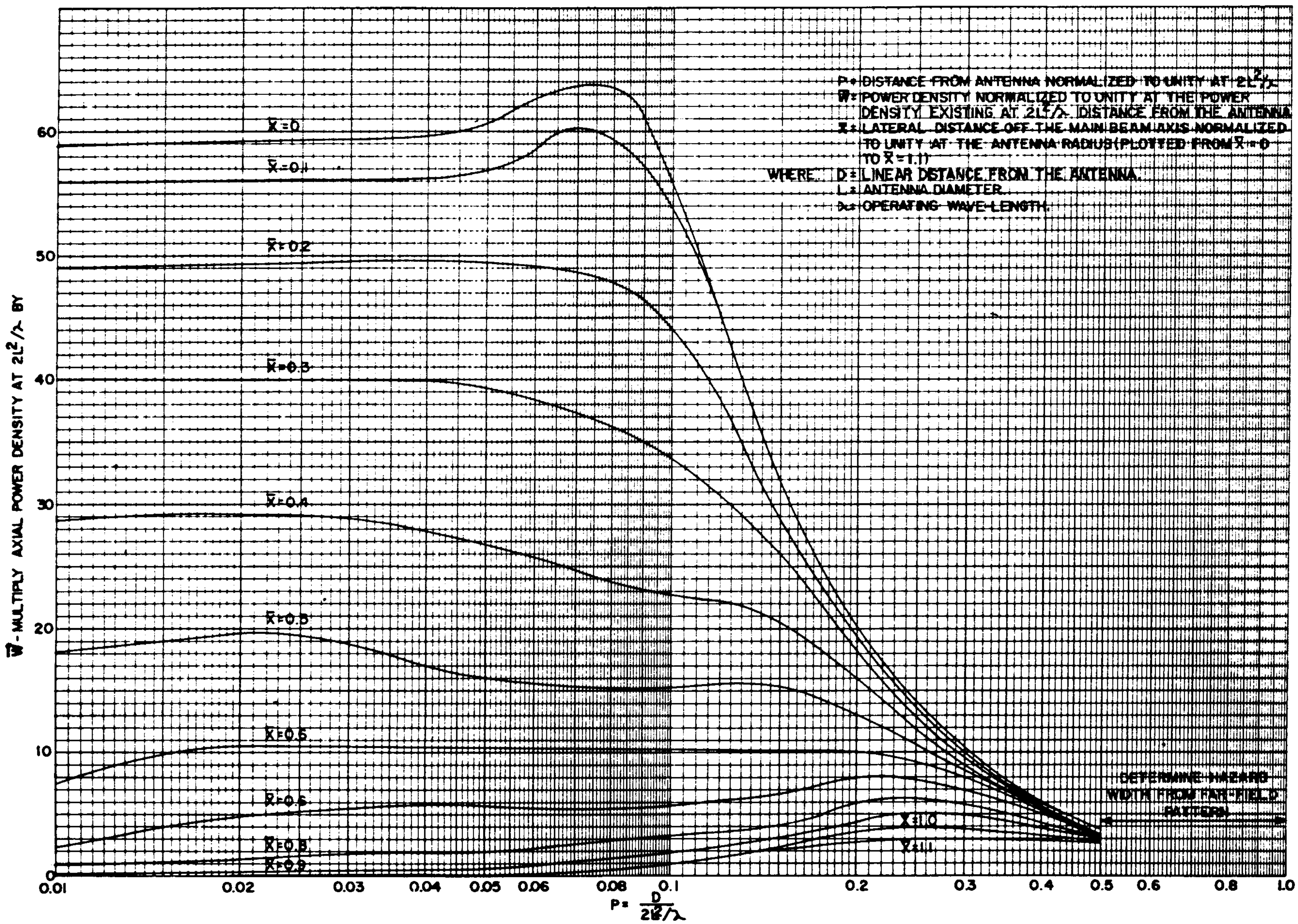


Figure 6-21. Power Density Dispersion from a Circular Aperture Antenna with $(1 - r^2)^2$ Illumination ($\bar{x}$ = 0 to 1)

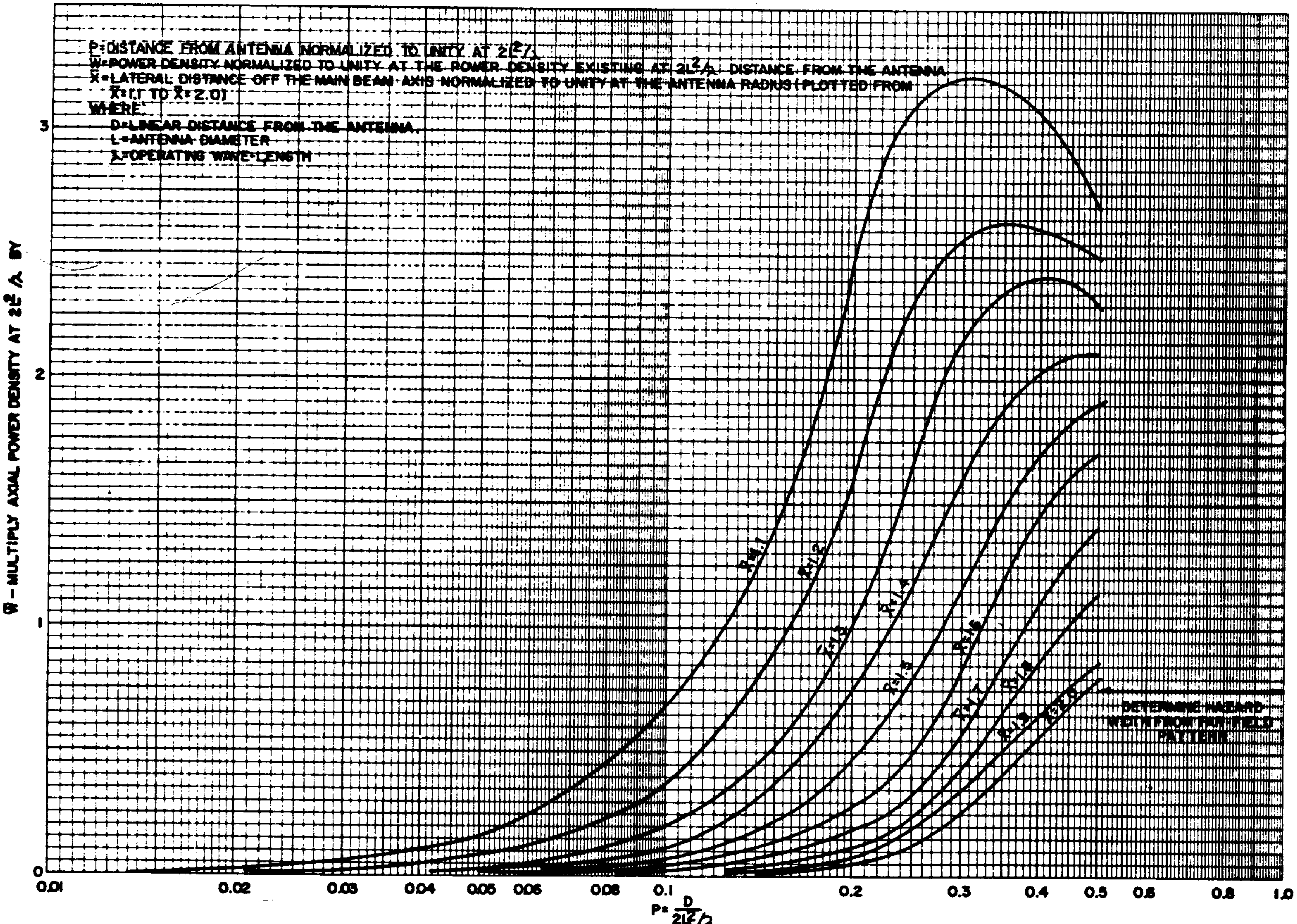


Figure 6-22. Power Density Dispersion from a Circular Aperture Antenna with $(1 - r^2)^2$ Illumination ($\bar{x}$ = 1 to 2)

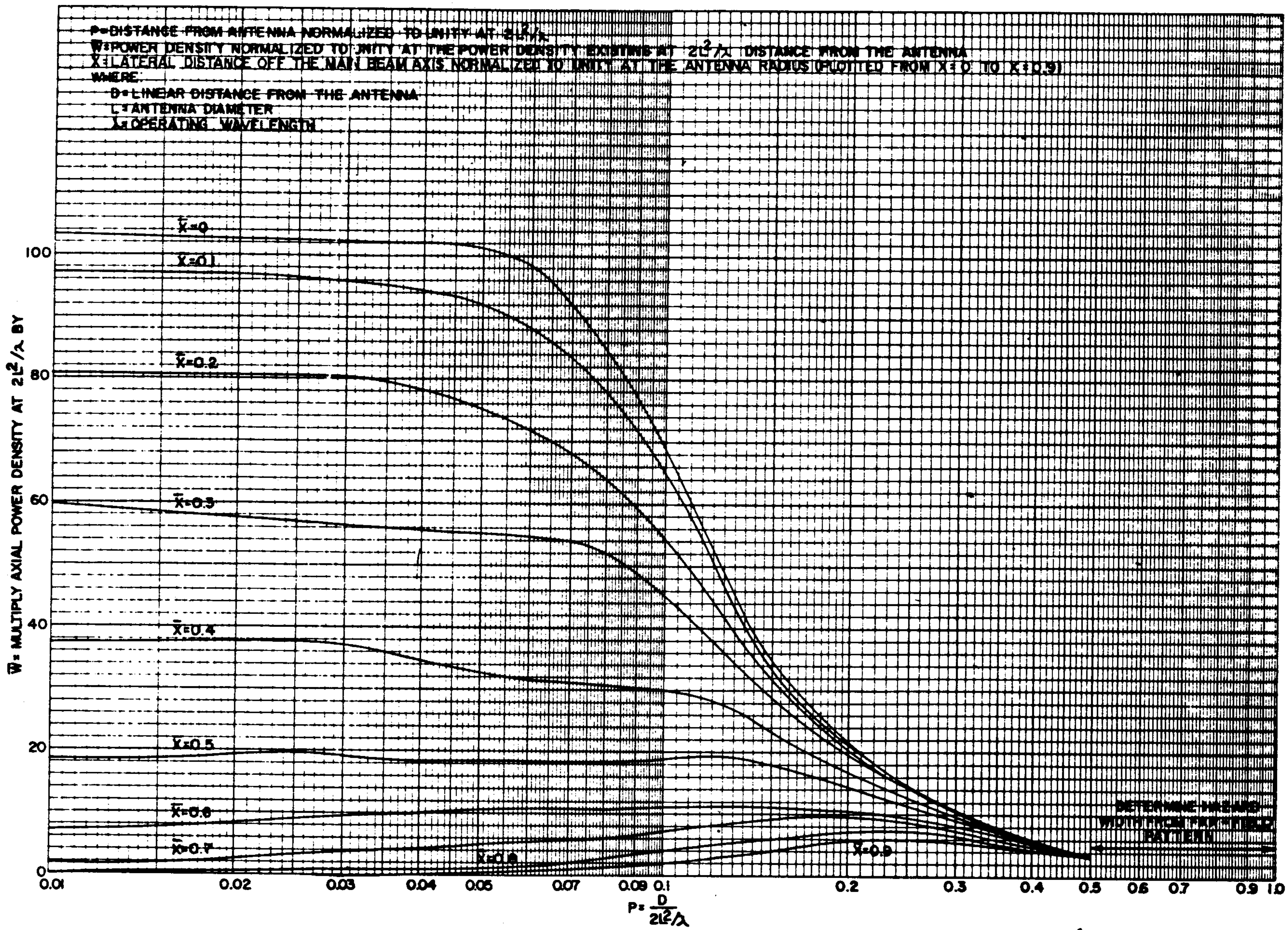


Figure 6-23. Power Density Dispersion from a Circular Aperture Antenna with $(1 - r^2)^3$ Illumination ($\bar{x}$ = 0 to 1)

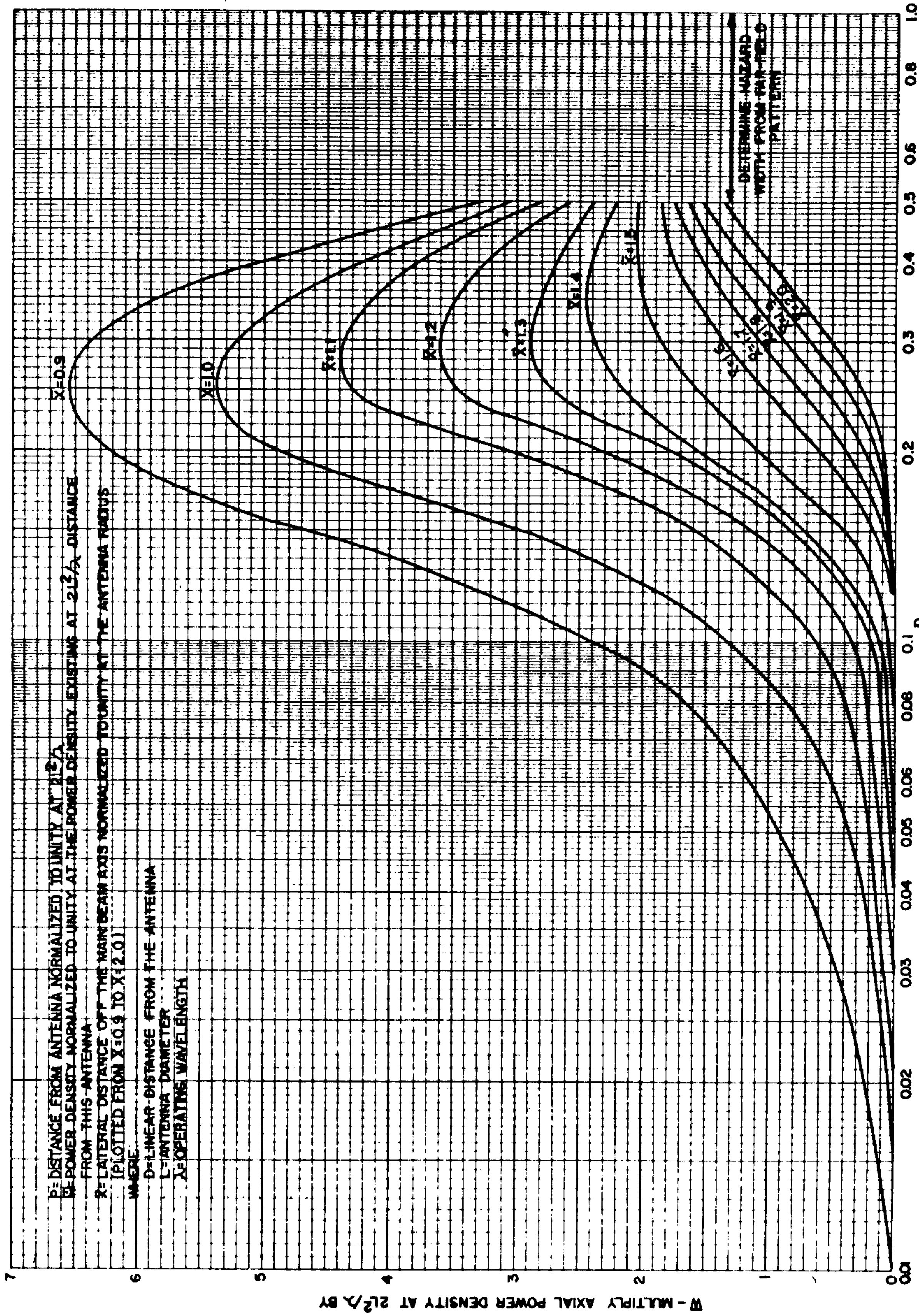


Figure 6-24. Power Density Dispersion from a Circular Aperture Antenna with $(1 - r^2)^3$ Illumination ($\bar{x}$ = 1 to 2)

APPENDIX A

OPERATING INSTRUCTION

(RADIATION HAZARD CONTROL)

(EXAMPLE)

UNIT: ZZZ Group, XXX Air Force Base.

VISITOR CONTROL: Visitors requiring access to the area will be advised of the posted locations.

ACCIDENT PREVENTION/REPORTING:

a. For overexposure, or suspected overexposure, obtain medical assistance promptly.

b. Any maintenance practices, operating procedures, equipment malfunction or personnel activity which appears to expose personnel, fuel, or EEDs to a radiation hazard should be brought to the attention of the local supervisor and the RPO.

c. Any accident shall be reported promptly in accordance with USAF and Command directives. The RPO Must file an accident report in accordance with AFR 127-4 and the appropriate command supplement thereto.

INFORMATION/GUIDANCE DOCUMENTS:

a. AFR 700-13

b. AFR 127-4

c. AFR 127-100

d. AFR 127-101

e. AFOSH Standard 127-38

f. AFOSH Standard 161-9

g. T.O. 00-25-172

h. T.O. 31Z-10-4

i. T.O. (Equipment)

j. T.O. 00-110N-7

k. Add others which apply

O&M TRAINING REQUIREMENTS:

a. Review T.O. 31Z-10-4, Chapters 1 through 5

b. View Air Force training film on radiation hazards

c. Review the OI

Attachment 1 provides the names and phone numbers of personnel to contact for assistance.

SAMPLE ATTACHMENT TO A RADIATION HAZARD CONTROL OI

For ZZZ Group, XXX Air Force Base

EMRH 1:

FACILITY: Airport Surveillance Radar (ASR).

TRANSMITTER/EQUIPMENT: AN/GPN-XXX

IDENTIFICATION OF HAZARDS:

a. RF to personnel, fuel, and EEDs.

b. X-ray to personnel.

c. Radioactive material.

SOURCE AND SYNOPSIS OF HAZARD DATA:

a. RF Hazards - EMRH Survey, AFCC 1839 EIG-EMC-YY-XX

In the "center of the main beam" the hazard distances are as follows:

Personnel - 321 ft

Fuel - 385 ft

EEDs - 436 ft

Due to the antenna elevation and operational tilt, no rf hazards exist at ground level (below 12 ft). The poles and tower identified by the survey as protruding into the hazardous region have been posted. The radar is blanked as the beam passes across Building 102 in accordance with RF Hazard Drawing XXX.

b. X-ray Hazard - Technical Manual (Equipment)

Unit 1A12 is a source of x-rays and should not be operated with the shield removed.

c. Radioactive Material - Technical Manual (Equipment)

Tube 1A12V2 contains radioactive material and should be handled/disposed of in accordance with technical manual instructions.

SPECIAL O&M PROCEDURES/RESTRICTIONS:

a. The transmitter shall not be placed in operation when the antenna is below normal operational tilt until the area to be exposed to main beam power has been cleared and access restricted.

b. Transmitter blanking is required in accordance with RF Hazard Drawing XXX.

SPECIAL COMMENTS/CONDITIONS: Any other comments/conditions may be listed here:

An example of an OI attachment listing equipment determined to be non-hazardous could look like:

FACILITY/BUILDING	TRANSMITTER/EQUIPMENT
TACAN/7752	AN/GRN-19A
ILS/6605	AN/GRN-27 (Localizer)
TOWER/4775	AN/GRT-21 (12 Units)
TOWER/4775	AN/GRT-22 (15 Units)

APPENDIX B

AFCC RF RADIATION HAZARD STUDY GUIDE

B-1. Rf radiation hazard studies are accomplished by several AFCC organizations; therefore, guidance is required to ensure the following:

a. All hazards are addressed.

b. Current criteria is used.

c. Adequate inputs are obtained.

d. Calculations are standardized.

e. Information provided in the report is complete, supported, qualified, and above all, safe.

B-2. Rf is a hazard to personnel, fuel, and EEDs. Even though current site conditions may not create a hazard to all of the above, each hazard will be addressed in the report. This places the information at-hand, and any operational or siting change that could create a hazard can be avoided.

B-3. Criteria for personnel, fuel and EED hazards are provided in:

a. AFOSH Standard 161-9, Exposure to Radiofrequency Radiation

b. AFOSH Standard 127-38, Hydrocarbon Fuels - General

c. AFR 127-100, Explosives Safety Standards

Criteria has changed in the past, therefore, the current values must be ascertained.

B-4. The information provided in the report should impose minimal operational restrictions and inconvenience. To accomplish this safely all of the pertinent equipment parameters and site conditions should be obtained from the customer. If the normal operating parameters do not provide "worst case" conditions then the report should indicate normal and worst case hazard information. The parameter change creating worst case conditions should be clearly identified. If the customer is unable to supply the required inputs the data can be obtained from the equipment manual, USAF OEHL/RZ or ECAC D-9 (SECRET) Communication-Electronic Equipment Directory. In this instance the worst case parameters must be used.

B-5. Hazard distances shall be based on the "Calculation of Power Density" provided in T.O. 31Z-10-4. The report shall clearly identify the hazard distance as:

a. Extending into the far field (Calculated by far-field formula).

b. Limited to the near field (Near-field correction factor applied).

c. Limited to the near field (Near-field correction factor not applied).

The situation of paragraph c above should only occur when the near-field correction factor cannot be determined with reasonable accuracy or when application of the correction factor would result in an insignificant change in the hazard distance. In cases where the calculated hazard distance may impact the operation/maintenance of the equipment the report should advise the customer that the calculated hazard distance could be significantly reduced by a survey.

B-6. The report shall be prepared and distributed in in accordance with EICR 100-1. The parameters and siting information used in the study shall be listed in an appendix. Drawings and photographs should be used to clarify and supplement the written information. If the equipment/situation requires an RF Hazard Drawing this should be so stated and action should be initiated to develop the drawing. If possible, the RF Hazard Drawing should accompany the report.

APPENDIX C

AFCC RF RADIATION HAZARD SURVEY GUIDE

C-1. GENERAL.

a. This guide is for use by AFCC survey teams. AFCC is responsible for conducting rf hazard surveys in support of the USAF Radiation Hazard Program. Based upon safe power level criteria developed by AFSC, AFCC offers an analysis, measurement and consultation service to the entire USAF. AFCC responsibilities include service to airborne, aerospace, and ground facilities and covers rf hazards to personnel, electroexplosive devices (EEDs) and fuel handling operations.

b. Accomplishing a comprehensive rf radiation hazard survey requires a systematic approach. Intricate measurements of rf energy and interpretation of the resulting data requires trained personnel who are knowledgeable of test equipment and experienced with the anomaly of the numerous radiators encountered. In addition to the requirement for technical excellence the members of the survey team must be proficient in both verbal and written communication. In some cases the information which they can convey to site personnel through discussions/briefings may be the most valuable part of the survey. After the fact, the professionalism of the survey can only be judged by the survey report and rf hazard drawings which must be relied on to implement the hazard control program.

C-2. PREPARATION. The first step is to obtain all the information required. Even if the survey request appears to provide adequate data, the customer should be contacted to ascertain the existence of additional equipment on site or in the local area which should be surveyed. Take this opportunity to inform the customer of what to expect (briefings, support required, downtime, etc). The local Bioenvironmental Engineer (BEE) can verify/add to this information and should be contacted and kept informed. (AFR 700-13 requires coordination with OEHL.) The customer should provide the parameters (both for normal operation and worst case) required to calculate the hazard distances for personnel, fuel and EED's. Current site conditions may not create a hazard to all of the above but the information should be on hand to avoid changes which would create a hazard. If a study or survey report and/or rf hazard drawings for the equipment can be obtained, these should be used to develop a survey test plan (test equipment required, measurement procedures, coordination required for transmitter operation and antenna positioning/array control). If a report is not available the hazard distances should be calculated (See T.O. 31Z-10-4) to develop the test plan. Two copies of the site rf hazard drawings should be taken to the site. Red line corrections should be made during the survey and one copy left on site and one returned to drafting for use in updating the master drawing. As soon as possible (suggest 30 day notice) a message should be sent to the RPO/BEE outlining the schedule and providing an open invitation to an on-site conference (info all interested parties).

C-3. BRIEFING/CONFERENCE. The local commander should be briefed on arrival. A conference to exchange information should be arranged with the unit RPO/BEE and any other interested parties. The survey team should take this opportunity to disseminate as much information as possible on hazards, control of hazards and the AFCC role. The survey test plan should also be reviewed to assure a coordinated effort and complete coverage.

C-4. CRITERIA FOR HAZARDS.

a. The official USAF criteria for safe rf exposure of personnel appears in AFOSH Standard 161-9.

b. The personnel hazard criteria for limited time occupancy should not be applied or recommended without prior coordination with 1842nd Electronics Engineering Group/EEITE.

c. The official USAF criteria for safety in fuel handling appears in AFOSH Standard 127-38.

d. The criteria for safe exposure of electroexplosive devices to rf fields appears in AFR 127-100.

e. The official rf radiation hazard sign is that sign designated as the American National Standards Institute, Sign C95-2. These signs are available as AF Form 737 and 747. Warning data and/or instructions to appear in the lower triangle of the sign are provided by the user. AFOSH Standard 161-9 provides an example and the information to manufacture signs of the required size.

C-5. MEASUREMENTS OF FIELD STRENGTHS. Jointly review all drawings prepared by the RPO/BEE and compare his calculated hazard distances to yours. Prepare a list of places to be surveyed and arrange them in a logical sequence. Request the unit RPO (and Group RPO, if not the same person) to join you in the survey.

a. Equipment Room. Commence making measurements in the vicinity of the equipment itself. Check for rf leaks at the seams and openings of the cabinet, at rotary rf connectors and waveguide flanges, etc. (If hazardous levels are found, an immediate remedy or safety precaution is required and the RPO should send exposed personnel to the dispensary.) Equipment containing voltages in excess of 15,000 volts should be brought to the attention of the RPO for possible X-ray hazards. Make no decisions concerning X-ray hazards but do refer him to the BEE for guidance.

b. Outside Plant.

(1) Before proceeding to the antenna farm, the efficiency of the transmitter and antenna must be determined. Verify the power output of the transmitter by calculations or with a wattmeter. If not operated at full power, a correction factor is required (to reduce the permissible exposure level to proper value for potential hazard distance). The efficiency of the antenna must be determined by comparing the existing vswr with the antenna specifications or by comparing it to the original vswr. Any minor changes in the vswr can be compensated for by a correcting factor (assume that the antenna will be restored to meet original specifications). However, if a major discrepancy is noted in the vswr, the survey should be held in abeyance until the antenna and/or transmission line has been rehabilitated. If the antenna and transmission line indicate no major discrepancies in efficiency, then add a correction factor for the existing frequency and its vswr to compensate for the most efficient frequency and its vswr. (Or make measurements when the transmitter is tuned to its most efficient assigned frequency; that is, the frequency with the highest antenna gain and lowest vswr.) When the total correction factor has been determined, measurements should commence.

(2) Antenna Field Strength Measurements. Antenna field strength measurements should be accomplished as follows:

(a) Proceed to the front of the antenna by a calculated safe route. Take measurements while approaching the antenna. Proceed to the appropriate permissible exposure level (or extrapolated value) determined from table 3-1 and define the boundary by following the hazardous contour. If a second antenna is radiating significant power, the contour must be determined by summation. If reflections are predicted or experienced, they must be accounted for. The ground reflection can easily extend the hazard area beyond the normal main beam distance, and all such areas must be located and documented. If there is a major discrepancy between the predicted and measured distance to the hazard level this must be accounted for. If the discrepancy is attributed to insufficient antenna gain the survey should be held in abeyance until this problem is corrected.

(b) An alternate method is to reduce the output of the transmitter to 50% of maximum (if possible) and define the one-half permissible exposure level boundary. This is advantageous for safety, expediency, pole climbing, etc.

(c) Perform measurements of power density (or field strength) in areas such as, walkways, parking lots, open fields, runways, taxiways, aprons, ramps, maintenance areas, towers, poles and roofs. These areas are specifically mentioned because of access possibility by people unfamiliar with either radiation hazards or the specific site. Measurements are made in front of and around antennas, both within and outside of radomes (if any).

(d) Cover fuel hazards and EED hazards wherever applicable by locating several points where the specific levels occur. Collect enough data points to define all accessible hazardous areas on a map. Determine where fuel and EEDs are stored in relation to the hazardous areas and place on appropriate maps.

(e) After all fixed station transmitters have been surveyed, evaluate all mobile transmitters and their safety precautions. Record their safety precautions for inclusion in your report.

(f) Contact the flight operations officer to determine if any of the calculated hazardous areas may be violated by aircraft. A survey by helicopter and/or flight safety OIs may have to be established.

(g) Assist the RPO in updating his C-E facility drawings depicting rf radiation hazardous areas. The C-E facility work center of the Drafting Section in each area is responsible for final updating of the C-E facility drawings. Send an updated copy to them when the survey is complete. Together, with the RPO, determine where radiation hazard signs should be placed, replaced or otherwise changed. Advise him to order AF Forms 737 through his local Publications Distribution Office. Review his OI on Radiation Hazard Safety or assist him in the preparation of one (be sure it includes instructions for the proper course of action in case of accidental overdoses).

(h) Retain a copy of all data, OIs, MOIs, etc, relating to rf radiation hazards for use in your final report.

c. On radar equipment, blanking angles (if any) are checked by actual measurements. If local operation permits, such angles should be adjusted while team is on site. NOTE: Normal blanking allows arms reach from structure being blanked without incurring hazard. Recommended blanking angles should be based upon displayed angle data. (Do not attempt to correct site bearing information.)

C-6. CONFERENCE FOR SAFETY PERSONNEL.

a. Preparation Requirements (24 to 48 hours prior to conference).

(1) Contact the local BEE and ask him to brief the conference attendees concerning hazards relative to his area of responsibility. Schedule a set time in the conference for his presentation.

(2) Confirm arrangements with the unit RPO for the showing of Air Force training film on radiation hazards. Schedule a specific time for the movie and projectionist.

(3) Prepare training outline. (Training aids such as power meters, hazard signs, blackboards, etc, should be used.)

(4) Prepare a sign-in sheet for attendees. This should include Name, Rank, Organization, Office Symbol and Duty Relative to Safety Programs (such as RPO, BEE, Base Safety Officer, etc). Arrange for sign-in at the entrance to the conference room to avoid the disruptions of a pass-around sheet.

b. Presentation. As desired by the speaker. The following is presented for assistance.

(1) Introduction.

(a) Introduce yourself and give a brief description of the duties of yourself as radiation hazard engineer.

(b) Introduce the local BEE provided that he has agreed to speak.

(c) Introduce the unit RPO and credit him with the arrangements for the conference.

(d) Others if deemed beneficial.

(2) RF Radiation Hazards (as pertains to the victim).

(a) Body and organs.

(b) Experiments with animals at lower powers.

(c) Hazards to fuel.

(d) Hazards to EEDs.

(3) Ionization Radiation Hazards (presented by the BEE).

(4) Air Force training film on radiation hazards.

(5) Break.

(6) Display copies and give brief summary of the contents of the standard radiation hazard references.

(a) T.O. 31Z-10-4.

(b) AFR 127-100.

(c) AFOSH Standard 161-9.

(7) Cover details of the rf hazard survey recently completed on base.

(8) Break (every two hours or less - - inversely proportional to interest shown).

(9) Cover examples of other rf hazard problems likely to occur (hf, vhf/uhf, microwave, radar). Include vertical presentation of a hazardous radar beam. Cover blanking (with operational considerations), shielding by reflectors and shielding by absorption materials.

(10) Emphasize that each RPO is responsible for all electronic equipment within his area of responsibility, not just that of AFCC. Explain that each RPO will be scheduled for personal consultation, that they should designate either a half hour or a full hour, depending upon the complexity of their individual problems. Specifiy which outlying sites will be visited for measurements if this information is presently known. Otherwise, determine which sites are to be visited during the personal interviews. After the interview schedules have been firmed, terminate the group conference.

C-7. INTERVIEWS. Interview RPOs according to the appointment schedule and survey those outlying sites that are deemed necessary.

C-8. OUTBRIEFING. Outbrief all appropriate personnel prior to departing each base or operating location. Discuss in detail all hazards found and recommend safety precautions. Emphasize the need for a hazard control program and OI.

C-9. REPORTS. Prepare reports in accordance with EICR 100-1. All maps, drawings, etc, should be reduced to fit the size of the report if possible. In addition, C-E facility drawings should be brought up-to-date. One red line copy should be forwarded to the C-E facility work center of Drafting Section. Photos for use in the report should be high contrast glossy prints. The report should include a copy of the appropriate OI and should be prepared as rapidly as possible after return to home station. Expeditious action is required because of the safety aspects of the task.

GPO 687-000/41660

APPENDIX D

TABLES, GRAPHS, AND NOMOGRAMS

D-1. INTRODUCTION. This section contains a number of mathematical tables, conversion tables, and nomograms, which will be found to be of assistance in the calculation or prediction of rf radiation hazards. Explanations regarding the use of the various tables are presented immediately preceding the table, where such explanations are deemed necessary.

D-2. FREQUENCY-WAVELENGTH CONVERSION. Table D-1 lists frequencies in 25-megahertz steps between the values of 200 and 10,000 megahertz, and the equivalent values of wavelength in meters and centimeters. For intermediate values interpolation should be used. The fourth column in the table lists the value of the square of the centimeter equivalent of wavelength, taken from the third column, for convenience in calculations.

Table D-1. Frequency (MHz), Wavelength (λ), Centimeters, cm^2

FREQUENCY (MHz)	METERS	CENTIMETERS	CM^2
200	1.500	150.0	22500.0
225	1.333	133.3	17769.0
250	1.200	120.0	14400.0
275	1.091	109.1	11903.0
300	1.000	100.0	10000.0
325	0.9231	92.31	8521.0
350	0.8571	85.71	7346.0
375	0.8000	80.00	6400.0
400	0.7500	75.00	5625.0
425	0.7059	70.59	4983.0
450	0.6667	66.67	4445.0
475	0.6316	63.16	3989.0
500	0.6000	60.00	3600.0
525	0.5714	57.14	3265.0
550	0.5455	54.55	2976.0
575	0.5217	52.17	2722.0
600	0.5000	50.00	2500.0
625	0.4800	48.00	2304.0
650	0.4615	46.15	2130.0
675	0.4444	44.44	1975.0
700	0.4286	42.86	1837.0
725	0.4138	41.38	1712.0
750	0.4000	40.00	1600.0
775	0.3871	38.71	1498.0
800	0.3750	37.50	1406.0
825	0.3636	36.36	1322.0
850	0.3529	35.29	1245.0
875	0.3429	34.29	1176.0
900	0.3333	33.33	1111.0
925	0.3243	32.43	1052.0
950	0.3158	31.58	997.3
975	0.3077	30.77	946.8
1000	0.3000	30.00	900.0
1025	0.2927	29.27	856.7
1050	0.2857	28.57	816.2
1075	0.2791	27.91	779.0
1100	0.2727	27.27	743.7
1125	0.2667	26.67	711.3
1150	0.2609	26.09	680.7
1175	0.2553	25.53	651.8
1200	0.2500	25.00	625.0
1225	0.2449	24.49	599.8
1250	0.2400	24.00	576.0
1275	0.2353	23.53	553.7
1300	0.2308	23.08	532.7
1325	0.2264	22.64	512.6
1350	0.2222	22.22	493.7
1375	0.2182	21.82	476.1
1400	0.2143	21.43	459.2
1425	0.2105	21.05	443.1
1450	0.2069	20.69	428.1
1475	0.2034	20.34	413.7
1500	0.2000	20.00	400.0
1525	0.1967	19.67	386.9
1550	0.1935	19.35	374.4
1575	0.1905	19.05	362.9
1600	0.1875	18.75	351.6
1625	0.1846	18.46	340.8
1650	0.1818	18.18	330.5
1675	0.1791	17.91	320.8
1700	0.1765	17.65	311.5
1725	0.1739	17.39	302.4
1750	0.1714	17.14	293.8
1775	0.1690	16.90	285.6
1800	0.1667	16.67	277.9
1825	0.1644	16.44	270.3
1850	0.1622	16.22	263.1
1875	0.1600	16.00	256.0
1900	0.1579	15.79	249.3
1925	0.1558	15.58	242.7
1950	0.1538	15.38	236.5
1975	0.1519	15.19	230.7

Table D-1. Frequency (MHz), Wavelength (λ), Centimeters, cm^2 (Continued)

FREQUENCY (MHz)	METERS	CENTIMETERS	CM²
2000	0.1500	15.00	225.0
2025	0.1481	14.81	219.3
2050	0.1463	14.63	214.0
2075	0.1446	14.46	209.1
2100	0.1429	14.29	204.2
2125	0.1412	14.12	199.4
2150	0.1395	13.95	194.6
2175	0.1379	13.79	190.2
2200	0.1364	13.64	186.0
2225	0.1348	13.48	181.7
2250	0.1333	13.33	177.7
2275	0.1319	13.19	174.0
2300	0.1304	13.04	170.0
2325	0.1290	12.90	166.4
2350	0.1277	12.77	163.1
2375	0.1263	12.63	159.5
2400	0.1250	12.50	156.2
2425	0.1237	12.37	153.0
2450	0.1224	12.24	149.8
2475	0.1212	12.12	146.9
2500	0.1200	12.00	144.0
2525	0.1188	11.88	141.1
2550	0.1176	11.76	138.3
2575	0.1165	11.65	135.7
2600	0.1154	11.54	133.2
2625	0.1143	11.43	130.6
2650	0.1132	11.32	128.1
2675	0.1121	11.21	125.7
2700	0.1111	11.11	123.4
2725	0.1101	11.01	121.2
2750	0.1091	10.91	119.0
2775	0.1081	10.81	116.9
2800	0.1071	10.71	114.7
2825	0.1062	10.62	112.8
2850	0.1053	10.53	110.9
2875	0.1043	10.43	108.8
2900	0.1034	10.34	106.9
2925	0.1026	10.26	105.3
2950	0.1017	10.17	103.4
2975	0.1008	10.08	101.6
3000	0.1000	10.00	100.0
3025	0.0992	9.92	98.41
3050	0.0984	9.84	96.83
3075	0.0976	9.76	95.26
3100	0.0968	9.68	93.70
3125	0.0960	9.60	92.16
3150	0.0952	9.52	90.63
3175	0.0945	9.45	89.30
3200	0.0938	9.38	87.98
3225	0.0930	9.30	86.49
3250	0.0923	9.23	85.19
3275	0.0916	9.16	83.91
3300	0.0909	9.09	82.63
3325	0.0902	9.02	81.36
3350	0.0896	8.96	80.28
3375	0.0889	8.89	79.03
3400	0.0882	8.82	76.79
3425	0.0876	8.76	76.74
3450	0.0870	8.70	75.69
3475	0.0863	8.63	74.48
3500	0.0857	8.57	73.44
3525	0.0851	8.51	72.42
3550	0.0845	8.45	71.40
3575	0.0839	8.39	70.39
3600	0.0833	8.33	69.39
3625	0.0828	8.28	68.56
3650	0.0822	8.22	67.57
3675	0.0816	8.16	66.59
3700	0.0811	8.11	65.77
3725	0.0805	8.05	64.80
3750	0.0800	8.00	64.00
3775	0.0795	7.95	63.20
3800	0.0789	7.89	62.25
3825	0.0784	7.84	61.47
3850	0.0779	7.79	60.68
3875	0.0774	7.74	59.91
3900	0.0769	7.69	59.14
3925	0.0764	7.64	58.37
3950	0.0759	7.59	57.61
3975	0.0755	7.55	57.00
4000	0.0750	7.50	56.25
4025	0.0745	7.45	55.50
4050	0.0741	7.41	54.91
4075	0.0736	7.36	54.17
4100	0.0732	7.32	53.58
4125	0.0727	7.27	52.85
4150	0.0723	7.23	52.27
4175	0.0719	7.19	51.70
4200	0.0714	7.14	50.98
4225	0.0710	7.10	50.41
4250	0.0706	7.06	49.84
4275	0.0702	7.02	49.28
4300	0.0698	6.98	48.72
4325	0.0694	6.94	48.16
4350	0.0690	6.90	47.61
4375	0.0686	6.86	47.06
4400	0.0682	6.82	46.51
4425	0.0678	6.78	45.97
4450	0.0674	6.74	45.43
4475	0.0670	6.70	44.89
4500	0.0667	6.67	44.49
4525	0.0663	6.63	43.96
4550	0.0659	6.59	43.43
4575	0.0656	6.56	43.03
4600	0.0652	6.52	42.51
4625	0.0649	6.49	42.12
4650	0.0645	6.45	41.60
4675	0.0642	6.42	41.22
4700	0.0638	6.38	40.70
4725	0.0635	6.35	40.32
4750	0.0632	6.32	39.94
4775	0.0628	6.28	39.44
4800	0.0625	6.25	39.06
4825	0.0622	6.22	38.69
4850	0.0619	6.19	38.32
4875	0.0615	6.15	37.82
4900	0.0612	6.12	37.45
4925	0.0609	6.09	37.09
4950	0.0606	6.06	36.72
4975	0.0603	6.03	36.36
5000	0.0600	6.00	36.00
5025	0.0597	5.97	35.64
5050	0.0594	5.94	35.28
5075	0.0591	5.91	34.93

Table D-1. Frequency (MHz), Wavelength (λ), Centimeters, cm^2 (Continued)

FREQUENCY (MHz)	METERS	CENTIMETERS	CM²
5100	0.0588	5.88	34.57
5125	0.0585	5.85	34.22
5150	0.0583	5.83	33.99
5175	0.0580	5.80	33.64
5200	0.0577	5.77	33.29
5225	0.0574	5.74	32.95
5250	0.0571	5.71	32.60
5275	0.0569	5.69	32.38
5300	0.0566	5.66	32.04
5325	0.0563	5.63	31.70
5350	0.0561	5.61	31.47
5375	0.0558	5.58	31.14
5400	0.0556	5.56	30.91
5425	0.0553	5.53	30.58
5450	0.0550	5.50	30.25
5475	0.0548	5.48	30.03
5500	0.0545	5.45	29.70
5525	0.0543	5.43	29.48
5550	0.0541	5.41	29.27
5575	0.0538	5.38	28.94
5600	0.0536	5.36	28.73
5625	0.0533	5.33	28.41
5650	0.0531	5.31	28.20
5675	0.0529	5.29	27.98
5700	0.0526	5.26	27.67
5725	0.0524	5.24	27.46
5750	0.0522	5.22	27.25
5775	0.0519	5.19	26.94
5800	0.0517	5.17	26.73
5825	0.0515	5.15	26.52
5850	0.0513	5.13	26.32
5875	0.0511	5.11	26.11
5900	0.0508	5.08	25.81
5925	0.0506	5.06	25.60
5950	0.0504	5.04	25.40
5975	0.0502	5.02	25.20
6000	0.0500	5.00	25.00
6025	0.0498	4.98	24.80
6050	0.0496	4.96	24.60
6075	0.0494	4.94	24.40
6100	0.0492	4.92	24.21
6125	0.0490	4.90	24.01
6150	0.0488	4.88	23.81
6175	0.0486	4.86	23.62
6200	0.0484	4.84	23.43
6225	0.0482	4.82	23.23
6250	0.0480	4.80	23.04
6275	0.0478	4.78	22.85
6300	0.0476	4.76	22.66
6325	0.0474	4.74	22.47
6350	0.0472	4.72	22.28
6375	0.0471	4.71	22.18
6400	0.0469	4.69	22.00
6425	0.0467	4.67	21.81
6450	0.0465	4.65	21.62
6475	0.0463	4.63	21.44
6500	0.0462	4.62	21.34
6525	0.0460	4.60	21.16
6550	0.0458	4.58	20.98
6575	0.0456	4.56	20.79
6600	0.0455	4.55	20.70
6625	0.0453	4.53	20.52
6650	0.0451	4.51	20.34
6675	0.0449	4.49	20.16
6700	0.0448	4.48	20.07
6725	0.0446	4.46	19.89
6750	0.0444	4.44	19.71
6775	0.0443	4.43	19.62
6800	0.0441	4.41	19.45
6825	0.0440	4.40	19.36
6850	0.0438	4.38	19.18
6875	0.0436	4.36	19.00
6900	0.0435	4.35	18.92
6925	0.0433	4.33	18.75
6950	0.0432	4.32	18.66
6975	0.0430	4.30	18.49
7000	0.0429	4.29	18.40
7025	0.0427	4.27	18.23
7050	0.0426	4.26	18.15
7075	0.0424	4.24	17.98
7100	0.0423	4.23	17.89
7125	0.0421	4.21	17.72
7150	0.0420	4.20	17.64
7175	0.0418	4.18	17.47
7200	0.0417	4.17	17.39
7225	0.0415	4.15	17.22
7250	0.0414	4.14	17.14
7275	0.0412	4.12	16.97
7300	0.0411	4.11	16.89
7325	0.0410	4.10	16.81
7350	0.0408	4.08	16.65
7375	0.0407	4.07	16.56
7400	0.0405	4.05	16.40
7425	0.0404	4.04	16.32
7450	0.0403	4.03	16.24
7475	0.0402	4.02	16.16
7500	0.0400	4.00	16.00
7525	0.0399	3.99	15.92
7550	0.0397	3.97	15.76
7575	0.0396	3.96	15.68
7600	0.0395	3.95	15.60
7625	0.0393	3.93	15.44
7650	0.0392	3.92	15.37
7675	0.0391	3.91	15.29
7700	0.0390	3.90	15.21
7725	0.0388	3.88	15.05
7750	0.0387	3.87	14.98
7775	0.0386	3.86	14.90
7800	0.0385	3.85	14.82
7825	0.0383	3.83	14.67
7850	0.0382	3.82	14.59
7875	0.0381	3.81	14.52
7900	0.0380	3.80	14.44
7925	0.0379	3.79	14.36
7950	0.0377	3.77	14.21
7975	0.0376	3.76	14.14
8000	0.0375	3.75	14.06
8025	0.0374	3.74	13.99
8050	0.0373	3.73	13.91
8075	0.0372	3.72	13.84
8100	0.0370	3.70	13.69
8125	0.0369	3.69	13.62
8150	0.0368	3.68	13.54
8175	0.0367	3.67	13.47

Table D-1. Frequency (MHz), Wavelength (λ), Centimeters, cm^2 (Continued)

FREQUENCY (MHz)	METERS	CENTIMETERS	CM^2
8200	0.0366	3.66	13.40
8225	0.0365	3.65	13.32
8250	0.0364	3.64	13.25
8275	0.0363	3.63	13.18
8300	0.0361	3.61	13.03
8325	0.0360	3.60	12.96
8350	0.0359	3.59	12.89
8375	0.0358	3.58	12.82
8400	0.0357	3.57	12.74
8425	0.0356	3.56	12.67
8450	0.0355	3.55	12.60
8475	0.0354	3.54	12.53
8500	0.0353	3.53	12.46
8525	0.0352	3.52	12.39
8550	0.0351	3.51	12.32
8575	0.0350	3.50	12.25
8600	0.0349	3.49	12.18
8625	0.0348	3.48	12.11
8650	0.0347	3.47	12.04
8675	0.0346	3.46	11.97
8700	0.0345	3.45	11.90
8725	0.0344	3.44	11.83
8750	0.0343	3.43	11.76
8775	0.0342	3.42	11.70
8800	0.0341	3.41	11.63
8825	0.0340	3.40	11.56
8850	0.0339	3.39	11.49
8875	0.0338	3.38	11.42
8900	0.0337	3.37	11.36
8925	0.0336	3.36	11.29
8950	0.0335	3.35	11.22
8975	0.0334	3.34	11.16
9000	0.0333	3.33	11.09
9025	0.0332	3.32	11.02
9050	0.0331	3.31	10.96
9075	0.0331	3.31	10.96
9100	0.0330	3.30	10.89
9125	0.0329	3.29	10.82
9150	0.0328	3.28	10.76
9175	0.0327	3.27	10.69
9200	0.0326	3.26	10.63
9225	0.0325	3.25	10.56
9250	0.0324	3.24	10.50
9275	0.0323	3.23	10.43
9300	0.0323	3.23	10.43
9325	0.0322	3.22	10.37
9350	0.0321	3.21	10.30
9375	0.0320	3.20	10.24
9400	0.0319	3.19	10.18
9425	0.0318	3.18	10.11
9450	0.0317	3.17	10.05
9475	0.0317	3.17	10.05
9500	0.0316	3.16	9.986
9525	0.0315	3.15	9.923
9550	0.0314	3.14	9.860
9575	0.0313	3.13	9.797
9600	0.0313	3.13	9.797
9625	0.0312	3.12	9.734
9650	0.0311	3.11	9.672
9675	0.0310	3.10	9.610
9700	0.0309	3.09	9.548
9725	0.0308	3.08	9.486
9750	0.0308	3.08	9.486
9775	0.0307	3.07	9.425
9800	0.0306	3.06	9.364
9825	0.0305	3.05	9.302
9850	0.0305	3.05	9.302
9875	0.0304	3.04	9.242
9900	0.0303	3.03	9.181
9925	0.0302	3.02	9.120
9950	0.0302	3.02	9.120
9975	0.0301	3.01	9.060
10,000	0.0300	3.00	9.000

D-3. MATHEMATICAL CONVERSION TABLE. Table D-2 lists distances in feet between the values of 0.5 foot and 10,000 feet, and the equivalent distances in meters and centimeters. Between the values of 0.5 and 30 feet, the distances are listed in increments of 25 feet; and between 1000 and 10,000 feet, in increments of 500 feet. For intermediate values interpolation should be used. Additional columns in the table give the values of centimeters squared, square root of feet, square root of meters, reciprocal of square root of feet, and reciprocal of square root of meters.

D-4. METRIC-ENGLISH EQUIVALENT LENGTHS. Table D-3 gives equivalent lengths of one inch, one foot, one yard, one centimeter, one kilometer, one statute mile, and one nautical mile in terms of each of the other units. The values given may be used as multiplying factors to convert from one unit to another.

D-5. POWERS OF TEN.

a. A thorough knowledge of the powers of ten and their use will greatly assist in solving problems. Use of the powers of ten will enable one to work problems involving very small decimal values or very large whole numbers with minimum difficulty, without having to write out combersome ten- or fifteen-digit numbers, which contain nearly all zeros.

b. Some multiples of ten, which will be extensively used in problems dealing with radiation hazards, are given below:

Expressed as a Number		Expressed as a Power to Ten
0.000001	=	10^{-6}
0.00001	=	10^{-5}
0.0001	=	10^{-4}
0.001	=	10^{-3}
0.01	=	10^{-2}
0.1	=	10^{-1}

Expressed as a Number		Expressed as a Power of Ten
1	=	10^{0}
10	=	10^{1}
100	=	10^{2}
1,000	=	10^{3}
10,000	=	10^{4}
100,000	=	10^{5}
1,000,000	=	10^{6}

As shown above, it is apparent that any decimal fraction may be readily changed to the number ten, times a negative power of ten. Also, any multiple of ten may be expressed as ten, to the proper (positive) power of ten.

c. In the same manner that multiples of ten may be expressed as ten to a certain positive or negative power of ten, so also may any decimal number be expressed as a whole number multiplied by some negative power of ten. Likewise, any large number may be represented by some smaller number multiplied by some (positive) power of ten. For example, take the number 452. This number could be expressed as:

$$452 = 4.52 \times 10^2$$

It could be expressed:

$$452 = 45.2 \times 10^1$$

Table D-2. Mathematical Conversion Table

FEET	METERS	CM	CM²	√FEET	√METERS	1/√FEET	1/√METERS
0.5	0.1524	15.24	2.33×10^2	0.708	0.391	1.41	2.56
1.0	0.3048	30.48	9.3×10^2	1.00	0.553	1.00	1.81
1.5	0.457	45.70	2.025×10^3	1.25	0.677	0.80	1.48
2.0	0.61	61.00	3.72×10^3	1.414	0.783	0.708	1.28
2.5	0.762	76.20	5.8×10^3	1.57	0.875	0.637	1.15
3.0	0.915	91.50	8.37×10^3	1.732	0.958	0.577	1.033
3.5	1.065	106.50	1.135×10^4	1.87	1.032	0.435	0.97
4.0	1.22	122	1.48×10^4	2.00	1.105	0.50	0.905
4.5	1.37	137	1.88×10^4	2.12	1.17	0.472	0.855
5.0	1.525	152.5	2.33×10^4	2.24	1.24	0.447	0.807
5.5	1.67	167	2.79×10^4	2.35	1.29	0.425	0.775
6	1.83	183	3.35×10^4	2.45	1.35	0.408	0.74
6.5	1.96	196	3.84×10^4	2.55	1.40	0.393	0.714
7	2.13	213	4.54×10^4	2.65	1.46	0.378	0.685
7.5	2.28	228	5.20×10^4	2.74	1.51	0.365	0.663
8	2.44	244	5.95×10^4	2.83	1.56	0.354	0.64
8.5	2.59	259	6.70×10^4	2.92	1.61	0.343	0.622
9	2.74	274	7.50×10^4	3.00	1.66	0.333	0.602
9.5	2.90	290	8.4×10^4	3.08	1.705	0.325	0.586
10	3.048	304.8	9.3×10^4	3.16	1.75	0.317	0.572
10.5	3.20	320	1.03×10^5	3.24	1.79	0.309	0.56
11	3.35	335	1.12×10^5	3.32	1.83	0.301	0.546
11.5	3.5	350	1.225×10^5	3.40	1.87	0.294	0.535
12	3.66	366	1.34×10^5	3.46	1.92	0.289	0.52
12.5	3.81	381	1.45×10^5	3.54	1.95	0.283	0.512
13	3.96	396	1.57×10^5	3.605	1.99	0.278	0.502
13.5	4.11	411	1.68×10^5	3.68	2.03	0.272	0.492
14	4.27	427	1.82×10^5	3.74	2.07	0.268	0.483
14.5	4.42	442	1.95×10^5	3.81	2.10	0.263	0.475
15	4.57	457	2.09×10^5	3.87	2.14	0.258	0.467
15.5	4.73	473	2.24×10^5	3.94	2.18	0.254	0.458
16	4.88	488	2.39×10^5	4.00	2.22	0.250	.0.45
16.5	5.03	503	2.53×10^5	4.06	2.25	0.247	0.445
17	5.18	518	2.69×10^5	4.12	2.28	0.243	0.438
17.5	5.33	533	2.84×10^5	4.18	2.31	0.239	0.433
18	5.5	550	3.03×10^5	4.24	2.35	0.236	0.425
18.5	5.64	564	3.18×10^5	4.30	2.38	0.233	0.42
19	5.8	580	3.36×10^5	4.36	2.41	0.229	0.415
19.5	5.95	595	3.54×10^5	4.42	2.44	0.226	0.41
20	6.1	610	3.72×10^5	4.47	2.47	0.224	0.405
20.5	6.25	625	3.91×10^5	4.54	2.5	0.220	0.40
21	6.4	640	4.10×10^5	4.58	2.53	0.218	0.396
21.5	6.55	655	4.29×10^5	4.64	2.56	0.215	0.391

Table D-2. Mathematical Conversion Table (Continued)

FEET	METERS	CM	CM^2	$\sqrt{FEET}$	$\sqrt{METERS}$	$\frac{1}{\sqrt{FEET}}$	$\frac{1}{\sqrt{METERS}}$
22	6.7	670	4.50×10^5	4.69	2.59	0.213	0.386
22.5	6.85	685	4.70×10^5	4.75	2.62	0.211	0.384
23	7.00	700	4.9×10^5	4.795	2.645	0.209	0.382
23.5	7.15	715	5.11×10^5	4.85	2.67	0.206	0.38
24	7.30	730	5.33×10^5	4.898	2.70	0.204	0.374
24.5	7.46	746	5.56×10^5	4.955	2.73	0.202	0.372
25	7.62	762	5.8×10^5	5.0	2.76	0.2	0.368
50	15.2	1520	2.31×10^6	7.01	3.9	0.1425	0.257
75	22.9	2290	5.25×10^6	8.66	4.78	0.1155	0.208
100	30.5	3050	9.3×10^6	10.0	5.52	0.1	0.1815
125	38.1	3810	14.5×10^6	11.18	6.16	8.95×10^{-2}	1.62×10^{-1}
150	45.8	4580	21.0×10^6	12.25	6.77	8.16×10^{-2}	1.48×10^{-1}
175	53.4	5340	28.5×10^6	13.23	7.3	7.6×10^{-2}	1.37×10^{-1}
200	61.0	6100	37.2×10^6	14.14	7.82	7.08×10^{-2}	1.28×10^{-1}
225	68.6	6860	47.0×10^6	15.00	8.28	6.67×10^{-2}	1.21×10^{-1}
250	76.3	7630	58.0×10^6	15.80	8.75	6.33×10^{-2}	1.14×10^{-1}
275	84.0	8400	70.5×10^6	16.60	9.17	6.02×10^{-2}	1.09×10^{-1}
300	91.5	9150	83.6×10^6	17.32	9.56	5.78×10^{-2}	1.05×10^{-1}
325	99.0	9900	98.0×10^6	17.90	9.95	5.6×10^{-2}	1.00×10^{-1}
350	106.5	10650	1.135×10^8	18.70	10.03	5.35×10^{-2}	9.96×10^{-2}
375	114.0	11400	1.30×10^8	19.35	10.70	5.17×10^{-2}	9.35×10^{-2}
400	122.0	12200	1.49×10^8	20.00	11.05	5.00×10^{-2}	9.05×10^{-2}
425	129.5	12950	1.68×10^8	20.60	11.40	4.86×10^{-2}	8.77×10^{-2}
450	137.0	13700	1.88×10^8	21.20	11.70	4.72×10^{-2}	8.55×10^{-2}
475	145.0	14500	2.10×10^8	21.80	12.05	4.60×10^{-2}	8.3×10^{-2}
500	152.0	15200	2.25×10^8	22.35	12.30	4.47×10^{-2}	8.14×10^{-2}
525	160.0	16000	2.56×10^8	22.90	12.65	4.36×10^{-2}	7.92×10^{-2}
550	167.5	16750	2.81×10^8	23.45	12.95	4.33×10^{-2}	7.72×10^{-2}
575	175.0	17500	3.07×10^8	23.95	13.20	4.17×10^{-2}	7.6×10^{-2}
600	182.0	18200	3.32×10^8	24.50	13.45	4.08×10^{-2}	7.45×10^{-2}
625	190.0	19000	3.62×10^8	25.00	13.75	4.00×10^{-2}	7.28×10^{-2}
650	198.0	19800	3.94×10^8	25.50	14.05	3.92×10^{-2}	7.12×10^{-2}
675	205.0	20500	4.22×10^8	26.00	14.30	3.85×10^{-2}	7.0×10^{-2}
700	213.0	21300	4.55×10^8	26.40	14.60	3.80×10^{-2}	6.85×10^{-2}
725	221.0	22100	4.90×10^8	26.90	14.85	3.72×10^{-2}	6.74×10^{-2}
750	228.0	22800	5.22×10^8	27.40	15.10	3.65×10^{-2}	6.62×10^{-2}
775	236.0	23600	5.58×10^8	27.80	15.25	3.60×10^{-2}	6.56×10^{-2}
800	243.00	24300	5.90×10^8	28.30	15.60	3.54×10^{-2}	6.42×10^{-2}
825	251.00	25100	6.3×10^8	28.7	15.80	3.48×10^{-2}	6.32×10^{-2}
850	259.00	25900	6.72×10^8	29.15	16.10	3.44×10^{-2}	6.22×10^{-2}
875	267.00	26700	7.14×10^8	29.60	16.30	3.38×10^{-2}	6.14×10^{-2}
900	274.00	27400	7.52×10^8	30.00	16.55	3.34×10^{-2}	6.05×10^{-2}
925	282.00	28200	7.92×10^8	30.40	16.75	3.30×10^{-2}	5.98×10^{-2}
950	290.00	29000	8.42×10^8	30.80	16.90	3.25×10^{-2}	5.92×10^{-2}
975	299.70	29970	8.98×10^8	31.20	17.30	3.20×10^{-2}	5.8×10^{-2}
1000	305.00	30500	9.3×10^8	31.60	17.45	3.165×10^{-2}	5.72×10^{-2}
1500	457.2	45720	2.09×10^9	38.73	21.38	2.58×10^{-2}	4.68×10^{-2}
2000	609.6	60960	3.72×10^9	44.72	24.69	2.24×10^{-2}	4.05×10^{-2}
2500	762.0	76200	5.81×10^9	50.00	27.60	2.00×10^{-2}	3.62×10^{-2}
3000	914.4	91400	8.35×10^9	54.77	30.23	1.83×10^{-2}	3.31×10^{-2}
3500	1066.8	106680	11.38×10^9	59.16	32.66	1.69×10^{-2}	3.06×10^{-2}

Table D-2. Mathematical Conversion Table (Continued)

FEET	METERS	CM	CM^2	$\sqrt{FEET}$	$\sqrt{METERS}$	$\frac{1}{\sqrt{FEET}}$	$\frac{1}{\sqrt{METERS}}$
4000	1219.2	121920	14.86×10^9	63.25	34.91	1.58×10^{-2}	2.86×10^{-2}
4500	1371.6	137160	18.81×10^9	67.08	37.04	1.49×10^{-2}	2.70×10^{-2}
5000	1524.0	152400	23.23×10^9	70.71	39.04	1.41×10^{-2}	2.56×10^{-2}
5500	1676.4	167640	28.10×10^9	74.16	40.94	1.35×10^{-2}	2.44×10^{-2}
6000	1828.8	182880	33.45×10^9	77.46	42.76	1.29×10^{-2}	2.34×10^{-2}
6500	1981.2	198120	39.25×10^9	80.62	44.51	1.24×10^{-2}	2.25×10^{-2}
7000	2133.6	213360	45.52×10^9	83.67	46.19	1.20×10^{-2}	2.16×10^{-2}
7500	2286.0	228600	52.26×10^9	86.60	47.81	1.16×10^{-2}	2.09×10^{-2}
8000	2438.4	243840	59.46×10^9	89.44	49.38	1.12×10^{-2}	2.02×10^{-2}
8500	2590.8	259080	67.12×10^9	92.20	50.90	1.08×10^{-2}	1.96×10^{-2}
9000	2743.2	274320	75.25×10^9	94.87	52.38	1.05×10^{-2}	1.91×10^{-2}
9500	2895.6	289560	83.84×10^9	97.47	53.81	1.03×10^{-2}	1.86×10^{-2}
10000	3048.0	304800	92.90×10^9	100.00	55.21	1.00×10^{-2}	1.81×10^{-2}

For convenience in calculations, the more generally used form of expressing numbers is to keep the number to the left of the decimal point limited to a one-digit number, i.e., a number between one and ten, with the remainder of the significant figures falling to the right of the decimal point, and adjust the power of ten multiplier accordingly. For example, various fractions and whole numbers containing the digits 452 may be expressed as follows:

0.0000452	=	4.52×10^{-5}
0.000452	=	4.52×10^{-4}
0.00452	=	4.52×10^{-3}
0.0452	=	4.52×10^{-2}
0.452	=	4.52×10^{-1}
4.52	=	4.52×10^{0}
45.2	=	4.52×10^{1}
452	=	4.52×10^{2}
4,520	=	4.52×10^{3}
45,200	=	4.52×10^{4}
452,000	=	4.52×10^{5}

d. By expressing cumbersome numbers as small numbers multiplied by the appropriate power of ten, problems involving multiplication, division, powers, and roots may be reduced to a form which is readily handled, and which in many cases may be solved mentally after being reduced to this form.

e. In using powers of ten, it is essential that the laws of exponents be thoroughly understood. Briefly, these laws may be expressed as follows:

(1) Multiplication of numbers having exponents to the same base (which in the present case is the base 10) is accomplished by adding the exponents.

Table D-3. Metric-English Equivalent Lengths

UNIT	INCHES	FEET	YARDS	CENTI-METERS	METERS	KILO-METERS	STATUTE MILES	NAUTICAL MILES
1 in.	1	0.0833	0.028	2.54	0.0254	0.0000254	0.00001575	0.0000137
1 ft	12	1.00	0.333	30.48	0.3048	0.000305	0.0001895	0.0001645
1 yd	36	3.00	1.00	91.44	0.9144	0.000915	0.000568	0.000494
1 cm	0.394	0.0328	0.0109	0.100	0.01	0.00001	0.00000622	0.0000054
1 meter	39.37	3.28	1.094	100	1.00	0.001	0.000622	0.00054
1 km	39,370	3,280	1,094	100,000	1,000	1	0.622	0.54
1 statute mile	63,360	5,280	1,760	160,934	1,609.3	1.609	1	0.87
1 nautical mile	72,960	6,080	2,026.7	185,318.4	1,853.18	1.853	1.15	1

(2) Division of numbers having exponents to the same base (10) is accomplished by subtracting the exponent of the divisor from the exponent of the dividend.

(3) Raising numbers to powers is accomplished by multiplying the exponent of the base (10) by the index of the power.

(4) Extracting a root of a number is accomplished by dividing the exponent of the base (10) by the index of the root.

In the following paragraphs the laws of exponents, which are briefly summarized above, are illustrated by means of examples.

D-6. MULTIPLICATION USING POWERS OF TEN. In multiplication, exponents having the same base are added. Since only powers of ten are being considered, the base is, of course, ten. Multiplication, then, is expressed as:

$$10^a \times 10^b = 10^{a+b}$$

For example, multiply 0.0001 by 0.00001.

Solution: $0.0001 = 10^{-4}$; $0.00001 = 10^{-5}$

$$0.0001 \times 0.00001 = 10^{-4} \times 10^{-5}$$

$$= 10^{-9} = 0.000000001$$

For a second example, multiply 10,000 by 0.0001.

Solution: $10{,}000 = 10^4$; $0.0001 = 10^{-4}$

$$10{,}000 \times 0.0001 = 10^4 \times 10^{-4} = 10^0 = 1$$

For a third example, consider numbers which may be encountered in actual calculations, such as 300,000,000 multiplied by 0.00628.

Solution: $300{,}000{,}000 = 3 \times 10^{8}$

$0.00628 = 6.28 \times 10^{-3}$

$$300{,}000{,}000 \times 0.00628$$
$$= 3 \times 10^{8} \times 6.28 \times 10^{-3}$$
$$= 3 \times 6.28 \times 10^{(8-3)}$$
$$= 18.84 \times 10^{5}$$
$$= 1{,}884{,}000$$

It is evident from the above example that the only actual multiplication involved is 3 x 6.28, which can be done mentally.

D-7. DIVISION USING POWERS OF TEN. In division, exponents of denominators are subtracted from exponents of numerators, provided that the bases are identical. Division, then, is expressed thus:

$$\frac{10^{a}}{10^{b}} = 10^{a-b}$$

For example, divide 0.0001 by 0.01.

Solution: $0.0001 = 10^{-4}$; $0.01 = 10^{-2}$

$$\frac{0.0001}{0.01} = \frac{10^{-4}}{10^{-2}} = 10^{-4-(-2)} = 10^{-2} = 0.01$$

For a second example, divide 0.0001 by 100,000,000.

Solution: $0.0001 = 10^{-4}$; $100{,}000{,}000 = 10^{8}$

$$\frac{0.0001}{100{,}000{,}000} = \frac{10^{-4}}{10^{8}} = 10^{-4-8} = 10^{-12}$$
$$= 0.000000000001$$

For a third example, consider numbers which may be used in actual calculations, such as 0.00627 divided by 300,000,000.

Solution: $0.00627 = 6.27 \times 10^{-3}$

$300{,}000{,}000 = 3 \times 10^{8}$

$$\frac{0.00627}{300{,}000{,}000} = \frac{6.27 \times 10^{-3}}{3 \times 10^{8}} = \frac{6.27 \times 10^{-3-8}}{3} = 2.09 \times 10^{-11}$$

D-8. RAISING TO POWERS USING POWERS OF TEN. In raising a number which is already expressed as a power of ten to an additional power, the exponent of the base is multiplied by the exponent indicating the power. Raising to a power is expressed as:

$$(10^a)^b = 10^{a \times b}$$

For example, square the number 0.001.

Solution: $0.001 = 10^{-3}$

$$(0.001)^2 = (10^{-3})^2 = 10^{-6}$$

$$= 0.000001$$

For a second example, cube the number 100.

Solution: $100 = 10^2$

$$100^3 = (10^2)^3 = 10^6$$

$$= 1{,}000{,}000$$

For a third example, consider a number which may occur in an actual calculation, such as 300,000,000 raised to the third power.

Solution: $300{,}000{,}000 = 3 \times 10^8$

$$(3 \times 10^8)^3 = 3^3 \times 10^{8 \times 3} = 27 \times 10^{24}$$

Or, expressing the 27 so that only a single digit is to the left of the decimal point: 2.7×10^{25}. The result, 2.7×10^{25}, is too unwieldly to represent conventionally, since it would necessarily be written as 27 followed by 24 zeros. Here is seen the real value of a knowledge of the use of powers of ten.

D-9. EXTRACTING ROOTS USING POWERS OF TEN. In extracting a root of a number which is already expressed as a power of ten, the exponent of the base is divided by the exponent indicating the root. Extracting a root is expressed as:

$$\sqrt[b]{10^a} = 10^{\frac{a}{b}}$$

For example, extract the square root of 10,000.

Solution: $10{,}000 = 10^4$

$$\sqrt{10^4} = 10^{\frac{4}{2}} = 10^2$$

$$= 100$$

For a second example, extract the square root of 10,000.

Solution: $100,000 = 10^5$

$$\sqrt{100,000} = 10^{\frac{5}{2}} = ?$$

In this case a difficulty is encountered, because a fractional power of ten cannot be easily reduced to a final answer, except by the use of logarithms. To avoid this difficulty, the number from which the root is to be extracted must be expressed as some number, multiplied by a proper power of ten which is evenly divisible by the index of the root. Therefore, the problem should be solved thus:

Solution: $100,000 = 10 \times 10^4$

$$\sqrt{100,000} = \sqrt{10 \times 10^4} = 10^2\sqrt{10}$$

$$= 100\sqrt{10}$$

For a third example, extract a root of a number which may be encountered in an actual calculation, such as the fourth root of 300,000,000.

Solution: $300,000,000 = 3 \times 10^8$

$$\sqrt[4]{300,000,000} = \sqrt[4]{3 \times 10^8}$$

$$= \sqrt[4]{3} \times 10^{\frac{8}{4}}$$

$$= \sqrt[4]{3} \times 10^2$$

$$= 100\sqrt[4]{3}$$

D-10. USING POWERS OF TEN IN SOLVING PROBLEMS. To understand the use of powers of ten in multiplication, division, and raising numbers to powers, consider the following example, in which the power density (W) in a radar beam is to be calculated.

Given:

$$W = \frac{P_tG_t}{4\pi D^2} = \frac{3600 \times 7400}{4 \times 3.14 \times (2755 \times 30.48)^2}$$

Solution:

$$W = \frac{3600 \times 7400}{4 \times 3.14 \times (2755 \times 30.48)^2}$$

$$= \frac{3.6 \times 10^3 \times 7.4 \times 10^3}{4 \times 3.14 \times (2.755 \times 10^3 \times 3.048 \times 10^1)^2}$$

$$= \frac{3.6 \times 7.4 \times 10^6}{4 \times 3.14 \times (2.755 \times 3.048)^2 \times 10^8}$$

$$= \frac{3.6 \times 7.4}{12.56 \times (2.755 \times 3.048)^2 \times 10^2}$$

This is as far as the problem can be simplified using powers of ten. If an approximation is desired, the final result can be calculated simply, by rounding off all decimal numbers to whole numbers, except the decimal numbers that are raised to a power (such as those within the parentheses in the above example). In this example, the decimal numbers that are squared can be rounded off to 2.75 x 3. The calculation then becomes:

$$W = \frac{4 \times 7}{13 \times (2.75 \times 3)^2 \times 10^2}$$

$$= \frac{28}{13 \times 68 \times 100} = \frac{28}{83200}$$

$$= 0.0003 \text{ watt/cm}^2$$

D-11. COMMON LOGARITHMS.

a. Table D-4 gives the common logarithms ($\log_{10}$ N) of numbers (N) from 10 to 99 inclusive.

b. A knowledge of logarithms is essential to an understanding of power relations in electronic equipments. Although the average person has been "exposed" to the study of logarithms in high school, it is often found that the basic principles regarding the use of logarithms are not clearly remembered, especially if several years have elapsed since the subject was studied. It is therefore felt that a brief review of the basic principles will be helpfull to the reader.

D-12. BASIC PRINCIPLES OF LOGARITHMS.

a. By definition, a logarithm of a given number is an exponent, which indicates the power to which a given base must be raised to equal the given number. This is a general rule for logarithms to any base. When "common" logarithms are specified, as they are here, the base used is the base 10. Therefore, the common logarithm of a given number is the exponent which indicates the power to which the base 10 must be raised to equal the given number.

b. In order to express the logarithm of a number N to the base 10, it is written $\log_{10}$ N. Since the logarithm of a number N is an exponent of 10, the logarithm of the number 100 is 2, because the base of 10 must be raised to the power of 2, or 10^2, to equal 100. Similiarly, the $\log_{10}$ 1000 is 3, because the base (10) must be raised to the third power, or 10^3, to equal 1000. It is evident, therefore, that the log of any number between the values of 100 and 1000 must be between 2 and 3. For example, by reference to table D-4 giving common logarithms, it can be seen that the $\log_{10}$ 500 is 2.6990. Stated in the "exponential form," this relationship is written:

$$10^{2.6990} = 500$$

Stated in "logarithmic form" it is written:

$$2.6990 = \log_{10} 500$$

It is obviously impractical to calculate the value of 10 raised to the 2.6990 power by normal longhand mathematics, in the manner that the value of 10^2 is calculated by multiplying 10 x 10, or the value of 10^3 by multiplying 10 x 10 x 10. However, reference to a log table reveals that the antilogarithm, which is the number corresponding to the given logarithm, of the number 2.6990 is 500.

c. Characteristic. In the preceding paragraph it was implied that the table of common logarithms gives the $\log_{10}$ 500 as 2.6990. Actually, the log table gives only the fractional value 0.6990, while the whole number 2, which is called the "characteristic," is an interger determined by the number of digits to the left of the decimal point. The characteristic of any logarithm may be determined by the following rules:

(1) Characteristics of positive numbers greater than 1 are positive, and have a value which is one less than the number of digits to the left of the decimal point.

(2) Characteristics of positive numbers less than 1 are negative, and have a value which is one more than the number of zeros to the right of the decimal point.

It is important to note that a negative number has an imaginary logarithm, which cannot be used in computations. However, since the numerical results are the same regardless of the algebraic sign, computations with negative numbers may be made by considering the numbers to be positive, and when the numerical value of the result is obtained, the proper sign may be added as determined by the conditions of the problem.

d. Mantissa. The mantissa is that part of the logarithm of a number which appears to the right of the decimal point. It is the number obtained from the log table, and it is the same regardless of the position of the decimal point in the original number. For example:

$$\log 500.00 = 2.6990$$
$$\log 50.00 = 1.6990$$
$$\log 5.00 = 0.6990$$
$$\log 0.50 = 9.6990 - 10$$
$$\log 0.05 = 8.6990 - 10$$

It will be noted that in all of the above examples, the figures 0.6990 remain the same; this portion of the logarithm is called the "mantissa." The position of the decimal point in the original number determines only the characteristic.

Table D-4. Common Logarithms

N	0	1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404
22	3434	3444	3464	3483	3502	3522	3541	3560	3579	3598
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900
31	4914	4928	4942	4955	4969	4983	4995	5011	5024	5038
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396

Table D-4. Common Logarithms (Continued)

N	0	1	2	3	4	5	6	7	8	9
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859
77	8865	8871	8876	8882	8887	8883	8899	8904	8910	8915
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996

D-13. MULTIPLICATION BY LOGARITHMS. Since a logarithm is an exponent of 10, multiplication is accomplished by the addition of exponents. By the laws of algebra:

$$a \times b = ab$$

$$10^a \times 10^b = 10^{a+b}$$

Also: $\log_{10} (a \times b) = \log_{10}a + \log_{10}b$

Finally: $a \times b = \text{antilog of } (\log_{10}a + \log_{10}b)$

For example, two of the numbers in the previous paragraph, 50 and 500, may be multiplied by the use of logarithms as follows:

$$50 \times 500 = \text{antilog of } (\log_{10}50 + \log_{10}500)$$

Since: $\log_{10}50 = 1.6990$

and: $\log_{10}500 = 2.6990$

then: $\log_{10}\text{product} = 1.6990 + 2.6990 = 4.3980$

Consulting the log table for the number whose mantissa is 3980 reveals that the number is 25. To determine the position of the decimal in the product of the multiplication, it is necessary to consider the characteristic. By the rule given in paragraph D-12c, the number has one more digit to the left of the decimal point than the value of the characteristic. Since the characteristic is 4, the number obtained above becomes 25 with a total of five digits to the left of the decimal point, or 25,000.

D-14. DIVISION BY LOGARITHMS. Division by logarithms is accomplished by subtraction of the log of the divisor from the log of the dividend. For example, using two of the numbers (500 and 25,000) given in paragraph D-12d, divide the smaller by the larger.

$$\frac{500}{25000} = \text{antilog of } (\log_{10}500 - \log_{10}25000)$$

Since: $\log_{10}500 = 2.6990$

and: $\log_{10}25000 = 4.3979$

then: $\log_{10}\text{product} = 2.6990 - 4.3979 = 8.3011 - 10$

Consulting the log table for the number whose mantissa is 3011 reveals that the number is 20. Once again this does not determine the position of the decimal. By the examples shown in paragraph D-12c a number whose characteristic is negative has one less zero to the right of the decimal point than the value of the negative characteristic. Thus the characteristic of 8 minus 10, or minus 2, indicates that there should be one zero after the decimal and before the number 20 obtained as a quotient. The final quotient, therefore, is 0.02.

D-15. RAISING TO A POWER BY LOGARITHMS. Raising a number to a power by logarithms is accomplished by multiplying the log of the number by the exponent of the power. For example:

$$25^3 = \text{antilog of } (3 \times \log_{10}25)$$

Since: $\log_{10} 25 = 1.3979$

then: $\log_{10}\text{product} = 3 \times 1.3979 = 4.1937$

Consulting the log table, the number whose mantissa is 1937 is 15625 (the last two digits 25 being obtained by interpolation, since 37 is approximately 1/4, or 0.25, of the difference between 1931 and 1959). The characteristic 4 provides five digits to the left of the decimal point. The final product, therefore, is 15,625.

D-16. EXTRACTING A ROOT BY LOGARITHMS. Extracting a root by logarithms is accomplished by dividing the log of the number by the exponent of the power. For example:

$$\sqrt[3]{125} = \text{antilog of} \left[\frac{\log_{10} 125}{3}\right]$$

Since: $\log_{10} 125 = 2.0969$

and: $\dfrac{\log_{10} 125}{3} = 0.6989$

then: antilog of $0.6989 = 5$

The characteristic 0 provides one digit to the left of the decimal point; the cube root of 125, therefore, is 5.

D-17. USE OF LOGARITHMS IN SOLVING PROBLEMS. To illustrate the use of logarithms in solving problems, the following example and its solution are presented:

Given: A radar set with the following parameters:

Average power: 4500 watts

Antenna gain: 30 dB (above that of an isotropic antenna)

To find: The power density in watts per square centimeter along the main beam axis at a point 300 feet from the antenna, assuming that this point is located in the far field.

Far Field Formula:

$$W_f = \frac{P_t G_t}{4\pi D^2}$$

where: P_t = transmitted average power

G_t = antenna gain (power gain)

D = distance in cm

W_f = power density in watts/cm^2

NOTE

The gain of the antenna, given as 30 dB above that of an isotropic antenna, must be converted to a power gain ratio for use in the formula. The 30-dB gain is equal to a power gain of 1000.

Substituting actual values in the formula:

$$W_f = \frac{4500 \times 1000}{12.56 \times (300 \times 30.5)^2}$$

(Note that the antenna gain of 30 dB is converted to a power gain of 1000.)

Changing to logarithmic values in the formula:

NOTE

This step is not necessary when the use of logarithms is understood. It is given here only for illustrating the actual conversion.

$$\log W_f = \frac{3.6532 + 3.0000}{1.0990 + [(2.4771 + 1.4843) \times 2]}$$

Changing now to logarithmic form: $\log W_f = 3.6532 + 3.000 - 1.0990 - 4.9542 - 2.9686$

Combining terms: $\log W_f = 6.6532 - 9.0218$

Subtracting: (Add 10 to the characteristic of the first logarithm, followed by -10 after the mantissa, to permit the subtraction to be completed.)

$$\begin{array}{rl} 6.6532 = & 16.6532 - 10 \\ & \underline{9.0218} \\ & 7.6314 - 10 \end{array}$$

Obtaining the antilog: $W_f = \text{antilog } 7.6314 - 10 = 0.00428 \text{ watt/cm}^2$

D-18. NATURAL SINES, COSINES, AND TANGENTS.

a. Table D-5 gives the natural sines, cosines, and tangents for angles of 0 degrees to 89 degrees inclusive, by degrees.

b. A brief review of the use of natural trigonometric functions is given in the following paragraphs, and their application to the solution of problems dealing with radiation hazards.

D-19. RIGHT TRIANGLES.

a. A triangle is a figure having three sides and three angles; the sum of the angles is equal to 180 degrees. A right triangle is a triangle in which one of the angles is a right angle or 90°; therefore the sum of the other two angles is 90°. The longer of the three sides, which in the case of the right triangle is the side opposite the right angle, is called the hypotenuse.

Table D-5. Natural Sines, Cosines, and Tangents

ANGLE	SIN	COS	TAN
0	0.0000	1.0000	0.0000
1	0.0175	0.9998	0.0175
2	0.0349	0.9994	0.0349
3	0.0523	0.9986	0.0524
4	0.0698	0.9976	0.0699
5	0.0872	0.9962	0.0875
6	0.1045	0.9945	0.1051
7	0.1219	0.9925	0.1228
8	0.1392	0.9903	0.1405
9	0.1564	0.9877	0.1584
10	0.1736	0.9848	0.1763
11	0.1908	0.9816	0.1944
12	0.2079	0.9781	0.2126
13	0.2250	0.9744	0.2309
14	0.2419	0.9703	0.2493
15	0.2588	0.9659	0.2679
16	0.2756	0.9613	0.2867
17	0.2924	0.9563	0.3057
18	0.3090	0.9511	0.3249
19	0.3256	0.9455	0.3443
20	0.3420	0.9397	0.3640
21	0.3584	0.9336	0.3839
22	0.3746	0.9272	0.4040
23	0.3907	0.9205	0.4245
24	0.4067	0.9135	0.4452
25	0.4226	0.9063	0.4663
26	0.4384	0.8988	0.4877
27	0.4540	0.8910	0.5095
28	0.4695	0.8829	0.5317
29	0.4848	0.8746	0.5543
30	0.5000	0.8660	0.5774
31	0.5150	0.8572	0.6009
32	0.5299	0.8480	0.6249
33	0.5446	0.8387	0.6494
34	0.5592	0.8290	0.6745
35	0.5736	0.8192	0.7002
36	0.5878	0.8090	0.7265
37	0.6018	0.7986	0.7536
38	0.6157	0.7880	0.7813
39	0.6293	0.7771	0.8098
40	0.6428	0.7660	0.8391
41	0.6561	0.7547	0.8693
42	0.6691	0.7431	0.9004
43	0.6820	0.7314	0.9325
44	0.6947	0.7193	0.9657

ANGLE	SIN	COS	TAN
45	0.7071	0.7071	1.0000
46	0.7193	0.6947	1.0355
47	0.7314	0.6820	1.0724
48	0.7431	0.6691	1.1106
49	0.7547	0.6561	1.1504
50	0.7660	0.6428	1.1918
51	0.7771	0.6293	1.2349
52	0.7880	0.6157	1.2799
53	0.7986	0.6018	1.3270
54	0.8090	0.5878	1.3764
55	0.8192	0.5736	1.4281
56	0.8290	0.5592	1.4826
57	0.8387	0.5446	1.5399
58	0.8480	0.5299	1.6003
59	0.8572	0.5150	1.6643
60	0.8660	0.5000	1.7321
61	0.8746	0.4848	1.8040
62	0.8829	0.4695	1.8807
63	0.8910	0.4540	1.9626
64	0.8988	0.4384	2.0503
65	0.9063	0.4226	2.1445
66	0.9135	0.4067	2.2460
67	0.9205	0.3907	2.3559
68	0.9272	0.3746	2.4751
69	0.9336	0.3584	2.6051
70	0.9397	0.3420	2.7475
71	0.9455	0.3256	2.9042
72	0.9511	0.3090	3.0777
73	0.9563	0.2924	3.2709
74	0.9613	0.2756	3.4874
75	0.9659	0.2588	3.7321
76	0.9703	0.2419	4.0108
77	0.9744	0.2250	4.3315
78	0.9781	0.2079	4.7046
79	0.9816	0.1908	5.1446
80	0.9848	0.1736	5.6713
81	0.9877	0.1564	6.3138
82	0.9903	0.1392	7.1154
83	0.9925	0.1219	8.1443
84	0.9945	0.1045	9.5144
85	0.9962	0.0872	11.4300
86	0.9976	0.0698	14.3000
87	0.9986	0.0523	19.0810
88	0.9994	0.0349	28.6360
89	0.9998	0.0175	57.2900

b. In the right triangle shown in figure D-1, functions of the angle A will be discussed. When the triangle is in the position as shown in figure D-1, it is said to be in the standard position. The side a, which is opposite the angle A, is called the altitude. Side b, which is opposite the angle B, is called the base. Side c, the hypotenuse, is opposite the right angle.

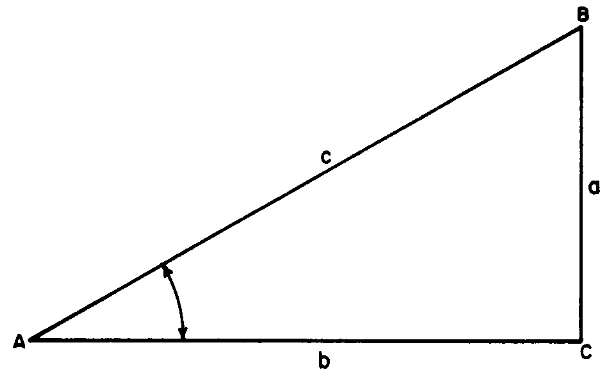


Figure D-1. Functions of a Right Triangle

D-20. TRIGONOMETRIC FUNCTIONS OF A RIGHT TRIANGLE.

a. In the right triangle shown in figure D-1, trigonometric functions of angle A are defined as follows:

$\frac{a}{c}$ is the sine of angle A, and is written sin A.

$\frac{b}{c}$ is the cosine of angle A, and is written cos A.

$\frac{a}{b}$ is the tangent of angle A, and is written tan A.

To illustrate the use of the above functions, consider a right triangle having an altitude of 3 units and a hypotenuse of 6 units. For these values, the sine of the angle A is:

$$\sin A = \frac{a}{c} = \frac{3}{6} = 0.5$$

By reference to table D-5, the angle whose sine is 0.5 is found to be 30°.

b. Now consider a right triangle having a base of 3 units and a hypotenuse of 8 units. The cosine of angle A is:

$$\cos A = \frac{b}{c} = \frac{3}{8} = 0.375$$

By reference to table D-5, the angle whose cosine is 0.375 is found to be 68° (approximately).

c. Finally, consider a right triangle having an altitude of 5 units and a base of 8 units. The tangent of angle A is:

$$\tan A = \frac{a}{b} = \frac{5}{8} = 0.625$$

Referring to the tangent column of table D-5, the angle whose tangent is 0.625 is found to be approximately 32°.

D-21. USE OF TRIGONOMETRIC FUNCTIONS IN SOLVING PROBLEMS. To illustrate the use of trigonometric functions in solving problems, consider the following example:

Given: A radar set in which the antenna has a radiation pattern that covers a vertical angle of 60 degrees, with the beam center elevated +20 degrees from the horizontal plane. The center of the antenna is 6 feet above the base of a pedestal, which is mounted on a 15-foot tower. See figure D-2.

To find: Whether any part of the main beam will illuminate a person who is 6 feet tall, and who is on the ground at a distance of 100 feet.

Solution: Lower edge of beam $= +20 - (1/2 \times 60)$
$= -10$ degrees

$$\tan 10^{\circ} = \frac{a}{b}$$

$$a = b \tan 10^{\circ} = 100 \times 0.1763 = 17.63 \text{ feet}$$

The center of the beam above ground (tower + pedestal) is 15 feet + 6 feet, or 21 feet, and the clearance of the beam above ground at 100 feet is 21 feet - 17.63 feet, or 3.37 feet; therefore, a 6-foot person would have 6 feet - 3.37 feet, or 2.63 feet of his body illuminated by the radar beam.

D-22. THE DECIBEL.

a. The decibel is part of a larger unit called the bel. As originally used, the bel represented a power ratio of 10 to 1 between the strength of two sounds. To gain a better understanding of the bel, consider three sounds of unequal power intensity. If the power intensity of the second sound is 10 times the power intensity of the first, its power level is said to be 1 bel above that of the first. If the third sound has a power intensity which is 10 times that of the second, its level 1 bel above that of the second. But, since the third sound is 100 times as intense as the first, its level is 2 bels above that of the first.

b. Thus a power ratio of 100 to 1 is represented by 2 bels; a power ratio of 1000 to 1, by 3 bels; a power ratio of 10,000 to 1, by 4 bels, etc. It is readily seen, therefore, that the concept of bels represents a logarithmic relationship, since the logarithm of 100 to the base 10 equals 2 (corresponding to 2 bels), the logarithm of 1000 equals 3 (corresponding to 3 bels), etc. The exact relationship is given by the formula:

$$\text{Bels} = \log \frac{P_2}{P_1}$$

where $\frac{P_2}{P_1}$ represents the power ratio

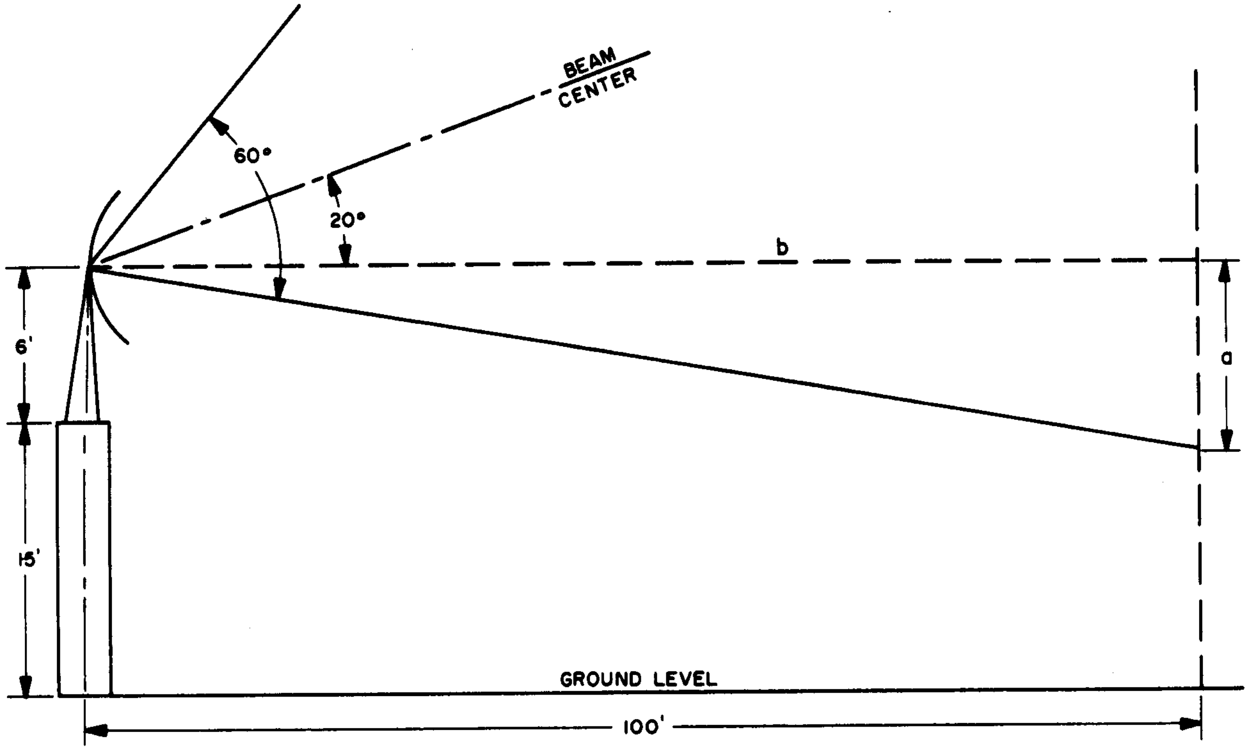


Figure D-2. Calculation of Beam Clearance Above Ground at a Given Distance from Antenna

c. This logarithmic characteristic of the bel makes it a very convenient means for expressing power ratios. Since the bel is a rather large unit, however, its use may prove inconvenient. Usually, therefore, a smaller unit, the decibel, is used. Ten decibels equal 1 bel. A 10-to-1 power ratio, which is represented by 1 bel, is also represented by 10 decibels (10 dB), a 100-to-1 ratio (2 bels) is represented by 20 dB, a 1000-to-1 ratio (3 bels) is represented by 30 dB, etc. The formula for bels may be rewritten to give a result in decibels merely by multiplying by 10. Thus, the formula becomes:

$$\text{Decibels (dB)} = 10 \log \frac{P_2}{P_1}$$

d. For example, assume that it is necessary to find the attenuation ratio of an rf attenuator which is to be used to measure transmitter power output. On test, it is found that 60,000 watts of rf input to the attenuator produces an output of 6 milliwatts. To find the attenuation ratio, use the equation:

$$\text{Attenuation ratio} = \frac{P_2}{P_1} = \frac{60{,}000}{0.006} = 10{,}000{,}000$$

This ratio can be expressed much more conveniently in terms of decibels.

$$\text{Decibels (dB)} = 10 \log \frac{P_2}{P_1} = 10 \log \frac{60{,}000}{0.006}$$

$$= 10 \log 10{,}000{,}000 = 70 \text{ decibels}$$

e. In this case, the attenuation ratio is 70 decibels. In other words, P_2 is said to be 70 decibels up with respect to P_1. In all instances where P_2 is numerically greater than P_1, as in the above example, the final result is expressed as a positive quantity. When P_2 is smaller than P_1, the numerical result is the same, but it is expressed as a negative quantity in dB. If, for example, P_2 is 0.006 watt and P_1 is 60,000 watts, then:

$$\text{Decibels (dB)} = 10 \log \frac{P_2}{P_1} = 10 \log \frac{0.006}{60{,}000}$$

$$= 10 \log 0.0000001 = -70 \text{ decibels}$$

In this case P_2 is said to be 70 decibels down with respect to P_1.

f. Voltage and current ratios may also be expressed in terms of decibels, provided that the resistance (or impedance) remains constant. For equal resistance, the formulas are:

$$\text{dB} = 20 \log \frac{E_2}{E_1}$$

$$\text{dB} = 20 \log \frac{I_2}{I_1}$$

The difference in the multiplying factor in these formulas (20 rather than 10, as in the case of power ratios) arises from the fact that power is proportional to voltage or current squared, and when a number is squared, the logarithm of that number is doubled. For power ratios, the dB value is 10 times the logarithm of the ratio. For voltage or current ratios, the dB value is 20 times the logarithm of the ratio.

g. The relation between decibels and current, voltage, and power ratios can readily be determined by referring to table D-6.

(1) To find current or voltage loss or gain ratio equivalent to a given number of decibels, find required number of decibels, in decibel (voltage) column and read correspondence ratio in loss or gain column.

(2) To find power loss or gain ratio equivalent to a given number of decibels, find required number of decibels in decibel (power) column and read corresponding ratio in loss or gain column.

h. Conversions from voltage, current, or power ratios to decibels may also be made by means of the graph shown in figure D-3.

Table D-6. Relation Between Decibels and Current, Voltage, and Power Ratios

DECIBEL (VOLTAGE)	LOSS	GAIN	DECIBEL (POWER)	DECIBEL (VOLTAGE)	LOSS	GAIN	DECIBEL (POWER)
0.0	1.0000	1.000	0.0	5.5	0.5309	1.884	2.75
0.1	0.9886	1.012	0.05	5.6	0.5248	1.905	2.80
0.2	0.9772	1.023	0.10	5.7	0.5188	1.928	2.85
0.3	0.9661	1.035	0.15	5.8	0.5129	1.950	2.90
0.4	0.9550	1.047	0.20	5.9	0.5070	1.972	2.95
0.5	0.9441	1.059	0.25	6.0	0.5012	1.995	3.00
0.6	0.9333	1.072	0.30	6.1	0.4955	2.018	3.05
0.7	0.9226	1.084	0.35	6.2	0.4898	2.042	3.10
0.8	0.9120	1.096	0.40	6.3	0.4842	2.065	3.15
0.9	0.9061	1.109	0.45	6.4	0.4786	2.089	3.20
1.0	0.8913	1.122	0.50	6.5	0.4732	2.113	3.25
1.1	0.8810	1.135	0.55	6.6	0.4677	2.138	3.30
1.2	0.8710	1.148	0.60	6.7	0.4624	2.163	3.35
1.3	0.8610	1.161	0.65	6.8	0.4571	2.188	3.40
1.4	0.8511	1.175	0.70	6.9	0.4519	2.213	3.45
1.5	0.8414	1.189	0.75	7.0	0.4467	2.239	3.50
1.6	0.8318	1.202	0.80	7.1	0.4416	2.265	3.55
1.7	0.8222	1.216	0.85	7.2	0.4365	2.291	3.60
1.8	0.8128	1.230	0.90	7.3	0.4315	2.317	3.65
1.9	0.8035	1.245	0.95	7.4	0.4266	2.344	3.70
2.0	0.7943	1.259	1.00	7.5	0.4217	2.371	3.75
2.1	0.7852	1.274	1.05	7.6	0.4169	2.399	3.80
2.2	0.7762	1.288	1.10	7.7	0.4121	2.427	3.85
2.3	0.7674	1.303	1.15	7.8	0.4074	2.455	3.90
2.4	0.7586	1.318	1.20	7.9	0.4027	2.483	3.95
2.5	0.7499	1.334	1.25	8.0	0.3981	2.512	4.00
2.6	0.7413	1.349	1.30	8.1	0.3936	2.541	4.05
2.7	0.7328	1.365	1.35	8.2	0.3890	2.570	4.10
2.8	0.7244	1.380	1.40	8.3	0.3846	2.600	4.15
2.9	0.7161	1.396	1.45	8.4	0.3802	2.630	4.20
3.0	0.7079	1.413	1.50	8.5	0.3758	2.661	4.25
3.1	0.6998	1.429	1.55	8.6	0.3715	2.692	4.30
3.2	0.6918	1.445	1.60	8.7	0.3673	2.723	4.35
3.3	0.6839	1.462	1.65	8.8	0.3631	2.754	4.40
3.4	0.6761	1.479	1.70	8.9	0.3589	2.786	4.45
3.5	0.6683	1.496	1.75	9.0	0.3548	2.818	4.50
3.6	0.6607	1.514	1.80	9.1	0.3508	2.851	4.55
3.7	0.6531	1.531	1.85	9.2	0.3467	2.884	4.60
3.8	0.6457	1.549	1.90	9.3	0.3428	2.917	4.65
3.9	0.6383	1.567	1.95	9.4	0.3388	2.951	4.70
4.0	0.6310	1.585	2.00	9.5	0.3350	2.985	4.75
4.1	0.6237	1.603	2.05	9.6	0.3311	3.020	4.80
4.2	0.6166	1.622	2.10	9.7	0.3273	3.055	4.85
4.3	0.6095	1.641	2.15	9.8	0.3236	3.090	4.90
4.4	0.6026	1.660	2.20	9.9	0.3199	3.126	4.95
4.5	0.5957	1.679	2.25	10.0	0.3162	3.162	5.00
4.6	0.5886	1.698	2.30	10.1	0.3126	3.199	5.05
4.7	0.5821	1.718	2.35	10.2	0.3090	3.236	5.10
4.8	0.5754	1.738	2.40	10.3	0.3055	3.273	5.15
4.9	0.5689	1.758	2.45	10.4	0.3020	3.311	5.20
5.0	0.5623	1.778	2.50	10.5	0.2985	3.350	5.25
5.1	0.5559	1.799	2.55	10.6	0.2951	3.388	5.30
5.2	0.5495	1.820	2.60	10.7	0.2917	3.428	5.35
5.3	0.5433	1.841	2.65	10.8	0.2884	3.467	5.40
5.4	0.5370	1.862	2.70	10.9	0.2851	3.508	5.45

Table D-6. Relation Between Decibels and Current, Voltage, and Power Ratios (Continued)

DECIBEL (VOLTAGE)	LOSS	GAIN	DECIBEL (POWER)
11.0	0.2818	3.548	5.50
11.1	0.2786	3.589	5.55
11.2	0.2754	3.631	5.60
11.3	0.2723	3.673	5.65
11.4	0.2692	3.715	5.70
11.5	0.2661	3.758	5.75
11.6	0.2630	3.802	5.80
11.7	0.2600	3.846	5.85
11.8	0.2570	3.890	5.90
11.9	0.2541	3.936	5.95
12.0	0.2512	3.981	6.00
12.1	0.2483	4.027	6.05
12.2	0.2455	4.074	6.10
12.3	0.2427	4.121	6.15
12.4	0.2399	4.160	6.20
12.5	0.2371	4.217	6.25
12.6	0.2344	4.266	6.30
12.7	0.2317	4.315	6.35
12.8	0.2291	4.365	6.40
12.9	0.2265	4.416	6.45
13.0	0.2239	4.467	6.50
13.1	0.2213	4.519	6.55
13.2	0.2188	4.571	6.60
13.3	0.2163	4.624	6.65
13.4	0.2138	4.677	6.70
13.5	0.2113	4.732	6.75
13.6	0.2089	4.786	6.80
13.7	0.2065	4.842	6.85
13.8	0.2042	4.898	6.90
13.9	0.2018	4.955	6.95
14.0	0.1995	5.012	7.00
14.1	0.1972	5.070	7.05
14.2	0.1950	5.129	7.10
14.3	0.1928	5.188	7.15
14.4	0.1905	5.248	7.20
14.5	0.1884	5.309	7.25
14.6	0.1862	5.307	7.30
14.7	0.1841	5.433	7.35
14.8	0.1820	5.495	7.40
14.9	0.1799	5.559	7.45
15.0	0.1778	5.623	7.50
15.1	0.1758	5.689	7.55
15.2	0.1738	5.754	7.60
15.3	0.1718	5.821	7.65
15.4	0.1698	5.888	7.70
15.5	0.1679	5.957	7.75
15.6	0.1660	6.026	7.80
15.7	0.1641	6.095	7.85
15.8	0.1622	6.166	7.90
15.9	0.1603	6.237	7.95
16.0	0.1585	6.310	8.00
16.1	0.1567	6.383	8.05
16.2	0.1549	6.457	8.10
16.3	0.1531	6.531	8.15
16.4	0.1514	6.607	8.20
16.5	0.1496	6.683	8.25
16.6	0.1479	6.761	8.30
16.7	0.1462	6.839	8.35
16.8	0.1445	6.918	8.40
16.9	0.1429	6.998	8.45
17.0	0.1413	7.079	8.50
17.1	0.1396	7.161	8.55
17.2	0.1380	7.244	8.60
17.3	0.1365	7.328	8.65
17.4	0.1349	7.413	8.70
17.5	0.1334	7.499	8.75
17.6	0.1318	7.586	8.80
17.7	0.1303	7.674	8.85
17.8	0.1288	7.762	8.90
17.9	0.1274	7.852	8.95
18.0	0.1259	7.943	9.00
18.1	0.1245	8.035	9.05
18.2	0.1230	8.128	9.10
18.3	0.1216	8.222	9.15
18.4	0.1202	8.318	9.20
18.5	0.1189	8.414	9.25
18.6	0.1175	8.511	9.30
18.7	0.1161	8.610	9.35
18.8	0.1148	8.710	9.40
18.9	0.1135	8.811	9.45
19.0	0.1122	8.913	9.50
19.1	0.1109	9.016	9.55
19.2	0.1096	9.120	9.60
19.3	0.1084	9.226	9.65
19.4	0.1072	9.333	9.70
19.5	0.1059	9.441	9.75
19.6	0.1047	9.550	9.80
19.7	0.1035	9.661	9.85
19.8	0.1023	9.772	9.90
19.9	0.1012	9.886	9.95
20.0	0.1000	10.000	10.00
	Use the same #'s as 0–20 dB., but shift point one step to left. Thus, since: 10dB= 0.3162 30dB= 0.03162	Shift point one step to the right 10dB= 3.162 30dB= 31.62	This column repeats every 10 dB instead of every 20 dB
40.0	0.01 10dB= 0.3162 50dB= 0.003162	100 10dB= 3.162 50dB= 316.2	20.00

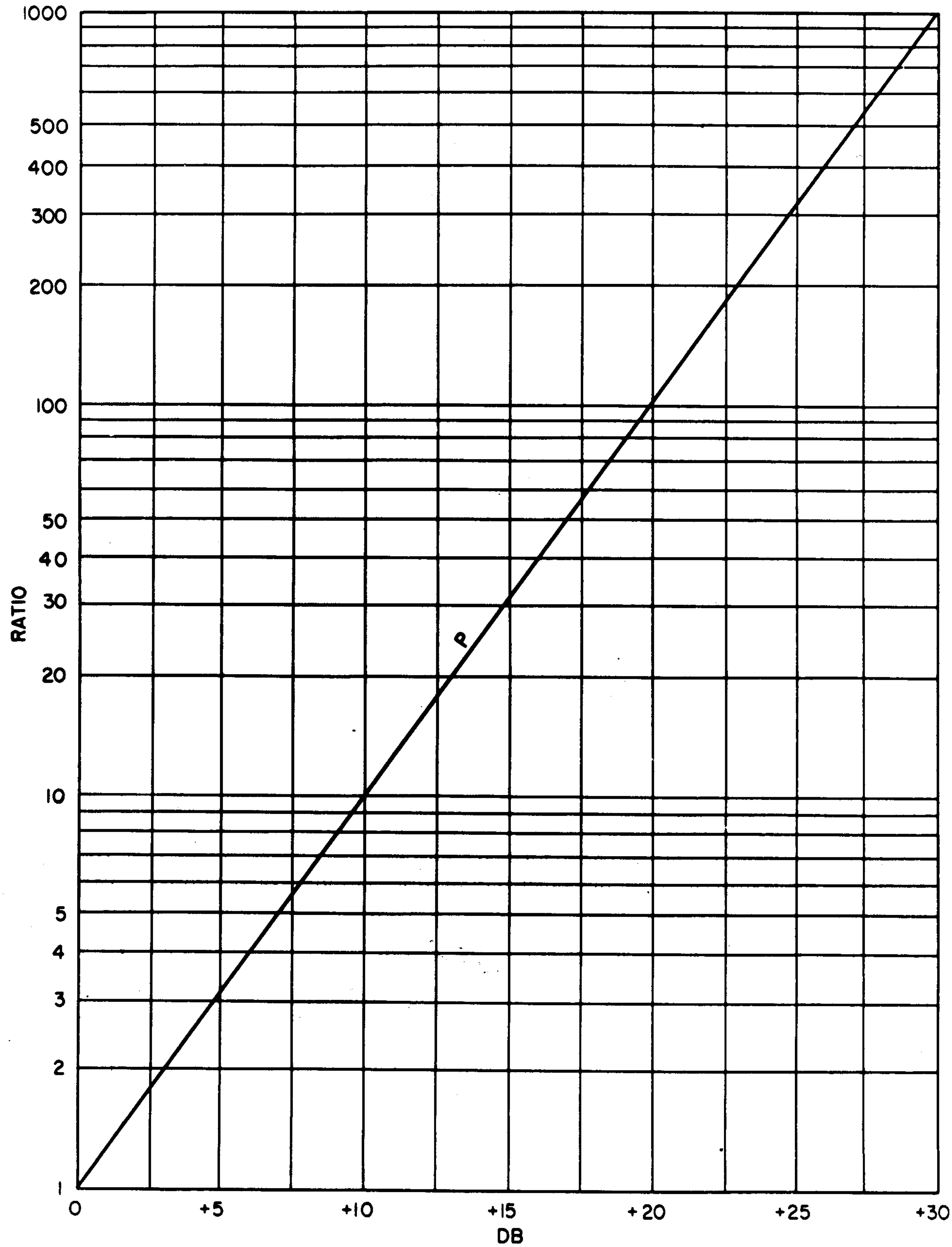


Figure D-3. Power Gain Ratio Versus Decibel Gain

D-23. THE DBM.

a. It should be clearly understood that the term decibel does not, in itself, indicate power, but rather a ratio of, or comparison between, two power values. It is very often desirable, however, to express a single level or quantity of power, voltage, or current in decibels, as for example in transmission line work, or in connection with the input or output of an amplifier. This can be done by using a fixed power level as a reference. The original standard reference level was 6 milliwatts (0.006 watt), but to simplify calculations a 1-milliwatt standard has been adopted and will be used hereafter as the reference level. (A few equipments use 1 watt as a standard.)

b. When 1 milliwatt is used as a reference level, the ratio is expressed in dBm's. The abbreviation dBm indicates decibels relative to a 1-milliwatt standard. Thus, a pulsed radar transmitter having an average power output of 100 watts is said to have an average power output of 50 dBm. The conversion from power to dBm can be made as follows:

$$\text{Average power (dBm)} = 10 \log \frac{P_2}{P_1}$$

(where P_1 is the reference value of 0.001 watt)

$$= 10 \log \frac{100}{0.001}$$

$$= 10 \log 100{,}000 = 50 \text{ dBm}$$

c. Conversions from power to dBm can be made more readily by means of the graph shown in figure D-4. Reasonable care should be exercised in reading the graph, using the appropriate dBm scale for power in either milliwatts, watts, kilowatts, or megawatts.

D-24. CONVERSION OF POWER OR DBM TO MICROVOLTS ACROSS 50, 72, 337, OR 600 OHMS.

a. Both the decibel and the dBm are power ratios; their adaptation to voltage or current ratios are meaningful only if the impedance is the same for both values of voltage (or current) in the ratio. For example, in the formula for the ratio, expressed in decibels, of two voltages E_2 and E_1:

$$\text{dB} = 20 \log \frac{E_2}{E_1}$$

It would not be possible to obtain correct information on the gain of a given amplifier if the input impedance differed from that of the output. Hence, in circuits where the impedances differ, the expression for the decibel equivalents of the voltage ratios becomes:

$$\text{dB} = 20 \log \frac{E_2\sqrt{Z_1}}{E_1\sqrt{Z_2}}$$

where: E_1 = input voltage

E_2 = output voltage

Z_1 = input impedance

Z_2 = output impedance

b. In calculations involving power in transmission lines, it is often required to convert extremely small amounts of power to dBm, or to convert either of these values to voltage, in microvolts, which would appear across a load impedance of 50, 72, 377, or 600 ohms. Conversions from dBm or power in picowatts to microvolts across 50, 72, 377, or 600 ohms, or vice versa, may be made directly by means of table D-7.

D-25. RADAR POWER DENSITY CALCULATION NOMOGRAM. Figure D-5 gives a radar power density calculation nomogram, which contains all the elements necessary for the solution of problems involving commonly used values of antenna input power and antenna gain. This nomogram does not incorporate near field gain reductions which should be applied to obtain realistic values in the near field (see paragraph 6-8). The nomogram provides a relatively fast and easy method for solving problems in power density, with a degree of accuracy that is sufficient for practical applications. The nomogram incorporates instructions for its use.

D-26. FREE-SPACE ATTENUATION NOMOGRAMS. Figures D-6 and D-7 present free space attenuation nomograms for distances of 100 to 10,000 feet, and 1 to 100 miles, respectively. The lefthand scales are the distance scales, in feet and miles, from the transmitting antenna. The middle scales are the path attenuation scales, calibrated in decibels (dB) of loss. The righthand scales are the frequency scales, from 200 to 10,000 megahertz. To use either of the nomograms, lay a straightedge between the points of distance on the lefthand scale of the nomogram and frequency on the righthand scale. Read the loss in dB, or path attenuation, where the straightedge crosses the middle scale.

Table D-7. dBm Conversion Table

DBM	MICROVOLTS ACROSS 50 OHMS	MICROVOLTS ACROSS 72 OHMS	MICROVOLTS ACROSS 377 OHMS	MICROVOLTS ACROSS 600 OHMS	PICOWATTS (1×10^{-12})
0	223,607.0	268,328.0	614,024.8	774,596.7	1,000,000,000.0
–3	158,314.0	189,976.0	434,730.2	548,379.4	501,200,000.0
–6	112,094.0	134,513.0	307,810.1	388,265.4	251,250,000.0
–9	79,358.0	95,230.0	217,917.1	274,845.4	125,900,000.0
–12	56,192.0	67,431.0	154,303.2	194,576.5	63,100,000.0
–15	39,780.0	47,736.0	109,235.9	137,738.9	31,620,000.0
–18	28,174.0	33,809.0	77,365.8	97,519.2	15,850,000.0
–21	19,932.0	23,919.0	54,733.3	69,034.8	7,943,000.0
–24	14,112.0	16,934.0	38,751.6	48,873.3	3,981,000.0
–27	9,990.0	11,988.0	27,432.5	34,597.7	1,995,000.0
–30	7,073.0	8,487.0	19,422.5	24,494.9	1,000,000.0
–33	5,009.0	6,011.0	13,754.7	17,341.3	501,200.0
–36	3,546.0	4,256.0	9,737.3	12,276.8	251,200.0
–39	2,511.0	3,013.0	6,895.2	8,691.4	125,900.0
–42	1,776.0	2,132.0	4,876.9	6,153.0	63,100.0
–45	1,258.0	1,509.0	3,454.5	4,355.7	31,620.0
–48	890.0	1,068.0	2,443.9	3,083.8	15,850.0
–51	630.0	756.0	1,730.0	2,183.1	7,943.0
–54	446.0	536.0	1,224.7	1,545.5	3,981.0
–57	316.0	379.0	867.7	1,094.0	1,995.0
–60	223.607	268.328	614.0	774.597	1,000.0
–63	158.314	189.976	434.7	548.379	501.2
–66	112.094	134.513	307.8	388.265	251.25
–69	79.358	95.230	217.9	274.845	125.9
–72	56.192	67.431	154.3	194.576	63.1
–75	39.780	47.736	109.85	137.739	31.62
–78	28.174	33.809	77.3	97.519	15.85
–81	19.932	23.919	54.72	69.035	7.943
–84	14.112	16.934	38.74	48.873	3.981
–87	9.990	11.988	27.42	34.598	1.995
–90	7.073	8.487	19.42	24.495	1.0
–93	5.009	6.011	13.75	17.341	0.5012
–96	3.546	4.256	9.73	12.277	0.2512
–99	2.511	3.013	6.89	8.691	0.1259
–102	1.776	2.132	4.88	6.153	0.0631
–105	1.256	1.509	3.45	4.356	0.03162
–107	0.999	1.199	2.74	3.460	0.01995
–108	0.889	1.067	2.441	3.019	0.0158
–109	0.794	0.963	2.179	2.750	0.0126
–110	0.707	0.849	1.942	2.449	0.01
–111	0.628	0.754	1.726	2.177	0.0079
–112	0.561	0.673	1.541	1.944	0.0063
–113	0.500	0.595	1.373	1.732	0.005
–114	0.447	0.537	1.228	1.550	0.004
–115	0.387	0.465	1.063	1.342	0.003
–116	0.354	0.424	0.971	1.225	0.0025
–117	0.316	0.379	0.868	1.095	0.002
–118	0.283	0.340	0.777	0.980	0.0016

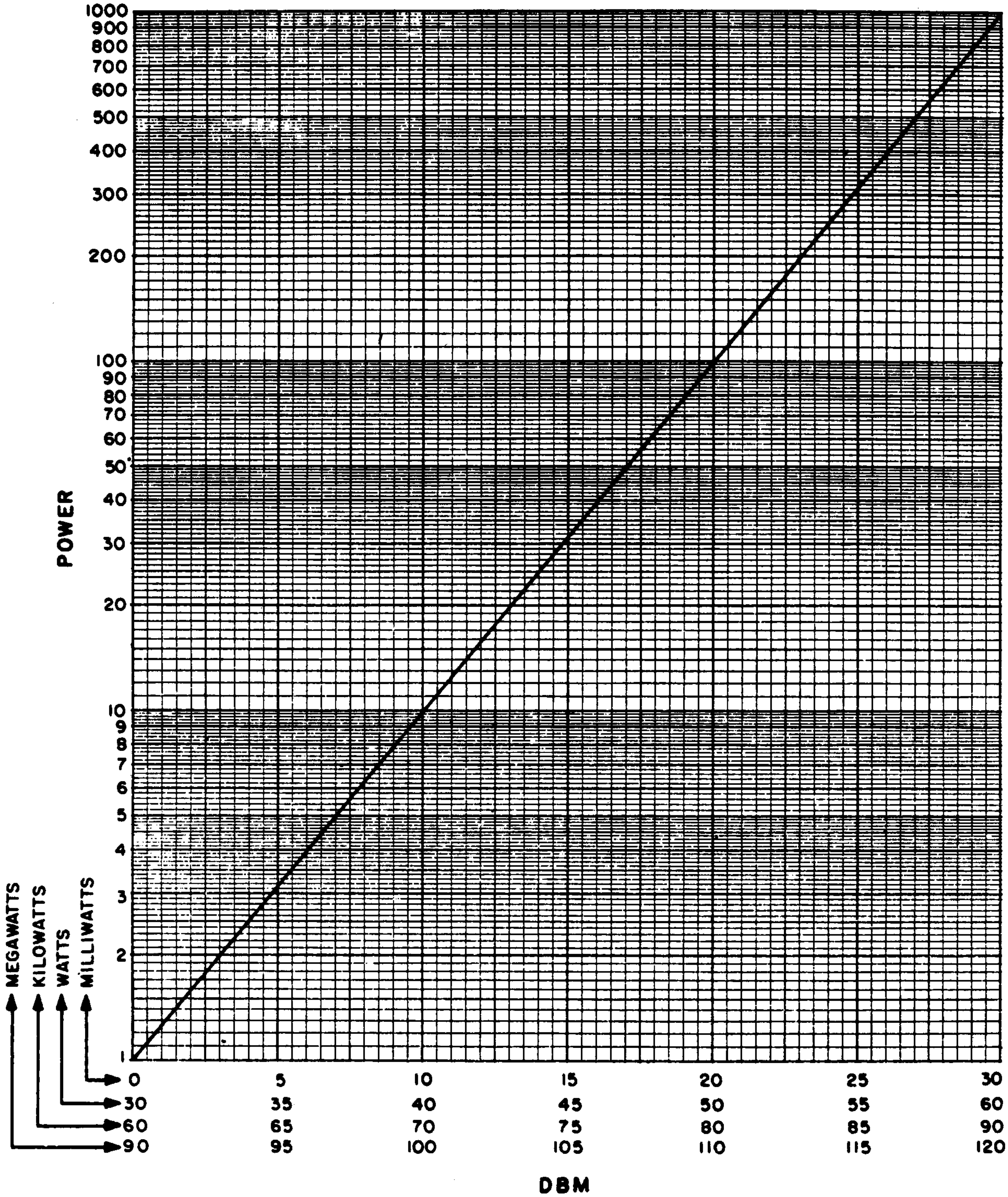


Figure D-4. Power Gain Ratio Versus dBm

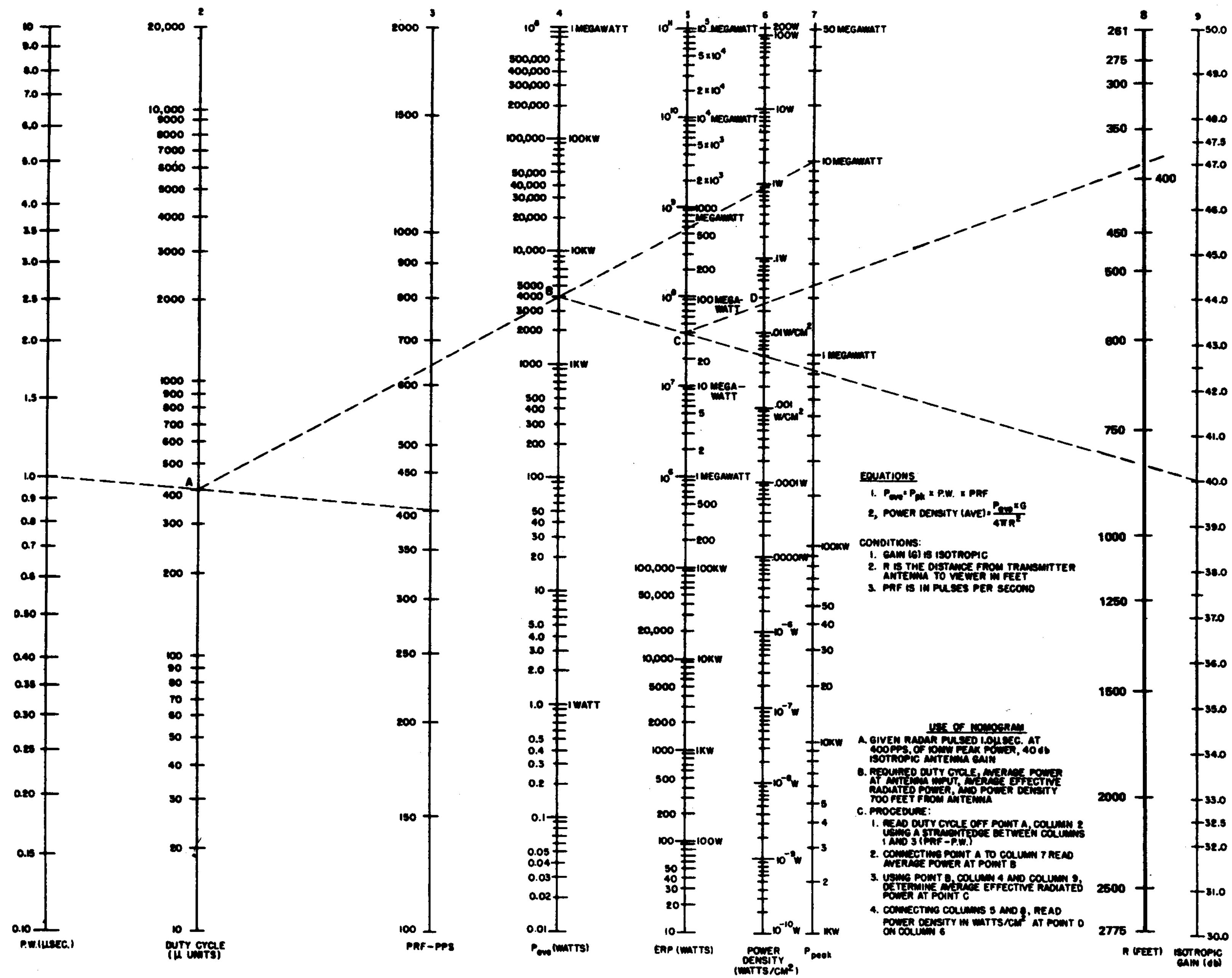


Figure D-5. Radars Power Density Calculation Nomogram

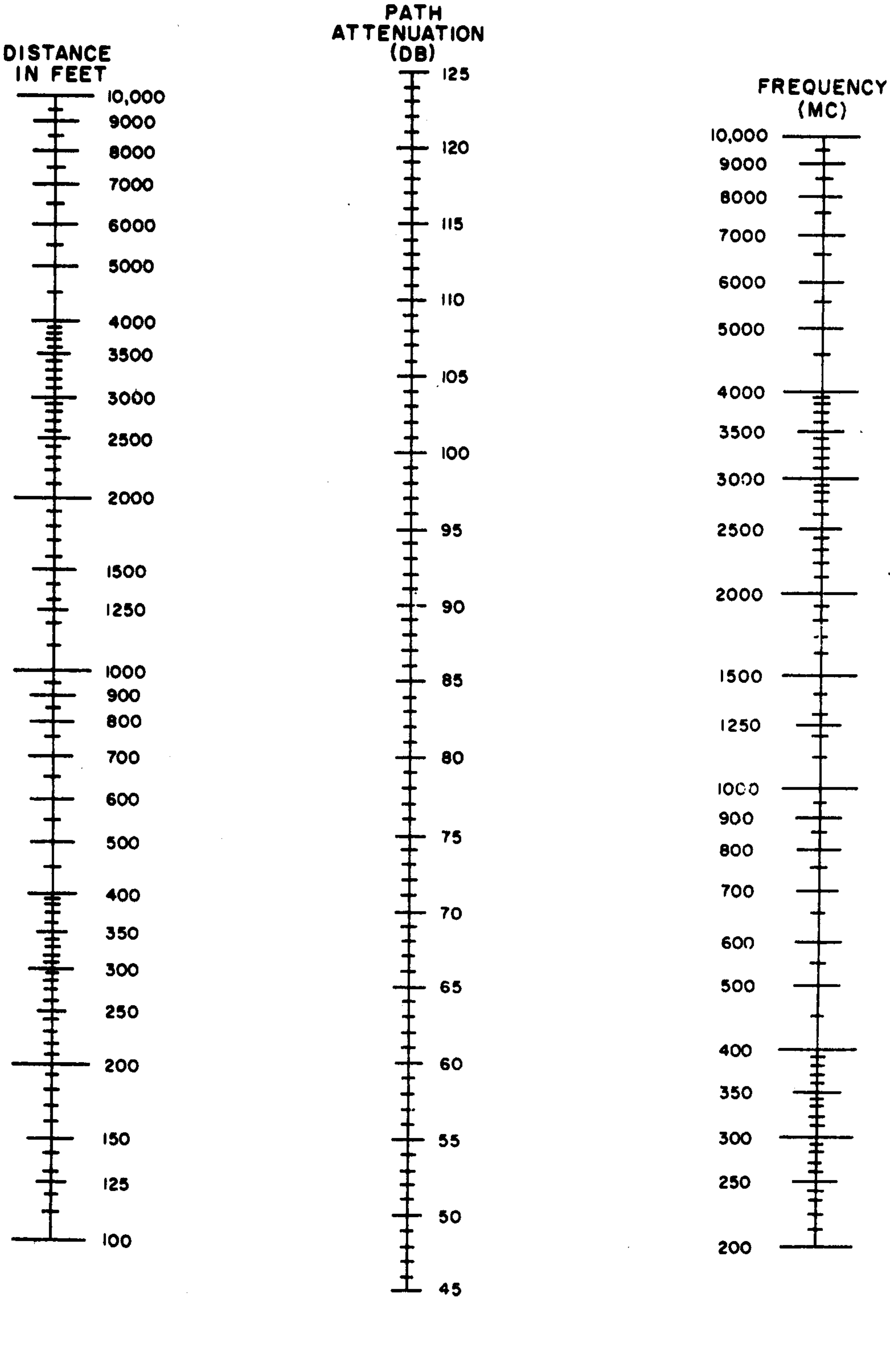


Figure D-6. Free-Space Attenuation Nomogram, 100 to 10,000 Feet

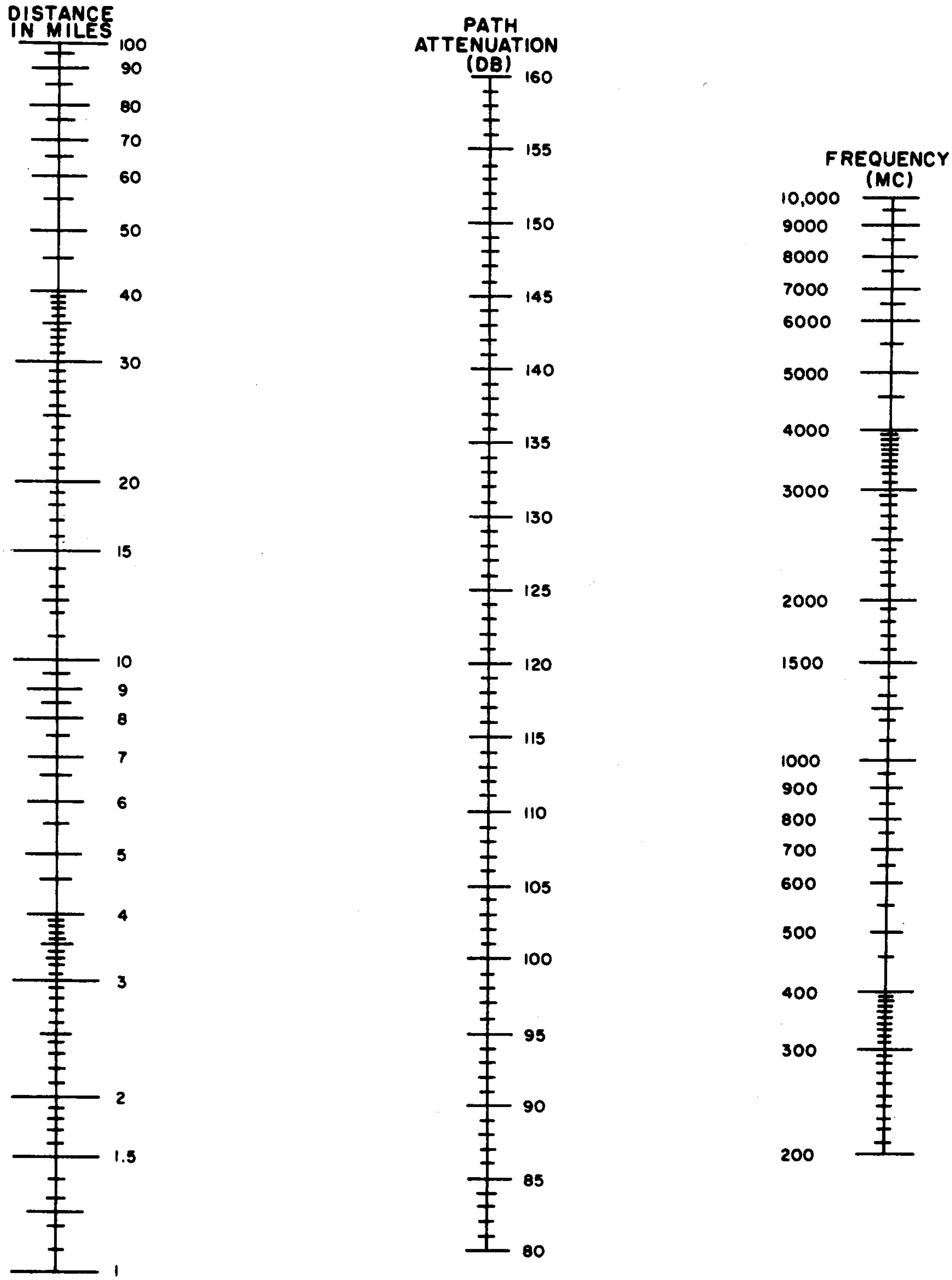


Figure D-7. Free-Space Attenuation Nomogram, 1 to 100 Miles

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