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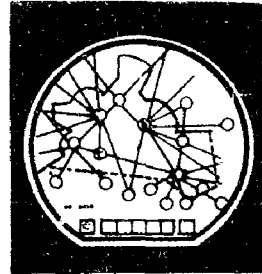
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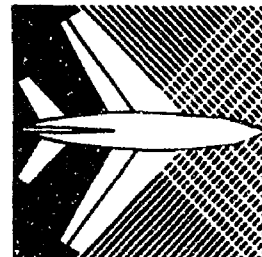
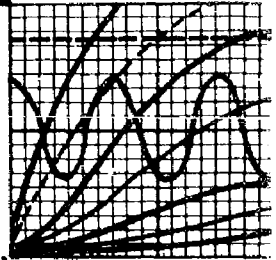
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REPORT NO. RD- 64-1



FINAL REPORT
Project No 110-302R



MICROWAVE RADIATION HAZARD
TO AIRCRAFT TRANSITING RADIO
AND RADAR BEAMS

DECEMBER 1963



FEDERAL AVIATION AGENCY
Systems Research & Development Service
RESEARCH DIVISION
Atlantic City, New Jersey

FINAL REPORT

MICROWAVE RADIATION HAZARD TO AIRCRAFT
TRANSITING RADIO AND RADAR BEAMS

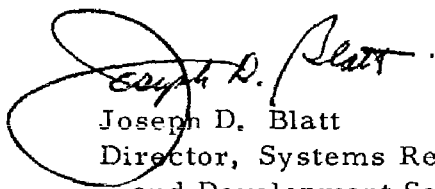
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Prepared by:

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December 1963

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Research Division, Systems Research and Development Service,
Federal Aviation Agency, Atlantic City, N. J.
MICROWAVE RADIATION HAZARD TO AIRCRAFT TRANSITING
RADIO AND RADAR BEAMS by John J. Kulik, Final Report
December 1963, 23 pp., Incl. 3 illus., plus 2 appendixes (14 pp.)
(Project No. 110-302R, Report No. RD-64-1)

ABSTRACT

A hazard to aircraft transiting high power density radio and radar beams exists unless appropriate safety measures are practiced. Susceptibilities of humans, aircraft fuel vapors, avionics, and electroexplosive devices to microwave radiation indicate limits of power densities of electromagnetic radiation to which aircraft may be safely exposed. From a study of the literature and analyses conducted herein, it is concluded that aircraft not carrying electroexplosive devices may be safely exposed to average power densities of 10 milliwatts per square centimeter (10 mw/cm^2) or less. Aircraft carrying electroexplosive devices may be safely exposed, under some conditions, to power densities of 1 mw/cm^2 . This report contains charts, and procedures for using them, which give distances along the antenna beam axis at which the aforementioned limits are reached. It is recommended that experiments be undertaken to verify analyses in this report and that progress of the military services on electroexplosive devices be monitored to assure the earliest possible implementation of less restrictive limits.

INTRODUCTION

This report is the result of a literature search conducted for information useful in establishing criteria to determine the amount of special use airspace to be set aside for the protection of aircraft transiting near high power radio and radar transmitting stations.

Numerous articles exist on the hazard to various items exposed to high power density microwave radiation. Human beings subjected to high intensity radio fields suffer physical damage (Reference 1). Electromagnetic fields cause ignition of aircraft fuel vapors (Reference 2). Receiver crystals suffer burnout when subjected to radar pulses of high energy content (Reference 3). Electroexplosive devices are ignited by radio fields (Reference 4). The susceptibility thresholds of humans and aircraft fuel vapors have been experimentally determined and safe limits of exposure have been established as a result of the experiments. An analysis of the susceptibility of various items of the avionics complement is included in this report with a recommendation for experimental verification of some of the statements made herein. The susceptibility thresholds of electroexplosive devices are being determined by destructive testing techniques under specialized configurations of interest to the military services. From these tests, standards for electroexplosive devices safe from limited radiation are being determined and specifications for those devices used at some military installations exist.

Safety limits for exposure to microwave radiation are written in terms of power densities. This report includes charts, and procedures for using them, to determine distances along the antenna beam axis at which the safe exposure limits exist.

DISCUSSION

A. Susceptibility Thresholds.

1. Humans. Extensive experimental research into the hazard to humans from exposure to microwave radiation has been carried on since about 1942. Tests on animals and accident

reports attributing physical damage to humans from microwave radiation spurred the Armed Services into issuing notices of levels of field power density considered hazardous to humans. The limit varied considerably over the years, but it is now accepted by the Armed Services and several industrial organizations that humans should not be exposed to microwave radiation of average power density greater than 10 mw/cm^2 . References 1 and 11 give a comprehensive review of experiments upon which the limit is based.

2. Aircraft Fuel. Experimental tests conducted on the possibility of igniting aircraft fuel vapors by exposure to microwave radiation indicate that intense fields produce ignition but only under highly specialized conditions. Using a mixture of vapor and air which can be ignited by sparks having the minimum energy, no ignitions occur in fields of average power density less than about 25 mw/cm^2 (Reference 2). Furthermore, ignition occurs only if metallic chips are introduced into the vapor-air mixture and, in many cases, vigorous shaking of the mixture, with chips, is necessary for ignition. The U. S. Air Force has established a limit on refueling operations near transmitting antennas of 5 watts/cm^2 peak power density. Depending on the duty cycle of the transmitting system, the value ranges from about 3.5 mw/cm^2 to 10 mw/cm^2 average field power density. The hazard to aircraft refueling in electromagnetic fields is far greater than the hazard to aircraft transiting radio and radar beams under normal circumstances. The limit of 10 mw/cm^2 average power density (the limit for human exposure) is considered safe for aircraft transiting radar and radio beams.

3. Avionics. The communication and navigation electronic instruments aboard aircraft fall into two groups with respect to the microwave radiation hazard. The first group is characterized by being in the lower frequency part of the microwave spectrum. The group has receiving sets as follows:¹

- a. VHF Communication
- b. Glideslope

¹The receiving sets listed in both groups are meant to be representative rather than complete.

- c. ADF
- d. VOR/LOC
- e. Marker Beacon

These receiving sets include first stages consisting of tube-type amplifiers.² In high power density fields these sets are susceptible to spurious response, intermodulation, desensitization, and other interference phenomena (Reference 5). These transient phenomena are reversible and damage to these sets does not occur upon exposure to fields of high power density. Exposure to 10 mw/cm² (limit for safe human exposure) presents no hazard to the first group of the avionics complement.

The second group of the avionics complement is characterized by being in the higher frequency part of the microwave spectrum. As the frequency increases, thermionic tube interelectrode spacings (cathode to grid and grid to plate) become appreciable with respect to wavelength, and the anomalous tube behavior under such conditions precludes using tube-type first stages for the following group of the avionics complement:

- a. Weather Radar
- b. DME
- c. ATC Transponder

These sets have receiver first stages which include crystals exposed to microwave radiation from external sources. There are two ways in which excessive power can impair the performance of a crystal. One is characterized by a continuous degradation of the signal-to-noise ratio of the crystal at applied powers of the order of 200 mw. The rate of deterioration depends only upon the total time of application of the power. For example, at a duty ratio of 1/1000 the crystal changes by about one decibel per hundred hours with 200 mw applied. If the same power is

²Transistorized (Solid State) sets are being introduced into the avionics complement and future studies should consider the possible hazard to such systems.

applied as continuous wave power, the crystal changes 1,000 times faster or in approximately 6 minutes. Furthermore, experimental evidence exists which shows crystals exposed to peak powers of less than about 5 watts suffer only temporary deterioration (Reference 6). Since aircraft transiting radio and radar beams are exposed at most for a few seconds, the deterioration under discussion does not constitute a serious problem.

The other type of crystal failure is thermal "burnout" in which local heating permanently changes the contact between the "cat whisker" and crystal. This type of failure occurs when peak powers in excess of 5 watts are applied to a crystal. Some modern crystals can withstand more than 5 watts peak power. For example, the 1N23C is supposed to be capable of sustaining about 12 watts peak power (under some conditions) with little deterioration. Some units can be subjected to as much as 25 watts peak power (Reference 7). In order to determine the possibility of damage to the avionics complement containing crystal detector type receivers, the systems must be considered in the environment in which they are normally used. All the systems in Group (2) are transmit-receive systems which use a common antenna for transmission and reception. As such, the systems employ duplexers incorporating T-R (Transmit-Receive) tubes (Reference 8). The T-R tube is installed to protect the receiver crystal from damage and to perform duplexer operation. Under POWER ON conditions, the T-R tube will fire at peak powers of 100 to 200 mw and will protect the crystal from damage. Under POWER OFF conditions, the T-R tube will not fire until the incident peak power level has reached 5 to 10 watts (Reference 9). This may damage the sensitive crystal rectifier.

To determine the relation between the peak powers required for crystal deterioration and the average field power density of 10 mw/cm^2 (limit for safe human exposure) some specific installations must be considered.

The avionics items have antennas with well defined effective areas and components which operate under very specific conditions. For example, airborne weather radars operate at frequencies of approximately 5400 megacycles and 9400 megacycles. The transfer of energy from antenna to receiver will be efficient only near these frequencies because of the band-limited operation of the T-R tubes. Frequencies below 5400 megacycles will be greatly attenuated since they are below the cut-off frequency of the waveguide between antenna and receiver. Assume the weather radar (5400 mc) is in the POWER OFF condition and is aimed at a transmitting antenna producing peak powers of 10 watts at the T-R tube. If the T-R tube does not fire, the crystal may suffer damage. The field power density (peak) is

$$W_p = \frac{P_r}{A_e}$$

For a parabolic dish antenna aimed at a source, the effective area is about equal to 1/2 its physical area. For weather radar, popular dish diameters are 12 inches and 18 inches. The effective area is, therefore, (for the 18 inch dish antenna)

$$A_e = 1/2 \pi r^2$$

$$A_e = 127 \text{ in}^2$$

$$A_e = 820 \text{ cm}^2$$

then

$$W_p = \frac{10 \times 10^3 \text{ mw}}{820 \text{ cm}^2}$$

$$W_p = 12.2 \frac{\text{mw}}{\text{cm}^2} \quad (\text{peak power density})$$

If the "rule of thumb" (duty cycle of $\frac{1}{1000}$) is used:

peak power = 1000 (average power) and $W = .0122 \frac{\text{mw}}{\text{cm}^2}$
(average power density).

Average field power densities far below $10 \frac{\text{mw}}{\text{cm}^2}$ will cause crystal deterioration provided the proper conditions exist. The conditions are:

- a. the antenna must be aimed at the source of energy
- b. the frequency must be near 5400 mc (for 5400 mc radar) or 9400 mc (for the 9400 mc radar)
- c. the set must be in the POWER OFF condition
- d. the T-R tube in the POWER OFF condition does not fire at peak powers of from 5 to 10 watts (it may - Reference 9)
- e. crystal deterioration will occur at 5 to 10 watts peak power (it may not - Reference 7).

For the other systems mentioned (DME, ATC BEACON), the first condition does not have to hold since they have omnidirectional antennas (their effective areas are much smaller as a result). The other conditions, however, must hold for crystal deterioration. The probability that all the conditions are met very often is small. For guaranteed crystal protection, the sets must be kept in the POWER ON condition so that the T-R tube will fire at small levels of peak power.

4. Electroexplosive Devices. Electroexplosive devices (EEDs) can be ignited by exposure to electromagnetic fields. As an introduction, some remarks from the literature on the subject are given:

- a. "Annual consumption of electric blasting caps is well over 100 million, and they are used in every section of the country. Yet there have been only 2 authenticated cases of a cap being accidentally fired by radio." (Reference 10)
- b. "The Institute of Makers of Explosives has not found it possible to detonate commercial electric blasting caps by means of radar;..." (Reference 10)
- c. "Squibs (EEDs) as supplied by the manufacturer, are normally shipped and stored in metal containers. These

metal storage containers provide an almost perfect r-f shield, and protect the squibs from ignition by r-f fields." (Reference 11)

d. "There is no danger from transmitters in the case of explosives that are not directly actuated by electricity. Examples of these explosives are fuse-type blasting caps, the detonating fuses such as "Primacord", and dynamite." (Reference 10)

e. "A large number of such "go, no-go" tests have been made, but only in a few instances have squibs (EEDs) been set off by r-f fields. In these cases it has been necessary to purposely idealize conditions to favor ignition, simulating conditions which are not too likely to occur in actual field use of the weapon system." (Reference 11)

f. "From a practical standpoint, the possibility of a premature explosion due to RF energy is extremely remote." (Reference 10)

In spite of the statements mentioned, a hazard to EEDs from radio frequency energy does exist. Since an EED has wires attached which can extract energy from a radio wave, ignition of the cap can occur. The leg wires of an EED can be considered an antenna with unknown effective area (A_e). The minimum firing current of commercial electric blasting caps now manufactured in this country is about 0.25 amperes (Reference 10). The bridge wire resistance of an EED varies, but some have values as low as 0.5 ohms. The power required for ignition of a sensitive EED is about:

$$P_r = I^2 R$$

$$P_r = (.25)^2 (.5) \text{ watts}$$

$$P_r = .0312 \text{ watts}$$

$$P_r = 31.2 \text{ milliwatts}$$

The leg wires of an EED can be used in a large variety of configurations so that the effective area of the device cannot be sensibly estimated. However, if precautions are taken along

the lines outlined in Reference 11, a conservative estimate can be made.³ If the EEDs are used as outlined in Reference 11, 10 cm² is a quite conservative estimate of the effective area of the "antenna" wires. The field power density required for ignition is:

$$W = \frac{P_r}{A_e}$$

$$W = \frac{31.2 \text{ mw}}{10 \text{ cm}^2}$$

$$W = 3.12 \frac{\text{mw}}{\text{cm}^2}$$

The computation yields a rough estimate of the field power density required for ignition of a very sensitive EED by microwave radiation. A number of considerations show that the estimate is very conservative and that far greater power densities are probably required for ignition of EEDs under normal conditions.

a. The estimate 10 cm² for effective area is very large if precautions according to Reference 11 are taken.

b. The wires are oriented to match the field polarization.

c. The calculation assumes that all the energy picked up by the leg wires is transferred to the load. That is, matched conditions are assumed. Antenna impedances are usually much higher than 0.5 ohms (load resistance assumed) so that most energy will be re-radiated rather than absorbed by the bridge wire.

d. It is assumed in the calculation that the EED and leg wires are completely exposed to the field. As used on aircraft armaments, it never is completely exposed. In fact, great efforts at complete shielding are made for protection against stray radio frequency fields.

³Proper wiring techniques and maximum shielding methods must be followed.

The U. S. Air Force has not set a safe "Minimum Distance" limit on aircraft carrying EEDs. Efforts are made instead, to make the systems incorporating EEDs in such configuration that maximum (or complete) shielding is provided. Since no limit is given in the literature, the considerations in this report dictate that aircraft carrying electroexplosive devices should not be exposed to fields of greater average power densities than 1 mw/cm^2 . When special circumstances warrant, data on specific EEDs and specific installations should be ascertained by "go, no-go" tests or from the literature.

Besides using the "complete shielding" philosophy, the Air Force is also making a limited attempt at standardizing EEDs. The Office of the Inspector General for Safety, Headquarters, Air Force Systems Command, has issued an Interim Standard to Minimize the Hazards of Electromagnetic Radiation to Electroexplosive Devices used at the National Ranges. It required electroexplosive devices to meet one of the following standards:

"1. EEDs will not fire as a result of the application of one watt of direct current power for five minutes and as a result of the application of one ampere of direct current for five minutes. This requirement must be met without the use of external shunts. Suitable testing, such as the Bruceton type statistical test, will be performed to validate a no-fire reliability of 0.999 with a 95 per cent confidence level."

"2. EEDs with electroexplosive elements that do not meet the above one watt/one ampere/five minute standard will be designed so that the integral unit will survive in an electromagnetic field intensity of 100 watts per square meter.⁴ Approved testing will be performed to establish a no-fire reliability of 0.999 with a confidence level at 95 per cent. Tests will include exposure to electromagnetic fields, pulsed and continuous wave, with frequencies ranging from 100 kilocycles to 40 gigacycles. Testing will include: evaluation of the RF sensitivity of the basic electroexplosive element; evaluation of the uninstalled EED in all normal modes of storage, transporting, handling, and installing; and evaluation of the complete EED system in the installed configuration."

⁴ $100 \text{ w/m}^2 = 10 \text{ mw/cm}^2$ (limit of safe human exposure)

With the issuance of these standards, the U. S. Air Force is attempting to make the EEDs used at the National Ranges compatible with the limit of 10 mw/cm^2 to which humans may be exposed. Progress of the Armed Services on hazards of electromagnetic radiation to ordnance must be monitored with a view to providing a less restrictive limit as soon as possible. Another problem related to EEDs and aircraft is discussed in Appendix I.

B. Safe Distance Limits.

A method is given for determining distances along the beam axis of an antenna at which power densities of 1 mw/cm^2 and 10 mw/cm^2 exist. It is useful to calculate first the maximum power density in the near field, since if the calculation reveals a power density less than the hazardous limits, there is no need to proceed with further calculation, for the maximum power density in the near field gives the maximum power density anywhere in the field.

An antenna can be considered as having an aperture with a number of Huygens sources radiating hemispherical wavelets into an infinite half space. Near the antenna, cancellations and reinforcements occur giving rise to a number of minima and maxima of power density. The region characterized by this oscillatory power density function is called the near field (Reference 12).

$$\text{In the near field } 0 \leq W \leq \frac{4P_m}{A_p} \quad (1) \text{ where:}$$

W = Power density

P_m = Power in the main beam

A_p = Physical area of the antenna aperture

It is assumed that the following information is given or easily obtainable:

1. Operating frequency
2. Total radiated power (or transmitter power)

3. Physical dimensions of the antenna (assumed equal to the physical area of the antenna aperture).

From equation (1) the maximum power density in the near field is:

$$W_{\max} = \frac{4P_m}{A_p}$$

The power in the main beam of the antenna is:

$$P_m = kP_t$$

where:

P_t = Total radiated power

$$k = \frac{G_a}{G_t}$$

with G_a = Actual antenna gain

G_t = Theoretical antenna gain

Obviously

$$0 \leq k \leq 1$$

G_t is calculable from

$$G_t = \frac{4\pi A_p f^2}{c^2} \quad (\text{Reference 13})$$

where:

f = Operating frequency

c = Velocity of light

A_p = Physical antenna area.

Since it was assumed that G_a is not given, a reasonable estimate of k must be made. The maximum value of k ever attained experimentally is 0.65 (Reference 14). For practically all operational antennas $k \leq 0.5$, and for this report it is assumed that $k = 0.5$. Since feed system losses are assumed negligible, the assumption $k = 0.5$ will be quite accurate in some cases and conservative in most.

Therefore:

$$P_{n1} = 1/2 P_t$$

and

$$W_{\max} = \frac{2P_t}{A_p} \quad (2)$$

Given the transmitter (or transmitted) power and the antenna dimensions, equation (2) gives the maximum power density anywhere in the field.⁵ Figures (1) and (2) are plotted from equation (2). When the maximum power density, as determined from Figure (1) or (2), exceeds hazardous limits, it is necessary to determine the distances at which the limits are reached.

The power density in the far field is given by:

$$W = \frac{G_a P_t}{4\pi R^2}$$

Therefore:

$$R = \left(\frac{G_a P_t}{4\pi W} \right)^{1/2}$$

$$\text{with } G_a = kG_t$$

$$\text{and } k = 1/2$$

$$R = \left(\frac{G_t P_t}{8\pi W} \right)^{1/2}$$

$$\text{where } G_t = \frac{4\pi A_p f^2}{c^2}$$

(3).

⁵A listing of maximum power densities for some Air Traffic Control radars ($k < 1/2$) is given in Appendix II.

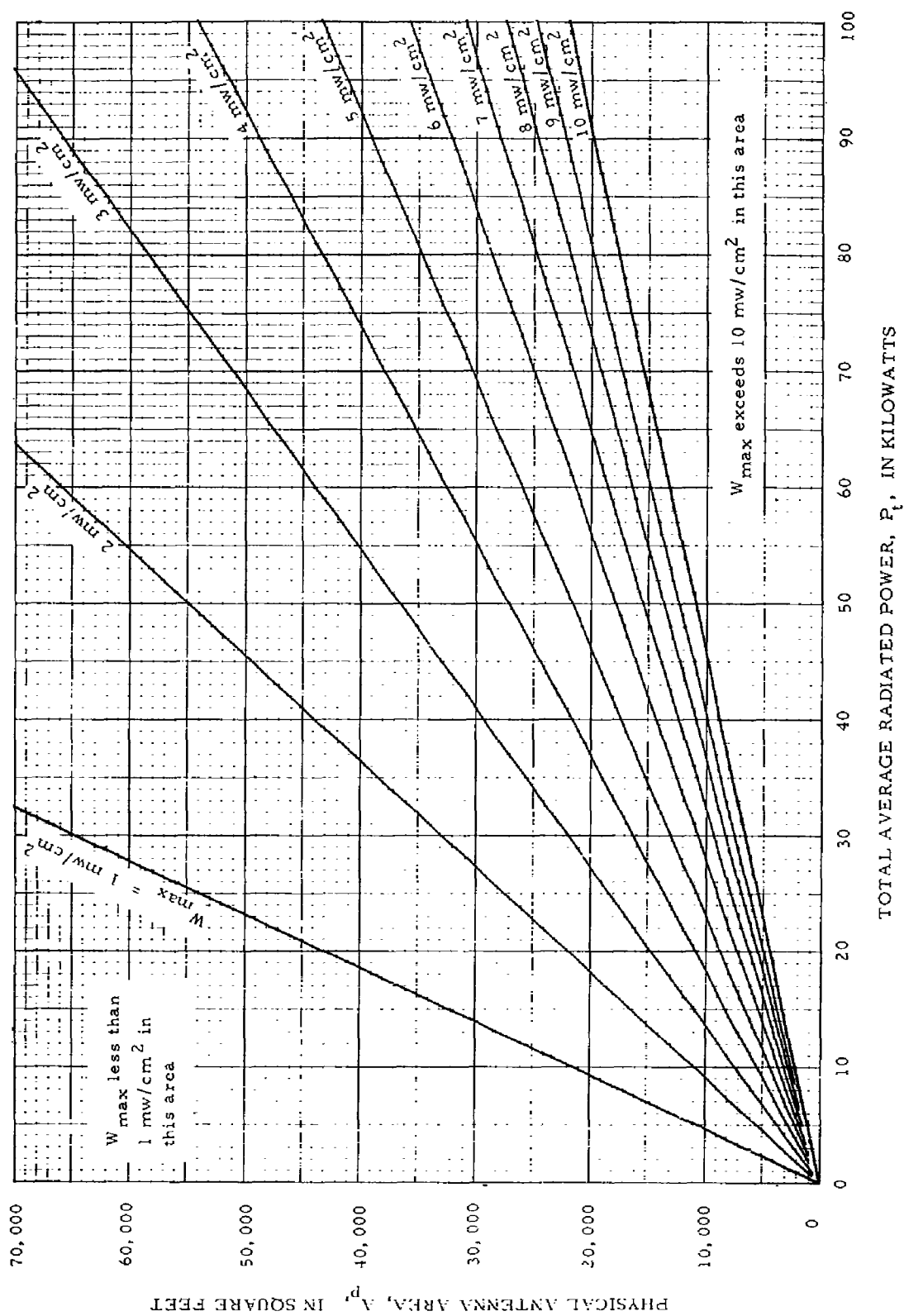


FIG. 1 CURVES FOR OBTAINING W_{MAX} (HIGH POWER/LARGE AREA CONDITIONS)

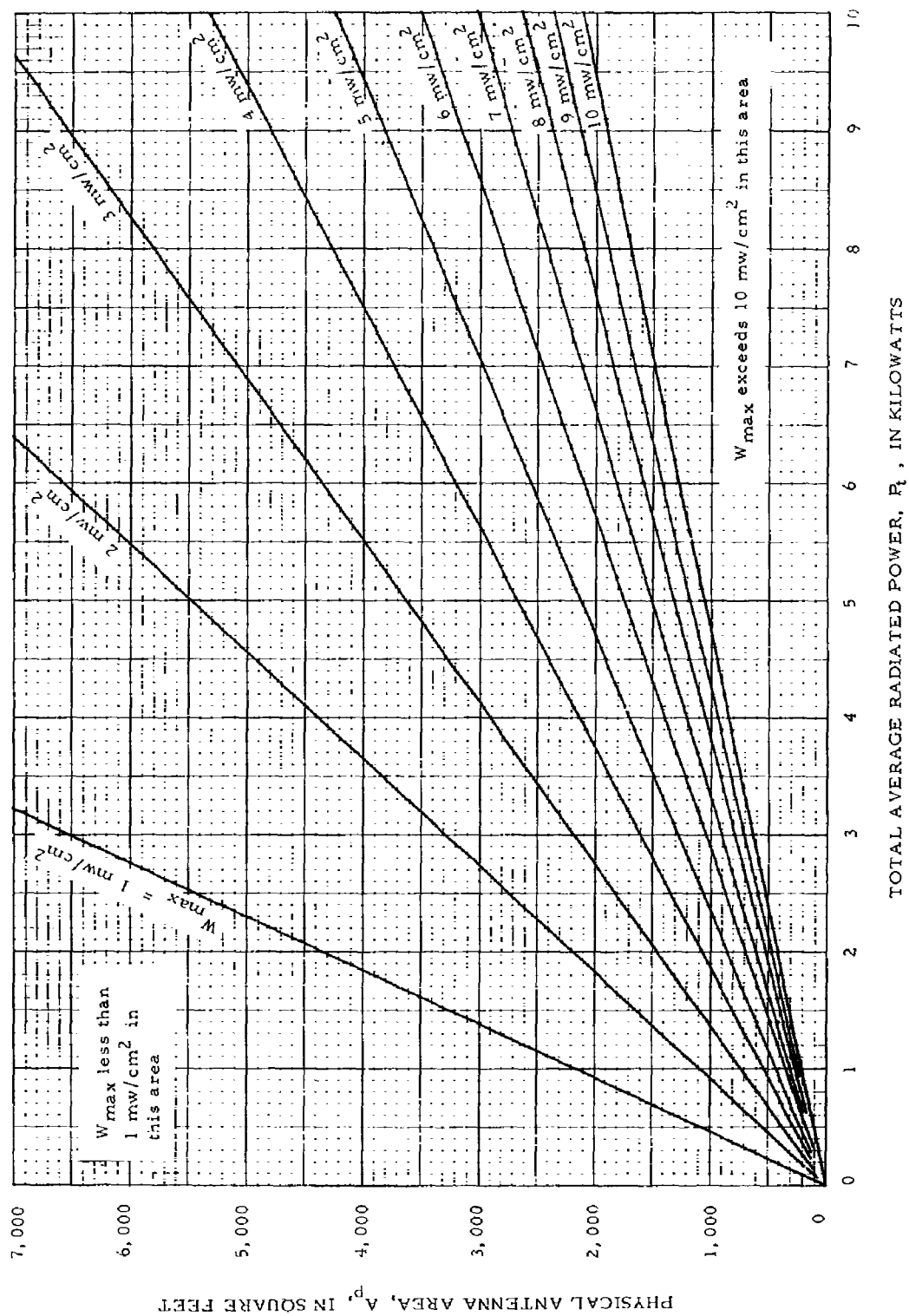


FIG. 2 CURVES FOR OBTAINING W_{MAX} (LOW POWER/SMALL AREA CONDITIONS)

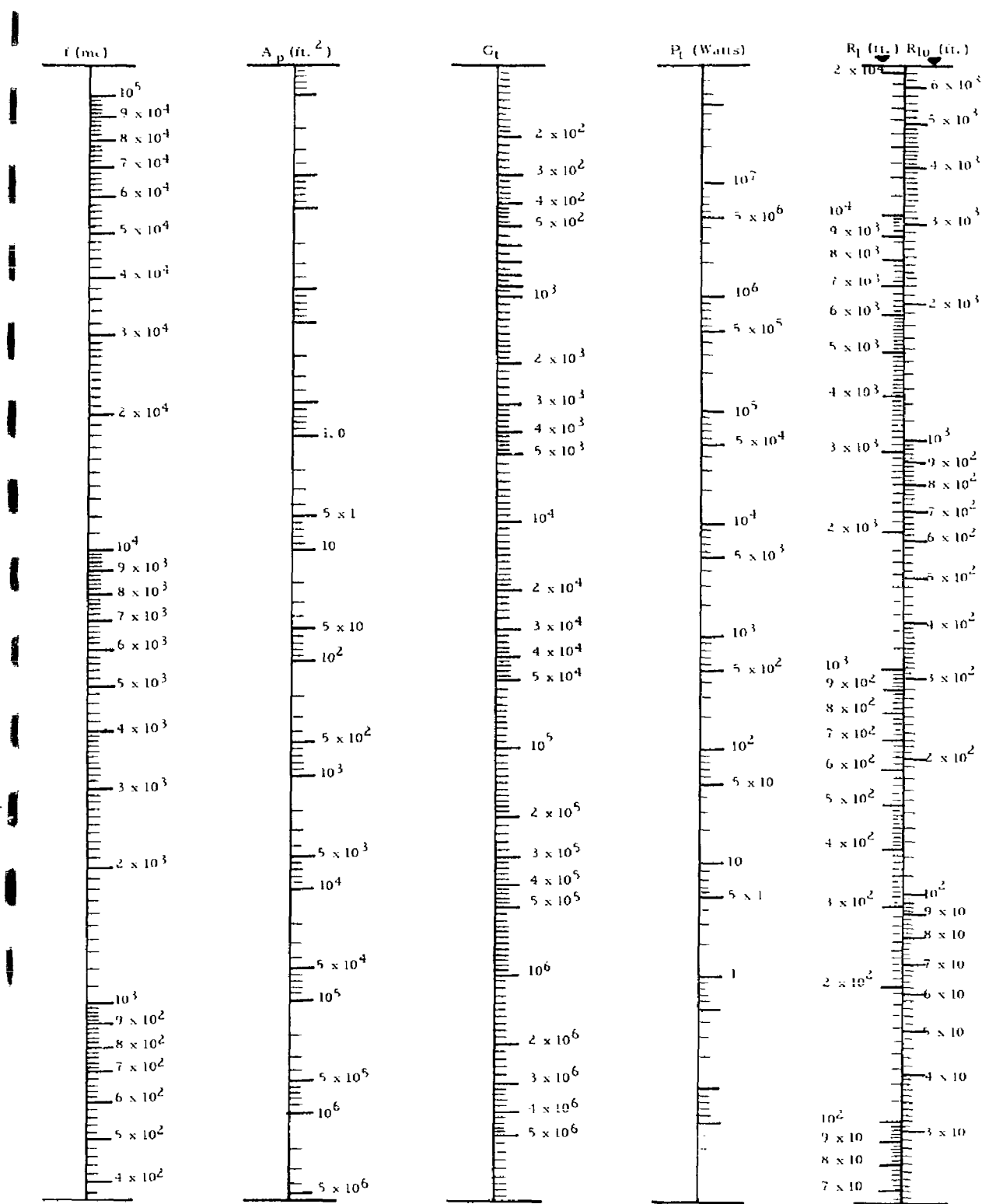


FIG. 3 NOMOGRAPH FOR OBTAINING MINIMUM SAFE DISTANCES
(FOR 1 MW/CM² AND 10 MW/CM² CRITERIA)

$$\text{When } W = W_1 = 1 \text{ mw/cm}^2$$

$$\text{and } W = W_{10} = 10 \text{ mw/cm}^2$$

$$R = R_1 = \left(\frac{G_t P_t}{8 \pi W_1} \right)^{1/2} \quad (4)$$

and

$$R = R_{10} = \left(\frac{G_t P_t}{8 \pi W_{10}} \right)^{1/2} \quad (5)$$

respectively. R_1 and R_{10} are the distances in the far field where the power densities are 1 mw/cm^2 and 10 mw/cm^2 respectively. Figure (3) is a nomograph designed from equations (3), (4), and (5).

1. Using the Figures (1), (2), and (3). The steps in using Figures (1), (2), and (3) are as follows:

a. Determine $W_{\max}$ from Figures (1) or (2) using given data or data calculated from given data. If $W_{\max}$ falls below hazardous limits no further analysis is required.

b. Determine R_1 and/or R_{10} from Figure (3) as follows:

(1) Using the operating frequency and physical area, determine G_t .

(2) Using G_t (from part (a)) and P_t (radiated or transmitter power) find R_1 and/or R_{10} .

Examples:

a. Jet Propulsion Laboratory, Deep Space Instrumentation Facility (Reference 15).

$$P_t = 10 \text{ Kilowatts}$$

$$f = 2295 \text{ Megacycles}$$

$$d = 85 \text{ Feet (Parabolic Dish Antenna)}$$

$$A_p = \pi d^2 / 4$$

$$A_p = \pi (85)^2 / 4$$

$$A_p = 5,680 \text{ ft.}^2$$

Use Figure (2) to determine:

$$3 \text{ mw/cm}^2 \leq W_{\max} \leq 4 \text{ mw/cm}^2$$

If it is necessary to find the distance at which the power density is 1 mw/cm^2 use Figure (3) to determine:

$$G_t = 3.9 \times 10^5$$

$$R_1 = 12,500 \text{ feet}$$

The distance at which the power density is 1 mw/cm^2 is 12,500 feet. It is worth noting that the above parameters, if used to determine R_{10} without using step 1 of the procedure, give:

$$R_{10} = 3,900 \text{ feet.}$$

It must be pointed out that such a determination is incorrect in that the far field function from which the nomograph was constructed is valid only to the distance where $W = W_{\max}$ which was previously determined to be between 3 mw/cm^2 and 4 mw/cm^2 . Therefore, it is possible to find R_1 and R_{10} only if step (1) of the procedure indicates $W_{\max} > 1 \text{ mw/cm}^2$ or $W_{\max} > 10 \text{ mw/cm}^2$ respectively.

b. Jet Propulsion Laboratory, Deep Space Instrumentation Facility.

$$P_t = 10 \text{ Kilowatts}$$

$$f = 960 \text{ Megacycles}$$

$$d = 85 \text{ Feet (Parabolic Dish Antenna)}$$

As before: $A_p = 5,680 \text{ ft.}^2$

From Figure (2):

$$3 \text{ mw/cm}^2 < W_{\max} < 4 \text{ mw/cm}^2$$

From Figure (3):

$$G_t = 5.37 \times 10^4$$

$$R_1 = 5,450 \text{ feet}$$

c. Given:

$$P_t = 5 \text{ Kilowatts}$$

$$f = 1,000 \text{ Megacycles}$$

$$d = 20 \text{ Feet (Parabolic Dish Antenna)}$$

$$A_p = \pi \frac{d^2}{4}$$

$$A_p = \pi \times 400/4$$

$$A_p = 314 \text{ Ft.}^2$$

From Figure (1):

$$W_{\max} > 10 \text{ mw/cm}^2$$

From Figure (3):

$$G_t = 4.2 \times 10^3$$

$$R_1 = 940 \text{ Feet}$$

$$R_{10} = 298 \text{ Feet}$$

d. Given:

$$P_t = 2 \text{ Kilowatts}$$

$$f = 2,300 \text{ Megacycles}$$

$$d = 80 \text{ Feet (Parabolic Dish)}$$

$$A_p = \pi (80)^2 / 4$$

$$A_p = 5,100 \text{ Feet}^2$$

From Figure (2):

$W_{\max} < 1 \text{ mw/cm}^2$ (There is no hazardous area in the vicinity of the antenna, therefore, no further analysis is necessary.)

The analysis does not include the possibility of reflections from ground or other objects in the field. Theoretically, the power density may be quadrupled at some point where reinforcement occurs between direct and reflected radiation. Such a condition occurs for perfectly conducting reflectors and is seldom realized in practice. One reference (Reference 17) shows that the power density is multiplied by a factor less than two when reflections exist. Assuming the possibility of reflection exists at some installation, and the power density is increased by a factor of two, R_1 and R_{10} as determined for any specific problem should be increased by the factor $\sqrt{2}$.

CONCLUSIONS

It is concluded that:

1. Aircraft transiting radio and radar beams of average power density 10 mw/cm^2 or less are safe, provided no electroexplosive devices are aboard. For guaranteed crystal protection, avionics items equipped with T-R (Transmit-Receive) tubes must be kept in POWER ON condition.
2. Aircraft carrying electroexplosive devices are safe in fields of average power density 1 mw/cm^2 or less when proper wiring procedures and maximum shielding efforts are used.
3. With regard to electroexplosive devices, progress by the military gives promise of yielding less restrictive limits in the near future.
4. The variety of high power installations precludes setting a single distance limit, and charts included in this report provide a rapid and simple means of converting from power density to distance along the antenna beam axis.
5. Power density calculations indicate that ATC radars have maximum power densities less than 10 mw/cm^2 (Appendix II).

RECOMMENDATIONS

It is recommended that:

1. Aircraft (not carrying electroexplosive devices) be prohibited from transiting electromagnetic fields in excess of average power density 10 mw/cm^2 . For guaranteed crystal protection, avionics items equipped with T-R (Transmit-Receive) tubes must be kept in POWER ON condition.
2. Aircraft carrying electroexplosive devices, which are properly wired and shielded, not be permitted to transit radio and radar fields in excess of average power density 1 mw/cm^2 .
3. Future progress of the military services on electro-explosive devices be monitored by the Research Division by attendance at, and limited participation in, meetings of the HERO (Hazards of Electromagnetic Radiation to Ordnance) Program with a view to establishing less restrictive limits as soon as possible.
4. Future studies in the area of radiation hazards should investigate the possibility of hazard to transistorized (solid state) avionics items being introduced into aircraft.
5. Experimental data be provided on the avionics items containing crystal rectifiers, using operational configurations. Tests should be made with T-R (Transmit-Receive) tubes in both active and quiescent states with frequencies compatible with tube bandwidth characteristics.
6. Experimental verification be made of the power density values calculated for the ATC radars in Appendix II.

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APPENDIX I

POSSIBLE RADIATION HAZARDS WHEN BLASTING NEAR AIRPORTS

A problem related to aircraft and electroexplosive devices is given as follows:

Blasting operations are taking place near a runway and an aircraft with transmitters operating passes overhead causing an electromagnetic field to which the EED on the ground is exposed. Determine the possibility of accidental ignition of the EED under such circumstances.

The body of this report suggests 1 mw/cm^2 average power density to which aircraft with EEDs may be safely exposed, provided precautions as per Reference 11 are taken. The situation in the problem being considered here indicates that precautions may not be taken, and the possibility exists that lack of knowledge of the radio frequency energy hazard may lead to setting up the blasting cap in a configuration which would be very effective in extracting energy from a radio field.

In calculating an estimate of power density required for accidental ignition, conditions which make ignition more likely are assumed:

1. The EED is sensitive - current for firing is .25 amperes and bridge wire resistance is .5 ohms.
2. The blasting cap is attached to wires with a configuration of a half-wavelength dipole.
3. The wires are oriented to match the field polarization.

$$\text{Now: } W = \frac{P}{A} \quad (\text{For any receiving antenna})$$

where: W is the field power density

P is the power received

A is the effective area of the antenna for absorption

$$\text{Now: } P = I^2 R$$

where I is the squib firing current

R is the squib resistance

$$P = (.25)^2 (.5)$$

$$P = 31.25 \text{ milliwatts (required for cap ignition).}$$

If matched conditions prevailed; that is, if the bridge wire resistance were 72 ohms rather than 0.5 ohms, the effective area would be:

$$A = \frac{3\lambda^2}{8\pi} \quad (\text{For half-wavelength dipole})$$

where λ is the wavelength of the radiation.

For any receiving antenna

$$P = A W$$

The power received under unmatched conditions can be determined from:

$$\frac{P_u}{P_m} = \frac{A_u W}{A_m W}$$

$$P_u = P_m \frac{A_u}{A_m}$$

where:

P_u is power received under unmatched conditions

P_m is power received under matched conditions

A_u is the effective area under unmatched conditions

A_m is the effective area under matched conditions.

In general:

$$A = \frac{d^2 R_o k}{(2\pi f L - 1/2 \pi f C)^2 + (R_o + R_r)^2} \quad (\text{Reference 16})$$

where:

R_r is the antenna resistance

R_o is the load resistance

k is the characteristic impedance of the medium

L is the antenna inductance

C is the antenna capacitance

f is the frequency

d is the antenna length

For a resonant antenna, the reactive part of the equation vanishes and

$$\frac{A_u}{A_m} = \frac{d^2 k \frac{R_o}{(R_o + R_r)^2}}{d^2 k \frac{R_r}{(R_r + R_r)^2}}$$

$$\frac{A_u}{A_m} = \frac{\frac{R_o}{(R_o + R_r)^2}}{\frac{R_r}{(R_r + R_r)^2}}$$

$$\frac{A_u}{A_m} = \frac{R_o (2R_r)^2}{R_r (R_o + R_r)^2}$$

$$\frac{A_u}{A_m} = \frac{4 R_o R_r}{(R_o + R_r)^2}$$

$$\text{Now: } P_u = P_m \frac{4 R_o R_r}{(R_o + R_r)^2}$$

$$\text{Therefore: } P_u = \left(\frac{4 R_o R_r}{(R_o + R_r)^2} \right) \left(\frac{3 \lambda^2}{8 \pi} \right) (W)$$

$$\text{and } W = \frac{2 \pi (R_o + R_r)^2}{3 R_o R_r \lambda^2} P_u$$

$$\text{Since } \lambda f = c$$

where f = operating frequency

c = velocity of light

$$\text{then } W = \frac{2 \pi (R_o + R_r)^2 f^2}{3 R_o R_r c^2} P_u$$

For the specific problem given:

$$R_r = 72 \text{ ohms}$$

$$R_o = 0.5 \text{ ohms}$$

$$P_u = 31.25 \text{ milliwatts}$$

Therefore:

$$W = \frac{2 \pi (0.5 + 72)^2 (31.25) f^2 \text{ milliwatts}}{3 (0.5) (72) (9) (10^{20}) \text{ cm}^2}$$

$$W = 1.05 \times 10^{-17} f^2 \frac{\text{mw}}{\text{cm}^2}$$

The power density required for ignition is proportional to the square of the frequency.

The lowest frequencies present the most dangerous conditions. As a practical matter, however, the wires attached to the EED in a dipole configuration probably would be limited in length. Assume a 15 foot dipole is attached to the EED, then:

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

$$\lambda / 2 = 15 \text{ feet}$$

$$\lambda = 30 \text{ feet}$$

$$\lambda = 360 \text{ inches}$$

$$\lambda = (2.54) (360) \text{ cm}$$

$$f = \frac{3 \times 10^{10} \text{ cm}}{2.54 \times 360 \text{ cm}}$$

$$f = 33 \text{ mc.}$$

For 33 mc:

$$W = 1.05 \times 10^{-17} \times 11 \times 10^{14} \frac{\text{mw}}{\text{cm}^2}$$

$$W = .0115 \frac{\text{mw}}{\text{cm}^2} \quad (\text{required for ignition})$$

Aircraft transmitters in the high frequency bands may be rated as high as 2 kilowatts.

The power density produced at the electroexplosive device, from a half-wavelength antenna aboard the aircraft, is given by:

$$W = \frac{PG}{4 \pi r^2}$$

where P is the transmitted power

G is the antenna gain

r is the distance between aircraft and the EED.

$$\text{If: } W = .0015 \frac{\text{mw}}{\text{cm}^2} = .115 \frac{\text{w}}{\text{m}^2}$$

$$r = \left(\frac{PG}{4 (0.115) \frac{\text{w}}{\text{m}^2}} \right)^{1/2} \text{ meters}$$

$$r = 3.28 \left(\frac{2 \times 2000}{4 \times .115} \right)^{1/2} \text{ feet}$$

$$r = 172 \text{ feet}$$

The aircraft transmitting 2 kilowatts at 33 mc. must be within 172 feet to produce a power density required for accidental ignition of a sensitive EED attached to a 15 foot half-wavelength dipole.

A somewhat more realistic case is the consideration of very high frequencies (since EED wires can more easily be placed in sensitive configurations). At 300 mc:

$$\lambda = \frac{c}{f} = \frac{3 \times 10^{10} \text{ cm}}{3 \times 10^8} = 10^2 \text{ cm}$$

$$\frac{\lambda}{2} = 50 \text{ cm (20 inches)}$$

For 300 mc.

$$W = 1.05 \times 10^{-17} \times 9 \times 10^{16} \frac{\text{mw}}{\text{cm}^2}$$

$$W = .95 \frac{\text{mw}}{\text{cm}^2}$$

About 1 mw/cm² is required for accidental ignition at 300 mc. Aircraft may carry VHF transmitters capable of producing 200 watts:

$$W = \frac{PG}{4\pi r^2}$$

$$r = \frac{PG}{4\pi W}$$

$$r = \left(\frac{200 \times 2}{40\pi} \right)^{1/2} \text{ meters}$$

$$r = 3.28 \left(\frac{10}{\pi} \right)^{1/2} \text{ feet}$$

$$r = 5.8 \text{ feet}$$

For an aircraft transmitting 200 watts on its VHF circuit (half-wavelength dipole) and an EED attached to a 20 inch dipole, also half-wavelength, the plane must be within 5.8 feet to cause accidental ignition. The greatest danger seems to be in the high frequency range (frequencies between 3 and 30 megacycles).⁶ Aircraft should stay about 250 feet above blasting operations in which EEDs are being used. For blasting operations not using electroexplosive devices, no danger exists from radio waves (Reference 10).

⁶Below the H-F range transmitter powers decrease and the antenna efficiencies decrease radically.

APPENDIX II

CHARACTERISTICS OF SOME AIR TRAFFIC CONTROL RADARS

A number of Air Traffic Control radars are designed with shaped beams to improve vertical coverage. Since the most efficient antennas (high k) have uniformly illuminated apertures, the shaped beam antennas with non-uniformly illuminated apertures have lower power densities along the line of maximum gain. To compute the maximum power density in the field along the line of maximum gain, use the formula

$$W_{\max} = k \frac{4P_t}{A_p}$$

where: P_t = Transmitted (or transmitter power)

A_p = Physical area of antenna

and $k = \frac{G_a}{G_t}$ where G_a = actual antenna gain
 G_t = theoretical antenna gain

The antennas considered in this appendix have published G_a values which will be used with calculated G_t (equal to $4\pi A_p f^2 / c^2$) values to determine specific k values.

Using published data, $W_{\max}$ is calculated for each antenna type, and a tabulation made. One complete calculation will be made explicitly on the ARSR-1A:

Given:

G_a = 34.2 decibels

f = 1300 megacycles

P_t = 3920 kilowatts (peak)

Pulse Recurrence Freq. = 360 pulses per second

Pulse Width = 2 microseconds

Reflector Dimensions = 40 x 11 square feet

Required:

G_a , G_t , k , P_t (average), and A_p .

a. $G_a = 34.2$ decibels

$$34.2 = 10 \log G_a$$

$$G_a = 2630$$

b. $G_t = \frac{4\pi A_p f^2}{c^2}$

$$G_t = \frac{4\pi \times 40 \times 11 \times (2.54)^2 \times (12)^2 \times (1.3)^2 \times 10^{18}}{9 \times 10^{20}}$$

$$G_t = 9640$$

c. $k = G_a / G_t$

$$k = 2630 / 9640$$

$$k = .273$$

d. P_t (average) = P_t (peak) x Pulse Recurrence Freq.
x Pulse Width

$$= 3920 \times 10^3 \times 360 \times 2 \times 10^{-6} \times 10^3$$

milliwatts

$$= 2.82 \times 10^6 \text{ milliwatts}$$

e. $A_p = 40 \times 11 \times (2.54)^2 \times (12)^2$

$$= 4.07 \times 10^5 \text{ (centimeters)}^2$$

Using the information from calculations (3) through (5)

$$W_{\max} = \frac{.273 \times 4 \times 2.82 \times 10^6}{4.07 \times 10^5} \frac{\text{mw}}{\text{cm}^2}$$

$$W_{\max} = 7.58 \frac{\text{mw}}{\text{cm}^2}$$

1. Circular Aperture. For a uniformly illuminated circular aperture, the power density function (W) is oscillatory from the antenna to some distance (R_0) where the function begins to fall with distance (R) according to the $1/R^2$ law. The function has a number of maxima (all equal) and a number of minima (all zero). Figure (4) is a sketch of the function.

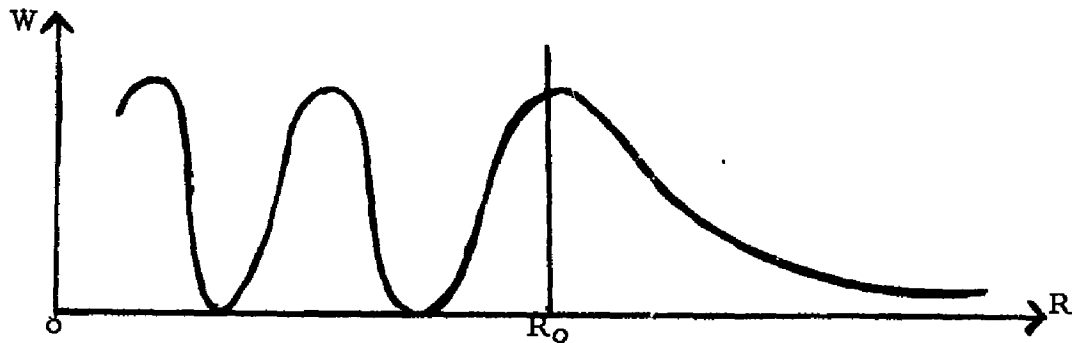


Figure (4). The power density (W) as a function of distance (R) for a uniformly illuminated circular aperture. R_0 is the distance at which the far field begins. R_0 can be found as follows:

In the near field

$$W_{\max} = k \frac{4P_t}{A_p}$$

In the far field

$$W = \frac{G_a P_t}{4\pi R^2}$$

At R_0 the far field function is a maximum and is equal to the near field function. Therefore,

$$\frac{4kP_t}{A_p} = \frac{G_a P_t}{4\pi R_0^2}$$

$$\text{with } k = G_a / G_t$$

$$\text{and } G_t = \frac{4\pi A_p f^2}{c^2}$$

where A_p = physical antenna
and c = velocity of light

$$\frac{4c^2 G_a P_t}{4\pi A_p^2 f^2} = \frac{G_a P_t}{4\pi R_o^2}$$

$$\text{thus } R_o^2 = \frac{A_p^2 f^2}{4c^2}$$

$$\text{and } R_o = \frac{A_p f}{2c}$$

Since the aperture is circular, $A_p = \frac{\pi d^2}{4}$ where d is the antenna diameter. Therefore,

$$R_o = \frac{\pi d^2 f}{8c}$$

2. Rectangular Aperture. For a rectangular antenna, the following description holds: very near the antenna to a distance R_{o1} the power density function is purely oscillatory. In the far field the power density falls with distance as $1/R^2$. In between a combined oscillatory and $1/R^2$ function exists. Figure (5) is a sketch of the function.

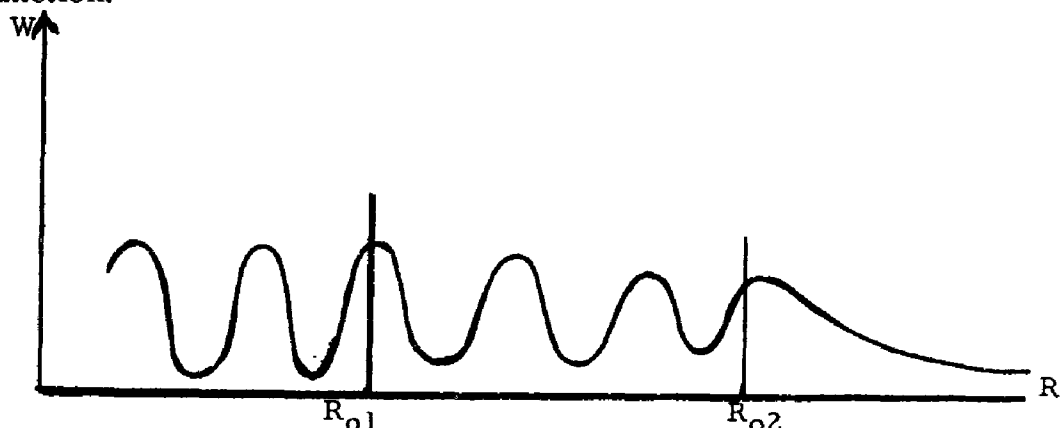


Figure (5). The power density as a function of distance for a rectangular aperture. To R_{o1} the power density function is purely oscillatory. From R_{o1} to R_{o2} the function is a combination of an oscillatory and a $1/R^2$ function. From R_{o2} the function follows the $1/R^2$ law.

Since for a circular aperture

$$R_o = \frac{\pi d^2 f}{8 c}$$

where d is the antenna diameter, it is assumed that

$$R_{o1} = \frac{\pi d_1^2 f}{8 c}$$

$$\text{and } R_{o2} = \frac{\pi d_2^2 f}{8 c}$$

where d_1 and d_2 are the smallest and largest linear antenna dimensions respectively. For the ARSR-1A

$$R_{o1} = \frac{\pi \times 11 \times 11 \times 1.3 \times 10^9 \times 2.54 \times 12}{8 \times 3 \times 10^{10}}$$

$$R_{o1} = 63 \text{ feet}$$

The maximum power density anywhere in the field of the ARSR-1A radar is 7.58 mw/cm^2 and this value exists at points between the antenna and 63 feet from the antenna along the line of maximum gain.

Now:

$$R_{o2} = \frac{\pi d_2^2 f}{8 c}$$

$$R_{o2} = \frac{\pi \times 40 \times 40 + 11 \times 11 \times 1.3 \times 10^9}{8 \times \frac{3 \times 10^{10}}{12 \times 2.54}}$$

$$R_{o2} = 892 \text{ feet}$$

The power density at R_{o2} can be determined from

$$W = \frac{G_a P_t}{4\pi R_{o2}^2}$$

$$W = \frac{2630 \times 2.82 \times 10^6}{4\pi \times 892 \times 892 \times 12 \times 12 \times 2.54 \times 2.54}$$

$$W = .8 \text{ mw/cm}^2$$

Although it is not possible in this case to determine the exact distance at which $W = 1 \text{ mw/cm}^2$ the analysis shows that the distance is less than 892 feet. When W at R_{o2} is greater than 1 mw/cm^2 it is possible to find the distance (R_1) at which the power density is 1 mw/cm^2 from

$$\frac{W_{R_{o2}}}{W} = \frac{R_1^2}{R_{o2}^2}$$

$$\text{that is } R_1^2 = R_{o2}^2 \quad W_{R_{o2}} / W$$

$$\text{where } W = 1 \text{ mw/cm}^2$$

$$R_1 = R_{o2} (W_{R_{o2}})^{1/2}$$

Table 1 gives W_{max} , R_{o1} , R_{o2} , $W_{R_{o2}}$ (power density at R_{o2}) and R_1 for a number of ATC radars. For the ARSR-1A the maximum power density is 7.58 mw/cm^2 from the antenna to 63 feet. From 63 to 892 feet the maximum power density varies from 7.58 to $.8 \text{ mw/cm}^2$. For all the antennas, the region between the feed horn and the reflector is a hazardous one since power densities greater than 10 mw/cm^2 will exist there.

TABLE I

Radar	$W_{\max} (\frac{\text{mw}}{\text{cm}^2})$	$R_{01} (\text{ft.})$	$R_{02} (\text{ft.})$	$W_{R_{02}} (\frac{\text{mw}}{\text{cm}^2})$	$R_1 (\text{ft.})$
ASR-2	2.58	112	272	1.01	272
ASR-3	5.90	112	300	2.08	432
ASR-4	3.12	63	366	0.72	$R_1 < 366$
ARSR-1A	7.58	63	892	0.80	$R_1 < 892$
ARSR-2	0.97	289	1592	0.02	$W_{\max} < 1$
FPS-8	1.95	102	425	0.58	$R_1 < 425$
FPS-20	6.58	133	964	1.26	1080
FPS-20A	6.58	133	964	1.26	1080
FPS-35	5.53	244	2720	0.74	$R_1 < 2720$
FPS-37	6.56	112	1126	0.21	$R_1 < 1126$
FPS-64	6.58	133	964	1.26	1080
FPS-66	6.58	133	964	1.26	1080
FPS-67	6.58	133	964	1.26	1080

TABLE I. Some characteristics of Air Traffic Control radars where

$W_{\max}$ is the maximum power density in the field.

R_{01} is the distance at which the field becomes part near and part far field. $W_{\max}$ exists at points between the antenna and R_{01} .

R_{02} is the distance at which the field becomes purely far field.

$W_{R_{02}}$ is the power density at R_{02} .

R_1 is the distance at which the power density is $1 \frac{\text{mw}}{\text{cm}^2}$.

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