RF HAZARDS: CALCULATIONAL METHODOLOGY

A theoretical analysis can be used to estimate RF/microwave hazard distances.

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The methodology presented in this article is a means by which the health physicist concerned with RF/microwave safety can make a very conservative estimate of the hazard distances involved, which will then be useful as a starting point in making actual field measurements. The factor of conservatism will vary from as little as one, to as great as five, depending on how far from the antenna the far field actually begins. There are some small aperture antennae in the J- and X-bands that have short near fields where these equations will yield very accurate predictions. The important point to remember is that *any* method other than actual measurements is only an estimate and/or prediction, and all are markedly influenced by a variety of factors, most of which are poorly understood. Actual measurements are always preferable, but estimates are useful as tentative numbers and as a starting place for any survey.

The first step in every RF/microwave hazard analysis is to compile a complete list of the system characteristics. As a minimum, the following emitter information should be obtained.

- Operating Frequency
- Transmitter Peak Power
- Pulse Width (PW), if any
- Pulse Repetition Frequency (PRF), if any
- Antenna Gain in dB
- Antenna Dimensions
- Beam Width
- Scan or Rotation Rate, if any

The next step is to develop as complete a theoretical analysis as possible. In certain circumstances, due to the inaccessibility of the radiated beam, a theoretical analysis may be the only way to proceed. As mentioned previously, this method of establishing hazard distances is based on a conservative, worst-case situation. The equations used in this section are all derived from basic antenna theory and provide results consistent with measured power densities.

When an antenna is radiating into space, it is generally agreed that there are four distinct zones or regions wherein dissimilar behavior of the antenna's electromagnetic field is experienced. These zones include the reactive near-field regions, the radiating near-field regions, the intermediate- and the far-field region. The reactive near-field region predominates over a very short range, usually less than 0.5 wavelengths from the active antenna element. Because of the short wavelengths involved, this region is not usually significant in the microwave portion of the spectrum. The reactive near field can become important when dealing with resonant type antennas at frequencies below 100 MHz at power levels greater than 35 W. It is in the reactive near-field region that separate measurements of E and H fields should be made in order to perform a hazard survey. In the radiating near field, the energy is collimated in a beam having approximately the same size and shape as the far-field beam. The radiating near field oscillates sinusoidally in amplitude with increasing range. The maxima are four times greater than the average power density, W_o, measured at the antenna aperture for an ideal antenna with 100 per cent illumination. This average power density is given by:

$$W_o = P_{ave}/A \qquad (1)$$

where P_{ave} equals the average transmitter power that is available for radiation after transmission line losses are subtracted. In pulsed systems, P_{ave} equals Peak Power x DF. A is the actual area of the antenna aperture.

In the radiating near field it is therefore convenient and adequate from a personnel hazard viewpoint to consider the power density in the radiating near field to be constant with range. The maximum radiating near-field power density, W_{nf}, is:

$$W_{nf} = \eta\, 4\, P_{ave}/A \qquad (2)$$

where η is the antenna aperture efficiency, typically on the order of 0.5 to 0.75. In the intermediate field the power density is decreasing linearly with range, and can be represented as:

$$W_{if} = W_{nf}(R_{nf}/R) \qquad (3)$$

where R_{nf} is the extent of the near field and R is some range in the intermediate field. For a *circular* antenna, R_{nf} is given by:

$$R_{nf} = D^2/4\lambda \qquad (4)$$

where D is the antenna diameter and λ is the wavelength of the radiation.

In the far field an antenna has the characteristic that the power density W decreases as the inverse square of the range. Equation 5 is a precise statement of the value of W_{ff} as a function of transmitter power, antenna gain, and range. This equation, (the Friss free-space transmission formula) predicts the worst-case envelope of radiated power density from *any* antenna system. It is technically only accurate for plane-wave, far-field conditions, though it can be used successfully as a worst-case predictor to zero range, where W would approach an infinite value. The formula is as follows:

$$W_{ff} = P_{ave}\, G/4\pi R^2 \qquad (5)$$

where W is the power density on axis; P_{ave} is the average power available for radiation; G is the absolute gain expressed as a power ratio; and $R > R_{ff}$, the distance which marks the beginning of far-field conditions. Again, for a circular antenna, R_{ff} is given by:

$$R_{ff} = 0.6\ D^2/\lambda \qquad \textbf{(6)}$$

If the gain of the antenna is not known, it can be closely approximated by the following:

$$G = 4\pi A\eta/\lambda^2 \qquad \textbf{(7)}$$

where λ is the wavelength of the radiated energy, η is the antenna efficiency and A is the actual antenna aperture area. Combining Equations 2 and 7 yields:

$$W_{nf} = 16\pi\ P_{ave}\ \eta^2/G\lambda^2 \qquad \textbf{(8)}$$

Equation 5 can be solved for range as follows:

$$R = \sqrt{(PG/4\pi\ W)} \qquad \textbf{(9)}$$

Once a power density is calculated using Equation 5, the power density W_2 at any other distance R_2 in the far-field is given by:

$$W_1/W_2 = (R_2)^2/(R_1)^2 \qquad \textbf{(10)}$$

This treatment was derived specifically for antennae with circular apertures. However, Equation 10 can be extended to non-circular aperture antennas by representing them by a circular aperture of the same physical size and gain. In this case the antenna equations can be generalized as follows:

$$R_{nf} = G\lambda/4\pi^2\eta \qquad \textbf{(11)}$$

$$R_{ff} = 0.6\ G\lambda/\pi^2\eta \qquad \textbf{(12)}$$

The equations for W_{nf}, W_{if} and G are as before.

The effects on the above calculations if a system is rotating or *nodding* can now be shown. The power density produced at any point by an antenna which is rotating is given by:

$$W = W_s \times f \qquad \textbf{(13)}$$

where W_s is the stationary power density and f is the so-called *rotational reduction factor*. In the near-field, the beam is considered to have a dimension in the plane of rotation equal to the length of the antenna axis, L, in that plane. The near-field rotational correction factor, f_{nf}, at R is given by:

$$f_{nf} = L/R\ \theta_s \qquad \textbf{(14)}$$

where L equals the antenna dimension in the plane of reduction, R is the distance from a point in the near field to the antenna, and θ_s is the scan angle in radians. The power density calculated in the near and intermediate field using the above reduction factor is an overestimate but is consistent with the conservative approach used in hazard calculations. The reduction factor f_{ff}, which W_{ff} is multiplied by to determine the time-averaged power density found in the far field of a scanning antenna, is given by:

$$f_{ff} = \theta_{1/2}/\theta_s \qquad \textbf{(15)}$$

where $\theta_{1/2}$ is the half-power beam width of the antenna and θ_s is the scanning angle of the emitter. *It is important to realize that f is independent of the scanning rate in revolutions per minute.*

Finally, a BASIC computer program which will perform some of these calculations for the far field is listed in Appendix I at the end of this article.

It should be noted that experience has shown that only about 15 per cent of the RF/microwave emitters account for the bulk of the measurement problems encountered in managing a safety program. In some cases the calculations detailed in this article are not required. There are a number of classes of emitters that can easily and promptly be removed from these calculations, however. For example, hand-held transreceivers, commonly known as *bricks*, which operate from 136 to 174 MHz and at the 510 MHz regions of the spectrum are considered to be non-hazardous to personnel if they emit less than 7 watts. As another example, many high-powered emitters have main beams which are normally inaccessible to personnel. Hazard calculations performed on these systems would be for academic interest only. A large class of emitters has characteristics which have been validated after a large number of surveys have been performed on them. Appendix II, generated by the USAF Occupational and Environmental Health Laboratory, shows just such results for emitters that utilize very thin horizontal or vertical antennae with omnidirectional patterns. Personnel hazards for these emitters are very easily managed using the results of this table and observing the caveats that are noted. Finally, it is important to note that there is a wealth of survey information on many *off-the-shelf* systems performed by many federal and state agencies. This data, coupled with interaction with the manufacturer of the system in question, can prove invaluable. ■

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APPENDIX I
BASIC COMPUTER PROGRAM FOR CALCULATING RF HAZARD DISTANCES

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01     REM CALCULATION OF THE HAZARD DISTANCE FOR AN RF
       EMITTER
10     REM CALCULATION OF ANSI PEL FOR A SINGLE RF OR
       MICROWAVE FREQUENCY
15     LPRINT "PLEASE INPUT THE FREQUENCY IN MHZ"
20     INPUT "PLEASE INPUT THE FREQUENCY IN MHZ", F
25     LPRINT F
30     IF F < .3 GOTO 95
40     IF F < 3 GOTO 99
50     IF F < 30 GOTO 200
60     IF F < 300 GOTO 300
70     IF F <  1500 GOTO 400
80     IF F< 100000 GOTO 500
90     IF F > 100000 GOTO 95
95     PRINT "THIS FREQUENCY IS OUTSIDE THE RANGE OF THE
       ANSI STANDARD"
96     LPRINT "THIS FREQUENCY IS OUTSIDE THE RANGE OF THE
       ANSI STANDARD"
97     GOTO 3000.
99     PEL = 100
110    GOTO 1000
200    PEL = 900/((F)^2)
210    GOTO 1000
300    PEL = 1
310    GOTO 1000
400    PEL = F /300
410    GOTO 1000
500.   PEL = 5
510    GOTO 1000
1000   PRINT "THE ANSI PEL IS"; PEL; "mW/cm^2"
1010   LPRINT "THE ANSI PEL IS"; PEL; "mW/cm^2
1100   LPRINT "PLEASE INPUT THE GAIN IN dB, IF UNKNOWN
       TYPE 0"
1150   INPUT "PLEASE INPUT THE GAIN IN dB, IF UNKNOWN
       TYPE 0", G
1175   LPRINT G
1200   LPRINT "PLEASE INPUT THE POWER IN WATTS"
1250   INPUT "PLEASE INPUT THE POWER IN WATTS", P
1260   LPRINT P
1275   PRINT "IF THE EMITTER IS CW, ENTER 1 FOR PULSE
       WIDTH  & PULSE REPETITION FREQUENCY"
1300   LPRINT "PLEASE INPUT THE PULSE WIDTH IN SECONDS"
1350   INPUT "PLEASE INPUT THE PULSE WIDTH IN SECONDS",
       PW
1375   LPRINT PW
1400   LPRINT "PLEASE INPUT THE PULSE REPETITION
       FREQUENCY IN HERTZ"
1450   INPUT "PLEASE INPUT THE PULSE REPETITION FREQUENCY
       IN HERTZ", PRF
1475   LPRINT PRF
1480   INPUT "PLEASE INPUT THE EMITTER EFFECTIVE DIAMETER
       IN FEET IF THE GAIN IN dB IS ZERO", D
1483   LPRINT "PLEASE INPUT THE EMITTER EFFECTIVE
       DIAMETER IN FEET IF THE GAIN IN dB IS ZERO", D
1485   D = D/3.281
1490   LAMBDA = (3E+08)/(F * 100000)
1500   DF = PW * PRF
1525   PRINT "THE DUTY FACTOR IS"; DF
1540   LPRINT "THE DUTY FACTOR IS"; DF
1550   PAV = P * DF
1600   PRINT "THE AVERAGE POWER IS"; PAV; "WATTS"
1625   LPRINT "THE AVERAGE POWER IS"; PAV; "WATTS"
1650   IF G >0 THEN GABS = 10^(G/10)
1670   IF G = 0 THEN GABS = (9.87 * D^2)/(LAMBDA)^2
1675   PEL = PEL * 10
1700   PRINT "THE ABSOLUTE GAIN IS"; GABS
1725   LPRINT "THE ABSOLUTE GAIN IS"; GABS
1750   R = ((PAV * GABS)/(12.57* PEL))^.5
1800   R = R * 3.281
1850   PRINT "THE DISTANCE IN FEET TO THE PEL IS:"; R; "FT"
1875   LPRINT "THE DISTANCE IN FEET TO THE PEL IS:"; R; "FT"
1900   PRINT "WOULD YOU LIKE TO KNOW THE POWER DENSITY
       AT ANOTHER DISTANCE? TYPE YES OR NO"
1925   LPRINT "WOULD YOU LIKE TO KNOW THE POWER DENSITY
       AT ANOTHER DISTANCE? TYPE YES OR NO"
1930   INPUT A$
1940   LPRINT A$
1950   IF A$ = "YES" THEN GOTO 1970
1960   IF A$ = "NO" THEN GOTO 3000
1970   LPRINT "PLEASE ENTER THE DISTANCE IN QUESTION IN
       FEET"
1975   INPUT "PLEASE ENTER THE DISTANCE IN QUESTION IN
       FEET", R1
1980   LPRINT R1
2000   PD =  (R^2 * PEL)/ R1^2
2025   PD = PD /10
2050   PRINT "THE POWER DENSITY AT"; R1; "FT IS"; PD;
       "mW/cm^2"
2075   LPRINT "THE POWER DENSITY AT"; R1; "FT IS"; PD
       mW/cm^2"
2100   GOTO 1900
3000   PRINT "WOULD YOU LIKE TO EXAMINE ANOTHER EMITTER?
       TYPE YES OR NO"
3025   LPRINT "WOULD YOU LIKE TO EXAMINE ANOTHER
       EMITTER? TYPE YES OR NO"
3050   INPUT B$
3055   LPRINT B$
3060   IF B$ = "YES" THEN GOTO 15
4000   IF B$ = "NO" THEN GOTO 4998
4998   PRINT "BYE"
4999   LPRINT "BYE"
5000   END
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Note: This program was written using MICROSOFT® Binary Basic Version 3.0 for the APPLE MACINTOSH®. It is case sensitive!

APPENDIX II
PERSONNEL HAZARD PREDICTIONS FOR THIN VERTICAL AND HORIZONTAL OMNIDIRECTIONAL ANTENNAE[2]

Transmitter Power in Watts	Vertical 10 mW/cm² Feet	Vertical 10 mW/cm² Meters	Vertical 1 mW/cm² Feet	Vertical 1 mW/cm² Meters	Vertical 0.1 mW/cm² Feet	Vertical 0.1 mW/cm² Meters	Horizontal 10 mW/cm² Feet	Horizontal 10 mW/cm² Meters	Horizontal 1 mW/cm² Feet	Horizontal 1 mW/cm² Meters
10	0.7	0.20	2.1	0.64	5.2	1.59	0.4	0.13	1.4	0.43
20	0.8	0.25	2.6	0.79	7.1	2.17	0.6	0.18	1.9	0.58
30	1.0	0.30	3.1	9.46	8.9	2.71	0.7	0.22	2.3	0.70
40	1.2	0.36	3.7	1.13	10.6	3.23	0.8	0.25	2.6	0.79
50	1.3	0.40	4.2	1.28	14.7	4.48	0.9	0.28	2.9	0.88
75	1.6	0.50	5.2	1.59	16.4	5.00	1.1	0.35	3.6	1.10
100	1.8	0.56	5.8	1.77	18.6	5.67	1.3	0.40	4.2	1.28
120	2.0	0.62	6.4	1.95	20.1	6.13	1.4	0.44	4.6	1.40
150	2.3	0.70	7.3	2.23	22.8	6.95	1.6	0.49	5.1	1.56
200	2.6	0.80	8.3	2.53	—	—	1.8	0.56	5.8	1.77
250	3.0	0.90	9.3	2.84	—	—	2.0	0.63	6.5	1.98
400	3.9	1.20	12.5	3.81	—	—	2.6	0.80	8.3	2.53
500	4.1	1.26	13.1	4.00	—	—	2.9	0.89	9.2	2.81
750	4.9	1.50	15.6	4.76	—	—	3.6	1.10	11.4	3.48
1000	5.8	1.78	18.5	5.64	—	—	4.1	1.26	13.1	4.00
1500	7.2	2.20	22.8	6.95	—	—	5.0	1.55	16.1	4.91
2000	8.2	2.50	25.9	7.90	—	—	5.8	1.78	18.5	5.64

Notes:

1. Predictions may be applied to omnidirectional antennae with gains of 6 dB or less.
2. Table may be applied to frequencies between 3 and 600 MHz.
3. Although these data do not represent a linear relationship, interpolation is possible, but will cause the distances to be even more conservative.