A basic methodology for microwave radiation hazard assessment and controls implemented by the U.S Army is presented. Analysis and measurement are used to determine the potential for personnel exposure. Account is taken of large aperture, small aperture and induction-type devices.

Summary

A combination of assessment of hazard potential by analysis and measurement by experienced antenna engineers, and implementation of recommendations made by the U.S. Army Environmental Hygiene Agency (USAEEA) is the backbone of the Army Microwave Radiation Protection Program. Primary responsibility for establishing safety criteria and recommending controls is assigned to USAEEA. By establishing radiation protection programs based on the Agency's recommendations, commanders have sought to comply with the Army's regulations and protect their personnel from continuous exposure to microwave power density levels in excess of 10 mW/cm², or any exposure to greater than 100 mW/cm²; the current U.S. Standard. Following the Federal Standard, the Army controls exposure from frequencies of 10 MHz and up. Sources include radar, communication equipment, physical therapy RF and microwave diathermy, industrial induction heaters, and microwave ovens and cooking devices.

Analysis

Three categories of radiators are evaluated by differing methods. Sources can be divided into large apertures, small apertures, and induction-type devices for analysis.

Large Apertures (Approximately Round or Square).

Large aperture sources include most radars and microwave communication systems; these can produce potentially hazardous (greater than 10 mW/cm²) power density in their main beams at considerable distance from the aperture if input power is sufficient. The hazard analysis in this section is limited to apertures with a major to minor dimension ratio of less than approximately 2:1, and would include round and square apertures as well as elliptical and rectangular apertures. To predict the microwave power density in the antenna main beam, several regions must be considered. Hansen describes the reactive near-field, radiating near-field, and the far-field regions. The reactive near-field of large apertures is within several wavelengths of the antenna and is not considered here. The radiating near-field extends to roughly $D^2/\lambda$ where $D$ is the largest dimension of the aperture and $\lambda$ is the wavelength. Hansen shows that the main beam splits and reforms within the radiating near field. This causes the effective gain of the antenna to vary with position along the main beam axis. Figure 1 shows gain variations vs. normalized on-axis distance from the antenna for circular apertures with different illumination tapers, $p$.

As the illumination taper, $p$, increases, the near-field power density increases and the gain reduction due to beam splitting becomes less of a factor. Hansen states that amplitude tapered apertures are equivalent to smaller uniformly illuminated apertures for on-axis near-field power density effects. For this reason, the author uses an effective area of the aperture for calculating near-field power densities; which is in agreement with the method recommended by ANSI. Far-field levels are calculated for all antennas using the Friis free-space transmission formula:

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

where $W$ = Power Density

$P$ = Power Transmitted

$G$ = Aperture Gain (Power Ratio)

$R$ = Distance from the Antenna
Log W is plotted vs. Log R for the far-field of the antenna ($R>2D$) is a very conservative criterion for the far-field). Power density is conservatively assumed to be constant from the antenna to $R = Ae/2\lambda$; where $Ae$ is the effective area of the aperture. $Ae$ is calculated from the following:

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

In this case, the gain, $G$ must be the gain of the aperture, not the specification gain which includes feed losses and transmission losses. Figure 2 is an example of the resulting power density vs. range plot.

**FIGURE 2**

Another method used in the analysis of uniformly illuminated circular apertures describes an intermediate field region. The near-field maximum power density is $4P/A$, and extends to a range of approximately $D^2/5.66A$ from the antenna. The intermediate region power density decreases to $2P/A$ at $D^2/2.83A$. The near-field power density approximation uses a modified area, $A$, in order to intersect with the far-field power density. The modified area essentially introduces an aperture efficiency correction. The envelope of maximum power density represented by the plot of Figure 2 is conservative as the far field, $1/R^2$ decreasing power density region, is assumed to exist into the region where gain reduction would occur. The near-field value used will always exceed the actual. As the illumination taper (Figure 1) increases, the near-field shortens:

$$G \propto 1/\rho$$

where $Ae \propto G$

and Near Field Range = $Ae/2\lambda \propto 1/\rho$

The accuracy of the hazard plot is dependent upon the accuracy of the transmitted power and aperture gain determination.

Selecting Correct Transmit Power and Gain.

A typical radar or communications set will have specifications available that delineate minimum values for transmit power, gain, etc, and maximum values for beam widths. Some modification of the specifications parameters is usually necessary to produce realistic hazard evaluation results. Without establishing elaborate test plans which would require accurate measurement of all contributing parameters on a given system, some approximations will produce adequate results based on these specification values. The aperture gain can be estimated from the antenna beamwidths:

$$G = \frac{41.253}{\theta}$$

where $\theta$ are the half-power beamwidths. This gain can also be obtained from nomographs. Feed loss, $L$, in power ratio:

$$L = \frac{G_s}{G};$$

where $G_s$ = Specification Gain

Transmit Power:

$$P = L \times P_s;$$

where $P_s$ = Specification Power

Because the illumination function is usually not available, the above approach to determining the aperture gain and transmit power is practical. The difference between the aperture gain and specification gain can be assumed to be feed losses; and the specification power can be reduced by the feed loss to establish the transmitted power. Adjustments in this method can be made if better data are available for the system. Normally, data are used which produce the worst-case potential hazard. Often, radar transmitters can produce significantly more than the specification power levels. Attempts are made to anticipate conditions which could cause a system to produce high power densities in the main beam.

Large Apertures Other Than Square or Circular; i.e., Line Sources.

Apertures considered here are defined as ones where the length to width ratio, or major to minor dimensions are greater than $\approx 2:1$. These apertures produce fan beams and require special treatment. For such apertures, including line arrays, there is a near-field region where the power density decreases as an oscillation about a $1/R$, or linear, fall off. Here as with circular apertures, the more amplitude taper, the less the effective area ($Ae$) and the shorter the $1/R$ fall off region. The power density approaches the power density at the center element of the array or source at short range ($R$).

Off-Axis Power Density.

In most cases, power density other than in the antenna main beam is not of concern for personnel hazard. Typical antennas, when properly focused, will produce out-of-beam power density levels well below that of an isotropic antenna with the same radiated power. If isotropic gain is assumed and the free-space formula used, worst-case approximations can be made for regions several beam widths off boresight.

Scanning Power Density.

Large aperture antennas, such as conventional radars, are most often operated scanning. When the antenna is scanned, the average power density at a point in the far-field is reduced by the ratio of the antenna beam width to the angle scanned. Therefore, it is usually
necessary to establish scanning as well as non-scanning hazard ranges for a source. The far-field scanning power density is:

\[ W_s = W \left( \frac{BW}{\delta_s} \right) \]

where \( W = \) Non-Scanning Power Density

\( W_s = \) Scanning Power Density

\( BW = \) Antenna Beam Width In Plane of Scan

\( \delta_s = \) Angle Scanned

In the antenna's near-field, within \( Ae/2\lambda \) of the antenna, the power density scanning is reduced by the ratio of 360D/2\pi R to \( \delta_s \). The 360D/2\pi R factor is the portion of an imaginary circle at range R that would be covered by the projection of the aperture. \( \theta_s \) is the portion of the circle scanned. The near-field scanning power density is:

\[ W_s(R) = W(R) \left( \frac{360D}{2\pi R} \right) \times \frac{1}{\delta_s} \]

where \( W_s(R) = \) Scanning Power Density at R from Antenna

\( W(R) = \) Stationary Power Density at R from Antenna

\( D = \) Aperture Dimension in Plane of Scan

\( R = \) Range to Antenna

If the antenna is never radiating while stationary, the shorter scanning hazard ranges can be used to control personnel exposure. Scanning power density is not used where the stationary power density exceeds 100 mW/cm², since this is a denied occupancy condition.

Small Apertures.

Electrically small apertures consist of such radiators as monopoles, dipoles, small horns; open-ended, broken or leaky waveguides; and microwave oven door seals. In most cases, hazard criteria are of interest in the far-field of such sources. This will usually occur within less than a wavelength from the aperture. The Friis free-space transmission formula:

\[ W = \frac{P_0}{4\pi R^2} \]

is valid for determining the power density in the far-field. When a leaky source is suspected, a gain approximation can be used, and the power leaking or radiated can be estimated. In the case of low frequency (HF and VHF) antennas, the near-field region may be of interest since personnel may be working within 1/4 wavelength or so of the radiator. The reactive near-field predominates to approximately \( \lambda/2\pi \). In this region, coupling of energy, rather than radiation, from the electric and magnetic fields is the hazard to be considered. Typically, the fields are measured rather than calculated and personnel are excluded from regions where the electric field exceeds 194 V/m and the magnetic field exceeds 0.5 A/m. Whether coupling is significant in any particular case is debatable, as conditions are likely to be variable so close to an antenna. Very likely, the antenna will be mismatched and a portion of the power reflected back toward the transmitter, decreasing the power available for coupling. It is possible for a person to interact with the antenna and a reflecting surface to increase the coupling into the person.

The person essentially is a "Tuner" or "Transformer" to improve the impedance match and absorb power from the antenna.

Induction-Type Devices.

RF induction devices, such as shortwave diathermy and industrial induction heaters, produce electric and magnetic fields in close proximity to the coupling plates or loops. The output couplings of these devices are designed to couple to lossy material rather than radiating to free-space, and the far-field radiation is usually negligible. When the device is operated without a load, power is not produced by the generator. With diathermy, biological tissue heating is deliberate and under control of a physician or physical therapist. Incidental RF coupling to personnel is of concern with diathermy and induction heaters. Measurements of electric and magnetic field strength are made with the devices typically loaded, and recommendations made to avoid greater than 0.5 A/m magnetic and 194 V/m electric field strength regions produced.

Measurement

To evaluate the potential hazard from a system, the power density levels to be expected are calculated as indicated above and measurements are made on systems to verify the analysis and to check for anomalies. Several broadband isotropic radiation hazard meters are available and are the most suitable devices for measurement in the near-field of large apertures. To detect the peaking effect and see the high power densities present, it is necessary to use an instrument with very wide, nearly isotropic antenna pattern response. Measurement in the far-field can be made with any calibrated instrument including a power meter and arbitrary antenna of known gain and polarization. If the test antenna polarization is linear, the power density must be summed for two perpendicular planes to be certain of measuring the total. Leakage from the antenna prime feed, spill-over from a reflector, reflections from structure, etc., are important to measure, and are not handled well by analysis. Misalignment of the antenna will also show up in measurement. These losses will serve to reduce the far-field power density while causing higher than normal close-in levels.

Controls

When the characteristics of a radiating system have been evaluated, recommendations are made to protect personnel. Controls are imposed on equipment, site, and personnel. Such controls include:

Equipment

- Minimize the maximum power density in accessible areas by design, if possible.
- Use limit switches, interlocks, etc., to prevent radiation in directions which would endanger personnel.
- Radiate while scanning only, if applicable.
- Use flashing lights to warn personnel when hazardous systems are radiating (approaching 100 mW/cm²).
- Provide signs on equipment and in the vicinity, warning personnel of potential hazards.
Minimize radiation to mission essential usage only.

Siting.

Limit access to regions of potentially hazardous power density with barriers, raised antenna emplacements, etc.

Install equipment sufficiently far from occupied areas, or on towers or elevated structures, as applicable, to prevent exposure to potentially hazardous power density levels.

Personnel.

Establish standing operating procedures (SOP) which provide controls to protect personnel.

Provide periodic briefings to inform personnel of hazards and safe procedures.

Conscientious application of the hazard control approach outlined here is effective in minimizing exposure of Army personnel to microwave radiation.

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References


