Cornell University

RF AND MICROWAVE SAFETY PROGRAM

Environmental Health and Safety

Contents

1 Purpose and Requirements

This program provides a summary of the basics of radiofrequency (RF) and microwave safety, biological effects, and exposure limits to be used at Cornell University.

Contact radiation-safety@cornell.edu with questions or comments concerning this program.

1.1 Scope and Regulations

This guide applies to all users of devices and equipment designed to generate RF and/or microwave fields. Examples include radar, telecommunications transmitters, cell phone transmitters, RF heat sealers, and microwave heating equipment.

Consumer-grade microwave ovens are not included in this guide. EHS will survey microwave ovens upon request.

1.2 General Federal Regulations

RF and microwave exposure limits are promulgated by the Federal Communication Commission (FCC) and the Occupational Health and Safety Administration (OSHA). In some cases regulations contradict each other, in which case the more conservative limit will be used.

1.3 FCC Requirements

Currently the FCC has adopted exposure limits from the National Council on Radiation Protection (NCRP) and can be found in the federal regulations at 47 CFR 1.1307(b), 1.1310, 2.1091, 2.1093, and at http://www.fcc.gov/oet/rfsafety/rf-faqs.html. The FCC recommendations covers 300 kHz to 100 GHz and tables of FCC limits can be found at http://www.fcc.gov/oet/info/documents/bulletins/#56.

Figure 1: FCC limits for Maximum Permissible Exposure (MPE)

(A) Limits for Occupational/Controlled Exposure

Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (mW/cm^2)	Averaging Time $\|E\|^2$, $\|H\|^2$ or S (minutes)
0.3-3.0	614	1.63	(100)*	6
3.0-30	1842/f	4.89/f	$(900/f^2)$*	6
30-300	61.4	0.163	1.0	6
300-1500	--	--	f/300	6
1500-100,000	--	--	5	6

(B) Limits for General Population/Uncontrolled Exposure

Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (mW/cm^2)	Averaging Time $\|E\|^2$, $\|H\|^2$ or S (minutes)
0.3-1.34	614	1.63	(100)*	30
1.34-30	824/f	2.19/f	$(180/f^2)$*	30
30-300	27.5	0.073	0.2	30
300-1500	--	--	f/1500	30
1500-100,000	--	--	1.0	30

f = frequency in MHz *Plane-wave equivalent power density

NOTE 1: Occupational/controlled limits apply in situations in which persons are exposed as a consequence of their employment provided those persons are fully aware of the potential for exposure and can exercise control over their exposure. Limits for occupational/controlled exposure also apply in situations when an individual is transient through a location where occupational/controlled limits apply provided he or she is made aware of the potential for exposure.

NOTE 2: General population/uncontrolled exposures apply in situations in which the general public may be exposed, or in which persons that are exposed as a consequence of their employment may not be fully aware of the potential for exposure or can not exercise control over their exposure.

1.4 OSHA Regulations

OSHA requirements can be found in 29 CFR 1910.97 and covers the range of 10 MHz to 100 GHz.

Figure 2: OSHA exposure guide

1910.97(a)(2)

"Radiation protection guide."

1910.97(a)(2)(i)

For normal environmental conditions and for incident electromagnetic energy of frequencies from 10 MHz to 100 GHz, the radiation protection guide is 10 mW/cm.(2) (milliwatt per square centimeter) as averaged over any possible 0.1-hour period. This means the following:

Power density: 10 mW./cm.^{2} for periods of 0.1-hour or more.

Energy density: 1 mW.-hr./cm.^{2} (milliwatt hour per square centimeter) during any 0.1-hour period.

This guide applies whether the radiation is continuous or intermittent.

1910.97(a)(2)(ii)

These formulated recommendations pertain to both whole body irradiation and partial body irradiation. Partial body irradiation must be included since it has been shown that some parts of the human body (e.g., eyes, testicles) may be harmed if exposed to incident radiation levels significantly in excess of the recommended levels.

2 Definitions

- **Specific Absorption Rate (SAR)**: The power absorbed by a body when exposed to electromagnetic radiation. The current SAR limit is 4 watts/kg (4 W/kg). To be conservative, standards setting organizations use 1/10 of this value.
- **Power Density**: Power per unit area, typically milliwatts/cm^2 or watts/m^2.
- **Near Field**: The region close to the RF emitter (i.e. antenna) where the electric and magnetic fields are not perpendicular to each other, and their orientation varies from point to point. The near field extends a distance less than one wavelength from the emitter. Power density measurements are not useful and often not possible in the near field.
- **Far Field**: Region where the electric and magnetic fields are perpendicular to each other, and do not vary from point to point. Power density measurements are possible in the far field.
- **ISM Bands**: Frequencies designated for industrial, scientific, and medical (ISM) use where radiated power is not regulated. Some typical ISM frequencies are 3.56 MHz, 27.12 MHz, 9.5 MHz, 2450 MHz, and 5800 MHz. Because emitted power is not regulated, safety hazards may be created due to high radiated power.
- **E Field**: Electric field strength component of RF energy measured in volt/meter (V/m).

- **H field**: Magnetic field strength component of RF energy measured in amps/meter (A/m).

3 Biological Effects

3.1 General Thermal Effects

The most pronounced biological effect from RF and microwaves radiation is heating, or thermal changes in the body. In its interaction with matter, RF energy may be reflected (as in the case of metals), transmitted through a medium (such as glass) with little energy loss, or be absorbed raising the temperature of the absorber. This increase in temperature can be attributed to two effects. Joule heating is due to ionic currents induced by the electric fields that are set up in the absorber. These ionic currents cause electrons to collide with molecules in tissue and resistance heating results. The other effect is due to the interaction between polar molecules in the absorber and high frequency electric fields. The polar molecules begin to oscillate back and forth in an attempt to maintain proper alignment with the electric field. These oscillations are resisted by other forces and this vibratory resistance is converted into heat.

Absorption of RF radiation and thus heating of the body tissues depends on several factors including wavelength and wave front characteristics. Frequencies greater than 10,000 MHz (10 GHz) are absorbed mostly in the outer skin.

Frequencies between 10,000 MHz and 2500 MHz penetrate more deeply (3 mm to 2 cm) and at wavelengths of 2500 MHz to 1300 MHz, penetration and absorption are sufficient enough to cause damage to internal organs by tissue heating. Therefore the absorption and penetration depth of RF and microwaves in tissue appear to be inverse functions of frequency.

Table 1: Depth of penetration in human tissue

Frequency (MHz)	Wavelength in air (cm)	Muscle, skin, tissues with high water content (cm)	Fat, bone, tissue with low water content (cm)
1	30,000	91.3	—
10	3,000	21.6	—
27.12	1,106	14.3	159
40.68	738	11.2	118
100	300	6.66	60.4
200	150	4.79	39.2
300	100	3.89	32.1
433	69.3	3.57	26.2
750	40	3.18	23
915	32.8	3.04	17.7
1,500	20	2.42	13.9
2,450	12.2	1.70	11.2
3,000	10	1.61	9.74
5,000	6	0.788	6.67
5,800	5.17	0.720	5.24
8,000	3.75	0.413	4.61
10,000	3	0.343	3.39

Heat absorption will be greatest in tissues that have high water content, such as muscle, with less heat absorption taking place in bone and fat.

In the past most biological effects have been related to the incident power density (mW/cm^2). However, the absorption of electromagnetic energy is strongly dependant on its frequency, the geometry of the exposure situation and the dielectric properties of the tissue. Because of these factors, biological effects are more properly related to the absorbed energy defined as the specific absorption rate or SAR.

After reviewing a large body of biological data, several standards setting organizations (e.g. ACGIH, IEEE/ANSI, ICNIRP, FCC, etc.) found that hazardous bio effects in humans occurs at a whole body SAR exceeding 4 W/kg; *to be conservative, standards setting organizations use 1/10 of this value*. For comparison purposes, the resting metabolic rate in humans is on the order of 1 W/kg and 5 W/kg when engaging in strenuous activity such as running. The heart's metabolic rate is 33 W/kg. The effectiveness of the circulatory system in redistributing thermal energy is dependent upon the degree of vascularization in any tissue, but is generally adequate to cope with varying metabolic rates in the human body.

Blood flow eventually distributes excess heat throughout the body. Sweating starts when the body becomes overheated and cools the body by evaporation. The additional heat load that is imposed on the body due to RF absorption must be dissipated like any other heat load, and can be a significant health concern. Body functions can be impaired when its temperature reaches 102°F and fatal near 107 to 108 °F.

Temperature rise will be greatest in tissues that lack or have poor thermoregulatory mechanisms such as high blood flow. Examples are the eyes and testes. "Hot spots" between tissue interfaces due to non-uniform heating can also develop caused by reflective wave reinforcement.

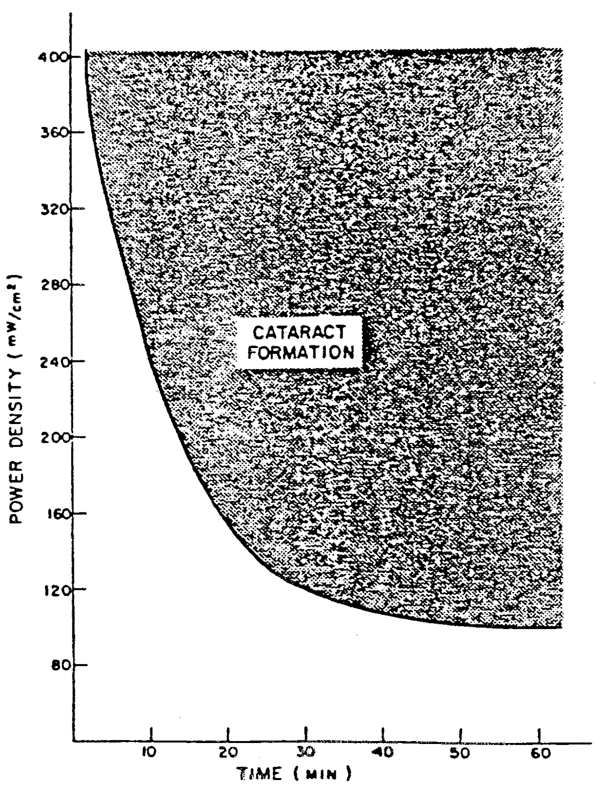
3.2 Specific Thermal Effects

3.2.1 Ocular Effects

Lens opacification sufficient to cause reduced or loss of vision is termed a cataract. Animal studies have shown that the critical range of frequencies is from 800 to 10,000 MHz.

Damage to the inside layer of the cornea may also occur resulting in corneal damage and loss of sight. This may occur from continuous wave exposure or pulsed exposure, and varying with time in animal studies.

Figure 3: Cataract threshold power density



Power density versus time threshold for cataract formation in the rabbit following free-field exposure at 2450 MHz. Calculated from the data of Carpenter and Van Ummersen (1968).

3.2.2 Auditory Effects

Exposure to pulsed RF or microwave energy may result in hearing a click or buzzing sound originating inside or behind the head. The cause is thought to be a microthermal mechanism, with pressure waves being formed in the middle ear. This effect is thought to be harmless, but reports should be treated as possible overexposure.

3.3 Nonthermal Effects

Some animal studies have shown central nervous system effects, altered cell membrane permeability, behavioral effects, and others. These biological effects are attributed to mechanisms other than thermal and are generally thought to be caused by exposures less than 10 mW/cm^2. However, they are not well understood or documented.

3.4 Other Effects

3.4.1 Behavioral

RF/microwave workers complaints have been noted to include nervousness, irritability, headache, depression, sleeplessness, and others.

3.4.2 Immunological

Studies have shown positive immune system effects while other studies have shown suppressed effect. The mechanisms are not well understood or documented.

3.4.3 Depressed Spermatogenesis

Sperm production may be impaired with extended exposures over 10 mW/cm^2. This is thought to be reversible after exposure ceases. As sperm production is very sensitive to heat, exposure to RF may understandable produce this effect. In animal studies prolonged exposure or exposure to high RF levels may cause testicular damage and debilitated or stillborn offspring.

3.4.4 Heat Sensation

Heat sensation may also be the result of over exposure to RF radiation. A documented incident where an RF worker “felt” heat involved an a exposure of 380 mW/cm^2.

4 RF and Microwave Exposure Limits

For occupational and public exposure limits, Cornell will follow the FCC limits shown in Figure 1 since the FCC limits tend to be conservative. For occupational exposures, the field strength is averaged over 6 minutes. For public exposures the field strength is averaged over 30 minutes.

For frequencies over 100,000 MHz, the 100,000 MHz FCC limits will be extended to 300,000 MHz.

5 Electric Shock Hazards

From kHz to 100 MHz, electric shock from induced currents in the free-standing body, or in contact with conductive materials, may be experienced.

6 Conversions

- $1\ W/m^2 = 0.1\ mW/cm^2$
- E = electric field strength in V/m
- H = magnetic field strength in A/m
- Power density (PD) = E x H $V\text{-}A/m^2$ = $watt/m^2$
- Approximate PD can be found from:
    - $PD = E^2 / 3770\ mW/cm^2$
    - $PD = 37.7H^2$

  Note: Direct measurement of PD in the near field is difficult and E and H values will change with position, use the maximum E or H values or move further away into the far field region.
- Impedance of free space = 377 ohms

7 RF & Microwave Equipment Safety Guidelines

1. RF and microwave equipment should be inspected regularly both visually and operationally.
2. Visual inspection should include:
    a. General safety / housekeeping conditions in the surrounding area
    b. Presence and functionality of safety interlocks
    c. High voltage safety features (e.g. grounding rods, etc.)
    d. Condition of cables and coax lines that transmit RF
    e. Presence and condition of RF shielding.
3. Operational inspection should include:
    a. Monitoring or survey of RF levels, especially in occupied spaces
    b. Test of interlocks to inhibit RF generation when tripped
    c. Use of "lock/tag/verify" for RF and/or high voltage equipment.
4. Engineering controls represent the best approach to RF / microwave safety and the use of shielding can greatly reduce or eliminate exposure.
    a. Shields can be solid panels or metallic mesh screening. Materials for shielding E fields include tin, copper, aluminum, silver, and gold. These have high reflective

losses for E fields. H field shielding materials include ferrous materials like iron, steel and special alloys (Hypernom and Permalloy for example).

5. Mesh screening can provide shielding and visibility and works well for shielding windows and view ports. The size of the mesh is determined by the power, frequency, and wire diameter.

Figure 4: Determination of shielding mesh size

PL = Power transmitted
PO = Incident power
r = Radius of wire
a = Space between wires
λ = wavelength of electro-magnetic radiation
a, r, and λ must have same units

Example - How to calculate reduction in transmitted power using wire mesh screens.

PO = 1000 watts
Freq. = 26 GHz (λ = 11.6 mm)
a = 2.5 mm
r = .25 mm

$\frac{a}{r} = 10$

$\frac{a}{\lambda} = .21$

Draw a straight line from .21 on left side of graph (a/λ) to 10 on right side of graph (a/r). -12 is found.

Using the equation:

$10 \log \frac{PL}{PO}$

substitute -12, getting

$10 \log \frac{PL}{PO} = -12 \therefore$

$\log \frac{PL}{PO} = \frac{-12}{10} = -1.2$

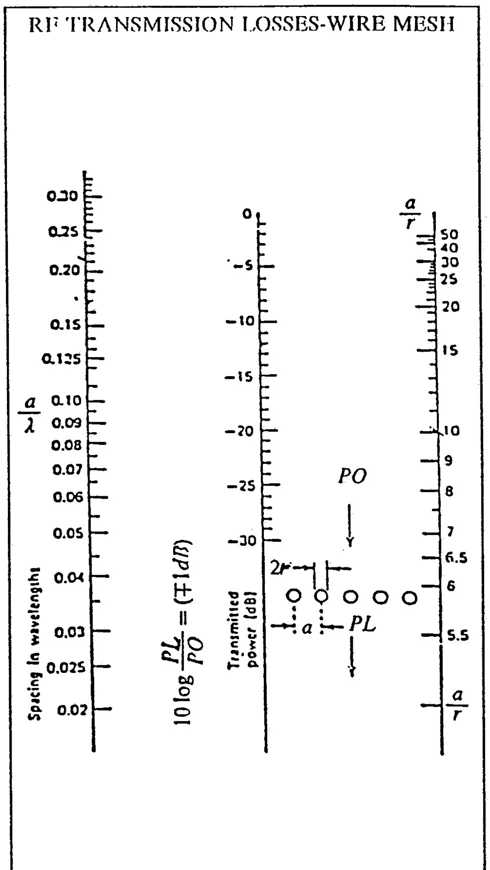
and

$10^{\log \frac{PL}{PO}} = 10^{-1.2}$

$\frac{PL}{PO} = .063 \therefore$

$\frac{PL}{1000W} = .063$

PL = 63 W



Transmission through a grid of wires of radius r and spacing a

6. Equipment enclosures, access panels, doors, etc. should be sealed with metal braid or other conductive gaskets.

7. Grounding straps and wires should not be bent at sharp angles - sharp angles act as antenna to radiate RF. Conductors and straps carrying RF should bend gently and blend smoothly at connection points. Screws used to connect conductors should have smooth, rounded heads, not sharp edged angular heads. Solder connections should be as large in area as possible.

8 References

- IRPA Guidelines, Health Physcis, Vol 54 No 1, pp.115-123, 1988.
- IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields 3 kHz to 300 GHz, IEEE/ANSI, C95.1-2005.
- Heat Stress Due to RF Radiation, Proc of IEEE, Vol 57 No 2, February 1969.
- Biomedical Aspects of Microwave Exposure, AIHA Jour, May, pp. 338-345, 1971.