EFFECTS OF ELECTROMAGNETIC RADIATION

We are, from the moment of conception, bathed in a sea of electromagnetic waves. Some of these waves are benign or even beneficial, while others are definitely harmful. Part of this radiation is natural and part is man-made. Natural radiation includes the light, radio-waves and cosmic rays from the Sun, Moon and stars; background radiation from the rocks, soil, water and atmosphere of our planets; and the internal radioactivity of our own bodies. Man-made radiation, which forms an increasingly large proportion of the whole, includes radio and radar waves.

It is obvious that we must be more or less immune to any kind of radiation which normally reaches us from outer space, yet earthworms are killed by sunlight even when kept damp and cool, and occasionally human children are born who are abnormally photosensitive and eventually die from the effects of sunlight. Moreover, sunlight can induce skin cancer as well as an attractive tan, and certain drugs have a strongly photosensitizing effect, which makes it necessary for patients who are taking them to use a barrier cream against the enhanced action of ultraviolet rays.

Magnetic Fields:

It would seem logical that the highest field strengths would be associated with the greatest detectable biological effects; however, the present literature does not support this thesis. While a host of relatively minor effects upon lower animals are reported, the most significant effect of high strength field exposure in mammals appears to be alterations in the electrical activity of the central nervous system, with possible associated pathological lesions in the brain. It would at this time, therefore, appear desirable to avoid exposure of humans (either total body or head alone) to field strengths in excess of 1,000 gauss, which might be found in the near vicinity of magnetohydrodynamic (MHD) equipment, in attempts to control atomic fusion reactions by intense magnetic fields, very large D.C. electrical transmissions, such as in the aluminum smelting industries, and in magmetic separation procedures, for anything other than short time periods. In particular, the suggestion to utilize magnetic shielding against radiation for space capsules, should also be most carefully evaluated before being put to use. Another caution would be in the application of high strength fields modulated at certain frequencies. Since certain definite effects seem to be associated with low strength, low frequency (0.1 - 0.2 Hz) fields, human exposure to high strength similarly modulated fields should definitely be avoided except under controlled experimental conditions.

Safe RF Fields:

The "magic" number for determining a radiation hazard condition is the field strength 10 milliwats per square meter. An explanation of how this value was derived can be found in the Handbook on *Radio Frequency Radiation Hazards* (T.O. 31-1-80) dated 15 April, 1958, published under authority of the Secretary of the Air Force. Two pertinent paragraphs are excerpted as follows:

"Based on evidence given in paragraph 1-7, that injury had been caused to experimental animals and could possibly be caused to personnel, all available information was researched in an effort to establish a safe exposure level to this form of possible injury. Many variables were considered, such as the frequency of the energy to which an individual may be exposed, the nature of the exposure, including time of exposure, field strength, and other aspects.

Sufficient factual data is not available to determine the safe exposure level for each frequency; therefore, it was decided to select one level satisfactory for all frequencies. Past research indicated that a power density of 0.2 watts/cm^2 was required to produce damage. The accuracy of the methods and instrumentation used was somewhat questionable, and possibly some cases of reported damage might have been caused by power densities of approximately 0.1 watts/cm^2. The expanded use of electronics has also resulted in adding minute amounts of microwave energy from incidental sources at many frequencies. Since it is impractical to measure the power density at each of these frequencies separately, and since the sum of all these assorted r-f sources would be extremely small, a safety factor of 10 was selected and the present USAF level of 0.01 watts/-cm^2 was established.

This level of 0.01 watts/cm^2 is an *average* power level and not peak power, since available data indicates the only detrimental effects are thermal in nature, and these effects depend upon average and not peak power levels. Sufficient data is not available to furnish complete correlation between length of exposure and power density. The present level of 0.01 watts/cm^2 is the maximum for either continuous or intermittent exposure, and precautions should be taken to avoid exposure of personnel to ambient power levels in excess of 0.01 watts/cm^2 for any period of time."

In October of 1961, T.O. 31-1-80 was superceded by T.O. 31Z-10-4. The revised handbook went deeper into the problem, but maintained the 10ms/sq. meter magic value. One of the new aspects introduced was the relationship of man's physical size to wavelength. It states that when considering the biological effects produced by r-f radiation, the wavelength (frequency) of the energy and its relationship to the physical dimensions of objects exposed to radiation become important factors. It has been determined that for any significant effect to occur, the physical size of the object must be the equivalent of at least a tenth of wavelength at the frequency of radiation.

Practically speaking, the human body is a three-dimensional mass having width and depth, as well as height. Therefore, when a man stands erect in an r-f field, he represents an object which not only has a height dimension, but also has width and depth dimensions that can be expressed in terms of wavelength. Again comparing the physical characteristics of the human body to those of a broadband receiving antenna, when the body is oriented so that any of these major body dimensions is parallel to the plane of polarization of the r-f energy, the effects produced are likely to be more pronounced than when the body is oriented to other positions.

The penetration of energy into the body and its absorption (loss of energy), and reflection will depend not only upon the physical dimensions and dielectric constant of the tissues, but also upon the frequency (wavelength) of the r-f radiation.

The handbook also discusses the frequency-dependent characteristics of whole body exposure. It states that the percentage of absorbed biologically effective energy approaches 40 percent of the incident energy for frequencies below 1000 mc (30 cm) and for frequencies above 3000 mc (10 cm).

The percentage of absorbed biologically effective energy is between 20 and 100 percent of the incident energy for frequencies between approximately 1000 and 3000 mc (30 to 10 cm wavelength).

The sensory elements of the body are located primarily in the skin tissues; for this reason radiation frequencies below 1000 mc are considered extremely hazardous because the presence of r-f radiation will not be detected by the human sensory system. Radiation at frequencies below 1000 mc causes heat to be developed primarily in the deep tissues as a result of the penetration of the energy. The energy absorbed in body tissues may be as high as 40 percent of the incident energy arriving at the body surface.

Frequencies greater than approximately 3000 mc cause heating of tissues in much the same manner as does infrared radiation or direct sunlight; therefore, the sensory reaction of the skin should normally provide adequate warning of the presence of r-f radiation. In general, the depth of energy penetration decreases rapidly with an increase in radiation frequency, and absorption occurs almost completely in the surface of the body where skin tissues and the sensory elements are located. Also, reflection of energy at the surface of the skin occurs at the higher frequencies. Thus, the percentage of energy absorbed may approach 40 percent of the energy incident on the body surface, with a greater portion of energy being reflected.

Radiation at frequencies between 1000 and 3000 mc is subject to varying degrees of penetration and is absorbed in both surface tissues and deeper tissues, depending upon the characteristics of the tissues themselves (thickness, dielectric constant, and conductivity) and the frequency of radiation. The percentage of incident energy absorbed varies from approximately 20 to 100 percent because of tissue factors governing impedance values, which range from complete mismatch, to a near perfect match, to the incident energy.

When electromagnetic energy is absorbed in tissues of the body, heat is produced in the tissues. If the organism cannot dissipate this heat energy as fast as it is produced, the internal temperature of the body will rise. This may result in damage to the tissue and if the rise is sufficiently high, in the death of the organism. The body's ability to dissipate heat successfully depends upon many related factors, such as environmental air circulation rate, humidity, air temperature, body metabolic rate, clothing, power density of the radiation field, amount of energy absorbed, and duration of exposure (time).

The limited ability of the body to dissipate heat when its temperature is elevated above normal is complicated by the fact that the basal metabolic rate increases as much as 14 percent for every degree of temperature rise above normal. The increase in temperature also causes abnormally rapid breathing, or fever hyperpnea. The lack of oxygen available in the blood for release to cells or tissues results in hemorrhages and damage to the brain cells, the central nervous system, and certain internal organs, and may also result in muscular irritability and sometimes convulsions. If these conditions persist, the results are usually coma and eventual death.

Certain organs of the body are considered to be more susceptible than others to the effects of r-f radiation. Organs such as the lungs, the eyes, the testicles, the gall bladder, the urinary bladder, and portions of the gastrointestinal tract are not cooled by an abundant flow of blood through the vascular system. Therefore, these organs are more likely to be damaged by heat resulting from excessive exposure to radiation. Of the organs just mentioned, presently available information and experience indicate that the eyes and testicles are the most vulnerable to microwave radiation.

Russian Regulation:

Report number AD 278 172 is based on a translation of a book by Professor A.A. Letavet and Decent Z.V. Gordon of the Institute of Labor Hygiene and Occupational Diseases of the Academy of Medical Sciences, U.S.S.R. The book is dated, Moscow, 1960 and bears the title, "The Biological Action of Ultrahigh Frequencies."

The following general effects of chronic exposure of humans to microwave energy were reported:

a. Bradycardia, or an inhibiting effect on the rhythm of heart contractions.
b. A disruption of the endocrine-humeral processes.
c. Hypotension, or low blood pressure.
d. Intensification of activity of the thyroid gland.
e. An exhausting influence on the central nervous system.
f. A decrease in sensitivity of the sense of smell.
g. An increase in the histamine content of the blood.

The report goes on to state that U.S. Army Regulation AR 40-583, dated 12 July 1961 specifies 10 milliwatts per square centimeter as a permissible limit for exposure of humans to microwave energy. The Russian safety regulations for exposure of humans to microwave energy are so much more stringent than those specified in AR 40-583 that the permissible limits are here reproduced for emphasis:

"The microwave radiation intensity in areas where personnel are required to be present should not exceed the following maximum permissible values:

a. In the case of irradiation during the entire working day - no more than 0.01 milliwatts/cm2.
b. In the case of irradiation for no more than two hours per working day - no more than 0.1 milliwatts/cm2.
c. In the case of irradiation for no more than 15 to 20 minutes per working day - no more than 1.0 milliwatt/cm2. (In this case the use of protective goggles is mandatory.)"

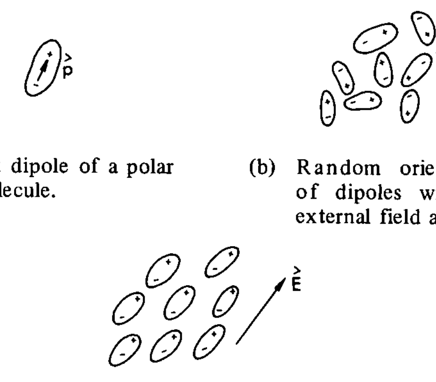
The problem with the reports emanating from the USSR is that the results, as reported, can not generally be repeated by tests performed in the U.S.A. A noted authority on the subject suggests that this is due to many factors. The main one is the style in which the Russians write their reports. There often seems to be a lack of complete detail of how the tests were performed and the test equipment that was used.

Although there is a lack of competition from private industry in Russia, the competition between their government agencies is prevelant. They must compete for funds, test equipment, etc., within themselves, even more so than the US Government agencies. In fact, some think that the lack of complete documentation is purposely designed to keep information from their own competing agencies. Another reason for incomplete information is that they often use military transmitters and must be vague on power levels and frequencies in order to preserve their military security.

Whatever the reason, the reports continue to flow out from behind the Iron Curtain warning of the many adverse effects of microwave radiation. If what they say is true, it would be most enlightening to learn how they implement and enforce their regulations for such low level, maximum values of field intensities. Maybe the FCC or HEW in the U.S. could pick-up some valuable pointers.

PHYSICS OF MICROWAVE HEATING

Because the interaction of radiation with matter often results in heating of the matter, the most widespread applications of microwaves to industry involve rapid heating and drying. The ability of a material to absorb radiation and convert it to heat is determined by its dielectric properties. Some substances, such as water, are able to absorb a great deal of energy, while others, such as metals, reflect rather than absorb the incident energy. Water is an example of a polar molecule—one which, although electrically neutral, has a dipole moment caused by the net displacement of the positive and negative charge centers. With no external fields applied to a substance made up of these polar molecules, the individual dipoles are randomly oriented and have no net field strength. Yet when an external electric field is applied, as shown in figure 1, the dipoles absorb energy from the field and align themselves with it.



(a) Net dipole of a polar molecule.

(b) Random orientation of dipoles with no external field applied.

(c) Dipoles lined up with external field.

Figure 1. Orientation of polar molecules in an electric field.

Table 1. Ranges and specific values of K for several common substances

Material	Range/value of dielectric constant, K
H_2O (3 GHz, 25°C)	77.5
H_2O (10 GHz, 25°C)	55.0
Douglas fir	1.8-1.86
Paper, royal gray	2.62-2.75
Steak, bottom round	30-50
Suet	2.5
Soap, Ivory	2.96

Table 2. Ranges and specific values of tan δ for several common substances

Material	Range/value of loss tangent, tan δ
H_2O (3 GHz)	0.157
H_2O (10 GHz)	0.54
Douglas fir	0.027–0.032
Paper, royal gray	0.040–0.066
Steak, bottom round	0.37–0.78
Suet	0.05–0.12
Soap, Ivory	0.1765

This energy is stored as potential energy within the system until the external field is removed, at which time the dipoles reorient themselves in a random fashion, transferring their potential energy to heat energy. At microwave frequencies, this process occurs about 10^9 times per second and results in rapid heating.

The above is the basic phenomenon that takes place during microwave heating. Not all substances, however, have the same ability to be polarized. Those molecules, for instance, which have large dipole moments, absorb more energy from an external field during alignment than those with smaller dipole moments. This greater energy storage results in greater energy dissipation when the field is removed and faster heating.

The dielectric constant, K, is a relative measure of the ability of a substance to be polarized (K = 1 for free space). It is tabulated for several common substances in table 1 below; the larger the value of K, the more energy a substance will absorb from an external field.

The table points our the wide range in values of K from 1.8 for Douglas fir to 77.5 for water at 3 GHz, factors which greatly affect the duration of exposure required to achieve a desired amount of drying. The variation of dielectric constant with frequency for such molecules as water will be discussed shortly.

In addition to the dipolar heating, many substances display significant heating due to conduction current in the material. The power dissipated per unit volume in such cases is

$$\frac{P}{V} = \underline{E} \bullet \underline{J}$$

where $\underline{E}$ is the applied electric field strength and $\underline{J}$ is the current density. This heating is identical to the I^2R heating of resistors and is most significant for metals and other conductors. For most of the materials presently under consideration for industrial processing (with the notable exception of electrolytic solutions) dipolar heating dominates at microwave frequencies, and the heating associated with conduction currents can often be ignored.

Two other factors associated with the dielectric properties of a material, which help to describe its behavior at microwave frequencies, are the skin depth and loss tangent. The skin depth is the distance the electric field penetrates into a conductor before it has attenuated to 1/e (3.68 percent) its value at the surface and is given by δ, where

$$\delta = 1/\sqrt{\pi f \mu \sigma}$$

and μ is the permeability of the conductor and σ is its conductivity. The most important feature in this expression is that the skin depth is inversely proportional to both the frequency and the conductivity. In other words, the higher the frequency of incident radiation and/or greater the conductivity of the conductor, the shallower will be the penetration of the wave into the material before the field strength has attenuated to (1/e) its initial value.

In substances with significant polarization, the loss tangent becomes the dominant measure of penetration depth because of the poor conductivity of the material. Table 1 shows that the dielectric constant, K, of many materials varies with frequency. This arises because the individual dipoles, after absorbing energy from the incident radiation, become oscillators themselves because of the coulomb attractive forces between the separated positive and negative charge centers. These dipole oscillators will absorb the greatest amount of energy when the frequency of the external field is a harmonic of the natural frequency of the molecules.

The above phenomenon can be described mathematically by assigning an imaginary term to the permitivity, ϵ, of the medium; that is, $\epsilon = \epsilon' - j\epsilon''$. The effect of the real and imaginary parts is to account for possible phase differences in the interaction between the incident radiation and the dipole oscillators, allowing stronger coupling when the two frequencies of oscillation are harmonics of each other. The loss tangent is then defined as $\tan \delta = \epsilon''/\epsilon'$. Like the skin depth for conductors, it is an indicator of the penetration depth to be expected in a dielectric medium at a given frequency. Table 2 shows the loss tangent for several materials currently being processed or considered for processing by industrial microwave equipment. The larger the value for tan δ, the shallower the penetration into the medium. The skin depth and loss tangent point out that as the frequency of radiation increases, more and more of the energy is dissipated near the surface of the material being processed. Materials with low loss tangents and/or large skin depths would most likely require the greater penetration depth of 915 MHz rather than 2450 MHz in order to achieve heating throughout the thickness of the material.

The rate at which microwave energy of frequency f and electric field amplitude E is absorbed by a material of dielectric constant K and loss tangent δ is given by the expression.

$$\frac{P}{V} = 2\pi f K \epsilon_o \tan\delta E^2$$

where ϵ_o is the permitivity of free space. The important feature in the above equation is that the power dissipated per unit volume is directly proportional to the frequency, dielectric constant, loss tangent, and square of the electric field strength. Since the dielectric constant and loss tangent of a material depend on the material and frequency, the designer of industrial microwave equipment must select the frequency of operation and field strength (power level) so that the power dissipated per unit volume is everywhere small enough to keep the material being processed from becoming singed and ruined by an overly high power density.

In summary, knowledge of a material's dielectric properties is essential in the design of industrial microwave equipment, both for determination of the proper frequency of operation to ensure adequate heating throughout the substance and for the proper selection of power levels and applicator design so that destructively rapid heating is avoided.

The Physics of Microwave Heating was extracted from Appendix A of BRH/DEP 70-10 "Survey of Selected Industrial Applications of Microwave Energy", published by the U.S. HEW, Division of Electronic Products, May 1970.