BIOLOGICAL EFFECTS AND HAZARDS OF MICROWAVE RADIATION

by

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ABSTRACT

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The purpose of this thesis is to make known the dangers associated with microwave radiation. Since most people are unaware of these dangers, this thesis attempts to uncover some of the fallicies attributed to the safety of microwaves and to convey the realistic hazards of microwaves to the reader.

The society is constantly being exposed to microwaves. For example, from driving down the road in an automobile being bombarded with radar from the highway patrol's speed-trap system to cooking a roast in a leaking microwave oven gives evidence that our environment is being polluted with microwaves. Since little is known about the long-term and the non-thermal effects, as well as the low-power exposures to microwaves, a comprehensive analysis should be undertaken to determine them and the results made known to the public. This thesis gives documented evidence that microwaves are injurious to man and the effects are discussed. A laboratory experiment was performed to determine how safe microwaves are when they passed through several common materials.

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LIST OF SYMBOLS

SYMBOL	DEFINITION	UNITS OR REFERENCE
a	Radius of skull models	cm
A	Constant in the complex transcendental function	none
C	Concentration of radiation field	W/cm^2
^oC	Temperature	degrees Centigrade
cc	Volume	cubic centimeter
d	Radial distance of parabolic antennae	meters
dc	Duty cycle	none
dB	10 log(P_2/P_1)	decibels
D	New voltage minimum	volts
DC	Direct current	volts, amperes
D_R	Rayleigh distance of antennae	meters
D_R	Voltage minimum	volts
e	Base of natural logarithms	2.71828...
eV	Electron volt, energy acquired by an electron (e = 1.6 x 10^{-19} coulomb) in falling through a potential difference of 1.0 volt	1.6 x 10^{-19} Joules
E	Electric field intensity	volts/meter
E_o	Electric field intensity of the plane wave incident upon a sphere	volts/meter
f	Frequency	Hertz
f_o	Frequency of rotational resonance of the water molecules	Hertz
^oF	Temperature	degrees Fahrenheit
G	Antenna gain	none
G	Giga	10^9

LIST OF SYMBOLS (CONT.)

SYMBOL	DEFINITION	UNITS OR REFERENCE
H	Magnetic field	Amperes/meter
Hz	Hertz	cycles/second
k	Wavenumbers for dielectric	none
k_o	Wavenumbers for air	none
K	Characteristic value	none
K	Constant in the complex transcendental function	none
K	Kilo	10^3
l	Length of waveguide	meters
l_ε	Length of waveguide sample	meters
l_R	Length of waveguide	meters
m	Length	meter
m	Milli	10^{-3}
M	Mega	10^6
n	Integer	0,1,2,3,...
P	Input power to antennae	watts
p_a	Mean power dissipated	watts/unit volume
P_a	Power absorbed by the sphere	watts
P_i	Power incident upon the geometrical cross section of the sphere	watts
P_D	Power density	mW/cm^2
P_R	Power incident upon receiving antenna	watts
P_T	Power radiated (total)	watts
t	Time	seconds
T	Relaxation time for biological tissues with a high H_2O content	seconds

LIST OF SYMBOLS (CONT.)

SYMBOL	DEFINITION	UNITS OR REFERENCE
T	Constant in the complex transcendental function	none
$T_{\varepsilon 1}$	Beginning of the sample in the waveguide	none
V	Voltage	volts
W	Power	watts
Y_{ε}	Admittance determinant	mhos
Z	Impedance of free space	377 ohms
Z_o	Characteristic impedance of transmission line	ohms/square
Z_{ε}	Intrinsic impedance of dielectrics	ohms/square
ε	Permittivity	Farads/meter
ε_r	Relative permittivity (dielectric constant)	none
η	Intrinsic impedance of free space	377 ohms
θ	Angle	radians
κ	Propagation constant	meter^{-1}
λ	Wavelength	meters
λ_g	Guide wavelength	meters
μ	Micro	10^{-6}
ν	Velocity of a wave	meters/sec
π	Constant	3.14159...
$\sum$	Summation of the mathematical terms that follow	
τ	Constant in the transcendental function	none
Ω	Ohm	ohms
ω	Angular frequency	radians/sec

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CHAPTER I

INTRODUCTION

The purpose of this work is to attribute health hazards and detrimental biological effects with microwaves. A literature research is presented discussing microwave hazards. Laboratory measurements at 9.5 GHz. were performed to approximate the transmissivity of microwaves through several common materials.

Since microwaves are part of the electromagnetic spectrum, a brief survey of electromagnetic waves is discussed in Chapter II. Parameters including wavelength, frequency, velocity and the relationship amongst them are explained.

Actual microwave absorption in biological tissue is considered in Chapter III. Variables determining the magnitude and the depth of penetration of absorbed energy are discussed. Animals were tested under the influence of microwave radiation ranging over a large portion of the microwave spectrum. This information enables one to design microwave equipment using a frequency that will not only be functional, but relatively safe. [1] (Note that brackets "[ ]" designate references).

The relative permittivity, ε_r, and conductivity, σ, of biological tissue also determine how much microwave energy is absorbed. Tables (1) and (2) list different tissues and their corresponding permittivity and [3] conductivity values. From these tables it then possible to calculate the magnitude of absorbed microwave energy.

Biological tissue, under the influence of microwave radiation, [4] will dissipate the heat generated by the blood vessels. Blood, analogous to water in an automobile engine's cooling system, acts as a coolant by rushing to the irradiated tissue and this increased flow removes the heat.

An experiment by William T. Joines and Ronald J. Spiegel [5] is included to demonstrate that standing waves in a model of a human skull are present when in a field of microwaves. Skull models with radii of 7 and 10 cms. were analyzed.

Pacemaker patients were at one time prohibited from being near operating microwave equipment. Today, better design and shielding of pacemakers permit patients to be relatively safe in a microwave field. Frequency is a factor in determining the safe field for a pacemaker patient. As the frequency of microwaves increases, the patient must be physically further from operating microwave equipment. For example, a patient is safe in a 380 Volt/meter microwave field of 2450 MHz.; while the same patient is safe in a microwave field of 2810 MHz with a maximum field strength of 250 V/m. Details are included for determining the gain and the far-field pattern of an antenna. From this information the field strength can be calculated. [6]

The controversial microwave oven is discussed to find whether or not it is safe to operate. Since very little is known about the nonthermal effects, long-term effects and the hazards associated with very low power microwave exposures, it is difficult to set a maximum power leakage level that will be completely safe. Proposals for operating a microwave oven safely are included. [7]

Microwave radiation has been found to alter blood composition. [9] Neural disorders are also found in individuals exposed to microwaves.[10] A safe value, dependent upon the concentration and exposure time of microwave energy, is provisionally set. See Chapter IV. [11]

Microwaves are also attributed to eye damage as explained in

Chapter V. The eyes and other biological tissue, containing little or no blood vessels, when irradiated with microwaves which in turn create heat, can cool themselves only by conduction. The most susceptible part of the eye is the lens because the depth of microwave penetration in the eyeball is around 1.0 cm; which is the exact distance the lens is from the surface of the eyeball. Documented evidence is given [14] supporting the fact that microwaves can cause cataracts and retinal damage.

Chapter VI describes how microwaves are electronically genererated. Klystrons and magnetrons are the most common methods of generating microwaves. It is pointed out that these generators are very inefficient and that transmission lines and antennae should thus be optimized. [16]

Several methods of measuring the dielectric constant of materials are discussed in Chapter VII. The two point method [17], one of the more practical methods, is discussed here. Since the lack of equipment prevented actual measurements involving one of these methods of determining the dielectric constant, a simplified method was employed to give approximate results. See Chapter VIII.

Boundary conditions are given for microwaves propagating through two parallel sheets and these can be found in Chapter VIII. These conditions are required when supporting an animal on dielectric materials in a field of microwaves for test purposes. The dielectric materials inherently cause reflections; through the procedure given, these reflections can be reduced and determined.

Finally, in Chapter VIII, methods of protection are included for individuals that must work in or near microwave fields. Table (5) lists shielding properties of several materials. [19]

CHAPTER II

ELECTROMAGNETIC WAVES

Electromagnetic waves contain both varying magnetic fields and varying electric fields. The energy is divided equally between the two fields. The nature of electromagnetic wave propagation is that the magnetic and electric fields are always perpendicular to each other as shown in Figure 1. (Note that this is a plane wave).

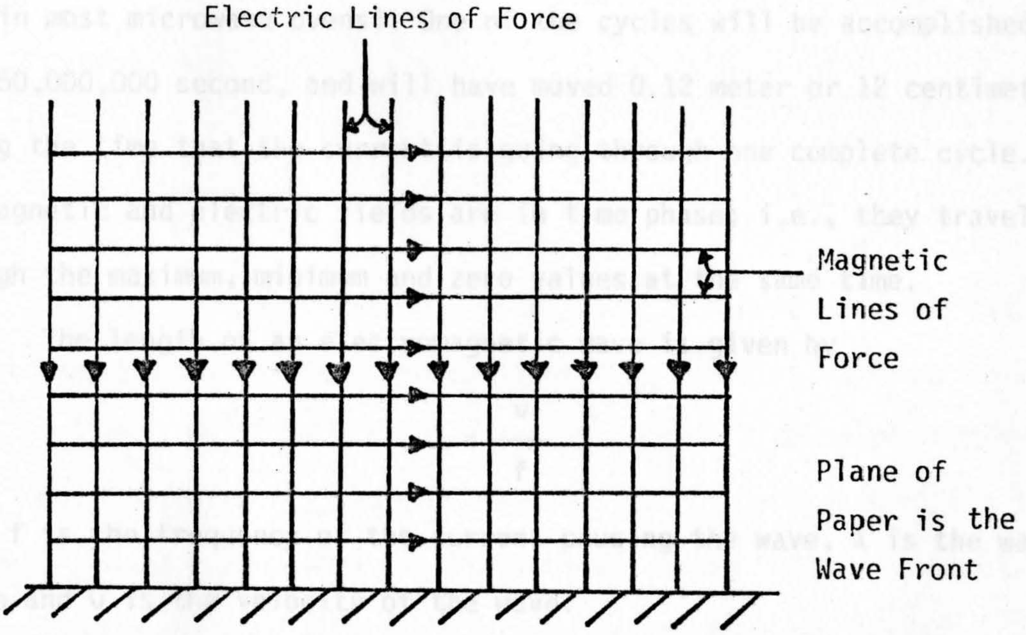

Figure 1. An electromagnetic wave traveling perpendicularly out of the page towards the reader. If one set of lines of force is reversed the direction of the wave goes perpendicularly into the paper (away from the reader). Changing both sets of line directions has no effect on the direction of the wave. (Note that this is a plane wave).

In free space electromagnetic waves travel at a speed of 299,793,077 meters per second or 186,282.386 miles per second. If the wave travels through another medium, the speed is less than 299,793,077 meters per second. If air is the medium, the reduction of speed is negligible. In distilled water the speed of a wave travels about 1/9 of that in free space. In metals the speed of a wave is so slow that it is practically nullified.

An electromagnetic wave commences from an alternating current flowing in a conductor which produces the necessary magnetic and electric fields. Consider a wave of 2,450,000,000 cycles per second (the frequency used in most microwave ovens). One of the cycles will be accomplished in 1/2,450,000,000 second, and will have moved 0.12 meter or 12 centimeters during the time that the current is going through one complete cycle. Both the magnetic and electric fields are in time phase; i.e., they travel through the maximum, minimum and zero values at the same time.

The length of an electromagnetic wave is given by

$$\lambda = \frac{\nu}{f} \qquad (1)$$

where f is the frequency of the current causing the wave, λ is the wavelength and ν is the velocity of the wave.

Microwaves are electromagnetic waves in the region of frequency between 300 Mhz. and 300 Ghz. (1 Mhz.= 10^6 Hz., 1 Ghz.= 10^9 Hz.), which corresponds to a wavelength of one meter and one millimeter, respectively. Since microwaves are short in wavelength, they can be transmitted through the interior of a single hollow conductor or waveguide. Coaxial lines can also be used in the transmission of microwaves but the losses are much higher and therefore can be used for only short distances. On the other hand, coaxial lines are easier to handle and have a broader bandwidth.

CHAPTER III

MICROWAVE ABSORPTION

Animals cool themselves by heat conduction, convection, radiation, and evaporation. The amount of cooling depends upon the surface area of the body, the insulating regions of the body and the ambient temperature. Microwaves absorbed in the body produce heat and in turn raise the body temperature. Temperature increases in the body are dependent upon the following variables:

A. The thickness of the skin
B. The position of the body in the electromagnetic field
C. The intensity of the field strength
D. The duration of exposure
E. The wavelength of the energy
F. The environmental conditions

If one portion of the body is exposed to microwaves, the unexposed portion compensates for the removal of heat by circulating blood to the exposed region. The blood acts as a coolant and will dissipate the heat. If the entire body is exposed to microwaves, it is evident that the body will have a hard time trying to dissipate the heat. If this is the case, the body temperature will rise and tissue destruction can result.

Figure 2 shows the depth of penetration of microwave power into a human eye lens and the vitreous humor (the clear, colorless, transparent jelly that fills the posterior chamber of the eyeball). These biological tissues are shown because they represent most of the tissue in the body with a high water content. The lens has a high protein content while the vitreous humor a low one. From Figure 2 it is evident that penetration is deep for frequencies below 1.0 Ghz. and superficial for frequencies above 1.0 Ghz. Thus the depth of penetration is inversely related to the frequency, or the depth of penetration is related to the wavelength. Above 10 Ghz., the depth of penetration is similar to infrared effects, with all the microwaves being absorbed in the skin. On a bright sunny day, 100 mW/cm^2 of infrared radiation is produced by the sun. This amount of radiation becomes quite annoying if continued exposures are permitted. It should be noted that the safe limit for microwave radiation has been set at a power density of 10 mW/cm^2, which is 1/10 the power from the sun.[1]

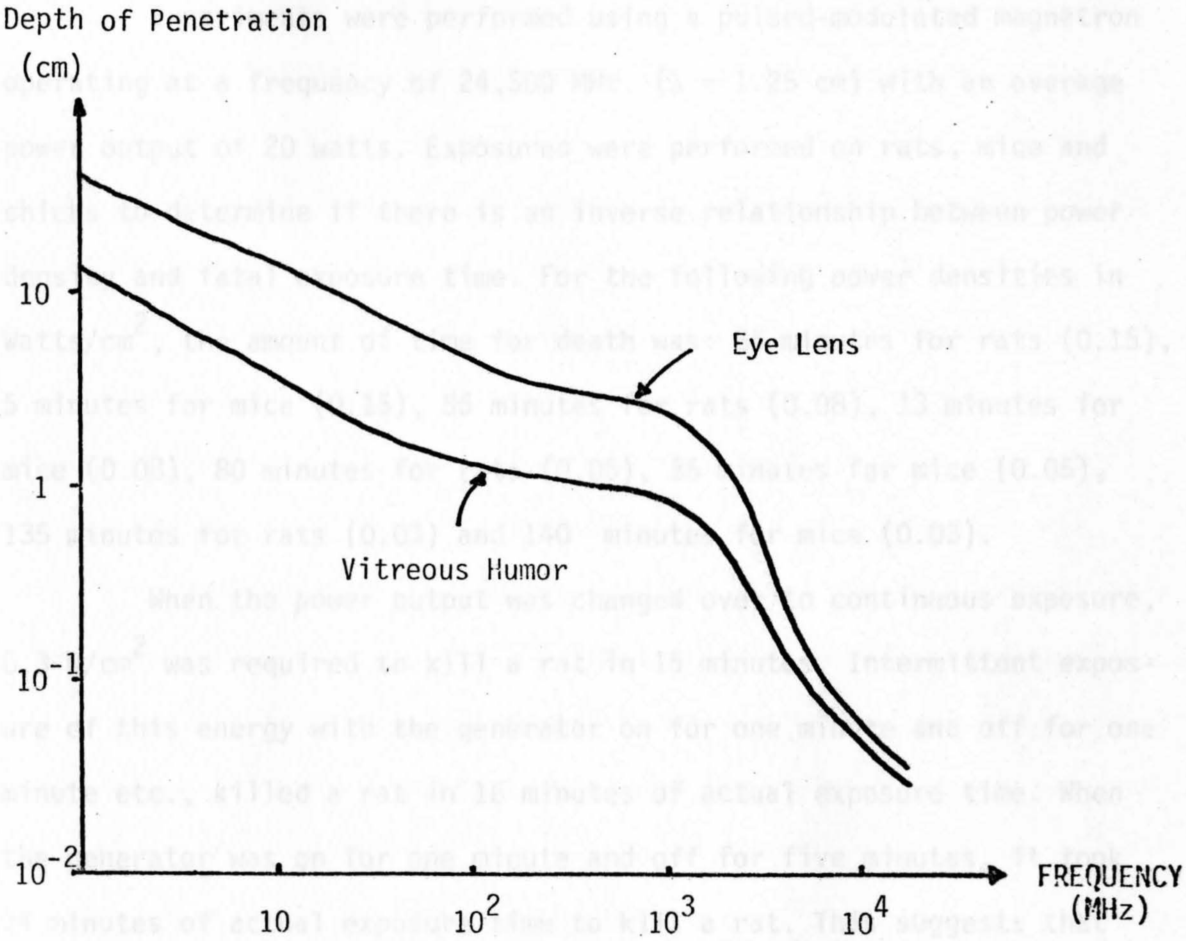

Figure 2. Depth of penetration as a function of frequency for eye lens and vitreous humor. These are typical tissues with high water content, just like muscle and body organs, with the lens and the vitreous humor representing the upper and lower limits, respectively.

Absorption of Diverse Microwave Frequencies [2]

This experiment dealt with the effects of exposure of the whole body, selected organs and tissues, single cells and enzyme systems using various power levels, pulsed and continuous waves, in the frequency spectrum from 200 through 24,500 MHz.

24,500 MHz.

Experiments were performed using a pulsed-modulated magnetron operating at a frequency of 24,500 MHz. ($\lambda \simeq 1.25$ cm) with an average power output of 20 watts. Exposures were performed on rats, mice and chicks to determine if there is an inverse relationship between power density and fatal exposure time. For the following power densities in Watts/cm^2, the amount of time for death was: 35 minutes for rats (0.15), 5 minutes for mice (0.15), 56 minutes for rats (0.08), 13 minutes for mice (0.08), 80 minutes for rats (0.05), 35 minutes for mice (0.05), 135 minutes for rats (0.03) and 140 minutes for mice (0.03).

When the power output was changed over to continuous exposure, 0.3 W/cm^2 was required to kill a rat in 15 minutes. Intermittent exposure of this energy with the generator on for one minute and off for one minute etc., killed a rat in 16 minutes of actual exposure time. When the generator was on for one minute and off for five minutes, it took 34 minutes of actual exposure time to kill a rat. This suggests that microwave energy causes subacute or chronic effects similar to a very high fever.

Exposure of the testes of rats was performed to see if the male endocrine system was affected. With a power of 0.25 W/cm^2 exposed to the testes, the output of androgen (sex hormone) was erratic.

10,000 MHz.

Experiments involving mice and rats were performed to determine the temperature regulation under the influence of 10,000 MHz. microwave radiation ($\lambda \simeq 3.0$ cm). Tests were run using continuous long-term irradiation with a low power intensity, and other tests using intermittent irradiation with power intensities fluctuating between 0.009 and 0.438 W/cm^2 were performed. The rise in body temperature reached a plateau just below the temperature at which death took place when mice were irradiated with a power intensity of less than 0.06 W/cm^2. A constant raised temperature level did not occur in animals that were exposed to low power intensities; rather the body temperature was erratic.

Tests were also made on the rate of cooling after an animal was exposed to microwaves. Mice were subjected to a radiation intensity between 0.156 and 0.438 W/cm^2. The rise in body temperature was about 5°C. above the normal body temperature. The rate of cooling was the same. Irradiation using an intensity of 0.04 W/cm^2 caused a steady-state rise in temperature of about 2.3°C. Another test was performed to find out if previous exposures had any effect on later exposures. It was found that the cooling system was more effective the second exposure than the first.

2800 MHz.

This experiment was performed to determine the biological responses caused by irradiation from a 2800 MHz. pulsed radar system. The results showed that animals exposed to high power density microwaves experienced thermal stress. As long as the thermal encumbrance is moderate, the animal can survive. Once this level is exceeded normal body functions are impaired. Both deep and superficial burns in any part of the body can occur.

Dogs were exposed to 2800 MHz. pulsed microwaves with a power intensity of 165 mW/cm^2 and an ambient humidity of 30%. After 0.5 hour of exposure the body temperature of the dog rose 3^{o}F. The body temperature remained at this temperature for another 30 minutes in a state of thermal equilibrium. After one hour had elapsed, thermal breakdown occurred where temperature increased rapidly. During this condition if exposure is not stopped, death will occur. With the same set of conditions except for a power density of 100 mW/cm^2, the dog remained in thermal equilibrium.

Rabbits were also subjected to the above conditions with a power intensity of 165 mW/cm^2. The exposure caused an extremely violent reaction. After five minutes of exposure, the rabbit made desperate attempts to get out his cage. Blood vessels became engorged and the skin started turning blue. After 40 minutes of exposure the rabbit died. Rabbits exposed to a power intensity of 100 mW/cm^2 became helpless after one hour.

2450 MHz.

Dogs were exposed to continuous wave 2450 MHz. microwave radiation in this experiment. The head of the dog was the only part exposed. Results showed an increase in temperature in the cisterna magna, midbrain, frontal lobe, fourth ventricle and rectum when irradiated by microwaves. The power density to the head never exceeded 0.8 W/cm^2. Using different sized dogs led to the conclusion that the amount of temperature increase is inversely related related to the physical size.

Rats were also investigated upon 2450 MHz. radiation. After exposure to microwaves, the rats lost weight. But after a long period of time they became obese. At this frequency a power density of 70 mW/cm^2 for 15 minutes caused rats to die.

Chick embryos were used in another experiment to analyze the effect of microwave exposure on biological systems by cell differentiation. These embryos were exposed to 200-280 mW/cm^2 of 2450 MHz. microwaves.

The radiation produced a temperature increase in the egg. This caused abnormalities such as inhibition or retardation of differentiation in the eye, brain, heart and an undeveloped embryo. The allantois (vascular fetal membrane) did not develop. Protein denaturation caused degeneration of cell structures from the heat created by the microwaves.

1240 MHz.

The temperature response in dogs exposed to 1240 MHz. was very similar to the results using 2800 MHz. Salivation and panting was less marked at 1240 MHz. than at 2800 MHz, suggesting that 1240 MHz. is relatively safer.

Exposures at 1240 MHz. daily to dogs for four weeks at a power density of 100 mW/cm^2, showed an increase in temperature after every exposure during the first week. The last three weeks of exposure caused only moderate temperature increases.

200 MHz.

In this experiment the position of the body in the microwave field determined how much energy would be absorbed. It was pointed out that the temperature increased the most when the body was positioned so that its longitudinal axis was parallel to the polarization plane of the microwave field. Qualitative differences in the shape of the head, body, etc., in the dog were factors in the amount of temperature response.

Death occurred in dogs exposed to 200 MHz. radiation at a power density of 330 mW/cm^2 in 15 minutes. Power densities around 200 mW/cm^2 required longer exposure time to cause death. No deaths resulted using 165 mW/cm^2 for exposures of one hour. All of the dogs that died had a body temperature increase of at least 7.5°F.

Properties of Organic Materials [3]

The amount of electromagnetic energy that penetrates a body is governed by the properties of the material and the frequency and also other characteristics of the incident wave. Effects related specifically to the frequency of radiation have been observed to change the molecular structure of cells. The variables of the material are permittivity and conductivity, which determine the thermal effects under exposure to microwaves. Table 1 lists some permittivity and conductivity values for several biological tissues.

TABLE 1

PROPERTIES OF VARIOUS TISSUES AT 27^{0} C.

Tissue	Relative Permittivity ε_r		Conductivity σ	
	at 0.4 Ghz.	1.0 Ghz.	at 0.4 Ghz. (millimhos/cm)	1.0 Ghz.
Muscle	54-56	54-57	9.5-10.0	12.0-12.7
Liver	46-53	50-51	6.7-8.3	9.1-9.6
Lung	36	-	6.1	-
Blood	64	63-67	11.0	12.8-14.2
0.9 NaCl	74	77	17.3	18.5
Fat	4-7	-	0.7-0.8	-

The difference in the properties of tissues is due to the presence of protein molecules. The temperature coefficient of the resistivity varies with frequency, i.e., it is always negative and it is similar to a saline solution. The temperature coefficient of the dielectric constant is positive at low frequencies and becomes negative as the frequency increases.

Table 2 lists values for the properties of muscle, fat and skin over a wide range of frequency. The properties given are the dielectric constant and the conductivity.

TABLE 2

PERMITTIVITY AND CONDUCTIVITY OF SEVERAL TISSUES AT 37^{0} C.

Frequency	Muscle		Wet Fat		Dry Fat		Skin	
Ghz.	ε_r	σ^a	ε_r	σ	ε_r	σ	ε_r	σ
0.15	66	10	7.6	0.66	3.8	0.33	63	8
0.4	58	10	6.8	0.78	3.4	0.39	47	9
0.9	54	11	6.1	0.91	3.1	0.45	44	10
3.0	54	22	4.4	1.18	2.2	0.59	41	21
10.0	45	125	3.3	2.62	1.7	1.31	34	82

σ^a in millimhos/cm

Tissues with Blood Vessels Exposed to Intense Fields [4]

Biological tissues exposed to intense microwave radiation leads to changes of their properties. These changes are primarily due to a rise in temperature from the absorption of the radiation. Tissues with blood vessels and without have different characteristics.

The thigh of a dog will be used for microwave experimenting because the inherent properties of the tissues can produce practically any temperature, depending upon the microwave power radiation and the duration of exposure. As soon as microwave energy is directed towards the tissue, the temperature begins to rise. After 20 minutes the temperature began to drop. Measurements of blood flow to the thigh of the dog increased when the temperature started decreasing. This suggests that the blood acts as a heat-dissipating mechanism.

Similar effects have also been observed in humans. As the temperature of the tissue increases, the flow of the blood to that tissue increases. This increased flow in blood acts as a coolant to prevent the development of too high temperatures. If the radiation is too intense, tissue damage will occur.

Medical diathermy uses heating of tissues by electromagnetic waves to be beneficial to the patient, as long as the heating is controlled. The optimum temperature is obtained from waves having a frequency in the UHF spectrum (300-3,000 Mhz.). When the temperature of normal tissue exceeds a certain limit, irreversible changes take place.

In Figure 3, the heat-exchange characteristics for an animal are given. Normal temperature is indicated and increases to the right while the heat gain from metabolism is above the reference line and heat loss is below it. Note that when the resultant curve becomes positive, the animal dies.

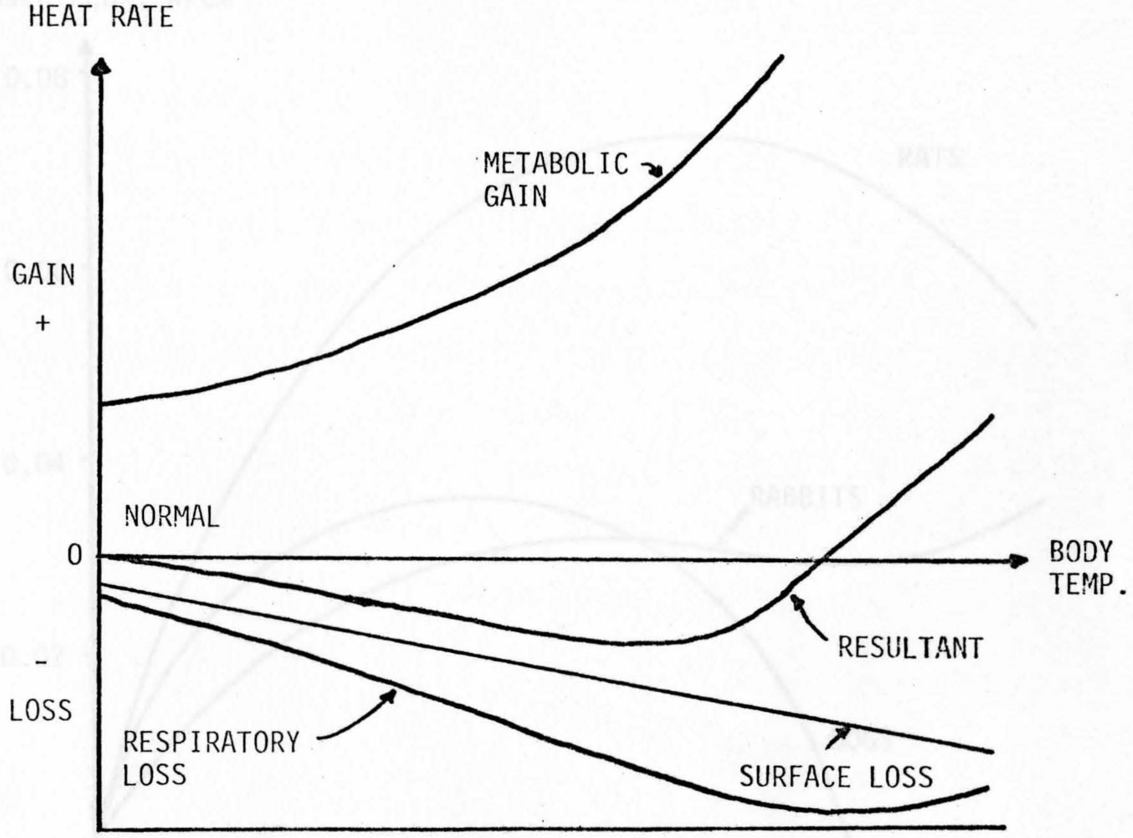

Figure 3. Heat exchange characteristics for animals. This graph is qualitative with arbitrary units.

In Figure 4, the average results of the body-temperature rise above normal with respect to the microwave power flux required to maintain this rise is shown. In this case, microwave power is used to provide additional heat necessary to cause the animal's net heat exchange to equal zero or to maintain constant body temperature. The rate at which the animal would lose heat without this additional heat represents the magnitude of microwave power. The average absorption of each species was about 40% of the power in the animal's geometrical design and the heat dissipation ability was such that a body temperature rise of 1.0 degree centigrade dissipated a flux of 0.025 W/cm^2.

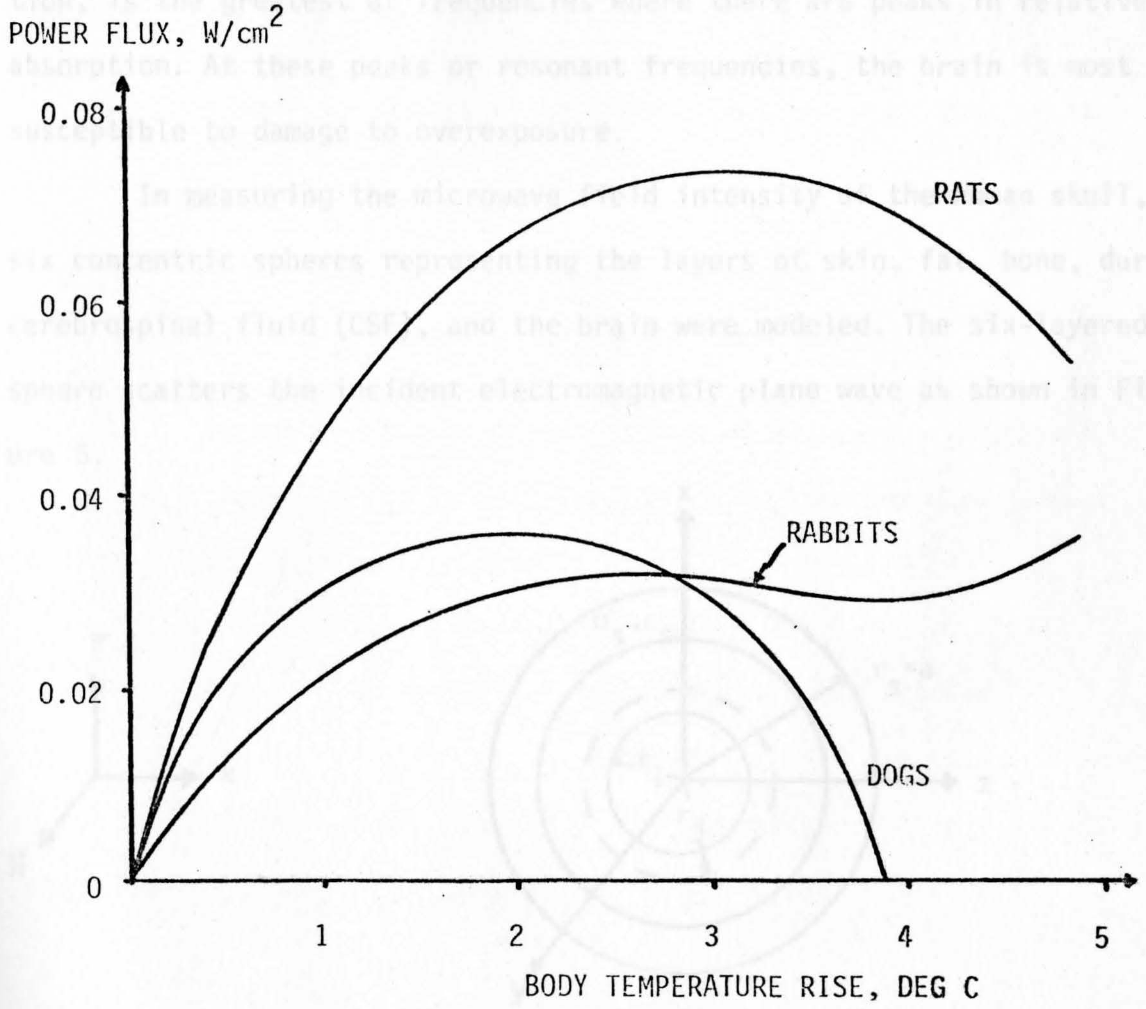

Figure 4. Heat exchange characteristics of animals. Results are at 3.0 Ghz.

In other tests, mice were exposed to 10.0 Ghz. microwave radiation with a power flux between 0.05 and 0.5 W/cm^2. As the power flux was increased, the temperature of the animal rose at a proportional rate. At 44.1 degrees centigrade, which is 6.7 degrees centigrade above the normal body temperature, death occurred in 50% of the subjects.

Absorption of Microwaves by the Human Skull [5]

Electromagnetic waves with a frequency in the 0.1 - 3.0 Ghz. band are absorbed by the human skull. The amplitude of the standing wave, which exists inside the skull under the influence of microwave irradiation, is the greatest at frequencies where there are peaks in relative absorption. At these peaks or resonant frequencies, the brain is most susceptible to damage to overexposure.

In measuring the microwave field intensity of the human skull, six concentric spheres representing the layers of skin, fat, bone, dura, cerebrospinal fluid (CSF), and the brain were modeled. The six-layered sphere scatters the incident electromagnetic plane wave as shown in Figure 5.

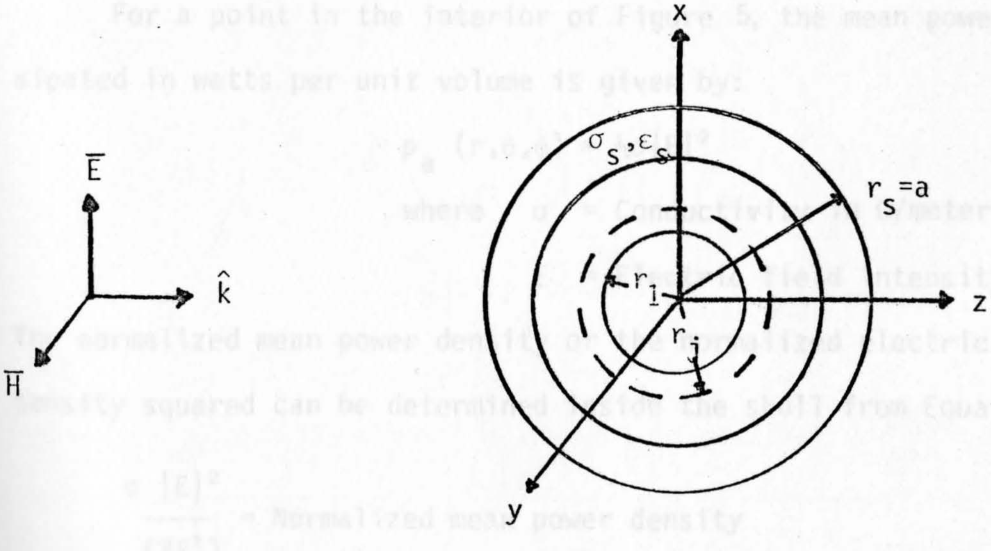

Figure 5. A sphere (s=6) model of a skull irradiated by incident plane wave traveling in the "z" direction.

The incident wave is traveling in the "z" direction and is linearly polarized along the "x" axis. Boundaries between the layers are $j = 1,2,\ldots s$, where "s" is the boundary between the last layer and the outside medium (in this particular case it's air). The dielectric constants and conductivities of the layers are $\varepsilon_1, \varepsilon_2, \ldots \varepsilon_s$ & $\sigma_1, \sigma_2, \ldots \sigma_s$. The relative absorption of electromagnetic energy within the dielectric sphere (of outer radius "a") is given by:

$$\frac{P_a}{P_i} = \frac{2}{\alpha^2} \sum_{n=1}^{\infty} (2n+1) \{\mathrm{Re}\,(a_n + b_n) - (|a_n|^2 + |b_n|^2)\} \tag{2}$$

where $P_a = \frac{1}{2} \int_V \sigma\, |E|^2\, dV$ = Power absorbed by the sphere in watts

P_i = Power incident upon the geometrical cross section of the sphere $= (E_0^2/2\eta)\pi a^2$ (watts)

α = $2\pi a/\lambda$

λ = Wavelength in outside medium in meters

η = Intrinsic impedance (377 Ω for free space)

a_n, b_n = Scattering coefficients dependent upon the conductivity, dielectric constant, and radius of the spherical layers.

For a point in the interior of Figure 5, the mean power dissipated in watts per unit volume is given by:

$$p_a\,(r,\theta,\phi) = \tfrac{1}{2}\sigma|E|^2 \tag{3}$$

where σ = Conductivity in Ω/meter

E = Electric field intensity in V/meter

The normalized mean power density or the normalized electric field intensity squared can be determined inside the skull from Equation 2.

$$\frac{\sigma\,|E|^2}{(2E_0^2)} = \text{Normalized mean power density} \tag{4}$$

$$\frac{|E|^2}{E_0^2} = \text{Normalized electric field intensity squared} \tag{5}$$

The conductivity σ and the dielectric constant ε must be determined to find the power absorption. The conductivity and dielectric constant of an electrically polarizable material are given by:

$$\sigma = \sigma_L \ (\sigma_H + \sigma_L) \ \frac{(\omega T)^2}{1 + (\omega T)^2} = \sigma_L \left[\frac{1 + \frac{\sigma_H}{\sigma_L} (\omega T)^2}{1 + (\omega T)^2} \right] \tag{6}$$

and

$$\varepsilon = \varepsilon_H + \frac{\varepsilon_L - \varepsilon_H}{1 + (\omega T)^2} = \varepsilon_H \left[\frac{\frac{\varepsilon_L}{\varepsilon_H} + (\omega T)^2}{1 + (\omega T)^2} \right] \tag{7}$$

where $T = \frac{1}{2\pi f_0}$ = Relaxation time for biological tissue with a high H_2O content

f_0 = 20 Ghz. = Frequency of rotational resonance of H_2O molecules

L corresponds to low frequency (DC)

H corresponds to high frequency (light)

For the brain, the ratio $\sigma_H / \sigma_L = 62$ and $\varepsilon_L / \varepsilon_H = 12$

Using these values, Equations 6 and 7 reduce to the following:

$$\sigma = \sigma_L \left[\frac{1 + 62 \ (f / f_0)^2}{1 + (f / f_o)^2} \right] \tag{8}$$

$$\varepsilon = \varepsilon_H \left[\frac{12 + (f / f_0)^2}{1 + (f / f_0)^2} \right] \tag{9}$$

where the conductivity and the dielectric constant are frequency dependent. In Equations 8 and 9, the frequency of rotational resonance, f_0, is equal to 20 Ghz.

The fat and bone layers, which have low H_2O content, are assigned frequency independent values of σ and ε. Similarily, the other layers are found and recorded in Table 3.

TABLE 3

DIMENSIONS AND ELECTRICAL PROPERTIES OF MULTI-LAYERED SPHERE MODEL OF A HUMAN SKULL

Layer	Radius (cm)	σ_L	ε_H
Skin	a	8	4
Fat	a - 0.15	1	6
Bone	a - 0.27	2	5
Dura	a - 0.70	8	4
CSF	a - 0.80	8	7
Brain	a - 1.10	6	5

The relative absorption of multilayered spheres, with an outside radius of 7 and 10 cm.,is shown as the upper curve in Figures 6 and 7. The lower curve is a result of all layers having the same σ and ε as that of the brain (homogeneous sphere). Note the absorption peak at 2.1 GHz. Also the resonant peaks are shifted downward in frequency as the radius is increased from 7 to 10 centimeters.

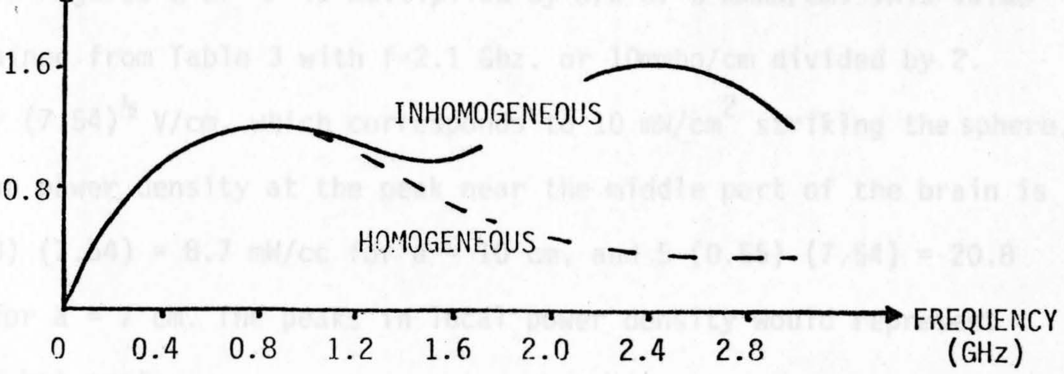

Figure 6. Relative power absorption vs. frequency for inhomogeneous (six-layered) and homogeneous (one-layered) sphere models of outer radius of 7 centimeters.

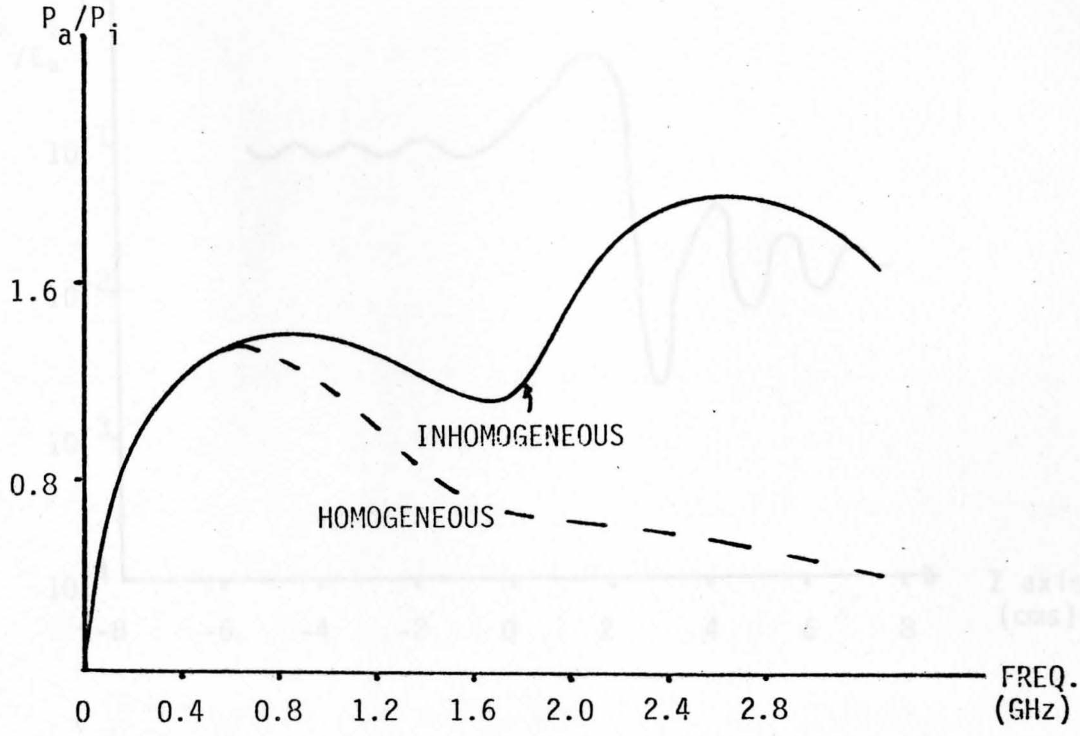

Figure 7. Relative power absorption vs. frequency for inhomogeneous (six-layered) and homogeneous (one-layered) sphere models of outer radius of 10 centimeters.

The electric field intensity ($|E|^2/E_0^2$) inside the inhomogeneous sphere for the 2.1 Ghz. peak is shown in Figure 8 for "a" equal to 7 centimeters and in Figure 9 for "a" equal to 10 centimeters. To find the mean power density at any point along the "z" axis, the ordinate in Figures 8 or 9 is multiplied by $\sigma/2$ or 5 mmho/cm. This value is obtained from Table 3 with f=2.1 Ghz. or 10mmho/cm divided by 2. If $E_0 = (7.54)^{\frac{1}{2}}$ V/cm, which corresponds to 10 mW/cm^2 striking the sphere, the mean power density at the peak near the middle part of the brain is 5 (0.23) (7.54) = 8.7 mW/cc for a = 10 cm, and 5 (0.55) (7.54) = 20.8 mW/cc for a = 7 cm. The peaks in local power density would represent intense hot spots.

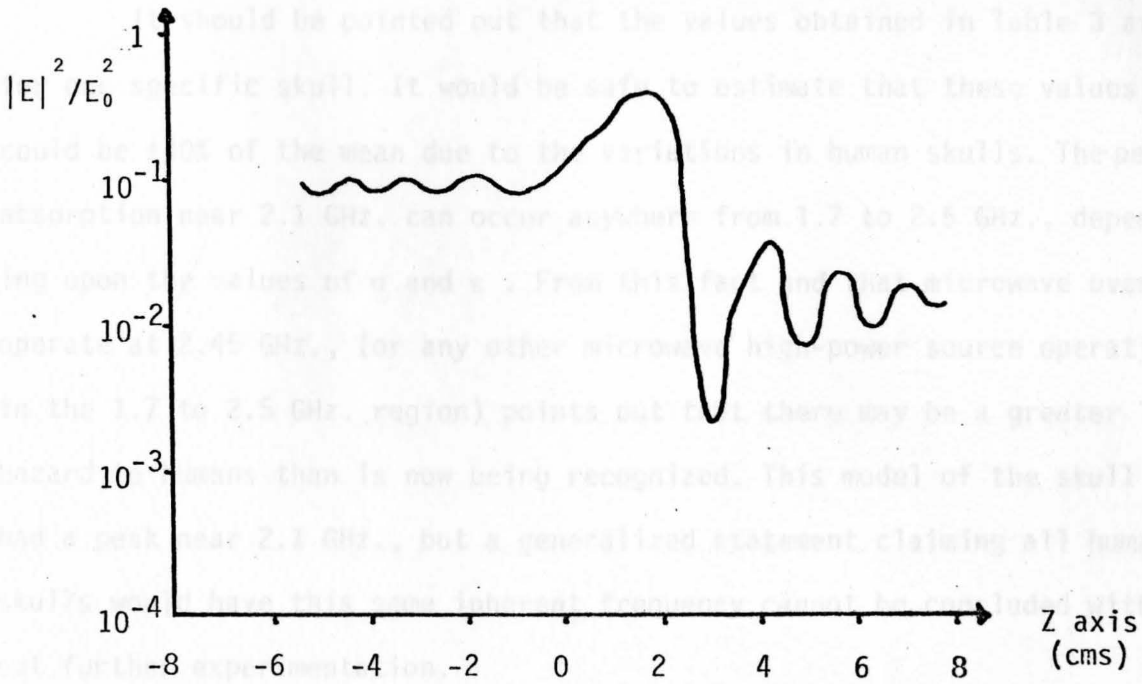

Figure 8. Z-axis distribution of normalized electric field intensity squared inside the simulated brain matter (first layer) of the six-layered sphere model. "a" = 7 cm., f = 2.1 GHz.

Figure 9. Z-axis distribution of normalized electric field intensity squared inside the simulated brain matter (first layer) of the six-layered sphere model. "a" = 10 cm., f = 2.1 GHz.

It should be pointed out that the values obtained in Table 3 are for one specific skull. It would be safe to estimate that these values could be ±40% of the mean due to the variations in human skulls. The peak absorption near 2.1 GHz. can occur anywhere from 1.7 to 2.5 GHz., depending upon the values of σ and ε . From this fact and that microwave ovens operate at 2.45 GHz., (or any other microwave high-power source operating in the 1.7 to 2.5 GHz. region) points out that there may be a greater hazard to humans than is now being recognized. This model of the skull had a peak near 2.1 GHz., but a generalized statement claiming all human skulls would have this same inherent frequency cannot be concluded without further experimentation.

Effects of the Microwave Oven and Radar on Pacemakers [6]

In this experiment, six pacemakers were implanted in dogs and then subjected to microwave irradiation at frequencies of 915, 2450, 2810 and 3050 MHz. Energy for these frequencies was obtained from klystron tubes and fed to a horn antenna via waveguide. The 2450 MHz. field was generated by a microwave oven with the energy delivered to a horn antenna. The far-field pattern of the antenna had an impedance of 377 ohms; which is the quotient of the magnitude of the electric and magnetic field vectors.

The gain of the irradiation antenna can be calculated by:

$$G = \frac{4\pi R}{\lambda} \sqrt{P_R / P_T} \tag{10}$$

where R = The distance between antennae in meters

λ = Microwave wavelength in meters

P_R= Power incident upon receiving antenna in watts

P_T= Total power radiated in watts

Once the gain of the antenna is found from Equation 10, the power density can be calculated by:

$$P_D = \frac{P_T G}{4\pi R^2} \tag{11}$$

where P_D = The power density in mW/cm^2

R = The distance between the animal and the antenna in meters

In order to keep the radiation field dominant, the animal was placed 15 feet from the antenna. The power density varied inversely with the square of the distance as shown in Equation 12.

$$P_D = \frac{K_B}{R^2} \tag{12}$$

where $K_B = \frac{P_T G}{4\Pi}$

Conversion of the power-density measurements with the use of a probe for situations involving a continuous wave, a modulated square wave and pulse modes can be obtained by Equation 13.

$$E = \sqrt{P_D Z / dc} \tag{13}$$

where P_D = The power density in mW/cm^2

dc = duty cycle

E = Electric field in V/m

Z = Impedance of free space which is equal to 377 ohms

For sine wave modulation the conversion takes the form of Equation 14.

$$E = \sqrt{P_D Z / dc}\,\sqrt{1.57} \tag{14}$$

Results of microwave irradiated pacemakers were changes in functioning or complete cutoff. Following exposures, all units returned to normal operation. This suggests that microwaves do not destroy pacemakers. Complete inhibition or cutoff of a pacemaker naturally means a threat to a patient. The most important variables that are a factor in cutoff are the frequency and the mode. Changes in the function of the pacemaker were noted at 2450 MHz., but complete inhibition did not exist. An older pacemaker, which is not available today, produced inhibition at 2450 MHz., which incidentally is the frequency used by most microwave ovens.

Since the patient will normally be moving in the electromagnetic field, the experimental conditions where the animal is permanently situated in the field represents the worse possible conditions. The field strength level, for these frequencies under test, which would be safe for pacemaker patients is 75 V/m, which is a nominal value. A better approach can be made considering field frequency, pulse repitition rate and field strength all together. This would allow a patient to be in a 380 V/m field in the 2450 MHz. frequency. Using a frequency of 2810 or 3050 MHz., a safe field strength would be 250 V/m.

To sum things up, pacemaker patients are relatively safe in a field of microwaves. Considerations of the pulse repetition rate and the electric field strength at these frequencies must be set at a conservative viewpoint.

Microwave Ovens [7]

Today, microwave ovens are widely available to consumers. With safety devices such as door seals and interlocks, these ovens should have little or no effect on the amount of electromagnetic radiation found in a typical city. But there are many variables that determine safe radiation levels; i.e., ambient temperature, microwave frequency, humidity, length of exposure, etc. Also very little is known about the nonthermal effects of microwaves. The only safe microwave oven would then be one that emits exactly no radiation.

Microwaves are in a sense classified as nonionizing radiation. They are classified as this because a quantum of microwave energy is only 10^{-5} eV; while an ionizing radiation requires an energy of 10-25 eV. The term nonionizing is very misleading when applied to microwaves because for example, a flourescent tube will light near a field of microwaves.

The amount of heating in a microwave oven is dependent upon the radiation intensity, the frequency of the microwaves and the molecular characteristics of the material being irradiated. For example, water is a very good absorber of microwave energy and is converted to heat. This is because the water molecules are electric dipoles that try to align themselves with the oscillating (2,450,000,000 oscillations per second) microwave field. The molecules are continuously moving and thus have kinetic energy. This movement causes increased collisions between the other water molecules which is termed friction and thus a generation of heat.

Glass, china, plastic, paper and any other material whose molecules are electrically neutral at all points, are transparent to microwaves. Microwave energy will only heat materials with a high water content. Even the metal inside the oven will remain cool when the oven is operating because the metal reflects microwaves.

Most microwave ovens today operate at a frequency of 2450 MHz. The frequency of operation determines the food penetration at which microwave energy can produce heating. The frequency 2450 MHz. has been criticized by Dr. Guy as "a classic example of how the historic lack of engineering in medicine has prolongated ill-conceived practices not only in medicine, but also in non-related industrial applications." For medical treatments, Dr. Guy claimed 915 MHz. to be "therapeutically more effective and safer in terms of leakage radiation than existing 2450 MHz. equipment."

Emissions of new microwave ovens, as set by the U. S. Department of Health, Education, and Welfare, are restricted to 1 mW/cm^2 at a distance of 5 cm from any point on the surface of the oven. Older ovens cannot exceed 5 mW/cm^2 as specified by HEW.

The Russians have adopted the power level of 0.01 mW/cm^2 before abandoning time restrictions as being safe. This is in comparison with the American National Standards Institute (ANSI), which allows 10 mW/cm^2 over an unlimited time interval (although it also states that under conditions of moderate to severe heat stress the guide number should be appropriately reduced). A booklet released by the Departments of the U. S. Army and Air Force lists the biological aspects of electromagnetic radiation. It is titled "Unexplained response of man to radar" and states "Epigastric (stomach) distress and/or nausea may occasionally occur at as low as 5-10 mW/cm^2 and are most commonly associated within the frequency range from 8×10^3 to 12×10^3 MHz." It is evident that a safe level of exposure has not yet been determined.

There are more problems concerning the microwave oven; i.e., new warning label requirements, biological effects from low-level irradiation (changes in behavior and reactions in the nervous system), and to attribute the formation of cataracts to microwave energy.

The Consumers Union stated that the following should be put on warning labels attached to new microwave ovens: (1) a warning against operating microwave ovens empty; (2) instructions to unplug after use to avoid inadvertent operation; (3) a warning to individuals with pacemakers; (4) specific notes on the importance of clean door seals unhampered by dirt or paper towels; (5) the importance of keeping one's face away from the door while the oven is operating; and (6) a clear statement that children not be permitted to operate a microwave oven.

Far-Field Absorption from Parabolic Antennae [8]

All equipment used in microwave frequencies should comply with the safe limits having been established. For example, a paraboloid antenna fed by a horn has a gain of 8 dB with the field at the edge being 10 dB less than that at the center. The field outside the reflector will be less than this and except for the region between the horn and the reflector, the direct field from the horn will be less than it would be from an isotropic radiator. With a radiated power of 10.0 KW, the minimum safe distance from the antenna is 3.0 meters; which means that the danger area due to direct radiation is small.

Of course the field due to the main beam of the antenna is of greater importance, as can be seen in Figure 10. This figure gives values for distances D_R to 10 D_R where D_R is the Rayleigh distance of the antenna. The contours are drawn relative to the maximum power flux on the axis at a distance D_R. The maximum value is approximately 1.9 P/d^2 but the actual flux will exceed this by up to 3.5 dB at some positions within the Rayleigh distance. The values shown in Figure 14 are taken in free space; if a perfect ground reflection is present, the field strength could be up to 6 dB greater.

Take for example a tropospheric-scattering system operating at a frequency of 0.855 GHz., a power input to the antenna of 20 KW., and a radial distance "d" of 10.0 meters. From this data the Rayleigh distance is calculated to be 1.41 x 10^2 meters and the maximum power flux is 0.046 W/cm^2. Using 10 mW/cm^2 as a safe flux with a safety factor of 4, the safe contour would be -13 dB. If the antenna is 10.0 meters above a level ground, the area between 270 and 620 meters in

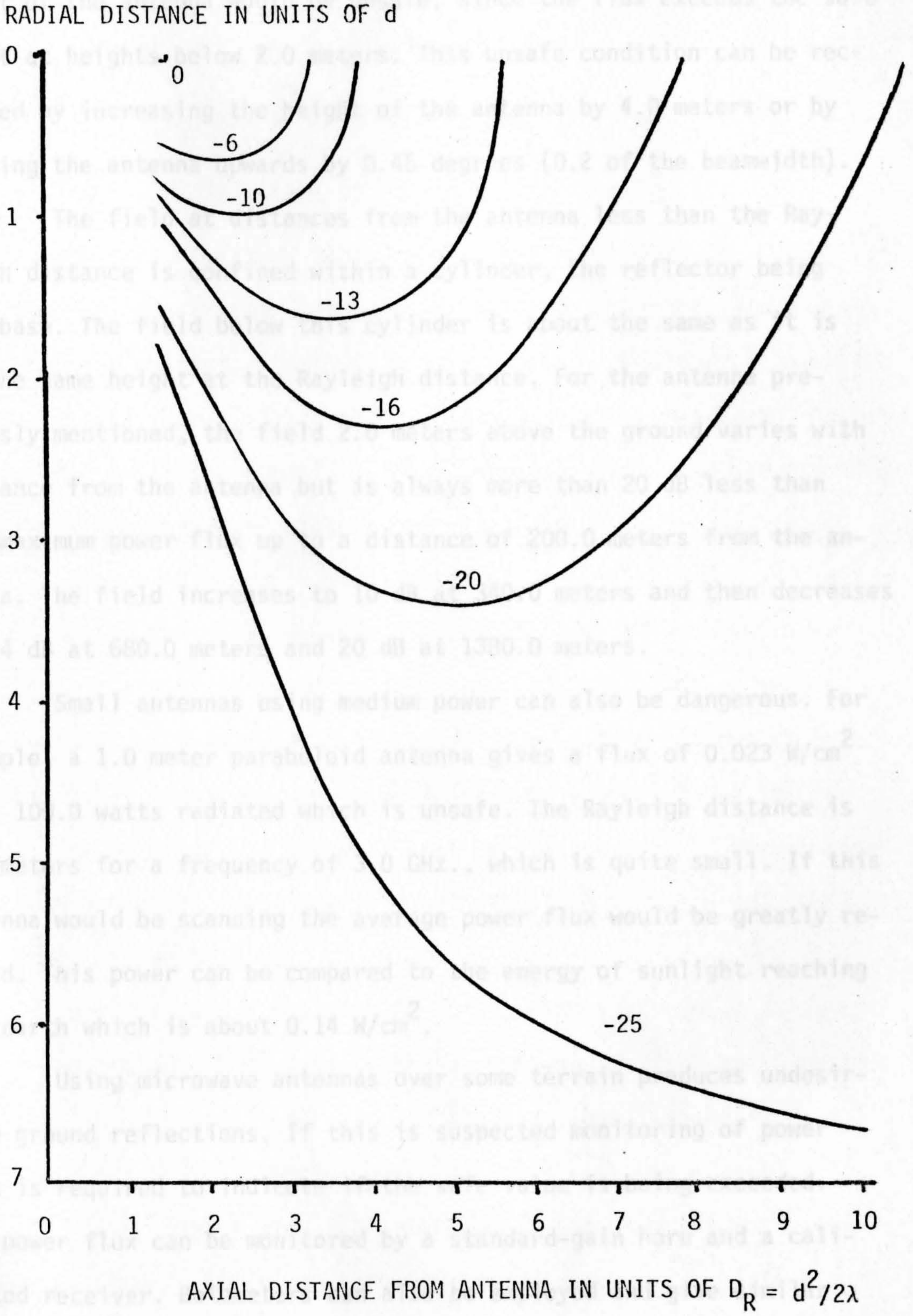

Figure 10. Power-flux contours of a radiating paraboloid. Parameter is decibels relative to 1.8 P/d^2 where "P" is the input power to the antenna.

front of the antenna would be unsafe, since the flux exceeds the safe limit at heights below 2.0 meters. This unsafe condition can be rectified by increasing the height of the antenna by 4.0 meters or by tilting the antenna upwards by 0.45 degrees (0.2 of the beamwidth).

The field at distances from the antenna less than the Rayleigh distance is confined within a cylinder, the reflector being the base. The field below this cylinder is about the same as it is at the same height at the Rayleigh distance. For the antenna previously mentioned, the field 2.0 meters above the ground varies with distance from the antenna but is always more than 20 dB less than the maximum power flux up to a distance of 200.0 meters from the antenna. The field increases to 10 dB at 340.0 meters and then decreases to 14 dB at 680.0 meters and 20 dB at 1380.0 meters.

Small antennas using medium power can also be dangerous. For example, a 1.0 meter paraboloid antenna gives a flux of 0.023 W/cm^2 with 100.0 watts radiated which is unsafe. The Rayleigh distance is 5.0 meters for a frequency of 3.0 GHz., which is quite small. If this antenna would be scanning the average power flux would be greatly reduced. This power can be compared to the energy of sunlight reaching the earth which is about 0.14 W/cm^2.

Using microwave antennas over some terrain produces undesirable ground reflections. If this is suspected monitoring of power flux is required to indicate if the safe value is being exceeded. The power flux can be monitored by a standard-gain horn and a calibrated receiver. Bolometers can also be employed and give similar results. Neon tubes are fine for qualitative analysis, but are useless for quantitative measurements.

CHAPTER IV

HEALTH ASPECTS OF MICROWAVE RADIATION

Reactions to Microwave Irradiation [9]

The investigations on the biological results of microwaves have been devoted to problems dealing with hygienic, clinical, experimental and ecological aspects. These studies are being conducted all over the world. Results from clinical reports show that after exposure to microwaves, changes in the function of the nervous, cardiovascular and other systems of the body take place.

Some of the complaints associated with microwave exposure are a heaviness of the head, tiredness, irritability, drowsiness during the day, anxiety and light sleep at night and a partial loss of memory. Several autonomic vascular changes were: inhibited or expressed dermographism (very sensitive skin), hyperhidrosis (sweating) of the hands, instability of pulse and arterial pressure, a tendency to bradycardia (a slow heart rate), very low or very high blood pressure and functional changes of the thyroid.

Cardiac pain has also been attributed to microwave exposure. Complaints included pain of a stabbing or boring feeling and sometimes constriction of blood to the arm and scapula. Heart sounds were dull and functional systolic murmur over the heart apex was present.

Minor changes were also observed in the blood of microwave-exposed personnel. There was some decrease in mean erythrocyte count (blood cells containing hemoglobin and transporters of oxygen), slight thrombocytopenia (a decrease in the number of blood platelets), moderate leukopenia (a decrease in the production of new cells) and leukocytosis (an increase in the production of new cells). Cytopenia (a deficiency of cells in the blood) occurred after long durations of exposure. There was also a decreased number of mature cells in the bone marrow. Other changes in the blood were protein composition differences, a change in the amount of sugar, an increase in the blood cholesterol and a change in the blood lipid (fat) level. A contraction of the blood vessels with an increase in blood pressure were typical of the vessels in the brain.

Patients suffering from microwave sickness for one to ten years, when subjected to previous microwave exposure, had symptoms increased in severity. In these patients autonomic vascular disturbances were present while cerebral and coronary insufficiencies progressed. The development of ischaemic (anemic) heart disease and hypertension was also observed. The removal of microwave irradiation from the patient for a period of time usually resulted in the stabilization of the ailments or even complete recovery, if the exposure was not too long.

Neural Effects in Persons Exposed to Microwaves [10]

Results from experiments indicate that neural effects are attributed to local heating of peripheral nerves and not by excitation of the central nervous system (CNS). The dominant effect observed was the incraese in the activity of the person. This effect was temperature dependent. Also, when microwaves are radiated on isolated nerves, the effect can be duplicated by convective heat or infrared radiation.

An experiment using 3-cm microwave radiation with a 1000 pulses per second and with an intensity of 200 mW/cm^2, showed nociceptive reflex (a reflex which causes an animal to shield itself against harm by movement) in cats. This reflex causes a rise in blood pressure and pulse rate, a change in the respiration rate and movements of the cat's body. These syptoms occur when a microwave exposed nerve reaches a temperature between 42^{o} and $47^{o}C$.

Experimental findings in people employed where they were exposed to electromagnetic fields showed they had changes in EEG (electroencephalogram, i.e., brain waves) recordings. They also had significant clinical and electrobiologic changes. These changes in turn cause an impairment of the central nervous regulatory mechanisms. Motor disturbances were also evident.

Symptoms were found in microwave workers which included headache, fatigue, excitability and anxiety. Autonomic nervous system disorders and cerebellar symptoms were also noted. A reduction of vigilance (response to stimuli) was found in more than half of the workers being exposed to microwave radiation.

One consequence of the heating effect is a rise in basal metabolism, which increases the oxygen requirement of the tissues. The rise in temperature reduces the oxygen-carrying power of the hemoglobin, which causes decreased oxygenation, and leads to respiratory convulsions. This metabolic effect explains why the EEG changes and results are similar to those of epilectic seizures.

Experiments have shown that non-thermal effects of microwave irradiation causes mutations in some organisms and that organisms can sense weak electric and magnetic fields. These effects also change the endocrine organs, membrane permeability and the chromosomes.

Molecular resonance, the splitting off of free radicals, and the interruption of enzymatic chain processes which in turn lead to disturbances in the fine regulatory mechanisms are all possible when organisms are under the influence of microwave radiation. These mechanisms explain why there are changes in the tissue that needs a great deal of oxygen. These changes in the skin slow down the inherent activity. The conducting and the reflecting properties of the skin also effect the distribution of energy.

Operational Hazards to Personnel [11]

There is still uncertainty as to what determines a dangerous microwave radiation field. Damage to a body by some radiation hazard can be expressed by the equation shown below.

$$Ct = K \tag{15}$$

where C = Concentration of the radiation field
t = Time
K = Characteristic value, when exceeded, damage occurs

The concentration "C" is dependent upon the field intensity, absorption of energy, and the depth of the tissue beneath the surface of the organism. The absorption of electromagnetic energy by several human tissues in the frequency range between 0.15 and 10.0 GHz. can be seen by the skin, subcutaneous fat and deep muscle, as shown in Figure 11. Using known values for the dielectric constant and the loss tangent of the skin, fat and muscle, the proportion and distribution of energy absorbed can be calculated.

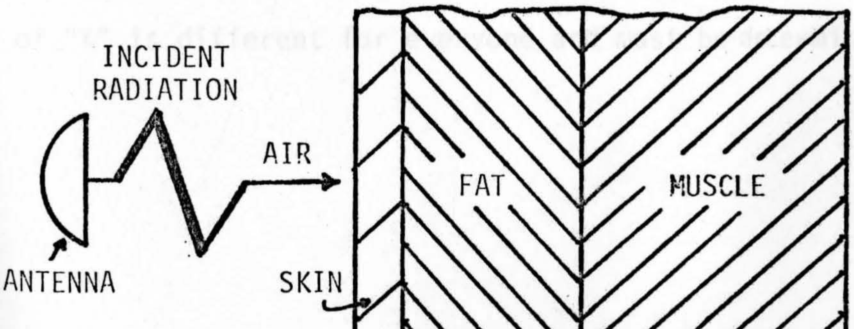

Figure 11. Absorption of microwave energy by the body. The triple-layer arrangement.

Figure 12 shows the fraction of radiation absorbed by the body as a function of the thickness of subcutaneous-fat layer. The different curves are for differing skin thicknesses in centimeters. At 0.15 GHz., the penetration of microwaves is deep while at 10.0 GHz. the energy is absorbed by the skin. Figure 13 shows the distribution of absorbed energy assuming a skin thickness of 0.2 centimeters at a frequency of 3.0 GHz.

Experimental results have been made to give limits on the concentration "C" for prolonged dosages. Power limits for frequencies below 0.5 GHz. are 0.03 W/cm^2 and for frequencies between 0.5 and 3.0 GHz. the limit is 0.01 W/cm^2. At frequencies higher than 3.0 GHz., a power limit of 0.02 W/cm^2 is considered safe. Above 0.1 W/cm^2, the short-term body effect of heat-stroke is apparent and the higher temperatures can be lethal.

An important factor involving tissue damage is the ability to repair itself under the influence of the radiation. Each individual will have varying recovery capacities, responses and time periods. Therefore it is hard to make one general statement regarding power limits because of the vast number of variables in a body. The value of "K" is different for everyone and must be determined individually.

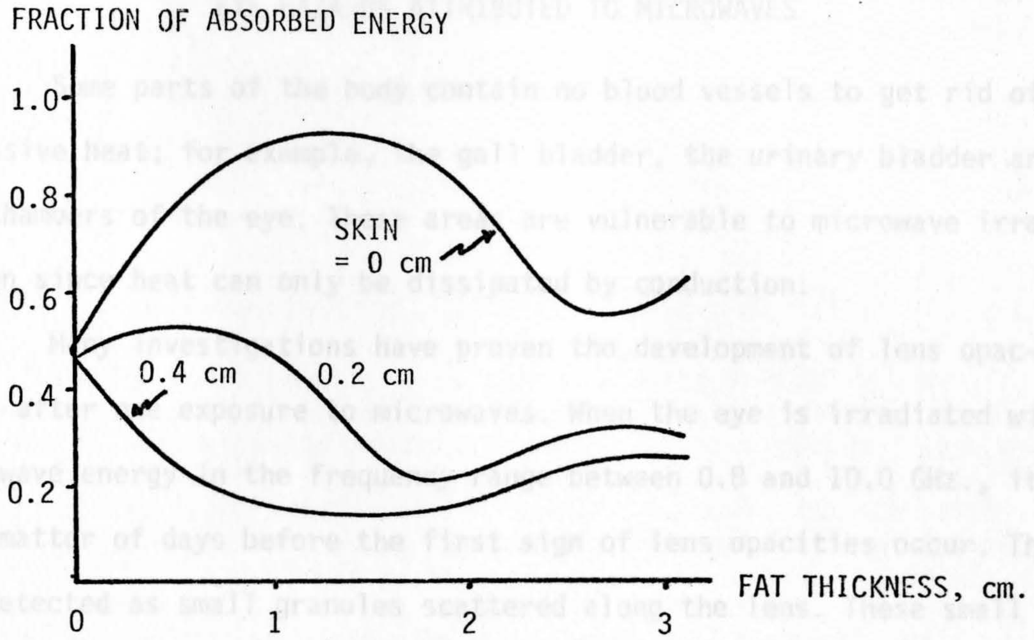

Figure 12. Absorption of microwave energy by the human body at 3.0 GHz.

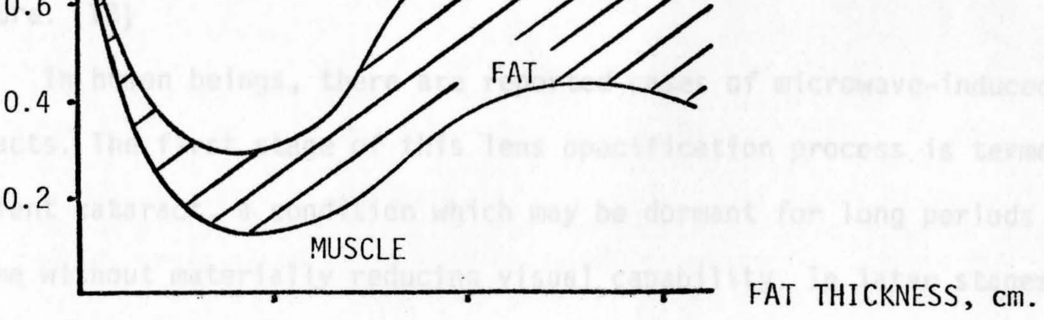

Figure 13. Distribution of microwave energy at 3.0 GHz. for a skin thickness of 0.2 centimeters.

CHAPTER V

EYE HAZARDS ATTRIBUTED TO MICROWAVES

Some parts of the body contain no blood vessels to get rid of excessive heat; for example, the gall bladder, the urinary bladder and the chambers of the eye. These areas are vulnerable to microwave irradiation since heat can only be dissipated by conduction.

Many investigations have proven the development of lens opacities after one exposure to microwaves. When the eye is irradiated with microwave energy in the frequency range between 0.8 and 10.0 GHz., it is a matter of days before the first sign of lens opacities occur. They are detected as small granules scattered along the lens. These small opacities are the end result of a series of events initiated within the lens when it has absorbed microwave power. [12]

The eye of a rabbit was exposed to microwaves with a frequency of 5.5 gigahertz.The eye of a rabbit was used because it is very similar to the eye of a human. Lens opacities formed within four days after exposures of sufficient intensity and duration. It only took three minutes of exposure at a one-watt level to exceed the cataract threshold. At a ½-watt level, no acute effect took place following a two-hour exposure. [13]

In human beings, there are reported cases of microwave-induced cataracts. The first stage of this lens opacification process is termed incipient cataract, a condition which may be dormant for long periods of time without materially reducing visual capability. In later stages, opacification spreads through the lens and becomes more dense. This results in vision so impaired, that the lens is classified as having a cataract. As a result, microwave-induced cataracts cause blindness.

Sometimes lens opacification (interruption of light transmission through the eye) does not appear for weeks after the exposure. Opacification occurring like this usually results in permanent, irreversible, acute lens injury. The opacification of the lens was almost always in the anterior portion.

SELECTED CASES OF MICROWAVE CATARACT IN MAN [14]

Case 1. Mrs. B. L., a 51 year old white female. The patient had been in excellent health throughout her life and the only history of potential radiation exposure was that she used a consumer type microwave oven regularly for five years between 1966 and 1971. Because of her failing sight due to cataracts of an unusual type, the oven was tested in 1971 and found to be leaking at a maximum level of 2.0 mW/cm^2 during operation and 40 mW/cm^2 when the door was opened. The oven was not used afterwards but it was retested in 1972, at which time it was reported to be leaking microwaves at a level of 1.0 mW/cm^2 during operation and 90 mW/cm^2 when the door was opened. Her exposures were covert and occurred between 1966 and 1971.

In prior years, her eyes were examined and found to be completely free of disease. In June 1969, because of a sense of blurred vision of the right eye, she was examined by her opthalmologist who reported that although her visual acuity could be corrected to 20/20 in the right eye and 20/15 in the left nevertheless incipient opacities were forming at the posterior subcapsular area of both lenses, being more pronounced in the right eye than the left. The cataracts progressed so that by April 1972 it was necessary to perform cataract surgery for the right eye and the best refracted vision of the left eye had been reduced to 20/50. The patient was referred to me for consultation in February 1973 and she had the typical findings of subacute microwave cataract in her left eye.

Case 2. Mr. D. B., a 41 year old white male examined in 1968. He was identified only as a member of a large group of researchers working with microwaves at field strengths lower than 10 mW/cm^2. He was a participant in a screening examination designed to identify microwave injury. His examination revealed the typical microwave-induced honeycombed opacification of the posterior capsule in both eyes. As the involved areas were large, about 3 millimeters in diameter for the left eye and 2 millimeters in diameter for the right, and inert because there was very little opacification of the contiguous cortex, the diagnosis was an early stage of delayed microwave cataracts. During the previous year, the patient had undergone surgical removal of a testicular malignancy.

Case 3. Mr. J. F., a 44 year old white male. The patient was first examined in 1971, when he was 42 years old, because he had been advised that he was developing microwave cataracts. Examination revealed extensive capsular cataract of the left eye, a late stage of subacute microwave cataract with beginning exfoliation of the capsule and a suspicion of posterior synechiae (which was confirmed at surgery) and an early stage of delayed microwave cataract in the right eye.

The patient had worked on several different radar systems from the time he was 26 years old until he was 35 during the period from 1955 through 1964. The highest field strength to which he was regularly exposed was about 1 mW/cm^2 for durations up to three hours and occasionally he could have been exposed to field strengths up to about 25 mW/cm^2 for a minute or less.

The patient fathered a son, born early in 1964, the product of a normal pregnancy, who did not appear as alert and did not not develop as rapidly as other children. The child sat at six months, stood at twelve months and walked at eighteen months. About that time, brief head nodding developed which progressed to a form of psychomotor epilepsy, subsequently exhibiting symmetrical clonic (alternating contractions and partial relaxations of muscles) movement of all extremities and the eyes lasting a few seconds and finally he developed lethargy (abnormal drowsiness). The boy died at age 7 and autopsy revealed that he had a rare, most unusual degeneration of his thalamus (the largest subdivision of the forebrain).

Case 4. Mr. A. K., a 44 year old white male. At age 21, he served in the United States Navy during the Korean War as a radar maintenance man. For about a year during 1950 to 1951 he was exposed repeatedly to microwave radiation from patrol aircraft radars at field strengths up to a maximum of 1.0 W/cm^2. The patient was first examined in 1964 when he was 35 years old and his opthalmic findings were immature subacute microwave cataract of the right eye and a minimal stage of delayed microwave cataract of the left eye. During the next nine years, the cataract of the right eye has progressed slowly but steadily so that it now involves practically the entire capsule and most of the contiguous lens cortex. The central portion of this lens remains clear so that it now can be classified clinically also as a capsular cataract. There has been very slight progression of the posterior capsulopathy in the left eye which can still be corrected to 20/20 visual acuity.

Since being discharged from the Navy, the patient has had episodes of mental illness, cardiovascular disease with depressed and inverted T waves, osteoarthritis and thyroid dysfunction.

Each of these cases, as compiled by Dr. M. M. Zaret, gives evidence that microwaves can cause eye cataracts. One of the most important findings was the pre-senile appearance of nuclear sclerosis of the lens which suggests that the aging process may be initiated prematurely or accelerated by microwave irradiation.

Other effects to the eye besides cataract from microwave radiation are hyrops of the lens, kerato-conjunctivitis, irido-cyclitis and chorioretinitis which can form right after microwave irradiation.

After a few days, keratopathy, capsular exfoliation, synechiae, glaucoma, retinal degeneration and melanomata can develop. After a few years, endothelial dystrophy of the cornea and nuclear sclerosis of the lens, indicating premature aging, also can form. To complicate matters, since the capsule between the lens and the iris is weaker than with other types of cataracts, surgical extraction of microwave-induced cataracts is more difficult.

Retinal Changes in Microwave Workers [15]

To determine if microwaves cause eye damage, an experiment was conducted at a factory where workers test microwave equipment. Results showed an increase of lens opacities in personnel in the lower age bracket. It was also noted that changes in the retina resembling chorioretinal scars were observed in many of the workers.

When microwaves are being absorbed in biological tissue they give an increased kinetic energy to the molecules exposed, which in turn increases the possibility of collisions between molecules. These collisions result in an increased temperature of the tissue. The transmission properties of microwaves in biological tissue do not explain why certain areas in the retina should be changed because of thermal effects. The dielectric constant between the layers of the retina are different and therefore the intensities are four times greater. This could account for the damage done to the retina.

It is still not known whether these changes are due to non-thermal radiation effects. The most important discovery here is that retinal lesions resulted in a comparable loss of vision. These retinal lesions were in the paramacular and the macular region. Six out of twenty exposed workers obtained retinal lesions.

CHAPTER VI

GENERATION OF MICROWAVES

Visible light differs from radio waves in the sense that light consists not of single frequencies of constant amplitude. However, by means of the vacuum tube, coherent radio waves (single frequency and constant amplitude) can be produced. These are not like visible light waves because light is dispersed over a narrow spectrum of frequency and generally, incoherent.

Because of the large physical dimensions of the vacuum tube, it is hard to generate waves which have a short wavelength, such as microwaves. Therefore, it was necessary to design a device that would incorporate these parameters in order to generate microwaves. Such devices are the klystron and the magnetron. The major difference between the two is that the klystron has a lower output power than the magnetron. These tubes are relatively low in efficiency, so that the chief concern in microwave systems is to maximize the efficiency of the transmission line.

<u>Operation of Reflex Klystron Tubes</u> [16]

Figure 14 shows a schematic diagram of a reflex klystron and the required voltage sources for operation. The components of the klystron are the cathode, a focusing electrode with the potential as that of the cathode, a cavity resonator which is the anode and a reflector (repeller) which has a negative potential.

The indirectly heated cathode emits electrons by thermionic emission. The electrons are attracted by the resonator gap and approach the reflector. Since the reflector is negative, the electrons reverse their direction and move through the resonator gap again.

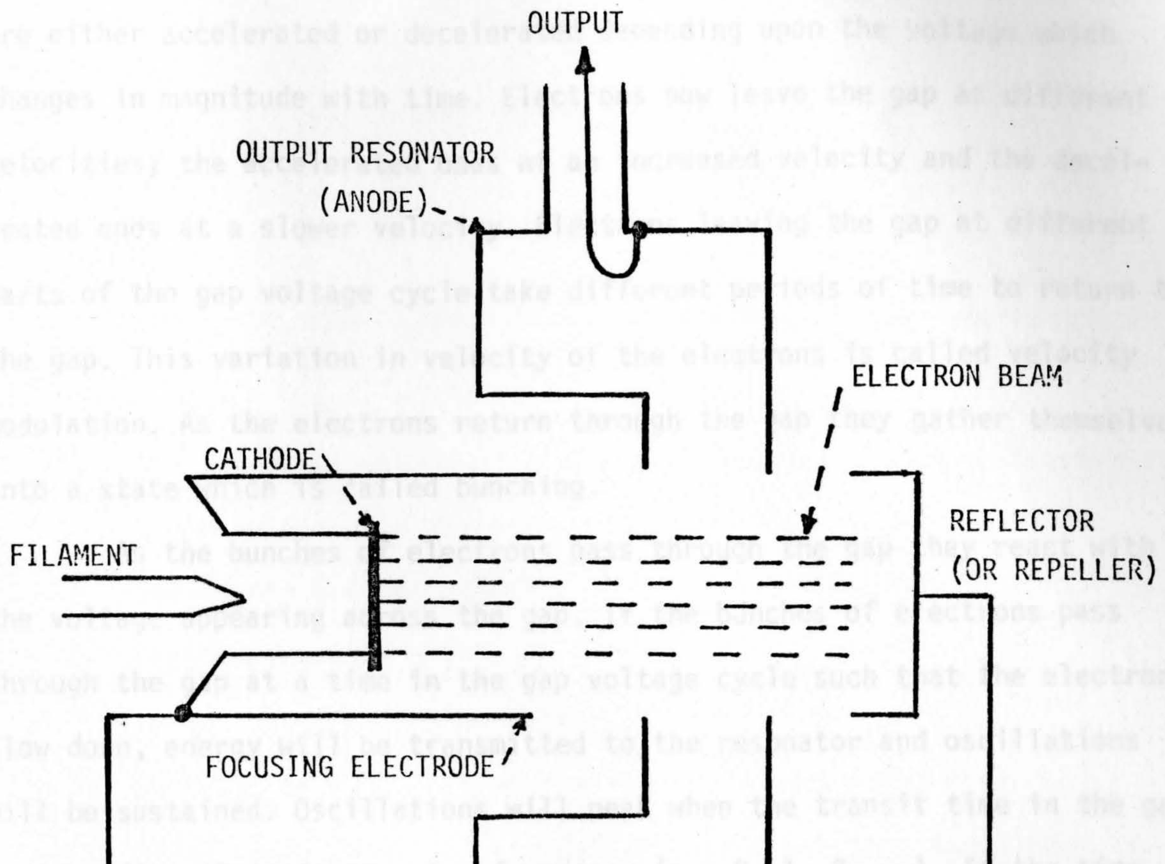

Figure 14. Cross section of a reflex klystron.

An alternating voltage appears across the gap of the resonator when the klystron is oscillating. As electrons pass through the gap, they are either accelerated or decelerated depending upon the voltage which changes in magnitude with time. Electrons now leave the gap at different velocities; the accelerated ones at an increased velocity and the decelerated ones at a slower velocity. Electrons leaving the gap at different parts of the gap voltage cycle take different periods of time to return to the gap. This variation in velocity of the electrons is called velocity modulation. As the electrons return through the gap they gather themselves into a state which is called bunching.

As the bunches of electrons pass through the gap they react with the voltage appearing across the gap. If the bunches of electrons pass through the gap at a time in the gap voltage cycle such that the electrons slow down, energy will be transmitted to the resonator and oscillations will be sustained. Oscillations will peak when the transit time in the gap is $n + 3/4$ cycles of resonator frequency ($n = 0, 1, 2, \ldots$). If the time of transit in the anode-reflector region is such as to cause the bunches to arrive at a time when they will be accelerated by the gap voltage, energy is removed from the resonator and oscillation will tend to stop.

There are two ways to generate oscillations at a given frequency. The first way is to vary the transit time in the anode-reflector space to a suitable value. This is accomplished by adjusting the reflector voltage. (As the reflector voltage becomes more negative, the transit time decreases). The second way is to change the resonator's physical dimensions. This is done by turning a screw on the klystron which directly changes the resonator's size. Most tubes can vary several per cent in frequency by these methods.

CHAPTER VII

MEASUREMENT OF DIELECTRIC CONSTANT

Methods [17]

There are several methods for determining the dielectric constant. They are:

A. The two point method of measuring dielectric constant involving the solution of a transcendental function.

B. Two reactive terminations.

C. Cavity methods.

D. Cavity perturbation methods.

E. Methods for high loss materials and ferromagnetic materials.

F. A method for determining the dielectric constant independent of the length or location of the sample.

Each method has advantages and disadvantages. For instance, some methods are more suitable for high loss materials than for lossless materials. Some methods require special equipment and techniques while others need only standard microwave equipment.

Since the two point method is most widely used today, a complete procedure section is included to determine the dielectric constant. Since precise machining of the samples is required and that the microwave components are limited in the laboratory, a laboratory experiment to determine the transmissivity of several materials was alternately performed. The results obtained are included in the next chapter.

Two Point Method of Measuring Dielectric Constant

This method of measuring dielectric constant is most advantageous for "lossless" or medium loss dielectrics. This method is widely used because it does not require special equipment or techniques. The material being tested is assumed to have a complex dielectric constant. Note that in the lossless case the VSWR is infinite.

Figure 15 shows theoretically what is happening using this method. The equipment consists of an empty waveguide with a short-circuit as the termination. A probe is placed at a voltage minimum, designated by D_R.

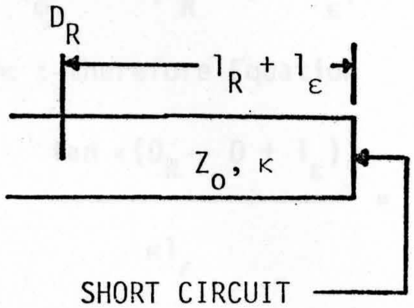

Figure 15. Dielectric Constant Measurement with Short-Circuited Waveguide. Sample excluded.

Figure 16 shows the same waveguide with a dielectric sample placed inside the waveguide with a length "l_ε". The probe is moved to a new voltage minimum "D".

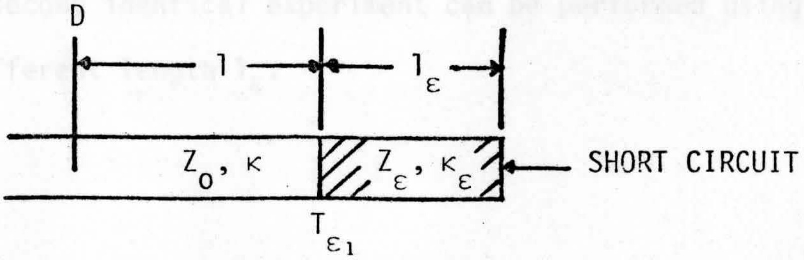

Figure 16. Dielectric Constant Measurement with Short-Circuited Waveguide. Sample included.

Looking from T_{ε_1}, the beginning of the sample towards the right and the left, the impedance equation is

$$Z_o \tan \kappa l = - Z_\varepsilon \tan \kappa_\varepsilon l_\varepsilon \tag{15}$$

In Figure 15 with no sample in the waveguide, the impedance equation is

$$Z_o \tan \kappa(l_R + l_\varepsilon) = 0. \tag{16}$$

Consider

$$\begin{aligned} \tan \kappa(D_R - D + l_\varepsilon) &= \tan \kappa\{(l_R + l_\varepsilon) - (l + l_\varepsilon) + l_\varepsilon\} \\ &= \tan \kappa\{(l_R + l_\varepsilon) - l\} \end{aligned}$$

Expanding the tangent and using Equation 16 gives

$$Z_o \tan \kappa(D_R - D + l_\varepsilon) = Z_\varepsilon \tan \kappa_\varepsilon l_\varepsilon \tag{17}$$

But $Z_o / Z_\varepsilon = \kappa_\varepsilon / \kappa$; therefore Equation can be rewritten as

$$\frac{\tan \kappa(D_R - D + l_\varepsilon)}{\kappa l_\varepsilon} = \frac{\tan \kappa_\varepsilon l_\varepsilon}{\kappa_\varepsilon l_\varepsilon} \tag{18}$$

All values associated with the left-hand side are measurable, while the right-hand side is of the form tan Z/Z. Once the measurement is performed, the complex number $Z = \kappa_\varepsilon l_\varepsilon$ is determined by the result of the transcendental equation and from this, κ_ε and ε_r can be found. Since the tangent function is periodic, there are an infinite amount of solutions for ε_r. It is necessary to approximately know ε_r. If this is not possible, a second identical experiment can be performed using a sample with a different length l_ε.

Equipment

The equipment used in determining the dielectric constant is shown in Figure 17. The slotted line is followed by a short circuited length of waveguide. In one part of the experiment the sample is placed adjacent to the short circuit; the other part of the experiment is with the sample removed from the waveguide.

To obtain the optimum results, the sample should have a length of $\lambda_{g\varepsilon}/4$, i.e., one quarter of the wavelength in the dielectric-filled waveguide. To compute this length, the dielectric constant (relative) ε_r must be known approximately. $(\lambda_{g\varepsilon}/4 = \pi/2\kappa_{\varepsilon})$

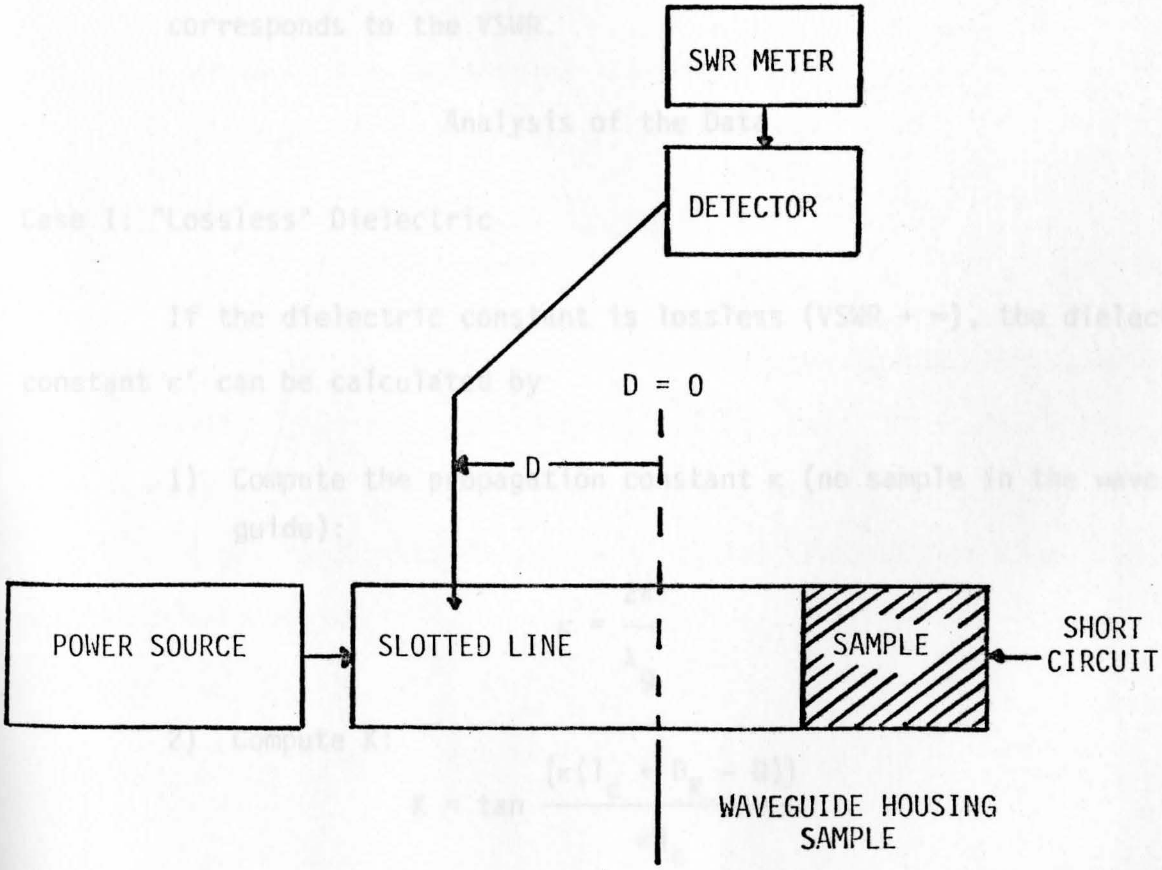

Figure 17. Two Point Method of Determining Dielectric Constant.

Procedure

A. Connect the equipment as shown in Figure 17 . (Do not insert the sample into the waveguide at this time).

B. Find D_R, the position of the minimum voltage point in the slotted line. This is accomplished by moving the probe in the slotted line until a maximum meter deflection is observed on the SWR meter. The reference control on the SWR meter is then set to a value of 1.0 and the probe is moved until a null is observed.

C. Measure the guide wavelength, λ_g. This is the distance between two nulls.

D. Place the sample into the waveguide so that it touches the short circuit.

E. Measure "D" as in step B with respect to the reference plane (D = 0). The minimum point, or null as observed on the SWR meter, corresponds to the VSWR.

Analysis of the Data

Case I: "Lossless" Dielectric

If the dielectric constant is lossless (VSWR $\rightarrow \infty$), the dielectric constant ε' can be calculated by

1) Compute the propagation constant κ (no sample in the waveguide):

$$\kappa = \frac{2\pi}{\lambda_g} \tag{19}$$

2) Compute K:

$$K = \tan \frac{(\kappa(l_\varepsilon + D_R - D))}{\kappa l_\varepsilon} \tag{20}$$

3) Solve the transcendental equation, (21), for "X":

$$K = \frac{\tan X}{X} \tag{21}$$

The above equation can be solved by plotting values of (tan X)/X vs X and determining graphically the values of (tan X)/X (and corresponding values of X) equal to "K" found in Equation (20).

If the sample was placed in rectangular waveguide, the dielectric constant is :

$$\varepsilon' = \frac{(a/\pi)^2 (X'/l_\varepsilon)^2 + 1}{(2a/\lambda_g)^2 + 1} \tag{22}$$

where

a = width of the rectangular waveguide

λ_g = guide wavelength in the empty waveguide

$\frac{X'}{l_\varepsilon} = \frac{\text{X (determined in step 3, above)}}{\text{length of sample}}$

If the sample was placed in a circular waveguide, the value of "a" in Equation (22) is replaced by 1.705 R, where "R" is the radius of the waveguide.

If the sample was placed in a coaxial transmission line, the dielectric constant is:

$$\varepsilon' = \frac{1}{\kappa^2}\left[\frac{X'}{l_\varepsilon}\right]^2, \quad \kappa = \frac{2\pi}{\lambda_g} \tag{23}$$

Example

From the previous procedure, the following data was obtained:

$a = 0.9''$, $l_\varepsilon = 0.4497''$, $\lambda_g = 1.7628''$, $D_R = 0.1842''$, $D = 0.693''$

It is known that $\varepsilon' \simeq 2$.

Equation (19): $\kappa = \dfrac{2\pi}{1.7628} = 3.5643$

Equation (20): $K = \dfrac{\tan\left(3.5643\,(0.4497 + 0.1842 - 0.693)\right)}{(3.5643)(0.4497)} = -0.1334$

The solutions for "X" are found to be 2.786, 5.638,...

Picking 2.786:

$$\varepsilon' = \frac{(0.9/\pi)^2(2.786/0.4497)^2 + 1}{\left((2)(0.9)/1.7628\right)^2 + 1} = 2.032$$

Case II: Complex ("Lossy") Dielectric

If the dielectric constant is complex ($\text{VSWR} \neq \infty$), the below procedure can be followed:

1) Determine: $\kappa = \dfrac{2\pi}{\lambda_g}$ (24)

2) Compute: $\Phi = 2\kappa(D - D_R - l_\varepsilon)$ (25)

3) Compute: $|\Gamma| = \dfrac{\text{VSWR} - 1}{\text{VSWR} + 1}$ (26)

4) Determine the complex number $C\underline{/\psi}$ from:

$$C\underline{/-\psi} = \frac{1}{j\kappa l_\varepsilon} \cdot \frac{1 - |\Gamma| e^{j\Phi}}{1 + |\Gamma| e^{j\Phi}} \tag{27}$$

5) Solve the transcendental equation for "T" and "τ":

$$C\angle -\psi = \frac{\tanh (T\angle \tau)}{T\angle \tau} \tag{28}$$

The quantities ψ, τ, and $(T/\kappa l_\varepsilon)^2$ fall into the following ranges:

$0 < \psi < 180^0$; $45^0 < \tau < 90^0$; $(T/\kappa l_\varepsilon)^2 > 1$

The admittance determinant Y_ε is obtained by:

$$Y_\varepsilon = (T/\kappa l_\varepsilon)^2 \angle 2(\tau - 90^0) \tag{29}$$

6) Compute ε_r using the value of Y_ε from the above equation.

An Approximate Solution for the Complex Transcendental Equation

With values of κ, $|\Gamma|$, and Φ calculated, the solution of the transcendental function can be approximated by the following procedure with good accuracy. One must assume that the dielectric loss is very small (τ is close to 90 degrees). The first step is to determine the constants "K" and "A" in the following equations:

$$K = \frac{-2\,|\Gamma|\,\sin\Phi}{\kappa l_{\varepsilon}\,(1 + |\Gamma|^2 + 2\,|\Gamma|\cos\Phi)} \tag{30}$$

$$A = \frac{|\Gamma|^2 - 1}{\kappa l_{\varepsilon}\,(1 + |\Gamma|^2 + 2\,|\Gamma|\cos\Phi)} \tag{31}$$

Solve for "X" in Equation (21) and find "R" in the following equation:

$$R = \frac{AX'^2}{\tan X' - X'(1 + \tan^2 X')} \tag{32}$$

and compute K'

$$K' = \frac{R \tanh R\,(1 + \tan^2 X') + X' \tan X'\,(1 - \tanh^2 R)}{(R^2 + X'^2)\,(1 + \tanh^2 R \tan^2 X')} \tag{33}$$

If "K" and "K'" are almost identical, the approximation is good. If they are not this method fails. "T" and "τ" can be found by:

$$T = \sqrt{R^2 + X'^2} \quad ; \; \tau = \tan^{-1}(X'/R), \quad 45^0 < \tau < 90^0 \tag{34}$$

and proceeding with Equation (29).

CHAPTER VIII

TRANSMISSIVITY OF MICROWAVES THROUGH VARIOUS MATERIALS

Laboratory Measurements

The purpose of this experiment was to determine the amount of microwave energy that can propagate through several common materials. By knowing the amount of microwave transmissivity through a material, better design of microwave equipment is possible.

The equipment used in measuring the transmissivity is shown in Figure 18. Waveguide was used for the transmission of the microwaves. The microwave generator was a surplus "2K25" reflex klystron tube. The voltage applied to the beam of the tube was 250 volts, the reflector voltage was 150 volts, the DC cathode current was 21 mA., and the reflector was modulated with 60 Hz. sine wave. (For a discussion on the operation of a klystron tube see Chapter VI).

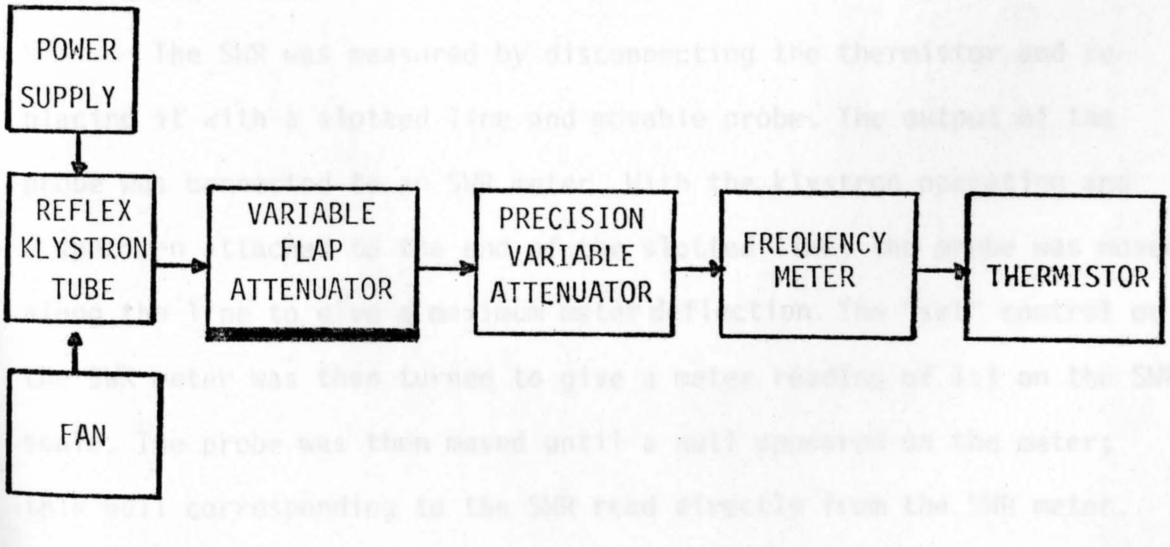

Figure 18. Block diagram of the equipment used in measuring the transmissivity of microwaves.

With the thermistor removed, a crystal detector was placed at the end of the waveguide. The output of the crystal detector was DC coupled to the vertical input of an oscilloscope. The frequency was determined by tuning the frequency meter until a "pip" was observed on the screen of the oscilloscope. A frequency of 9.5 GHz. was read directly on the frequency meter.

The crystal detector was removed and the thermistor was placed back on the end of the waveguide. The output of the thermistor was connected to a microwave power meter. Sufficient time was allowed to stabilize the thermistor. With the klystron in operating condition, the variable flap attenuator was set at 5.0 dB and the precision variable attenuator at 1.9 dB to give an output of 1.0 mW. to the thermistor.

The different specimens were connected between the waveguide ends of the precision variable attenuator and the frequency meter. In a previous attempt of the experiment the specimen was placed between the frequency meter and the thermistor. This method gave erroneous results because every time the thermistor was touched, the temperature would change.

The SWR was measured by disconnecting the thermistor and replacing it with a slotted line and movable probe. The output of the probe was connected to an SWR meter. With the klystron operating and a specimen attached to the end of the slotted line, the probe was moved along the line to give a maximum meter deflection. The "set" control on the SWR meter was then turned to give a meter reading of 1:1 on the SWR scale. The probe was then moved until a null appeared on the meter; this null corresponding to the SWR read directly from the SWR meter.

The results are tabulated in Table 4. It appears that the only safe attenuator for microwaves is aluminum foil or steel. Other materials are relatively transparent to microwaves. Therefore in the design of microwave equipment, metals should be used to keep radiation from leaking out.

TABLE 4

TRANSMISSIVITY OF MICROWAVES THROUGH VARIOUS MATERIALS

Material	Power to thermistor in mW.	SWR
Reference	1.0	1.85
Polyethylene	0.85	2.0
Plexiglas	0.61	3.6
Fiberglass	0.6	>4.0
Bakelite	0.58	4.0
Paper	1.0	1.88
Cardboard	0.7	2.25
Aluminum Foil	0.0	∞
Steel	0.0	∞
Plastic	0.8	3.02
Teledostos Paper	0.7	1.98
Styrafoam	0.89	1.85

Propagation of Plane Waves through Two Parallel Dielectric Sheets [18]

Consider a plane electromagnetic wave propagating through two parallel dielectric sheets in a normal direction to that of the dielectric boundaries. Standing waves will be set up between the two sheets. The region between the sheets is analogous to an animal exposed to microwave radiation.

When any tests involving microwave radiation are performed, it is important that the power density or exposure rate be defined. It is easy to measure the power density from a microwave radiator of known gain, such as a horn antenna; but when an animal is placed in the field of the antenna, dielectrics are usually required to support the animal. Dielectrics inherently cause reflections in the field and hence complicate power density measurements.

Plexiglas sheets with thicknesses of 1/8, 3/16 and 1/4 inch placed in the field of a horn antenna caused up to a 11 dB change in power density. Two plexiglas spheres in a similar field of 2450 MHz. plane waves caused a 19 dB deviation in field strength. This gives evidence that dielectrics cause reflections in a electromagnetic field.

For this particular experiment, two dielectric sheets of the same thickness "d" were separated by a distance "L", as shown below.

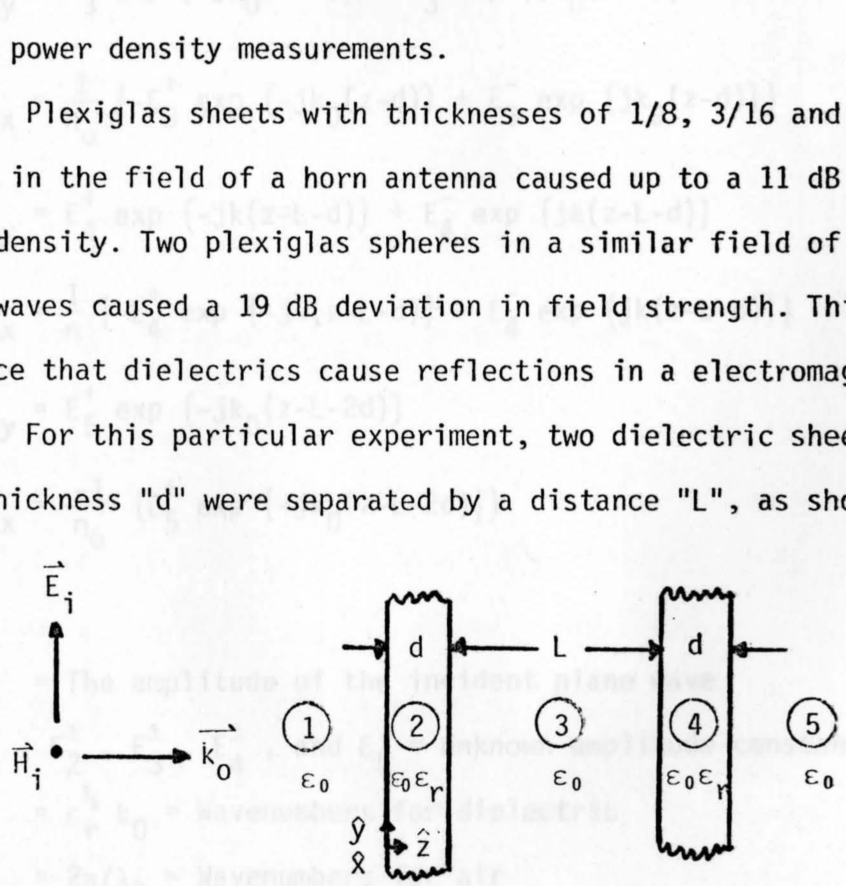

Figure 19. Plane wave propagating through dielectric sheet model.

The Z = 0 reference plane is the first boundary between air and the dielectric. Plane electromagnetic waves travel through the system normal to the boundaries of the dielectrics. The "E" and the "H" fields for the five different regions in Figure 19 are given in the equations below.

$$E_{1y} = E_i \exp(-jk_0 z) + E_1^- \exp(jk_0 z) \tag{35}$$

$$H_{1x} = \frac{1}{\eta_o} \{-E_i \exp(-jk_0 z) + E_1^- \exp(jk_0 z)\} \tag{36}$$

$$E_{2y} = E_2^+ \exp(-jkz) + E_2^- \exp(jkz) \tag{37}$$

$$H_{2x} = \frac{1}{\eta} \{-E_2^+ \exp(-jkz) + E_2^- \exp(jkz)\} \tag{38}$$

$$E_{3y} = E_3^+ \exp\{-jk_0(z-d)\} + E_3^- \exp\{jk_0(z-d)\} \tag{39}$$

$$H_{3x} = \frac{1}{\eta_o} \{-E_3^+ \exp(-jk_0(z-d)) + E_3^- \exp(jk_0(z-d))\} \tag{40}$$

$$E_{4y} = E_4^+ \exp(-jk(z-L-d)) + E_4^- \exp(jk(z-L-d)) \tag{41}$$

$$H_{4x} = \frac{1}{\eta} \{-E_4^+ \exp(-jk(z-L-d)) + E_4^- \exp(jk(z-L-d))\} \tag{42}$$

$$E_{5y} = E_5^+ \exp(-jk_0(z-L-2d)) \tag{43}$$

$$H_{5x} = \frac{-1}{\eta_o} (E_5^+ \exp\{-jk_0(z-L-2d)\}) \tag{44}$$

where

E_i = The amplitude of the incident plane wave

E_1^-, $E_2^\pm$, $E_3^\pm$, $E_4^\pm$, and E_5 = Unknown amplitude constants

$k = \varepsilon_r^{1/2} k_0$ = Wavenumbers for dielectric

$k_0 = 2\pi/\lambda_0$ = Wavenumbers for air

λ_0 = Free space wavelength

ε_r = Relative permittivity of the dielectric material

$\eta = \eta_o/\varepsilon_r^{1/2}$ = Wave impedance

$\eta_o = (\mu_o/\varepsilon_o)^{1/2}$ = Wave impedance

In region "5" all the power is transmitted with no reflections present. The incident wave in region "1" is vertically polarized. From the "E" and "H" equations for the five regions, boundary conditions can be applied by equating the tangential components of the "E" and "H" fields E_y and H_x to the various air-dielectric boundaries. These boundaries are z = 0, d, L + d, and L + 2d. The result with E_1^- removed is:

$$\begin{bmatrix} 1+n & 1-n & 0 & 0 & 0 & 0 \\ \exp(-jkd) & \exp(jkd) & -1 & 0 & 0 & 0 \\ n\exp(-jkd) & -n\exp(jkd) & -1 & 0 & 0 & 0 \\ 0 & 0 & -\exp(-jk_0L) & 1 & 1 & 0 \\ 0 & 0 & -\exp(-jk_0L) & n & -n & 0 \\ 0 & 0 & 0 & \exp(-jkd) & \exp(jkd) & -1 \\ 0 & 0 & 0 & n\exp(-jkd) & -n\exp(jkd) & -1 \end{bmatrix} \cdot \begin{bmatrix} E_2^+ \\ E_2^- \\ E_3^+ \\ E_3^- \\ E_4^+ \\ E_4^- \\ E_5^+ \end{bmatrix} = \begin{bmatrix} 2E_i \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

where $n = \varepsilon_r^{1/2}$ = Refractive index of the dielectric.

To determine the field between the two dieleectric sheets, the above matrix must be solved for E_3^+ and E_3^-. If the sheets are separated by any multiple of a half-wavelength $m\lambda_0/2$, then $k_0L = m\pi$. This reduces the matrix to the following equation:

$$\left|\frac{E_{3y}}{E_i}\right|^2 = \frac{\begin{array}{c} 4n^2\left(\cos k_0(z-d)\cos kd + \sin k_0(z-d)\sin kd\right)^2 + \ldots \\ \ldots + \left(\cos k_0(z-d)\sin kd - n\sin k_0(z-d)\cos kd\right)^2 \end{array}}{4n^2\cos^2 2kd + (1+n^2)^2\sin^2 2kd} \tag{45}$$

Equation(45)can be plotted against (z-d) for values of relative permittivity ε_r, and sheet thickness "d"; a standing wave in the form of a sinusoidal is shown with maximum and minimum values in figure 20. $(|E_{max}|/|E_{min}|)^2$ is the standing wave ratio for the field between two sheets. (See figure 20.). The ratio d/λ is the normalized thickness; with $\lambda = \lambda_0/\varepsilon_r^{1/2}$ representing the wavelength within the dielectric (Bakelite, Plexiglas, Teflon, and Styrofoam).

By changing the distance "L" between the dielectric sheets does not change the SWR (Standing Wave Ratio). The values of $|E_{max}|^2$ and $|E_{min}|^2$ change, but in equal proportions. Therefore the results found in figure 20 are for any sheet separation.

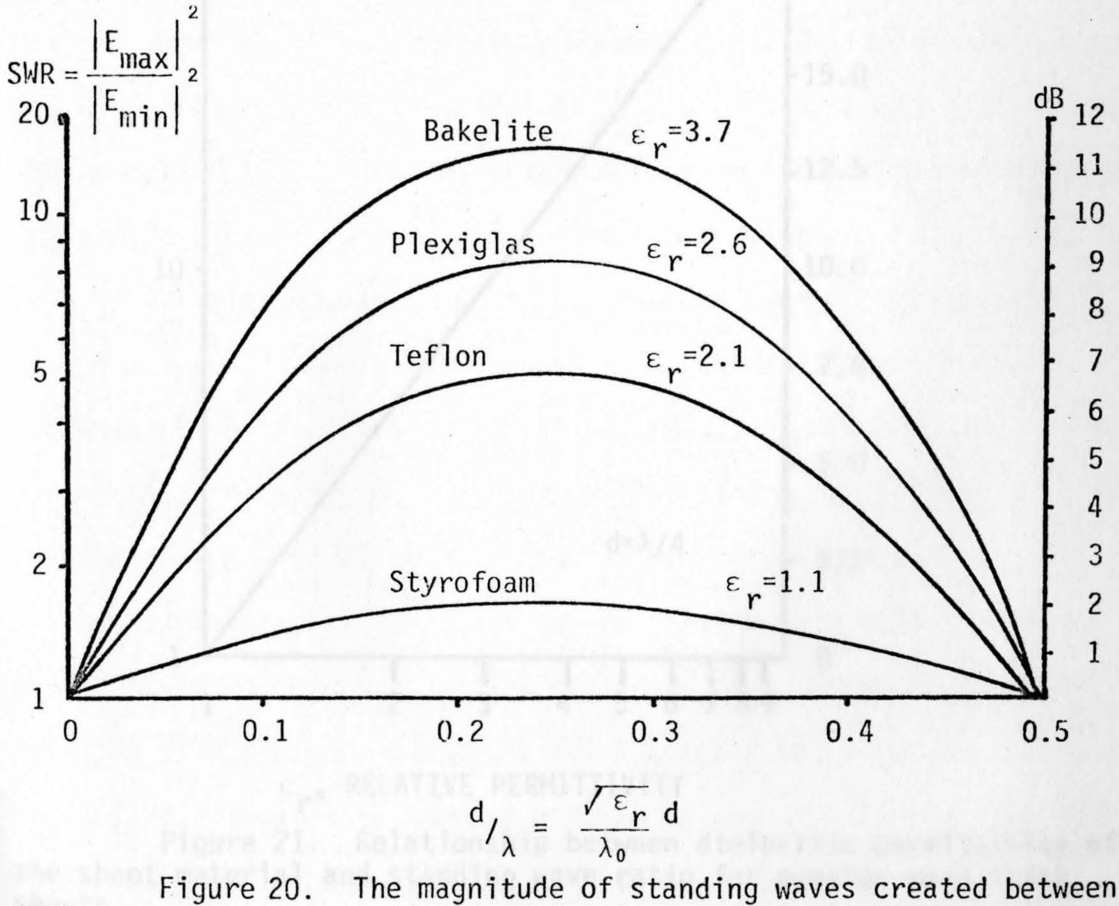

Figure 20. The magnitude of standing waves created between dielectric sheets as a function of normalized sheet thickness.

Figure 21 shows what happens when the dielectric permittivity ε_r increases with the dielectric thickness equaling a quarter-wavelength within the dielectric $d = \lambda/4$. It is apparent from looking at Figures 20 and 21 that standing waves are present between dielectric sheets. The SWR is proportional to the relative permittivity ε_r and is dependent on the sheet thickness. In conclusion, The SWR is maximum when $d = \lambda/4$ and zero when $d = \lambda/2$. Therefore a material of low permittivity, such as styrofoam, should be used in power density experiments.

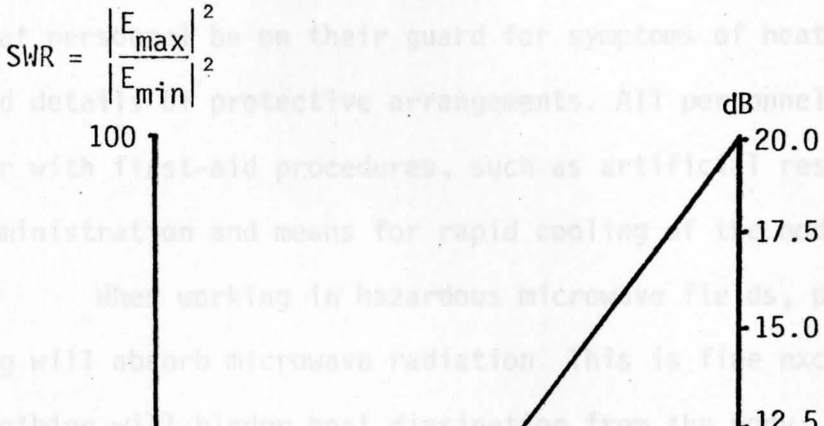

Figure 21. Relationship between dielectric permittivity of the sheet material and standing wave ratio for quarter-wave-thick sheets.

Methods of Microwave Protection [19]

The maximum safe power flux for personnel is considered to be 0.01 W/cm^2 over the entire frequency range, although this value is provisionally accepted. For areas with a power flux greater than this value, fences or other barriers should be erected to keep unauthorized people from entering. For personnel working in these hazardous areas a code of practice should be followed; this includes minimum safe distances, familiarization of the dangers that are present, a request that personnel be on their guard for symptoms of heat or discomfort and details of protective arrangements. All personnel should be familiar with first-aid procedures, such as artificial respiration, oxygen administration and means for rapid cooling of the body.

When working in hazardous microwave fields, personnel's clothing will absorb microwave radiation. This is fine except that the clothing will hinder heat dissipation from the body. Therefore clothing should be worn made out of a reflective material.

The eyes should be protected from microwave radiation by the use of a special face shield or goggles. Materials that should be used must be optically transparent but opaque to microwaves. Table 5 gives shielding properties of several materials. This table represents reflection and absorption of microwave energy by listing the power transmission factors. It is easily seen that as microwave shielding is increased so is visible light shielding. The attenuation of the metallic film depends upon their thickness and the frequency. A suitable pair of goggles would have a lense coated with a gold film and a wire mesh on the sides. The 3.2% visible light transmission for

for gold film (75 mμ thick on glass) is good for outdoor work or indoors in well-lighted rooms. Exposure to direct radiation can be avoided by periscopes or closed-circuit television.

TABLE 5

SHIELDING PROPERTIES OF SEVERAL MATERIALS

Material	Power-transmission factor at			
	5.9 GHz %	9.7 GHz %	18.8 GHz %	0.55 μ %
Gold film, 11 mμ thick on plastic (300 Ω/square)	23.0	10.0	0.8	49.0
Gold film, 30 mμ thick on plastic (12 Ω/square)	0.16	0.1	0.01	24.0
Gold film, 75 mμ thick on glass (1.5 Ω/square)	0.04	0.01	0.004	3.2
Corning glass, 1.5μ conductive coating (15 Ω/square)	1.6	1.2	0.08	45.0
Electraplane glass, 300 mμ conductive coating (70 Ω/square)	9.0	10.0	8.0	80.0
Copper mesh (20 per inch)	0.1	0.2	0.2	50.0
Copper mesh (8 per inch)	1.0	1.3	2.5	60.0

$1\ \mu = 10^{-6}$ meters

CHAPTER IX

SUMMARY

A description of biological effects and health hazards has been presented along with a method for measuring the transmissivity of several common materials. This method was approximate; a more accurate method requires precision machining of the sample, special equipment, etc.

Frequency and wavelength are inversely related. The depth of penetration is dependent upon the frequency or wavelength and the properties of the material, i.e., the relative permittivity and the conductivity. It was concluded that as the frequency increases, the depth of penetration decreases; thus they are inversely related. Since frequency and wavelength are inversely related, the depth of penetration is then related to the wavelength. Permittivity and conductivity values are greater when the tissue is at a higher temperature. When a biological tissue is exposed to an increasing microwave frequency, the values for the permittivity decrease while the values for the conductivity increase.

Any material with a water content will absorb microwaves and convert them to heat. This heat can cause damage to tissue if it is excessive. The velocity of blood flow increased [4] when tissues were exposed to microwaves. This suggests that the blood acts as a heat-dissipating mechanism.

The model of the human skull had peaks of power absorption when the amplitude of the standing waves was at a maximum value [5]. At these peaks, the brain is most susceptible to damage. Inadvertently, these peaks occur around 2.1 GHz; close to the frequency used in most microwave ovens which is 2.45 GHz. Since most microwave ovens leak some amount of energy, the frequency of operation should be changed such that a null exists in power absorbed rather than a peak. From Figures (6) and (7), a frequency of 1.6 GHz. would appear to be less hazardous.

Today, pacemaker patients are relatively safe in a field of microwaves with a field stength of 75.0 Volts/meter. This ia a conservative value since this value was obtained under worst possible conditions. The results from the experiment [6] indicate that a higher microwave frequency can be more dangerous than a lower one.

Microwave ovens are permitted to leak a power density of 1.0 mW per cm^2 when they are new and 5.0 mW/cm^2 when they are considered old, whenever that is, as set by the United States Department of Health, Education and Welfare. This is in contrast with the Russian's safe power level of 0.01 mW/cm^2! Better engineering design and safer operating procedures of microwave ovens must be followed to make them less dangerous.

Microwave antennae should be placed where they will not cause a dangerous field for individuals near the antenna. Ground reflections should be minimized and measurements should be conducted as to where fences should be erected to keep unauthorized personnel from entering a hazardous field.

Little is known about the non-thermal effects of microwave absorption. Individuals that were in contact with microwave energy which could not detect any thermal heating, had ailments ranging anywhere from irritability to loss of memory; giving evidence that there is a correlation between microwaves and adverse body reactions.

The composition of blood was also altered when an individual was exposed to microwave radiation. Ailments such as heart pain, a change in blood pressure and alterations in the protein of the blood were attributed to microwaves. [9]

Neural effects such as headache, fatigue and anxiety were found in individuals exposed to microwaves. Brain wave patterns (EEG) were distorted in individuals that were exposed to microwave radiation.

The eye is especially vulnerable, as is any other tissue containing little or no blood vessels, to microwave radiation. This is due to the fact that blood acts as a coolant to dissipate microwave-induced heat. The long-term effects of microwave absorption are not completely known but there have been reported cases of eye damage years after exposure [14]. The damage most frequently occurring to a microwave irradiated eye is a cataract.

The two point method [17] of measuring the dielectric constant is especially suited for lossless or medium-loss dielectrics. Advantages of employing this method are that special equipment and techniques are not required.

The simplified method of determining transmissivity through materials gave approximate results as compared with the two point method. In this method the sample was "sandwiched" between two ends of waveguide with aluminum foil wrapped around the connection to prevent microwave leakage. The results indicated that paper did not impede the propagation of microwaves while aluminum foil did. Thus it is evident that metals reflect microwaves and should be considered when designing microwave equipment. The SWR increased when the amount of microwave transmissivity decreased; making them inversely related. This proves that energy which is not propagated through the material is reflected back through the transmission line, in this case, waveguide.

When selecting materials that are to be placed in microwave fields, it is imperative to select one with a low permittivity. Styrofoam, with a permittivity of 1.1, gives excellent results. Also, the thickness of the sheets should be as close to half of the wavelength as possible. This minimizes the SWR so that accurate results can be obtained when making tests on animals exposed to microwaves.

When working in microwave fields, all parts of the body should be protected. Clothes with a metallic content are excellent since they will reflect microwaves. Eye goggles should be designed to give good visible light transmission and simultaneously to suppress microwaves. Goggles designed to do this would have lenses coated with gold film and a wire mesh on the sides.

More work must be done to determine the interactions of microwave radiation with biologic systems. Specifically [20]:

A. An investigation into the occurrence of cumulative effects and delayed effects.

B. A study of low-intensity effects.

C. Determination of possible threshold values.

D. A study of combined effects of radiation and other environmental factors.

E. Investigation of differential radiation sensitivity as a function of organ system and age or intrauterine development.

F. A study of effects related to cellular transformations.

G. A study of effects occuring at the molecular level.

H. The determination of absorbed energy dose and its spatial distribution.

REFERENCES

[1] Sol M. Michaelson, "The Tri-Service Program - A Tribute to George M. Knauf, USAF (MC)," IEEE Trans. Microwave Theory Tech., vol. MTT-19, pp. 131-144, February 1971.

[2] Herman P. Schwan, "Microwave Radiation: Biophysical Considerations and Standards Criteria," IEEE Trans. Biomed. Eng., vol. BME-19, pp. 304-312, July 1972.

[3] A. F. Harvey, Microwave Engineering. New York: Academic Press, 1963, pp. 973-990.

[4] ibid, pp. 973-990.

[5] William T. Joines and Ronald J. Spiegel, "Resonance Absorption of Microwaves by the Human Skull," IEEE Trans. Biomed. Eng., vol. BME-21, pp. 46-48, January 1974.

[6] Charles H. Bonney, Pedro L. Rustan, Jr., and Gary E. Ford, "Evaluation of Effects of the Microwave Oven (915 and 2450 MHz) and Radar (2810 and 3050 MHz) Electromagnetic Radiation on Noncompetitive Cardiac Pacemakers," IEEE Trans. Biomed. Eng., vol. BME-20, pp. 357-364, September 1973.

[7] Don Mennie, "Microwave Ovens: What's Cooking?" IEEE Spectrum, vol. 12, pp. 34-39, March 1975.

[8] A. F. Harvey, Microwave Engineering. New York: Academic Press, 1963, pp. 973-990.

[9] M. N. Sadcikova, "Clinical Manifestations of Reactions to Microwave Irradiation in Various Occupational Groups," a paper presented at Proceedings of an International Symposium on Biologic Effects and Health Hazards of Microwave Radiation, October 15-18, 1973, Warsaw, Poland.

[10] E. Klimková-Deutschová, "Neurolgic Findings in Persons Exposed to Microwaves," a paper presented at Proceedings of an International Symposium on Biologic Effects and Health Hazards of Microwave Radiation, October 15-18, 1973, Warsaw, Poland.

[11] A. F. Harvey, Microwave Engineering. New York: Academic Press, 1963, pp. 973-990.

[12] R. L. Carpenter, E. S. Ferri and G. J. Hogan, "Assessing Microwaves as a Hazard to the Eye - Progress and Problems," a paper presented at Proceedings of an International Symposium on Biologic Effects and Health Hazards of Microwave Radiation, October 15-18, 1973, Warsaw, Poland.

[13] Leo Birenbaum, Gerard M. Grosof, Saul W. Rosenthal and Milton M. Zaret, "Effect of Microwaves on the Eye," IEEE Trans. Biomed. Eng., vol. BME-16, pp. 7-14, January 1969.

[14] M. M. Zaret, "Selected Cases of Microwave Cataract in Man Associated with Concomitant Annotated Pathologies," a paper presented at Proceedings of an International Symposium on Biologic Effects and Health Hazards of Microwave Radiation, October 15-18, 1973, Warsaw, Poland.

[15] B. Tengroth and E. Aurell, "Retinal Changes in Microwave Workers," a paper presented at Proceedings of an International Symposium on Biologic Effects and Health Hazards of Microwave Radiation, October 15-18, 1973, Warsaw, Poland.

[16] Irving L. Kosow, Microwave Theory and Measurements. Englewood Cliffs, N. J.: Prentice-Hall, 1962, pp. 45-47.

[17] Max Sucher and Jerome Fox, Handbook of Microwave Measurements . New York: John Wiley and Sons, 1963, pp. 495-508.

[18] Claude M. Weil, "Propagation of Plane Waves Through Two Parallel Dielectric Sheets," IEEE Trans. Biomed. Eng., vol. BME-21, pp. 165-168, March 1974.

[19] A. F. Harvey, Microwave Engineering. New York: Academic Press, 1963, pp. 973-990.

[20] ——, Biologic Effects and Health Hazards of Microwave Radiation. Poland: Polish Medical Publishers, 1974, pp. 334-335.