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MORTALITY IN RATS EXPOSED TO CW MICROWAVE RADIATION AT 0.95, 2.45, 4.54, AND 7.44 GHz

P. Polson, et al

Stanford Research Institute

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/a

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MORTALITY IN RATS EXPOSED TO CW MICROWAVE RADIATION AT 0.95, 2.45, 4.54, AND 7.44 GHz

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ABSTRACT

Dose-response (lethality) data have been obtained for rats exposed frontally to CW microwave radiation in the frequency range 0.9 to 8 GHz. Approximately 1400 male rats of the Sprague-Dawley strain have been exposed in equal groups to four separate frequencies: 0.95, 2.45, 4.54, and 7.44 GHz. Power density levels have ranged from approximately 0.2 W/cm^2 to 12 W/cm^2, and lethal exposure durations from approximately 10 sec to 300 sec. Gross and histologic evaluation of selected tissues from some 20 animals has been obtained. The cause of death has been established as congestion, hemorrhage, and obstruction of nasal passages and/or congestion, hemorrhage, and often edema of the lungs. The lethality data have been subjected to a probit analysis, yielding LD_{50} curves for each of the four frequencies, and the LD_{50} values have been empirically fitted with a mathematical model. The LD_{50} curves very closely approximate the shape of rectangular hyperbolae.

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I INTRODUCTION

Despite the vast literature that exists on the biological effects of microwave radiation,[1,2*] there appears to be very little reliable quantitative data published on microwave lethality. Many researchers have included baseline mortality studies in their work,[3] but such results have frequently taken the form of time-to-death under various exposure conditions. However, because the different exposure facilities were oriented to other than lethality studies, it is difficult to obtain quantitative comparisons between the results. In addition, such studies do not present mortality data for durations less than several minutes.

There appear to be only two exceptions to the general statements above. The first is a series of reports from the University of California, Berkeley,[4,5,6] part of the research carried out under the Joint Tri-Service Program on Biological Effects of Microwave Energy. Mice were exposed over the entire ventral surface to 3-cm pulsed microwave radiation at various average power densities from 0.05 to 0.5 W/cm^2. Experimental LD_{50} data were obtained for exposure durations ranging from approximately 2 to 12 min. These results are also noteworthy because an attempt was made to fit the experimental data with an exponential mathematical model.

The second exception is the recent preliminary report of research carried out by Walter Reed Army Institute of Research.[7] Rats were

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[*] References are listed at the end of the report.

irradiated with 10-cm-wavelength CW microwave radiation, with power densities ranging from 0.40 to 2.40 W/cm^2. The corresponding exposure durations ranged from 30 to 240 sec. Again, a single frequency LD$_{50}$ curve was obtained.

The objective of the present research was to provide dose-response (lethality) data for rats exposed to CW microwave radiation in the frequency range 1 to 8 GHz. Approximately 1400 male rats of the Sprague-Dawley strain have been exposed in equal groups to four separate frequencies: 0.95, 2.45, 4.54, and 7.44 GHz. Power density levels have ranged from approximately 0.2 W/cm^2 to 12 W/cm^2, and lethal exposure durations from approximately 10 sec to 300 sec. The rats were all restrained and positioned facing the source. Gross and histologic evaluation of selected tissues from some 20 animals has been accomplished. The lethality data have been subjected to a probit analysis, yielding LD$_{50}$ curves for each of the four frequencies, and the LD$_{50}$ values have been empirically fitted with a mathematical model.

II ENGINEERING METHODS

A. General Exposure Facilities

The common features of the exposure facilities are described below. Engineering considerations for the individual frequencies are described in detail.

All exposures were carried out in an RF-shielded room, 20 ft by 12 ft by 8 ft, lined with microwave-absorbent material. An ellipsoidal reflecting antenna 5 ft in diameter was erected toward one end of the chamber and with its axis coincident with the long axis of the chamber. The ellipsoidal antenna was constructed of fiberglass laminate with an integral 40-inch-diameter bolt-ring at the back. The reflecting surface was flame-sprayed aluminum, 0.010 inch thick. Surface tolerance was not checked, but was claimed by the manufacturers[*] to be within 0.010 inch rms of the "true" surface. The microwave feeds were introduced through the side wall of the chamber and positioned at the first focus, 32 inches from the vertex of the dish. To illuminate the dish at each frequency, a circular unflared and unflanged horn was used. The horn's dimensions were designed to provide very nearly equal beam width angles in the E and H planes, with 3-dB points close to 90°. Polarization was vertical (circular waveguide in the TE_{11} mode). Transitions between the rectangular feed waveguide and the horns were all adjusted to give minimum VSWR at the frequencies employed. The ellipsoidal reflector focused the microwave energy to a second focal area 74 inches from the vertex of the dish. Theory predicts, and experimental measurement

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[*] Structural Technology, Inc., Santa Clara, CA 95050.

confirmed, the microwave beam to be focused to a "zone of confusion" at the second focus, the diameter of the zone being directly proportional to the wavelength. By the use of encapsulated liquid crystal (ELC) sheets, with a backing capable of absorbing a very small amount of the incident RF energy, it was possible to directly visualize the focused microwave beams at the three highest frequencies. (These crystals change color with temperature.) Phase measurements made with a Hewlett-Packard Automatic Network Analyzer were constant to within ±5° across the focal plane, indicating a quasi-far-field condition at this region.

B. Power Density Calibration

Power density distribution in the vicinity of the exposure region was measured by a similar method for all four frequencies. Firstly, the relative power distribution was measured using either a half-wave dipole or a receiver horn identical with the transmitter horn. Accurate and rapid measurements were made possible through the use of an 8542B Hewlett-Packard automatic network analyzer (ANA) for all frequencies.

One disadvantage of using this relative-distribution technique is that the readings obtained at each point represent some weighted average of the power available across the effective area of the receiving probe. It was not possible to pursue this field-quantification problem further in the present work, and it awaits further exploration at a later stage.

Next, an accurate measure of the power density at the receiving probe, averaged over the probe's effective area, was obtained at the point of maximum received power as follows. The power, P_r, available at the terminals of the receiving probe antenna is related to the probe effective area, A_r, and the incident power density, P_d, by

$$P_r = A_r P_d \quad . \tag{1}$$

From the measured gain, G_r, of the receiving probe, the effective area can be calculated by

$$A_r = \frac{\lambda^2 G_r}{4\pi} \quad . \tag{2}$$

The ratio of probe received power to the power, P_t, input to the transmitting antenna (the circular feed horn) can be measured using the HP 8542B automatic network analyzer. This ratio is

$$\frac{P_r}{P_t} = |S_{21}|^2 \tag{3}$$

where S_{21} is a scattering parameter.

The unknown power density can thus be found from measured quantities

$$P_d = \frac{P_r}{A_r} = P_t |S_{21}|^2 \frac{4\pi}{\lambda^2 G_r} \quad \mathrm{W/cm^2} \tag{4}$$

when P_t is in watts and λ is in cm.

Values of $|S_{21}|^2$ were obtained directly in the relative-distribution mapping. Values for receiving-probe gains were obtained using a proprietary antenna-calibration software program and the automatic network analyzer.

1. Calibration

a. Frequency 1: 0.95 GHz

Microwave power at 0.95 GHz was obtained from an Energy Systems Inc. Model 11-127, 2-kW CW klystron amplifier having an Eimac 4KM3000LR air-cooled klystron. Although this system is rated for 2-kW CW output when the tube is new, it was found that not more than 1200 W output could be obtained in its present condition without exceeding the rated collector dissipation limits. The amplifier was driven from an HP Model 612A UHF signal generator followed by two Avantek preamplifiers, Models 1502 and 1503, and an isolator. RF output power was conveyed into the chamber via a coaxial transmission line 1-5/8 inches in diameter. A coax-to-circular waveguide transition was then made into an unflared and unflanged circular feed horn, 9 inches in diameter, positioned facing the dish, and with its front edge 27-1/2 inches from the vertex of the dish.

Output and reflected power were continuously monitored by means of directional loop couplers in the coaxial line. The couplers were accurately calibrated on the HP Model 8542B automatic network analyzer. Coupled power was measured on an HP Model 432 power meter using thermistor mounts whose calibrations are directly traceable to the National Bureau of Standards. A Sanborn Model 320A chart recorder was used to obtain permanent records of individual irradiations.

Plots of the distribution of the scattering parameter, $|S_{21}|^2$, an index of power density, are given in Figures 1 through 3. A second measurement, made at the point of maximum power density, yielded a true power density conversion factor. Figure 3 shows that the maximum power density fluctuation across the internal cavity of the exposure box was approximately 0.2 dB.

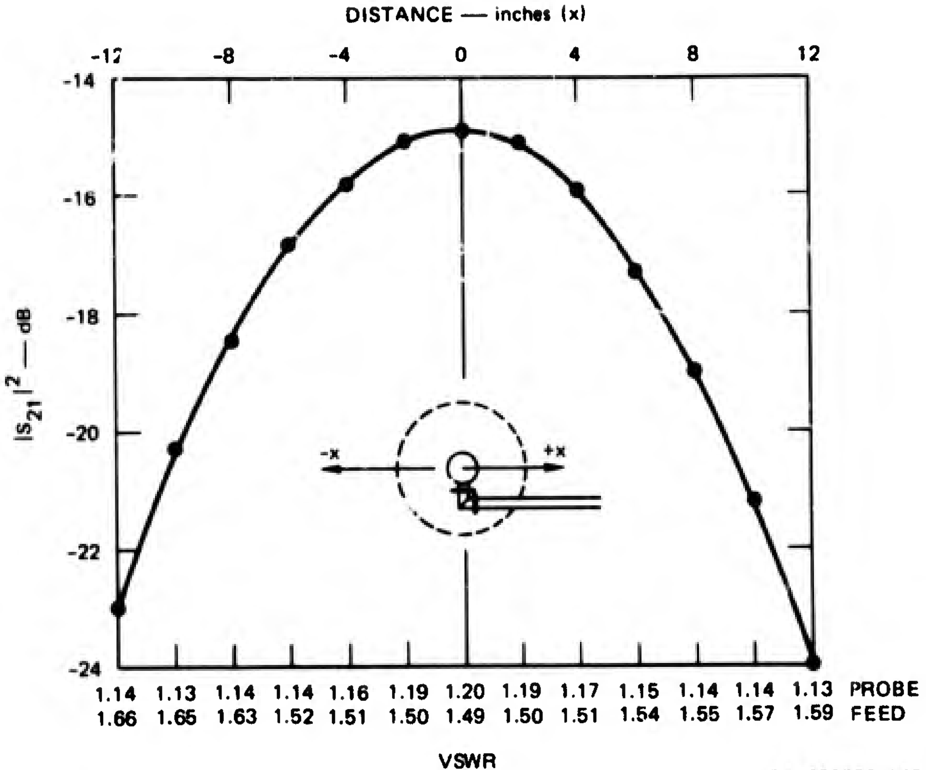

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FIGURE 1 SIX-INCH DIPOLE AS RECEIVER, VERTICAL POLARIZATION. f = 950 MHz, x = y = 0.

b. Frequency 2: 2.45 GHz

A Genesys Systems, Inc. Model 4003-4006 variable power source operating at a measured frequency of 2.457 GHz provided 0 to 2.4 kW of CW microwave power. Output from this system was monitored by an appropriate arrangement of accurately calibrated cross-guide couplers and the HP Model 432A power meter. The S-band waveguide was led into the chamber and terminated in a specially designed, quarter-wave, rectangular-to-circular waveguide transition. The feed to the ellipsoidal dish was an unflared circular horn with an internal diameter of 3-1/2 inches. For accurate timing of exposure durations, the timer incorporated in the Genesys Systems Model 4006 was replaced with a Gra-Lab Model 172 industrial timer, modified appropriately.

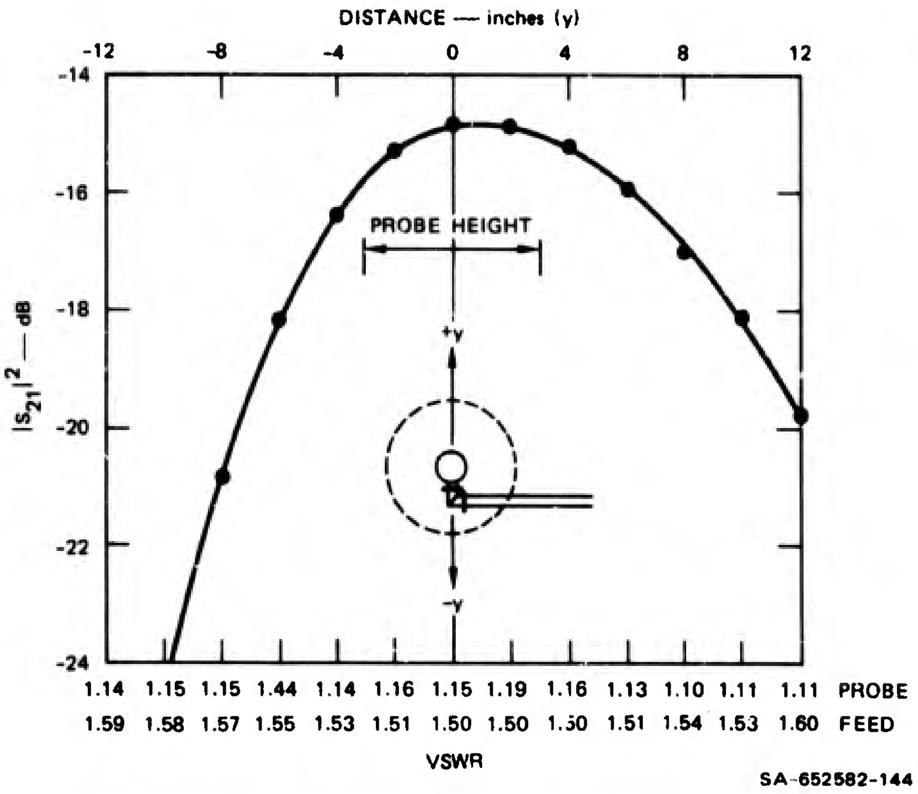

FIGURE 2 SIX-INCH-DIPOLE PROBE, VERTICAL POLARIZATION. f_o = 950 MHz.

Calibration of the power density distribution at the second focus was made with both a half-wave dipole and a circular receiver horn, the latter identical with the feed. Relative distributions of power density were made for both probe types by measuring $|S_{21}|^2$ (Figures 4 through 7). The gains of the dipole and horn were measured as for the 0.95-GHz case. Excellent agreement was obtained between the two probes. The dipole yielded a power-density conversion factor of 2.01 W/cm^2/kW input. The circular horn yielded a figure of 2.05 W/cm^2/kW input. Figure 8 shows that the exposure box was inadvertently located slightly off axis. However, the power density distribution was still uniform within approximately 1 dB over the internal compartment cross section of the exposure box.

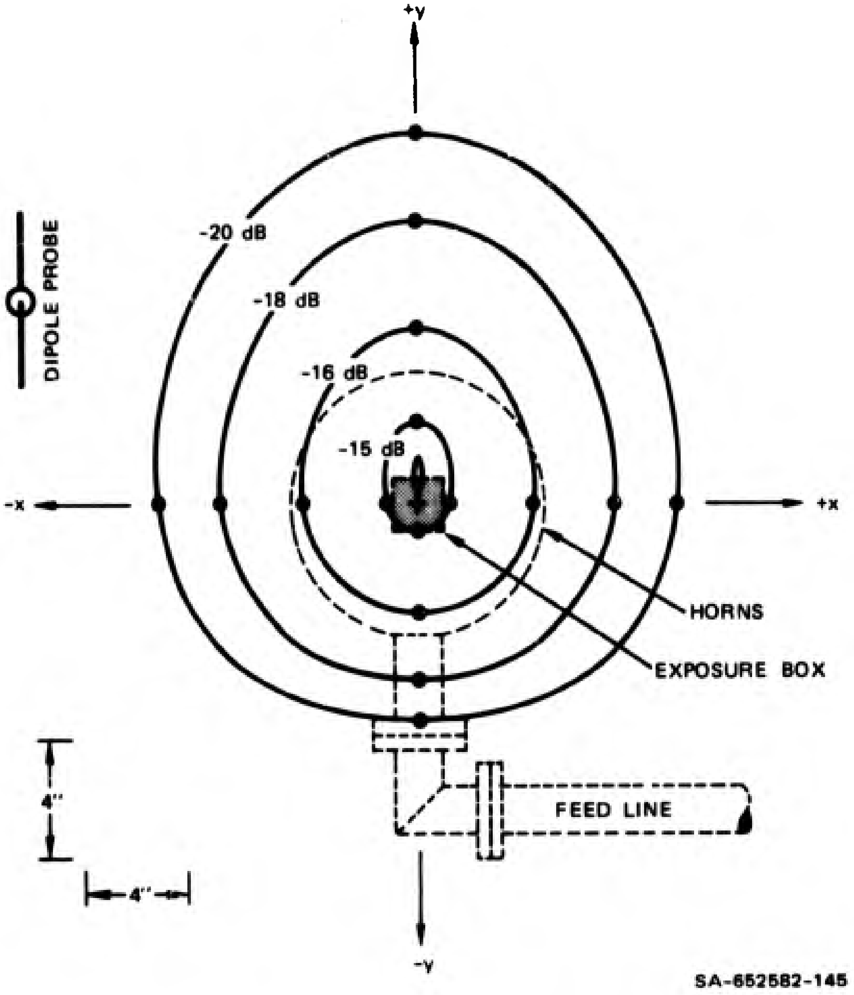

FIGURE 3 DIPOLE PROBE, VERTICAL POLARIZATION. $|S_{21}|^2$ Contours in xy plane at z = 0 (second focal plane). f_o = 950 MHz.

c. Frequency 3: 4.54 GHz

Microwave power was obtained by tuning a Microwave Cavity Laboratories Model 10150 klystron power amplifier to its maximum output (1.2 kW) in the vicinity of 4.5 GHz. The measured frequency was 4.54 GHz. Again, an accurately calibrated arrangement of cross-guide couplers, attenuators, and loads was used to sample forward and reflected power. Forward power was monitored on an HP Model 432A power

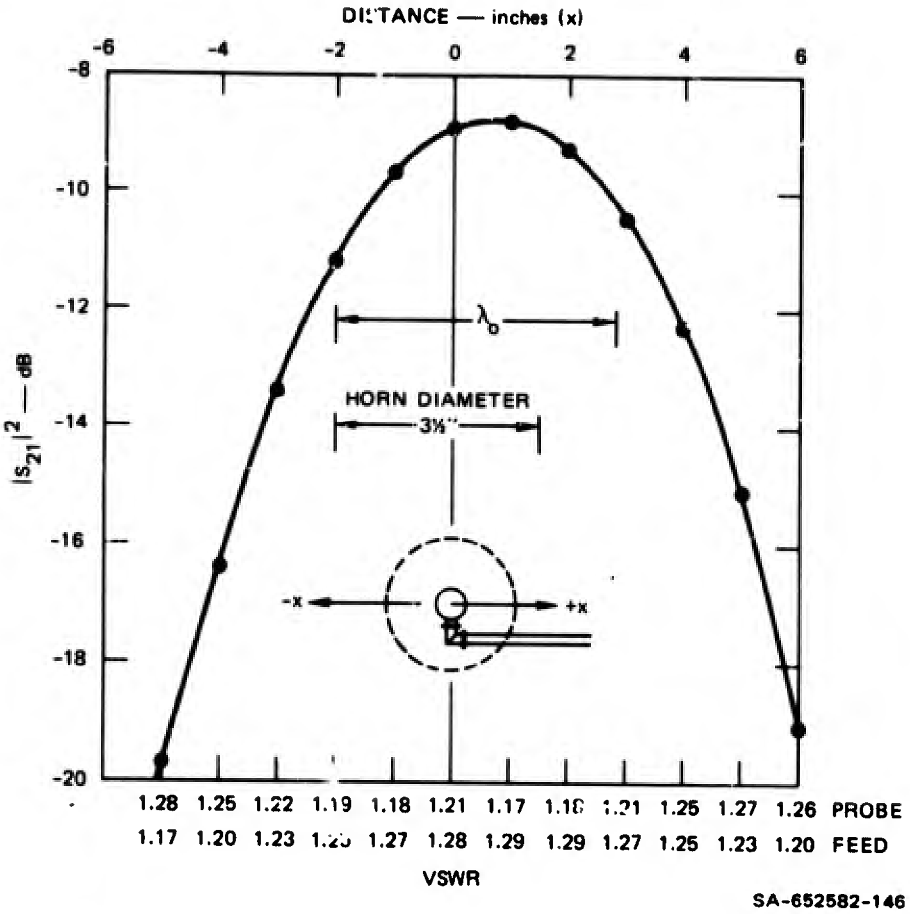

FIGURE 4 HORN PROBE, VERTICAL POLARIZATION. f_o = 2457 MHz.

meter. The feed to the dish was an unflared circular horn with an internal diameter of 1-7/8 inches connected to the rectangular WR-187 waveguide by a matched quarter-wave transformer section.

Measurement and calibration of the power density in the exposure region was made with a receiver horn identical with the transmitter horn, following the methods already described for the previous frequencies. Figures 9 through 11 show these results. The power density distribution across the whole of the inner compartment is seen to be uniform to within just over 1 dB.

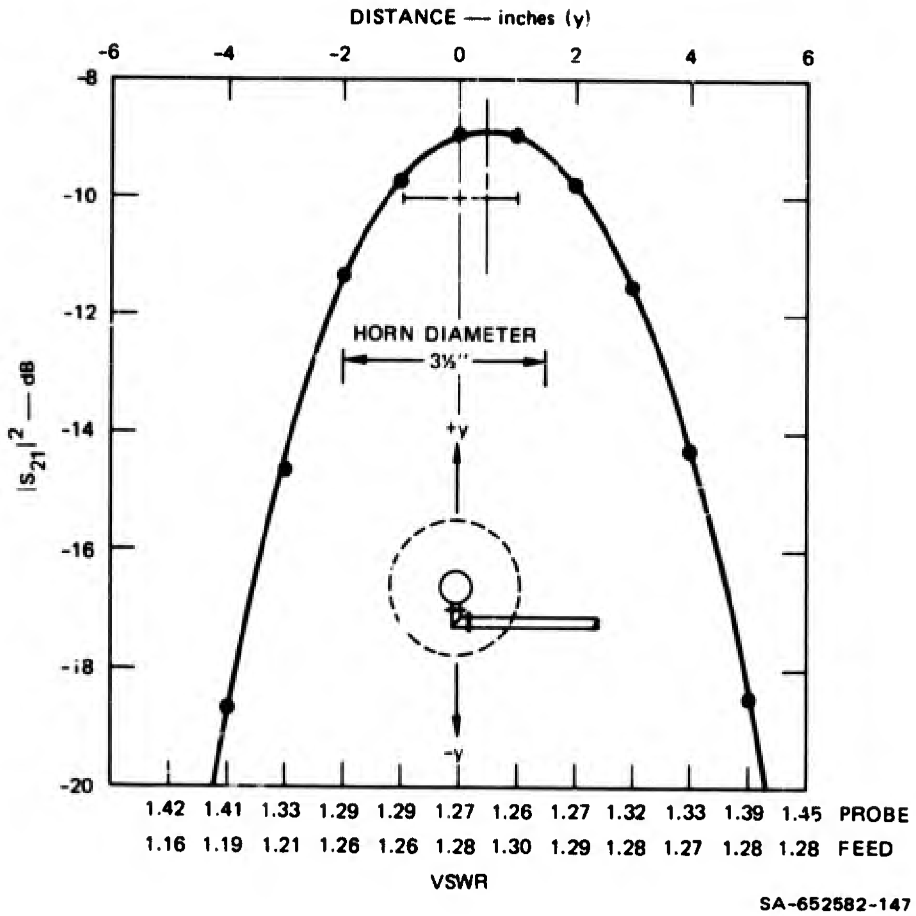

FIGURE 5 HORN PROBE, VERTICAL POLARIZATION. f_0 = 2457 MHz.

d. Frequency 4: 7.44 GHz

A Sierra/Philco Model 210A CW klystron power amplifier fitted with a Varian VA-856B klystron was used as the microwave source. Power into the chamber was monitored by calibrating the cross-guide directional coupler, attenuator, and 10-GHz low-pass filter section already existing in the amplifier and reading the sampled power on the HP 432A power meter as done for previous frequencies. The ellipsoidal dish was fed, with appropriate scaling, in a manner identical to that used in the 4.54 GHz case. WR-137 waveguide was used to convey power from the amplifier to the quarter-wave transition.

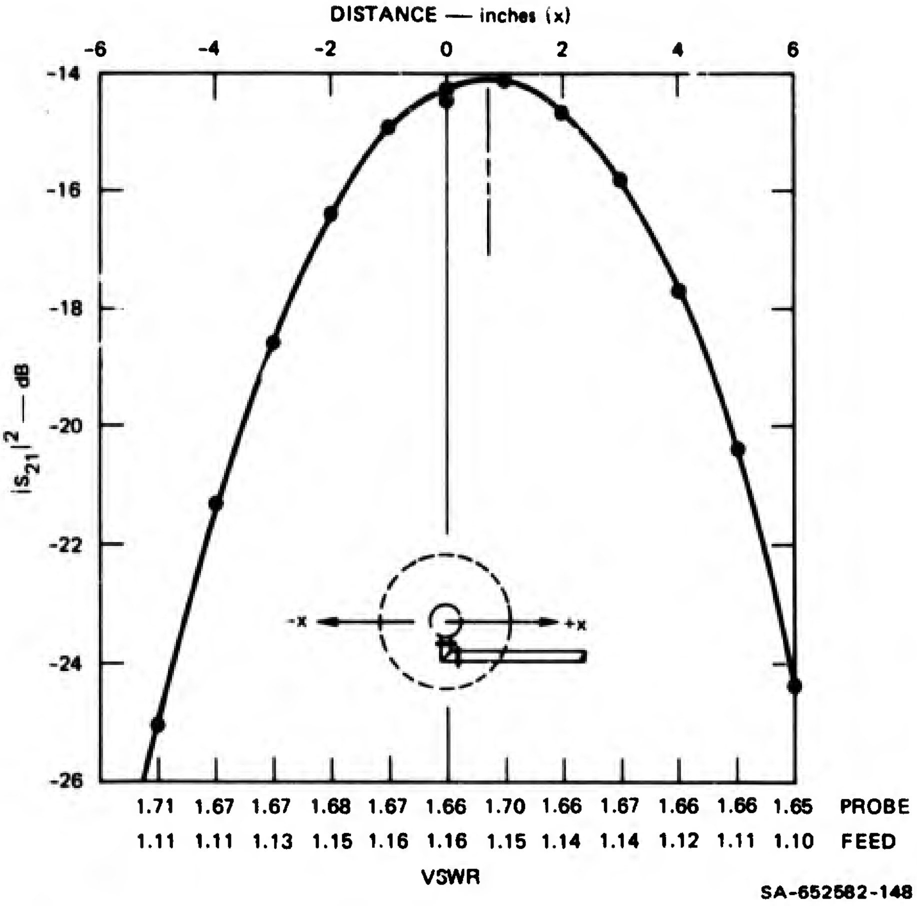

FIGURE 6 DIPOLE PROBE, VERTICAL POLARIZATION. f_0 = 2457 MHz.

The automatic network analyzer was used to measure and calibrate the fields in the vicinity of the exposure region as was done for the three lower frequencies. High losses in the flexible cable used to link the ANA and the anechoic chamber required the acquisition and use of special low-loss cables.

In the interim period, an alternative calibration procedure was used. An Alfred Model 650 signal generator tuned to 7.44 GHz and square-wave-modulated at 4.50 kHz was used to provide power to the feed horn. The output from the probe horn was connected to an HP Model 415D standing-wave-ratio meter, after the received signal had passed

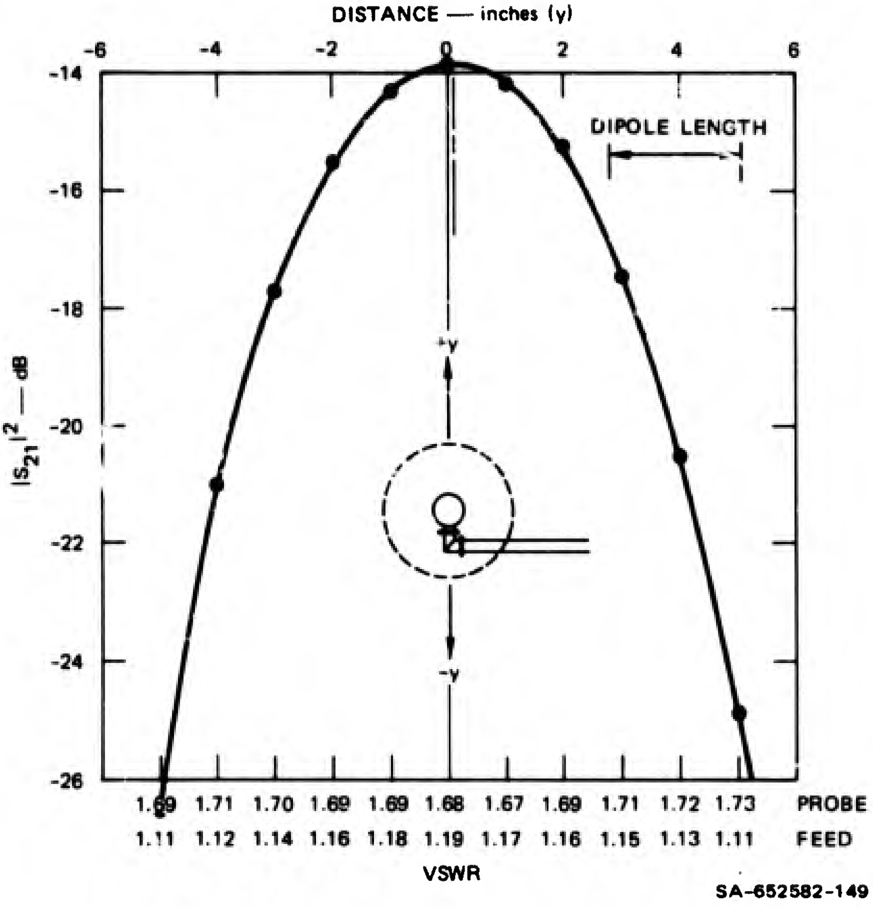

FIGURE 7 DIPOLE PROBE, VERTICAL POLARIZATION. f_0 = 2457 MHz.

through an HP 420 detector. The two horns were first positioned face to face to give a zero-dB-insertion-loss reading. The field was then probed with the receiving horn in the same manner as for the three previous frequencies. The 415D SWR meter readings were used in place of $|S_{21}|^2$ in calculating relative and absolute power densities. (This assumes that $|S_{11}|$ is zero, which is approximately correct, since both horns were optimally matched to the feeds by adjusting the quarter-wave transitions before use.)

At the highest frequency, the zone of confusion of the focused beam was much smaller than for the other frequencies. In fact,

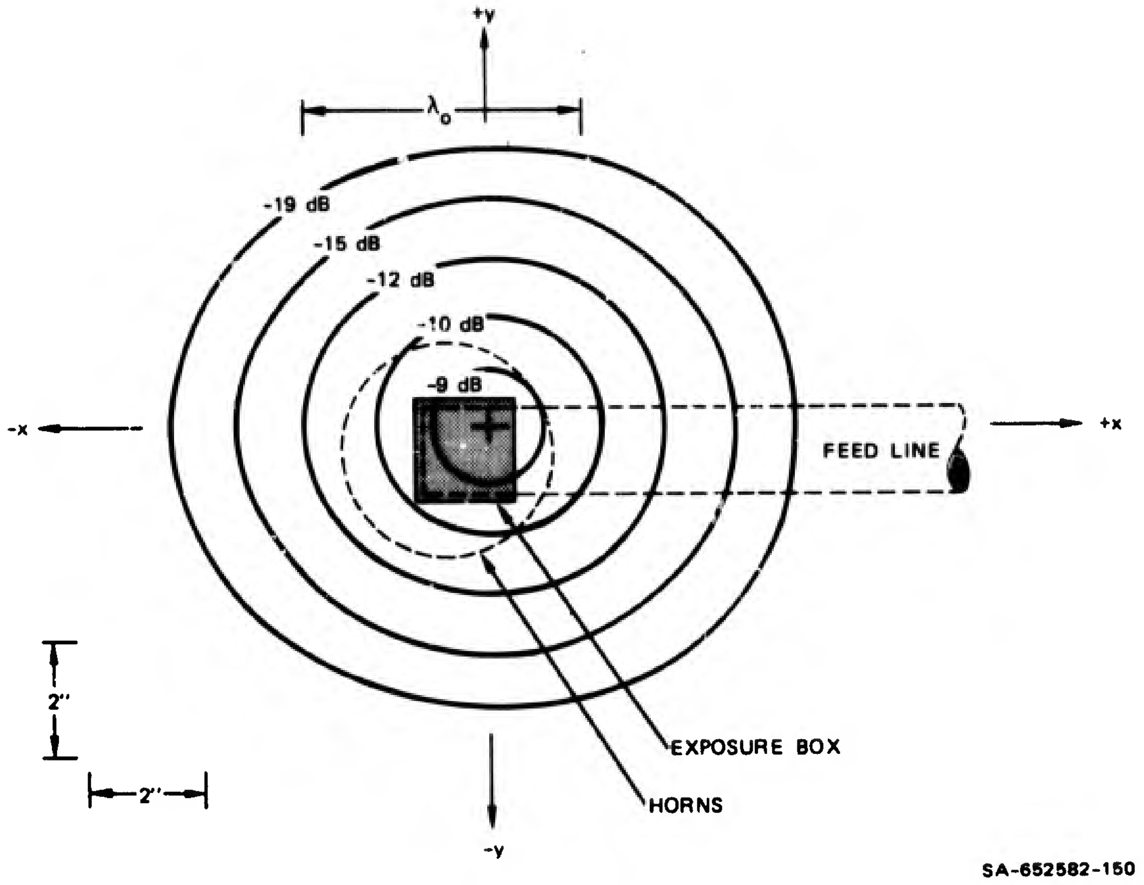

FIGURE 8 HORN PROBE, VERTICAL POLARIZATION. $|S_{21}|^2$ Contours in xy plane at $z = 0$. $f_o = 2457$ MHz.

the 3-dB dimensions were smaller than the cross-sectional dimensions of the inner compartment of the exposure box. To ensure more uniform illumination, it was necessary to move the exposure box away from the dish to a location 15 inches beyond the second focus. Figures 12 through 14 show the power density distribution.

The insertion loss from feed horn to dish to receiving horn at the exposure point was calculated as 16.2 dB. Once again, the rats were subjected to an illumination uniform to within approximately 1 dB.

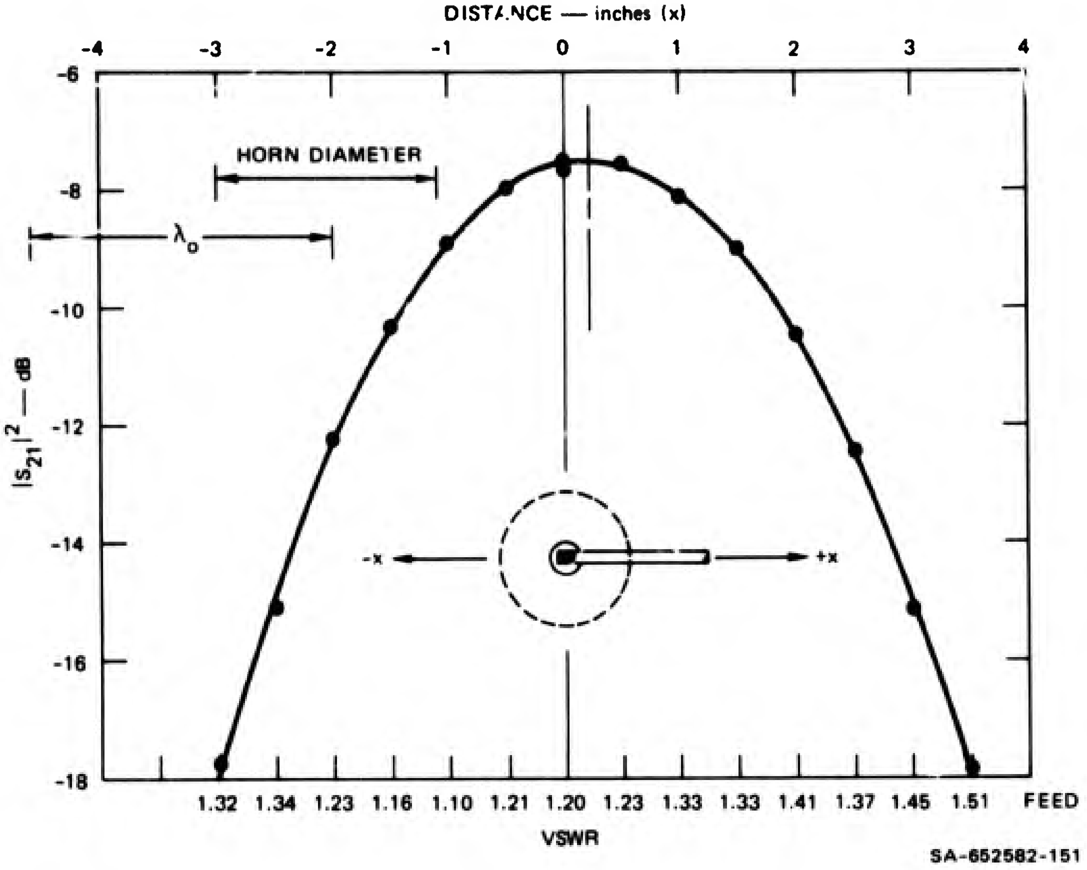

FIGURE 9 HORN PROBE, VERTICAL POLARIZATION. f_o = 4540 MHz.

Excellent agreement was obtained between power density conversion factors derived from the two calibration procedures. The 415D SWR meter readings were within 0.3 dB of the $|S_{21}|^2$ values provided by the automatic network analyzer.

2. Discussion of Power-Density Calibrations

A major aim of the research was to enable comparison between effects at the four different frequencies. For all four frequencies, 0.95, 2.45, 4.54, and 7.44 GHz, similar calibration methods and apparatus were employed. In addition, independent calibrations at 2.45 GHz using dipole and circular horn probes were in excellent

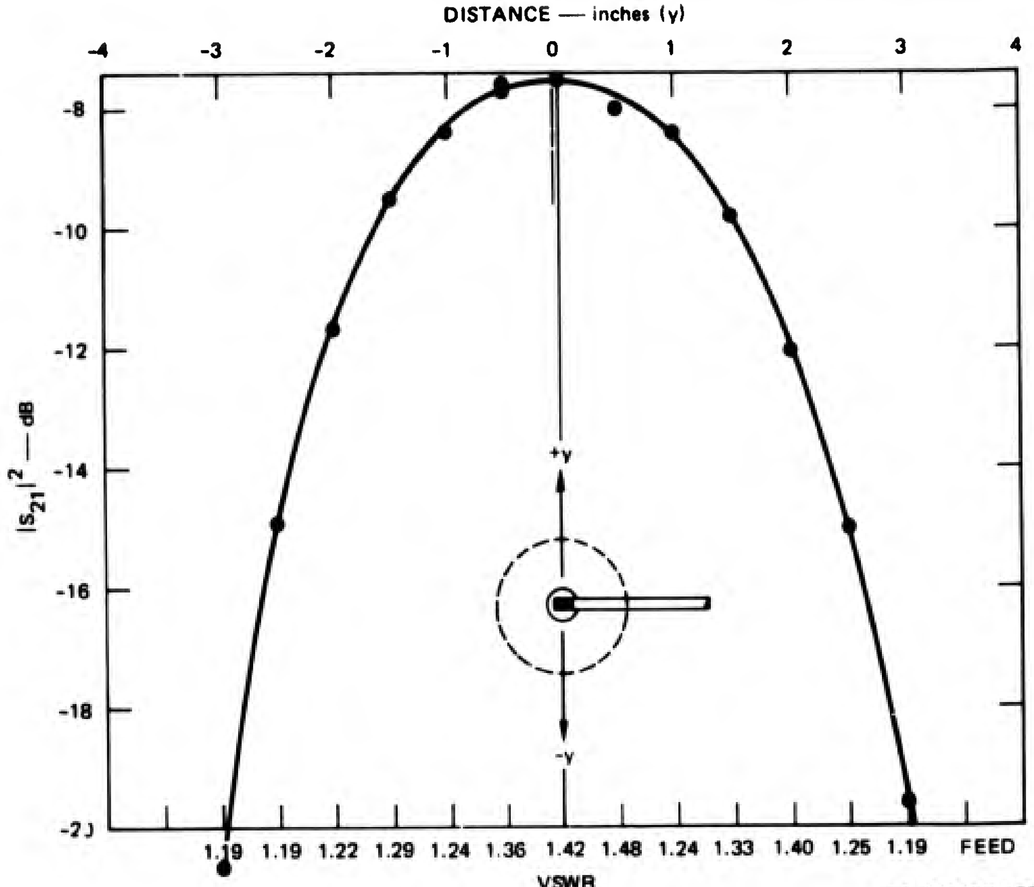

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FIGURE 10 HORN PROBE, VERTICAL POLARIZATION. f_0 = 4540 MHz.

agreement, as were independent calibrations at 7.44 GHz. Although no rigorous error analysis has been carried out on these calibrations and measurements, it is felt that the power densities so obtained are accurate to better than ±0.5 dB absolute, and to better than ±0.25 dB on a relative basis between frequencies. In obtaining the power-density conversion factors, errors of a few tenths of a dB (maximum) may have arisen in measuring $|S_{21}|^2$ and in measuring the gains of the probes. Measurement of forward power to the feed was estimated to be accurate to within a few tenths of a dB, absolute. A further assumption made was that the power-density conversion factor was invariant with the output microwave power level.

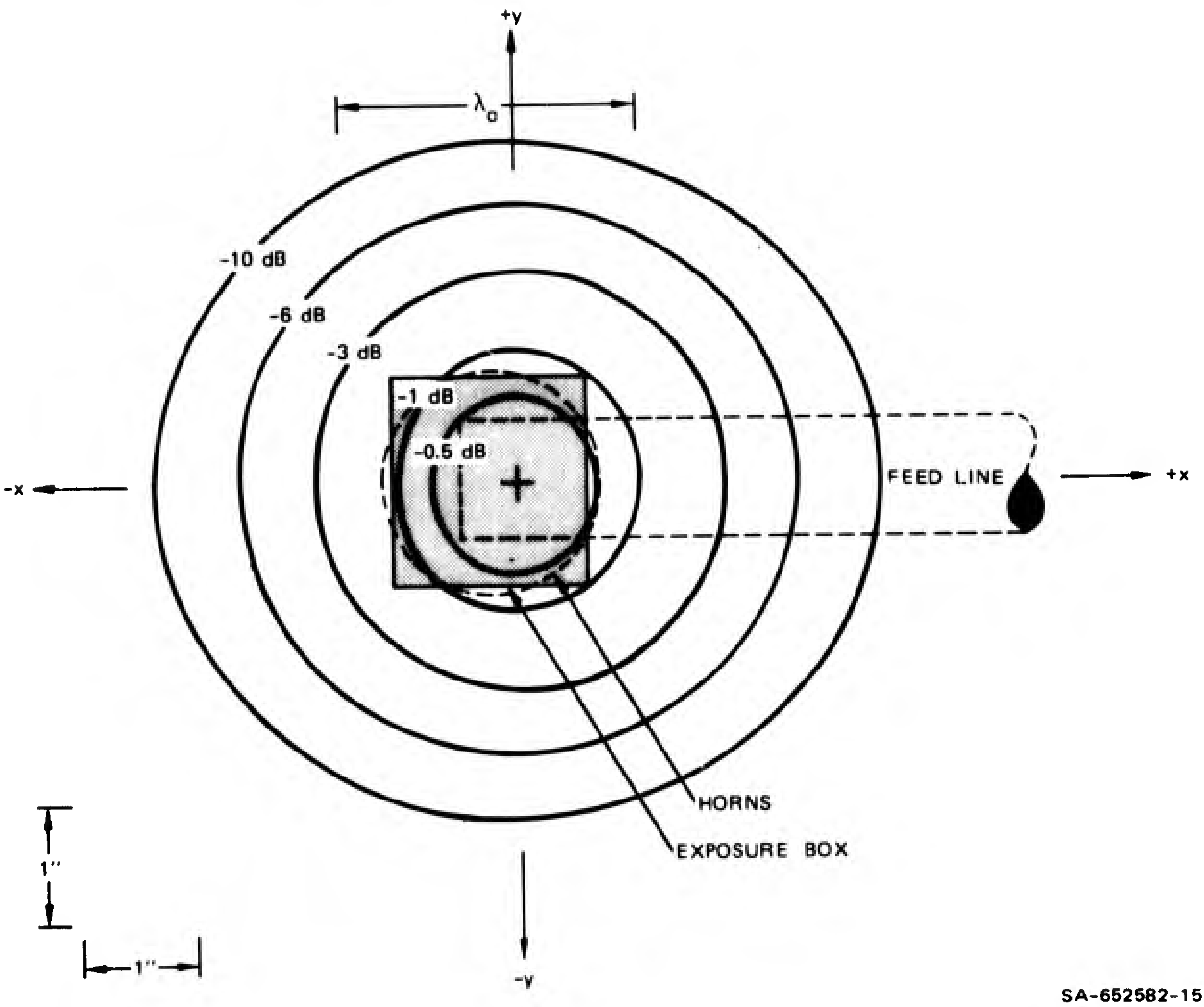

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FIGURE 11 HORN PROBE, VERTICAL POLARIZATION, xy PLANE AT SECOND FOCUS ($z = 0$). $|S_{21}|^2$ Contours (relative). $f_o = 4540$ MHz.

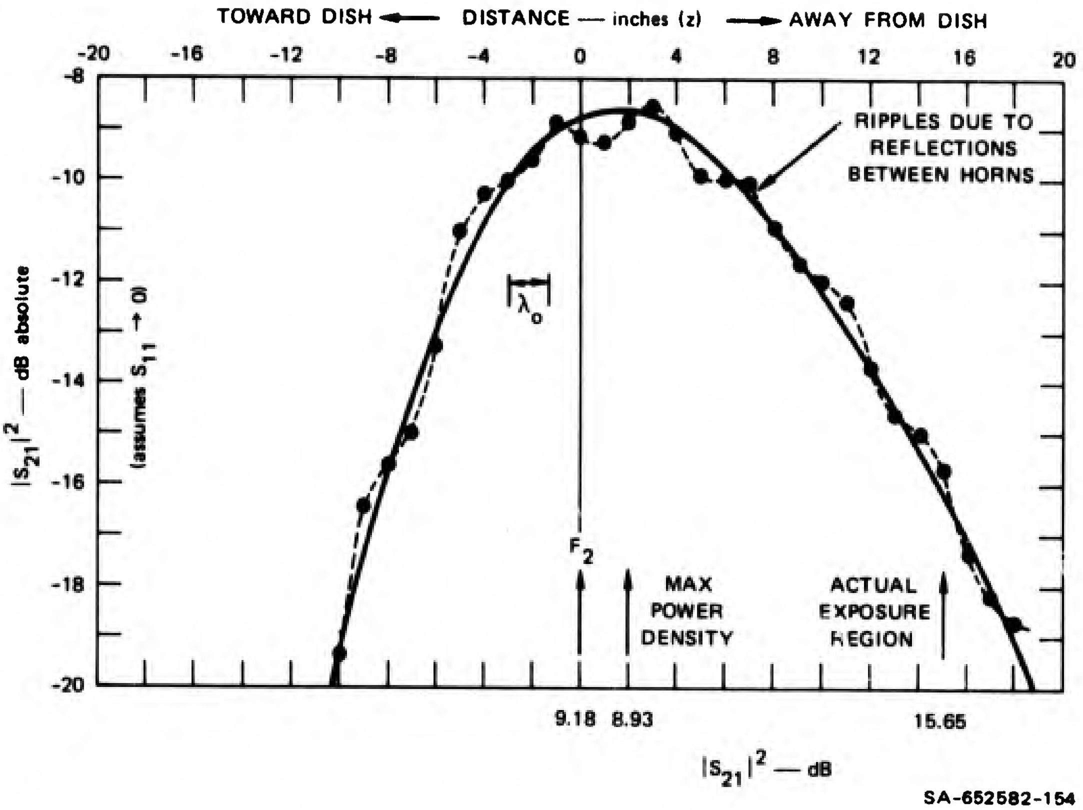

FIGURE 12 HORN PROBE, VERTICAL POLARIZATION. Axial variation. f_o = 7.44 GHz.

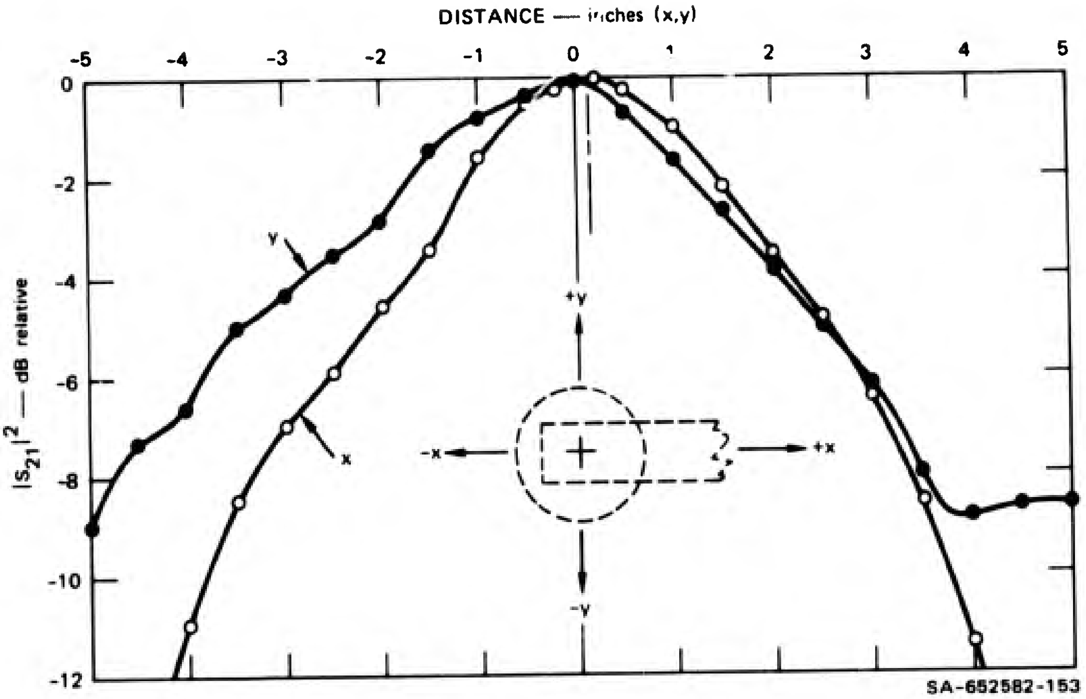

FIGURE 13 HORN PROBE, VERTICAL POLARIZATION. Field profiles at z = +15 inches beyond focal plane. f_0 = 7.44 GHz.

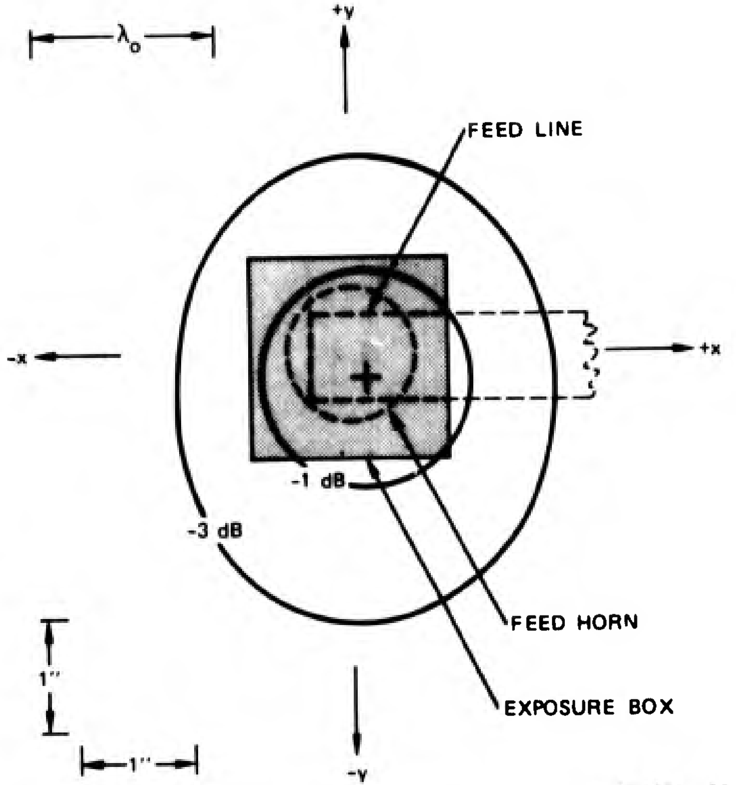

FIGURE 14 HORN PROBE, VERTICAL POLARIZATION. Field contours at z = +15 inches beyond focal plane. f_o = 7.44 GHz.

III BIOLOGICAL METHODS

Male Sprague-Dawley strain rats (approximately 3-1/2 weeks old) were received from the supplier (Simonsen Laboratories, Gilroy, California) in cohorts of about 125. They were caged singly in air-conditioned rooms maintained at 72 ± 2°F, fed Purina Lab Chow pellets, and given water ad libitum. Room lights were on from 0600 to 1800 hr daily. To observe for any potentially unsatisfactory animals, and to habituate them to handling, each animal was handled once a week during each of the subsequent three weeks. Each handling session consisted of removing the animal from its cage, weighing and/or placing it on the handler's arm for about one minute, and returning it to its cage.

For each cohort, irradiation occurred during the fourth week after delivery. A rack (60 cages) of animals was transported by truck from the animal facility to the irradiation facility and placed in a temperature-controlled holding room with the same light cycle as above. Irradiation occurred on the day of transport or on the next day. Approximately 30 rats were irradiated in the period 0900 to 1200 hr, and a similar number from 1330 to 1700 hr. After all animals on a rack had been irradiated, the rack remained overnight in the holding room, and was then transported back to the animal facility the next day. Feed was available at all times, and water was available except during transport.

For each frequency, three cohorts of animals were used on a two-week exposure cycle: one cohort was used to establish appropriate exposure times at several power densities during the first week, then the other two cohorts were used to expand and fill in the exposure schedule during the second week.

The exposure boxes (see Figure 15) were designed to minimize movement by the animal. They were constructed of glued styrofoam pieces, with external dimensions of 9-5/8 by 5-3/4 by 5 inches and an inner compartment of 7-5/8 by 1-3/4 by 1-3/4 inches. The removable rear and top pieces were secured by Velcro fastenings. The forward end of the rectangular compartment was cone-shaped so as to hold the head of the animal in place. Appropriate air holes were drilled through the walls at the tip of the nose cone and along the sides.

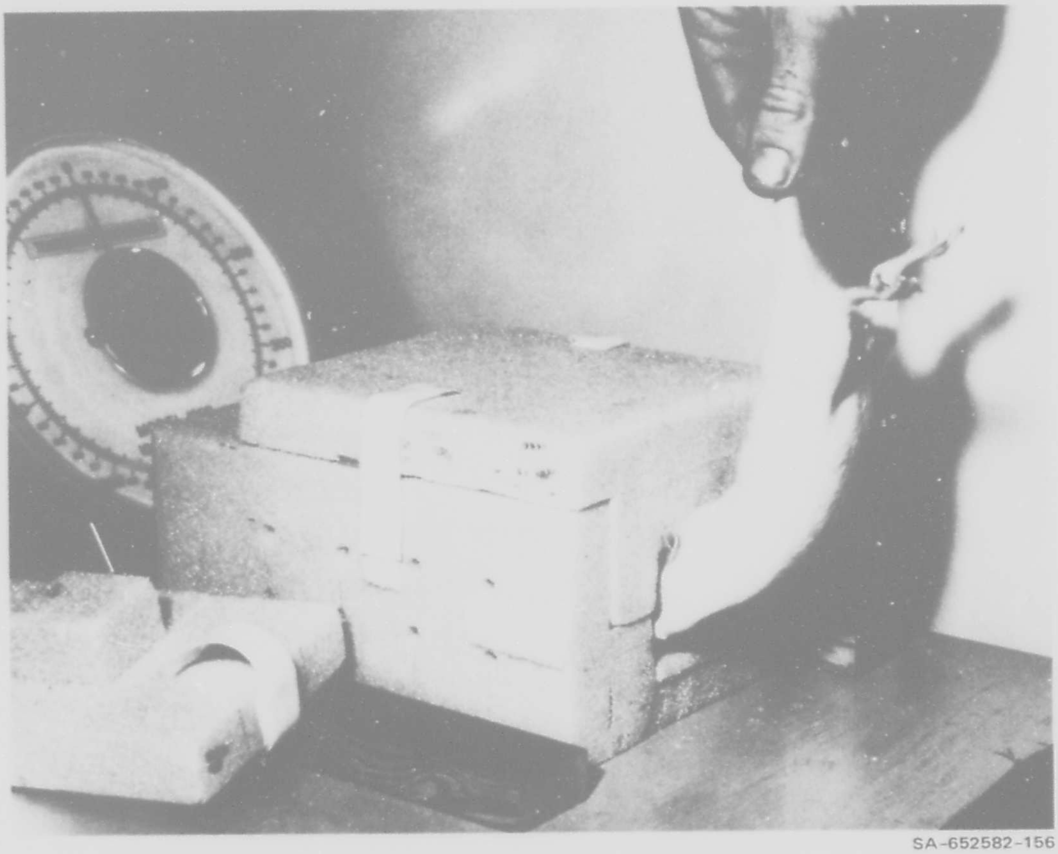
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FIGURE 15 RAT EXPOSURE BOX WITH RAT ABOUT TO ENTER

Animals were irradiated one at a time between 0900 and 1700 hr. The animal was removed from its cage, weighed, and allowed to move into the exposure box through the rear entrance (Figure 15). The box was then sealed, carried into the adjacent exposure facility, and placed in pre-aligned chocks on top of a pedestal. The box was positioned with the rat facing the incident radiation. After exposure, the box was returned to the holding room, the back and top pieces were removed, and the animal was returned to its cage.

Each animal was observed for mortality at removal from the exposure box and at frequent intervals during the remainder of the day. Mortality observations occurred again at the end of the exposure day and during each of the next three days. After three days, surviving animals were sacrificed.

At the two lower frequencies, sample deep-rectal temperatures were taken using a Yellow Springs Telethermometer Model 42 and Thermistor Probe Model 402, immediately on removal from the exposure box. Twenty-four animals were subjected to a gross necropsy, and sections of brain, kidney, liver, spleen, and lung were stained with hematoxylin and eosin and evaluated histologically. For all but the latter tissue, the histologic evaluation revealed no abnormalities associated with microwave irradiation. Subsequent consideration of the findings will be limited to the gross necropsy results and to the histologic evaluation of the lung changes.

The relationship of lethality to exposure time was analyzed by converting the percentage mortality to probit and computing the regression of probit of mortality on the natural logarithm of exposure time, in accordance with established procedures.[8] The actual computation process is rather complex, involving the estimation of statistical weights and unbiased values of probit for each mortality point, and uses a series of approximations to arrive at a final regression line.

The statistical parameters calculated by this method are listed in tabular form for each frequency and power density. The parameters $\bar{X}$, $\bar{Y}$, and B are the mean log exposure time, the mean probit of mortality, and the slope of the regression line, in probit units per log cycle, respectively. They have the same significance and function as in any regression calculation. The regression equation, then, is

$$y - \bar{Y} = B(x - \bar{X}) \qquad (5)$$

where y is the expected probit of percentage mortality for an exposure time whose natural logarithm is x. Probit of percentage mortality can be converted to percentage mortality by use of probit tables or by the relation

$$\text{Fraction Dead} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{y-5} e^{-\frac{1}{2}u^2} \, du \qquad (6)$$

where values of the integral can be found in standard handbooks of mathematical tables.

The statistical parameter Sum wi is the sum of (number of animals) times (statistical weighting coefficient) for all dose points. The parameter Sxx is the weighted sum of $(x - \bar{X})^2$ for all time points.

The statistical parameter Chi-square is calculated from the deviations of the probits of actual percentage mortality at each does point from the values estimated from the fitted line, thus

$$\text{Chi-square} = \sum \frac{(Yi - yi)^2}{yi} \qquad (7)$$

where Yi and yi indicate the observed and fitted probits, respectively, and the number of degrees of freedom is two less than the number of dose groups. Where the value of Chi-square exceeds the 95% value for the appropriate number of degrees of freedom, the data are not considered to be well represented by the probit analysis, and the tabulated value is so marked. In such cases, the calculated variance of y must be increased by a heterogeneity coefficient, listed below Chi-square and calculated as (Chi-square)/(degrees of freedom).

The parameter t is the coefficient for determing confidence intervals of the estimated values of y. The values listed are for 95% confidence intervals, but appropriate values for any desired confidence interval may be substituted. Where the value of Chi-square does not exceed the expected 95% value, the probit analysis is considered to be a good fit to the data, and the value of t is that for the 95% boundaries of a normal distribution. Where the value of Chi-square does exceed the expected 95% value, the value of t is that for the 95% boundaries of "Student's" t distribution, with the number of degrees of freedom equal to two less than the number of dose groups tested.

The variance of y, the expected probit for a given log exposure time, x, is

$$V(y) = \frac{1}{\Sigma wi} + \frac{(x - \bar{X})^2}{Sxx} \quad . \qquad (8)$$

The standard deviation is, then, $[V(y)]^{\frac{1}{2}}$, and the confidence interval of y is

$$y \pm t[V(y)]^{\frac{1}{2}} \quad . \qquad (9)$$

The variance of the regression is defined in terms of the dependent variable, y, but the question of the uncertainty of x, the log exposure time for a specified percentage mortality, frequently arises. An approximate estimate of the confidence interval of x can be obtained by computing from Eq. (5) the values of x corresponding to the values of y at the extremes of the confidence interval for y, as defined by Eq. (9). For values near the median lethal does (LD_{50}), the approximate estimate is usually adequate. However, the exact value of the confidence interval of x is defined as

$$\text{Confidence interval} = x + \frac{g}{1-g}(x-\bar{X}) \pm \frac{t}{B(1-g)}\left[\frac{1-g}{\Sigma wi} + \frac{(x-\bar{X})^2}{Sxx}\right]^{\frac{1}{2}} \qquad (10)$$

where $g = t^2/B^2 Sxx$. If heterogeneity occurs, the value of g and the expression within the brackets should be multiplied by the heterogeneity factor. In such cases, however, the exact confidence interval frequently cannot be calculated, and the approximate confidence interval is used instead. Such cases are indicated.

The expected doses and confidence intervals for mortality rates ranging from 1 to 99% of the animals are tabulated. The calculated exposure times have been computed from Eq. (5) and the confidence intervals from Eqs. (9) and (10). In general, the confidence intervals of the exposure time are quite narrow in the region of 30 to 70% mortality, but tend to become wide and noticeably unsymmetrical at the extremes of mortality or survival. This phenomenon is an inherent feature of the probit analysis. In the absence of significant heterogeneity, the confidence interval of dose depends on a number of factors, including the value of B, the variance of B, and the fact that in the calculations, the value of exposure time is carried as a logarithmic transformation. In comparisons among power levels and frequencies, the calculated values of exposure times for 50% mortality (the LD_{50}) are used exclusively because the values generally have the highest certainty.

Where significant heterogeneity occurred, the data were carefully examined to determine whether variation was due to experimental procedures. It was found that appreciable deviations of groups were not related to experimental batch, location of animals in the room, personnel involved in conducting the experiments, or time of day when exposures were made. In a number of cases, exclusion of a single dose group from a set of exposures at a given power density gave a reduced set with a homogeneous lethality response. In such cases, the reduced set had virtually the same LD_{50} as the full set, but the confidence intervals of both dose and mortality were much narrower. Reported calculations are based on the full set of animals in the cases noted below, and the heterogeneity is accepted as part of the nature of the lethality response to the radiation.

IV BIOLOGICAL RESULTS

The results will be presented first on a frequency-specific basis, including a consideration of each experimental observation, then on a combined basis, including a consideration of the relationships between mortality and power density as a function of frequency.

A. Frequency 1: 0.95 GHz

Mortality data for this frequency are summarized in Tables 1 through 5. Only 5 of the 140 decedents died more than 1 hr after exposure, the longest survival time being approximately 12 hr. About half the animals were dead (defined be cessation of respiration) on removal from the exposure box. Thus, although all decedents are included in the calculations, the data are essentially for mortality occurring within 1 hr of exposure.

No consistent relationship between power density and slope of the mortality curves was apparent. All Chi-square and heterogeneity values for this frequency were low, indicating that these data are well represented by the probit analysis. There was a consistent inverse relationship between LD_{50} and power density with values ranging from 162 sec at 0.301 W/cm^2 to 291 sec at 0.178 W/cm^2. Rectal temperatures for unirradiated animals ranged up to 37.5°C after a 300-sec confinement in the exposure box. Subjectively, irradiated animals felt warmer to the hand than controls on removal from the exposure box. The mean body weight (± S.D.) for animals exposed at this frequency was 218 ± 24g, and there was no apparent relationship between individual body weights and mortality. Rectal temperatures were taken for all rats of the first

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Table 1

EXPERIMENTAL DATA

FREQUENCY: 0.95 GHz

POWER DENSITY: 0.301 **watts/cm^2**

Lethality Data

Exposure Time (sec)	Number of Rats	Number Dead
120	4	0
152	4	1
157	9	2
160	10	5
162	14	6
165	10	6
170	10	9
180	1	1
182	4	4

Statistical Parameters

X-bar:	5.088
Y-bar:	5.028
B:	18.93
Sum wi:	32.41
Sxx:	0.02480
Chi-square:	1.955
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

		95% Confidence Interval	
% Dead	Exposure Time (sec)	Exposure Time (sec)	Percent Dead
1	143	112 - 150	<0.1 - 23.0
5	148	125 - 154	0.2 - 31.1
10	151	132 - 156	1.4 - 36.2
30	157	148 - 160	15.3 - 49.1
50	162	158 - 166	36.5 - 63.5
70	166	163 - 176	52.0 - 84.1
90	173	168 - 197	65.1 - 98.5
95	176	170 - 208	70.1 - 99.7
99	183	174 - 231	78.1 ->99.9

Table 2

EXPERIMENTAL DATA

FREQUENCY: 0.95 GHz

POWER DENSITY: 0.278 watts/cm^2

Lethality Data

Exposure Time (sec)	Number of Rats	Number Dead
180	10	5
182	10	2
185	10	4
188	10	6
190	10	8

Statistical Parameters

X-bar: 5.220
Y-bar: 5.004
B: 18.89
Sum wi: 30.22
Sxx: 0.01170
Chi-square: 4.149
Heterogeneity : 1.000
t: 1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)	 Percent Dead
1	163	8.99 - 174	<0.1 - 47.5
5	170	21.7 - 177	<0.1 - 49.1
10	173	34.8 - 179	0.5 - 50.1
30	180	92.6 - 184	12.6 - 53.8
50	185	173 - 197	36.1 - 63.9
70	190	186 - 366	46.5 - 87.2
90	198	191 - 973	50.2 - 99.5
95	202	193 -1560	51.2 ->99.9
99	209	197 -3770	52.8 ->99.9

Table 3

EXPERIMENTAL DATA

FREQUENCY: 0.95 GHz

POWER DENSITY: 0.256 watts/cm^2

Lethality Data

Exposure Time (sec)	Number of Rats	Number Dead
162	4	0
174	4	2
175	10	3
180	10	2
215	9	3
220	10	7
225	10	5
236	3	3

Statistical Parameters

X-bar:	5.301
Y-bar:	4.809
B:	3.944
Sum wi:	34.55
Sxx:	0.4922
Chi-square:	6.955
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

		95% Confidence Interval	
% Dead	Exposure Time (sec)	Exposure Time (sec)	Percent Dead
1	117	31.0 - 148	<0.1 - 21.8
5	139	55.9 - 164	0.3 - 28.7
10	152	76.4 - 174	1.7 - 33.0
30	184	143 - 201	17.5 - 45.4
50	211	193 - 254	35.9 - 64.1
70	241	217 - 384	46.7 - 87.1
90	291	246 - 732	57.4 - 99.1
95	320	261 -1000	61.9 - 99.9
99	380	289 -1810	69.6 ->99.9

Table 4

EXPERIMENTAL DATA

FREQUENCY: 0.95 GHz

POWER DENSITY: 0.222 watts/cm ^{2}

Lethality Data

Exposure Time (sec)	Number of Rats	Number Dead
223	4	0
240	10	1
245	10	3
250	9	3
253	10	8
255	9	6
260	4	4

Statistical Parameters

X-bar: 5.521
Y-bar: 4.995
B: 33.92
Sum wi: 26.38
Sxx: 0.01224
Chi-square: 2.832
Heterogeneity: 1.000
t: 1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)	95% Confidence Interval Percent Dead
1	233	216 - 239	<0.1 - 14.6
5	238	225 - 242	0.5 - 24.0
10	240	230 - 244	2.0 - 30.4
30	246	240 - 249	16.0 - 47.8
50	250	247 - 253	35.1 - 64.9
70	254	251 - 260	52.1 - 84.0
90	259	255 - 271	69.5 - 98.0
95	262	257 - 277	75.9 - 99.5
99	268	261 - 289	85.3 ->99.9

Table 5

EXPERIMENTAL DATA

FREQUENCY: 0.95 GHz

POWER DENSITY: 0.178 watts/cm^2

Lethality Data

Exposure Time (sec)	Number of Rats	Number Dead
240	4	0
280	10	3
285	3	2
290	10	4
295	9	5
300	14	10
305	10	7

Statistical Parameters

X-bar: 5.681
Y-bar: 5.112
B: 13.16
Sum wi: 34.03
Sxx: 0.03883
Chi-square: 1.485
Heterogeneity: 1.000
t: 1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval: Exposure Time (sec)	95% Confidence Interval: Percent Dead
1	244	137 - 264	<0.1 - 32.5
5	257	169 - 273	0.2 - 39.2
10	264	189 - 277	0.9 - 43.0
30	279	238 - 288	13.3 - 51.5
50	291	276 - 300	35.5 - 64.5
70	303	295 - 338	52.6 - 83.7
90	320	307 - 424	63.1 - 98.7
95	329	312 - 474	66.9 - 99.8
99	347	322 - 586	73.2 ->99.9

cohort, with values ranging from 39.5 to 44°C. There was no discernible correlation between rectal temperature and mortality.

The animals categorized as dead on removal from the exposure box usually showed a foamy mucus nasal discharge, and were either limp or in convulsions. Observation of the latter symptom gave the impression of a forced inspiration with a blocked airway. With the few exceptions noted above, the remaining decedents usually died with a few minutes of removal; death was usually associated with the symptoms of fluid discharge and convulsion. In rare cases, some nasal discharge was observed shortly after exposure in animals that ultimately survived. With this exception, and that of an elevated temperature immediately after exposure, survivors appeared normal during the entire three-day observation period.

Because of scheduling difficulties, no animals at this frequency were subjected to gross necropsy or histologic evaluation. However, with two exceptions, the clinical pattern observed at cessation of exposure and the appearance of the survivors during the three-day, post-irradiation observation were identical to those seen at the next higher frequency, where necropsies and histologic evaluation were done.

B. Frequency 2: 2.45 GHz

Mortality data for this frequency are summarized in in Tables 6 through 13. Only 1 of the 165 decedents died more than 1 hr after exposure (at about 4 hr). About 60% of the decedents were considered dead on removal from the exposure box. Thus, these data also represent mortality within 1 hr of exposure.

There was no apparent consistent relationship between slope of the mortality curves and power density. With one exception, Chi-square and heterogeneity values indicated acceptable representation of mortality

Table 6

EXPERIMENTAL DATA

FREQUENCY: 2.45 GHz

POWER DENSITY: 3.920 watts/cm^2

Lethality Data

Exposure Time (sec)	Number of Rats	Number Dead
10	10	0
11	10	5
11.5	10	6
12	11	8
12.5	10	6
15	1	1

Statistical Parameters

X-bar: 2.440
Y-bar: 5.000
B: 8.859
Sum wi: 28.08
Sxx: 0.1387
Chi-square: 4.473
Heterogeneity: 1.000
t: 1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)	 Percent Dead
1	8.82	5.97 - 9.78	<0.1 - 18.5
5	9.53	7.20 -10.3	0.4 - 27.4
10	9.93	7.95 -10.6	1.7 - 33.2
30	10.8	9.71 -11.3	15.7 - 48.4
50	11.5	10.9 -12.1	35.6 - 64.4
70	12.2	11.7 -13.6	51.6 - 84.3
90	13.3	12.4 -16.5	66.8 - 98.3
95	13.8	12.8 -18.3	72.6 - 99.6
99	14.9	13.5 -22.0	81.5 ->99.9

Table 7

EXPERIMENTAL DATA

FREQUENCY: 2.45 GHz

POWER DENSITY: 3.450 watts/cm^2

Lethality Data

Exposure Time (sec)	Number of Rats	Number Dead
11	4	0
12	4	2
13	4	3

Statistical Parameters

X-bar: 2.494
Y-bar: 4.814
B: 14.86
Sum wi: 5.753
Sxx: 0.02190
Chi-square: 0.454
Heterogeneity: 1.000
t: 1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval	
		Exposure Time (sec)	Percent Dead
1	10.5	3.17 - 11.3	<0.1 - 40.1
5	11.0	4.81 - 11.7	<0.1 - 45.7
10	11.2	6.00 - 11.9	0.5 - 49.7
20	11.8	9.26 - 12.7	8.1 - 63.6
50	12.3	11.3 - 14.7	20.2 - 79.8
70	12.7	12.0 - 19.4	30.5 - 94.0
90	13.4	12.5 - 30.6	39.7 - 99.8
95	13.7	12.7 - 38.2	42.8 ->99.9
99	14.3	13.1 - 58.1	47.7 ->99.9

Table 8

EXPERIMENTAL DATA

FREQUENCY: 2.45 GHz

POWER DENSITY: 2.900 watts/cm^2

Lethality Data

Exposure Time (sec)	Number of Rats	Number Dead
15[a]	10	6
16	15	2
16.5	15	10
17	15	4
17.5	5	3

Statistical Parameters

X-bar:	2.810
Y-bar:	4.697
B:	8.048
Sum wi:	30.11
Sxx:	0.02581
Chi-square:	9.751[b]
Heterogeneity:	4.875
t:	4.30

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)[c]	95% Confidence Interval Percent Dead
1	12.9		
5	14.1		
10	14.7		
30	16.2	12.0 - 21.7	0.2 - 96.8
50	17.3	12.2 - 24.5	0.2 - 99.8
70	18.4	8.4 - 40.4	
90	20.2		
95	21.2		
99	23.0		

[a] Excluded from computation.

[b] Exceeds 95% confidence interval.

[c] Estimated by approximation method.

Table 9

EXPERIMENTAL DATA

FREQUENCY: 2.45 GHz

POWER DENSITY: 2.273 watts/cm²

Lethality Data

Exposure Time (sec)	Number of Rats	Number Dead
19	10	2
20	10	4
21	10	4
22	10	9

Statistical Parameters

X-bar:	3.021
Y-bar:	4.956
B:	12.08
Sum wi:	21.83
Sxx:	0.05824
Chi-square:	2.459
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)	95% Confidence Interval Percent Dead
1	17.0	11.4 - 18.4	<0.1 - 23.1
5	18.0	13.6 - 19.1	0.3 - 31.2
10	18.5	14.9 - 19.5	1.3 - 36.3
30	19.7	17.8 - 20.4	14.6 - 50.2
50	20.6	19.7 - 21.6	33.7 - 66.3
70	21.5	20.7 - 24.1	48.3 - 86.3
90	22.9	21.7 - 28.9	61.7 - 98.8
95	23.6	22.2 - 31.6	66.8 - 99.8
99	25.0	23.0 - 37.5	75.1 ->99.9

Table 10

EXPERIMENTAL DATA

FREQUENCY: 2.45 GHz

POWER DENSITY: 1.646 watts/cm^2

Lethality Data

Exposure Time (sec)	Number of Rats	Number Dead
27	13	3
28	10	4
30	11	7
31	10	6

Statistical Parameters

X-bar:	3.364
Y-bar:	4.889
B:	7.645
Sum wi:	26.12
Sxx:	0.07816
Chi-square:	0.525
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

		95% Confidence Interval	
% Dead	Exposure Time (sec)	Exposure Time (sec)	Percent Dead
1	21.6	0.88 - 25.0	<0.1 - 39.8
5	23.6	2.56 - 26.2	0.1 - 42.6
10	24.8	4.52 - 26.9	0.8 - 44.4
30	27.4	14.7 - 28.8	14.4 - 50.6
50	29.3	27.2 - 36.8	34.6 - 65.4
70	31.4	29.7 - 80.0	43.1 - 88.9
90	34.7	31.5 -262	47.9 - 99.6
95	36.4	32.4 -464	49.6 ->99.9
99	39.7	34.0 -1360	52.3 ->99.9

Table 11

EXPERIMENTAL DATA

FREQUENCY: 2.45 GHz

POWER DENSITY: 0.862 watts/cm^2

Lethality Data

Exposure Time (sec)	Number of Rats	Number Dead
57	9	1
60	14	8
63	10	6
66	10	6

Statistical Parameters

X-bar:	4.118
Y-bar:	4.966
B:	7.634
Sum wi:	25.87
Sxx:	0.06674
Chi-square:	3.074
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval: Exposure Time (sec)[a]	95% Confidence Interval: Percent Dead
1	45.5	33.6 - 61.6	<0.1 - 49.4
5	49.7	40.1 - 61.7	0.1 - 50.1
10	52.1	44.0 - 61.8	0.5 - 50.7
30	57.6	53.1 - 62.5	11.6 - 53.9
50	61.7	58.6 - 64.9	34.9 - 65.1
70	66.1	60.5 - 72.2	44.0 - 88.5
90	73.0	61.0 - 87.2	46.8 - 99.6
95	76.5	61.1 - 95.7	47.3 ->99.9
99	83.7	61.3 -114	48.0 ->99.9

[a] Estimated by approximation method.

Table 12

EXPERIMENTAL DATA

FREQUENCY: 2.45 **GHz**

POWER DENSITY: 0.490 **watts/cm^2**

Lethality Data

Exposure Time (sec)	Number of Rats	Number Dead
116	10	1
120	14	8
124	10	6
128	10	6

Statistical Parameters

X-bar:	4.802
Y-bar:	4.938
B:	12.03
Sum wi:	26.23
Sxx:	0.03108
Chi-square:	3.497
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)	95% Confidence Interval Percent Dead
1	101	10.2 - 111	<0.1 - 42.1
5	106	21.5 - 114	0.1 - 44.7
10	110	31.9 - 116	0.7 - 46.4
30	117	72.4 - 121	13.6 - 52.0
50	122	115 - 138	34.9 - 65.1
70	128	124 - 234	44.5 - 88.3
90	136	128 - 532	49.3 - 99.5
95	140	131 - 791	50.9 ->99.9
99	149	135 -1665	53.5 ->99.9

Table 13

EXPERIMENTAL DATA

FREQUENCY: 2.45 GHz

POWER DENSITY: 0.342 watts/cm^2

Lethality Data

Exposure Time (sec)	Number of Rats	Number Dead
180	14	9
185	10	2
190	10	4
200	10	3
220	10	6
240	5	4

Statistical Parameters

X-bar:	5.283
Y-bar:	4.936
B:	2.203
Sum wi:	36.97
Sxx:	0.3000
Chi-square:	7.581
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval: Exposure Time (sec)[a]	95% Confidence Interval: Percent Dead
1	70.5	13.2 - 376	<0.1 - 91.4
5	96.0	29.6 - 311	<0.1 - 82.8
10	113	45.6 - 281	<0.1 - 76.5
30	160	110 - 231	9.0 - 61.5
50	203	174 - 236	36.8 - 63.2
70	257	163 - 406	31.5 - 93.7
90	363	133 - 988	17.7 ->99.9
95	428	120 - 1520	12.5 ->99.9
99	582	99.4 - 3410	5.8 ->99.9

[a] Estimated by approximation method.

by the probit analysis. The exception occurred at the 2.900-W/cm^2 power density, and no experimental basis for the heterogeneity of the data at this power density was discernible. There was a consistent inverse relationship between LD_{50} and power density, with values ranging from 11.5 sec at 3.920 W/cm^2 to 203 sec at 0.342 W/cm^2.

Body weight at exposure averaged 213 ± 21 g. For the first cohort, rectal temperatures on removal from the exposure box ranged from 39.5 to 42.5°C. Again, there was no apparent relationship between either body weight or rectal temperature and mortality.

With two exceptions, clinical symptoms at the end of exposure and during the subsequent hour were similar to those described above for the 0.95 GHz frequency, including convulsions and nasal discharge. The first exception was that the technician grasping the rat's tail to remove it from the exposure box reported that the tail surface felt soft in many of the animals exposed at 2.45 GHz, an observation not noted for the 0.95 GHz animals. In addition, some of the survivors showed dark discolorations of the tail at the grasping site on the next day. These subjective observations are consistent with those of other investigators[9] that, during the second week following exposure, the tails of surviving rats subjected to 3.0 GHz irradiation frequently underwent spontaneous amputation at about the point where they had been grasped.

The second exception is that at 2.45 GHz, reddening of the ears, nose, and forepaws, swollen muzzles, and frank burns in the area of the ears and in narrow bands on the tail were apparent in some survivors the day after exposure. The swollen muzzles were also seen by the WRAIR group.[9] The localized tail burns may have been related to the coiling of the tails as the animals were inserted in the exposure boxes, with consequent inhomogeneity of exposure of the tail to the microwave beam.

In addition to the externally apparent symptoms, froth in the trachea and frank hemorrhage in the lung were apparent at gross necropsy in decedents. These findings were confirmed by histologic evaluation, with congestion and edema also apparent at the microscopic level. Survivors sacrificed after the three-day observation period also showed histologic evidence of lung damage in terms of congestion, hemorrhage, and edema, but no gross damage was apparent. Thus, mortality at this frequency appears to be associated with asphyxia consequent to damage to the lung.

C. Frequency 3: 4.54 GHz

Compared with the two lower frequencies, there were marked differences in the chronology of mortality and in the clinical symptoms associated with exposure at this frequency. About a quarter of the 208 decedents were considered dead on removal from the exposure box. Another half of the 208 decedents died within 1 hr of exposure, most of them within 15 min. Except for six animals, the remaining decedents succumbed by the end of the first day post-irradiation.

In view of the above chronologic distribution of mortality, the 1-hr mortality data are summarized in Tables 14 through 19, and data for 72-hr mortality are shown in Tables 20 through 25, although the latter analysis is substantially equivalent to a 24-hr evaluation. The uncertainties in maintaining constant power level become critical in an area where small changes in power are associated with large changes in the exposure time for a given effect. Thus, it was considered desirable to hold the exposure time of 300 sec constant and to vary the power density at the low power (< 0.72 W/cm^2) portion of the exposures at this frequency. Accordingly, the mortality data in Tables 19 through 25 are in terms of power density rather than in exposure time.

Table 14

EXPERIMENTAL DATA

FREQUENCY: 4.54 GHz

POWER DENSITY: 12.376 watts/cm^2

Lethality Data - 1 hr

Exposure Time (sec)	Number of Rats	Number Dead
8	14	0
8.5	10	1
9	10	5
9.5	9	1
10	13	9
11	4	2
12	2	2

Statistical Parameters

X-bar:	2.236
Y-bar:	4.582
B:	7.713
Sum wi:	28.70
Sxx:	0.2465
Chi-square:	10.987
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

		95% Confidence Interval	
% Dead	Exposure Time (sec)	Exposure Time (sec)[a]	Percent Dead
1	7.31	5.59 - 8.01	<0.1 - 10.0
5	7.98	6.67 - 8.53	0.9 - 16.9
10	8.37	7.31 - 8.84	3.2 - 24.0
30	9.23	8.68 - 9.71	18.6 - 43.9
50	9.83	9.42 -10.8	33.6 - 66.4
70	10.6	9.98 -12.2	46.8 - 87.1
90	11.7	10.7 -14.8	63.2 - 98.7
95	12.2	11.1 -16.3	70.1 - 99.7
99	13.4	11.8 -19.5	80.9 ->99.9

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[a] Estimated by approximation method.

Table 15

EXPERIMENTAL DATA

FREQUENCY: 4.54 GHz

POWER DENSITY: 6.188 watts/cm^2

Lethality Data - 1 hr

Exposure Time (sec)	Number of Rats	Number Dead
15	10	1
16.5	10	0
18	10	8
20	14	8
22	4	1
25	4	4

Statistical Parameters

X-bar: 2.915
Y-bar: 4.802
B: 4.741
Sum wi: 28.47
Sxx: 0.5266
Chi-square: 15.499[a]
Heterogeneity: 3.874
t: 2.78

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)[b]	 Percent Dead
1	11.8	5.58 - 24.8	<0.1 - 88.7
5	13.6	7.99 - 23.1	<0.1 - 80.9
10	14.7	9.61 - 22.4	<0.1 - 76.5
30	17.2	13.5 - 21.9	4.7 - 73.4
50	19.2	15.3 - 24.1	14.2 - 85.8
70	21.5	15.5 - 29.7	15.5 - 98.1
90	25.2	14.7 - 43.3	9.9 - >99.9
95	27.2	14.1 - 53.4	7.2 - >99.9
99	31.4	13.1 - 75.3	3.5 - >99.9

[a] Exceeds 95% confidence interval.

[b] Estimated by approximation method.

Table 16

EXPERIMENTAL DATA

FREQUENCY: 4.54 GHz

POWER DENSITY: 2.285 watts/cm²

Lethality Data - 1 hr

Exposure Time (sec)	Number of Rats	Number Dead
45	10	0
50	21	4
55	35	26
60	18	13

Statistical Parameters

X-bar:	3.987
Y-bar:	5.057
B:	9.682
Sum wi:	42.65
Sxx:	0.2280
Chi-square:	6.880[a]
Heterogeneity:	3.440
t:	4.30

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)[b]	95% Confidence Interval Percent Dead
1	42.1		
5	45.2		
10	46.9		
30	50.7	43.1 - 59.7	1.8 - 85.4
50	53.6	47.2 - 60.8	11.0 - 89.0
70	56.5	48.6 - 65.8	17.4 - 97.7
90	61.1		
95	63.5		
99	68.1		

[a] Exceeds 95% confidence interval.

[b] Estimated by approximation method.

Table 17

EXPERIMENTAL DATA

FREQUENCY: 4.54 GHz

POWER DENSITY: 1.142 **watts/cm²**

Lethality Data - 1 hr

Exposure Time (sec)	Number of Rats	Number Dead
110	10	2
113	10	5
115	14	6
120	14	9
125	4	2
130	4	4

Statistical Parameters

X-bar: 4.756
Y-bar: 4.983
B: 10.50
Sum wi: 32.81
Sxx: 0.06207
Chi-square: 3.199
Heterogeneity: 1.000
t: 1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval	
		Exposure Time (sec)	Percent Dead
1	93.4	42.2 - 103	<0.1 - 28.7
5	99.6	62.4 - 107	0.2 - 35.3
10	103	71.5 - 109	1.1 - 39.2
30	111	94.6 - 115	15.0 - 49.5
50	117	111 - 123	36.7 - 63.3
70	122	118 - 145	49.8 - 85.4
90	132	124 - 192	59.9 - 99.0
95	136	127 - 220	63.8 - 99.8
99	145	132 - 284	70.5 - >99.9

Table 18

EXPERIMENTAL DATA

FREQUENCY: 4.54 GHz

POWER DENSITY: 0.762 watts/cm^2

Lethality Data - 1 hr

Exposure Time (sec)	Number of Rats	Number Dead
155	10	3
160	10	3
165	10	0
170	14	6
180	4	2
190	4	2

Statistical Parameters

X-bar:	5.117
Y-bar:	4.502
B:	3.810
Sum wi:	29.63
Sxx:	0.09818
Chi-square:	5.340
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval	
		Exposure Time (sec)[a]	Percent Dead
1	103	46.7 - 228	<0.1 - 75.5
5	124	74.7 - 204	<0.1 - 60.7
10	136	95.7 - 193	0.4 - 52.2
30	166	151 - 182	18.7 - 43.6
50	190	150 - 240	18.6 - 81.4
70	218	139 - 342	11.7 - 98.8
90	266	123 - 576	4.8 - >99.9
95	293	116 - 741	2.9 - >99.9
99	350	103 -1190	1.0 - >99.9

---

[a] Estimated by approximation method.

Table 19

EXPERIMENTAL DATA

FREQUENCY: 4.54 GHz

EXPOSURE TIME: 300 sec

Lethality Data - 1 hr

Power Density (watts/cm^2)	Number of Rats	Number Dead
0.409	10	2
0.428	10	9
0.438	10	5
0.476	14	9
0.495	4	3
0.524	4	3

Statistical Parameters

X-bar:	-0.8023
Y-bar:	5.234
B:	4.023
Sum wi:	31.36
Sxx:	0.1667
Chi-square:	8.559
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Power Density (watts/cm^2)	95% Confidence Interval Power Density (watts/cm^2)[a]	95% Confidence Interval Percent Dead
1	0.237		
5	0.281		
10	0.307		
30	0.371	0.291 - 0.472	6.7 - 67.2
50	0.423	0.379 - 0.473	32.7 - 67.3
70	0.482	0.426 - 0.545	51.3 - 84.5
90	0.582		
95	0.637		
99	0.754		

---

[a] Estimated by approximation method.

Table 20

EXPERIMENTAL DATA

FREQUENCY: 4.54 GHz

POWER DENSITY: 12.376 watts/cm^2

Lethality Data - 72 hr

Exposure Time (sec)	Number of Rats	Number Dead
8	14	1
8.5	10	2
9	10	9
9.5	9	8
10	13	11
11	4	3
12	2	2

Statistical Parameters

X-bar:	2.191
Y-bar:	5.088
B:	9.551
Sum wi:	29.24
Sxx:	0.2015
Chi-square:	17.767[a]
Heterogeneity:	3.553
t:	2.57

Expected Death Rate

		95% Confidence Interval	
% Dead	Exposure Time (sec)	Exposure Time (sec)[b]	Percent Dead
1	6.95		
5	7.46		
10	7.75	6.43 - 9.35	0.1 - 69.4
30	8.39	7.45 - 9.45	4.9 - 72.8
50	8.86	8.06 - 9.74	18.4 - 81.6
70	9.36	8.41 -10.4	30.9 - 93.9
90	10.1	8.56 -12.0	36.8 - 99.8
95	10.5		
99	11.3		

---

[a] Exceeds 95% confidence interval.

[b] Estimated by approximation method.

Table 21

EXPERIMENTAL DATA

FREQUENCY: 4.54 GHz

POWER DENSITY: 6.188 watts/cm ^{2}

Lethality Data - 72 hr

Exposure Time (sec)	Number of Rats	Number Dead
15	10	3
16.5	10	0
18	10	10
20	14	10
22	4	3
25	4	4

Statistical Parameters

X-bar:	2.885
Y-bar:	5.147
B:	5.304
Sum wi:	27.47
Sxx:	0.4425
Chi-square:	15.305[a]
Heterogeneity:	3.826
t:	2.78

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval: Exposure Time (sec)[b]	95% Confidence Interval: Percent Dead
1	11.2	5.33 - 23.7	<0.1 - 94.8
5	12.8	7.32 - 22.3	<0.1 - 90.4
10	13.7	8.64 - 21.6	<0.1 - 87.5
30	15.8	12.0 - 20.8	2.3 - 82.7
50	17.4	14.3 - 21.3	14.4 - 85.6
70	19.2	15.4 - 24.1	25.3 - 95.7
90	22.2	15.1 - 32.5	22.6 - >99.9
95	23.7	14.7 - 38.3	18.8 - >99.9
99	27.0	13.9 - 52.4	11.7 - >99.9

[a] Exceeds 95% confidence interval.

[b] Estimated by approximation method.

Table 22

EXPERIMENTAL DATA

FREQUENCY: 4.54 GHz

POWER DENSITY: 2.285 watts/cm²

Lethality Data - 72 hr

Exposure Time (sec)	Number of Rats	Number Dead
45	10	0
50	21	10
55	35	30
60	18	14

Statistical Parameters

X-bar:	3.968
Y-bar:	5.327
B:	8.408
Sum wi:	42.72
Sxx:	0.2832
Chi-square:	8.329[a]
Heterogeneity:	4.164
t:	4.30

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval: Exposure Time (sec)	95% Confidence Interval: Percent Dead[b]
1	38.6		
5	41.8		
10	43.7		
30	47.8	37.0 - 61.6	0.4 - 94.7
50	50.8	42.6 - 60.7	6.8 - 93.2
70	54.1	45.8 - 63.9	19.1 - 97.3
90	59.2		
95	61.8		
99	67.1		

[a] Exceeds 95% confidence limits.

[b] Estimated by approximation method.

Table 23

EXPERIMENTAL DATA

FREQUENCY: 4.54 GHz

POWER DENSITY: 1.142 watts/cm^2

Lethality Data - 72 hr

Exposure Time (sec)	Number of Rats	Number Dead
110	10	3
113	10	6
115	14	9
120	14	10
125	4	3
130	4	4

Statistical Parameters

X-bar:	4.751
Y-bar:	5.285
B:	10.75
Sum wi:	31.72
Sxx:	0.05461
Chi-square:	1.686
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)	95% Confidence Interval Percent Dead
1	90.8	38.2 - 101	<0.1 - 39.8
5	96.7	50.9 - 105	0.1 - 46.1
10	100	59.3 - 107	0.5 - 49.6
30	107	81.4 - 112	10.6 - 57.8
50	113	100 - 116	34.0 - 66.0
70	118	114 - 131	55.2 - 82.1
90	127	121 - 177	66.6 - 98.4
95	131	124 - 207	70.1 - 99.7
99	140	128 - 276	75.7 - >99.9

Table 24

EXPERIMENTAL DATA

FREQUENCY: 4.54 GHz

POWER DENSITY: 0.762 watts/cm²

Lethality Data - 72 hr

Exposure Time (sec)	Number of Rats	Number Dead
155	10	3
160	10	4
165	10	0
170	14	7
180	4	2
190	4	3

Statistical Parameters

X-bar:	5.116
Y-bar:	4.661
B:	5.536
Sum wi:	30.63
Sxx:	0.09749
Chi-square:	6.875
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval: Exposure Time (sec)[a]	95% Confidence Interval: Percent Dead
1	116	77 - 176	<0.1 - 48.2
5	132	100 - 173	0.1 - 45.1
10	141	115 - 172	0.8 - 43.8
30	161	150 - 174	17.5 - 45.5
50	177	161 - 195	30.1 - 69.9
70	195	161 - 235	30.3 - 94.1
90	223	159 - 313	27.8 - 99.9
95	239	158 - 360	26.4 - >99.9
99	270	156 - 468	24.0 - >99.9

---

[a] Estimated by approximation method.

Table 25

EXPERIMENTAL DATA

FREQUENCY: 4.54 GHz

EXPOSURE TIME: 300 sec

Lethality Data - 72 hr

Power Density (watts/cm^2)	Number of Rats	Number Dead
0.409	10	2
0.428	10	9
0.438	10	6
0.476	14	10
0.495	4	4
0.524	4	3

Statistical Parameters

X-bar:	-0.8078
Y-bar:	5.370
B:	5.538
Sum wi:	29.49
Sxx:	0.1469
Chi-square:	9.338
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Power Density (watts/cm^2)	95% Confidence Interval	
		Power Density (watts/cm^2)[a]	Percent Dead
1	0.274	0.174 - 0.431	<0.1 - 57.5
5	0.310	0.220 - 0.436	<0.1 - 59.9
10	0.331	0.249 - 0.439	0.2 - 61.2
30	0.380	0.322 - 0.446	7.7 - 64.7
50	0.417	0.381 - 0.456	30.9 - 69.1
70	0.458	0.427 - 0.492	55.4 - 81.9
90	0.526	0.445 - 0.620	64.3 - 98.6
95	0.561	0.449 - 0.701	66.1 - 99.8
99	0.635	0.455 - 0.885	68.6 ->99.9

[a] Estimated by approximation method.

As previously noted, there was no consistent relationship between slopes of the mortality curves and power density. However, there was much more heterogeneity at this frequency, with the approximation method of estimating confidence limits required at all but one power density (1.142 W/cm^2) at this frequency. Computed 1-hr LD$_{50}$ values ranged from 9.88 to 190 sec for power densities between 12.376 and 0.762 W/cm^2, and continued to be inversely related to power density. Comparable 72-hr LD$_{50}$ values were somewhat less.

The mean body weight for this frequency was 207 ± 24 g, and, as at lower frequencies, no correlation between body weight and mortality was apparent. Since rectal temperatures had not been useful in predicting mortality at the lower frequencies, and since this time-consuming procedure was thus unlikely to provide useful information at the less-penetrating higher frequencies, this measurement was not taken at either 4.54 or 7.44 GHz. It should be noted, however, that the technician handling the animals reported that the animals did not feel abnormally warm when grasped around the body, as did those irradiated at the two lower frequencies.

Although animals considered dead at removal or that died within the next hour showed symptoms of convulsion and respiratory insufficiency, the nasal discharge was not a prominent feature, although a foamy fluid could be expressed by pressure on the thorax. More prominent was copious wetting of the region around the mouth, apparently from marked salivation. Many of these early decedents has swollen and extended tongues. Frank burning of ears, eyes, and skin in the muzzle area was noted, as was swelling of the muzzle area. The latter symptoms were also apparent in many of the decedents surviving beyond the first day post-exposure, and in some of the animals surviving to the end of the three-day observation period.

Gross necropsy of decedents revealed hemorrhage into the nasal passages, froth in the trachea, and hemorrhage in the lung. Histologic evaluation of nasal passage tissues was not done. In addition to hemorrhage, congestion and edema were evident in the lung. No evidence of lung hemorrhage was seen in survivors sacrificed one week after irradiation, but there was histologic evidence of congestion and edema in the lung. For this frequency, mortality appeared associated with asphyxia consequent to hemorrhage in the lung and/or nasal passages.

D. Frequency 4: 7.44 GHz

Exposure at this frequency resulted in a further modification of the chronology of mortality and in the clinical symptoms observed post-irradiation. About a quarter of the 219 decedents were recorded as dead at cessation of exposure, and another quarter were dead within the next hour, usually within 30 min. Those decedents dying after one hour but within the first day comprised about 40% of the total decedents, the remaining 10% dying over the next two days.

For purpose of comparison with the 4.54-GHz findings, the mortality data summarized in Tables 26 through 37 have been analyzed in terms of both 1- and 72-hr mortality. The slopes of the curves for this frequency were the most widely distributed of all, and there was significant heterogeneity and/or the necessity of estimating confidence limits by the approximation method in 5 of the 12 analyses. Indeed, in one case ($5.720\ W/cm^2$ at 72 hr), it was necessary to assume initial values of $\bar{X}$, $\bar{Y}$, and slope and refit the actual mortality data to the assumed values to obtain a curve fit. The resulting regression line was technically acceptable, but still of doubtful reliability. Calculated 1-hr LD_{50} values were, as expected, inversely proportional to power densities, ranging from 16.8 sec at $5.720\ W/cm^2$ to 176 sec at $0.629\ W/cm^2$. Comparable 72-hr LD_{50} values were appreciably less. For the reasons

Table 26

EXPERIMENTAL DATA

FREQUENCY: 7.44 GHz

POWER DENSITY: 5.720 watts/cm^2

Lethality Data - 1 hr

Exposure Time (sec)	Number of Rats	Number Dead
11[a]	7	0
12[a]	7	0
13[a]	7	0
14	7	0
15	7	4
16	7	1
17	7	5
18	7	4

Statistical Parameters

X-bar:	2.777
Y-bar:	4.757
B:	5.912
Sum wi:	20.05
Sxx:	0.1464
Chi-square:	7.522
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)	95% Confidence Interval Percent Dead
1	11.3	1.14 - 13.4	<0.1 - 31.9
5	12.7	2.68 - 14.3	0.2 - 36.2
10	13.5	4.24 - 14.9	1.1 - 38.9
30	15.3	10.6 - 16.6	15.3 - 49.1
50	16.8	15.4 - 23.3	31.4 - 68.6
70	18.3	16.8 - 43.5	39.3 - 90.7
90	20.8	18.2 -112	45.6 - 99.6
95	22.1	18.9 -178	48.1 ->99.9
99	24.8	20.1 -420	52.3 ->99.9

---

[a] Excluded from computation.

Table 27

EXPERIMENTAL DATA

FREQUENCY: 7.44 GHz

POWER DENSITY: 2.860 watts/cm^2

Lethality Data - 1 hr

Exposure Time (sec)	Number of Rats	Number Dead
25	7	0
26	7	1
27	7	0
28	7	1
30	12	3
32	14	6
34	7	2

Statistical Parameters

X-bar:	3.405
Y-bar:	4.262
B:	5.156
Sum wi:	27.50
Sxx:	0.2312
Chi-square:	3.106
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)	95% Confidence Interval Percent Dead
1	22.1	6.84 - 25.6	<0.1 - 15.5
5	25.3	12.8 - 27.8	0.7 - 20.2
10	27.1	17.7 - 29.2	3.2 - 23.8
30	31.4	29.0 - 39.0	17.5 - 45.4
50	34.8	31.9 - 61.0	24.4 - 75.6
70	38.5	34.1 - 98.3	29.4 - 94.4
90	44.6	37.2 -197	36.0 - 99.8
95	47.8	38.7 -276	39.1 ->99.9
99	54.6	41.7 -518	45.0 ->99.9

Table 28

EXPERIMENTAL DATA

FREQUENCY: 7.44 GHz

POWER DENSITY: 1.430 watts/cm^2

Lethality Data - 1 hr

Exposure Time (sec)	Number of Rats	Number Dead
50[a]	7	0
52	7	0
55	14	1
58	7	1
60	10	3
65	10	5
67	10	8

Statistical Parameters

X-bar:	4.120
Y-bar:	4.663
B:	11.10
Sum wi:	24.42
Sxx:	0.1341
Chi-square:	0.958
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)	95% Confidence Interval Percent Dead
1	51.4	43.2 - 54.9	<0.1 - 9.9
5	54.7	48.5 - 57.4	0.8 -18.4
10	56.5	51.5 - 58.9	3.0 -24.9
30	60.5	57.7 - 62.8	17.6 -45.3
50	63.4	61.2 - 67.0	33.4 -66.6
70	66.5	63.9 - 72.6	48.0 -86.2
90	71.2	67.3 - 82.3	65.8 -98.4
95	73.6	68.9 - 87.5	72.9 -99.6
99	78.2	72.0 - 98.3	87.7->99.9

---

[a] Excluded from computation.

Table 29

EXPERIMENTAL DATA

FREQUENCY: 7.44 GHz

POWER DENSITY: 0.858 watts/cm²

Lethality Data - 1 hr

Exposure Time (sec)	Number of Rats	Number Dead
110[a]	4	0
115	10	0
117	10	2
120	14	8
122	17	5
124	17	6

Statistical Parameters

X-bar:	4.793
Y-bar:	4.514
B:	12.29
Sum wi:	37.93
Sxx:	0.02354
Chi-square:	7.934[b]
Heterogeneity:	2.644
t:	3.18

Expected Death Rate

		95% Confidence Interval	
% Dead	Exposure Time (sec)	Exposure Time (sec)[c]	Percent Dead
1	104		
5	110		
10	113		
30	120	112 - 129	8.5 - 62.6
50	126	110 - 143	5.8 - 94.2
70	131	104 - 166	0.9 ->99.9
90	139		
95	144		
99	152		

[a] Excluded from computation.

[b] Exceeds 95% confidence limits.

[c] Estimated by approximation method.

Table 30

EXPERIMENTAL DATA

FREQUENCY: 7.44 GHz

POWER DENSITY: 0.629 watts/cm^2

Lethality Data - 1 hr

Exposure Time (sec)	Number of Rats	Number Dead
170[a]	7	5
175	7	4
180	7	2
185	14	4
190	7	6

Statistical Parameters

X-bar: 5.210
Y-bar: 4.895
B: 5.776
Sum wi: 21.98
Sxx: 0.01699
Chi-square: 6.850[b]
Heterogeneity: 3.425
t: 4.30

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)[c]	 Percent Dead
1	125		
5	140		
10	149		
30	170		
50	186	131 - 265	2.1 - 97.9
70	204		
90	233		
95	248		
99	279		

---

[a] Excluded from computation.

[b] Exceeds 95% confidence limits.

[c] Estimated by approximation method.

Table 31

EXPERIMENTAL DATA

FREQUENCY: 7.44 GHz

EXPOSURE TIME: 300 sec

Lethality Data - 1 hr

Power Density (watts/cm²)	Number of Rats	Number Dead
0.400[a]	4	0
0.415	7	0
0.423	7	3
0.429	7	2
0.435	7	2
0.443	7	6
0.486	4	3

Statistical Parameters

X-bar:	-0.8369
Y-bar:	4.720
B:	14.07
Sum wi:	21.78
Sxx:	0.02948
Chi-square:	7.276
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Power Density (watts/cm²)	95% Confidence Interval Power Density (watts/cm²)	95% Confidence Interval Percent Dead
1	0.375	0.200 - 0.400	<0.1 - 26.9
5	0.392	0.258 - 0.412	0.2 - 32.2
10	0.403	0.295 - 0.420	1.4 - 35.7
30	0.426	0.386 - 0.440	16.1 - 47.6
50	0.440	0.429 - 0.492	31.6 - 68.4
70	0.458	0.443 - 0.592	40.1 - 90.3
90	0.483	0.458 - 0.784	47.9 - 99.6
95	0.498	0.466 - 0.898	51.1 - >99.9
99	0.521	0.478 - 1.158	56.8 - >99.9

---

[a] Excluded from computation.

Table 32

EXPERIMENTAL DATA

FREQUENCY: 7.44 GHz

POWER DENSITY: 5.720 watts/cm^2

Lethality Data - 72 hr

Exposure Time (sec)	Number of Rats	Number Dead
11	7	0
12	7	6
13	7	6
14	7	7
15	7	7
16	7	6
17	7	7
18[a]	7	7

Statistical Parameters

X-bar:	2.531
Y-bar:	5.509
B:	7.539
Sum wi:	16.17
Sxx:	0.1928
Chi-square:	19.863[b]
Heterogeneity:	3.972
t:	2.57

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval: Exposure Time (sec)[c]	95% Confidence Interval: Percent Dead
1	8.63		
5	9.44		
10	9.91		
30	11.0	8.36 - 14.4	0.5 - 93.6
50	11.7	9.63 - 14.3	6.7 - 93.3
70	12.6	10.6 - 14.9	22.7 - 96.4
90	13.9		
95	14.6		
99	16.0		

[a] Excluded from computation.

[b] Exceeds 95% confidence limits.

[c] Estimated by approximation method.

Table 33

EXPERIMENTAL DATA

FREQUENCY: 7.44 GHz

POWER DENSITY: 2.860 watts/cm^2

Lethality Data - 72 hr

Exposure Time (sec)	Number of Rats	Number Dead
25	7	2
26	7	3
27	7	3
28	7	2
30	12	11
32	14	12
34	7	7

Statistical Parameters

X-bar:	3.346
Y-bar:	5.322
B:	8.248
Sum wi:	28.78
Sxx:	0.2306
Chi-square:	4.789
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)	95% Confidence Interval Percent Dead
1	20.6	14.9 - 23.0	<0.1 - 16.7
5	22.4	17.6 - 24.4	0.4 - 27.2
10	23.4	19.1 - 25.2	1.6 - 34.2
30	25.6	22.8 - 27.0	14.0 - 51.3
50	27.3	25.5 - 28.6	34.5 - 65.5
70	29.1	27.8 - 30.9	55.8 - 81.7
90	31.9	30.2 - 36.3	75.3 - 97.0
95	33.3	31.2 - 39.5	81.5 - 99.2
99	36.2	33.1 - 46.3	89.8 ->99.9

Table 34

EXPERIMENTAL DATA

FREQUENCY: 7.44 GHz

POWER DENSITY: 1.430 watts/cm^2

Lethality Data - 72 hr

Exposure Time (sec)	Number of Rats	Number Dead
50	7	1
52	7	3
55	14	4
58	7	3
60	10	10
65[a]	10	10
67[a]	10	10

Statistical Parameters

X-bar:	4.016
Y-bar:	4.953
B:	10.93
Sum wi:	24.27
Sxx:	0.08337
Chi-square:	7.585
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)	95% Confidence Interval Percent Dead
1	45.0	31.8 - 49.0	<0.1 - 19.6
5	47.9	37.5 - 51.0	0.3 - 28.2
10	49.5	40.8 - 52.2	1.6 - 33.8
30	53.1	48.5 - 55.1	15.4 - 48.9
50	55.7	53.3 - 58.5	34.5 - 65.5
70	58.4	56.3 - 64.8	49.7 - 85.5
90	62.6	59.3 - 77.1	64.3 - 98.6
95	64.7	60.6 - 84.0	69.9 - 99.7
99	68.9	63.1 - 98.8	78.8 - >99.9

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[a] Excluded from computation.

Table 35

EXPERIMENTAL DATA

FREQUENCY: 7.44 GHz

POWER DENSITY: 0.858 watts/cm^2

Lethality Data - 72 hr

Exposure Time (sec)	Number of Rats	Number Dead
110	4	2
115	10	3
117	10	6
120	14	11
122	17	12
124	17	8

Statistical Parameters

X-bar:	4.784
Y-bar:	5.210
B:	3.827
Sum wi:	44.87
Sxx:	0.04838
Chi-square:	7.027
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)[a]	95% Confidence Interval Percent Dead
1	61.7		
5	73.7		
10	81.0		
30	98.7	62.8 - 155	1.2 - 88.7
50	113	97.6 - 131	28.5 - 71.5
70	130	106 - 160	39.6 - 90.5
90	158		
95	174		
99	208		

[a] Estimated by approximation method.

Table 36

EXPERIMENTAL DATA

FREQUENCY: 7.44 GHz

POWER DENSITY: 0.629 watts/cm^2

Lethality Data - 72 hr

Exposure Time (sec)	Number of Rats	Number Dead
170[a]	7	6
175	7	4
180[a]	7	7
185	14	7
190	7	6

Statistical Parameters

X-bar:	5.212
Y-bar:	5.272
B:	6.353
Sum wi:	17.14
Sxx:	0.01555
Chi-square:	2.072
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

% Dead	Exposure Time (sec)	95% Confidence Interval Exposure Time (sec)[b]	95% Confidence Interval Percent Dead
1	122		
5	136		
10	144		
30	162		
50	176	154 - 200	20.5 - 79.5
70	191	169 - 216	39.8 - 90.5
90	215		
95	228		
99	254		

[a] Excluded from computation.

[b] Estimated from approximation method.

Table 37

EXPERIMENTAL DATA

FREQUENCY: 7.44 GHz

EXPOSURE TIME: 300 sec

Lethality Data - 72 hr

Power Density (watts/cm)	Number of Rats	Number Dead
0.400	4	0
0.415	7	1
0.423	7	3
0.429	7	2
0.435	7	3
0.443	7	7
0.486[a]	4	4

Statistical Parameters

X-bar:	-0.8459
Y-bar:	4.894
B:	33.91
Sum wi:	18.55
Sxx:	0.008831
Chi-square:	4.168
Heterogeneity:	1.000
t:	1.96

Expected Death Rate

		95% Confidence Interval	
% Dead	Power Density (watts/cm^2)	Power Density (watts/cm^2)	Percent Dead
1	0.403	0.360 - 0.412	<0.1 - 18.8
5	0.409	0.380 - 0.418	0.4 - 27.6
10	0.415	0.392 - 0.420	1.6 - 33.5
30	0.423	0.412 - 0.429	14.7 - 49.9
50	0.432	0.423 - 0.438	32.3 - 67.7
70	0.438	0.432 - 0.455	47.1 - 86.9
90	0.446	0.438 - 0.478	62.3 - 98.8
95	0.452	0.440 - 0.492	68.3 - 99.8
99	0.460	0.449 - 0.518	77.7 - >99.9

[a] Excluded from computation.

described above, the exposure time was held constant at 300 sec for the lowest power levels (below 0.629 W/cm^2) and the power levels were varied to establish the mortality curve. At 300 sec, the 1-hr LD_{50} was estimated to be 0.442 W/cm^2.

The mean body weight for this frequency was 213 ± 21 g with the usual apparent lack of correlation between body weight and mortality. For the reasons decribed above, rectal temperatures were not taken, but, again, the animals did not feel abnormally warm at removal.

For animals considered dead on removal or during the next hour, convulsions and the appearance of respiratory insufficiency were again prominent. Swollen tongues were not observed. Bloody discharge from the nostrils and eyes was common. Third degree burns about the ears, eyes, and the tip of the muzzle were seen, with tissue loss from the rhinarium frequently occurring on contact with the cage. Salivation was not a usual finding. Similar symptoms were seen in many of the animals surviving more than 1 hr, even in those that survived to the three-day termination point.

At gross necropsy the additional findings were similar to those at 4.54 GHz--i.e., hemorrhage into the nasal passages and the lung--and a similar spectrum of lung changes was apparent on histologic evaluation. For this frequency, mortality appeared associated with asphyxia primarily due to blockage of the nasal passages, either by hemorrhage or by third degree burns, with some contribution from lung hemorrhage also probable.

V RELATIONSHIPS BETWEEN MORTALITY AND FREQUENCY

The pathologic findings described above indicate that, regardless of frequency, the primary site of damage appears to be the blood vessels, with edema and hemorrhage representing the result of changes in permeability of vessel walls, including frank rupture. The vessels themselves are probably not the only, or even the principal, sites for deposition of the microwave energy, but they do appear to be the most sensitive of the tissues in the area of deposition. The lack of information on the detailed distribution of absorbed energy within the animal makes further interpretation too speculative. Other factors, such as the contribution to the damage caused by convulsive inhalation, particularly with a blocked airway, may also be involved.

Nonetheless, it is of interest that the area of damage appears to move from the lungs toward the nose as the microwave frequency increases from 0.95 to 7.44 GHz. This appears generally consistent with the well-known inverse relationship between penetration and frequency and for the animal oriented head-on to the source. Of additional interest is the fact that both the lung and the nasal passages involve tissue in close contact with moist air, which may contribute significantly to deposition of the energy in the surface epithelium in those areas.

In considering the overall relationships among frequency, power density, and exposure time, certain restrictions can be made in the interests of simplicity of analysis:

(1) It was noted previously that the time or power level for lethality generally had the narrowest confidence limits at the point where the mortality was 50% (LD_{50}). This time or power density will be used exclusively for

the remainder of the discussion. Likewise, the computed values for LD_{50} for all measurements will be treated with equal weight, without regard for the confidence intervals of the individual values or the degree of heterogeneity of the data from which they were derived.

(2) For the two higher frequencies, data have been presented separately for death within one hour of exposure and within 72 hr of exposure. Except where noted below, the analysis will use LD_{50} values for 72 hr after exposure.

The relationship between LD_{50} and power density for the frequencies is shown in Figures 16(a) and 16(b). It can be seen that LD_{50}s and power densities for each frequency appear to form a rectangular hyperbola. The lethality of the radiation appears to decrease with frequency in the order of: 0.95 > 2.45 > 7.44 > 4.54 GHz. The reversal between 7.44 and 4.54 GHz is clearly discernible in the figure. Since the power density calibrations were all made using similar equipment and procedures, and since independent calibrations at the lowest and highest frequencies were also in agreement, this reversal must be taken as real, and not a calibration artifact. The difference in effectiveness between 4.54 and 7.44 GHz seems to imply a real difference in biological response but the causes underlying this difference are not at all clear at present.

To test whether the relationship between power density and exposure times does form a hyperbola, the products of power density (W/cm^2) times the LD_{50} (sec) are calculated and the resulting energy densities ($W\text{-}sec/cm^2$) were plotted against exposure time, as shown in Figure 17. At each frequency, the values of energy density (W/cm^2) increased with increasing exposure time, up to 200-250 sec, and thereafter appeared to decrease. The lines in the figure were fitted from the linear regression of energy density ($W\text{-}sec/cm^2$) on exposure time, excluding the points at or near 300 sec. At all four frequencies, the linear regressions appear to be

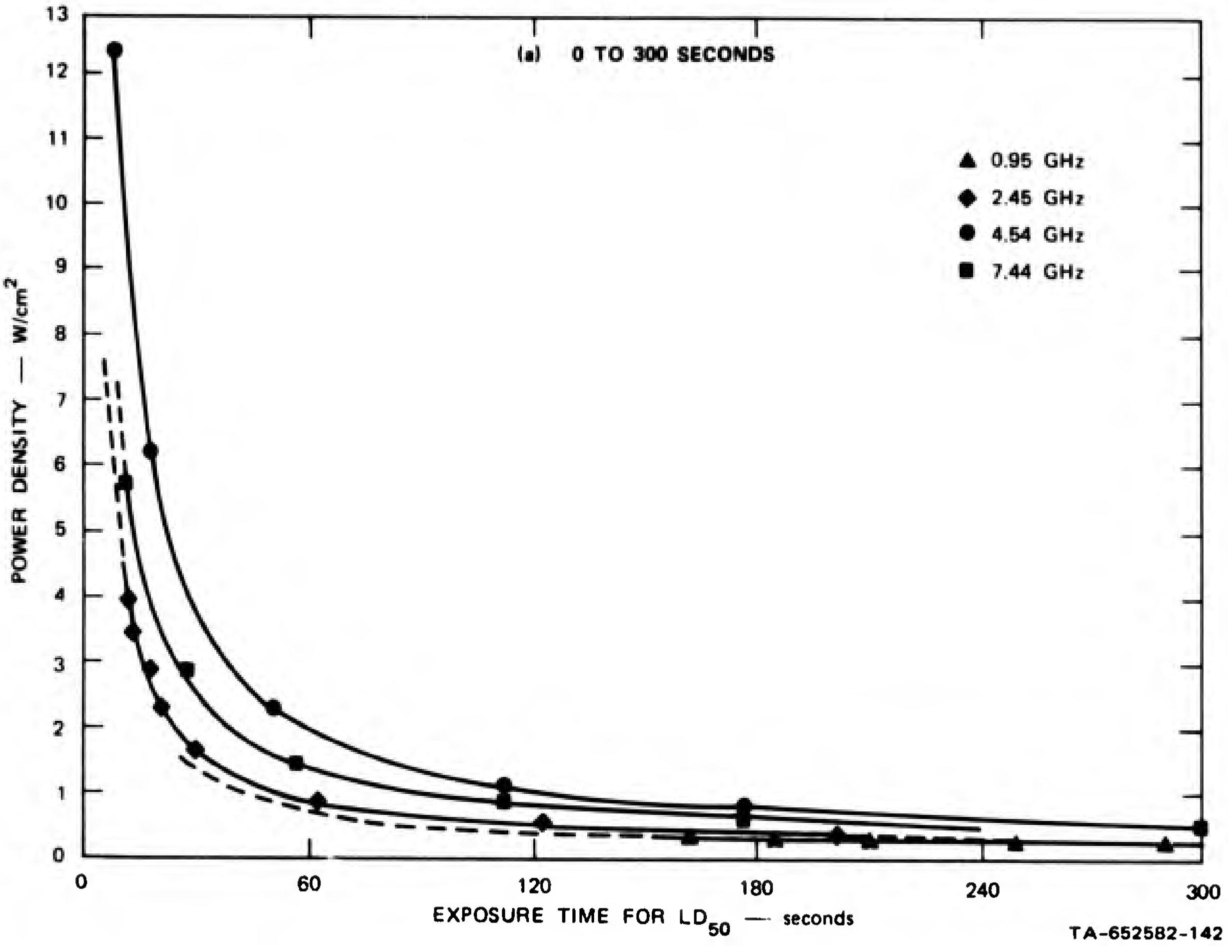

FIGURE 16 RELATIONSHIP BETWEEN POWER DENSITY AND LD_{50} EXPOSURE TIME FOR RATS EXPOSED TO MICROWAVES AT VARIOUS FREQUENCIES

reasonable fits to the data points, with the exception of the points at 300 sec. The slopes of all lines are significantly greater than zero and have the dimensions of W/cm^2. This result implies that the power density during exposure of the animals is reduced by a quantity D (a measure of the tissue power dissipation), and that the relationship between density (P) and LD_{50} is:

$$LD_{50} \times (P - D) = K \qquad (11)$$

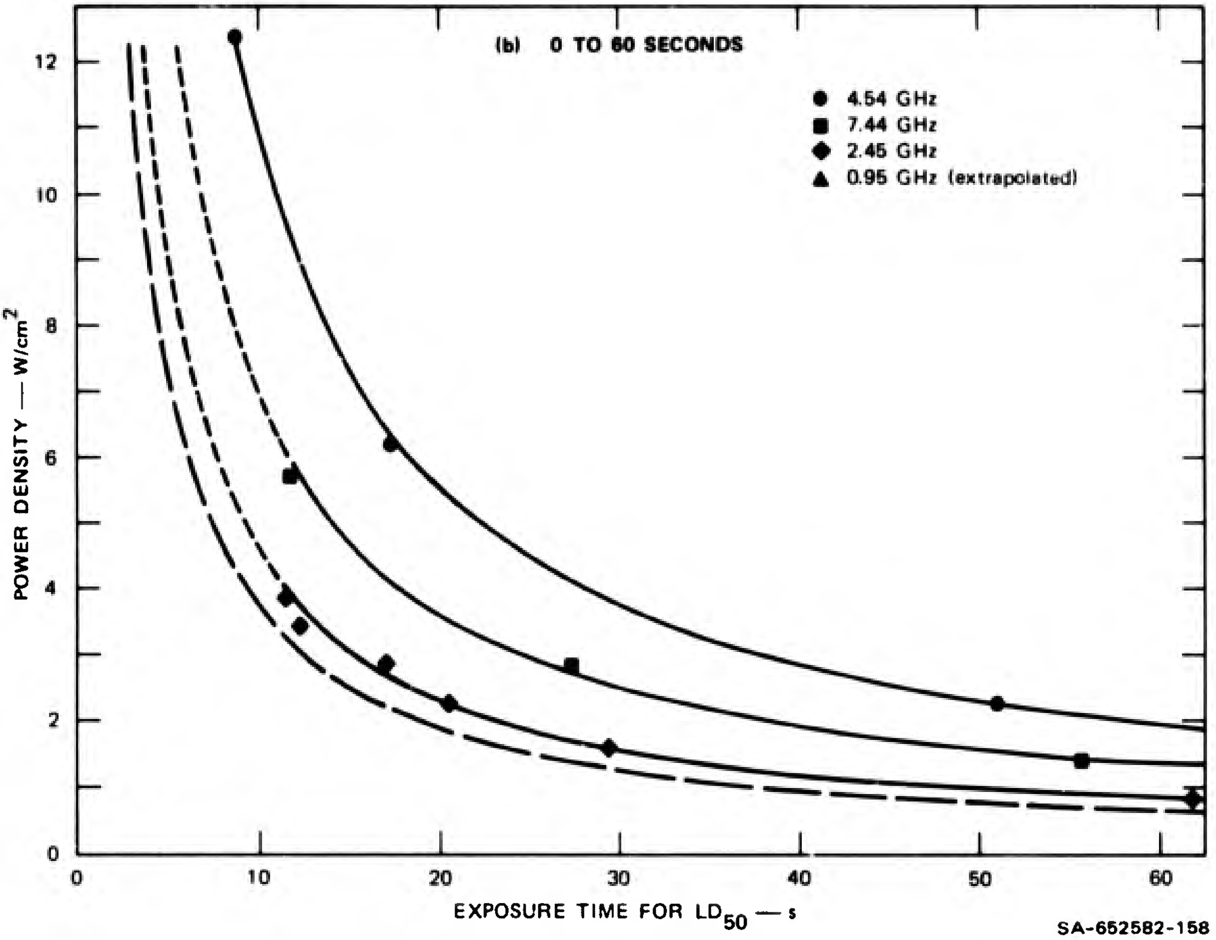

FIGURE 16 (Concluded)

where LD_{50} is in sec, P and D are in W/cm^2, and K in $W\text{-}sec/cm^2$. This is the equation of a rectangular hyperbola. The values of D and K for the various frequencies were obtained from the calculated regressions of energy density ($W\text{-}sec/cm^2$) on exposure time since they are the slope and the y-intercept, respectively. They are summarized in Table 38. The lines drawn in Figures 16(a) and 16(b) were calculated using Eq. (11) and the constants in Table 38. The lower part of Table 38 also shows the lethality constants for death within 1 hr at the 4.54- and 7.44-GHz

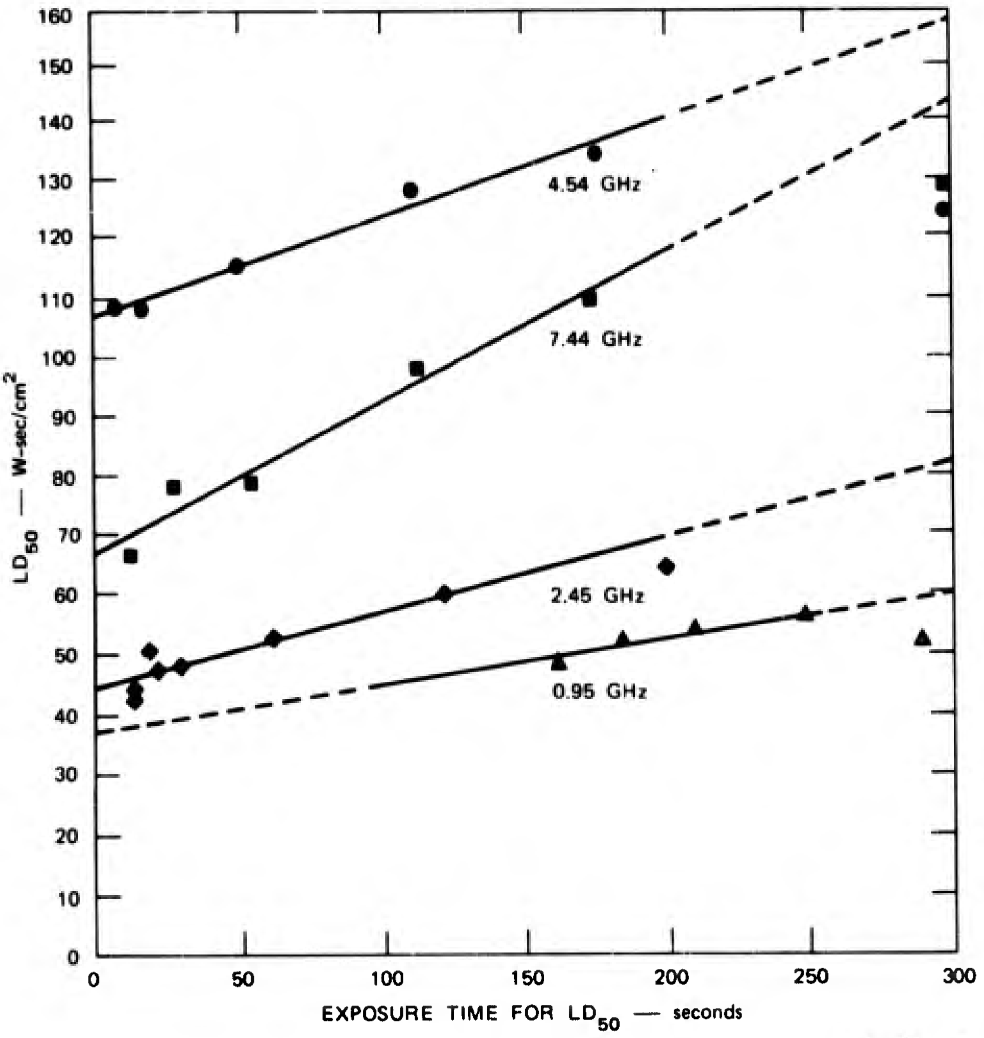

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FIGURE 17 DEPENDENCE OF MICROWAVE LD_{50} IN RATS ON DURATION OF MICROWAVE EXPOSURE. Lines were fitted by linear regression, excluding points at or near 300 s.

frequencies. For each frequency, the values of both D and K were statistically different, when 1- and 72-hr death rates were compared. The result implies that there is a real difference betweeen the deaths occurring within 1 hr and those occurring subsequently, even though the analysis of mortality for the individual experiments does not consistently show a difference.

Table 38

CONSTANTS FOR DETERMINING THE RELATIONSHIP OF POWER LEVEL TO LETHAL EXPOSURE TIME FOR MICROWAVE IRRADIATION AT VARIOUS FREQUENCIES

Frequency (GHz)	Tissue Power Dissipation, D (W/cm^2)	Lethal Energy Constant, K ($W\text{-}sec/cm^2$)
72-hr Mortality		
0.95 2.45 4.54 7.44	0.078 0.126 0.166 0.252	36.643 44.350 107.340 67.230
1-hr Mortality		
4.54 7.44	0.138 0.131	117.542 90.944

Conceptually, the relationship between power density and lethality exposure time implies that the lethal effect is determined by the deposition in the tissue of a definite quantity of energy. The energy actually deposited cannot yet be measured, but the relative power density in the incident plane-wave microwave radiation in W/cm^2, can be specified with reasonable accuracy. In this conceptual framework, the values of D estimate the effective rates of energy dissipation in the vitally sensitive tissues at the various frequencies, and have a significance that can be interpreted in terms of the physics of energy transfer.

However, the value of D is estimated on a functional basis in terms of biological response and not by physical measurements. The relationship between energy density (W-sec/cm^2) and exposure time (Figure 17) appears to break down after 3 to 4 min of exposure. The departure of the LD$_{50}$s at 300 sec from the values predicted by the regression lines may result from a number of events, including changes in blood flow or development of secondary pathological effects that are time dependent. Moreoever, values of D and K listed in Table 38 show that the constant describing lethality depend not only on frequency but also on time of observation.

Subject to the reservations noted, significant and consistent relationships among frequency, exposure time, and power density to produce mortality have been demonstrated for microwave irradiation in this range from 0.95 to 7.44 GHz.

VI CONCLUSIONS AND RECOMMENDATIONS

The research described in this report provides comprehensive mortality data for rats exposed to plane-wave CW microwave radiation under accurately controlled and measured conditions. Power density levels have ranged from 0.2 W/cm^2 to 12 W/cm^2, with corresponding lethal exposure durations from 300 to 8 sec. Four frequencies have been employed, 0.95, 2.45, 4.54, and 7.44 GHz. At each frequency, approximately 360 rats have been individually exposed for a total of approximately 1440 rats irradiated.

It is believed that this is the first time that more than one frequency has been employed in the same microwave lethality study. As a result, it has been possible to detect frequency-dependent effects. At each frequency, it has been found that, if the data points near 300 sec are excluded, the energy density to achieve LD_{50} is a linear function of the exposure duration. The function parameters are different for each frequency. An alternative expression of this relationship is that, for each frequency, the power density to achieve LD_{50} is a rectangular hyperbolic function of the exposure duration. The four curves so obtained lie one above the other in the order, from lowest to highest, $0.95 < 2.45 < 7.44 < 4.54$ GHz. In terms of lethal effectiveness, therefore, the ordering is, from most effective to least effective, $0.95 < 2.45 < 7.44 < 4.54$ GHz. The non-monotonic ordering is unexpected, and further research should be carried out to discover its cause.

If energy-density versus exposure-duration plots are extrapolated to zero exposure duration, there exists for each frequency a finite value of energy density that can cause "instantaneous" mortality. These "lethal energy constants" have the same ordering, described above, as the comparative effectiveness of the four frequencies, with the same non-monotonicity involving the 7.44 and 4.54 GHz frequencies.

It is worth pointing out that American National Standard, C95.1, "Safety Level of Electromagnetic Radiation with Respect to Personnel," recommends an energy-density radiation protection guide of 1 mW-hr/cm^2 averaged over any 0.1 hr period. For the most lethal frequency (0.95 GHz) the lethal energy constant was found to be 36,643 mW-sec/cm^2 or 10.2 mW-hr/cm^2. This is approximately a factor of ten greater than the radiation protection guide.

The slope of the straight lines on the energy-density versus exposure-duration plots, a quantity which we have chosen to call the "tissue power dissipation," has certain interesting properties. Unlike the variation of lethal energy constant with frequency, there is a monotonic increase in the value of tissue power dissipation with increasing frequency. In fact, the relationship between tissue power dissipation and frequency for 72 hr mortality is a linear one, with the value at 7.44 GHz approximately three times as great as that for 0.95 GHz. The reason for this is undetermined. Since the ANS C95.1 power-density radiation protection guide takes into account the ability of the person to dissipate absorbed energy, it is worth indicating that the minimum "tissue power dissipation" value (occurring at the most lethal frequency, 0.95 GHz) is 78 mW/cm^2 which may be compared with the radiation protection guide of 10 mW/cm^2.

In all of the research, no effects which could be attributed to circadian rhythms were observed. Another result, although based on a limited number of pathological samples (17 animals), was that the prime site of action of the microwaves causing death appeared to be the blood vessels of the lung and respiratory tract. The pathology report indicated that cause of death was due to congestion, hemorrhage and obstruction of nasal passages and/or congestion, hemorrhage and often edema of the lungs. This point should be investigated further. The effects on brain tissue should also be investigated using more sophisticated histochemical techniques than the routine hemotoxylin and eosin sections used here. In addition, further research into microwave lethality should be carried out with modifications of the methodology used in the present study, for example: different orientations of the animal; different species; a comparison of pulsed versus CW microwave radiation (again at different frequencies). Also, the apparent anomaly in effectiveness of the microwaves involving the 4.54 and 7.44 GHz frequencies should be investigated.

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