Add √ Glaser

AD 774 823

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

Final Technical Report — Type III

January 1974

By

P. Polson D.C.L. Jones A. Karp J. S. Krebs

Stanford Research Institute
(Menlo Park, California)

Prepared for

U.S. ARMY MOBILITY EQUIPMENT RESEARCH
AND DEVELOPMENT CENTER
FORT BELVOIR, VIRGINIA 22060 under

Contract DAAK02-73-C-0453

*Approved for Public Release; Distribution Unlimited.*

Research was conducted according to the principles enunciated in the "Guide for the Care and Use of Laboratory Animals" prepared by the NAS-NRC.

Karl
Oscar

**STANFORD RESEARCH INSTITUTE**
Menlo Park, California 94025 · U.S.A.

*January 1974*

Final Technical Report — Type III

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

*By:* P. Polson D.C.L. Jones A. Karp J. S. Krebs

*Prepared for:*

U.S. Army Mobility Equipment Research and Development Center
Fort Belvoir, Virginia 22060

Contract DAAK02-73-C-0453

*Approved for Public Release; Distribution Unlimited.*

*Approved by:*

RAY L. LEADABRAND, *Executive Director*
*Electronics and Radio Sciences Division*

W. A. SKINNER, *Executive Director*
*Life Sciences Division*

*Copy No.* 55

# 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.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge able engineering assistance received from Mr A.B. Tomlin and Mr. M. DiDomenico, and competent support in the maintenance, handling, and exposing of rats from Mr D.L. Low, Mr W. Washburn, Ms S.A. Lininger, Mr F.L. Hall, and Mr P.E. Gardner. Mr W.B. Weir calibrated the antennas used in this research.

The research reported herein was performed under the direction and support of the Barrier Division, U.S. Army Mobility Equipment Research and Development Center, Fort Belvoir, Virginia. The contract technical monitor was Kenneth J. Oscar, and the contract number was DAAK02-73-C-0453.

# CONTENTS

# ILLUSTRATIONS

# TABLES

# 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

---

[*] 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

---

*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

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

when $P_t$ is in watts and $\lambda$ 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.

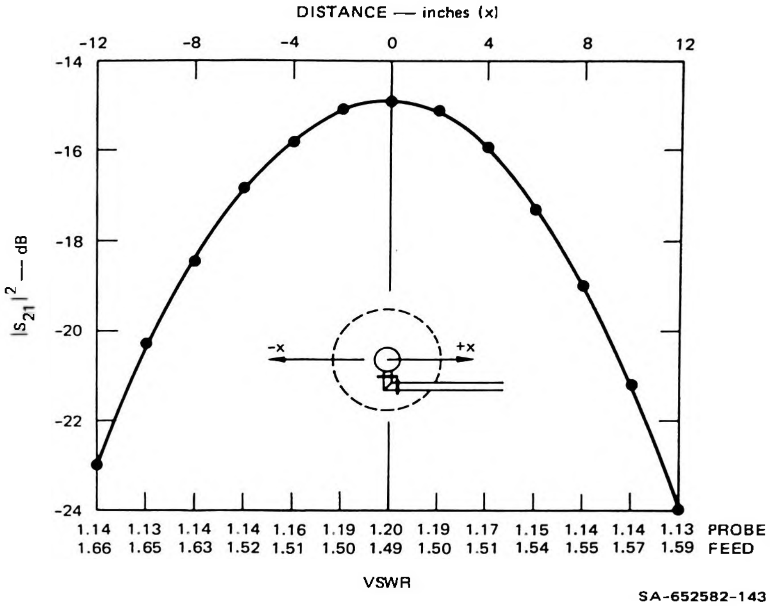


FIGURE 1 SIX-INCH DIPOLE AS RECEIVER, VERTICAL POLARIZATION. f = 950 MHz, x = y = 0.

b. <u>Frequency 2: 2.45 GHz</u>

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.

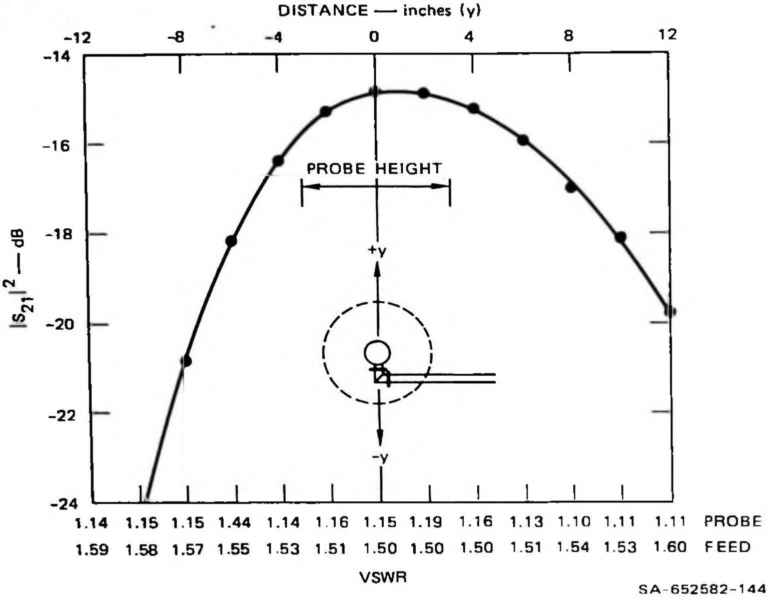


FIGURE 2 SIX-INCH-DIPOLE PROBE, VERTICAL POLARIZATION. $f_o$ = 950 MHz.

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.

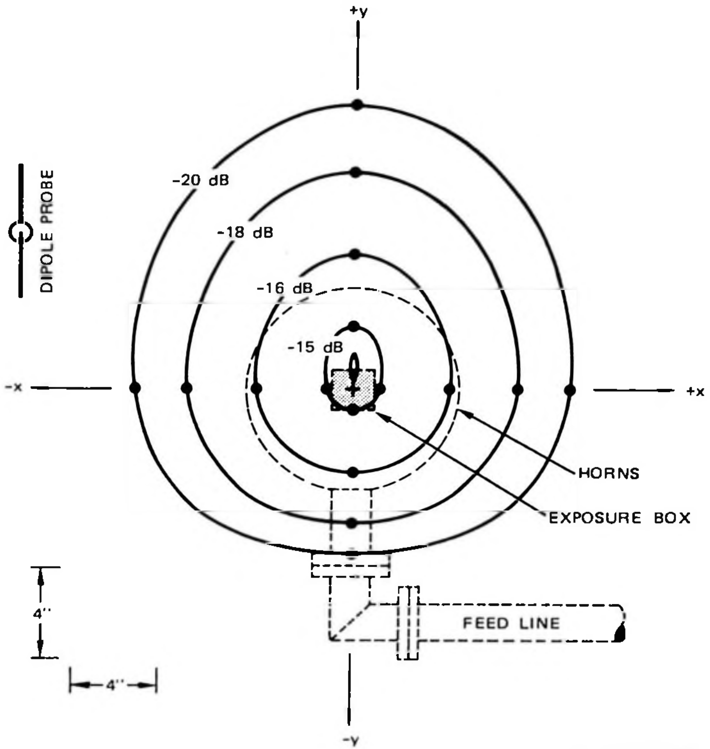


FIGURE 3 DIPOLE PROBE, VERTICAL POLARIZATION. $|S_{21}|^2$ Contours in xy plane at z = 0 (second focal plane). $f_o$ = 950 MHz.

### 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

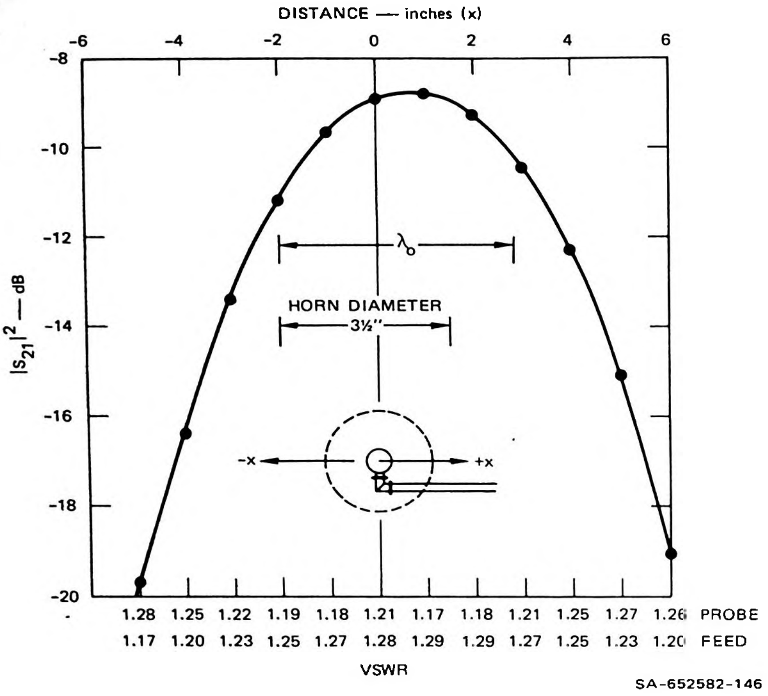


FIGURE 4 HORN PROBE, VERTICAL POLARIZATION. $f_o$ = 2457 MHz.

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.

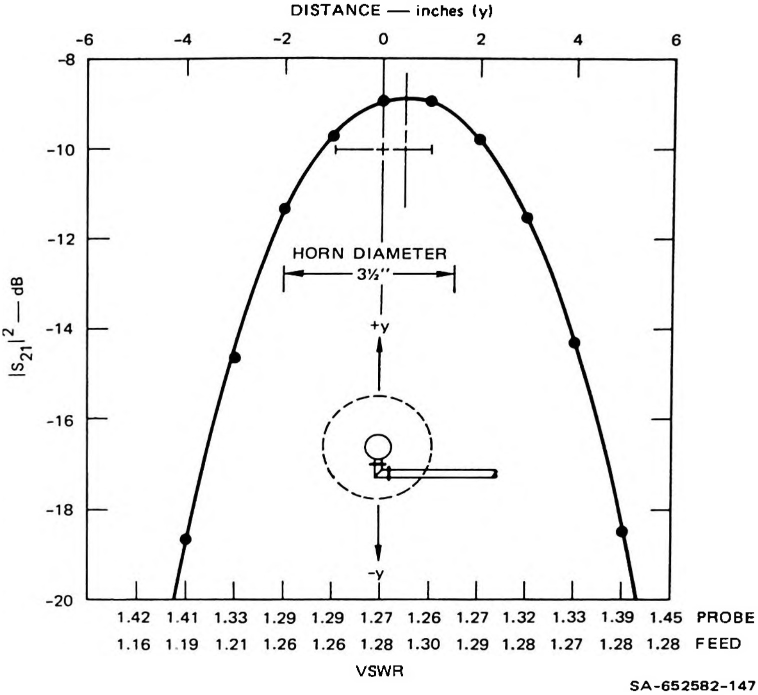


FIGURE 5 HORN PROBE, VERTICAL POLARIZATION. $f_o$ = 2457 MHz.

d. <u>Frequency 4: 7.44 GHz</u>

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.

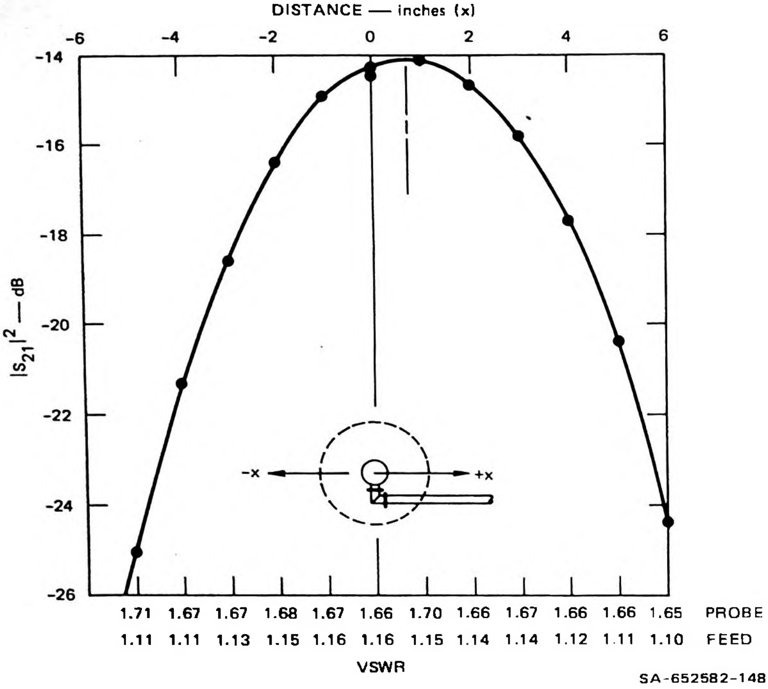
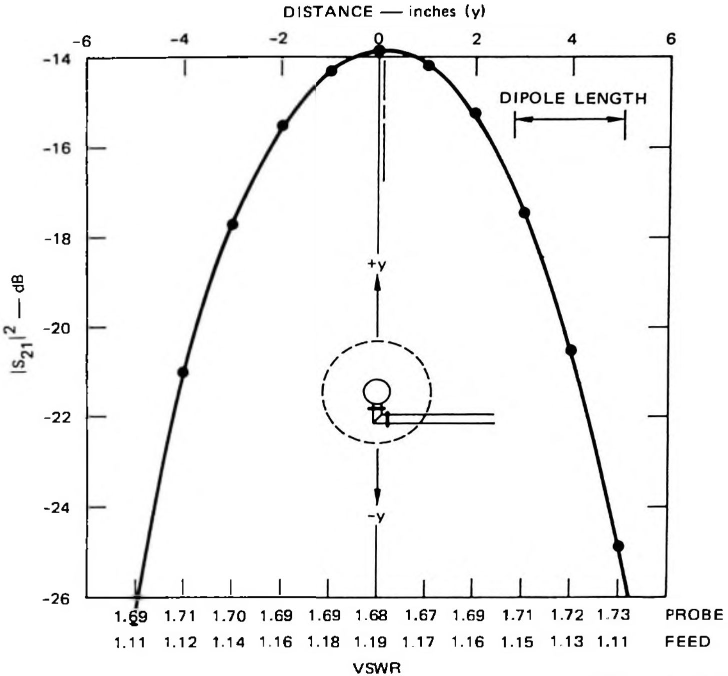


FIGURE 6 DIPOLE PROBE, VERTICAL POLARIZATION. $f_0$ = 2457 MHz.

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



SA-652582-149

FIGURE 7 DIPOLE PROBE, VERTICAL POLARIZATION. $f_o$ = 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,

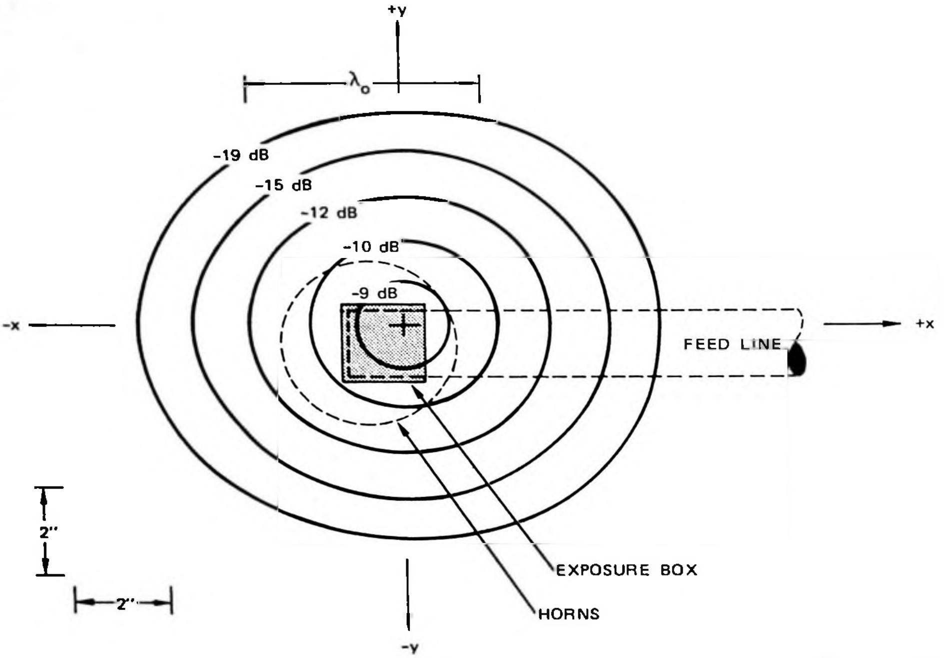


FIGURE 8 HORN PROBE, VERTICAL POLARIZATION. $|S_{21}|^2$ Contours in xy plane at z = 0. $f_o$ = 2457 MHz.

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.

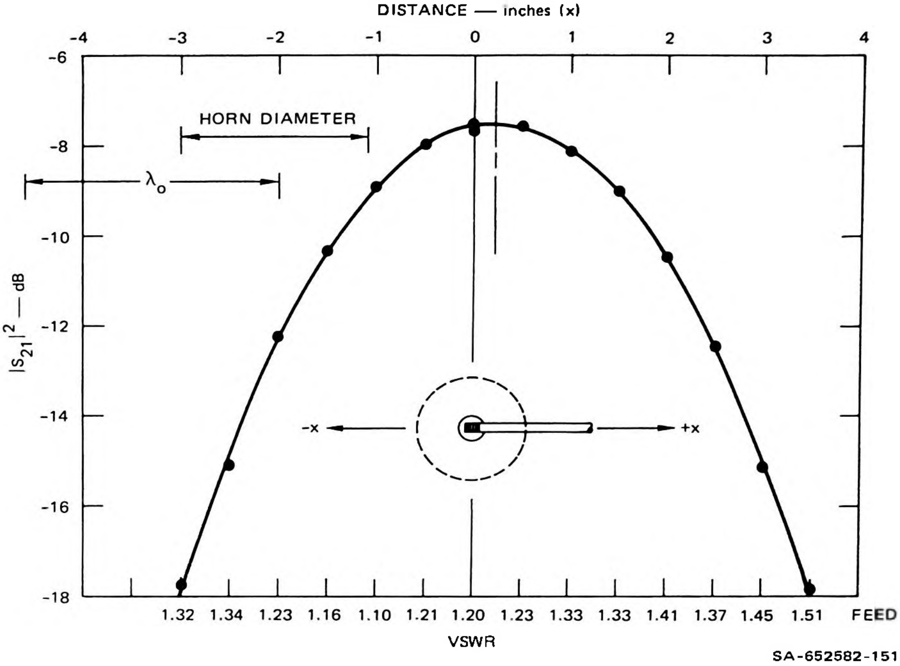


FIGURE 9 HORN PROBE, VERTICAL POLARIZATION. $f_o$ = 4540 MHz.

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

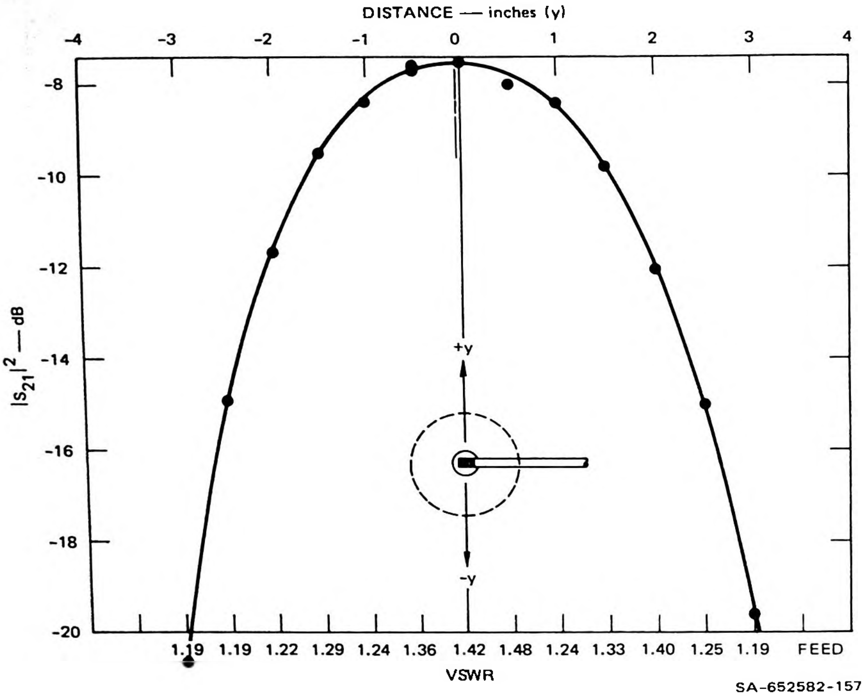


FIGURE 10 HORN PROBE, VERTICAL POLARIZATION. $f_o$ = 4540 MHz.

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.

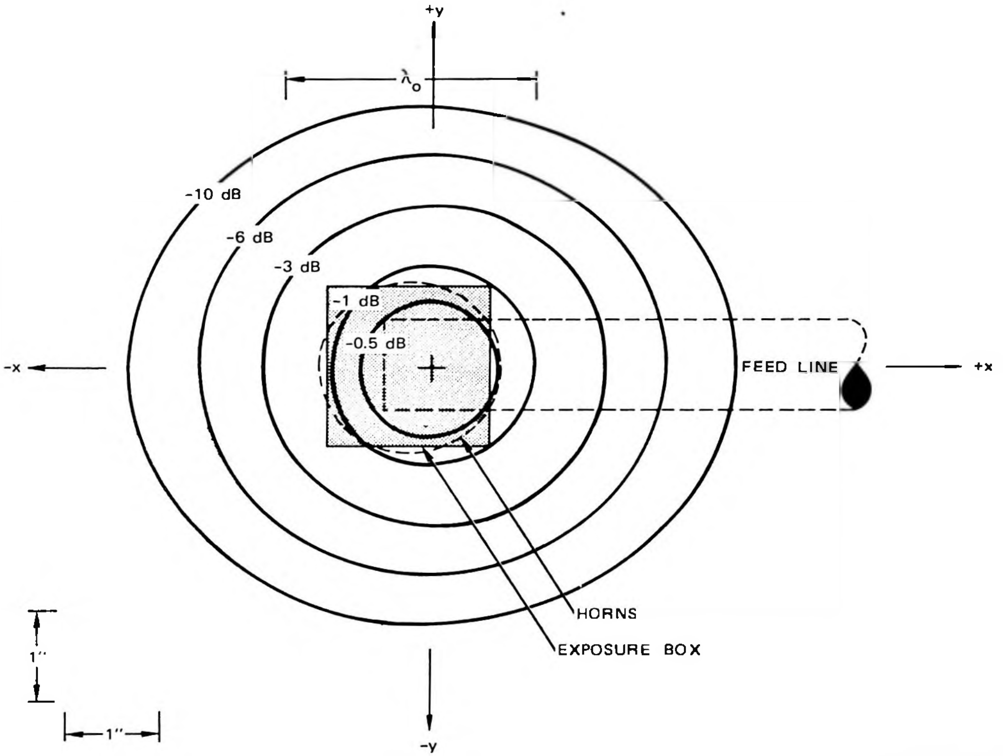
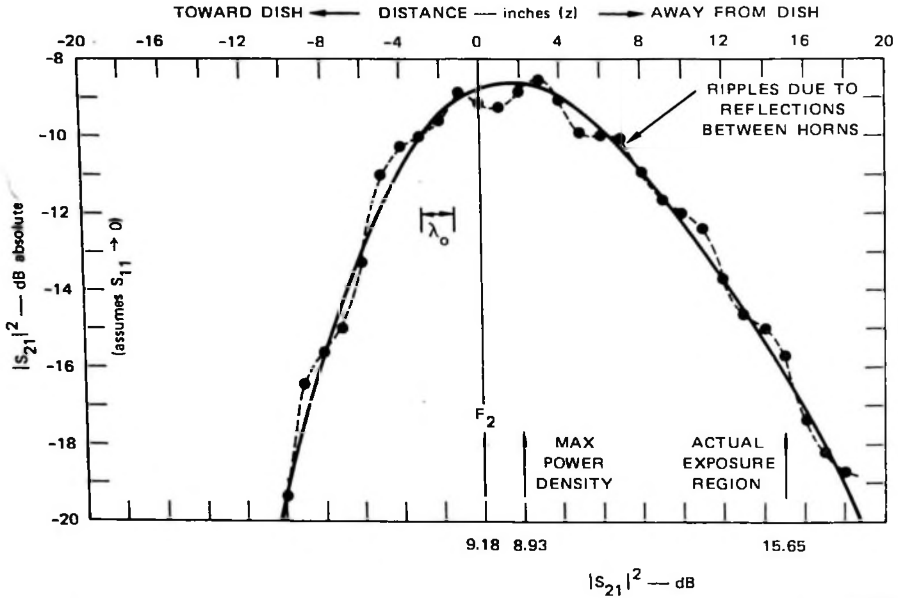


FIGURE 11 HORN PROBE, VERTICAL POLARIZATION, xy PLANE AT SECOND FOCUS (z = 0). $|S_{21}|^2$ Contours (relative). $f_o$ = 4540 MHz.



SA-652582-154

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

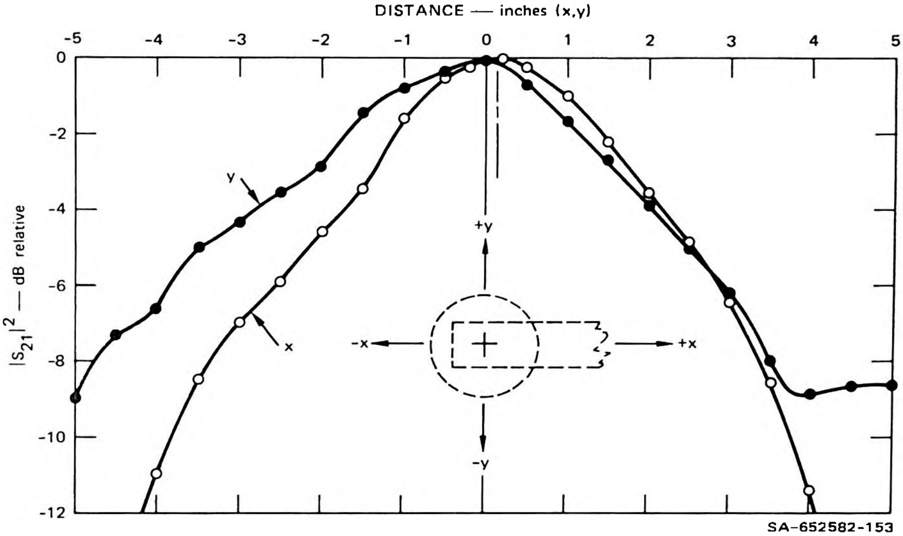
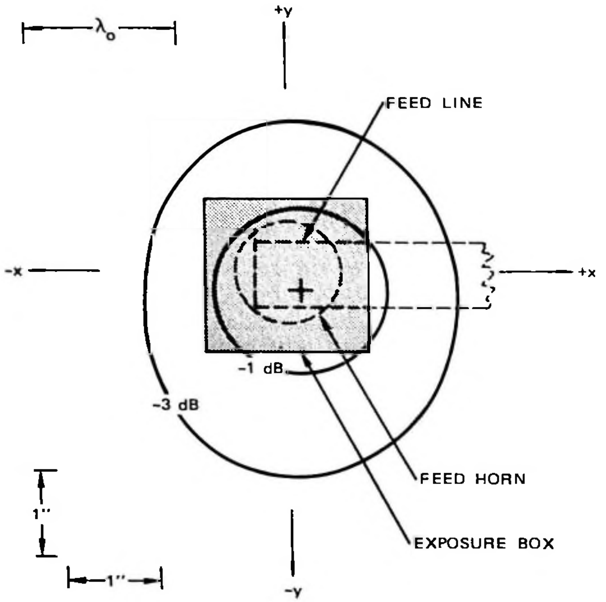


FIGURE 13 HORN PROBE, VERTICAL POLARIZATION. Field profiles at z = +15 inches beyond focal plane. $f_o$ = 7.44 GHz.



SA-652582-155

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

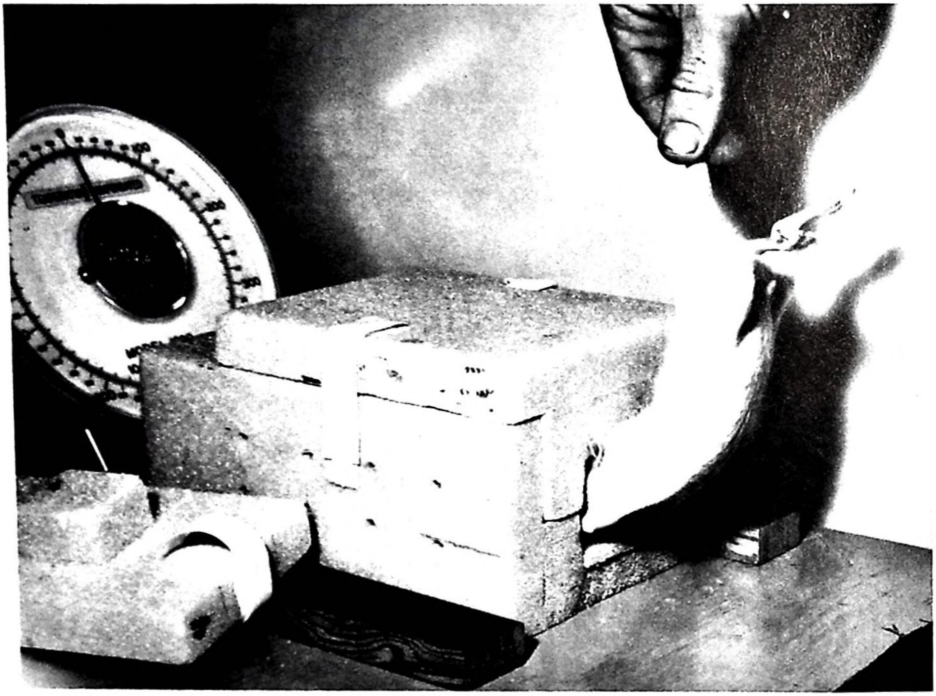
# III BIOLOGICAL METHODS

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.



SA-652582-156

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 $\overline{X}$, $\overline{Y}$, 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

$$y - \overline{Y} = B(x - \overline{X}) \tag{5}$$

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

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

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 $(x - \overline{X})^2$ 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

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

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 $g = t^2/B^2Sxx$. 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

## 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**

| % Dead | Exposure Time (sec) | 95% Confidence Interval<br>Exposure Time (sec) | 95% Confidence Interval<br>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) | 95% Confidence Interval 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**

| % Dead | Exposure Time (sec) | 95% Confidence Interval Exposure Time (sec) | 95% Confidence Interval 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**

| | | 95% Confidence Interval | |
|---|---|---|---|
| % Dead | Exposure Time (sec) | Exposure Time (sec) | 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<br>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) | 95% Confidence Interval 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 |
| 30 | 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/cm$^2$

**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**

| | | 95% Confidence Interval | |
|---|---|---|---|
| % Dead | Exposure Time (sec) | Exposure Time (sec)[a] | 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.