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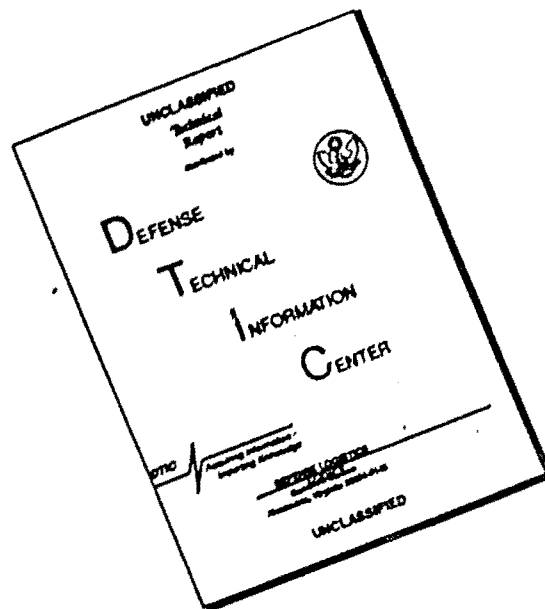
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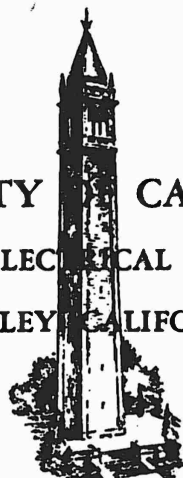
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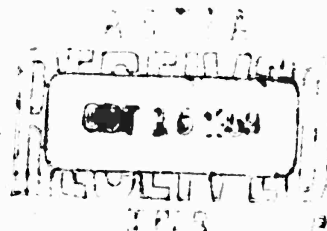
Annual Scientific Report (1957-58) on Contract AF41(657)-114

BIOLOGICAL EFFECTS OF MICROWAVE RADIATION

by

Charles Susskind and Staff

Institute of Engineering Research
Series No. 60, Issue No. 205
June 30, 1958



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University of California
Division of Electrical Engineering
Berkeley, California
Electronics Research Laboratory

BIOLOGICAL EFFECTS OF MICROWAVE RADIATION

Annual Scientific Report on Contract AF41(657)-114
(1957-58)

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SCOPE OF THE REPORT

The present report is an interim annual report summarizing the work done at the University of California under Contract AF41(657)-114 with the U. S. Air Force Rome Air Development Center during 1957-58. The original contract period, 1 December 1956-30 November 1957, was extended by Supplemental Agreement No. 2 to 31 May 1958, with a Final Report due on 30 June 1958. The contract was again extended, by Supplemental Agreement No. 5, to 15 March 1959; since the second extension obviates the necessity for the above-mentioned Final Report, the present Annual Scientific Report (1957-58) is submitted instead.

The work accomplished falls conveniently into three parts: (1) experiments with laboratory animals, (2) experiments with cellular organisms and insects, and (3) microwave-engineering experimentation. The latter category does not comprise the considerable amount of work undertaken in the process of setting up the sources of X-band microwave power, which consisted of a converted airborne-radar transmitter and modulator used principally in the cellular-organisms experiments and in trying out new methods of field measurements; and of a government-furnished AN/TPS-10D radar used in the majority of the experiments with animals. The installation and maintenance of these transmitters, as well as much of the work involved in providing instrumentation for the various experiments, was carried out largely by O. WESTWICK.

The experiments with laboratory animals, and with cellular organisms and insects, were carried out principally by S. B. PRAUSNITZ and P. O. VOGELHUT, respectively. Dr. B. JACOBSON played an important part in the later phases of these experiments, and in the evaluation of the data.

The microwave-engineering experimentation was in the hands of A. HADIK-BARKOCZY, with contributions from E. D. HOAG and A. JOHNSON.

Dr. C. A. TOBIAS and Dr. H. C. MEL of the Donner Laboratory of Medical Physics at the University of California helped with many fruitful discussions and certain laboratory services, which are hereby gratefully acknowledged, as are the services provided by Dr. C. W. RIGGS of the Donner Laboratory Animal House, and the autopsies carried out by Dr. S. H. MADIN of the university's Bacteriology Department.

The project was under the over-all direction of Dr. C. SÜSSKIND, who acted as Principal Investigator.

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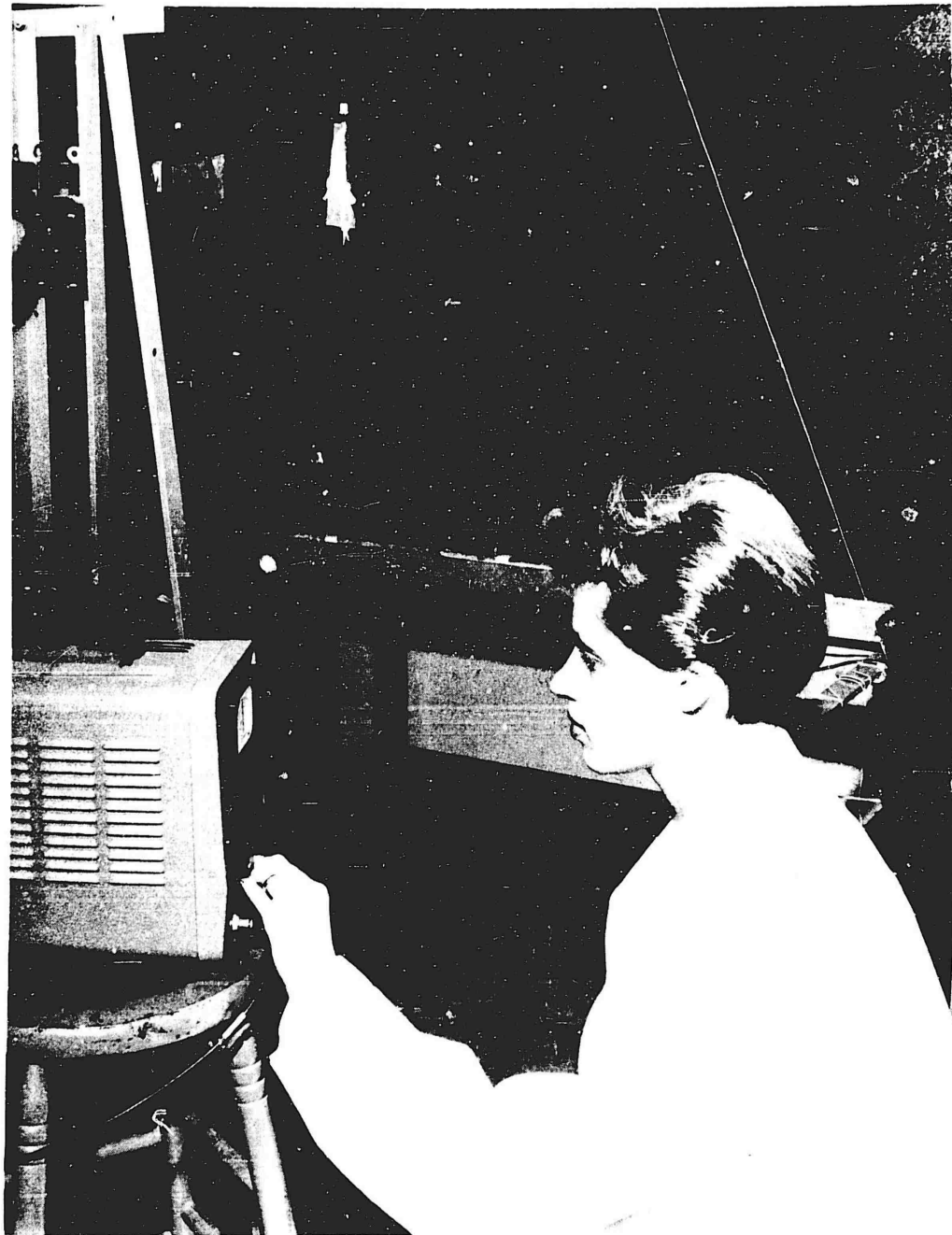
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I. EXPERIMENTS WITH LABORATORY ANIMALS

A. INTRODUCTION

The principal objectives of this phase of the project were (1) the establishment of experimental procedures, and (2) studies of the effect of X-band microwave radiation on the survival, fertility, and longevity of albino mice, with particular emphasis placed on the investigation of the nature of the mechanisms involved in the effects observed. Progress toward each of these objectives has been considerable, and is reported below, with the exception of the longevity experiments, which are being scheduled to begin in the next contract period.

The work with animals accomplished during 1957-58 includes:

- (1) Establishment of procedures.
- (2) Determination of the lethal dose (LD50) at various levels of power density.
- (3) Evaluation of the results of (2) to determine whether the energy density needed to reach LD50 is independent of power density.
- (4) Studies of the irradiation of mice whose body temperatures had been lowered by about 10°C by the injection of chlorpromazine.
- (5) Comparison of results obtained in irradiation of groups of mice at various pulse repetition rates at constant average power density.
- (6) Studies of gross pathological effects of whole-body irradiation.
- (7) Determination of the effect of single and multiple whole-body irradiations upon the fertility of male mice.

B. EXPERIMENTAL PROCEDURE

Male and female albino mice weighing 30-40 g are used. The animal is placed in a sack made of low-loss plastic screening of the type employed in window insect screens. The sack is supported by two thin bakelite rods and keeps the animal essentially immobile in a vertical position facing the power source, with the hind legs spread out to expose the genitals; the feet are secured with low-attenuation adhesive tape. The animals do not appear to be unduly agitated, so that there is no need for a general anaesthetic or tranquilizer. Body temperature is measured rectally by means of a small glass-covered Vico thermistor with an OD of 0.100 in., which is inserted to a distance of 0.5 in. The thermistor and the animal's tail are taped to the above-mentioned bakelite rods to insure stability. The thermistor forms one arm of a d-c unbalanced bridge, the output of which is connected to a Perkin-Elmer Model 53 amplifier, which in turn operates a 1-ma Esterline-Angus Model AW recording ammeter. The system is capable of resolving temperature readings of 0.1°C, and is calibrated before each irradiation.

(I. LABORATORY ANIMALS)

ation; the total deviation during any one irradiation does not exceed 0.2°C . No r-f pick-up by the probe has been observed in exhaustive tests regardless of its orientation or that of its leads.

The established procedure consists of weighing the animal and placing it in the sack; inserting the thermistor and beginning the temperature record; establishing the normal or "baseline" temperature; and switching on the microwave power. One mouse at a time is irradiated. The room temperature is relatively constant, between 22 and 25°C . Most of the tests have taken place at a distance of either 5 or 6λ from the apex of the source horn, i.e., 16.5 or 19.5 cm away.

C. DETERMINATION OF THE LETHAL DOSE AT VARIOUS POWER-DENSITY LEVELS

It is found that the dose which kills 50 per cent of the animals, the LD50, corresponds to irradiating them at a certain power density for a certain time, the combination being such as to raise the rectal temperature to a maximum that lies (for both male and female mice) between 43.9 and 44.2°C , as shown in Tables I and II. The lethal temperature is therefore taken to be 44°C . In Fig. 1, in which survivals are shown as circles and deaths as crosses, the data are plotted in terms of power density vs length of irradiation. Also shown is the experimental LD50 for each group, and a curve of statistically "corrected" values of the LD50's, obtained according to a procedure that is described below. Death occurs sometimes during the irradiation, and sometimes shortly after it, but always within 24 hr, a result which confirms that obtained by Ely and Goldman.¹

The results summarized in Fig. 1 show a marked resemblance to the eye-cataract results reported by Williams,² who showed a similar curve separating the cases in which cataracts occurred, in rabbits, from those in which they did not occur. Although producing eye cataracts calls for irradiation techniques that differ substantially from those used in whole-body irradiations, the similarity of the results would seem to suggest that the basic mechanism producing the observed effect is essentially the same, and that either experiment constitutes a useful method of measuring the effect of microwave power. Below a certain power density, about 0.100 w/cm^2 , the cooling mechanism of mice operates to re-establish an equilibrium at which the animal can be kept for an hour or more without observable effects, other than a slight temperature rise.

Figure 2 illustrates variations in the slopes of the curves of temperature rise vs time with power density for three groups of animals irradiated at different power densities. Each curve is normalized to the same baseline temperature to facilitate comparison. The curves also give some indication of the rate at which normal temperature begins to be re-established after the power is turned off. Not only are the temperature-rise curves less steep for the lower power densities, but they also stop rising almost immediately after the power is turned off; whereas at the higher power densities, the temperature

(I. LABORATORY ANIMALS)

TABLE I.--Correlation of survival and maximum body temperature reached.

Max. body temp. (deg C)	Number of survivals	Number of deaths
41.0-41.9	6	0
42.0-42.9	16	0
43.0-43.4	21	5
43.5-43.9	13	6
44.0-44.4	8	18
44.5-44.9	1	14
45.0+	0	19

TABLE II.--Correlation of survival and maximum body temperature reached: an analysis of Table I.

Max. body temp. (deg C)	Number of survivals	Number of deaths
43.5	2	0
43.6	1	1
43.7	3	1
43.8	6	1
43.9	1	3
44.0	6	4
44.1	0	2
44.2	2	2
44.3	0	5
44.4	0	5

(I. LABORATORY ANIMALS)

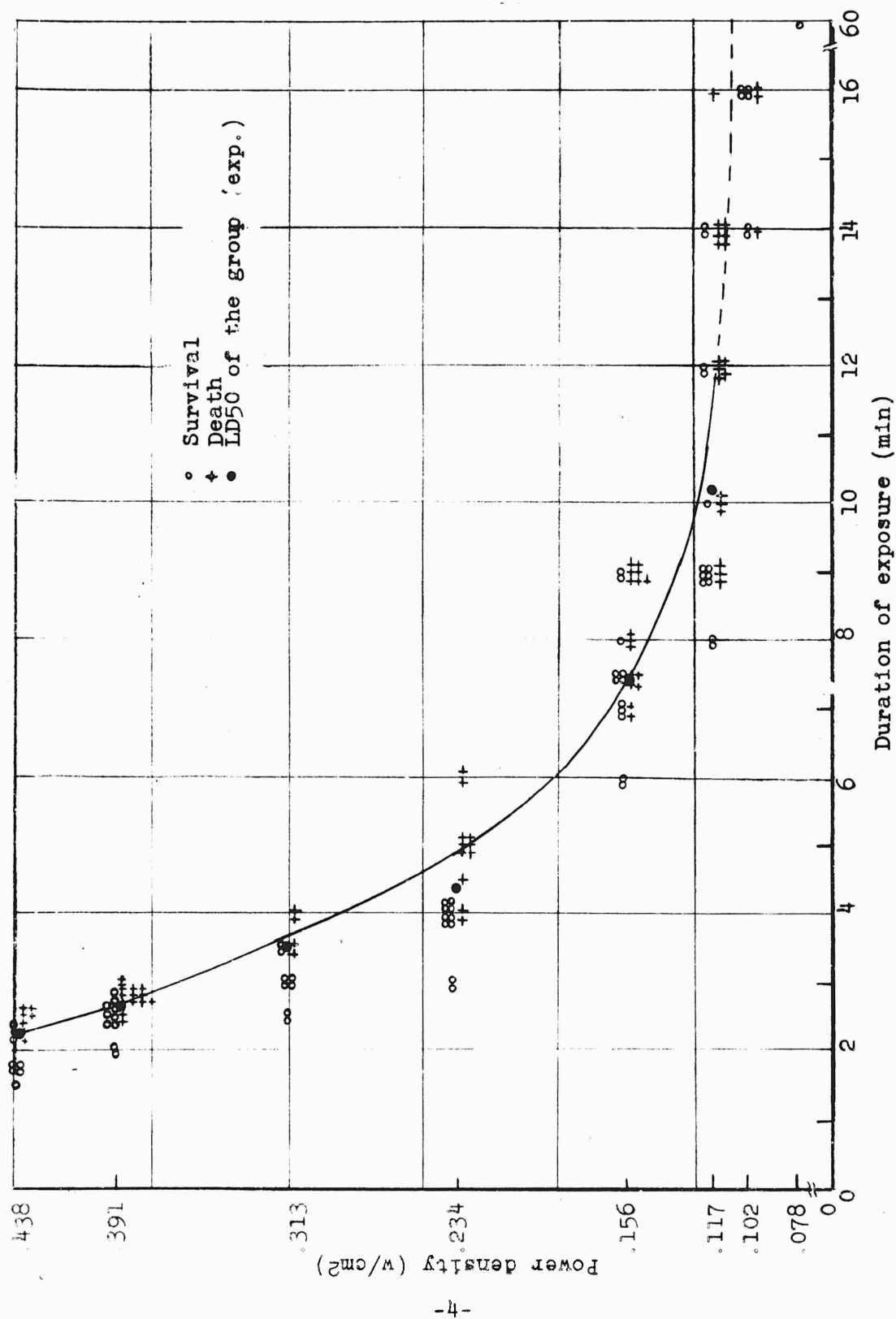


FIG. 1. Survival of mice as a function of power density and duration of exposure.

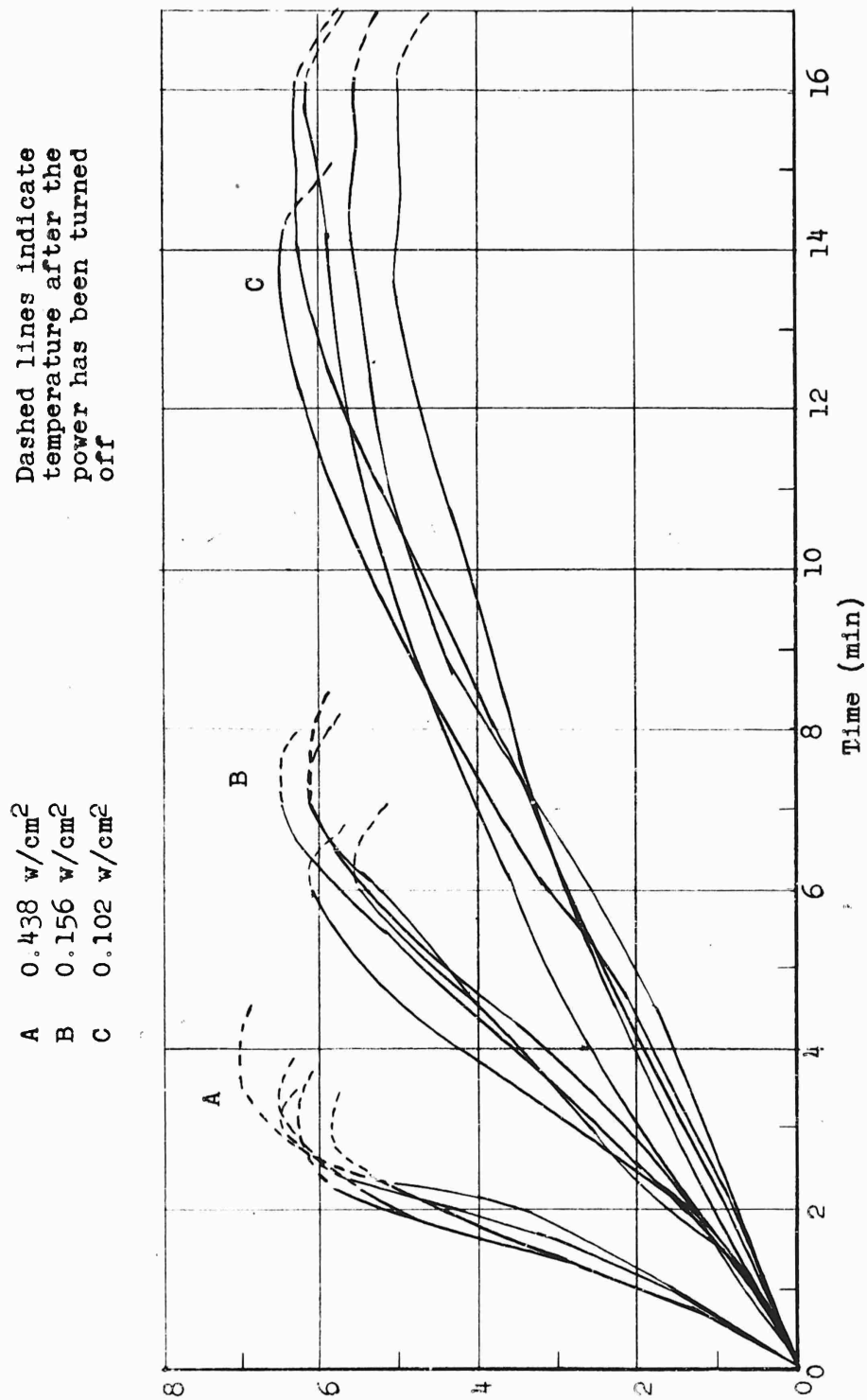


FIG. 2.--Typical temperature-vs-time curves of mice irradiated at three different power densities.

(I. LABORATORY ANIMALS)

continues to rise for some time after the power is turned off. The average temperature rise observed at the end of the tests corresponding to the highest power density shown, 0.438 w/cm^2 , was 1°C . Another observation is the flattening out of the curves at the lowest density shown, 0.102 w/cm^2 ; if this flattening out occurs below the temperature at which the mice usually begin to die, no deaths are observed, even after an hour's irradiation, as mentioned above. The reproducibility of these curves for the lower power densities is within 1.5°C in the region where the flattening out takes place.

The average temperature rise of each group is plotted as a function of time in Fig. 3. The baseline rectal temperature varies from 36 to 38°C , with a mean of 37.4°C , to which the curves are normalized. In view of the 44°C temperature mentioned above as corresponding to LD50, the average temperature rise at LD50 is thus 6.6°C . This value is indicated by the limiting horizontal line, which has been slightly lowered at the higher power-density curves (i.e., the steepest curves) to correct for the temperature rise observed after the power is turned off, as mentioned in connection with Fig. 2 above. The intersects of the LD50 curve and the temperature rise-vs-time are thus statistically more correct than the values of the LD50 based directly on the results of each group, and are shown as the "corrected" curve separating survivals from deaths in Fig. 1.

An adequate number of control tests was made. These animals received the same handling as the irradiated animals, except that the power was not turned on. Temperature records of some of the controls are shown in Fig. 4. It is seen that the average mouse undergoes a temperature drop of a maximum of 0.6°C over a period of 15 min.

D. RELATIONSHIP BETWEEN ENERGY DENSITY, POWER DENSITY, AND LD50

Figures 5 and 6 illustrate the fact that the energy density (w-min/cm^2) required to attain a given rectal temperature is relatively constant and independent of the power density for small temperature rises, but increases steeply (at the lower power densities) for temperature rises of several degrees centigrade. This observation is doubtless related to the increased rate of cooling at the higher temperatures, a point that is discussed further in Sec. I-K.

E. EFFECT OF ARTIFICIALLY LOWERING INITIAL TEMPERATURE

Figure 7 illustrates the effect of lowering the baseline temperature by the injection of $6 \times 10^{-3} \text{ mg}$ per gram of body weight of chlorpromazine intramuscularly. One hour after the injection, body temperatures averaged 10°C below the normal. Fourteen tranquilized animals were irradiated at a power density of 0.390 w/cm^2 . At this power density, untreated animals exhibit an LD50 at 2.6 min and an LD100 at 3.0 min. The tranquilized animals withstood doses well in excess of these values, with death occurring only when a certain temperature was reached--essentially the same (about 44°C) as that which is

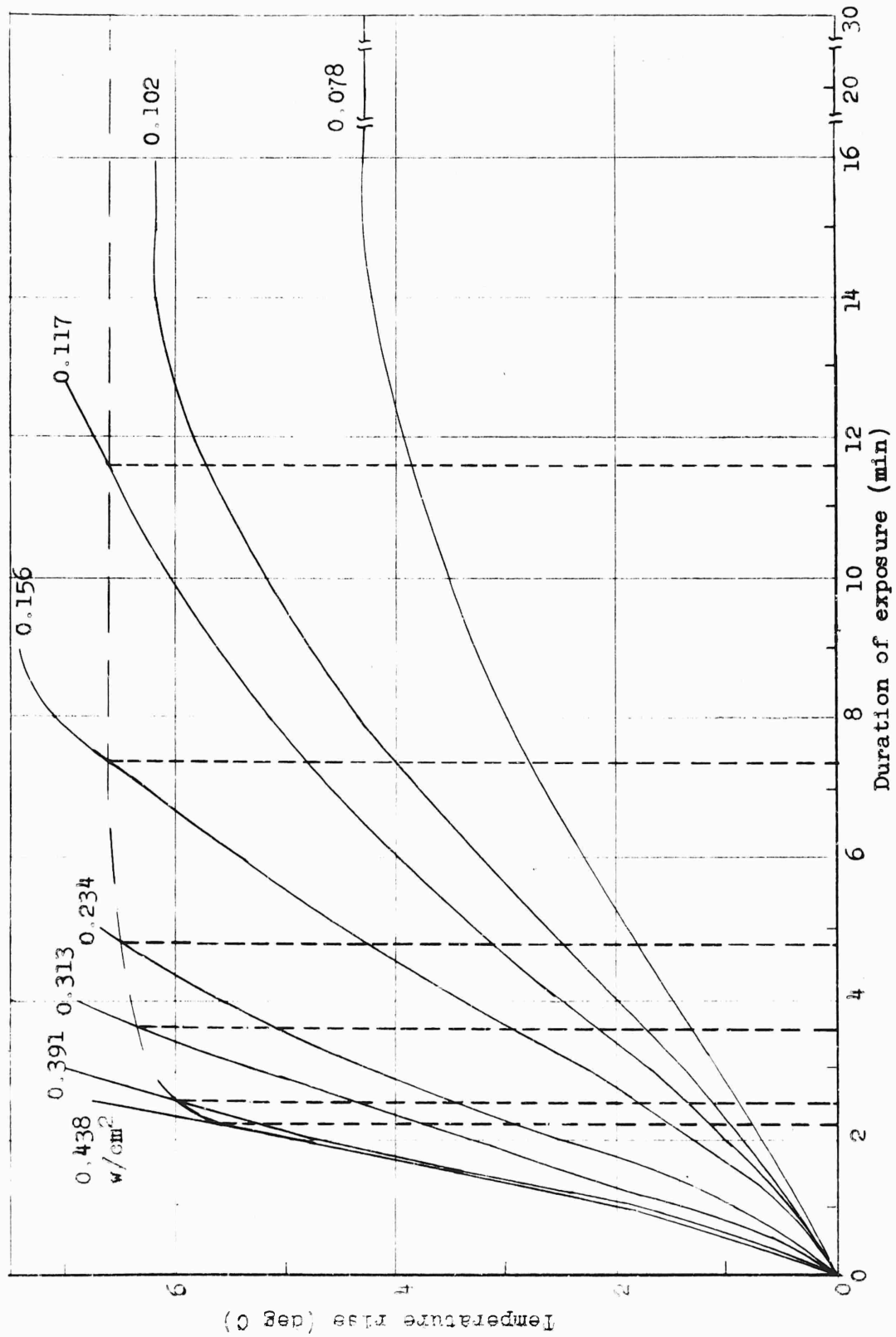


FIG. 3.- Average temperature rise as a function of time at various power densities. Dashed lines indicate LD50 for the various power densities.

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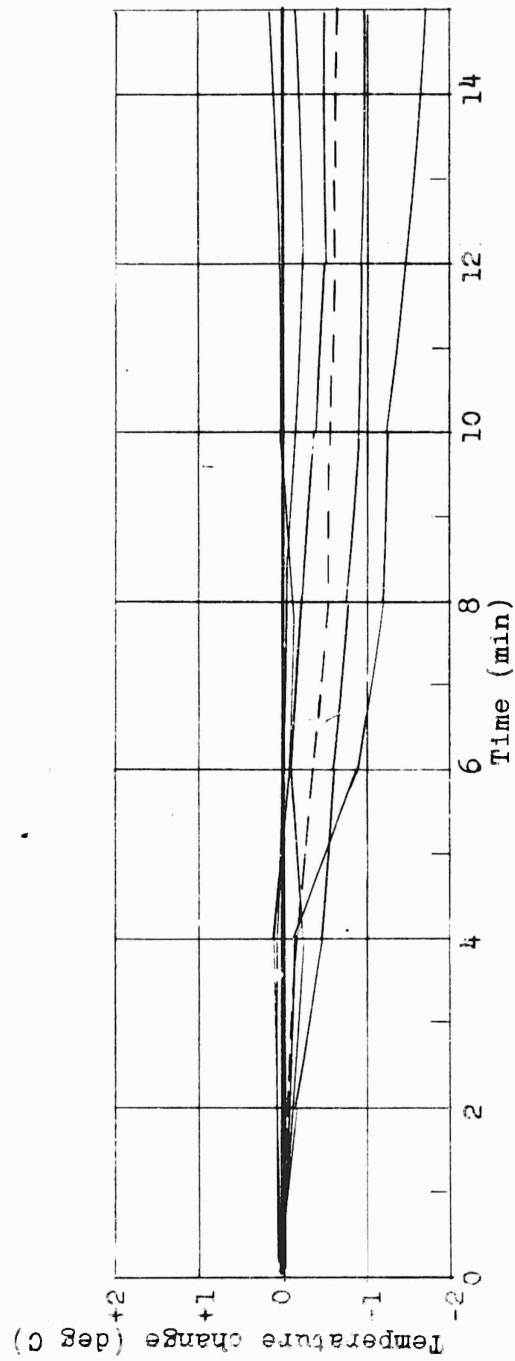


FIG. 4.--Temperature records of controls. Dashed line indicates mean curve of all controls tested.

Temperature
rise
(deg C)

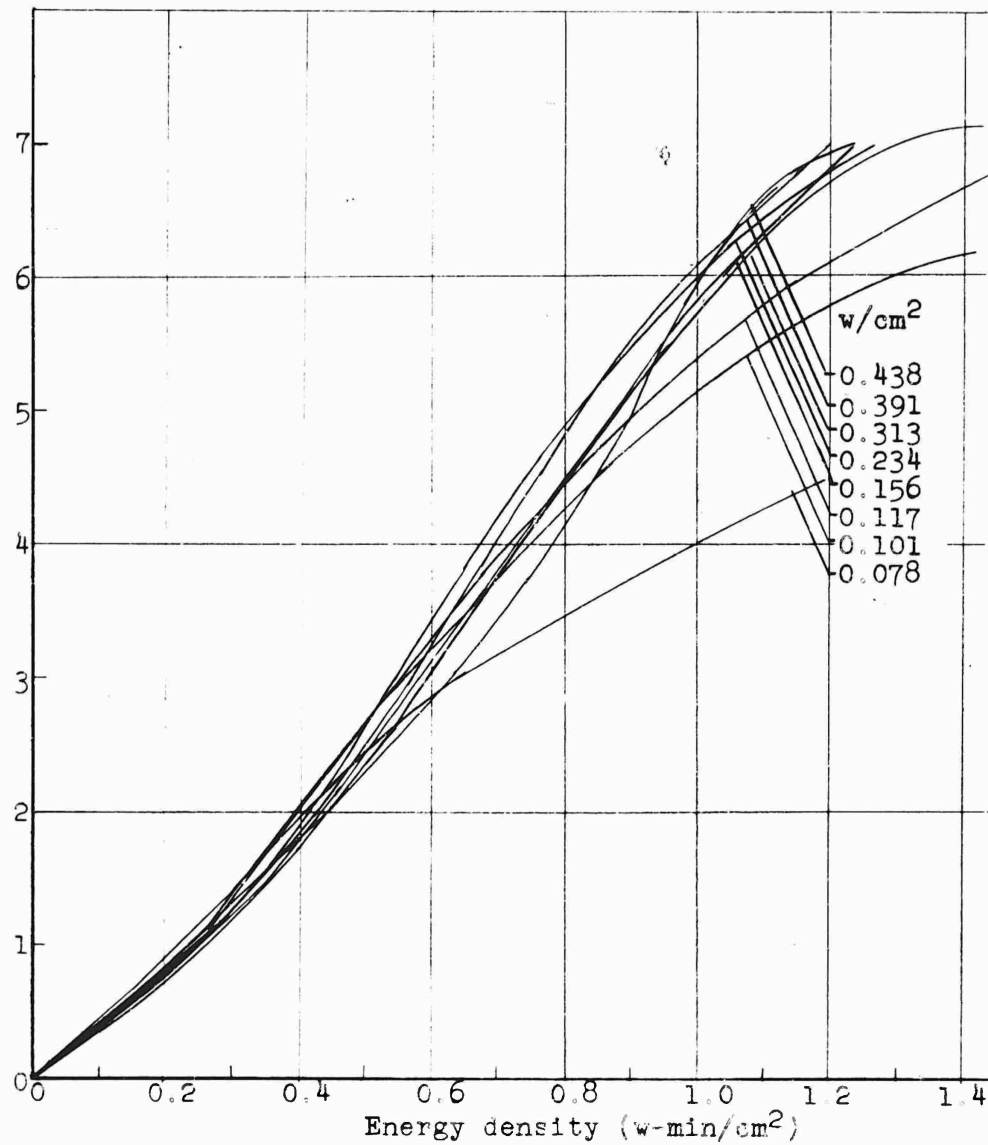


FIG. 5.- Comparison of energy densities necessary to achieve a given temperature rise at various power densities.

(I. LABORATORY ANIMALS)

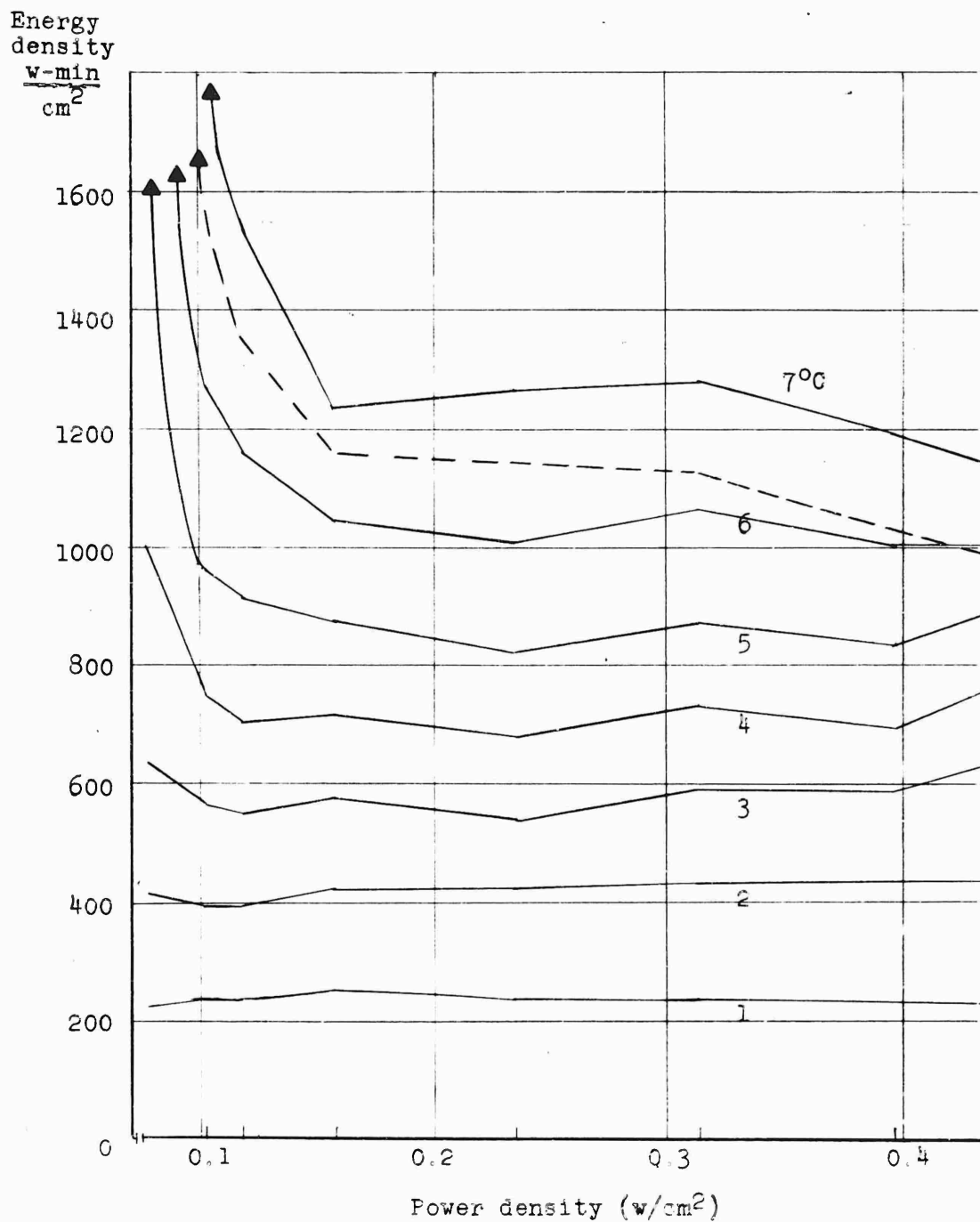


FIG. 6. --Comparison of energy densities needed to achieve a given temperature rise at various power densities. Dashed curve indicates "corrected" LD50 curve

(I. LABORATORY ANIMALS)

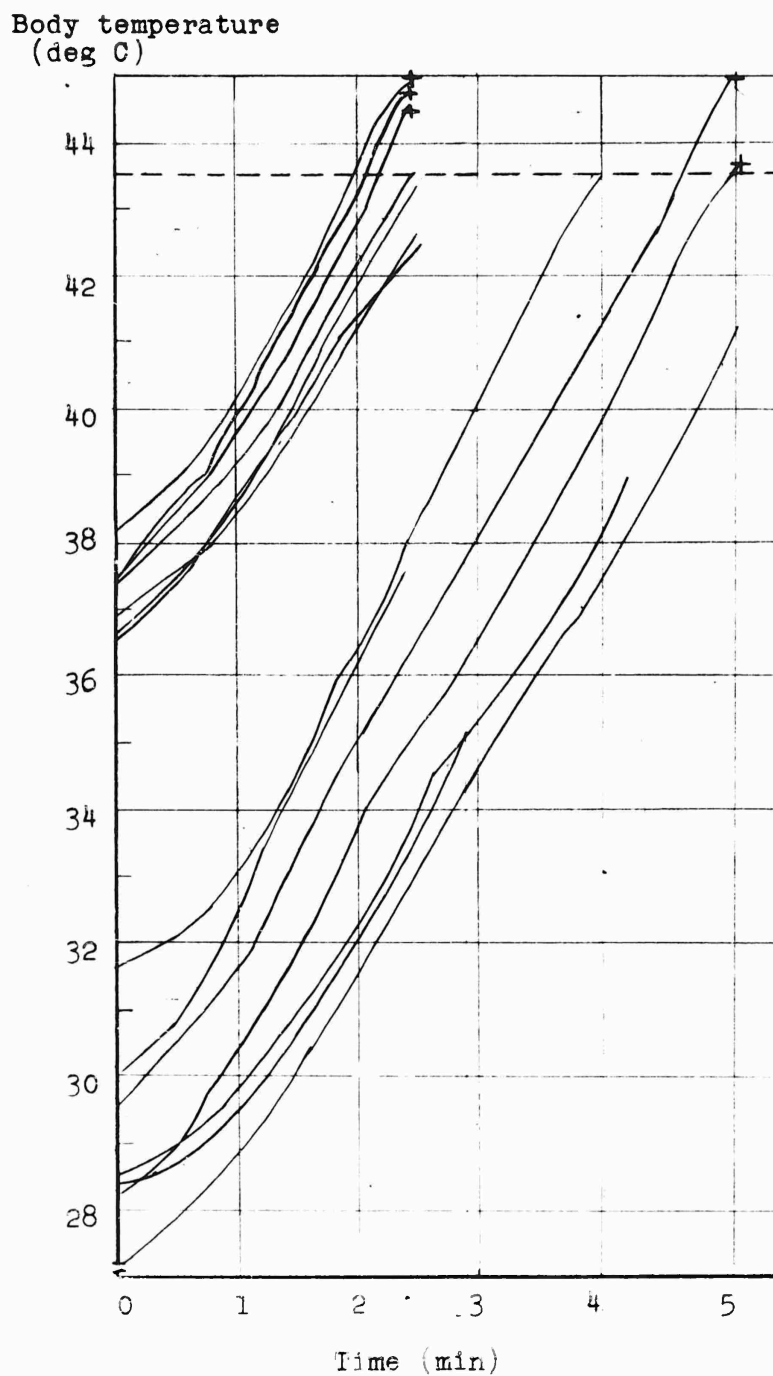


FIG. 7.--Body temperature curves and survival of mice with a normal baseline temperature and with a depressed baseline temperature. Cross indicates death.

(I. LABORATORY ANIMALS)

found to be lethal to untreated animals. This observation appears to bear out the previous result that death occurrence correlates better with the final temperature reached than with any other parameter. Another interesting observation is that the slopes of the temperature-vs-time curves, not normalized in Fig. 7, exhibit substantially identical values for the single power density used, both for treated and untreated animals.

F. EFFECT OF VARYING PULSE REPETITION FREQUENCY

A brief investigation of varying the pulse repetition frequency (prf) while keeping the average power constant was undertaken. The power density was kept constant by adjustments in the height (and to some extent in the width) of the pulse made to keep the total average power constant at 25.1 w while the prf was varied between 500 and 1500 pps. The results are summarized in Fig. 8. No significant changes are observed as the prf is varied. The LD50 is substantially independent of the prf, as is the average time required to achieve a given temperature rise. A total of 60 mice was used in this experiment. Although the scope of this portion of the investigation is perhaps too small to permit definite conclusions, and should be extended in a future investigation, the preliminary results serve to reinforce the conclusion of other investigators that the effects of whole-body irradiation by microwave power are entirely, or at least predominantly, of a thermal nature.

It should be noted that this experiment was performed with mice of a strain somewhat different from that used in the previous investigation, having an LD50 corresponding to approximately to 43°C; this strain was also used in the fertility studies reported in Sec. I-H.

G. PATHOLOGICAL FINDINGS

Gross and microscopic examinations were made of a sampling of mice which had survived near-lethal doses at 0.390 w/cm². In general, no gross changes were observed. One mouse, however, showed marked congestion of the subcutaneous vessels.

Histological sections made of the skin, heart, lungs, liver, and intestines revealed hyperemia and cloudy swelling. These effects were especially prominent in the skin. The damage observed is of the same nature as would be expected from heat injury. It is suggested that the sponsoring installation should establish uniform procedures for histological examinations to permit ready comparison of such future results as may be reported by various investigators at the several frequencies being used in the present program.

H. EFFECT OF SINGLE WHOLE-BODY IRRADIATIONS UPON FERTILITY OF MALE MICE

A number of workers have reported pathological studies made upon the testes following local exposure of the genitals

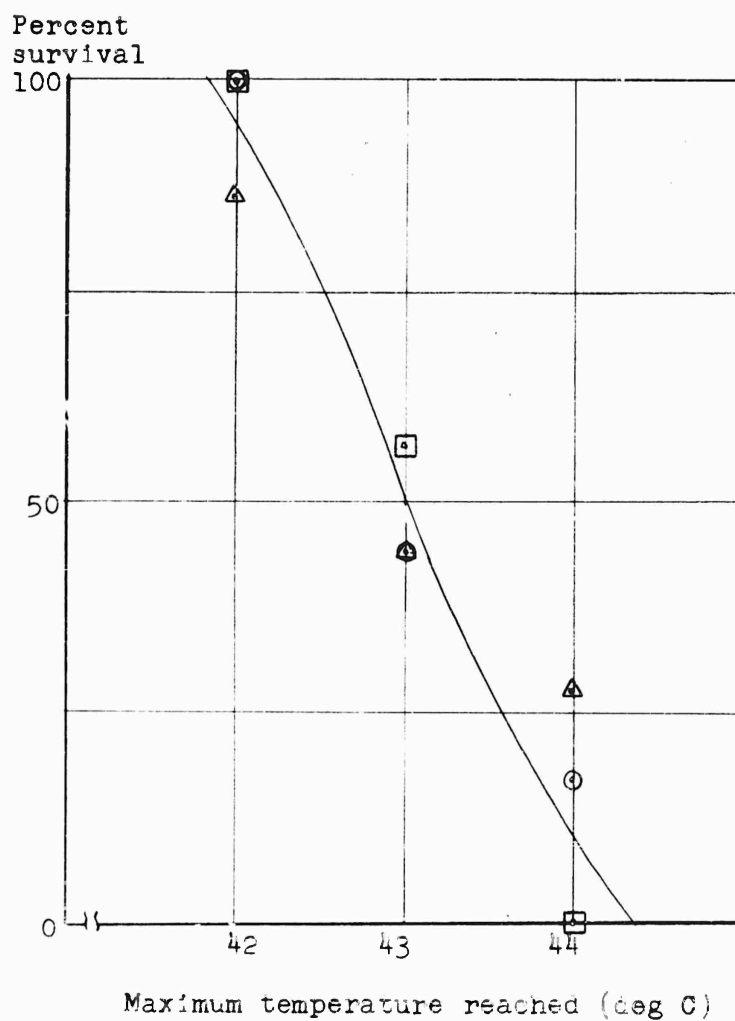


FIG. 8.--Survival of three groups totalling 62 mice as a function of pulse repetition frequency at constant average power. Circles indicate 500 pps; squares, 1000 pps; triangles, 1500 pps.

(I. LABORATORY ANIMALS)

to microwave radiation at various frequencies.^{3,4} Considerable damage to the tissue has been reported, the extent of damage being such as to cause sterility in the animal.

In the present investigation the effects of whole-body irradiation upon fertility were studied, the criterion for fertility being ability to sire a litter of normal size.

A total of 78 fertile male mice was irradiated in 6 groups, each group receiving a different dose. The power density remained constant at 0.124 w/cm^2 , but the length of exposure differed. Dose was defined as the amount of irradiation required to raise the rectal temperature to a given maximum. The maximum body temperatures reached were 38, 39, 40, 41, 42, and 43°C . The power density used was such that there was little or no temperature rise after the power was turned off. It was shown in Sec. I-F that the LD50 is that dose which raises the body temperature to 43°C (in this strain).

Fertile males were irradiated and then immediately placed for four days (the length of the oestrus cycle) into separate breeding cages, each containing 5 virgin females. The 6 mice in each of the cages were then separated and their litters counted as soon as they appeared. A group of controls was subjected to the same procedure after mock irradiations.

Table III summarizes the results. The average litter produced by the controls contained 7.6 mice. Most of the irradiated males sired litters, which were the same size as those of the controls. The nonlittering mouse in Group V was rebred one month after irradiation and was found to be fertile. The two nonlittering males in Group VI, unfortunately, were sacrificed before they could be rebred. Subsequent breedings indicated that there had been at least one fertile female in each of the original breeding cages.

To test whether sterility other than one of an immediate nature may result from microwave exposure, 9 males were rebred 1 month following irradiation. Five of them were taken from Group IV (41°C) and 4 were taken from Group V (42°C). Table III shows that all sired average-sized litters. The next step will be to breed the mice 3-6 months after exposure.

In summary, the evidence above indicates that a single whole-body exposure to a near-lethal dose of microwave radiation usually does not cause sterility in the male mouse.

J. EFFECT OF MULTIPLE WHOLE-BODY IRRADIATIONS UPON FERTILITY OF MALE MICE

Two groups consisting of 8 male albino mice each were irradiated daily at a power density of 0.124 w/cm^2 for 5 consecutive days. Each mouse was exposed from the ventral side until it reached a given maximum body temperature each time. The first group was irradiated for a period of time sufficient to raise the body temperature to a maximum of 41°C ; the body temperature of the second group reached 42°C . Immediately after the fifth irradiation each mouse was bred for 4 days with 3 fertile females. A control group of 4 males was used. All mice except 1 in Group I (see Table IV) survived the 5 exposures

(I. LABORATORY ANIMALS)

TABLE III.--Effects of a single whole-body exposure to microwave radiation upon the fertility of male mice.

Group	Max. temp. (deg C)	Ave. no. of mice per litter	No. of irradiated males	
			Bred	Sired litters
I	38	7.0	8	8
II	39	7.6	10	10
III	40	7.8	9	9
IV	41	7.1	8	8
V	42	7.2	8	7
VI	43	8.2	18	16
Contr.		7.6	13	13
Rebred		7.5	9	9

TABLE IV.--Effects of multiple whole-body exposures to microwave radiation upon the fertility of male mice.

Group	Max. temp. (deg C)	Ave. no. of mice per litter	No. of irradiated males	
			Bred	Sired litters
I	41	10.2	7	7
II	42	9.9	8	8
Contr.		8.1	4	4

(I. LABORATORY ANIMALS)

The results show that the controls sired an average of 8.1 mice per litter, Group I (41°C) sired 10.2 mice per litter, and Group II (42°C) sired 9.9 mice per litter. These differences are not significant because the number of litters involved is small. It is evident, however, that five consecutive near-lethal exposures to microwave radiation do not cause short-range sterility in the male mouse.

K. STUDY OF TEMPERATURE AFTER IRRADIATION CEASES

As mentioned in Sec. I-C, the temperature flattens out after the power is turned off, except in the steep temperature-rise curves corresponding to the higher power densities, as shown in Fig. 2, in which it continues to rise briefly before reversing. Some interesting results are obtained from a study of the cooling curves, which tend to decrease nearly exponentially--except that the temperature actually continues to decrease below the baseline temperature. A typical curve is shown in Fig. 9. Such a study might lead to new insight into the mechanism of heat regulation in mammals, by a comparison between the cooling curve for an inert mass obtained from classical heat-flow equations and the data obtained in the present experiment. The possible consequences of such a comparison are presented below; a more thorough analysis must be deferred until a larger number of cooling curves becomes available.

The amount of incident energy required to raise the body temperature of a mouse is independent of the power density, provided that the temperature rise is small. It can be assumed that the rate of heat loss by the mouse increases with its temperature. If this is the case, the rate of temperature rise is given by

$$\frac{dT}{dt} = aP - f(T) \quad (1)$$

where T is temperature, t is duration of exposure, P is power density, a is a constant determined by the physical characteristics of the mouse, and $f(T)$ represents the increase in the amount of heat dissipated by the mouse, as compared with its normal heat loss. Where $f(T)$ is small compared to aP (i.e., for a small temperature rise or a large power density), the temperature-time relationship is nearly linear and the temperature rise is proportional to the energy absorbed per unit of body mass.

From the data, it is estimated that a temperature rise of 10°C results from exposures to 2 cal of incident energy per gram of body weight. If the mean specific heat of the mouse is assumed to be close to unity, then about 50 per cent of the incident energy is accounted for by temperature rise. This appears to agree with the calculations of Schwan and Li.⁷ The simplest assumption as to the nature of $f(T)$ is that it is proportional to the change in temperature

$$f(T) = b(T - T_0) \quad (2)$$

Temperature
above normal
(deg C)

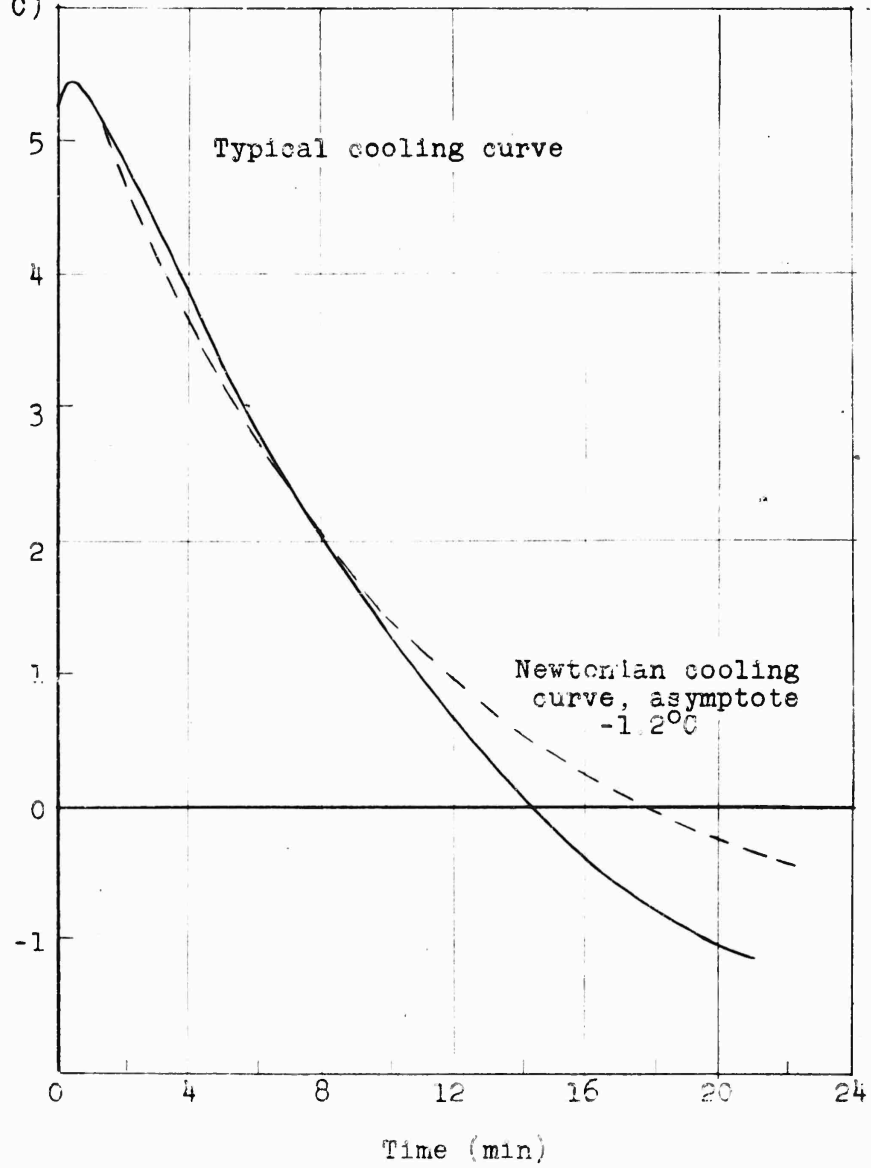


FIG. 9.- Postirradiation cooling curve.

(I. LABORATORY ANIMALS)

in accordance with Newton's law of cooling,⁵ where b is a constant and T_0 is the initial temperature. The poor thermoregulatory ability of the mouse renders this assumption plausible. Equation (1) then yields, upon integration,

$$T - T_0 = aPt \frac{1 - e^{-bt}}{bt} \quad (3)$$

For small values of bt , the approximation

$$T - T_0 = aPt = aE \quad (4)$$

where E is the cumulative energy density, is adequate. For large values of t , Eq. (3) approaches the value

$$T - T_0 = (a/b)P \quad (5)$$

From the initial slope (see Fig. 5), $a = 5 \text{ deg-cm}^2/\text{w-min}$; a value of $b = 0.3 \text{ min}^{-1}$ will give the observed "half life" of the cooling curve. At low doses, a steady-state temperature is eventually reached as predicted by Eq. (5).

Equation (2) is not precisely verified by preliminary studies of the rate of cooling of mice after irradiation ceases. However, the cooling curve does show that the rate of cooling decreases as the temperature falls. Presumably, then, the rate of cooling increases as the temperature rises.

The actual cooling curves appear to follow more closely an empirical equation that takes the lower "overshoot" into consideration. For instance, for the curve shown in Fig. 9, a good approximation over most of the range is obtained by plotting

$$T - T_0 + 1.2 = Ae^{-bt} \quad (6)$$

where the 1.2 value represents the overshoot and b has the same value as before; A is related to the maximum temperature, and is obtained empirically. To be sure because of the overshoot, Eq. (6) cannot be used to account for the heat loss during irradiation. It is reasonable to assume that in the initial period of irradiation, the contribution of the cooling term $f(T)$ to Eq. (1) can be neglected. It is also obvious from Eq. (1) that if T increases sufficiently so that $f(T) = aP$, a steady state will be attained.

Equation (3) is valid only in a qualitative sense, but shows the approximate form of the heating curve. Equation (4) remains valid and is verified by experiment. To correspond more closely to the experimental data, Eq. (5) would have to be slightly modified to read

$$T - T_0 = F(P) \quad \text{Steady state} \quad (7)$$

where $F(P)$ is some increasing function of P .

The pulse repetition frequency does not appear in Eq. (1). It can be shown that on the basis of thermal considerations alone, no pulse effect can be observed unless the heat lost

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between successive pulses is appreciable. At the pulse rates used, this is not the case. Hence, the failure to observe a pulse-rate effect, as described in Sec. 1-F, is also explained on the basis of the mathematical considerations above.

L. CONCLUSIONS

The data are thus consistent with the assumption that death is caused by excessively high temperature. Death occurs in 50 per cent of all mice which reach a rectal temperature of 44°C regardless of the intensity of the radiation, as shown by the fact that the LD50 can be predicted from the temperature-rise curve. It seems unlikely, therefore, that death is due to radiation per se. It is more probable that death is due to hyperthermia in the mouse.

If hyperthermia is the primary cause of death, then any agent that reduces the internal temperature should produce a corresponding degree of protection. In mice rendered initially hypothermic by chlorpromazine, death did not occur unless exposure was prolonged sufficiently to produce the lethal temperature. Any changes that occurred at sublethal temperatures failed to affect short-term survival.

The pathological findings have been entirely consistent with the hypothesis that death is caused by heat. Apparently the mouse dies because it is unable to maintain its internal temperature, in contrast to the rat,⁶ which shows more damage that would be expected from the temperature increase alone.

Further light on the problem of possible long-term effects may be shed by the proposed accumulation of longevity data.

There have been numerous reports of testicular damage induced by microwave radiation; however, localized irradiation was involved in these tests. When the entire ventral surface is irradiated, death precedes sterilization. It is recognized that considerable reduction in sperm count may remain undetected by the present method; however, the failure of repeated irradiations to induce sterility suggests that sterilization requires higher testicular doses than can be achieved with whole-body irradiation without lethal consequences.

In attempting to postulate an athermal mechanism of microwave damage, theoretical difficulties have arisen. It is usually assumed by modern biologists that every biological change involves a chemical reaction. According to the Einstein-Stark equation, a necessary condition for a reaction involving electromagnetic radiation is that $Nh\nu \geq E^*$, where N is Avogadro's number, h is Planck's constant, ν is the frequency, and E^* is the energy necessary to activate one mole of the reacting substance. For weak chemical bonds, such as hydrogen bonds, E^* is of the order of 5000 cal/mole. For 3-cm radiation, however, $Nh\nu$ is of the order of 1 cal/mole, which is far too low to bring about any reaction that would not occur spontaneously at physiological temperatures. For longer wavelengths, the available energy is even less.

The possibility remains, however, that physical rather than chemical changes might occur. Modification of the geomet-

(II. CELLULAR ORGANISMS AND INSECTS)

ric arrangements within cells could produce irreversible changes. If this phenomenon occurs, it is anticipated that further experiments will demonstrate it. A possible mechanism is suggested in Sec. II-B.

II. EXPERIMENTS WITH CELLULAR ORGANISMS AND INSECTS

A. INTRODUCTION

With regard to short-wave diathermy, it is generally accepted that it produces certain physiologic effects which are due to the local or systemic heating produced by the radiation. Controversy has arisen as to whether such radiation also produces specific effects other than heating. With regard to the physiologic effects caused by its heating of tissues, Follis⁸ concluded that daily exposure for 3 hours through 8 weeks with rays of 10-cm wavelength from a radar set of peak power output of 45 kw did not retard the growth of guinea pigs, appreciably affect their reproductive organs, or produce any pathologic lesions. Knudson and Schaible⁹ arrived at the same conclusion when they employed short-wave diathermy for daily systemic heating of rats to 105°F. In the years 1932-1935, experiments were performed by Bierman,¹⁰ Boak,¹¹ Heinle and Phelps,¹² and Eidinow,¹³ all of which confirm the point of view that no effects are observed other than those due to heating. Weissenberg claims¹⁴ that low-intensity treatments produce definite physiologic effects, and Stiebock asserts¹⁵ that short exposures of 5 min or less have a marked action other than mere heating. These 1937 claims are somewhat supported by more recent experiments by Imig, Thomson, and Hines.¹⁶ Comparing the effects of infrared and microwave radiation, they come to the conclusion that, although the type of degeneration of testicular tissue cannot be distinguished, microwave radiation produces testicular damage resulting from a single exposure at 30 and 35°C, but damage due to infrared waves could be only observed at a temperature of 40°C and above. The experiment also supports to some extent the claim of Schliephake¹⁷ that when "short-wave therapy" is employed one is not dealing with heating effects in the ordinary sense, as still asserted by some authors, but rather with a heating that often differs from that of "thermotherapy and diathermy." Kobak¹⁸ does not seem to agree with Schliephake's claim that there are "specific effects on colloids" but says that the primary action of short waves is essentially that of heat due to the phenomena of displacement and conduction.

One year after Canti published a statement regarding the absence of nonthermal effects,¹⁹ Curtis and Dickens refuted the claims of both Reiter²⁰ and Schliephake.¹⁷ Curtis, Dickens, and Evans wrote in 1936: "So far as is known at present from physical and chemical evidence, radiation of these wavelengths (3-15 m) is not directly convertible into atomic or molecular energy." After checking Reiter's and Schliephake's experiments they concluded: "The variations of surface tension in the short-wave field has been referred to in the literature as the 'Schliephake effect,' but in our opinion proof of its existence

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is entirely lacking." They also concluded that if specific effects other than heating exist, "it should be possible for the discoverers to describe at least one clear-cut experiment which could be repeated by other workers. In the absence of such evidence we consider that the great mass of inconclusive observations which has been presented is a very insecure foundation for the rapidly growing belief in specific effects of short-wave therapy."

At that time the consensus very definitely seemed to be that no specific physiologic effects other than those attributable to heat had been proved to exist. Nevertheless, the remote possibility of the existence of such effects could not be denied. Not a few research workers agree that there is a need for more investigations, especially with regard to non-thermal effects, as well as on the temperature distributions in living tissues and on the action of extremely short wavelengths.

The above controversy has not been solved yet but another one has been added. With the development of new electronic devices one is now able to obtain wavelengths very much shorter than 1 m. After World War II, investigations on thermal and nonthermal effects of microwave radiation on biological tissues were again taken up, but this time with shorter wavelengths. A controversy has again arisen as to these experiments.

As has been mentioned above, the experiment of Follis⁸ confirms claims of the earlier workers that only thermal effects can be observed. On the other hand, Imig and his coworkers tend to support the point of view of nonthermal effects associated with microwave radiation. Iwase²¹ assumes also that biological effects in a high-frequency field are due to specific phenomena more than to thermal phenomena. Schwan and Piersol²² say that "to the best of our knowledge none of the statements about these (nonthermal effects) can withstand criticism." Hines and Randall²³ assert that the irradiation effects with 12-cm waves are probably entirely thermal. Herrick and Krusen²⁴ confirm that primary effects are due to heating. Schwan and Li²⁵ merely state that "previously formulated opinions concerning the relative heating of fat-muscle layers with radiation diathermy are, therefore, justified." Nor do Roberts and Cook²⁶ take sides in the controversy when they say that "high-power microwave generators have been used to study tissue heating, the heating pattern comparing favorably with predictions from the radiation propagation constants and the thermal properties of the materials."

Here again there seems to be a definite need to clear up the controversial issue once and for all by performing exact experiments especially designed for this purpose. At the same time studies can be made as to what specific nonthermal effects occur if they do. If they are what they are suspected to be, a great many important points can be studied concerning the permeability of cell walls, the speed of ion exchange, and the nature of the electric double layer constituting part of the cell membrane.

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B. POSSIBILITY OF NONTHERMAL EFFECTS

It is well known that the energy levels associated with molecular rotation lie in and about the microwave region. Spectroscopy in this region is based upon the production of excited rotational states by absorbed radiation, as well as upon paramagnetic resonance effects. The effects of these excited states upon a complex, dynamic system, such as a metabolizing cell, are difficult to predict. The possibility of nonthermal changes cannot, therefore, be excluded. If sufficient microwave energy can be absorbed by a biological sample without raising its temperature unduly, the tolerance limits of the cells for any such changes would eventually be exceeded. Lethal effects would be a probable consequence of such changes. Ultramicroscopically localized heating, if sufficiently intense, would have the same consequence. Effects on bioelectric function of the cell, such as ion transport and nerve type of conduction, would not be surprising. The view that the nervous system is sensitive to r-f fields also finds support from Russian investigators.²⁷

The question of the existence of these phenomena can be resolved only by experiments. Some preliminary data will be presented in the following sections

C. EXPERIMENTAL METHODS

As one can see from the above-mentioned discussion of the microwave radiation, the possibility of a nonthermal effect exists. The problem therefore is to find a method of approach to demonstrate the actual occurrence of such phenomena.

The first method employed in the present investigation consisted of pumping a yeast-cell suspension through a microwave absorption cell which was oriented perpendicularly to the waveguide and comprised two mica windows spaced 2 mm apart by a stainless-steel shim. The purpose of this experimental arrangement is to irradiate microorganisms with microwave power in such a way that the temperature of the organisms under irradiation remains constant or within negligible temperature differentials. Air pressure regulated by a needle valve controls the rate of flow of the liquid medium, which is forced through a valve system to permit cyclic irradiation of the microorganisms suspended in the medium. The temperature difference between input and output of the medium is measured by a sensitive thermistor bridge, the liquid is exposed to the electromagnetic waves while passing over the waveguide cross-section. Two mica sheets confine the liquid in the region of exposure and a stainless-steel shim between the sheets serves to diminish the discontinuity and also to restrain the medium within the necessary boundaries for exposure. Several thicknesses of mica were tested for reflection and absorption characteristics and found to be suitable; polystyrene was found to introduce too high a reflection in the system. The factor limiting the use of the absorption cell is the flexibility of the mica sheet, which would be only eliminated by using a sheet of appreciable thickness, introducing too much absorption

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and reflection, or a different material with a high coefficient of elasticity. Sapphire was thought to have good properties, but has not been tested yet.

Unfortunately, the investigation showed that a considerable change in voltage standing-wave ratio (VSWR) can result from a rather minute change in dimensions. The observed change can also be approximately calculated, as follows. It is assumed, first, that the dielectric constant of water is approximately 80, and second, that the change in thickness of the cell is approximated by a shift in the cell wall parallel to itself. With these assumptions and with the known relationship that the reflection coefficient of a dielectric slab is given by

$$\Gamma = \Gamma_0 \left[\frac{1 - \frac{t^2 e^{j2\beta d}}{1 - \Gamma_0 e^{j2\beta d}}}{1 - \Gamma_0 e^{j2\beta d}} \right] \quad (8)$$

where Γ_0 is the magnitude of the reflection coefficient due to a single interface, t is the transmission coefficient, and d is the thickness of the slab, we can thus obtain an expression for the effect of change in thickness. Since

$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (9)$$

and

$$\begin{aligned} \Gamma &= \Gamma_0 \left[\frac{2(1 - \cos 2\beta d)}{1 - 2\Gamma_0^2 \cos 2\beta d + \Gamma_0^4} \right]^{1/2} \\ &= \frac{2\Gamma_0 \sin \beta d}{[1 - 2\Gamma_0^2 \cos 2\beta d + \Gamma_0^4]^{1/2}} \end{aligned} \quad (10)$$

at $\beta d = \pi$, we have, to a very rough approximation.

$$\text{VSWR} = (\text{VSWR})_{\beta d = \pi} \cdot \frac{4\beta \Gamma_0 \Delta d}{1 + \Gamma_0^2 \frac{\Delta d}{\lambda_g}} \quad (11)$$

Thus, if $\epsilon = 80$ and $\Delta d/\lambda_g = 0.025$, which is equivalent to a 0.1-mm displacement of the wall, the change in VSWR is

$$\Delta(\text{VSWR}) = \pm 75 \quad (12)$$

As the pressure varies, when the liquid is pumped from one test tube to the other, the VSWR changes appreciably and erratically in such a manner that a tuning out of the reflections is impossible. The next step, therefore, is to replace the mica by a less flexible material.

Another method of irradiating microorganisms in suspension has been investigated. The liquid is introduced and conducted through the waveguide in the E plane at an angle of 10° with the H plane; an absorption of 10 db can be obtained. If a metal

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wedge is inserted between the glass rod and the waveguide, up to 40 db of absorption is possible. The other part of the system is a medium flowing around a resistance-heated element. By comparing the relative biological effects of this bridge arrangement using the resistance-heated medium as the control, information about the specific action of microwaves on microorganisms can be gained. The system is shown in Fig. 10.

In the first part of this experiment, yeast was pumped through the power-absorbing section of the water-load attenuator (Fig. 11) at a concentration of 10^6 cells/cc. and at such a rate that heating of the medium from 25 to 31°C occurred, as measured by thermometers in intimate contact with the outer walls of the glass tubing. Thirty cc was pumped through the tube; the period for 1 cycle of pumping was 1.2 min. During the passage through the absorbing section the yeast was not cooled. After each cycle a sample of 0.1 cc was taken and plated on yeast extract dextrose. Between cycles, the suspension was cooled back down to 25°C.

D. RESULTS

Survival of the yeast cells was observed on 5 plates after each cycle and compared with untreated and heat-treated controls.

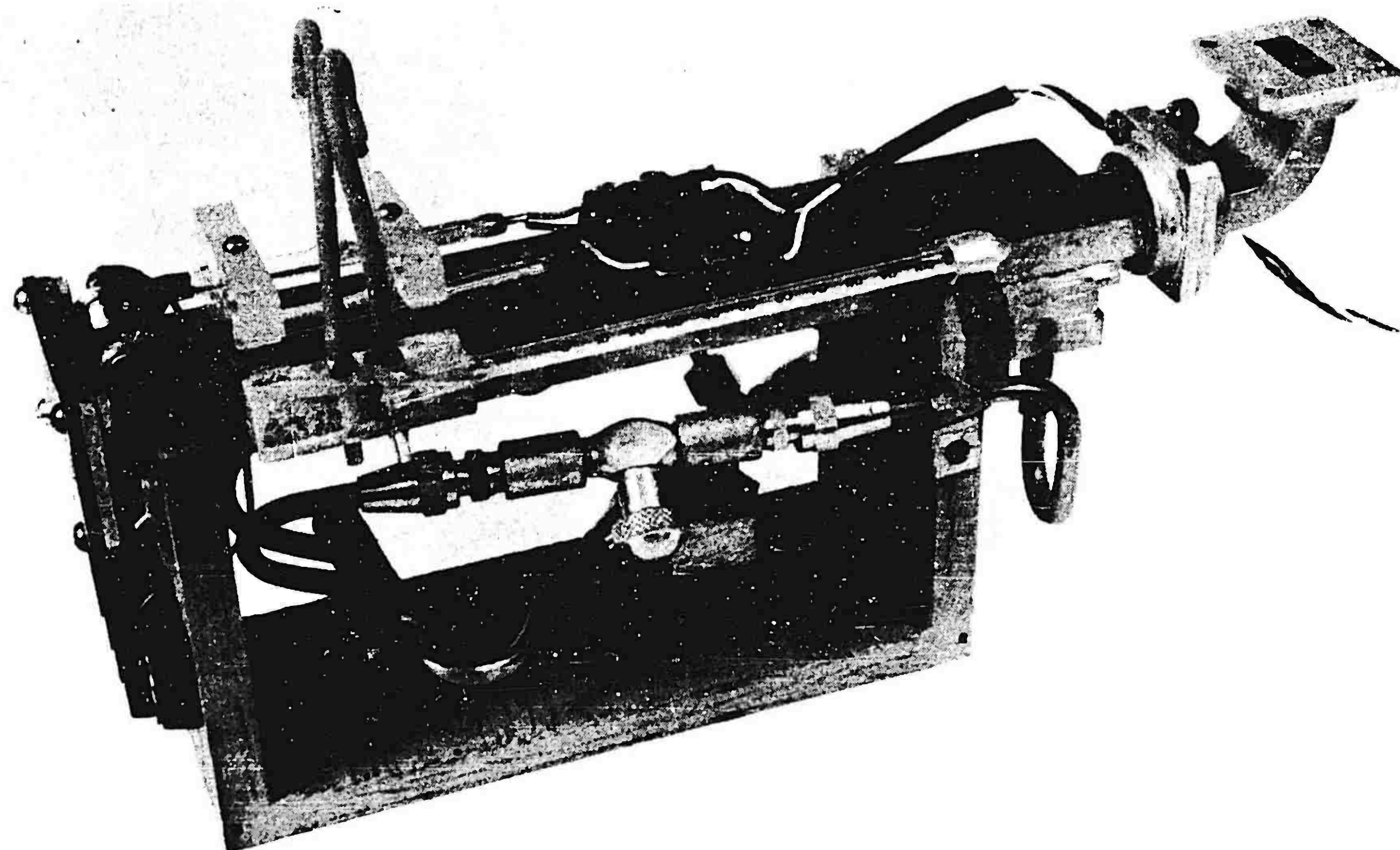
TABLE V.--Yeast colony counts.

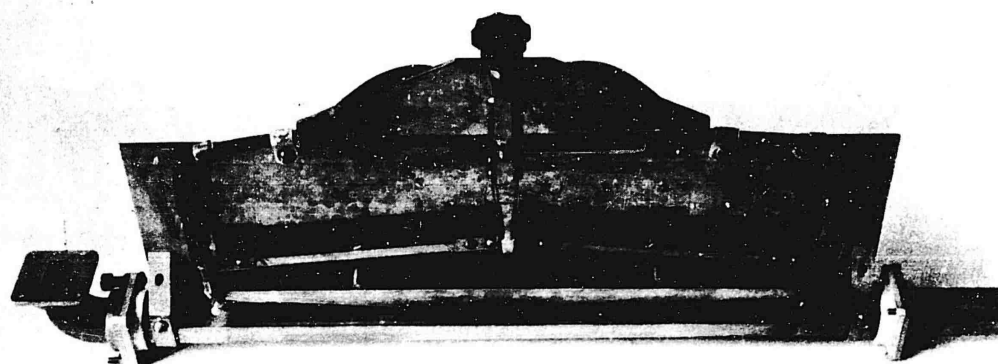
Plate	Untreated control	Heated control	Irradiated cycle		
			1	2	3
A	279	343	336	317	350
B	284	460	371	310	306
C	312	331	341	327	336
D	271	294	277	324	349
E	227				
Sum	1373	1428	1325	1278	1341
Mean	275	357	331	319	335

From these data one can conclude that treatment of yeast with microwave power did not affect the survival of the cells. In fact, they continued to grow during the experiment. The heated controls were kept at a temperature of 34°C for 12 min. Unheated controls were plate first, heated controls last.

E. DISCUSSION

The total power delivered to the individual cells in this pilot experiment seems to be too small to have any killing effect, if there is one. A new instrument will allow cycling over 100 cycles or more, with samples taken after every 10 cycles, the temperature of the medium kept constant at a pre-set value, and the absorbing section of the water-load attenuator cooled automatically if the temperature exceeds a predetermined value. In this way, it will be possible to determine





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with certainty and accuracy any lethal effect that microwave radiation has on single cells.

It may be necessary to look for genetic or physiologic changes, rather than lethality, if the cells fail to show in-activation at the higher dose.

F. EXPERIMENTS WITH INSECTS

In order to investigate the full extent of the effects of microwave power, an experiment in which psychological changes can be measured has been initiated. Since heat shock applied to Camponotus herculeaneum produces a brief amnesia and the action of microwaves is largely thermal, an application of microwaves to this ant species might produce similar results.

Two colonies of ants were collected in the Sierra Nevada Mountains of California and transferred to Fielde type nests where they were allowed to familiarize themselves with their new environment. The nests were then connected by means of plastic tubes to a maze (Fig. 12), in the center of which food was placed. The motive for solving the maze was food in all experiments. The maze itself was made of polystyrene. The carpenter ants were then permitted to explore the new environment in order to find food after a short starvation period. After they were familiar with the apparatus, different types of food were introduced. It was found that calf liver sweetened with molasses was the best stimulus, as previously determined by Smith.²⁸ A measurement of their maze-solving ability was made on sheets (Fig. 12) designed to correlate behavioral patterns to learning ability.

Irradiation of the Camponotus ants (worker class) with infrared radiation produced temporary amnesia; i.e., on starting to go back from the food, the ant made significantly more mistakes than a control.

Since infrared irradiation is related to microwave radiation, it is expected that similar results may be obtained with microwave irradiation.

III. MICROWAVE ENGINEERING

A. GENERAL CONSIDERATIONS

The art of power measurement is basically divided into two major fields, measurement of guided energy and measurement of radiated energy. The majority of the methods that have been developed fall into the category of guided energy measurements. However, many of the techniques are common to both fields. A brief discussion and evaluation of some of the known methods is given below.

The physical principles involved in the operation of most power meters are grouped into two main divisions:

- (1) Thermal and other material methods, by which changes in temperature or in electron properties are measured.
- (2) Radiation-pressure devices, by which mechanical forces exerted on vanes are measured.

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Errors:

Date:

es:

Infrared:

Reversals:

Microwave:

Feeding time:

Normal:

Total time:

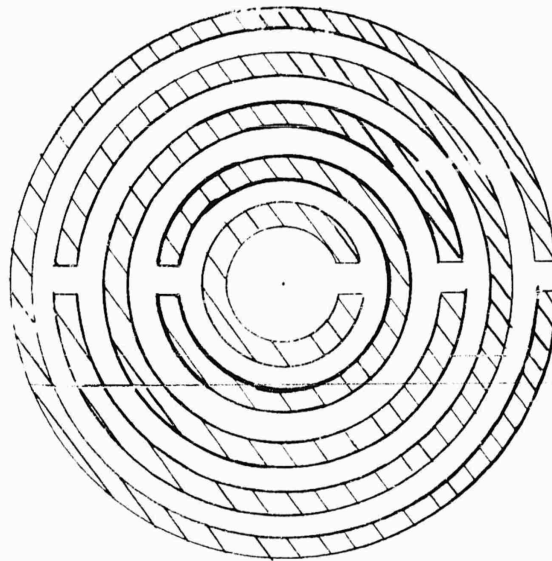
Duration of radiation:

Total errors:

Position a:

Total path length:

b:



Size of ant:

Red: toward center

Food transfer at:

Green: from center

Food used:

Age of food:

Comments:

FIG. 12.--Evaluation sheet for maze-solving ability of ants under irradiation

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The more common power measuring devices utilize some variation of the thermal effect. The most accurate meter of the thermal type is the calorimeter. Calorimetric methods of measuring power are based on the complete transformation of incident electromagnetic energy into heat. The power can be determined by making standard measurements of temperature rise, mass, and time. The continuous-flow water calorimeter is considered the power standard in the range of 1 to 10^4 w. With special techniques, powers of the order of 10^{-3} w can also be measured.²⁹ The general operating procedure, which is common to all calorimeters of this type, is to measure the temperature rise of a water load. In general, the load consists of a waveguide partially filled with a constant-flow stream, which is located so as to cause a minimum of reflection. Since water is an extremely lossy material, complete absorption can be achieved in a few wavelengths. The accuracy of this instrument is better than ± 0.5 per cent. A variation of this type of instrument is being used in the present project, and is further described below.

The measurement of power in the range below 1 w is most commonly achieved by bolometers. Bolometric measurements are based on the dissipation of energy in a small temperature-sensitive resistive element. The heating effect of the absorbed power causes a change in the electrical resistance of the element. This change of resistance is then detected by means of a bridge network. Some examples of bolometers are barretters, wallaston wires, thermistors, and semiconductor films. In practice, bolometers are usually mounted in a waveguide termination.³⁰ The termination is constructed so as to produce as small a discontinuity as possible. A favorable characteristic of bolometers is their small size, which makes them well suited to low-power measurements, since their heat loss to the surroundings is very small. The disadvantages of bolometric measurements are many, the most important being uncertainty of calibration, since equal amounts of r-f power and low-frequency power do not heat the bolometer in the same way. Other sources of error are inherent in the detecting device. The accuracy of bolometers is typically of the order of 5-10 per cent.³¹

Force-operated wattmeters, if carefully used, can approach the accuracy of calorimetry. The principle of operation³² of this type of meter is to utilize radiation pressure. A small metallic plate is suspended in the r-f field, and owing to the interaction between field and plate, a torque is exerted on the plate, tending to rotate it into a preferred orientation. The power is proportional to the developed torque. A torsion support can be used for the plate, together with an optical indicating system, so that small deflections can be detected. Several variations of this basic principle have been developed for measuring power levels³³⁻³⁵ in the range of 0.01-0.10 w. However, this type of instrument is really better suited for measuring high powers. Its major disadvantage lies in the configuration of the system. The meter is extremely delicate and easily damaged.

There are other techniques for measuring power that do not fall into the above categories. One method is to suspend

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a small piece of semiconductor in a waveguide. A current is passed through the crystal along one axis, and the developed Hall-effect voltage is measured in quadrature.³⁶ This voltage is proportional to the power.

Another interesting technique is to measure the backscattering from an obstacle.³⁷ This method involves suspending a small rotating disk in the center of a waveguide. The disk is rotated at a constant audio frequency. The back scattering is detected by means of a system that is synchronized to the disk rotation frequency. This measurement of the back scattering is proportional to the incident power.

Measurement of radiated power utilizes the same methods as are discussed above. However, coupled with the measuring device is some type of receiver. The receiving antenna is in general a horn or a dipole. The fact that the antenna must be coupled to the measuring device adds to the complexity of the problem. The standard methods involve using a calibrated horn and some type of bolometer. This method is not desirable in the present application, since it adds the error of 5-10 per cent inherent in the bolometer to the error of the receiving system. A real solution to the problem of measuring radiated power accurately and compactly quite likely lies in the field of solid-state physics. What is needed is a material that responds to incident power. This response must be capable of being amplified into an observable quantity. There are many materials which change their properties in the presence of electromagnetic energy. Semiconductors are materials which have this property. For instance, transistor operating characteristics are a function of temperature. It might be possible to absorb electromagnetic energy and to detect these changes. Such a device could be calibrated to read power. The depletion-layer transistor³⁸ is potentially another solid-state power meter. The utilization of the physical effects that occur in depletion layers under suitable electromagnetic exciting conditions might be profitably explored.

The use of microwave ferrites is still another possible source. Ferrites have many interesting properties that might be utilized. The property of rotation and of absorption might possibly be used. In many ferrites these properties undergo large changes as the temperature is varied. The utilization of these effects might further be explored for use as a power meter.

Another possible approach might be in the utilization of some variation of the force-operated device. A small vane in conjunction with some sort of amplification system could be conceivably developed into a portable radiated-power meter.

Additional sources containing information pertinent to the subject of absolute microwave power measurements are listed in the references 39-45. Regrettably, most are not very explicit on the subject.

B. MEASUREMENTS OF RADIATED POWER

The purpose of these measurements was to determine the absolute power density at the target. Assumption of a plane wave was not applicable as the available power, in conjunction with the low-gain radiators used, did not allow the positioning of the target at distances sufficiently large to produce plane-wave conditions. Therefore, several experimental methods were used to determine power density at the required distances and the results were compared.

The radiator used throughout these experiments was a standard horn with dimensions as follows: apex-to-aperture distance, 17.7 cm; aperture, 4 x 6 cm; length of horn edge, 10.3 cm. The Fraunhofer zone starts at approximately 1 m measured from the aperture, whereas the distances used were 50 cm or less. The target was positioned along the radiation axis.

1. ORDER OF MAGNITUDE MEASUREMENT. A resonant half-wave dipole loaded by a neon bulb was developed (Fig. 13). The light output of the neon bulb is proportional to the power incident on the dipole; this light is guided along a 3/8-in.-diameter, 12-in.-long Lucite rod toward a Type 931 photomultiplier tube, whose amplified output is calibrated in terms of the known output of the source at a given distance. (The final reading is a voltage read on a WFVM.) The distance is of the order of 12 wavelengths from the apex of the radiator horn and is dictated by the capability of the source to deliver a lethal dose to an animal placed at this position. To calibrate the equipment, it is assumed that the power density at any point is proportional to the known total power flowing along the waveguide to the horn. A transfer curve (horn input vs voltage on the WFVM) gives a reading proportional to the power density at the dipole, which must be multiplied by a constant factor to obtain the absolute power density. To obtain this constant factor, readings are taken over a large area (1 sq ft) normal to the horn axis and containing the initial point, and a family of relative-density curves is constructed and integrated with a planimeter to obtain a number proportional to the total power flowing through that area. This area is large enough to permit the assumption that essentially all of the horn output power is passing through the area. (The edge of the pattern shows a power reading 12 db below that of the center.) Since the total power is known (see Sec. III-C), the proportionality constant is thus obtained. The procedure was repeated and results that differed by less than 1 per cent were obtained, thus demonstrating the repeatability of the measurements. Under the conditions described above, full power from the source (25 w) yields an average power density of 0.16 w/cm² at the center position.

In an attempt at a more accurate measurement, a resonant half-wave dipole (cut to within 1 per cent of a half wavelength) was connected to a thermistor by means of a balun line, a Microdot co. 44, and a 100-ohm precision attenuator (Fig. 14). The thermistor output was measured by a precision HP 430E power meter. To find the relationship

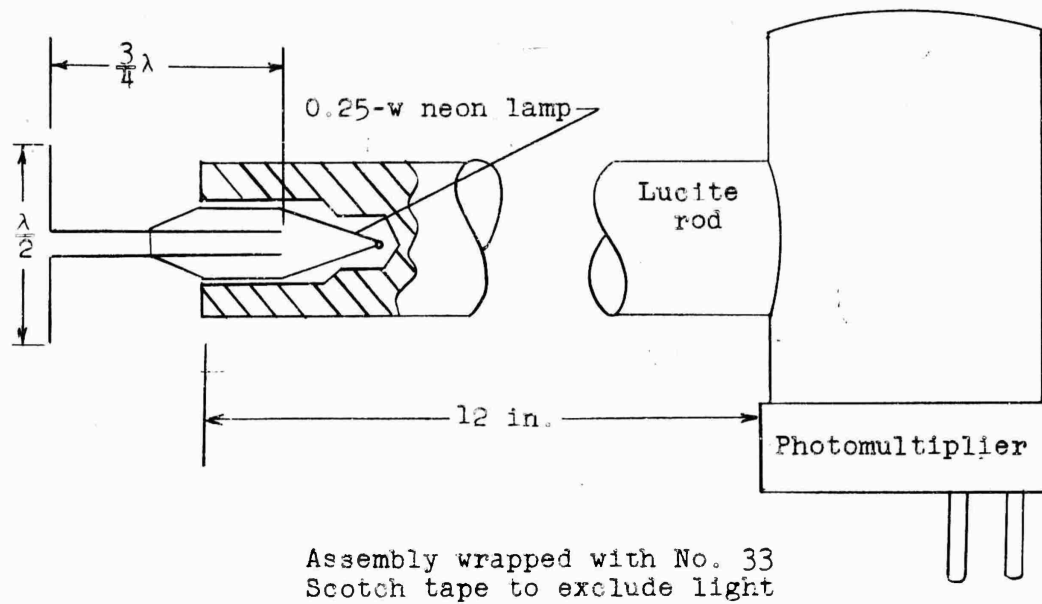


FIG. 13.--Dipole antenna with light-output measurement.

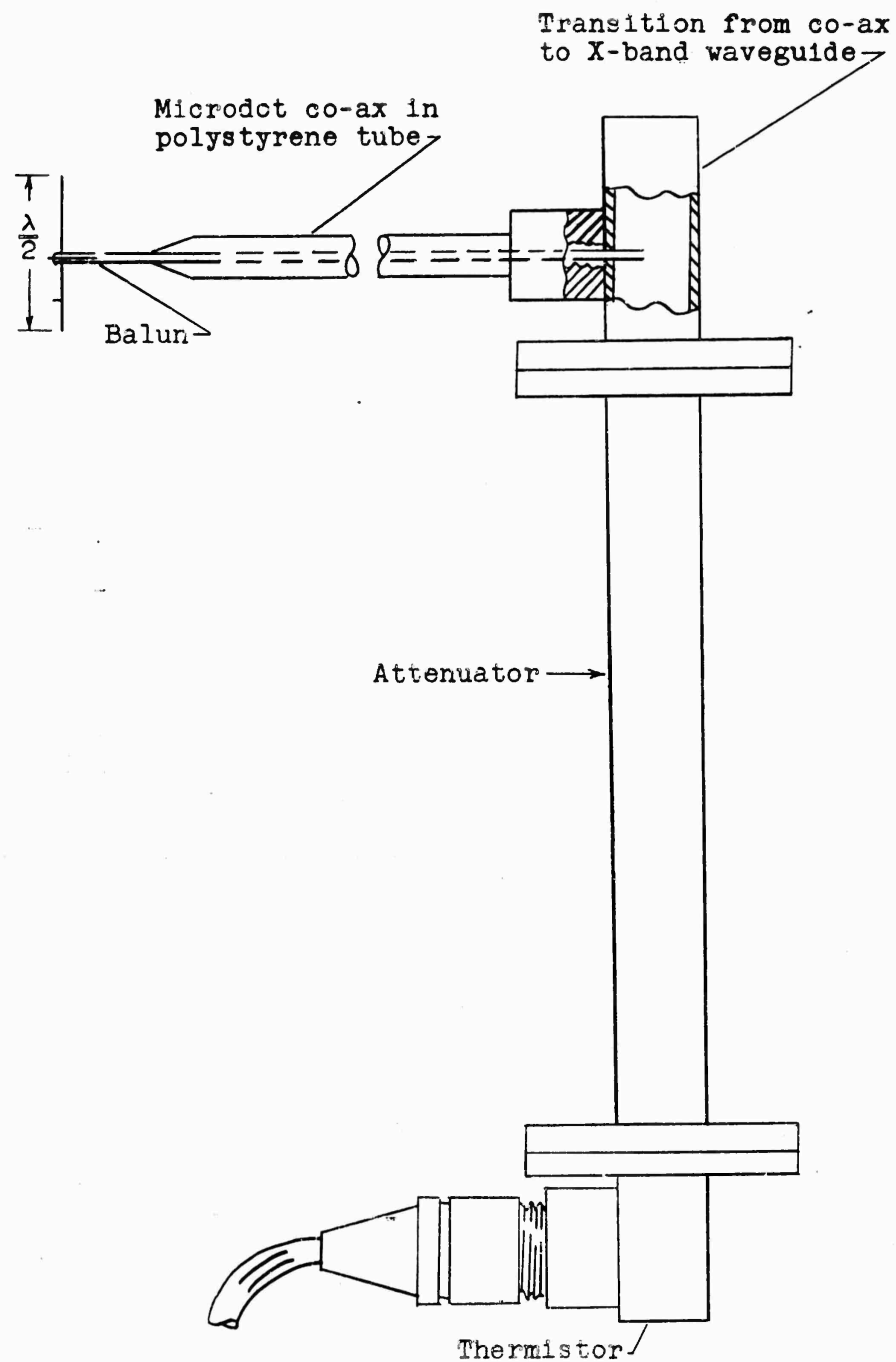
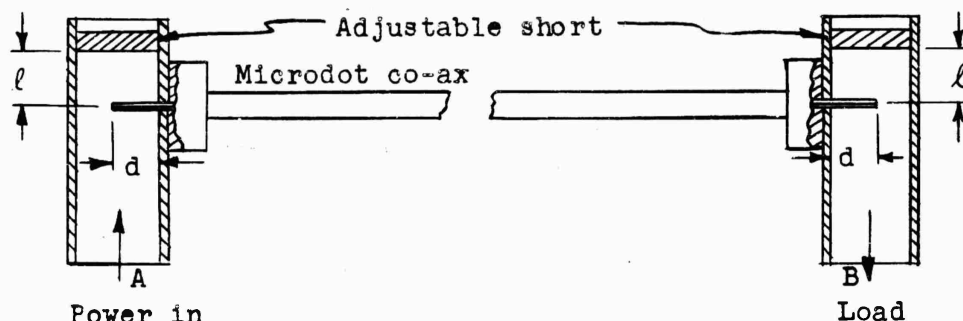


FIG. 14.--Dipole antenna with precision-attenuator measurement.

$$\frac{G(\theta, \phi)}{A(\theta, \phi)} = \frac{4\pi}{\lambda^2}$$

where θ and ϕ are the angles of the position vector with the axis, in the E and H planes, respectively, we obtain the effective cross-sectional area $A(\theta, \phi)$ in terms of the gain function $G(\theta, \phi)$ for any wavelength λ . As all quantities are evaluated for $\theta = 0$, $\phi = 0$, and $G(0,0)$ is known to be 1.65 for a resonant dipole, $A(0,0)$ can be calculated for the frequency used. Next, it is necessary to determine the attenuation between dipole and thermistor. This value is determined as follows. A 23-in. Microdot coaxial cable is E-field matched into two identical waveguide sections equipped with adjustable shorts, as shown in the sketch below. The arrangement is ex-



cited at A, and terminated at B with a load; next, d and L are adjusted for minimum VSWR at 9385 Mc. Then the process is repeated with reversed connections. Alternate adjustments are made until the best match is obtained, below 1.03 VSWR, with the d 's and L 's identical in both sections. The attenuation measured from A to B was 3 db. The assembly was cut at half distance, yielding 1.5 db of attenuation. The other half appeared as the mirror image, and the resonant dipole with a Balun matching section was mounted. Instrument accuracy was 1 per cent. This method yielded a reading of 0.16 w/cm^2 .

2. SPHERICAL INTEGRATION OF POWER DENSITY. This method employs a near-zone pattern range equipment specifically built for this purpose. The radiator is mounted at the center, and constant-radius E and H field patterns are taken by means of the dipole over $\pm 145^\circ$ from the radiation axis. These measurements are then repeated for various distances from the radiator, first with the resonant dipole, and then with the small horn in conjunction with a square-law detector and a standing-wave amplifier. An experimental formula is used to compute the power density on the radiation axis, as follows:

$$P(0,0) = \frac{P_t}{\Delta F(0,0) \pi r^2 \sum_{i=1}^n \phi_i \theta_i} \quad (13)$$

where

r = radius from horn apex to target
 ϕ_1 = H-plane angle in radians, measured from the axis
 θ_1 = E-plane angle in radians, measured from the axis
 n = number of segments in the numerical integration
 $\Delta F(0,0)$ = element of normalized power function, or height of segment
 P_t = total power in waveguide

Plots of normalized power $F(\phi, \theta)$ are plotted as functions of angle, on linear scales, for E and H planes. The "three-dimensional" plot of this radiation pattern is then integrated numerically and equated to the total radiated power that is measured separately (see Sec. III-C).

In the measurements, only the relative gain variation from the radiation axis is of interest. At the extremes of 145° , the power was 35 db down from maximum.

These calculation yielded a power density of 0.146 w/cm^2 at the same distance from the aperture as used in the measurements described in Sec. III-B-1.

As an additional measurement, the angles ϕ and θ were held constant, and equal to zero, and the radius was varied. The resulting data make it possible to extend the use of Eq. (13) to other distances. In all the above measurements, care was taken to eliminate reflections by means of absorbing walls set up in the proper fashion.

A further measurement might be made by a method in which the boundary of the far zone is found experimentally. Then, a very accurate pattern is taken, and a theoretical aperture phase and amplitude distribution found by means of curve fitting. Once the mathematical expression is known, the effective cross-sectional area for a suitable pick-up horn can be calculated and calibrated for absolute power level. The equipment necessary for pattern measurements, with emphasis on accuracy, has already been available from previous measurements. However, the boundary separating the far zone from the near zone is generally taken to be greater by an order of magnitude than $2\pi D^2/\lambda$, where D is the larger dimension of the horn aperture. The power levels required in the present experiments are such that it is necessary to remain within the near zone to achieve them, even with the government-furnished radar, and this particular set of measurements must be, therefore, postponed.

C. MEASUREMENTS OF WAVEGUIDE POWER

The purpose of this set of measurements was to determine waveguide power P_t and the percentage error associated with the power monitoring circuit.

To account for operation at various power levels, it is also required to find the frequency characteristics of the magnetron as a function of magnetron current I_m and the effects of the frequency variations on the attenuators employed in the power-monitoring circuit.

The power in the waveguide is monitored by tapping a neg-

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ligible amount through a 40-db decoupler, passed through a 16-db attenuator, and absorbed by a thermistor-type detector which in turn drives a calibrated amplifier. The power P_i incident on the thermistor is read on the power meter directly in milliwatts. Waveguide power is, therefore,

$$P_t = KP_i$$

where K is the inverse attenuation in ratio due to the decoupler and attenuator pad. The error involved in determining P_t depends on K and on the properties of the thermistor-power meter circuit. Therefore, it is desirable to determine K as accurately as possible, and also to verify the measurements obtained from the monitoring circuit.

1. FREQUENCY-SHIFT MEASUREMENT. Incident energy is tapped by means of a cross-coupler and fed into a test-bench set-up. Care is taken not to change the equipment from its regular operational condition, other than absolutely necessary, in order to avoid unwanted loading of the magnetron. At resonance, the cavity-type frequency meter causes a dip on the standing-wave amplifier which is driven by a square-law detector.

2. POWER-LEVEL MEASUREMENT. The equipment overload control prevents operation at a power level higher than that corresponding to a magnetron current of 25 ma. With 23 ma as abscissa on a 0-db ordinate, the power is decreased by limiting the magnetron current.

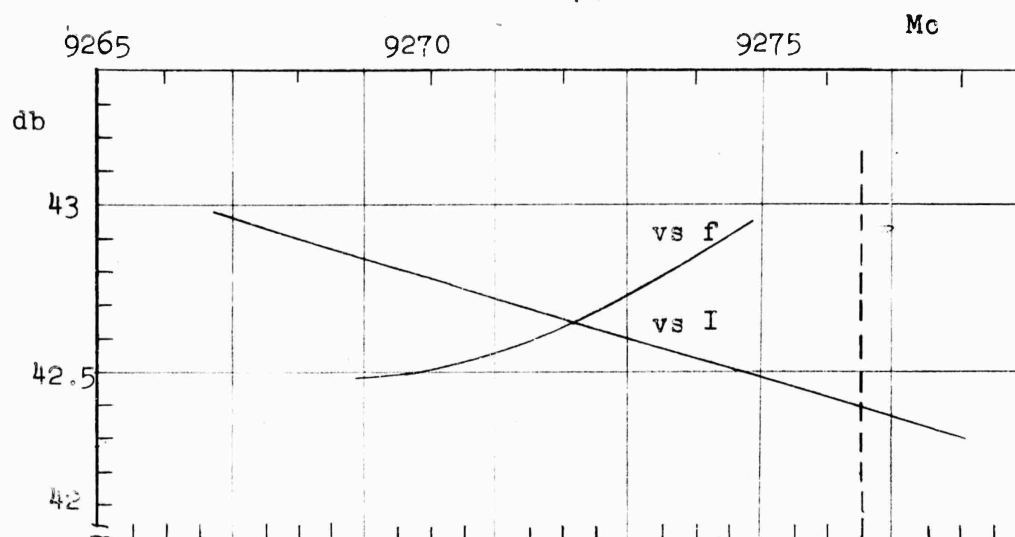
3. MEASUREMENT OF K . For the sake of convenience, define K_1 as the attenuation of the 40-db decoupler alone, and K_2 as the attenuation of the 40-db decoupler plus the 16-db pad. Then K_1 is measured in the following manner:

- (a) Set precision attenuator to zero and insert decoupler; set the VSWR amplifier to 0 db at a convenient level by adjusting the input attenuator.
- (b) Set the precision attenuator to maximum and remove section under test.
- (c) Decrease the precision attenuator until the 0-db reference is read on the VSWR amplifier; the attenuation is read on the calibrated scale.

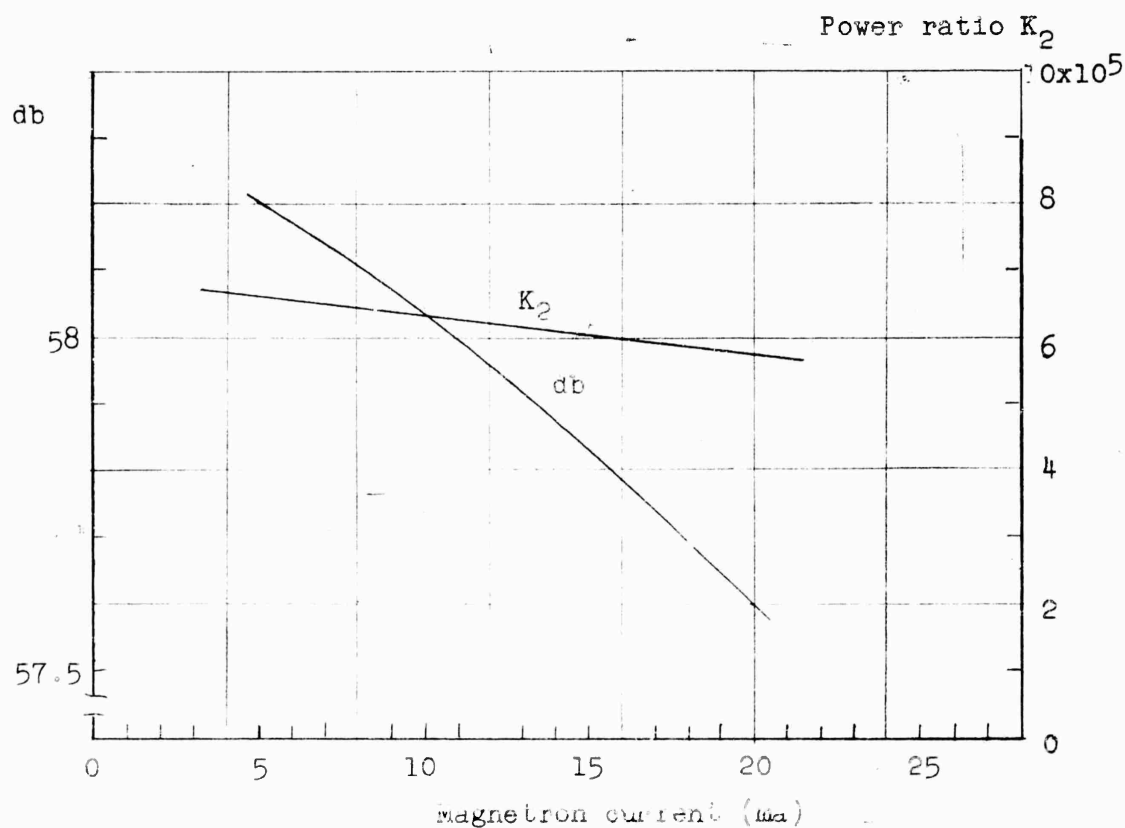
This procedure is repeated for various magnetron current settings and K_1 is plotted. Next, the attenuation of the 16-db pad is found in an identical fashion. From these measurements, K_2 is determined. The reason why K_2 could not be found directly lies in the limitation (45 db) of the precision attenuator. The results are shown in Fig. 15

4. POWER-COMPARISON MEASUREMENTS. With the results of the above measurements, waveguide power was monitored for magnetron currents from 5 to 14 ma. The bulk of the power was absorbed by a nonadiabatic, flow-type water-load calorimeter, as described below. By simultaneous readings of the two fundamentally different pieces of apparatus, unexpected errors were bound to

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(a)



(b)

FIG. 15.--Determination of attenuation parameter K : (a) 40-db decoupler (K_1); (b) 40-db decoupler plus 16-db pad (K_2).

appear. The calorimeter was adjusted for even-flow rates by means of a precision flowmeter at 185 ml/min. At this flow rate, the temperature rise in the load branch was kept under 100°C in order to minimize conduction-heat losses. A heating element is employed in the comparison branch, and the temperature rise in the load branch is balanced by means of two thermistors and a Wheatstone bridge specifically built and calibrated for use with the calorimeter. From a knowledge of the power absorbed in the comparison branch at balance, the power absorbed in the water load is thus determined. In Fig. 16, the data are plotted for two sets of measurements, using K_1 and K_2 in the monitoring circuit.

5. CALORIMETER. The calorimeter (Fig. 17) is a nonadiabatic constant-flow device of conventional design. It consists of two identically built waveguide sections, to insure identical heat losses due to conduction. One branch absorbs microwave power and is called the absorption branch; the other branch is heated by means of an a-c heating element and is called the comparison branch.

Both branches incorporate a 2-mm ID, 20-cm-long Pyrex glass tubing that traverses the waveguide at a slope of 40°. A suitably tapered wedge is mounted under the glass tube in order to concentrate and distribute the E field, and thus attain higher absorption. At the outlet, two thermistors sample the temperature difference existing due to the microwave power absorbed on the one hand, and the a-c power on the other.

The electrical properties of the absorption branch are as follows: VSWR less than 1.02 from 9100 to 9500 Mc; peak breakdown power over 200 w (ave). These figures suggest an error of the order of 0.1 per cent due to reflection.

The water system consists of a main valve controlling the total flow, a tee branch separating the flows, and two needle valves controlling the flow in the two separate branches. On the outlet the water flows separately through two thermistor sections; the water from the absorption branch is passed over a 0-100°C thermometer. Both lines are separately led into a flow-meter bridge with a precision flow meter with a range of 1-200 ml/min. The thermistors are attached to a Wheatstone bridge sensitive to temperature differences of 0.01°C.

The heating element is energized by a low-voltage, high-current source in order to minimize hydrolysis of the water, which may occur in the a-c field. Line voltage is stepped down to 34 v, passed over a Variac, and led into the heating element through the precision a-c ammeter.

Operation of the calorimeter consists of adjusting the flow rate equally in both branches to a value that results in a temperature rise of less than 10°C in the absorption branch. The current is then adjusted in the comparison branch until the thermistor bridge is balanced. The current is noted, and from the resistance of the heating element, the power introduced in the comparison branch is determined. Since

$$Q_{01} = Q_{11} + dQ_1$$

$$Q_{02} = Q_{12} + dQ_2$$

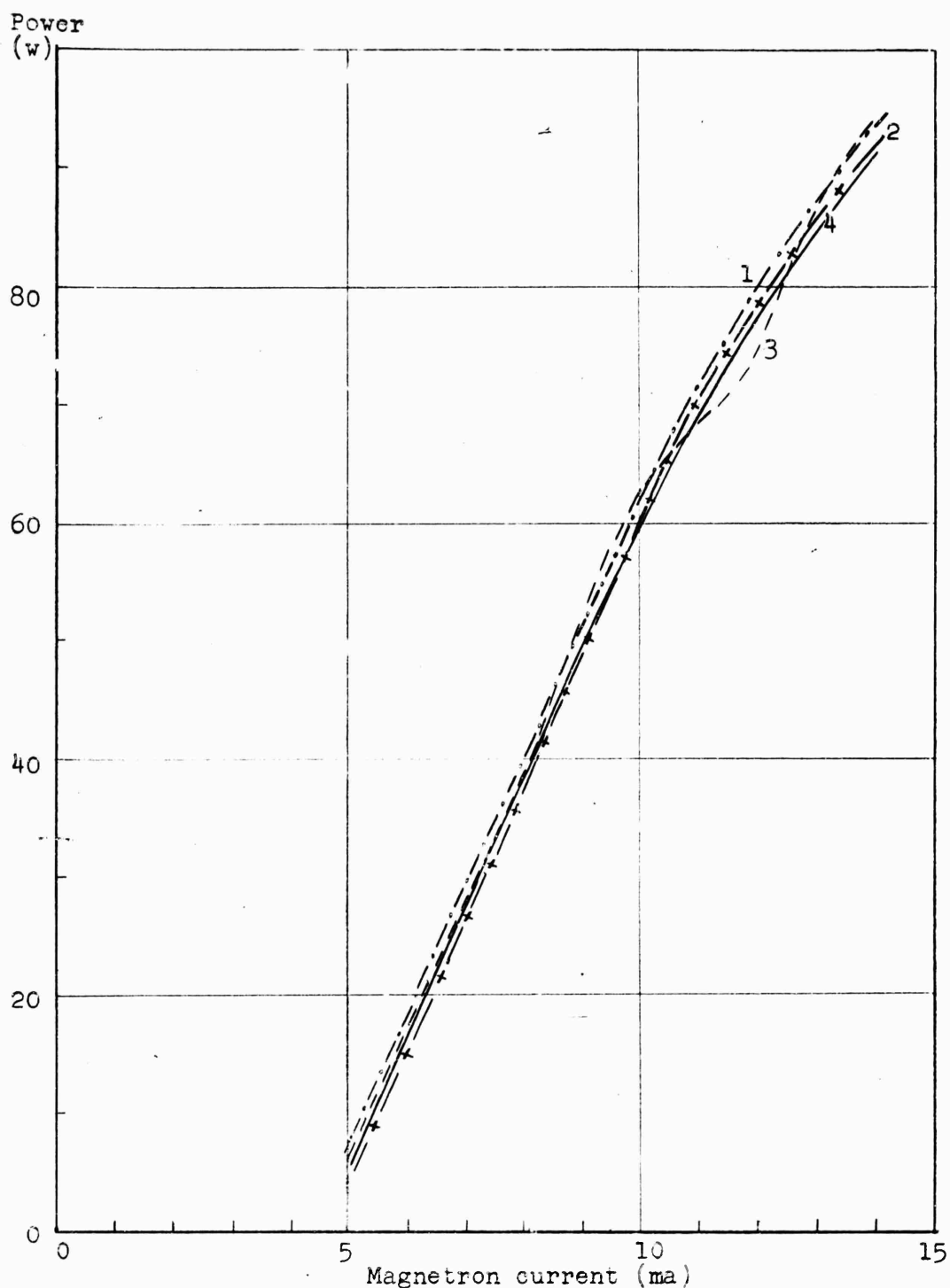


FIG. 16.--Comparison of measurements made by several methods. (1) HP readings with 00-db decoupler, 10-mw scale; (2) corresponding calorimeter readings; (3) HP reading with additional 16-db pad; (4) corresponding calorimeter reading.

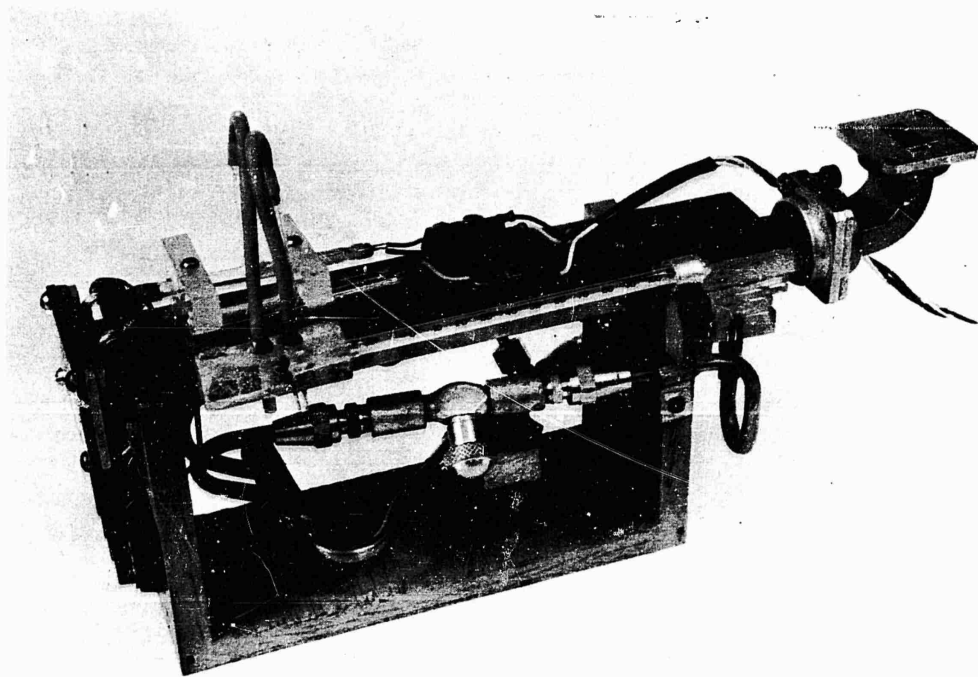


FIG. 17.--Calorimeter used in measuring total waveguide power.

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where subscripts 1 and 2 refer to comparison and absorption branches, respectively, and "o" and "i" to "out" and "in," respectively, we have

$$Q_{o1} = Q_{o2}$$

if $dQ_1 = dQ_2$; i.e., if the heat losses are equal.

The following sources of error are present.

(a) Flow Rate. An unbalance of 3 ml/min has negligible effect at flow rates above 150 ml/min; this is the average flow-rate error caused by water-pressure variations.

(b) Water. Tap water is used because no distilled water is available in the quantities and at pressures sufficient to operate the calorimeter.

(c) A-C Meter Accuracy. This is a calibrated a-c meter and accuracy is no better than the lowest readable scale unit, or 1 per cent.

(d) Resistance Wire. Resistance was determined by means of an impedance bridge accurate to within 5×10^{-4} ohm. Conduction of tap water along the surface of the heating element was found to be constant over a range of temperature of 10°C . Temperature coefficient of the wire immersed in the water was found to vary only slightly from the tabulated temperature coefficient and the variation is negligible for temperature differences up to 10°C .

6. CONCLUSIONS. A frequency shift of 7 Mc for the power range seems normal. Concerning the power level, the curve can be extrapolated, since it apparently approaches 1 db asymptotically above the 0-db reference. This measurement implies a maximum power output of 186 w (ave). Maximum attainable power is about 163 w at 25 ma of magnetron current, because of the difficulty of operating at full power (voltage breakdown in the equipment). As for the measurement of K , the measured 0.5-db change for K_1 over 7 Mc does appear to be rather high. For K_2 , the variation over the same frequency shift is 0.6 db.

The power comparison between monitor and calorimeter is expressed in terms of percentage error in Fig. 18. It must be noted that the monitor thermistor pickup drifts appreciably on the 0.1-mw range (K_2), although it provides more convenient scale readings for levels up to 10 ma of magnetron current. It is noteworthy that the difference is less or equal to a 5-percent error, which is the error specified by the manufacturer for the thermistor-power meter combination.

Investigation of the curves in Fig. 18 reveals that taking $K_1 = 1.85 \times 10^4$ and $K_2 = 6.0 \times 10^5$ gives sufficiently close results; rather than using K as a function of magnetron current, or taking average values from Fig. 15, the average values are obtained from the error curve of Fig. 18. It is suggested that for the 0.1-mw range on the power meter, K_2 should be used up to a magnetron current of 10 ma, and K_1 should be used above magnetron currents of 10 ma for the 10-mw range on the power meter. Under these condition, an error of 5 per cent is a safe assumption.

Percentage
error

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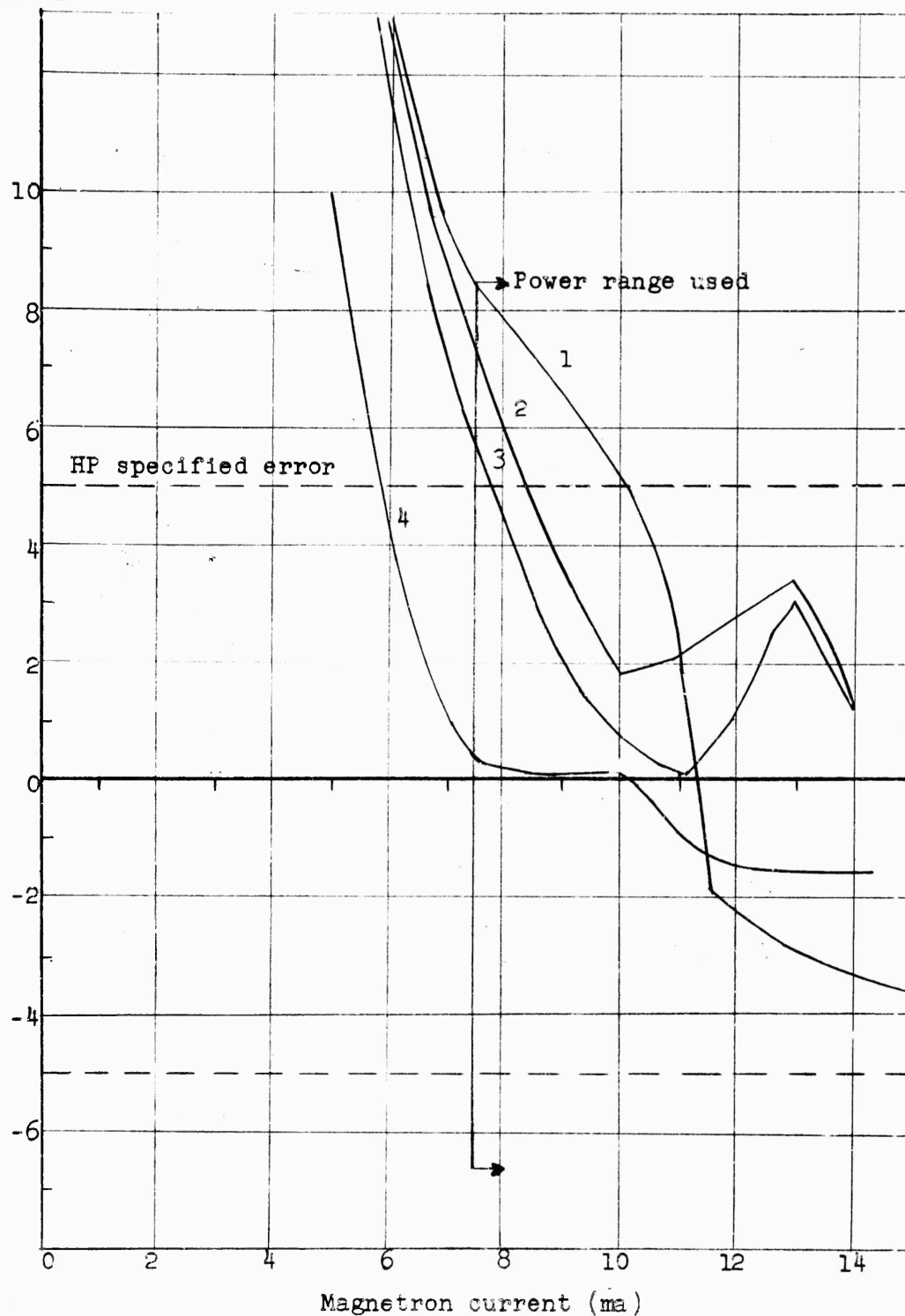


FIG. 18.--Error in power readings due to attenuation and thermistor drift, based on calorimeter. (1) 0.1-mw range; (2) 10-mw range; (3) error for $K_1 = 1.85 \times 10^4$; (4) for $K_2 = 6 \times 10^5$.

D. DOSIMETRY

Microwave radiation monitors and dosimeters may take a variety of forms. Antenna pickups may be frequency-sensitive or not, and may be large or small. Output indicators may be meters, lights, or sounds.

A design that may prove to be immediately useful for a personnel safety indicator, as proposed at this Laboratory, would use an oscillator tone indicator. The antenna is arranged to provide the d-c voltage to power a transistor oscillator that sounds an audible note at a predetermined level of radiation. No batteries or other power sources would be needed.

As a specific embodiment, a simple compact transistor oscillator circuit has been considered, one version of which would have only four very small components, as shown in Fig. 19. D-c input is from an antenna unit containing several elements spaced approximately half a wavelength apart, and output is to a 1.5-in. speaker.

The complete device would fit conveniently into a shirt pocket, thus making its constant use by personnel more likely than if some more cumbersome equipment were provided.

It is proposed that a more sophisticated version should be developed in very compact form for measuring radiation at dangerous levels. Such an instrument might perhaps have meter indicators to enable monitoring personnel to assess the intensity levels with respect to danger and also to determine the amount of improvement attained by actions taken to reduce undesirable radiation fields in work areas.

A model radiation monitor such as that described in Fig. 19 has been constructed and work is in progress to determine the most compact antenna arrangement that would still provide a sufficient amount of d-c power to actuate the oscillator at the desired level.

The calibration of a radiation monitor in such a way as to make dosimetry possible would have to take integrated time into account, in a manner that still remains to be determined. In addition, the effective radar cross-section of a man at each frequency must be considered, possibly utilizing recently published data on this subject.⁴⁷

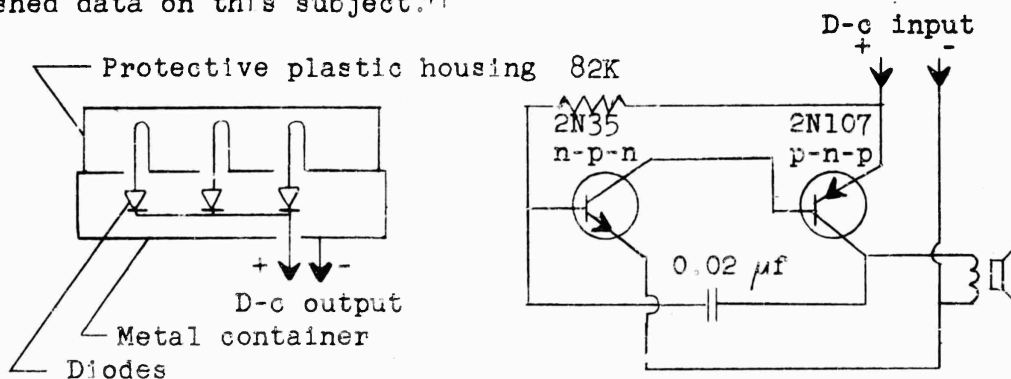


FIG. 19.- Simple version of transistor-oscillator circuit used as an audio radiation monitor.

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