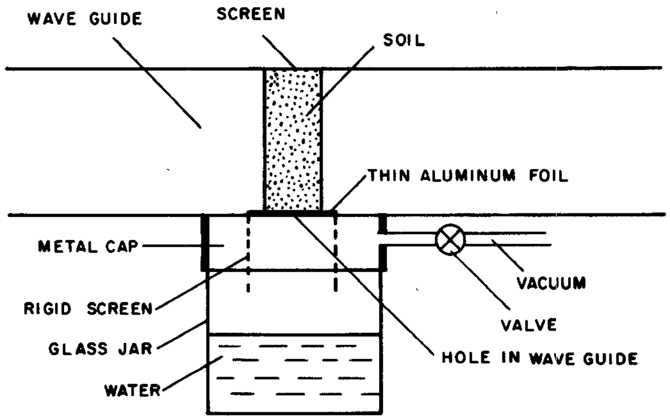

Fig. 9. System for rapid cooling of soil after irradiation.

into the cold water, dispersed, and cooled quickly. Any differences in temperature in the post exist for such a short time that they are negligible.

Conclusion

A microwave irradiation chamber has been developed in which homogeneous agricultural materials with simple geometries can be heated uniformly in a controlled manner. The conditions under which this can be achieved are discussed. In addition, experimental verification of the theory is presented. The chamber can be used to quantify causal relationships between microwave radiation and its effects.

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A Multiple-Animal Array for Equal Power Density Microwave Irradiation

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Abstract—**The introduction of multiple subjects into a microwave field invariably results in perturbations and interference patterns which make it difficult to accurately determine power densities at any specified location. To overcome this problem, investigators have restricted the number of subjects, which is inefficient, or used techniques to illuminate large volumes, which still results in large variations in power density due to curvature of the microwave field. An exposure array has been devised that negates these disadvantages and enables simultaneous irradiations of multiple animals at uniform average power density (±5 percent). The array consists of microwave transparent cages positioned in accordance with the natural characteristics of the microwave field and separated sufficiently to insure minimum interaction between animals due to microwave reflection. The results of testing the array in an anechoic chamber at a frequency of 2450 MHz using an isotropic field probe are presented.**

I. Introduction

Microwave research on biological subjects has in the past experienced problems in irradiating significant numbers of animals with a uniform power density electromagnetic field. The problem of generating such a uniform field has led some investigators to develop new techniques for producing microwave exposure systems which can irradiate large volumes using parabolic reflectors and a minimum of anechoic material [1]. While such techniques are certainly useful in increasing the area over which power density can be maintained to within a ±3-dB variation, they cannot help to reduce the perturbations which are created in the field by the introduction of biological subjects, which are capable of scattering in random directions large percentages of the microwave energy incident upon them. The interference patterns created by such scattering have been reported [2]. These interference patterns have made it impossible to predict with accuracy the exact power density at any particular location within a closely-spaced multiple-animal array. In addition, many exposure facilities which do not utilize techniques for broadening the uniform field as described previously have been constructed and are in use. The cage arrays used in multiple-animal exposures have typically been of the "checkerboard" variety, with closely adjacent cubicals of Styrofoam lined up compactly in a plane perpendicular to the axis of the transmitting antenna. Such an exposure facility allows significant variation in the power density incident on the animals, due to some animals being off the axis of the transmitting antenna, and to the interference patterns set up by scattering from the animals themselves.

In the past, the aforementioned techniques have been adequate in determining the gross effects of microwave exposure on biological subjects. The necessity today, however, is not to be certain of the incident power density to within a few decibels,

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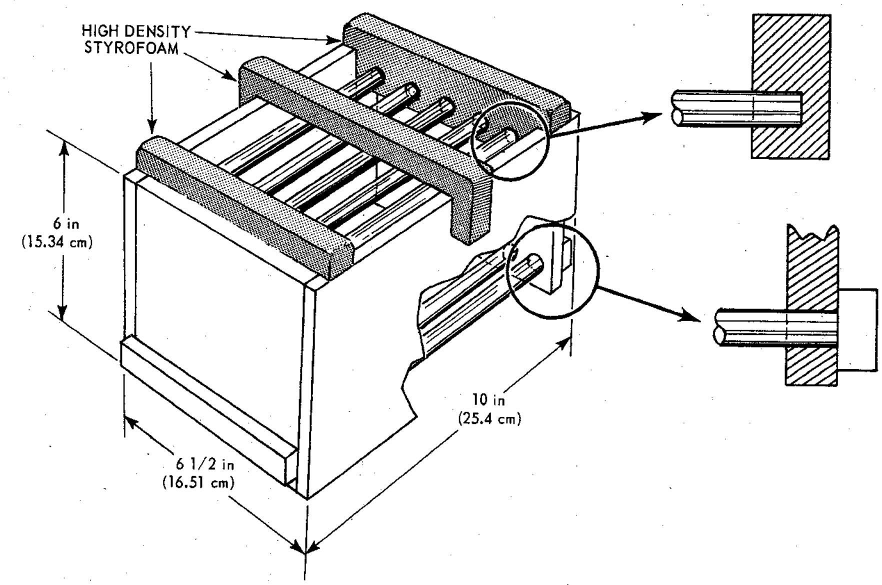

Fig. 1. Styrofoam and Plexiglas cage.

but to be certain to within a few percent. A facility which insures equal average power density at all exposure locations to within ±5 percent has been developed.

II. Theory

An ideal exposure situation for multiple-animal experiments would be for each animal to be exposed to equal power density from a uniform plane wave field. Practical considerations, such as the size of the available anechoic chamber, and the necessity of spacing the animals close enough to allow a statistically significant number of animals to be exposed which permits scattering from the animals to destroy the plane wave nature of the field, usually make the ideal exposure situation impractical. However, if each animal could be located on the equal power density locus of the antenna used in the experiment, and a small enough number of animals were used to allow reasonable separation between animals, then, while none of the animals would be receiving a true plane wave exposure, at least all of the animals would be receiving the same exposure with minimal perturbations.

For any antenna transmitting along an axis in the x direction, power density at a point P is given by

$$W = \frac{\alpha G P_T}{4\pi x^2} \tag{1}$$

where

- W power density at P;
- G antenna gain;
- P_T transmitted power;
- x distance to P projected along the axis of transmission;
- α relative power density, i.e., the ratio of power density at P to the power density on the axis of x.

On the axis of transmission, $\alpha = 1$. Thus, for a given power density on the axis at a distance x_0, with G and P_T fixed,

$$\alpha = \left(\frac{x}{x_0}\right)^2 \tag{2}$$

and the reductions in off-axis power density necessary to obtain the equal power density locus at various distances x, where $x \leq x_0$, are determined.

A typical antenna used for biological irradiation is the standard gain horn [3]. The universal radiation patterns in the far field of horns flared in both the E and H planes have been calculated [4], [5]. From these patterns, reductions in relative power density at any point relative to power density on the axis may be found to be functions of the angle to the point from the axis of transmission. Equations (1) and (2) thus enable the equal power density locus in a given plane to be determined by simple trigonometry.

III. Facility Design

A. Cages

A Styrofoam and Plexiglas cage was developed (Fig. 1) [6]. Although the relatively nonperturbating characteristics of Styrofoam are known, and since the cages were coated with quinine to prevent the escape of rats during long-term chronic exposures, it was decided to test the cages for microwave transparency after coating. The cages were tested using the facilities of the Electromagnetic Branch, Bureau of Radiological Health, Rockville, MD, utilizing a miniature isotropic probe [7] developed by personnel of the Bureau of Radiological Health. The facilities consisted of a small anechoic chamber and an S-band truncated pyramidal horn with 10-dB gain (Scientific-Atlanta, Atlanta, GA, 30324; Model 23-1.7/8). The microwave energy was generated from a crystal controlled oscillator at a frequency of 2450 MHz driving a traveling-wave tube amplifier with a power leveling loop directed to the antenna by coaxial cable. The cages were tested by moving the probe toward and through the walls of the cage, through small (1 cm) holes in the sides of the cage, or through the bars, depending on the orientation of the cage. The cages were tested in three orientations: with the plastic bars perpendicular to the axis of transmission and perpendicular to the E field; with the bars parallel to the axis of transmission and perpendicular to the E field; and with the bars parallel to the E field. The probe was mounted with the central dipole parallel to the E field, and the readings from all three dipoles were summed. The tests showed typical perturbation of 0–0.65 dB, depending on orientation. Typical examples are shown in Fig. 2. The probe was mounted on a motor-driven slide assembly suitably covered with microwave absorbing material and inserted from the side, perpendicular to the axis of transmission.

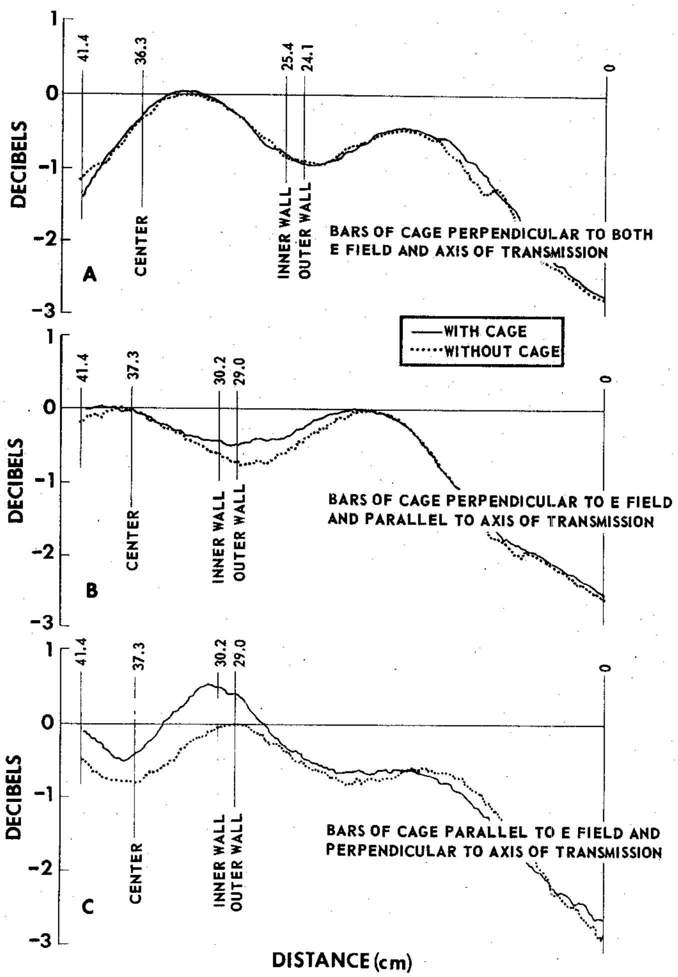

Fig. 2. Power density variations due to cages in field.

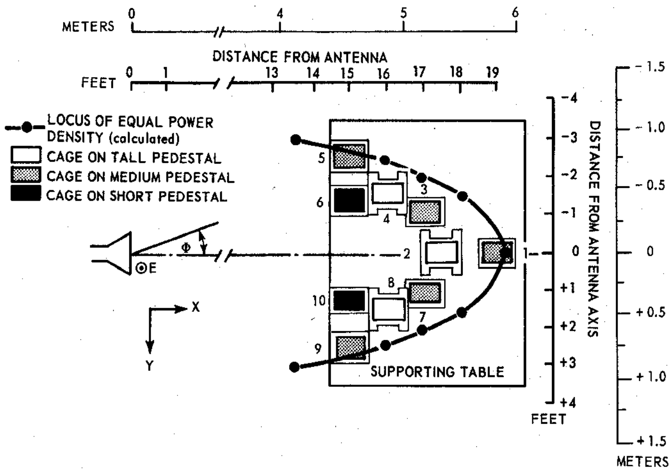

Fig. 3. Locus of equal power density in the H plane through the axis of the transmitting antenna.

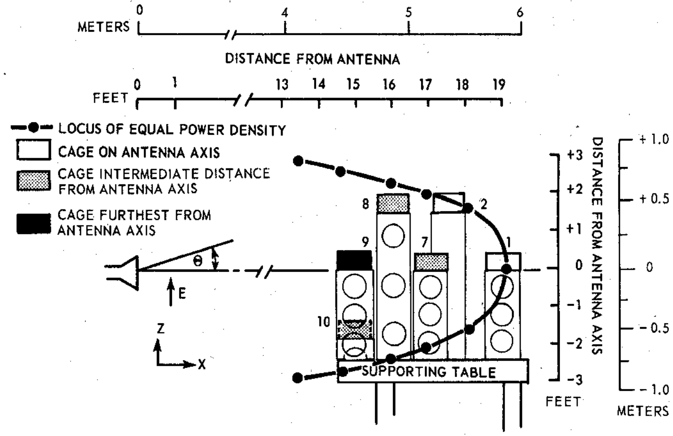

Fig. 4. Locus of equal power density in the E plane through the axis of the transmitting antenna.

B. Cage Positioning

The array was developed for use in an anechoic chamber located at the Walter Reed Army Institute of Research, Department of Microwave Research, Silver Spring, MD. The size of the chamber was 37 × 13 × 15 ft (11.27 × 3.96 × 4.57 m). The distance to the center of a cage to be located on the axis of transmission was chosen to be 19 ft (5.79 m) based on the necessity of keeping all the cages in the far field of the antenna and on the physical arrangement and size of the anechoic chamber. Using this distance, (1) and (2), as previously described, and the universal radiation patterns for the pyramidal standard gain horn (Scientific-Atlanta Model 12-1.7) at a frequency of 2450 MHz, the equal power density locus for both E and H planes was calculated (Figs. 3 and 4). The two curves formed by these calculations represent two orthogonal slices through the axis of a three-dimensional figure, somewhat resembling a paraboloid. Cages positioned so as to intersect the surface of the paraboloidlike figure are therefore on the equal power density locus.

C. Cage Separation

The farther the cages are separated, the less effect scattering from the animals will have on the power density at the location of other animals. However, statistical considerations in biological experiments indicate that the number of animals irradiated should be as large as possible. Thus cage separation must be a compromise between the physical size of the anechoic chamber and the number of animals to be irradiated. From statistical considerations it was decided that the minimum acceptable number of animals for the desired experiment would be 10; therefore, based on the shape of the equal power density locus and the size of the quiet zone in the chamber, a minimum acceptable lateral separation of 1 ft between outside walls of the cages was chosen.

D. Cage Locations

Based on the calculated equal power density locus and a minimum lateral separation of 1 ft, pedestals of Styrofoam were constructed to elevate the cages to intersect the equal power density locus, and the cage locations shown in Figs. 3 and 4 were determined. The cages in the figures are numbered for reference purposes.

IV. Results

With all cages and pedestals placed in position on a Styrofoam table inside the anechoic chamber at the Walter Reed Army Institute of Research, the power density in the center of cages 1–6 was measured using the miniature isotropic probe developed by the Bureau of Radiological Health. The power density in the other cages was not measured since they are symmetrically located, and physical access from the walkway of the anechoic

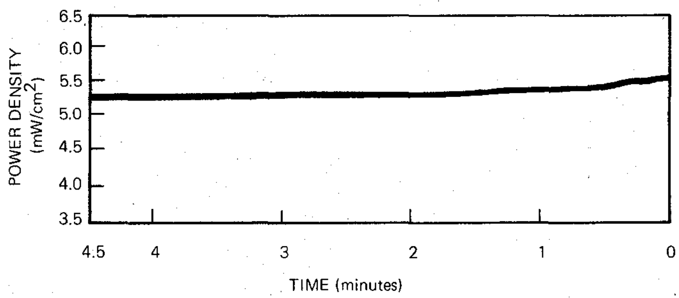

Fig. 5. Power density in cage 1 with all other cages empty.

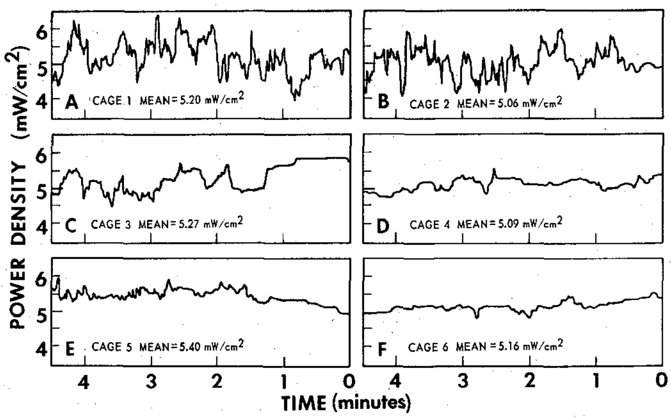

Fig. 6. Power density in given cage with rats in all other cages.

chamber was difficult. Microwave energy was generated from a klystron tube driven at a frequency of 2450 MHz and directed to the *S*-band standard gain pyramidal horn antenna by waveguides and coaxial cable. The positions of various cages were slightly adjusted to ensure that the power density in the center of each cage was exactly the same (5.3 mW/cm) with the center dipole of the probe oriented parallel to the *E*-field vector. The readings from the three dipoles were summed. The cages were oriented with the bars parallel to the axis of transmission of the horn, i.e., perpendicular to the *E*-field vector. With no animals in the cages, the power density in each cage when the power was turned on varied as shown in Fig. 5. The power density was recorded using a strip chart recorder (Bausch and Lomb; Model VOM-7) for 10 min. The probe was then placed in cage 1 and 200-g Sprague–Dawley rats placed in all other cages, the power turned on and a 10-min recording made of the power density. This procedure was repeated sequentially for cages 2–6. Fig. 6 shows the results of recording the power densities in the center of cages 1–6.

V. Discussion and Conclusion

As may be seen in Fig. 6, the power density in the cages farthest from the antenna may vary by as much as ± 23 percent from the average value in those cages due to scattering from the moving rats in other cages closer to the antenna. The cages located closer to the antenna were correspondingly less perturbed. However, the average value in any cage varied by no more than ± 5 percent from the composite average of all cages. The phase differences between cages were not considered as the size of the cages was greater than 1 wavelength in all dimensions. The animals, being free to move, would thus be exposed to the field in many different phases, depending on their location in the cage

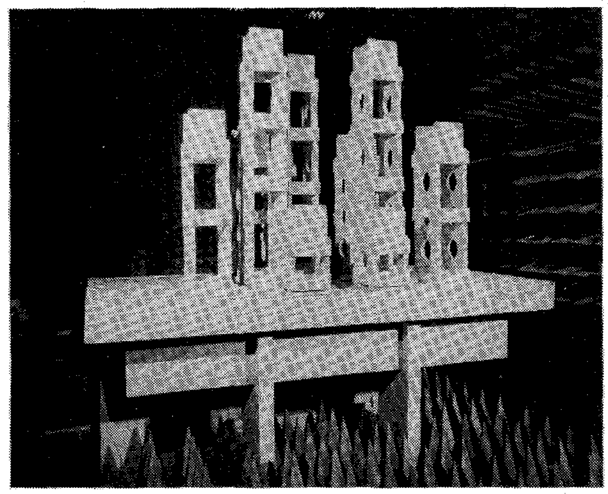

Fig. 7. Multiple-animal array for equal power density microwave irradiation.

at that time. The array is located in the far field of the antenna, the closest cage being 4.5 m from the antenna. Although it is obvious that none of the animals exposed would be in the ideal situation of being in the far field of a perfect plane wave, it is felt that all animals exposed in a given experiment would receive equal exposure at a given average power density. The differences in perturbations between cages closest to the antenna and those farther to the rear may be compensated for by rotating the animals through all cages on a day-to-day basis. The array described (Fig. 7) provides significant advantages to many of the exposure facilities for multiple-animal exposure currently in use by providing equal average power density exposures to multiple animals to within ± 5 percent.

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