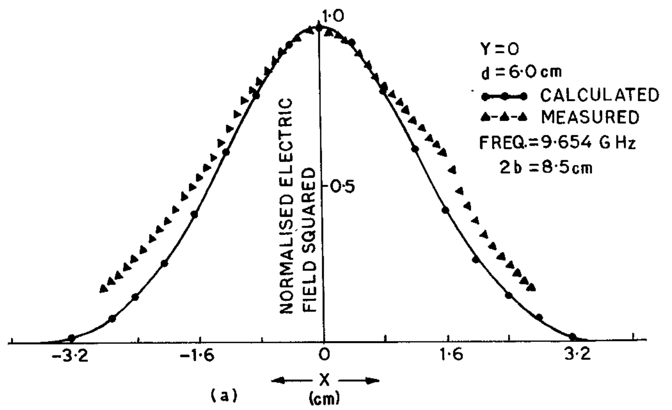

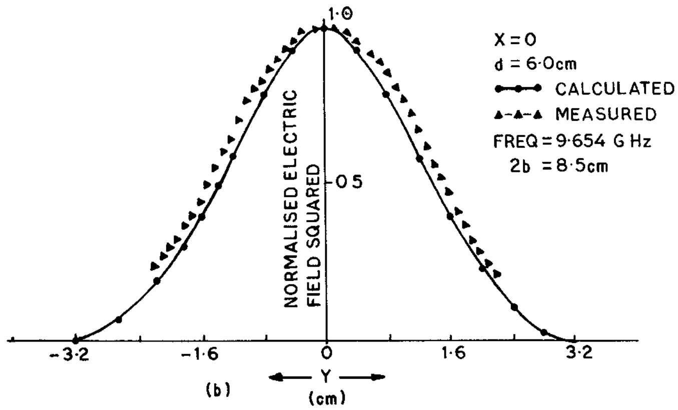

Fig. 3. Comparison of calculated and measured normalized electric field squared in a XY plane, 6 cm behind the dielectric sphere of the test launcher. (a) Along the direction of the incident electric-field vector. (b) Along the direction of the incident magnetic-field vector.

However, the enhancement of the focusing factor for a given sphere diameter to wavelength ratio can be achieved by decreasing the edge taper of the field distribution at the aperture of the scalar horn. A method to control this edge taper by means of changing the scalar-horn dimensions has been discussed in [7]. 3) Lastly, the effect of the dielectric constant of the sphere on the performance of the launcher can be considered. For the system shown in Fig. 1, the paraxial focal length is given by [8]

$$f_L = \frac{b}{2}\frac{\sqrt{\varepsilon_r}}{\sqrt{\varepsilon_r} - 1}. \tag{7}$$

Therefore, for the value of ε_r in the range of from 1 to 4, the focal point where the maximum intensity occurs will always lie outside the sphere. As against this, the selection of sphere diameter is rather critical with the plane-wave irradiation, in order to get the focal point outside the sphere [1].

In the present method, to obtain the focal length as given by (7), the sphere-illuminating aperture should be kept offset at a distance given by

$$s_0 = (f_L - b). \tag{8}$$

However, s_0 is usually selected on the basis of minimum input VSWR, as indicated before [2], [3]. Hence the resulting noncoincidence of the selected value for s_0, with the value given by $(f_L - b)$, causes a defocusing error and axially displaces the focal point in the image zone. But for a given launcher, a compromise between the minimum input VSWR and the defocusing error can be arrived at to get an optimum value for s_0.

Thus the present investigation indicates that by proper choice of the sphere diameter to wavelength ratio and the scalar horn dimensions, a specified Gaussian beam can be produced for localized exposure of biological subjects. A suitable dielectric material can be selected (with $1 \leq \varepsilon_r \leq 4$) for the spherical lens, so that the focal point is at a convenient location outside the sphere. The polystyrene-foam support ($\varepsilon_r \simeq 1$), which holds the sphere in front of the scalar horn, does not interfere with the launcher performances to a significant extent.

Research efforts are being made to improve the focusing action of the present setup by partially covering the sphere with a metallic surface [9] and/or by providing a sphere-to-air dielectric matching [10]. Furthermore, a detailed theoretical study is being carried out to analyze the beam wave behind the lens, taking into account the perturbing effects of the biological test object.

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A Microwave Irradiation Chamber for Scientific Studies on Agricultural Products

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Abstract—**The design and testing of a chamber for uniform heating of objects with an intense microwave field is described. Methods for direct and inferred measurement of temperature in the microwave field during irradiation are discussed. A theoretical analysis was made to determine the range of electrical parameters for which heating will be uniform. This analysis was verified experimentally. Curves for determining the rate of energy absorption in cylindrical posts are given for a wide range of electrical parameters.**

Introduction

In recent years there have been many attempts to quantify the causal relations between the effects of high-intensity microwave irradiation and various measures of the radiation dosage. Effects have been reportedly correlated with the following quantities:

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electric field intensity, incident power density, and absorbed energy density. Probably the most significant measure of radiation dosage is the temperature distribution throughout the sample because thermally induced effects appear to be dominant.

Temperature probes which function during irradiation are difficult to design. Unless thermocouple wires are perpendicular to the electric field at all points, they will scatter the electromagnetic field and cause localized hot spots. Other temperature-sensing devices use lossy dielectrics which can absorb power directly from the irradiating field. Then, instead of responding to the temperature in its vicinity, at least part of its response will be due to the direct heating by the irradiation field. Recent work which describes efforts to develop a nonperturbing temperature probe has been reported [1], [2].

Another technique is to measure the temperature immediately following irradiation. The temperature distribution in the interior of a model or a biological subject can be recorded by a thermographic camera after irradiation [3]. This technique is especially valuable for subjects with complex shapes, though it cannot be used with live animals. A calorimeter can be used to measure the average temperature of objects immediately following irradiation with microwaves. This technique requires that the objects be removed rapidly from the chamber to the calorimeter. It is useful in the case of objects which are known to have a uniform temperature distribution.

One cannot always measure the most significant quantities when measuring radiation dosage. For experiments performed on complex biological systems, some measurements are inherently difficult, such as the measurement of absorbed energy density, or temperature profile, in living tissue. In these cases the measurement of incident power density is usually used for convenience. However, this measurement does not provide as much information as some other criteria [4]. Exposure chambers for this class of experiment are often designed to utilize either plane-wave radiation or the known field of a waveguide mode [5]–[8].

The discussion of this short paper will be limited to the case of irradiating relatively less complex agricultural material such as seeds and soil. In this case more quantitative experiments can be performed.

Exposure Chamber Requirements

The irradiation chamber for experiments designed to produce quantitative data of a more fundamental nature should have several important characteristics. It should be designed so that a meaningful measure of radiation dosage may be monitored. Its design should facilitate accurate measurements. It should be designed for a uniform distribution of absorbed energy throughout the irradiated material. One should note, however, that a uniform incident field does not ensure uniform absorbed energy density.

It was decided to use a section of waveguide as the irradiation chamber for several reasons. The absorbed energy density can be computed from the incident power density for waveguide obstacles with simple geometries and known electrical properties. This computation is useful for identifying the conditions under which the absorbed energy density is uniform. Uniform absorbed energy density will result in a uniform temperature increase in a homogeneous material when the exposure time is short enough that thermal conduction can be ignored. Secondly, a significant percentage of the incident power can be dissipated in the irradiated material. For most materials the waveguide irradiation system may be designed such that the material is the most absorbent part of the system. This results in an efficient transfer of energy to the material. Lastly, with a closed waveguide system, operator safety is a much less severe problem.

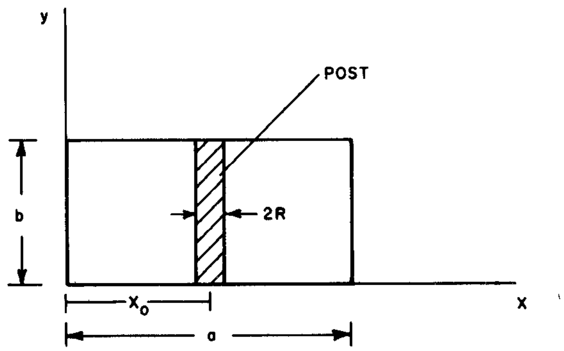

Fig. 1. Geometry of the waveguide and post.

In the following paragraphs the theoretical basis for the chamber is discussed. The conditions under which energy is uniformly absorbed throughout a cylindrical subject are determined. Following this, the exposure chamber which is being used by the authors is described, and experimental results are presented which confirm the theory.

The Exposure Chamber—Theory

The waveguide type of chamber has been used for irradiating enzymes, peas, and tree seeds [12]–[15]. In such cases care must be taken to ensure that the field inside the irradiated object is uniform. The case for irradiating a large number of small spherical objects is discussed by Schrader and Patel [12]. In this short paper the irradiated object is a circularly cylindrical post of radius r oriented parallel to the incident electric field (Fig. 1). To show the range of parameters for which energy absorption is nearly uniform throughout a lossy post, an approximate variational solution for this energy absorption is compared to that obtained by assuming that the unperturbed fields are present in the post.

The approximate analysis for dielectric post loading of a waveguide based on the variational technique has been available for some time [16], [17]. More recently, numerical solutions to the problem have been obtained by Nielsen [18] and Okamoto *et al.* [19]. For the present short paper, all computations were carried out using the variational solution reported by Schwinger [17].

It is well known that a waveguide with a single propagating mode can be represented as an equivalent transmission line with characteristic impedance Z_g. The voltage and current on the equivalent transmission line are related to the electric and magnetic fields in such a way that the power flowing through any waveguide cross section is $P_f = \frac{1}{2}\,\mathrm{Re}[V(z)I(z)^*]$. Discontinuities in the waveguide structure such as posts and windows may be represented as lumped-circuit loads on the transmission line. In particular, the T network shown in Fig. 2 can be shown to be an equivalent circuit for a dielectric post excited by a TE_{10} mode in a rectangular waveguide. It is assumed that the post is lossy and has a relative dielectric constant $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$, where $e^{j\omega t}$ time variation has been assumed.

Schwinger has published variational formulas for Z_1 and Z_2 derived under the assumption that the electric field is the same as the electric field in the absence of the post. These approximate formulas are accurate to within a few percent if $R/a < 0.15$ and $0.2 < x_0/a < 0.8$, provided neither Z_1 or Z_2 is near a resonance.

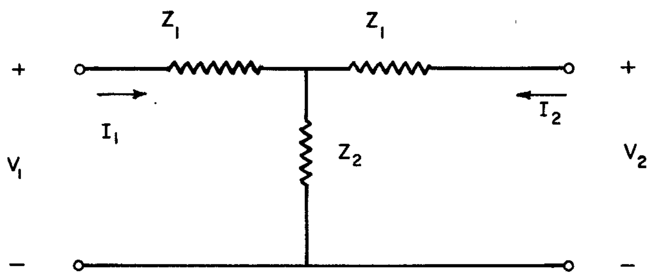

Fig. 2. Equivalent circuit for the lossy post.

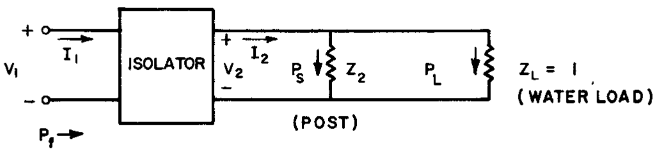

Fig. 3. Microwave system used to compute power dissipation.

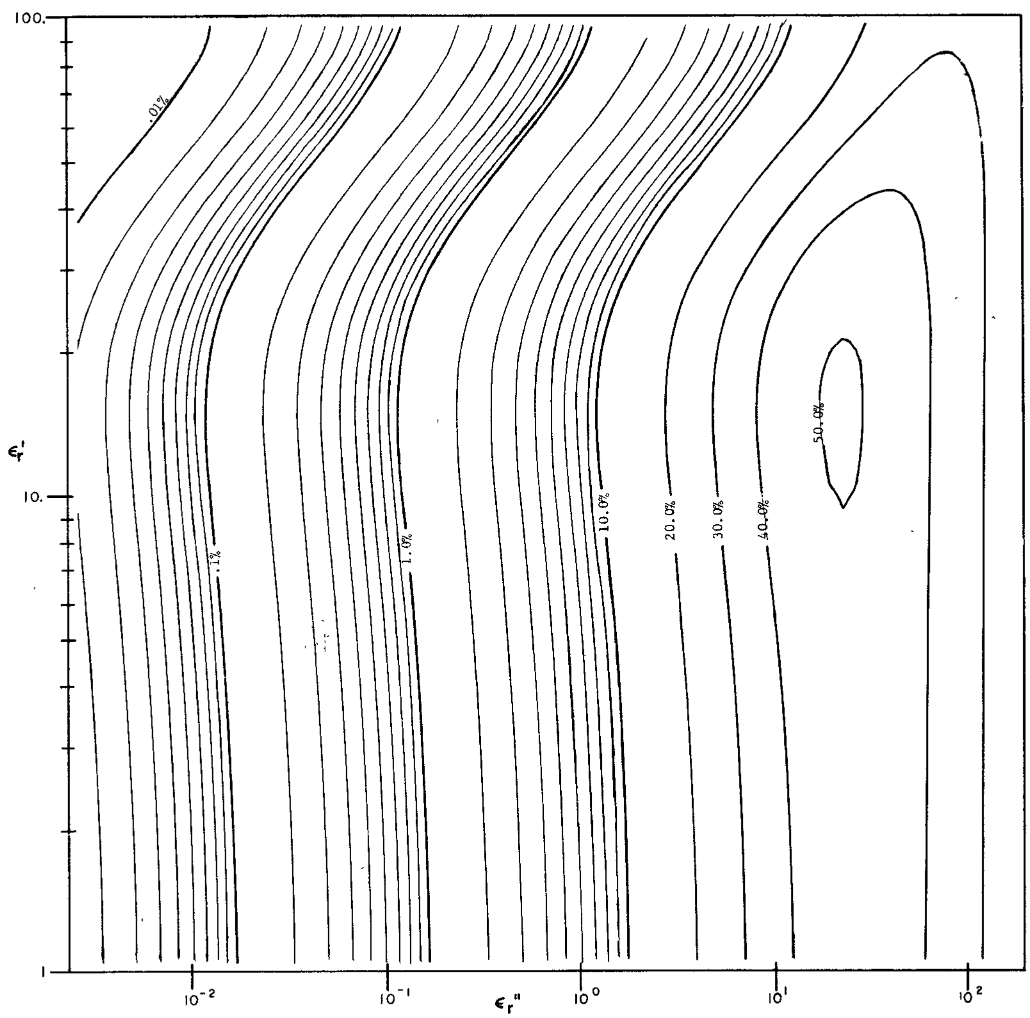

Fig. 4. Dependence of power absorption ratio P_s/P_f on ε_r' and ε_r'' in WR-975 for the conditions $f = 915$ MHz, $R = 1.0$ cm.

Values of Z_1 and Z_2 were computed for a wide range of dielectric constants for centered posts with several values of radii [20]. The range of dielectric constants used in this calculation covers the range of dielectric constants expected for agricultural material [21]. It can be concluded that Z_1 is small enough to be neglected and that the T network can be replaced by a single shunt element.

The rate of energy absorption in the post sample P_s depends upon the configuration of the microwave system. The ratio of P_s to the incident power P_f has been computed for a system equivalent to that used by the authors (Fig. 3), using the formula

$$P_s/P_f = \left|\frac{1 + \Gamma}{1 + Z_2}\right|^2 \operatorname{Re}(Z_2) \tag{1}$$

in which Z_2 is normalized to the guide impedance and where

$$\Gamma = \frac{1}{2Z_2 + 1}$$

and

$$P_f = \tfrac{1}{2} \operatorname{Re}(I_1^* V_1).$$

Figs. 4 and 5 are contour plots of the rate of energy dissipation in the sample as a fraction of the incident power for the system shown in Fig. 3.

It is of interest to examine the expression for rate of energy dissipation for a post of radius and dielectric constant satisfying the condition

$$\left(\frac{2\pi R \varepsilon_r^{1/2}}{\lambda}\right)^{1/2} \ll 1.$$

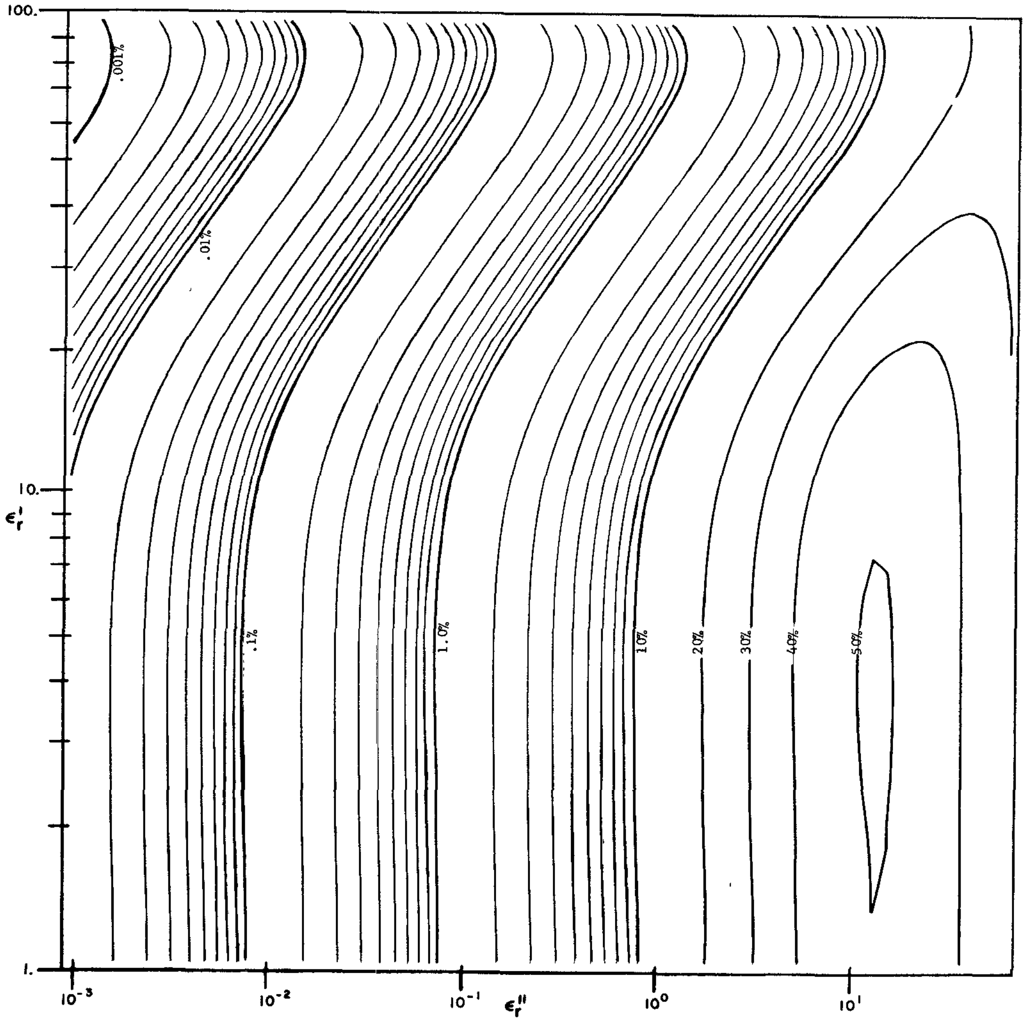

Fig. 5. Dependence of power absorption ratio P_s/P_f on ε_r' and ε_r'' in WR-284 for the conditions $f = 2450$ MHz, $R = 0.4$ cm.

Retaining only the dominant term of Z_2, an approximate expression for the rate of energy dissipation for the post can be shown to be

$$\frac{P_s}{P_f} \simeq \frac{(2\pi R)^2 \varepsilon_r''}{\lambda a(1 - (\lambda/2a)^2)^{1/2}} \tag{2}$$

where λ is the free-space wavelength. This expression can be obtained by assuming that the electric field inside the post is exactly what the field would be if the post were not there. This is a common approach to the problem and one whose validity is discussed in the next section.

For a 915-MHz signal in WR-975 waveguide ($a = 0.248$ m), (2) reduces to

$$\frac{P_s}{P_f} = 675 R^2 \varepsilon_r''. \tag{3}$$

A comparison with Fig. 4 indicates that (3) is accurate to within 10 percent over the range of values $\varepsilon_r' < 5$, $\varepsilon_r'' < 2$ for $R = 1$ cm. The range of validity will be wider for posts of smaller radius [20]

For a 2450-MHz signal in WR-284 waveguide ($a = 0.072$ m), (2) reduces to

$$\frac{P_s}{P_f} = 8450 R^2 \varepsilon_r''. \tag{4}$$

A comparison with Fig. 5 indicates that (4) is accurate to within 10 percent over the range of values $\varepsilon_r' < 8$, $\varepsilon_r'' < 2$ for a 0.4-cm radius post. Again the range will be larger for smaller post size.

It follows that the electric field inside the post is approximately the same as it would be in the absence of the post. Thus, for the centered post, the electric field inside is virtually uniform throughout the cross section. In addition, the electric field is uniform over the height of the post since the incident field is approximately TE_{10}. A uniform electric field inside a homogeneous post implies a uniform absorbed energy density.

If the post is exposed to microwave radiation for a time short compared to the thermal time constant of the material, the temperature rise of the post is the same at all points and can be computed to be

$$\frac{dT}{dt} = \frac{P_d}{\rho C} \ ^\circ\mathrm{C/s} \tag{5}$$

where

- P_d absorbed energy-rate density (W/m³);
- C heat capacity (J/kg/°C);
- ρ density of the sample (kg/m³).

The Exposure Chamber—Experiment

A 25-kW microwave source operating at 915 MHz was coupled to WR-975 waveguide and terminated in a water load. The material to be irradiated was formed into a post and placed in the center of the waveguide as shown in Fig. 6. The incident

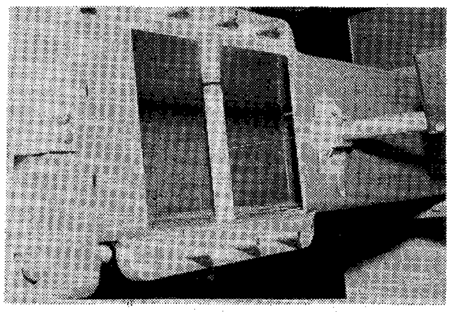

Fig. 6. The irradiation chamber.

power was determined (prior to inserting the post) by a calorimetric measurement at the water load in which the input and output water temperatures and water flow rate are measured. A small thermocouple (iron–constantan junction using 0.08-mm-diam wire) was inserted into the center of the post. In order to minimize the effect of the lead wires, they were placed perpendicularly to the electric field in the waveguide.

The samples used in the experimental verification of the theory were made from a block of plaster of Paris (57 parts water to 100 parts plaster of Paris by weight). Posts and test samples for dielectric constant and heat capacity measurements were machined from this block. The posts and test samples were oven dried at 105°C for 16 h and then were allowed to reabsorb water by exposure to room temperature and humidity. After this treatment the density of each piece was within 1 percent of the mean density. Thus the posts and the test samples could be assumed to have identical properties. Between their manufacture and use the pieces were sealed in a jar to prevent a significant change in the moisture content.

The dielectric constant of the plaster of Paris was measured by loading a section of General Radio 50-Ω rigid coaxial cable with plaster of Paris and measuring the admittance of the loaded line. A sample of plaster of Paris 13.9 cm in length was measured to have a dielectric constant $\varepsilon_r = 2.43 - j0.017$. The imaginary part of the dielectric constant may be 10 percent in error.

The heat capacity was measured using a calorimetric technique. A sample of known mass wrapped in a thin plastic wrap for waterproofing was cooled in a 0°C ice water bath for 12 h, a time sufficient to ensure a uniform interior temperature. The sample was then placed into a known mass of warm water at a known temperature. A quantity of heat was introduced into the water-sample mixture by immersing a precision resistor with a known current for a time sufficient to bring the sample to its original temperature. This technique was used to minimize the effect of the walls of the insulating bottle. The quantity of heat (Q) is related to the sample mass (M_s), heat capacity (C_s) and the water temperature (T_w) by

$$Q = M_s C_s T_w \tag{6}$$

from which the sample heat capacity can be measured. The measured heat capacity of the plaster of Paris samples was 0.164 ± 5 percent.

A 32.2-g post of 0.9-cm radius was placed in the waveguide and irradiated with 18 kW of incident power. Using (5), the rate of increase in temperature can be predicted to be 0.74 °C/s. The actual record of temperature in the center of the post is shown in Fig. 7. (The abrupt changes in thermocouple output at the beginning and ending of the irradiation are thought to be due to a rectification of the RF signal at the thermocouple junction.) The rate of increase is found from Fig. 7 to be 0.85 °C/s.

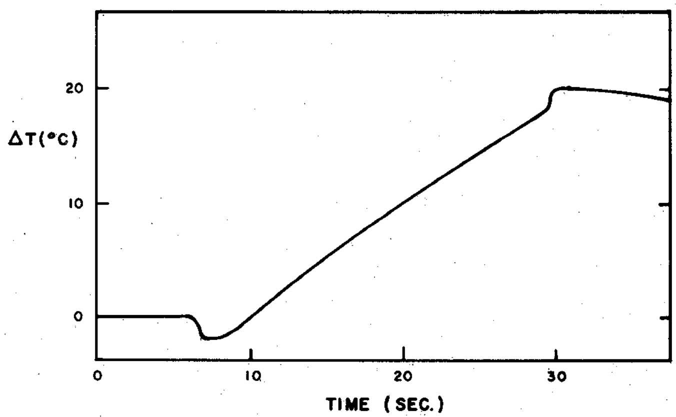

Fig. 7. Center temperature rise of plaster of Paris post due to microwave irradiation ($\varepsilon_r = 2.43 - j0.017$, $R = 0.9$ cm, $P_f = 18$ kW, $C = 0.164$ J/kg/°C).

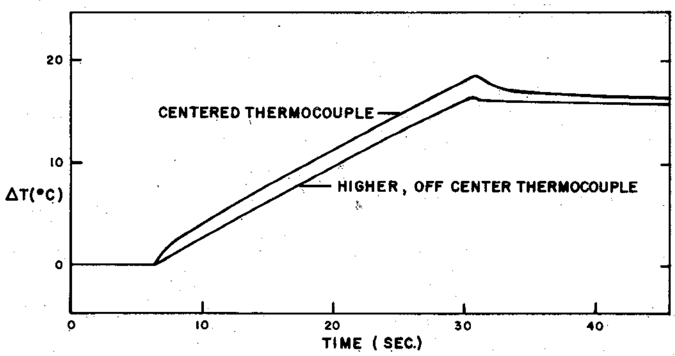

Fig. 8. Comparison of center and off-center temperature rise of plaster of Paris post due to microwave irradiation.

The error between the experimental value and the theoretical value based upon the assumption of uniform energy absorption in the post is smaller than the experimental error bound. This result supports the assumption that energy is absorbed uniformly in the post and that, as a result, the temperature rise is uniform. In order to further validate this assumption, a post with two imbedded thermocouples was placed in the center of the guide. Thermocouple 1 was located at the center of the post ($x = a/2$, $y = b/2$) as before (Fig. 1). Thermocouple 2 was located close to the surface and halfway to the top of the post ($x = a/2 + 2R/3$, $y = 3b/4$). Fig. 8 shows the result of this experiment. It can be seen that the two temperatures differ by less than 1°C out of a 16 °C rise. (The small overshoot on the center thermocouple is attributed to localized heating and was ignored.) This result further confirms the uniform heating assumption.

It is clear that if the post is allowed to cool naturally after irradiation, a nonuniform distribution of temperature will be established during the cooling period. This effect would violate the vital design criteria that the temperature distribution be uniform during the entire test period (until the sample returns to or below ambient temperature). Equipment may be designed to overcome this difficulty. An example is the system that has been designed to be used for irradiation tests on soils. In this system, shown schematically in Fig. 9, the soil is to be placed inside a cylindrical container constructed of lossless dielectric. A hole was machined in the waveguide below the soil and was covered by a thin piece of aluminum foil during irradiation. A pipe connected the hole to a jar of cold water and a vacuum chamber which was sealed during irradiation. Upon cessation of irradiation, the vacuum chamber was opened and the soil quickly drawn

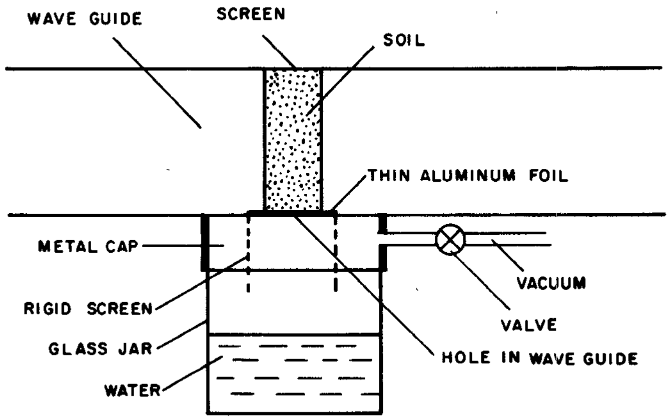

Fig. 9. System for rapid cooling of soil after irradiation.

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

STEPHEN A. OLIVA, MEMBER, IEEE AND
GEORGE N. CATRAVAS

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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