Microwave Meat Roasting*

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ABSTRACT

Investigation of microwave and conventional heating of cylindrically shaped beef roasts, excluding end heating effects, has led to a better understanding of the microwave and heat transfer phenomena involved. A computer program written to simulate microwave/conventional cooking of cylindrical meat roasts has demonstrated good agreement with limited experimental data. It was found that the cylindrical shape of roasts used in this work gave an advantage to the microwave frequency with deepest penetration, 915 MHz, in both cooking time and final temperature uniformity due to "focusing" of microwave energy at the roast central axis. Widely used 2450 MHz microwave power was shown to be notably inferior to 915 MHz for roasting beef cylinders with diameters greater than 6 cm. While no definite conclusion can be made concerning an optimum cooking method, methods using 300 W at 915 MHz, or the combination of 600 W at 915 MHz for the first 20 min and 300 W at 915 MHz thereafter appear to be superior.

INTRODUCTION

Roast beef is a major component of the U.S. Military man's diet. Since it is one of the most costly components and is frequently served, roast beef represents a substantial subsistence budget item.

Conventional roasting techniques used in military kitchens are based on conventional (natural convection) heating in thermostatically controlled ovens. The U.S. Army Recipe Service directs the use of a 163°C oven and cooking for two to four hours depending on the size of the roast and the desired degree of cooking. The quality and yield of the finished product depend on factors such as the geometry of the roast, its initial and final temperature, fat covering and degree of fat marbling, oven temperature, oven size, and, to a variable extent, the conscientiousness of the cook.

The objective of the research was to develop a more complete understanding of the roasting process in an effort to optimize the yield and quality of the finished product. The application of microwave energy alone or in combination with conventional heat sources was considered because of the possibility of reducing the cooking time, reducing roast temperature gradients, and providing closer control of the cooking process. This paper deals only with radial temperature variation at the roast center. Axial temperature variation, including end heating, is a very important consideration but was not within the scope of this preliminary work.

The literature on microwave roasting of beef has not been overly complimentary. In most instances, yield has been much lower for the microwave method (Marshall [15], Kylen et al. [11], Ruyack and Paul [21], Ream et al. [20]). Early research did not

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take into consideration the much higher post-oven temperature rise associated with microwave roasting and so roasts were often overcooked as compared to controls. When adjustments were made for this effect much better yields were reported. This problem was related in part to the fixed power level of most microwave ovens, applying power at a rate so much greater than the rate of heat conduction in the roast that a body of heat was built up about 2 cm below the surface of the roast. Decareau [4] suggested that beef roasts cooked in a microwave oven be removed from the oven at an internal temperature substantially less than usually recommended for a rare-done condition. The temperature will then equilibrate by thermal conduction to complete the cooking process as shown in Figure 1. The temperature at the surface of the roast is typically lower than the temperature at the 2 cm depth because of evaporative cooling and the low ambient temperature condition of the microwave oven.

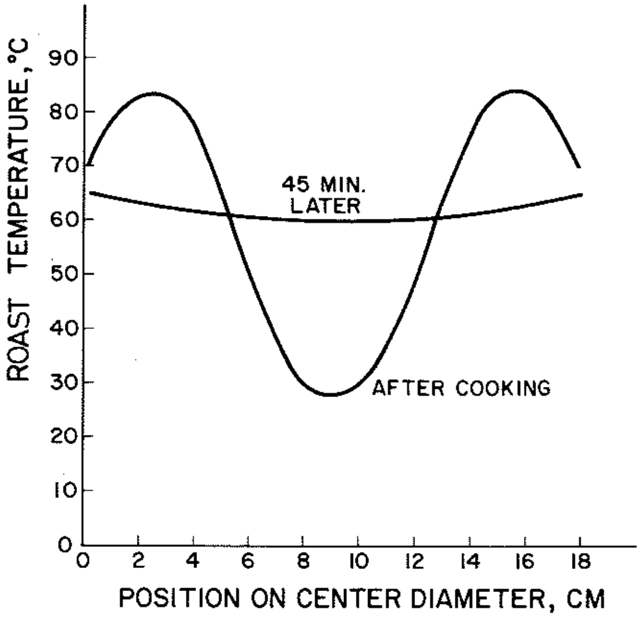


Figure 1 Temperature pattern in beef roast (from Decareau [4]).

Previous research on tenderness and yield aspects of meat cooking has provided detailed temperature-based information on phenomena such as protein denaturation, collagen shrinkage, etc., which directly affect both tenderness and yield. Machlik and Draudt [14]measured the dependence of Warner-Bratzler shear values of beef on temperature and pointed out that a marked decrease in shear occurs between 50 and 60°C, and an increase between 60 and 70°C. Laakkonen et al. [12] summarized meat heating by stating that the final temperature of the meat has a critical influence on weight loss and tenderness. They stated that heating to the collagen shrink point, 60°C, will provide a major increase in tenderness without a large weight loss. Lawrie [13] stated that as meat is heated, its water holding capacity (WHC) decreases due to protein denaturation. According to Paul and Palmer [19], this denaturation process frees previously bound water, which is lost from the meat at a rate dependent upon the rate of temperature rise and the internal temperature to which the meat is heated.

This work was directed toward finding means of determining and modifying the temperature profile within the roast. Ideally, then, the meat temperature profile could be tailored to optimum values suggested in the literature. A computer program was developed which computed the meat temperature profile under any cooking condition, greatly simplifying the search for the optimum cooking method.

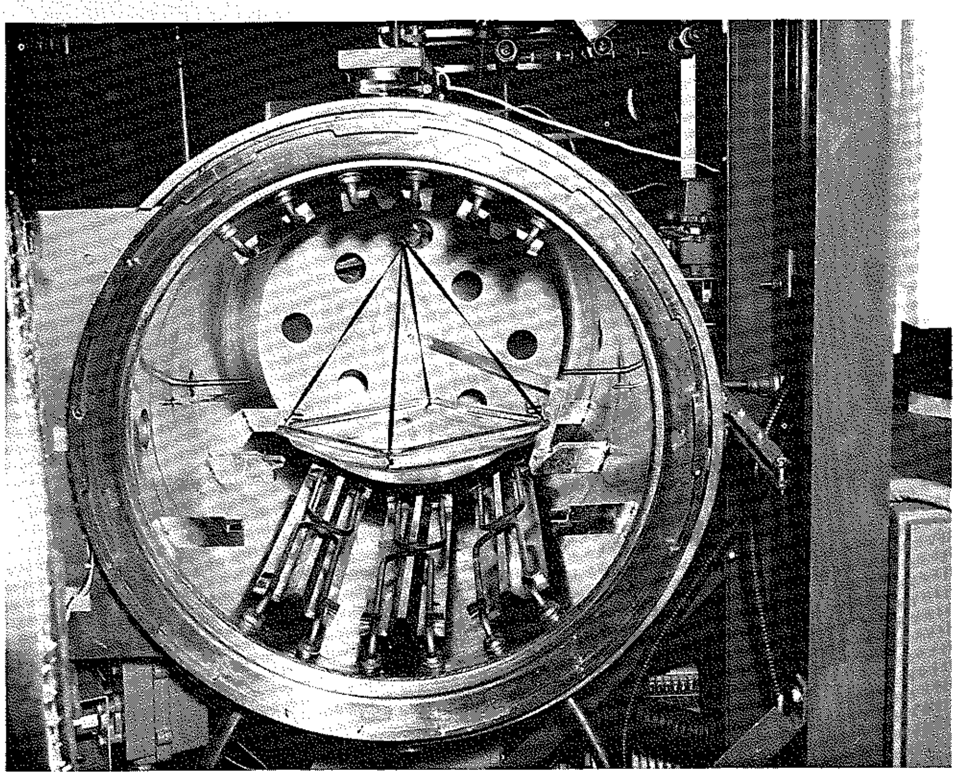


Figure 2 Cavity of multi-energy-source oven.

COOKING APPARATUS

Cooking studies were carried out in the equipment[1] shown in Figure 2. The oven cavity has a diameter of 58.4 cm and a length of 94 cm. Its multi-energy capabilities include microwave power at two frequencies, steam, and radiant heat, with specific capabilities as follows: 0-1 kW at 915 MHz, 0-2 kW at 2450 MHz; steam pressure at 34.5, 68.9, 103.4 kPa (5, 10, and 15 psi); oven temperature settings of 93.3, 121.1, 148.9, 176.7, 204.4, and 232.2°C (200, 250, 300, 350, 400 and 450°F). These energy sources can be applied singularly or simultaneously in any combination in a manual or automatic mode. Automatic operation is achieved by a single prepunched computer card inserted into a card reader, which automatically switches on machine functions as coded on the card. When used for conventional roasting in this research, the oven was not pressure tight and only natural convection occurred. A group of six heating elements is located both at the top and bottom of the oven interior, and each element has an individual control. Strap heaters located behind the inner oven walls are used to provide quick oven wall heat-up and therefore fast oven temperature response. The oven is thermostatically controlled with cycling error of ± 5°C about the setpoint. Other features include a vent system to evacuate steam from the cavity, a mode stirrer, and microwave shielded glass viewing port.

MEASUREMENTS AND PROCEDURES

Top rounds of beef, approximately 8 to 10 kilograms, were trimmed, cut in half, and cooled to a tempered condition of −2°C throughout. In his tempered state, the

1 Product of Raytheon company, Waltham, Ma. 02154.

beef was partially frozen and readily cut or formed. The top round halves were formed to an 12.7 cm square cross-section in a meat-forming press[2] operated at 4.14 MPa (600 psi) pressure. The roasts were then frozen, and when needed, were allowed to thaw at 5°C for approximately 72 hours. Prior to cooking, the roasts were trimmed to approximate a circular cross-section and tied with string to aid in holding a cylindrical shape during cooking.

Evaporative cooling on the roast surface during cooking is substantial, as shown by Schoman [22] and Shoemaker et al. [23], and is of the same order of magnitude as drip loss. Evaporative losses from the roast surface were determined for conventional roasting by an arrangement in which the roast was placed on a Pyrex platter suspended from a scale mounted on the top of the oven. A teflon drain tube, attached to the platter extending through the bottom of the oven, permitted drip losses to be collected in a beaker on a balance outside the oven. Care was taken to insure that the drain tube was freely suspended in the oven. Roast weight measurements with an estimated accuracy of ± 5 g, and drippings weight measurements with an estimated accuracy of ± 2 g were possible with this apparatus.

Data taken to determine shrinkage consisted of eight measurements taken before and after cooking. Five equally spaced radial circumferences, two axial circumferences 90 degrees apart, and the overall length were recorded.

Temperature measurement techniques varied depending on the cooking method. Copper-constantan thermocouples sheathed in 1.6 mm diameter stainless steel tubes were used when cooking in heated air. These were inserted, when possible, on an axial isotherm to minimize errors due to disturbing the more important radial thermal gradient in the area of measurement. The exact position of the probe tip was determined by cutting the roast upon completion of cooking. The very small cross-sectional area of these probes also minimized probe-related conduction of heat to the roast interior.

Measurement of roast temperatures in a microwave field was more difficult, however. Metallic probes were found to concentrate the microwave field and cause overcooking and charring at the probe entrance to the meat, in addition to producing erratic readings at times. Watanabe et al. [27] achieved good results measuring temperatures in a microwave field by sheathing a metallic probe with a low loss dielectric. This minimized local overheating of the material in contact with the probe. However, the presence of a metallic probe in the meat, whether sheathed in a low loss dielectric or not, may still alter the microwave pattern. A technique similar to that of Johnson and Guy [10] was used to monitor the roast center temperature during the cooking process. A 4 mm outer diameter (OD) glass tube was inserted, sealed end first, to the proper depth in the roast prior to cooking, with the open end extending outside the oven. A 2 mm OD glass tube with a thermocouple anchored inside was inserted into the 4 mm tube. When a temperature reading was desired, the microwave power was switched off, the 2 mm tube was quickly inserted to the tip of the 4 mm tube, approximately 15 seconds allowed for thermal equilibration, the temperature recorded, the 2 mm tube withdrawn, and then the microwave power was restored. This procedure required 20 to 25 seconds which was an acceptable delay when readings were taken every 10 minutes.

When the roast reached the desired central temperature, it was removed from the oven, cut in half, and temperature profiles of the central cross-section were recorded with a specially constructed 13 point thermocouple jig.[3] This jig consisted of pointed

2 Model 70, Bettcher Press Co., Birmingham, Ohio.

3 A 24-channel Honeywell model 115 temperature recorder was used.

stainless steel tubes 2 cm long and 1.6 mm diameter spaced 1 cm apart on a jig, each tube having a 30 gage copper-constantan thermocouple at its tip.

A specially constructed glass trivet, made by joining semicircular glass rods on 5 cm centers, provided a microwave-tranparent cradle which held the roast in a cylindrical shape during the cooking period.

PROPERTY VARIATIONS

Values of the specific heat of raw beef with 74% moisture content are 0.82 cal/gr°C (Awberry and Griffiths [1]) and 0.84 cal/gr°C (Dickerson [5]), while at 72% moisture, 0.76 cal/gr°C (Ohlsson and Bengtsson [16]). The beef used in this study averaged 72% moisture content and the 0.76 cal/gr°C value was used in the computer program. This value was assumed constant over the temperature range 0 to 100°C.

Many authors have measured thermal conductivity of raw lean beef (summarized in Hill et al. [8]) at various moisture contents and grain orientations either parallel or perpendicular to heat flow. The data were somewhat contradictory with respect to grain orientation effects, but all data for 70 to 79% moisture lie between 0.00095 and 0.00125 cal/sec°C cm. An intermediate value of 0.0012 cal/sec°C cm was used and assumed constant over the range 0 to 100°C since the only reference reporting thermal conductivity values at temperatures well above freezing (Hill et al. [8]) showed a negligible temperature effect.

The dielectric properties of beef reported in the literature varied somewhat, possibly due to differences in sampling and measuring techniques, frequencies used, and the inherent variability of biological materials. The attenuation coefficient is shown as a function of frequency and temperature in Figure 3. This coefficient, calculated from several authors' dielectric data, was the only dielectric property used in the computer program. When this research was underway, dielectric data at 915 and 2450 MHz was not available at temperatures greater than 65°C. An attempt to use the 2450 MHz data, using approximations to extend it to 100°C, resulted in a poor experimental/computed temperature profile match, with indications that the attenuation coefficient values were too high. Use of the lower attenuation coefficient values at 2800 MHz [2], which extended over a much more adequate temperature range of −40 to 140°C, gave good results. At 900/915 MHz, better literature agreement

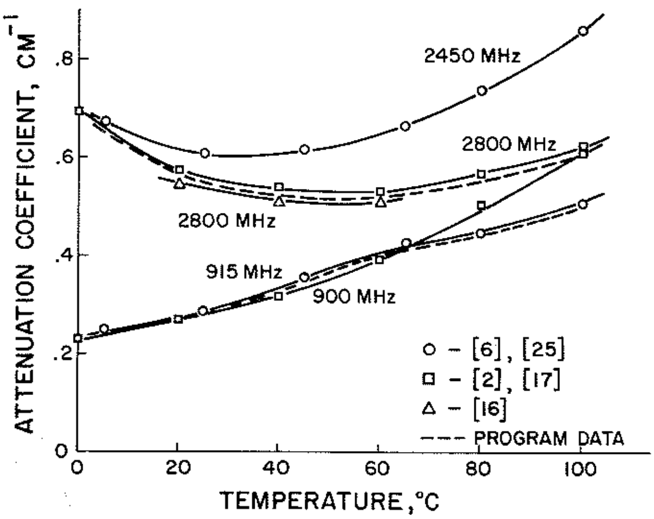


Figure 3 Attenuation coefficient variation with comparison of several authors' data, and data used in computer program.

exists, and To's data[25] for 915 MHz was used. The dotted lines of Figure 3 represent the attenuation coefficient variation actually used in the computer program.

MATH MODEL

Since the U.S. Military is actively developing a formed beef roast specification, shaped roasts will probably soon be in common usage. A cylindrically shaped roast, in addition to being easily modeled mathematically, is a wise choice for microwave heating since any deviation from a circular cross-section, such as square or triangular, would result in overcooking of corner areas. Accordingly, this work was only concerned with cylindrically shaped beef roasts.

Symmetry about the two center axes of the cylinder was assumed. As shown in Figure 4, determination of the temperature pattern in a 1/4 lengthwise cross-section (shaded area) is representative of the temperature distribution throughout the entire roast.

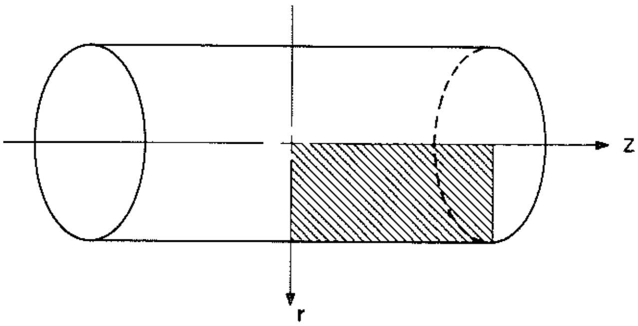


Figure 4 Symmetry assumptions.

The differential equation for heat transfer to a solid cylinder, neglecting angular terms, is

$$\partial^2T/\partial r^2 + (1/r)\partial T/\partial r + \partial^2T/\partial z^2 + \dot{q}/K = (\rho C/K)\partial T/\partial t \qquad (1)$$

where $T = T(r, z, t)$ is the temperature, r is the radial distance, z is the axial distance, $\dot{q}$ is the rate of heat addition per unit volume, K is the thermal conductivity, ρ is the density, C is the specific heat and t is the time.

In conjunction with the boundary conditions which follow, equation (1) was solved numerically by a finite difference method on a digital computer. A network of nodes was superimposed over the shaded area of Figure 4 and by means of finite difference approximations for the differentials, the temperature at each point was calculated for each time period Δt. The radial and axial node spacing, Δr and Δz, and the time increment Δt were chosen within constraints outlined by Holman[9] to ensure stability of the numerical solution.

In applying this finite difference technique several assumptions were made. Meat was assumed to be perfectly homogeneous with no air or fat voids or grain effects, and perfectly cylindrical in shape throughout the cooking period. Radiation incident on the meat surface, both infrared and microwave, was assumed to be uniformly distributed over the entire surface. It was assumed that dielectric and thermal properties did not change with percent moisture variation during cooking, and that evaporative loss was uniform over the entire roast surface.

Assuming that, prior to cooking, the roast was at some uniform initial temperature T_o, the initial condition is

$$T = T_0 \text{ at } t = 0 \qquad (2)$$

On the inner boundaries of the shaded area of Figure 4 the boundary conditions were derived by symmetry considerations

$$\partial T/\partial r = 0 \text{ at } r = 0 \quad (3)$$

$$\partial T/\partial z = 0 \text{ at } z = 0 \quad (4)$$

On the outer boundaries, heat may enter the roast by convection, thermal radiation, and microwave radiation, while heat is lost by evaporative cooling and dripping fluids. For the case of conventional roasting, the outer boundary conditions are

$$\partial T/\partial r = H(T_A - T)/K + Q_R - E_V \text{ at } r = R \quad (5)$$

$$\partial T/\partial z = H(T_A - T)/K + Q_R - E_V \text{ at } z = L/2 \quad (6)$$

where T_A is the oven temperature, Q_R is the radiant heat exchange, E_V is the heat exchange due to evaporation and drippings, R is the radius of roast, L is the length of roast, H is the convective heat transfer coefficient and K is the thermal conductivity.

For the case of microwave roasting in a room temperature oven, the Q_R term is negligible and extra terms involving the microwave energy absorbed by the surface finite element must be added.

For the conventional roasting case, Q_R was determined by a radiant interchange analysis since heating elements, heated oven walls, and unheated oven walls attained different temperatures at a given temperature setting, had different emissivities, and had different geometric shape factors. Experimental determination of the above surface temperatures and geometric shape factors permitted the calculation of radiant heat transfer within the computer program.

With the current apparatus, rotation of the roast during microwave cooking made measurement of evaporative loss impossible. It was necessary, therefore, to use indirect methods to determine values of H and E_V for use in the computer program.

Evaporative loss was measured for the conventional roasting case, however, and a typical example of its time variation appears in Figure 7. Using this data, plus literature values of K, ρ, and C, and calculated values of Q_R, a single value of H was determined which provided the best computed/experimental time-temperature data match over several experiments with different cooking conditions. Then, for each individual roasting experiment, using this universal value of H, the value of the time varying E_V term was set by trial and error to achieve the best computed/experimental data match. Since E_V and H are treated in a similar manner mathematically, picking up any variation of H in the E_V term has no ill consequences.

The interaction of microwave energy with a meat roast is a very complex phenomenon. As an electromagnetic wave arrives at the surface of the roast, a portion of the incident energy is reflected, and a portion is refracted, transmitted and attenuated. Neglecting DC conductive losses and losses due to polarization since they are negligible for most dielectrics heated at microwave frequencies (Stuchly and Hamid [24]). one dimensional attenuation of microwave energy in a dielectric occurs as

$$P = P_0 e^{-2\alpha d} \quad (7)$$

where P is the remaining microwave power at depth d, P_o is the microwave power transmitted through the surface, α is the attenuation coefficient and d is the depth.

The attenuation coefficient was calculated from the dielectric constant ϵ_r', the dielectric loss factor ϵ_r'', and the wave length in a vacuum, λ_o according to Ohlsson and Bengtsson [16] as

$$\alpha = (\pi\sqrt{2}/\lambda_0)\left[\sqrt{(\varepsilon_r')^2 + (\varepsilon_r'')^2} - \varepsilon_r'\right]^{1/2} \quad (8)$$

Values of ϵ_r' and ϵ_r'' for beef have been measured by several authors [2, 6, 16, 17, 18, 25] and the resulting attenuation coefficient-temperature variation is illustrated in figure 3.

Ohlsson and Bengtsson [16] used a one dimensional finite difference numerical solution of the heat transfer equation for an infinite slab to approximate microwave heating of 3 cm thick meat blocks, and obtained excellent agreement between experimental and numerical results. In their computer model, they assumed the microwave field to be a plane wave propagating perpendicularly to the surface of the heated sample.

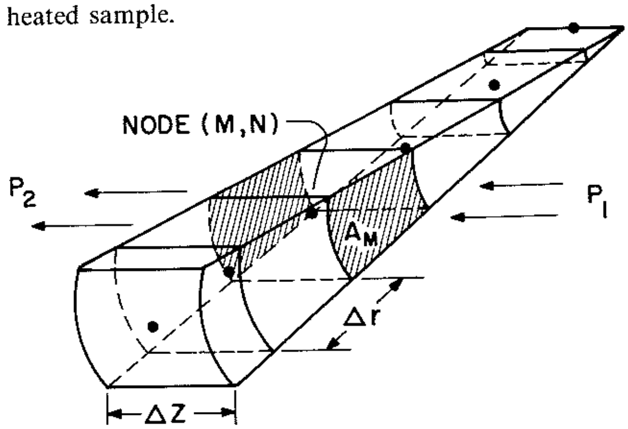


Figure 5 Wedge of cylindrical roast showing axial microwave penetration.

Since this is a two dimensional problem, microwave energy entering from the sides (radially) and from the ends (axially) must both be considered. The simplest case, that of axial microwave penetration, will be discussed first. Consider a wedge of a cylinder as shown in Figure 5, where each temperature node is surrounded by a volume $A_M \Delta z$. Incident axial microwave energy P_1 associated with node (M, N) passes perpendicularly through area A_M (shaded), is attenuated, and passes out of the node-volume through the same area with energy P_2. From equation (7)

$$P_2 = P_1 e^{-2\alpha z} \tag{9}$$

For node (M, N) the energy absorbed, P_A, is therefore

$$P_A = (P_1 - P_2)A_M = A_M P_1 (1 - e^{-2\alpha \Delta z}) \tag{10}$$

In the computer program, calculation of energy absorbed occurs stepwise from the surface to the center of the roast, taking into account energy entering from both ends.

The simplifying assumption that the microwave field is a plane wave propagating perpendicularly to the meat surface, although assumed for the end faces of the roast cannot be directly applied for radially incident waves. If all microwaves penetrated exactly radially, all would pass through the axis of the roast and would exhibit a very large "focusing" effect there. Even though radially incident microwave power is greatly attenuated by the time it reaches the roast central axis, the small quantity of energy is dissipated in very small node-volumes, thereby creating locally high temperatures.

In actuality, some focusing effect does occur when cylindrical shaped dielectrics are subjected to microwave radiation. Copson [3], in work with agar cylinders, found a substantial center temperature peak for 10.2 to 20.3 cm diameter cylinders when irradiated with 2450 MHz microwave energy. Guy [7], in work with phantom meat models, found center temperature peaks in 6 cm diameter spheres when subjected to both 918 MHz and 2450 MHz microwave energy.

Incident microwave radiation does experience a large refraction as it enters the roast surface. Assuming that meat has a negligible magnetic loss and has a permeability equivalent to that of a vacuum. Von Hippel [26] gives the index of refraction n_r to be:

$$n_r = [(\varepsilon_r'/2)\{\sqrt{1 + (\varepsilon_r''/\varepsilon_r')^2} + 1\}]^{1/2} \tag{11}$$

Using dielectric data from Goldblith and Wang [6], Bengtsson and Risman [2], and Ohlsson and Bengtsson [17] for raw beef, the value of n_r over 0 to 100°C ranges from 6.5 to 7.7 for frequencies from 900 to 2800 MHz. Thus a wave incident at the surface at 1.2 radians (70 degrees) from the normal will be refracted to an angle of about 0.13 radians (7.7 degrees) from the normal as it penetrates the meat. Theoretically, no radiation should penetrate the cylinder greater than 0.17 radians (10 degrees) from the normal. Realistically, however, experimental roasts were not perfectly cylindrical, and penetration at angles greater than 0. 17 radians (10 degrees) from a radial direction undoubtedly occurred.

To find the extent of the focusing effect, one must first consider the direction of electromagnetic wave propagation within the roast. For simplification, electromagnetic waves were considered as individual "beams". Although conceptually unrealistic, this approach permitted simple mathematical modeling. Consider a concentric set of rings imposed on a roast cross-section made by a 2π radian rotation of the wedge of Figure 5 about the axis, as shown in Figure 6. For clarity, only 5 rings are shown. A uniform microwave field was approximated by assuming a large number of beams to be distributed over the surface of the roast. Of this large number of beams, one group is incident at angle ϕ_1, another group at ϕ_2, etc. Each group of beams will be refracted upon entering the roast surface and these groups will penetrate the meat at angles θ_1, θ_2, etc. Trigonometric analysis permitted the calculation of the distance each representative beam travelled through each ring, and application of equation (9) permitted the calculation of the energy dissipated in each ring. Since the ratio of the area of the node-volume to the area of the associated ring is known, the energy dissipated in each node-volume was computed.

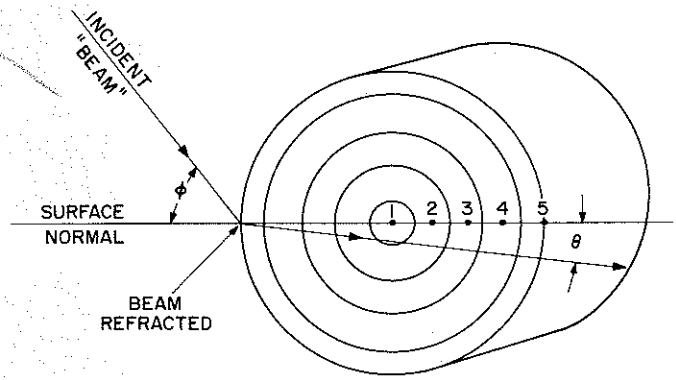


Figure 6 Incident wave angular distribution.

For each group of beams penetrating the roast at angle θ_1, an area in the roast center with radius r sin θ_1 will not receive any microwave energy. The penetration angles θ_i and the percent power entering the roast at each angle, for use in the computer program, were estimated and then tested by a trial and error procedure, until a good match between experimental and computer-generated data was achieved.

Since temperatures in the roast near the surface are sensitive to changes in E_V but are quite insensitive to changes in θ_i, this trial and error procedure was nearly independent of the trial and error procedure used to determine E_V.

Typical values of some variables used in the computer program were $\Delta r = \Delta z =$

0.5 cm and $\Delta t = 30$ sec. Information supplied to the program consisted of roast dimensions, initial roast temperature, oven temperature, radial and axial distance increments, time increment, printout time interval, maximum cooking time, density, initial percent moisture, convective heat transfer coefficient, microwave frequency and power level, microwave incident angles with percent radiation entering at each, specific heat, and thermal conductivity.

RESULTS AND DISCUSSION

The results presented here are of a preliminary nature. This research was conducted in an exploratory manner setting groundwork for future more exacting studies, and therefore paired roasts were not used and multiple replications were not carried out.

The following results concern only center temperatures, those in a plane described by $z = 0$ (see Figure 4). Heat entering the roast at the ends does overcook the end area to some extent, especially with microwave heating. Although the computer program is set up for the determination of temperatures throughout the entire roast, first efforts will be expended towards achieving methods which optimize cooking only in the roast center. Later work can examine end heating resulting from the optimum methods determined here, with efforts directed to minimize end overheating. Though not considering axial meat shrinkage, computer results for a 20 cm long roast have shown $99.9^{+}\%$ of the energy entering through the ends of the roast is absorbed prior to reaching the roast center, so the results presented here are independent of end heating effects.

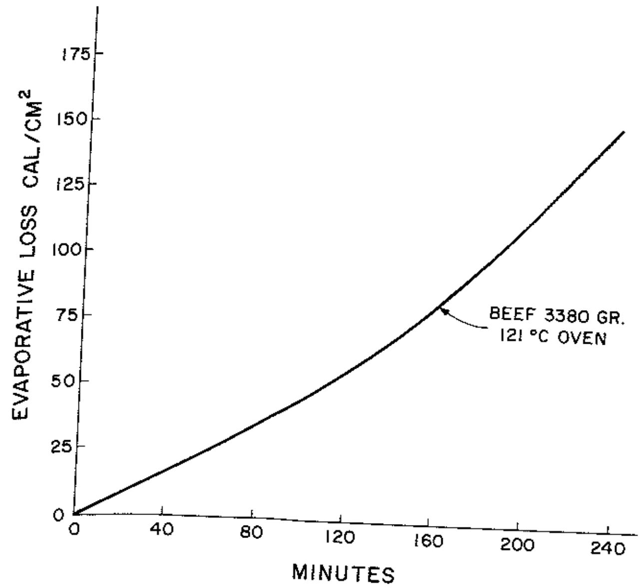


Figure 7 Evaporative loss, conventional oven.

A typical plot of evaporative loss as a function of cooking time for conventional roasting as measured in the research oven is shown in Figure 7. This data was used to set a value for H, as previously discussed. In microwave roasting the evaporative loss vs. time curve is similar to that of Figure 7, except the slope is much steeper. Excellent agreement between computed results and experimental data for a 121°C oven is shown in Figure 8.

Before microwave roasting results are discussed, details of the interaction of microwave energy with beef should be considered. The main difference between heating at 915 MHz and 2450 MHz lies in differing penetration depths. Penetration

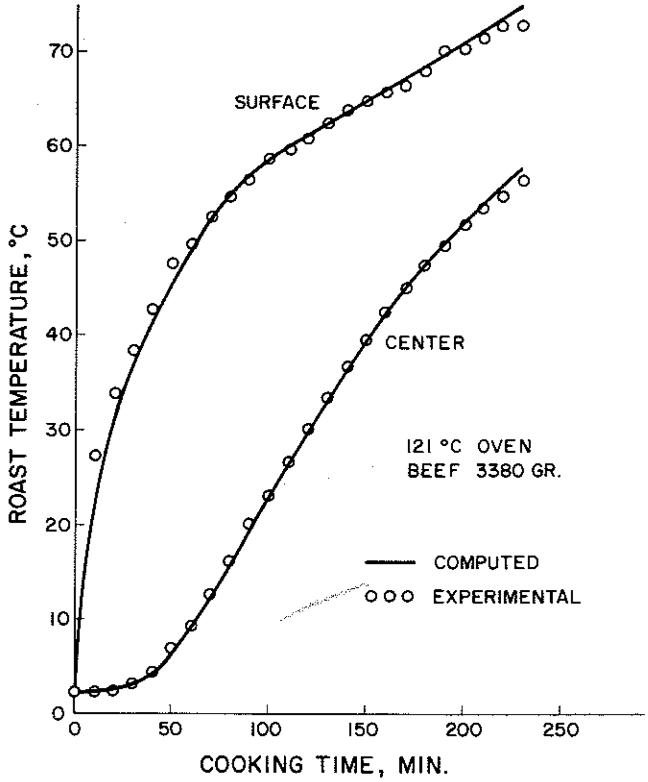
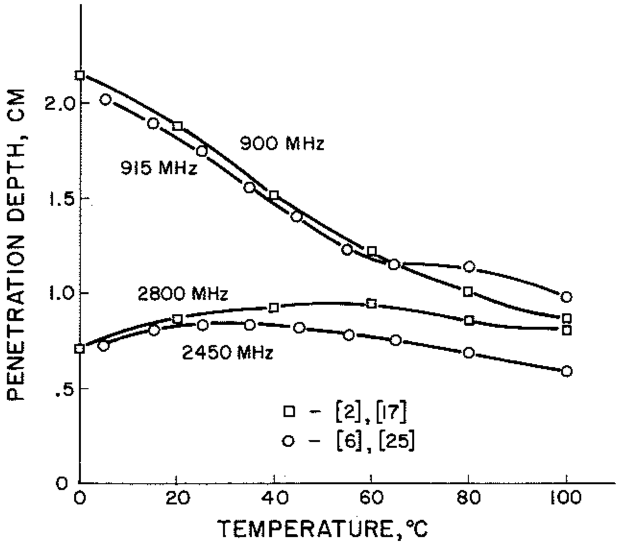


Figure 8 Experimental/computed comparison of temperature histories of roast in conventional oven.

depth is defined as the distance from the meat surface at which the transmitted microwave power drops to 1/e (37%) of the surface value. Microwave energy at 915 MHz initially has a decided penetration advantage over 2450 and 2800 MHz but loses it as temperature is increased, as shown in Figure 9. An even clearer illustration of penetration differences can be seen if one considers a 12 cm thick infinite beef slab, uniformly at 10°C, subjected to microwave radiation on both faces. The percent power

Figure 9 Penetration depth in raw beef at 915, 2450 and 2800 MHz from 0 to 100°C.



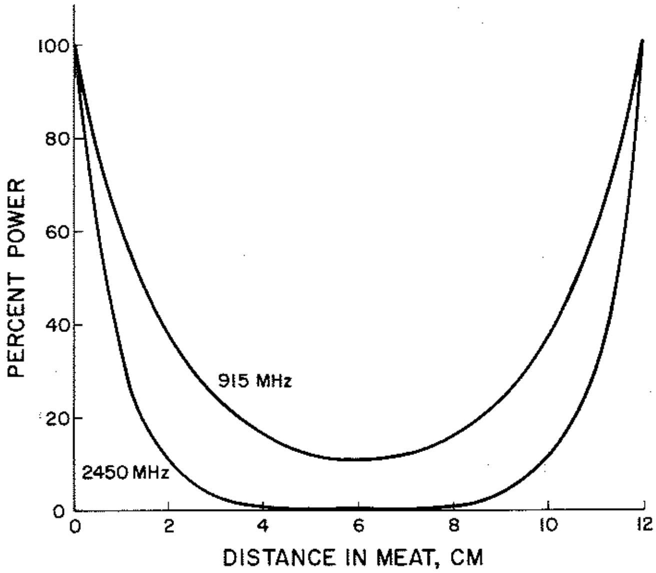


Figure 10 Power profile in raw beef at 915 and 2450 MHz, 12 cm infinite slab at 10 °C, irradiated on both sides.

remaining at a given depth diminishes exponentially as the center is approached as shown in Figure 10 (using program data of Figure 3). A slab was chosen to eliminate any confusion caused by the focusing effect, and the 12 cm dimension is typical of the cylindrical roast diameters used in this study. It is noted that 44 times more energy reaches the center at 915 MHz than at 2450 MHz. At uniform roast temperatures of 60°C where penetration differences due to microwave frequency are diminished, 4.2 times more energy reaches the center at 915 MHz than at 2450 MHz.

The controls on our research oven do not permit accurate direct readings of the microwave power level within the oven. Prior to roasting, the oven wattage was determined by briefly heating a water load of similar weight, shape, and temperature as the meat to be cooked, placed in the same position in the oven. Since the dielectric properties of beef and water differ, the wattage absorbed by water may not represent the wattage absorbed by the meat. Therefore, a separate test was conducted in which 1600 g each of beef and water, at the same initial temperature and in identical containers, were separately heated for the same amount of time (8 min) at the same microwave power setting (about 350 W). The containers were placed in the same location in the microwave oven and were rotated at 2/3 RPM. Tests were carried out for each frequency, with several trials conducted per test. Wattage absorbed by water was calculated directly from the temperature rise; the wattage absorbed by the meat (in 2 cm cubes) was determined by calorimetry using a large Dewar flask. At 915 MHz the meat absorbed 5% less wattage, while at 2450 MHz both meat and water absorbed the same wattage. These results were used to determine experimental power levels.

A comparison between experimental and computer-generated data for a roast cooked at 300 W at 2450 MHz is shown in Figure 11. In the lower part of the figure the center ($r=z=0$) temperature-time history is shown, while in the upper part the center temperature profile (along a diameter) at completion of cooking is shown. For the computed data, the microwave penetration angles and the percent energy entering at each angle is tabulated. For this figure, 40% of the radiation transmitted through the meat surface penetrates at 0 degrees from the surface normal, or exactly radially, while 30% penetrates at 10 and 20 degrees from the surface normal. This is the angular variation which, determined by trial and error, created the best match between experimental and computer-generated temperature data. The variation in thermal and dielectric properties due to the variation of percent moisture from roast center to surface arising from surface evaporation during cooking, is not accounted for throughout this paper. This may explain, in, part, the experimental/computed temperature profile differences in Figure 11.

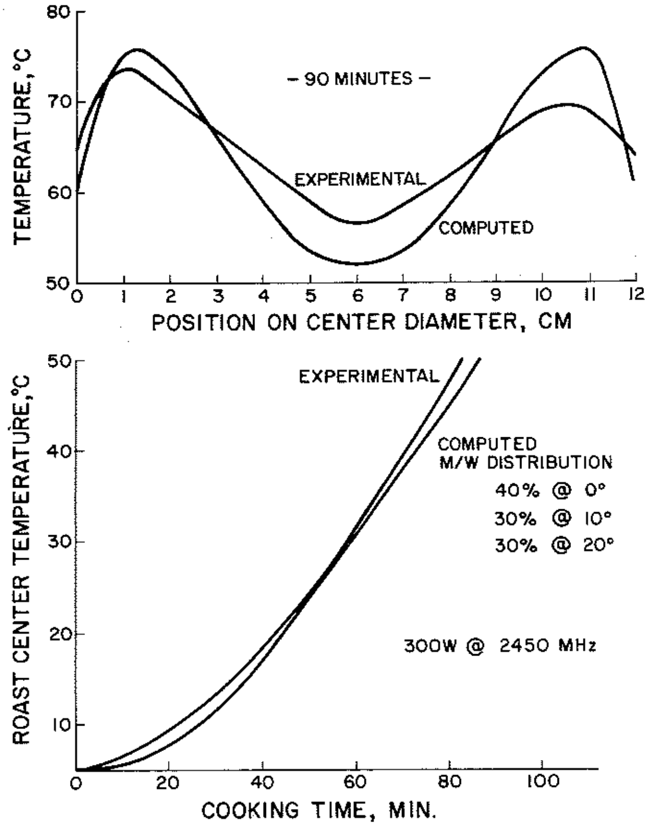


Figure 11 Experimental/computed temperature comparison of beef roast cooked at 300 W at 2450 MHz.

The experimental temperature profile shown in the upper half of Figure 11 is an average of vertical and horizontal temperature profile data taken upon completion of cooking. The roasts tended to assume a rounded triangular shape as they cooked, thereby causing differences in vertical/horizontal temperature profiles. Also, some unevenness of the microwave field was present from the oven top to bottom causing roast profile differences. The horizontal temperature profile was quite symmetrical due to the 2/3 RPM rotation of the roast, however. Differences of 10°C between the vertical and horizontal temperature profiles at a given diametral position were sometimes realized.

Figure 12 is similar to Figure 11, except that the cooking conditions were 285 W at 915 MHz. The experimental/computed results again show good agreement. The experimental 50 minute profile shows quite uneven cooking, largely a result of uneven microwave field intensity from the roast top to bottom.

A comparison of the experimental curves of Figures 11 and 12 is illustrated in Figure 13. From this figure it is seen that, cooking at approximately the same power level, a considerable advantage in cooking time is realized by heating at 915 MHz. Although difficult to visualize due to profile unevenness, a flatter temperature profile at 915 MHz is also realized. The 0.4 cm difference in roast diameters of Figures 11 and

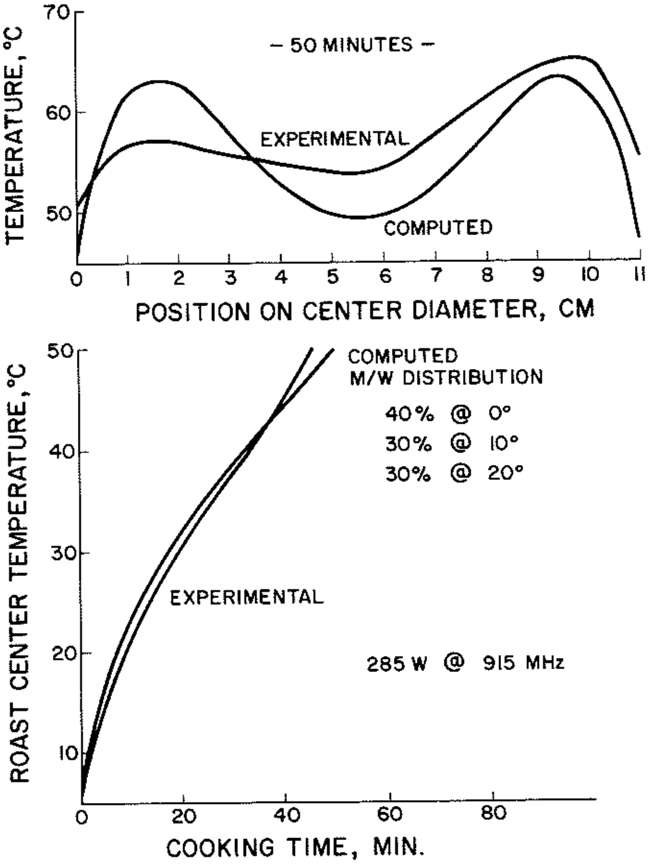


Figure 12 Experimental/computed temperature comparison of beef roast cooked at 285 W at 915 MHz.

12, resulting from difficulties in controlling roast dimensions, offsets the 15 W lower power level at 915 MHz.

Since many microwave ovens today operate at power levels near 600 W, some idea of the 600 W temperature response of the roast would be of interest. The computer-generated temperature history of a 12 cm diameter roast subjected to 600 W microwave power is shown in Figure 14. With post-cooking equilibration in mind (Figure 1), at center temperatures well below 60°C (where 60°C=rare) the profile for 2450 MHz indicates high temperatures throughout much of the roast, resulting in substantial overcooking. At 2450 MHz, the rate of energy input at this power level is so much greater than the rate of thermal conduction that excessively uneven cooking results even when allowing for post-cooking temperature equilibration to raise the center temperature. The profile for 915 MHz is marginally acceptable since it is noted that over 50% of the cross-sectional area is at temperatures between 70 and 80°C to achieve a rare cooked condition at the center, after a 20 to 30 minute thermal equilibration period.

The results of combined conventional heating (104°C) and microwave heating (285 W at 915 MHz) are shown in Figure 15. Here the computed results at 285 W are somewhat high in comparison to experimental results; computed results at 265 W show much better agreement. The cause for this discrepancy of 20 W is probably due to the fact that the roast diameter was actually 10.5 cm, but the computer program is set up for integral values of diameter in centimeters, and 10 cm was chosen to match the number of experimental data points. This is the only case where the microwave

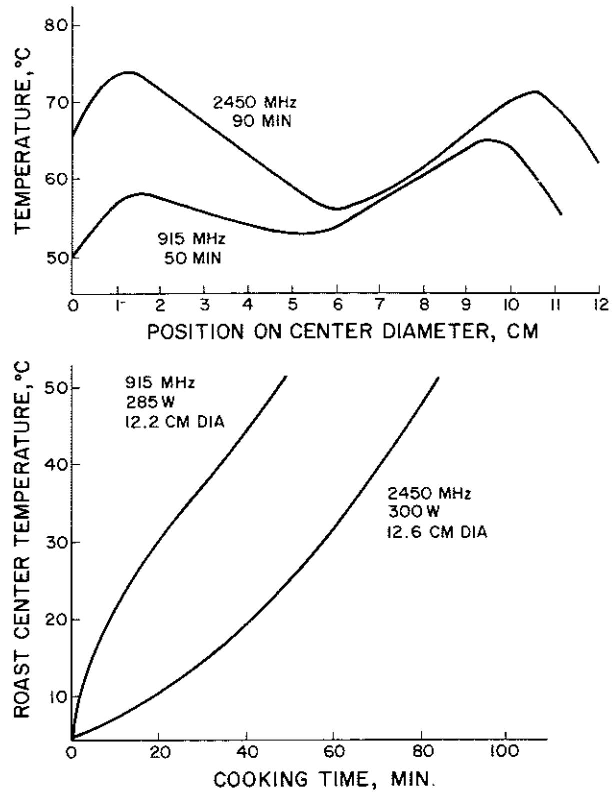


Figure 13 Comparison of experimental temperature data; 285 W at 915 MHz vs. 300 W at 2450 MHz.

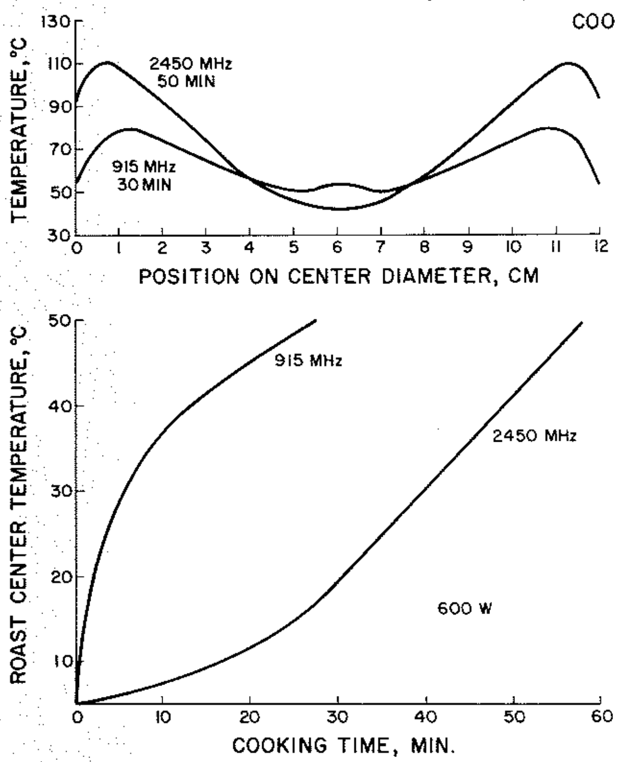


Figure 14 Computer generated temperatures for beef roast cooked at 600 W at both 915 MHz and 2450 MHz.

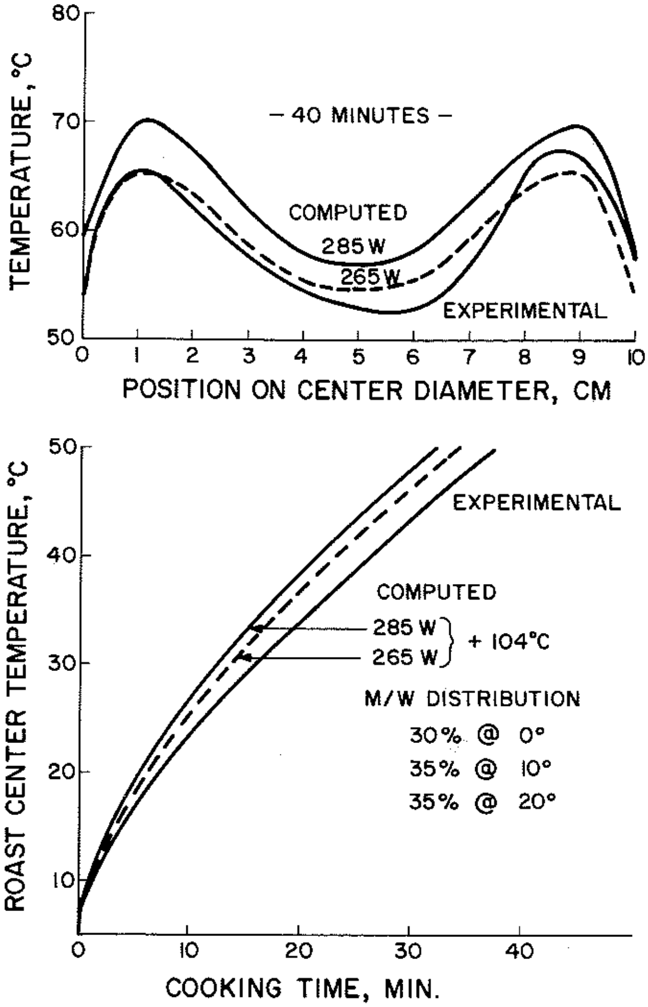


Figure 15 Experimental/computed temperature comparison of beef roast cooked at 285 W at 915 MHz in a 104°C oven.

distribution differs from the usual 40% at 0°, 30% at 10°, and 30% at 20°. More experimental work may provide an explanation.

In Figure 16 a comparison between experimental results for the combined case of a 104°C oven temperature plus 915 MHz microwave power and a 104°C oven temperature plus 2450 MHz microwave power is shown. For comparison, other results are superimposed. It is seen that the combination with 915 MHz still achieves the fastest cooking time but the resulting temperature profiles at completion of cooking do not differ very much. It is likely that the hot oven air heats the meat surface up more quickly, thus minimizing penetration differences between frequencies (see Figure 9) in the near-surface region where most power is dissipated, resulting in somewhat similar final temperature profiles. While addition of a 104°C oven temperature to microwave roasting speeds up cooking without adversely affecting the center temperature profile, evaporative losses are substantially increased, as will be shown later.

The fact that the angular distribution of microwave penetration was the same for both frequencies is easily understandable when one considers Figures 17 and 18. In these figures, sensitivity to focusing of microwaves is examined by comparison of computer generated results for all absorbed power being transmitted exactly radially

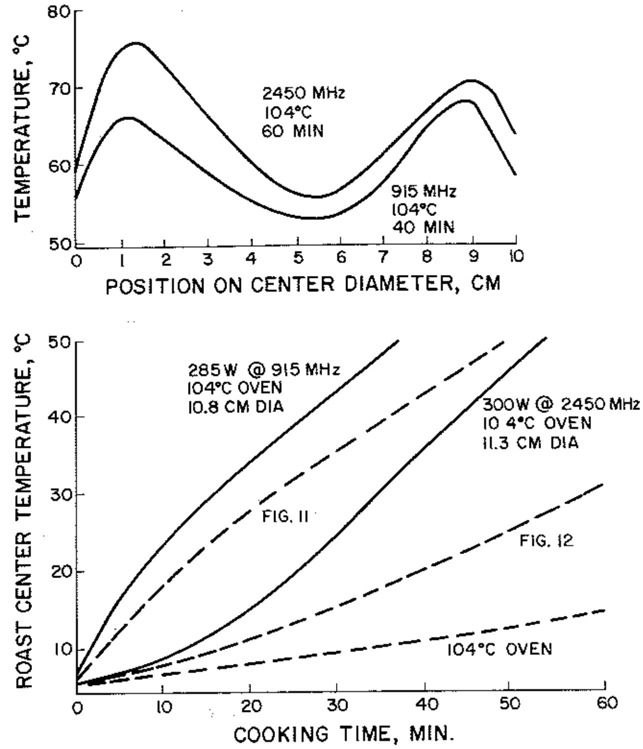


Figure 16 Comparison of experimental temperature data; 285 W at 915 MHz in a 104°C oven vs. 300 W at 2450 MHz in a 104°C oven. Other results are shown for comparison.

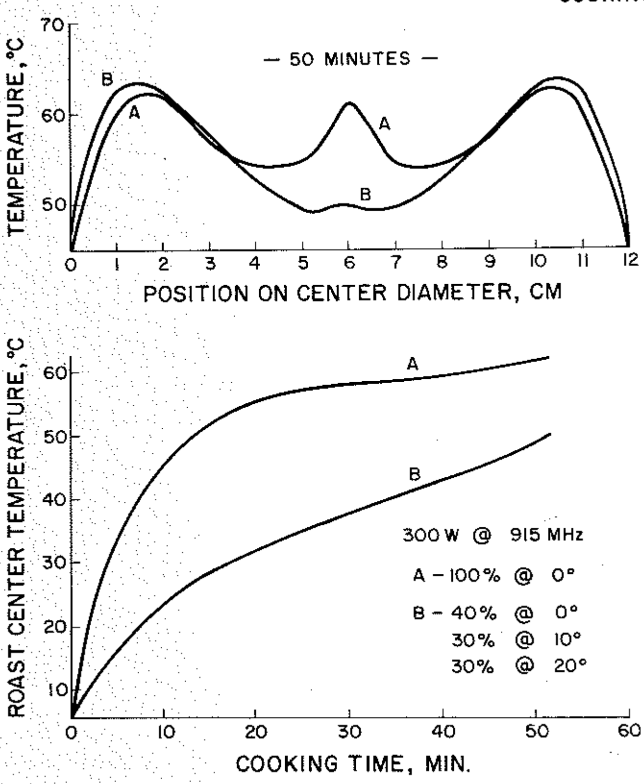


Figure 17 Microwave angular distribution effect for 300 W at 915 MHz; all radiation penetrating exactly radially (case A) vs. distributed (case B), computed results.

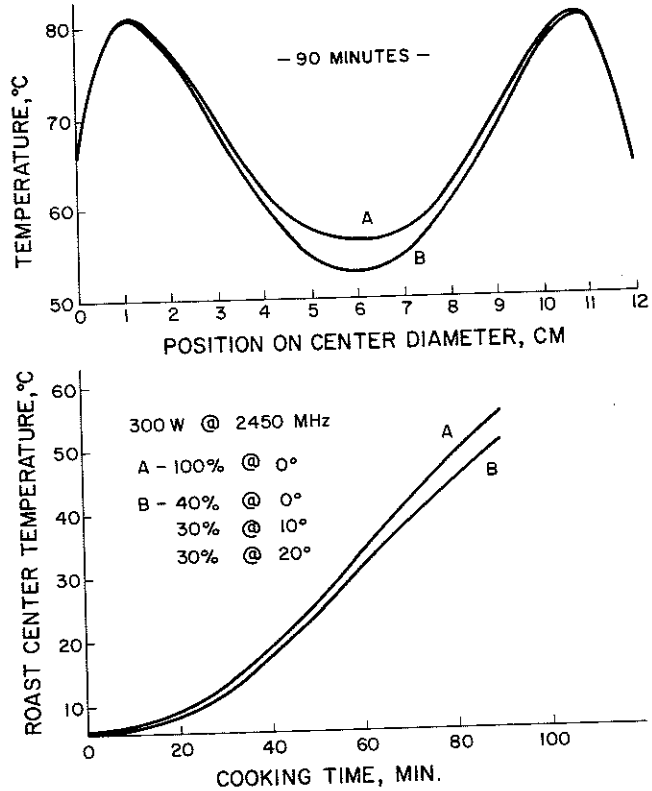


Figure 18 Microwave angular distribution effect for 300 W at 2450 MHz; all radiation penetrating exactly radially (case A) vs. distributed (case B), computed results.

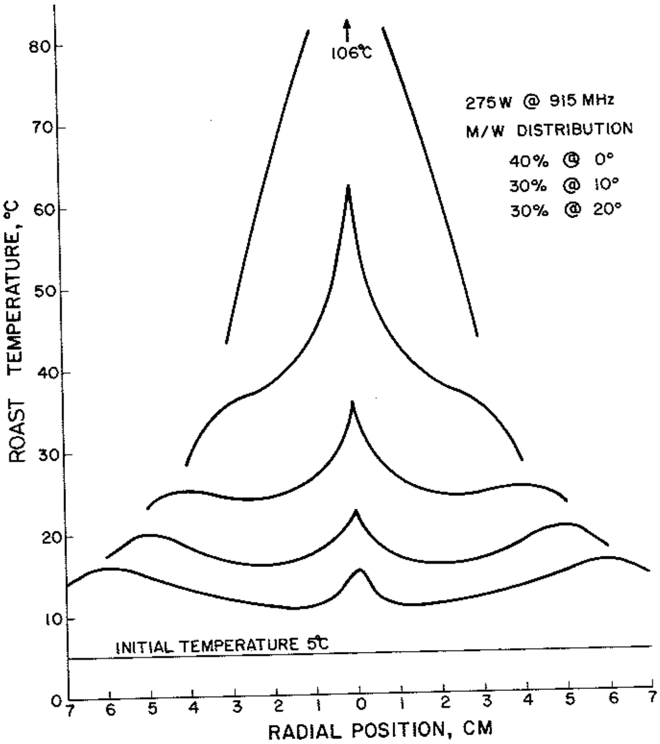


Figure 19 Effect of diameter variation on roast center temperature profiles, 10 minutes heating at 275 W at 915 MHz.

(case A) and power distributed as shown in Figures 11 and 12 (case B). It is seen that, due to less penetration, 2450 MHz heating is not nearly as sensitive to focusing as 915 MHz heating.

From Figure 17, it is apparent that any means that promotes radial microwave penetration, such as perfect roast cylindrical shape, etc., will provide faster cooking with a more uniform temperature profile.

The effect of roast diameter on the resultant temperature profiles for the same applied wattage is seen in Figures 19 and 20. For these computer-generated results at 275 W, the 10-minute temperature profiles (along a central diameter) reveal vastly different temperatures for roast diameters ranging from 6 to 14 cm. These figures illustrate the greater energy dissipation near the roast surface for the 2450 MHz case, resulting in higher surface temperatures, less power penetration and therefore less energy to be "focused", and relatively low center temperatures.

Figure 19 is somewhat deceptive, however. As the roast surface heats up, the penetration depth for 915 MHz decreases (see Figure 9), thus decreasing the amount of energy reaching the roast center. The center temperature peak generated early in the roasting period gradually levels off by means of thermal conduction as a result of the decreased energy available for focusing.

In Figure 20, some focusing takes place on 6 cm diameter roasts, and a very uniform temperature profile is achieved. Thus 2450 MHz heating is superior for roasts with diameters of 6 cm or less.

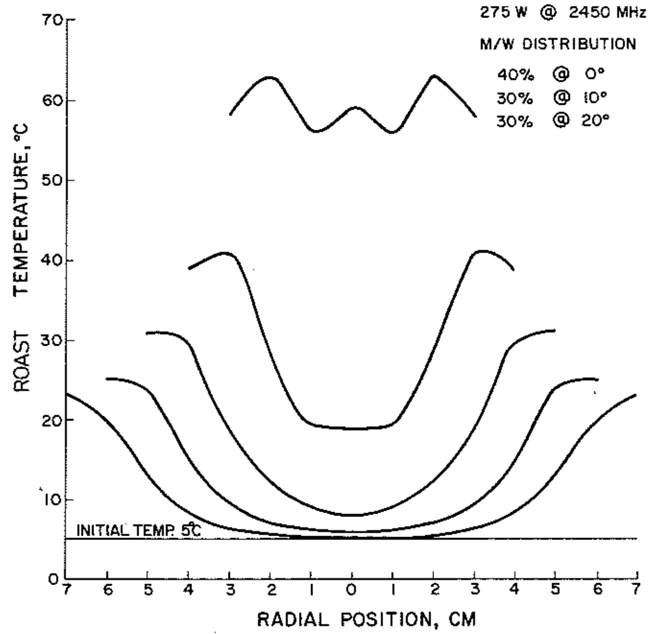


Figure 20. Effect of diameter variation on roast center temperature profiles, 10 minutes heating at 275 W at 2450 MHz.

Based on the limited experimental work, the computer program is capable of giving some indication of an optimum cooking method by predicting the temperature profile, cooking time, and evaporative loss for many different cooking schemes. The optimum cooking method is the one in which drip loss, evaporative loss and cooking time are minimized while yield and palatability are maximized. Since tenderness is a primary aspect of palatability, and it is dependent upon the cooked meat temperature, achieving a roast temperature which enhances tenderness is a first step toward maximizing palatability. Since drip loss is directly related to loss of bound water by protein denaturation, and this process is both time and temperature dependent, both a flat roast temperature profile and a short cooking period will minimize drip loss. Evaporative loss is also dependent on cooking time; the shorter the cooking period the less time for evaporation to occur. If drip loss and evaporative loss are both minimized, then yield is maximized.

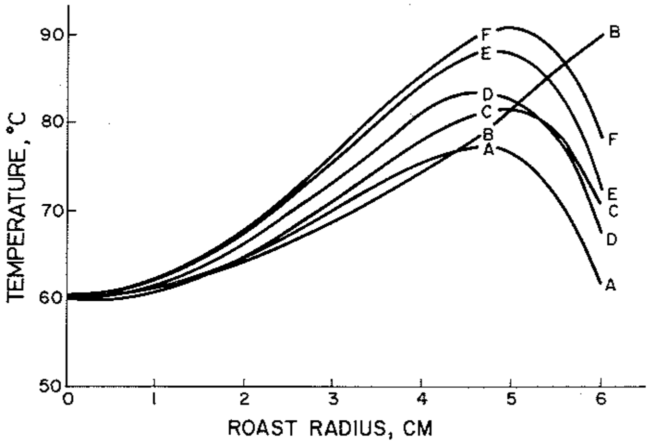


Figure 21 Comparison of center temperature profiles for several cooking methods.

CURVE	APPROX. EVAP. LOSS GR.	COOKING TIME MIN.	OVEN COOKING CONDITIONS
A	194	66.5	300 W @ 915 MHz
B	600	180	163°C
C	232	67	300 W @ 915 MHz + 121°C @ 45 MIN.
D	178	49.5	600 W @ 915 MHz < 20 MIN. 300 W @ 915 MHz > 20 MIN.
E	424	101	300 W @ 2450 MHz
F	327	68.5	300 W @ 915 MHz + 121°C

In Figure 21, the computer-generated results of six different cooking methods are compared. As an aid to interpretation of this figure, it is noted that Paul and Palmer [19] suggest temperatures of 58-60°C as rare, 66-68°C as medium rare, 73-75°C as medium, and 80-82°C as well done. Either curve A, with the flattest temperature profile, or curve D, with the lowest evaporative loss and cooking time could represent the optimum cooking condition. The expected higher drip loss experienced by the method of curve D is the unknown determining factor. Both methods use microwave energy in an unheated oven, as the cool oven surroundings help keep the surface temperature down and help minimize evaporative loss by the achievement of a higher relative humidity within the oven.

A roast with a 12 cm diameter has over 55% of its cross-sectional area within 2 cm of the surface, so careful attention to the temperature of the outer 2 cm is very important. When ends are considered, this figure jumps to 65% of the roast volume.

Although the problem of overcooking the roast ends is not discussed in this paper, it is a very important consideration in choice of an optimum cooking method. Since both candidate methods are based totally on microwave energy, this problem can probably be solved by shielding the ends in some manner. From the results of this study, regardless of the method chosen, cylindrical meat roasts could have cooking time reduced by a factor of about 3, increased yield, and a more uniform temperature profile than in conventional roasting.

Further study of these two cooking methods, resulting in elimination or minimization of end overheating, coupled with measurements of tenderness and consumer acceptance, could determine the optimum method.

CONCLUSIONS

From computer generated results based on limited experimental data, the following conclusions are made:

1. Past microwave studies used too much microwave power at the least effective frequency, thereby overcooking a large percentage of the roast.
2. Roast geometry has a very strong influence on the diametral temperature profile. Variations in the diameter and shape of the cross-section greatly affect the extent of microwave focusing and the resulting temperature profile.
3. For roast diameters greater than 6 cm, 2450 MHz microwave power is notably inferior to 915 MHz in roasting time and evenness of temperature profile.
4. For a 12 cm diameter by 20 cm long beef roast, either 300 W at 915 MHz alone, or the combination of 600 W at 915 MHz for the first 20 min. and 300 W at 915 MHz thereafter may be optimum roasting methods.

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