MICROWAVE HEATING

Microwave heating is only part of the noncommunications applications of electromagnetic energy and only part of the range of electromagnetic heating (1,2). The *microwave* range of the spectrum is variously defined. One prefers to think it is characterized by the fact that the dimension of the object to be heated is of the order of the wavelength. In practical terms this means heating at either 915 MHz or 2450 MHz, two of the Industrial, Scientific and Medical (ISM) frequency assignments (in the United States) for power or noncommunications applications. There are some medical heating applications (hyperthermia) at non-ISM frequencies where the expense of reducing leakage radiation to meet FCC (Federal Communications Commission) or CISPR (Special International Committee on Radio Interference) limits can be tolerated.

Industrial heating applications of microwaves exist at both 915 MHz and 2450 MHz but the higher power applications tend to use 915 MHz for meat tempering, bacon cooking, curing of rubber tires, and many other applications. Power levels of such systems range from 5 kW to 500 kW. At 915 MHz the dominant source of power is the magnetron providing power from 25 kW to 75 kW protected by a circulator. By far the most dominant heating application is the microwave oven, which today operates only at 2450 MHz. There are roughly 200 million ovens in the world and roughly 20 to 25 million ovens are manufactured each year. Most of these are for the consumer market, although a small but significant number are produced for commercial and professional use. The widespread microwave oven market is made possible only because of the unique properties of the *cooker* magnetron. These include high efficiency (~70%) at power on the order of 1 kW, compatibility with simple unfiltered power supplies and arbitrary loads, and above all, low cost (~$10 per tube in large quantities). An unavoidable (so far) concomitant to efficiency is high noise and other anomalous phenomena. A basic text on the microwave oven (3) and a broader treatment of industrial heating (4) have been published.

Most applications, whether for the microwave oven or industrial machine, correspond to the simple schematic depicted in Fig. 1. The basic objective is to deliver microwave power efficiently to the load. Thus, the system must be designed to minimize the reflected power. A practical microwave oven will not have a circulator or directional coupler, but in the design stage these tools or their equivalents will be present.

The absorption of microwave power depends on the dielectric properties of the load, which are temperature dependent, its size and shape. Given these parameters, the extensive literature on dosimetry permits one to calculate or estimate the power absorbed by the load when it is exposed to a plane wave of given flux density. A convenient reference is the Radiofrequency Radiation Dosimetry Handbook (5) published by the U.S. Air Force. Most nonmedical applications must be carried out in an enclosure. Thus, the modal and quasioptical properties of that enclosure will influence the equivalent plane waves that irradiate the object. The task of efficiently coupling energy from the power source waveguide to the enclosure is the function of the *feed,* which may be an antenna, aperture, or other coupling device. To achieve reasonable uniformity of heating, there must be some randomizing element in the system, for example, a rotating stirrer or scatterer or rotating feed antenna. Alternatively, there could be a rotating turntable on which the load is placed or a load-bearing belt which moves through a conveyorized oven of one or more cavities.

Because the magnetron is a key component of practical systems, knowledge of its properties is necessary. Frequency pushing, as the tube anode current varies, as well as frequency pulling as the load varies per stirrer rotation and load temperature increase, both spread out the power spectrum and average out or smear modal properties of the field pattern around the load. These variations also produce a complex pattern of electromagnetic noise both at microwave frequencies and at base-band frequencies. This information influences the design of the door-seal and other parts of a practical system to meet limits imposed by the FCC or CISPR as well as the Food and Drug Administration (Center for Devices and Radiological Health).

At present, design procedures are basically empirical, in view of the complex dependence of the heating pattern on many variables, making prediction, and even experimental replication, impractical if accuracy (a few percent) is required. There are some pilot studies on computer codes for microwave heating, but they are useful only for the simplest systems, for example, a uniform rod in a waveguide. In the future, as tube sources are improved in noise, efficiency, and available frequencies coupled with improvements in applicators (e.g., multiple feeds), one can expect significant advances in microwave heating. Still further ahead are more exotic heating applica-

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering.*

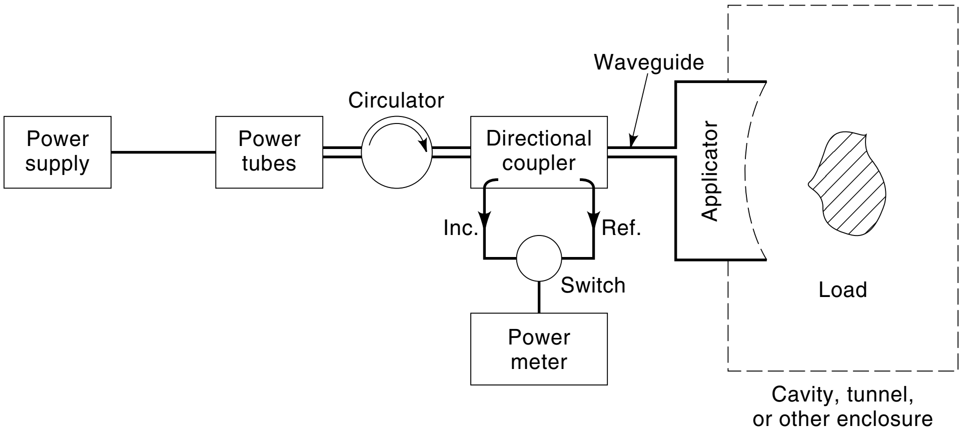


Figure 1. Basic elements of a microwave power system for processing of materials.

tions where the pulse or modulation characteristics of the source are important (e.g., in the stimulation of chemical catalysts).

BASIC PRINCIPLES OF MICROWAVE HEATING

The principles of microwave heating are well-established (1–5). It is generally assumed that the material to be heated is adequately specified in terms of the macroscopic complex dielectric permittivity, ϵ, defined by

$$\epsilon = \epsilon_0(\epsilon_r + j\epsilon_i) = \epsilon_0\left(\epsilon_r + \frac{j\sigma}{\omega\epsilon_0}\right) \tag{1}$$

where $\epsilon_0 = 8.86 \times 10^{-12}$ F/m, the permittivity of free space, ϵ_r is the real part of the relative dielectric constant, and σ is the conductivity in S/m (mho/m) which is equivalent to the following:

$$\epsilon_i = \frac{\sigma}{\omega\epsilon_0} \tag{2}$$

where ω is the assumed radian frequency of the fields. It is convenient to define auxiliary terms like the loss tangent, tan δ:

$$\tan\delta = \frac{\epsilon_i}{\epsilon_r} = \frac{\sigma}{\omega\epsilon_r\epsilon_0} \tag{3}$$

The rate of internal density of absorbed energy, or power P, is derived from the real part of the product of current density, from Maxwell's equations, and the internal electric field E_i, yielding:

$$P = \sigma|E_i|^2 = \omega\epsilon_r\epsilon_0 \tan\delta\ |E_i|^2 \tag{4}$$

where P is in terms of watts per cubic meter. Equation (4) is the practical formula for computing power dissipation in materials and objects of uniform composition when adequately described by the simple dielectric parameters.

Given the values of the dielectric parameters, one can then calculate the penetration depth D, at which, for plane-wave irradiation of a material, the fields are reduced by a factor of $1/e$. The result is

$$D = \frac{0.225\lambda}{\epsilon_r^{1/2}} \cdot [(1 + \tan^2\delta)^{1/2} - 1]^{1/2} \tag{5}$$

or for low-loss materials where tan $\delta < 1$:

$$D \cong \frac{0.318\lambda}{\epsilon_r^{1/2}(\tan\delta)} \tag{6}$$

where λ is the free-space wavelength of the microwave radiation.

For low frequencies or small objects, the components of electrical fields normal to a material boundary are related by the following equation:

$$\left|\frac{E_i}{E_o}\right| \cong \frac{\omega\epsilon_0}{\sigma} \tag{7}$$

where E_i and E_o are the internal and external fields, respectively. The material is characterized by σ, and the outside volume is free space. If the applied field E_o is parallel to the surface, then the internal field is equal to E_o. Thus, if the applied field is parallel to the long axis of a body, the internal field is approximately equal to the external field. Otherwise, if the applied field is perpendicular to the long axis, the internal field, according to Eq. (7) is much less than the external field even for moderate conductivity of the order of 1 S/m.

The principal task in microwave heating problems is the determination of internal fields in an object that permit through Eq. (4) the determination of the heating distribution over time. The dielectric parameters are key data for such a calculation, particularly the dependence on temperature. Standard methods for measurement of these parameters are readily available (6). The simplest technique, and often the preferred method, is that in which rods or long slender samples of the material of interest are placed in the central vertical plane of a rectangular waveguide through small access holes centrally located on top and bottom walls (7). This is also a method for uniform heating of such a small sample, except for small volumes near the top and bottom access holes. Classical perturbation theory (7) permits the determination of ϵ and tan δ. Considerable data for a wide range of

Table 1. Dielectric Properties of Foods and Other Materials at 2450 MHz and 20°C

Material	ϵ	$\tan \delta$
Distilled water	78	0.16
Raw beef	49	0.33
Paper	2–3	0.05–0.1
Wood	1.2–5	0.01–0.1
Alumina	7.8	0.001
Borosilicate glass	4.5	0.004–0.007
Neoceram	6.2	0.003
Plastics		
ABS	2.85	0.006
Ultem	3.0	0.001–0.004
Polysulfone	2.1	0.006
Polypropylene	2.2	0.0005
Teflon	2.0	0.0004
Liquid crystal polymer	3.9	0.007

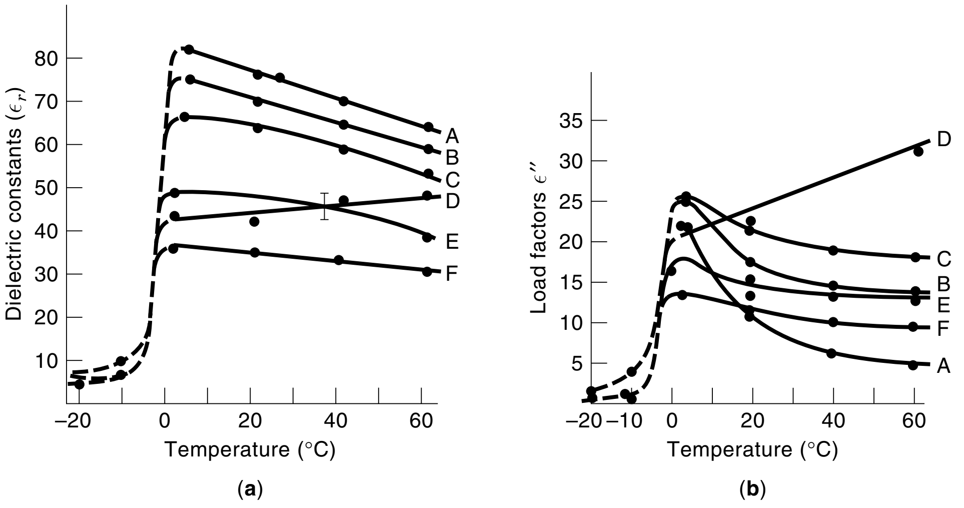
materials at room temperature and at various microwave frequencies are found in the literature (8).

Table 1 lists such data for a few important materials at 2450 MHz, the most commonly used frequency for microwave heating. Values of $\tan \delta$ well below 0.01 signify negligible absorption and heating, whereas values above 0.1 are considered good absorbers. Data on temperature dependence of dielectric parameters are not widely available in the literature. The classic data from Bengtsson and Risman (9) on temperature dependence for foods are reproduced in Fig. 2. They illustrate some general properties for heating of foods. The high value of ϵ, in the range of 40 to 80, signifies substantial reflection at the boundary of large food volumes of the order of 50%. For most foods, the value of $\tan \delta$ decreases with temperature, following that of water. This dependence is the basis for stabilization of heating, which aids a trend to uniformity of heating. On the other hand, a few foods such as ham that have significant salt content (ionic conductivity) show an increase in $\tan \delta$ with temperature. This tends to trigger thermal runaway at hot spots and nonuniform heating. When this happens in a glass or even ceramic tray in an empty oven, this can lead to dramatic melting at one spot. Although data for foods are generally limited to below 100°C, the temperatures of interest are much higher for oils and nonfood objects. Interest in ferrite materials as browning aids at a stable Curie temperature in recent years has been replaced by the development of the *susceptor* (10), in which a very thin (less than 100 Å) film of aluminum that is deposited on suitable insulating dielectrics highly absorbs impinging microwave radiation.

The calculation of absorption distributions in simple geometries (e.g., spheroids) is amply described in the literature (5). Only for very small spheres is heating uniform and approximately uniform in long thin rods aligned with the *E* field. At very high frequencies penetration and heating is superficial. In general, heating is nonuniform. For frequencies in the resonance range and for some materials and certain frequencies, dramatic hot spots are possible in the center of objects. Figure 3 shows the visualization of such a hot spot in a sphere of glue with a cloud point near 50°C. This can lead to superheating and explosive phenomena associated with such spherical objects. This is an example where the geometry of the sample is the prime factor determining temperature distribution in an object rather than external field patterns or modal properties of the applicators. Another such factor is the concentration of field and heating at corners and cusps of objects to be heated.

MICROWAVE APPLICATORS

Figure 1 depicts an *applicator* acting as a transducer or coupling agent between the feed waveguide and the load object. The simplest applicator may be a rectangular guide with access holes on top and bottom walls (7) allowing thin rods or tubes of flowing liquid to be heated. More specialized applicators include helices and slow-wave applicators. These have been described by Metaxas and Meredith (4). Antennas and other applicators for heating limited parts of the human body for diathermy or hyperthermia are reviewed by Guy (11), who restricts the reader's attention to the multi-mode cavity because it is the basis of most ovens and industrial machines that must handle large quantities of material or a large variety of objects. The engineering literature on waveguides is dominated by papers on properties at low frequencies where one or only a few modes can propagate. Considerable litera-



(**a**) (**b**)

Figure 2. Properties of foods near 2.45 GHz as a function of temperature, where A represents distilled water; B, cooked carrots; C, mashed potatoes; D, cooked ham; E, raw beef; F, cooked beef; and G, corn oil: (a) dielectric constants and (b) load factors, $\epsilon'' = \epsilon \tan \delta$ (9). From (9) with permission. © International Microwave Power Institute.

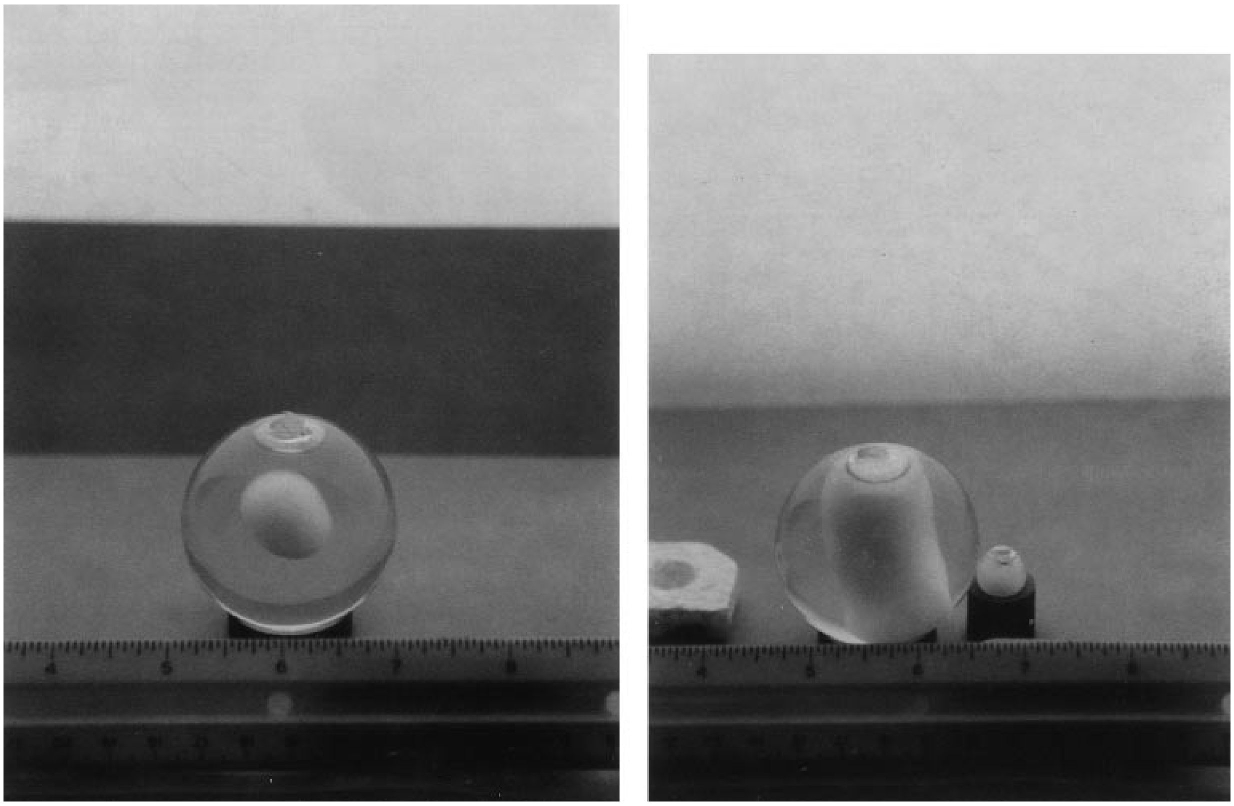


Figure 3. Samples of phantom material heated in a microwave oven, Sekusui Glue—R-500 (water and polyvinyl alcohol), cloud temperature of 51°C.

ture also exists for the high-frequency limit where optical properties come into the forefront. Little exists on the properties of waveguides that influence the performance of microwave heating systems.

A series of tests were conducted by the author on a machined aluminum cavity of dimensions 7 ft long by 2 ft^2. The cavity was excited by various antennas at one end and the transmitted signal was received at the other end with the same or a different antenna. Measurements were made of the incident, reflected, and transmitted signals over a broad range of frequencies from 0 GHz to 8 GHz. The upper frequency limit corresponds to a factor of over 32 times the lowest cut-off frequency of the 2 ft by 2 ft waveguide or a transverse dimension of 16 free-space wavelengths. It may be noted that the transverse dimension of most microwave ovens and industrial machines is approximately three wavelengths.

Figure 4 shows transmission data when a 4 in. axially aligned monopole is used at both ends of the 7 ft long waveguide, over the frequency range of 0 GHz to 1.8 GHz. Although the maximum transmission peaks reflect an insertion loss of only 2 to 3 dB, there are occasional severe dips in transmission. It can be shown that these occur at or near the cut-off frequencies of transverse magnetic (TM) modes which tend to be excited by an axial monopole. Reflection measurements show that the low transmission is associated not only with dissipative losses at cut-off resonances, but also severe reflection losses just below cutoff. One can see that according to the above relation for $D \sim 3\lambda$, the typical microwave oven might correspond to about 1.5 GHz. One can see a large dip near that frequency that can be related to mode indices of three and five. In fact, in practical microwave oven work, it has been found that when an antenna exciting TM modes is used in an oven with transverse dimensions near such a cut-off relation, an input impedance match cannot be achieved with ordinary tuning elements. Quine (12) has shown that properties near such TM mode cut-off resonances are related to the blind-spot phenomenon found in the radiation properties of phased-array antennas. He shows that the application of the image theorem for an antenna near a ground plane clarifies the connection between a waveguide and a phased array.

If a shielded loop antenna is substituted at the ends of the cavity in place of the monopoles, the transmission data shown in Fig. 5 are obtained. Absent are the severe transmission dips at cut-off frequencies. The effects at cut-off frequencies are greatly diminished when present. Data taken above 2 GHz with this waveguide show the diminishing effect of cut-off resonances as frequency increases, and the increasing density of modes as a cavity with three mode indices. Furthermore, although absorption by an object in the guide is affected by its size-dependent cross section, there is some suggestion that higher frequencies yield more consistent absorption. One might speculate that this results from the lesser prevalence of sizable *cold spots* in field patterns at higher frequencies.

One can see that studies of such a waveguide can yield valuable insights for understanding practical microwave heating cavities. Location of the load object is an important parameter. One can intuitively judge that the location of objects near a conducting wall is not desirable. In this case, if the space between the object and the wall is less than a free-

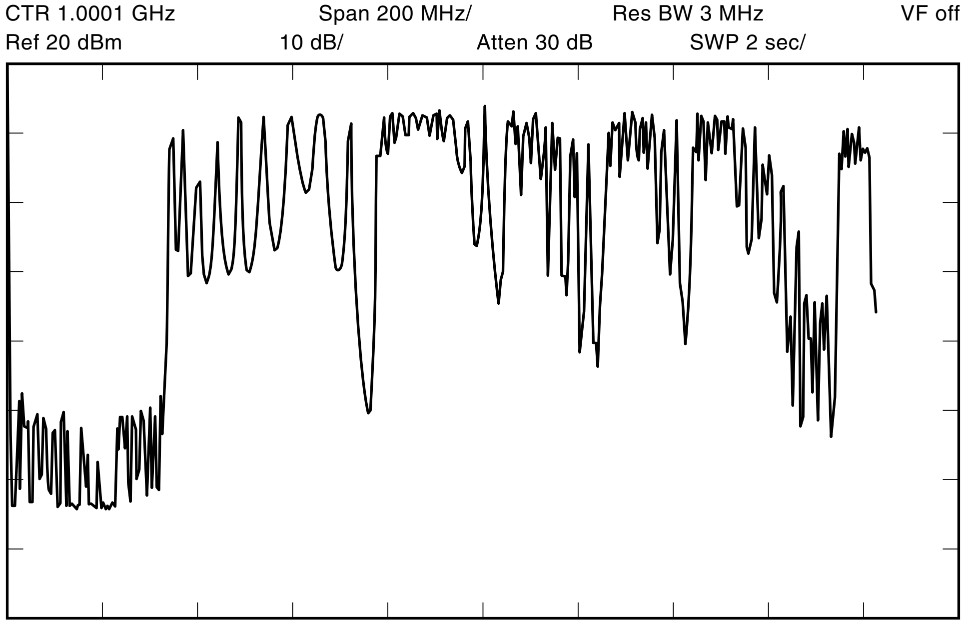


Figure 4. Transmission of microwaves through a 7 ft long section of waveguide (2 × 2 ft), 0.0 to 1.8 GHz with axially aligned 4-in. monopole antennas at each end. This antenna preferably excites TM modes.

space wavelength, it can be shown (13) that the only modal propagation in that interspace is of the slow-wave or bound-wave variety that exhibits a large propagation attenuation constant, α.

It is of interest to review the mode density of such cavities as a function of frequency. A review of such mode-counting exercises by Voss (14) shows that although the increase of density with frequency will on the average follow simple formulas, there are discrete regions where the mode density is quite low and other regions where it is much greater, for example, a factor of five or more when considering a bandwidth of 50 MHz or more at 2.45 GHz. A typical microwave oven cavity may be expected to show an average mode separation of approximately 4 MHz. Therefore, in the ISM band of 2.4 GHz to 2.5 GHz, one could conceivably benefit from the mixing of up to 25 modes. In practice, any such benefit is not exploited because a much smaller frequency variation of the practical magnetrons is used. There is enough frequency variation, however, to prevent simple single frequency calculations to be of any direct relevance to practical performance.

PRACTICAL MICROWAVE HEATING SYSTEMS

Most practical microwave heating systems employ a heating space confined by metal walls, that is, a cavity or waveguide. The basic reason is related to efficiency, although limitation of radiated leakage and out-of-band noise is also a determining factor. Today all microwave ovens operate at 2450 MHz.

Figure 6 shows an exploded view of a typical microwave oven. Shown are the main features or components that relate

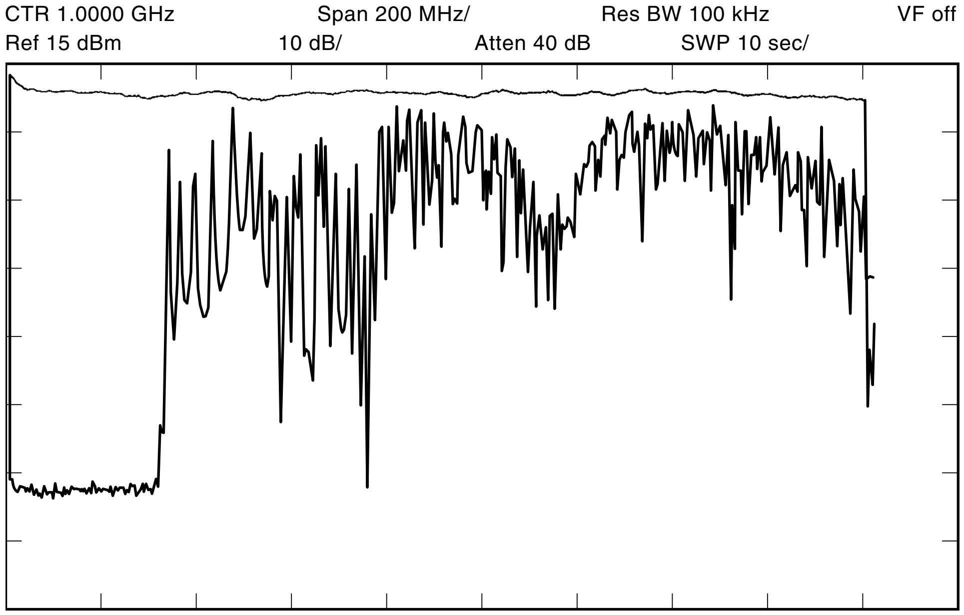


Figure 5. Transmission of microwaves through a 7 ft long section of waveguide (2 × 2 ft), 0 GHz to 18 GHz with shielded-loop antennas at each end. This antenna preferably excites TE modes.

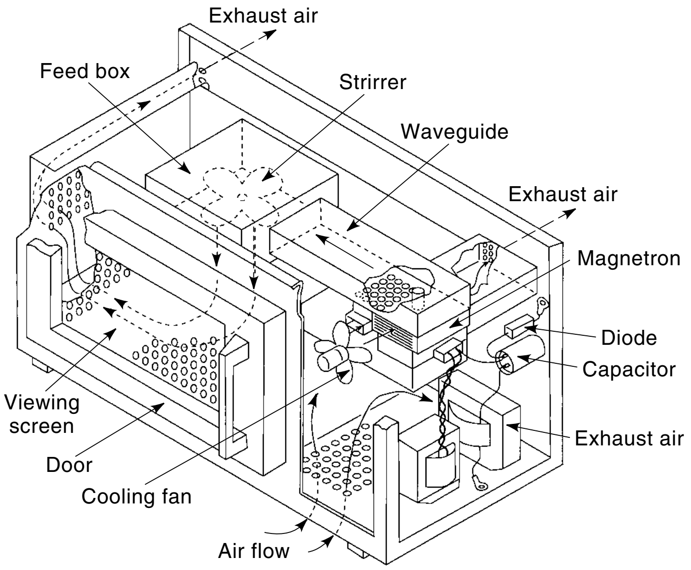
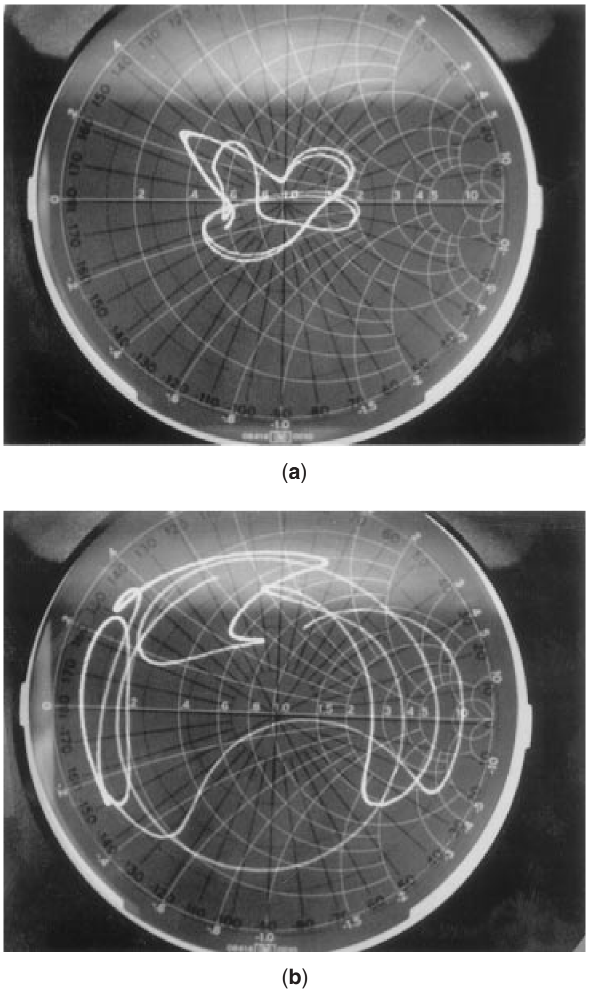


Figure 6. Exploded view of a microwave oven showing power components, microwave components, and cooling system; electronic control circuits are not shown.

to power and efficiency. Not shown are the electronic timer and control circuitry or the door interlock system. The basic elements are the microwave power generator, the magnetron, driven by an ac high-voltage power supply connected to the electricity source. The magnetron is connected to a short section of low waveguide which, in turn, couples energy into the oven cavity either through an antenna similar to a monopole, strip, or patch antenna or through a simple waveguide aperture. Most ovens employ a randomizing element such as the rotation of an antenna or a rotating *stirrer* (a scatterer) in the case of an aperture coupling. Contemporary oven designs also include a rotating turntable for the load placement in addition to (or in a few cases the substitution for) the stirrer. Moving conveyor belts also help smooth out heating patterns, but they are employed almost exclusively in industrial systems.

Practical microwave ovens dispense with a circulator and means of monitoring reflection (Fig. 1). These elements, however, are almost mandatory in high-power industrial systems, which operate at powers of many tens of kilowatts. Because the magnetron is not isolated from the variable load by a circulator, it will exhibit significant pulling, on the order of 10 MHz to 20 MHz. The effect of the changing load on the power and frequency of the magnetron is shown in the Rieke diagram supplied by the tube manufacturer. For maximum efficiency, this diagram points the oven designer to the selection of a load impedance of a matched load or somewhat into the sink region of the diagram.

Because of the complexity of the situation, including the need for accommodating any food load, the feed design is optimized by empirical techniques. With water loads or even actual food loads, the input impedance is determined with a suitable reflectometer circuit (3,4). Data obtained are a Smith chart representation similar to that shown in Fig. 7, where at a fixed frequency (e.g., 2450 MHz) the recurring path of the impedance locus is shown as the oven stirrer goes through its cycle. Figure 7(a) shows the impedance pattern for a large load of 2000 mL. It is desirable that the pattern be located close to the center match point or slightly into the sink phase of the magnetron [determined by appropriate techniques, (3,4)]. This is done by appropriate tuning techniques, for example, by adjusting the length of the waveguide or adding a tuning post. Of course, all of this was done at a single frequency, hopefully to approximate the dominant frequency emitted by the magnetron at full power. But the oven impedance is a rapid function of frequency as well. For example, Fig. 8 shows a typical recorded impedance at a fixed position of an antenna (or stirrer) over the frequency range of 2.4 to 2.5 GHz. Thus, the designer must examine a two-dimensional array of data sets or plots such as those of either Fig. 7 or Fig. 8 and adjust for an optimum feed match over the anticipated range of frequency and stirrer position. Figure 7(b) shows the impedance plot at one frequency for an empty oven as the stirrer rotates. The wildly gyrating pattern is not susceptible to matching, of course; but its importance lies in signifying that when an oven operates with no load or light load (like popcorn), it will subject the magnetron to an extreme of impedance variations. This in turn leads to a wider range of frequency and noise emissions including frequency skips, etc.



(a)

(b)

Figure 7. Input impedance contour of a microwave oven at a constant frequency as the variable element (stirrer) goes through its cycle: (a) for a 2000 mL water load, (b) for an empty cavity.

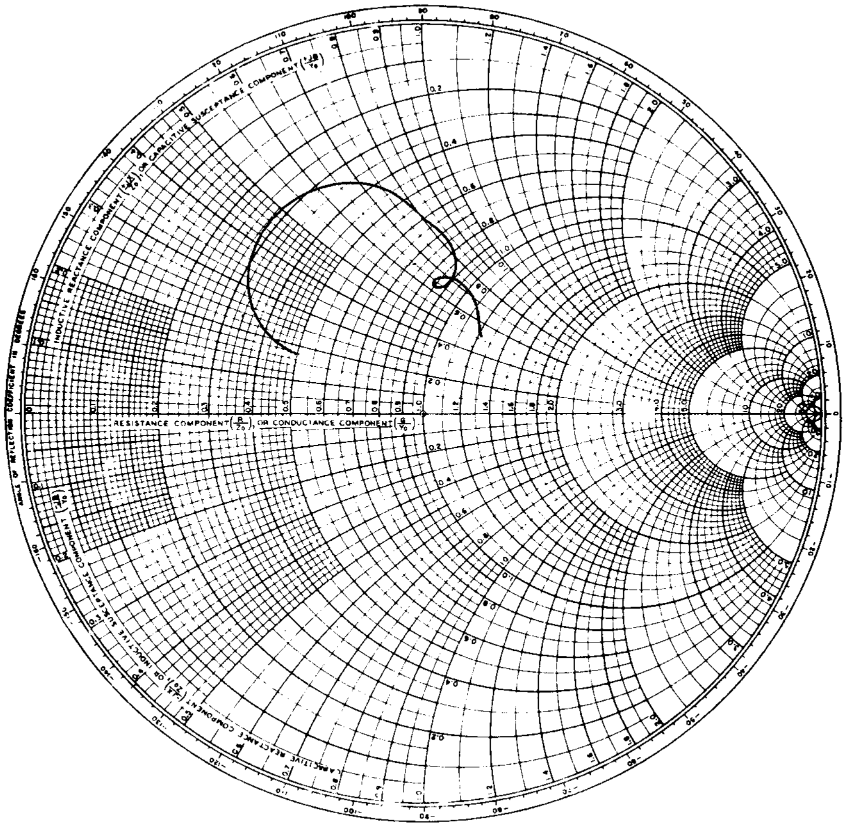


Figure 8. Input impedance contour of a microwave oven at a constant position of the variable element (stirrer) as frequency is swept from 2.4 to 2.5 GHz.

Current magnetrons at 2.45 GHz may exhibit an efficiency of 70%. Because of losses in the power supply and losses in the feed and cavity, the net efficiency for a large load may be only of the order of 50%. For smaller loads down to 50 mL, there will be a further significant reduction of efficiency as shown in Table 2 taken from a typical set of data for several current ovens. The dominant causes for low efficiency at small loads are reduced magnetron efficiency at unfavorable load phases and reduced microwave circuit efficiency with significant heating of metal walls and dielectric parts, such as a tray.

Heating patterns, especially at 2.45 GHz, are notoriously difficult to replicate and optimize. An acceptable variation in array tests is a 10 to 20% variation in temperature rise values. The prediction of an even measurement of heating patterns is a complex problem and no ideal solution has been found. For very thin sheets, frequency diversity as provided by a traveling wave tube (TWT) (e.g., 2 to 4 GHz) yields dramatically improved uniformity (15). For most applications however, TWTs remain unacceptably high in cost.

Table 2. Effective Power Levels for Various Size Water Loads in a Typical Microwave Oven (Three Different Models); 1–2 Min Operation

Water Load (mL)	Measured Power Relative to Power at 1000 mL		
	Oven A[a]	Oven B[b]	Oven C[c]
100	0.61	0.52	0.59
250	0.44	0.88	0.74
500	0.83	0.96	0.80
1000	1.00	1.00	1.00

[a] Oven A Power at 1000 mL: 673 W.

[b] Oven B Power at 1000 mL: 705 W.

[c] Oven C Power at 1000 mL: 754 W.

Conveyor systems, by virtue of varying load position, measurably and usually acceptably improve heating uniformity. Most high-power systems at 915 MHz utilize conveyors. On the other hand, circulators are used so that the magnetron frequency is not pulled. There remains only a few megahertz of frequency pushing, which is not a large contribution to frequency diversity as an element in improving uniformity.

POWER SOURCE PROPERTIES

Because the magnetron is almost exclusively the microwave generator of choice for microwave heating systems, it is important to focus on the properties of that tube and its associated power supplies. These determine the operating power spectrum from pushing and pulling characteristics. Furthermore, the noise and moding characteristics of the magnetron impacts on interference phenomena and the ability to meet increasingly stringent radiated and conducted noise limits imposed by regulatory authorities. Figure 9 is a schematic depicting the main electronic circuits and elements in a microwave oven. A half-wave high-voltage power supply is indicated with both filament and high-voltage secondary on the same transformer. This reflects the fact that most microwave ovens are cold-start. Thus, the magnetron current is a rectified pulse of roughly half-sinusoidal shape with a repetition frequency of 60 Hz and a pulse width of roughly 8 ms. The peak current is about 1 A for an average current of 0.3 A for a 700 W to 800 W oven.

The magnetron is known to exhibit high noise at currents below 0.3 A, occasional discrete spurious sideband signals for currents between 0.3 A and 0.6 A, and is typically quiet above 0.6 A (16). The result is that the typical magnetron radiates spurious noise and signals in 1 ms pulses during the rise and fall of each pulse. Figure 10 depicts a full-wave power supply that yields a current waveform of two rectified half-waves per 60 Hz period and, therefore, lower peak current for the same average current. This does little to reduce magnetron noise. Note that in this supply there is a separate filament transformer. This supply may be used in commercial ovens. Figure 11 is a photo of several modern magnetrons. Note the small size (approximately 4 in. maximum dimension) and the *filter box* that reduces base-band radiation and emissions conducted to the power line.

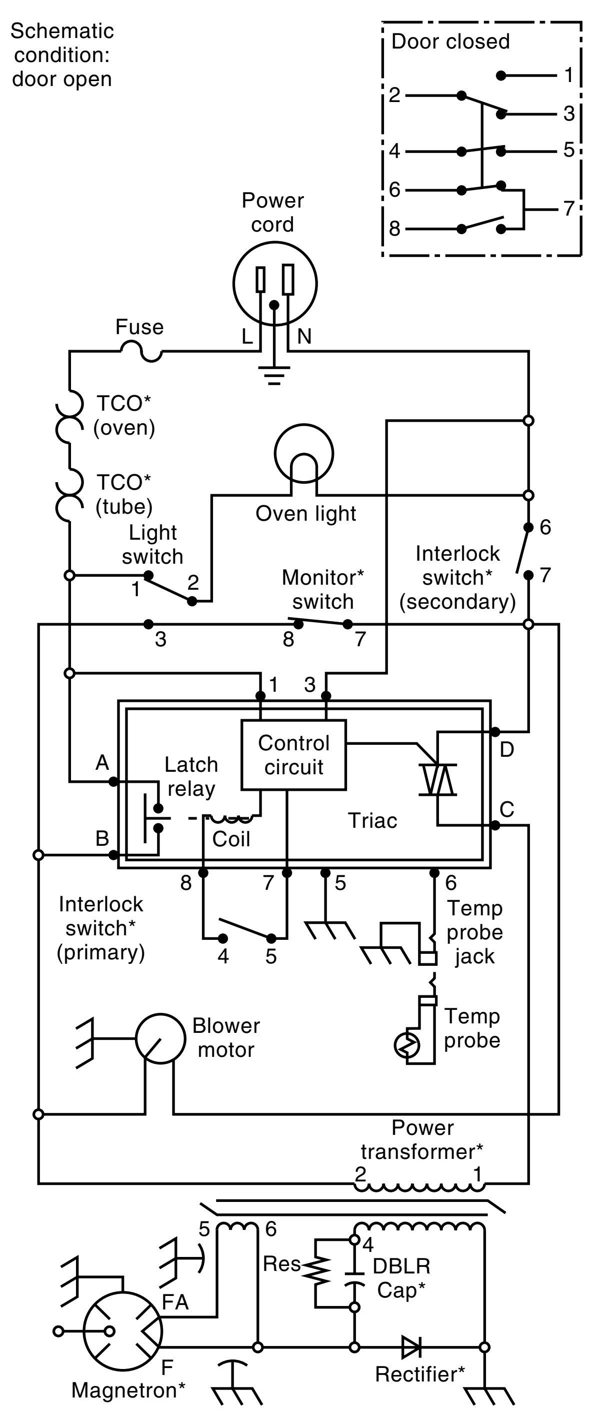


Figure 9. Schematic diagram of a microwave oven showing half-wave doubler power supply, interlock system, and electronic controls. (Courtesy of Amana Appliances.)

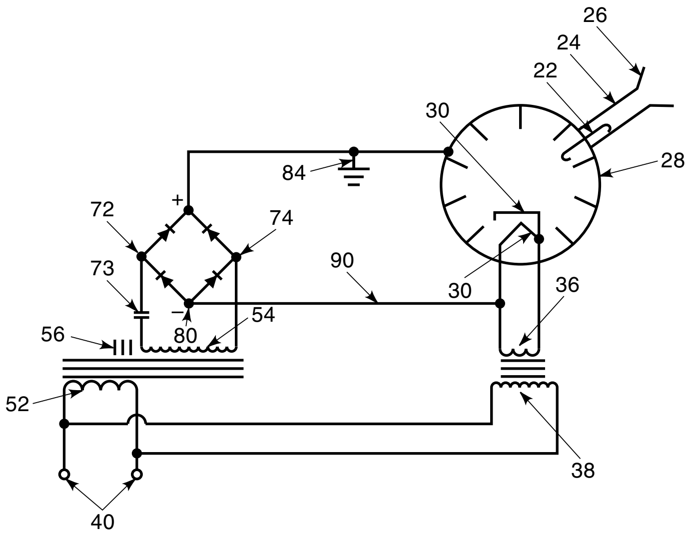


Figure 10. Schematic diagram of a full-wave doubler supply with separate filament transformer sometimes used in commercial products.

Figure 12 is an example of the radiated noise (peak signals) a few feet from a microwave oven when operating with a light load. Peak levels approaching 100 dB/pW effective radiated power are not uncommon in the range between 2.3 and 2.4 GHz. Because of the potential interference with various wireless communications systems, there is activity within CISPR (Special International Committee on Radio Interference) to apply more stringent limits on noise radiated from magnetron-powered systems (17).

Magnetrons can mode and produce spurious signals in the 4 to 5 GHz range that have interfered with satellite communication links. This can occur when there is insufficient cathode emission (as at the end of life) or even when there is too much emission. This occurs because high emission may strengthen spurious sideband oscillations that can also cause moding. Figure 13 shows an example of a recorded magnetron voltage-current trace during such a moding event. Magnetrons in microwave ovens will exhibit as much as 4 to 5 MHz pushing and up to 20 MHz of frequency pulling.

In the higher power systems at 915 MHz for industrial use, the magnetrons are always protected by a circulator. Therefore, there is no pulling by load variations. Furthermore, the high-voltge power supplies have a moderate amount of filtering. There still might be a residual ripple of ±10% in anode current. This will yield as much as 2 MHz pushing of frequency.

SAFETY CONSIDERATIONS

The greatest perceived risk from microwave heating systems is that of potential exposure to microwave energy which leaks

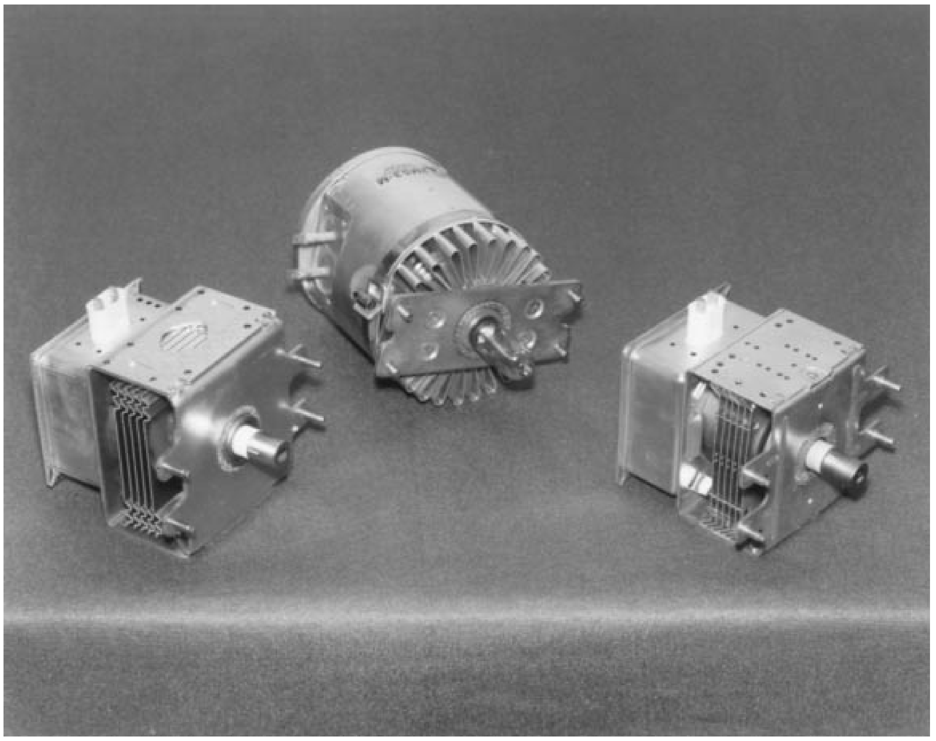


Figure 11. Photograph of some current cooker magnetrons for microwave ovens.

from the machines or ovens. Historically there has been general agreement among health and safety agencies in the United States (i.e., the FDA and OSHA) that the voluntary consensus C95.1 standard (18) should be the basis for assessment of potential exposure hazards. Microwave ovens, however, are regulated by stringent emission standards developed by the FDA—a limit of 5 mW/cm^2 at any point 5 cm from the external surface of the oven (when new, 1 mW/cm^2). The conservative nature of this limit as well as design techniques for screen and door seals has been reviewed by the author (19). In addition, multiple interlocks and monitor circuits as Figure 9 depicts, insure a very small probability of inadvertent exposure if an access door is opened during operation of a microwave oven. Similar safety procedures are followed voluntarily for industrial systems.

Other potential hazards in high-power microwave heating systems involve potential superheating and explosions (related to hot spot phenomena, see Fig. 3). In addition, there is the possibility of fires, which are sometimes related to hot spots but more often to arcing phenomena. Safety considerations for industrial systems have also been reviewed in more detail recently (20).

When dealing with food stuffs, there is some concern that nonuniform heating (or cooking) in microwave systems (the

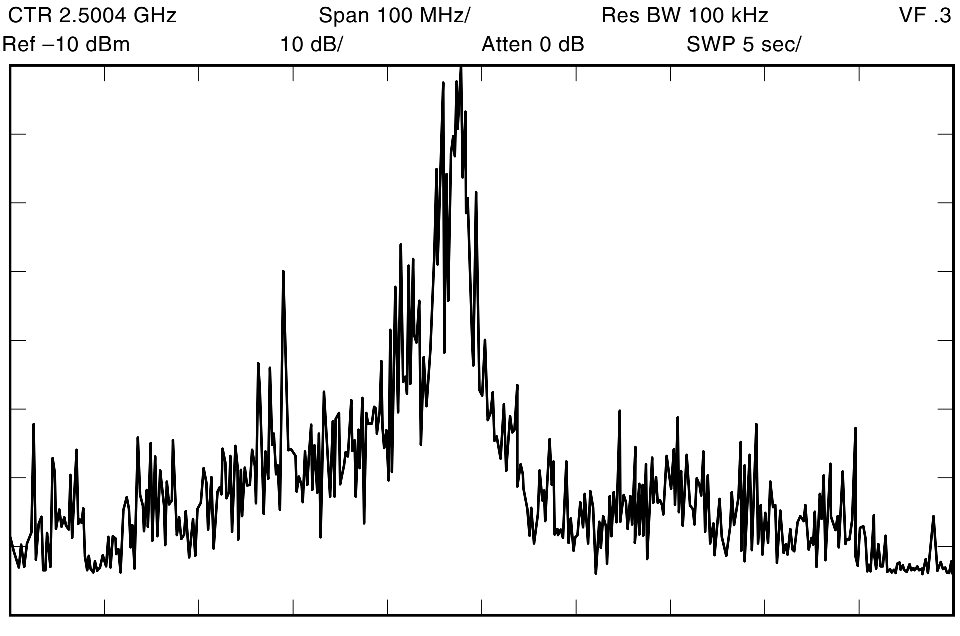


Figure 12. Measured radiated noise from a microwave oven with no load; spiral antenna 3 ft from the front of the oven.

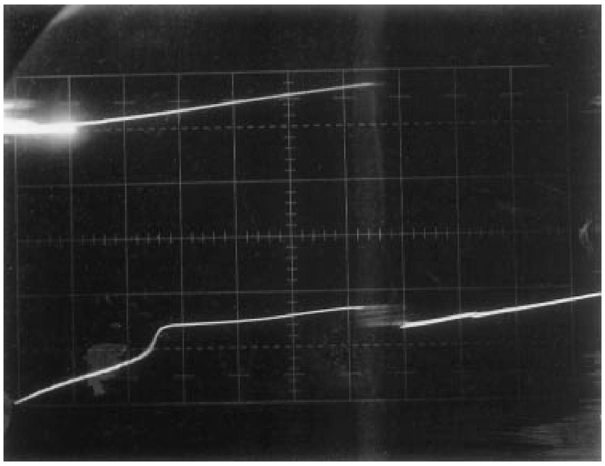


Figure 13. Voltage-current trace of a magnetron depicting moding at a spurious oscillation discontinuity; vertical—250 V/div.; horizontal—0.1 A/div.

defect of a cold spot in the heating pattern) will result in insufficient killing of unhealthy bacterial or viral agents on the surface of the food. This has led to some unwise recommendations for extra high temperatures when heating by microwaves. The most recent consensus is that more emphasis should be placed on food standards without relying on the heating of foodstuffs for food safety.

FUTURE ADVANCES IN MICROWAVE HEATING

Microwave heating is in its infancy as pointed out by Kapitza (21). Future expansion in large part awaits the development of efficient and low-cost power sources at various frequencies and power levels beyond what is now available. Thus, in the future one expects such power sources at 5.8 GHz, 24.125 GHz, and the millimeter-wave ISM frequencies. In addition, the availability at power levels down to 100 W, as well as high powers of many kilowatts, will spur many new applications. At present, many such applications are being explored (22) in the fields of chemistry, ceramics, and materials processing. In addition, there are applications to agriculture, pharmaceuticals, and various medical procedures.

In parallel with heating applications are important nonheating power applications, such as microwave-powered lighting (23). The list of research needs includes: (*1*) a resolution of the efficiency versus noise tradeoff inherent in magnetrons, (*2*) the achievement of successful computer models (24) for characterizing real-life microwave heating systems, (*3*) improved applicators of various types, (*4*) improved door seals and suppression tunnels to meet noise limits, and (*5*) the exploitation of pulse modulation techniques for special interactions as in chemistry (25).

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