MICROWAVE TECHNOLOGY

1. Introduction

The application of electrical or electromagnetic (EM) energy to materials as part of some chemical process is a broad subject that has a long history in chemical technology. Electrical energy can be delivered to materials through conductive, near-field coupling, or radiative techniques. The microwave portion of the electromagnetic spectrum in its role as a power source for chemical and materials processing is discussed herein. Microwave is the name applied to the central portion of the nonionizing radiation part of the electromagnetic spectrum. Nonionizing radiation has quantum energy too low to ionize an atom on a single event basis (1) and conventionally is defined as ranging from d-c power to visible light. This portion of the spectrum can be divided into five regions in order of increasing frequency: static, quasistatic, microwave, quasioptical (nanowave), and optical.

Microwaves may be used to ionize gases when sufficient power is applied, but only through the intermediate process of classical acceleration of plasma electrons. The electrons must have energy values exceeding the ionization potential of molecules in the gas (see Plasma technology). Ionizing radiation exhibits more biological-effect potential whatever the power flux levels (2).

The term radio waves has evolved to refer to coherent generation of energy in the nonionizing spectral region and its application for information processes such as communication, broadcasting, and target location, eg, radar. The development of radio-wave technology began at lower frequencies where electromechanical, then vacuum-tube, and later solid-state techniques are easiest to apply. The term microwaves was introduced just before World War II (3). Vacuum-tube development had proceeded far enough toward higher frequency to permit significant power levels to be transmitted in hollow pipes (waveguides) of practical laboratory size (ca 15-cm dia) and high (>20 dB) antenna gain to become feasible using practical rotating diameters, eg, <5 m. This led to definitions of the microwave spectrum as >1000 MHz. Over the years, these definitions have been variously specified to include frequencies as low as 100 MHz to as high as 3000 GHz. The more scientific meaning of microwaves refers to the principles and techniques applying to electromagnetic systems (4) where the principal dimensions are of the order of a wavelength, γ, or more broadly ca $0.1-10\,\mu$.

For many materials, in particular biological tissue, maximum penetration of the electromagnetic energy irradiating objects of macroscopic size occurs in the microwave range (5). At low frequencies, the human body acts as a conductor and the electric field is shunted out, ie, the body has a shielding effect. At high frequencies, the penetration depth (decay by 1/*e* in field strength) rapidly becomes much smaller than body dimensions. Only in the microwave range, ca 100 MHz, is deep penetration significant. At low frequencies, penetration of magnetic fields into most materials is efficient. Almost all microwave interactions with lossy materials, ie, those absorbing microwave energy, involve the electric field which penetrates only in the microwave range, however. The property of resonance in lossy materials is related to resonant conducting antennas and resonant low loss dielectric modes. Most materials of potential interest for microwave processing have dielectric properties that permit interpretation in terms of geometric resonance. A consequence is the scaling of processing frequency having some characteristic size of the material or the container in which it is processed.

Another reason for interest in microwaves in chemical technology involves the fields of dielectric spectrometry, electron spin resonance (esr), or nuclear magnetic resonance (nmr) (see MAGNETIC SPIN RESONANCE). Applications in chemical technology relating to microwave quantum effects are of a diagnostic nature and are not reviewed herein.

Microwave power is an important factor in the commercial processing of materials. These processes almost exclusively utilize classical interactions such as dielectric heating in solids or plasma heating. Other interactions may also be possible. The field of microwave power applications as distinct from information processing is relatively new. Development and possibilities were recognized in 1965 (6). Interest followed (7–9). The International Microwave Power Institute (IMPI), founded in 1966 in Canada, has offices in Manassas, Virginia. Publications of IMPI include two newsletters, symposium digests and proceedings, and workshop proceedings as well as the *Journal of Microwave Power*. A number of reviews (10–13) and books (14,15) are available covering microwave power applications in a wide range of areas including food processing (qv), ceramics (qv) processing, biological tissue fixation, chemical analysis and processing, and plasma applications as well as microwave power transmission.

2. Microwave Power Applications

2.1. Frequency Allocations. Under ideal conditions, an optimum frequency or frequency band should be selected for each application of microwave power. Historically, however, development of the radio spectrum has been predominantly for communications and information processing purposes, eg, radar or radio location. Thus within each country and to some degree through international agreements, a complex list of frequency allocations and regulations on permitted radiated or conducted signals has been generated. Frequency allocations developed later on a much smaller scale for industrial, scientific, and medical (ISM) applications.

Table 1. **Frequency Allocations for ISM Applications**[a,b]

Frequency, MHz	Region	Conditions
6.765–6.795	worldwide	special authorization with CCIR[c] limits; both in-band and out-of-band
13.553–13.567 26.957–27.283 40.66–40.70 433.05–434.79	worldwide	free radiation bands
433.05–434.79	selected countries in Region 1[d]	free radiation bands
433.05–434.79	rest of Region 1[d]	special authorization with CCIR[c] limits
902–928	Region 2[e]	free radiation band
$2.40-2.50\times10^3$	worldwide	free radiation band
5.725–5.875	worldwide	free radiation band
24.0–24.25	worldwide	free radiation band
61.0–61.5 122–123 244–246	worldwide	special authorization with CCIR[c] limits; both in-band and out-of-band

[a]Ref. 16.
[b]ISM = industrial, scientific, and medical.
[c]CCIR = Internationa Radio Consultative Committee of the International Telecommunications Union (ITU).
[d]Region 1 comprises Europe and parts of Asia; the selected countries are Germany, Austria, Liechtenstein, Portugal, Switzerland, and Yugoslavia.
[e]Region 2 comprises the western hemisphere.

In 1979, the ISM frequency allocations were revised as a result of the World Administrative Radio Conference (WARC) (16). A considerable effort was made to increase the number and worldwide uniformity of ISM frequency allocations. Most of those proposals were rejected. The resulting allocations are listed in Table 1.

The three frequencies 13.56, 27.12, and 40.68 MHz are well-known allocations for radio-frequency (r-f) heating using quasistatic coupling to loads, such as a capacitor arrangement. The most popular of these assignments is 27.12 MHz for which the broadest bandwidth is authorized. This frequency also overlaps the frequency allocations for citizen's band (CB) radio in the United States. The techniques used at these frequencies are not generally considered microwave for small loads, but would be considered microwave if energy were applied to sufficiently large loads, as in the tentative attempts to heat oil shale (qv) *in situ*. The frequency 433.92 MHz, a harmonic of these three frequencies, is allocated only in some European countries (see Table 1). It is used mostly for medical diathermy and hyperthermia.

The remaining ISM allocations above 433.92 MHz are not harmonically related. This is unfortunate in terms of the problem of minimizing radio-frequency interference (RFI), except for the harmonic relation in the millimeter wave range.

The frequency bands at 915 and 2450 MHz (2375 MHz in the past in eastern Europe) are the most developed bands for microwave power applications. Microwave ovens are almost all at 2450 MHz. Many industrial heating applications are at 915 MHz. After the 1979 WARC, eastern Europe adopted 2450 MHz in place of 2375.

The higher frequencies, 5800 and 24,125 MHz, have been allocated for ISM for some years but have not been further developed. The unavailability of inexpensive efficient power sources (tubes) at those frequencies is the limiting factor. At the 1979 WARC, additional ISM allocations were adopted at 61.25, 122.5, and 245 GHz in anticipation of future applications. Power sources, especially gyrotrons, are available >30 GHz, but are expensive and generally <50% in efficiency, hindering the exploitation of this higher frequency region called millimeter waves.

In general, ISM applications at allocated frequencies are permitted to freely radiate energy within the allocated band. Any other users of this band must tolerate possible interference from such emissions. Emissions outside of these bands, however, must be limited to values specified by regulatory bodies such as the Federal Communications Commission (FCC) in the United States and verified by certain certification procedures (17). Typically, field strengths for signals within a 5 MHz band must be below 10 μV/m at a distance of 1.6 km from industrial heating equipment. In other countries, the RFI regulations must conform to similar limitations. In many cases, the Comité International Spécial de Perturbations Radioélectriques (CISPR) limits, are applicable (18).

Experiments and even production operations can be conducted at any frequency providing the radiated and conducted signals meet the applicable rfi limits for ISM equipment. Tests to certify this stipulation must be carried out before inception of operations. This implies well-shielded enclosures at high power levels which is expensive but justified in certain applications.

There has been increasing co-use of ISM bands by communications interests, technically under the condition that any interference that may result from co-existing ISM applications be accepted. Proposals to reallocate part of the ISM bands for communication purposes have been made and the FCC had proposed auctioning a part (2402–2417 MHz) of the 2.45 GHz ISM band for primary use under co-use conditions. The number of microwave ovens has grown enormously (ca 200 million as of 1995). The CISPR has therefore been studying new limits in the 1–18 GHz range in order to minimize interference with wireless communications systems expected to occupy allocations across the band from 1 to 3 GHz by the late 1990s. The resulting regulations are likely to have some impact on microwave oven and higher power equipment design because of the well-known excess noise produced by magnetrons in sideband regions, ie, 2.2–2.4 and 2.5–2.7 GHz for a 2.45 GHz source (19).

2.2. Principles in Processing Materials. In most practical applications of microwave power, the material to be processed is adequately specified in terms of its dielectric permittivity and conductivity. The permittivity is generally taken as complex to reflect loss mechanisms of the dielectric polarization process; the conductivity may be specified separately to designate free carriers. For simplicity, it is common to lump all loss or absorption processes under one constitutive parameter (20) which can be alternatively labeled a conductivity, σ, or an imaginary part of the complex dielectric constant, ϵ^{i}, as expressed in the following equations for complex permittivity:

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

where ϵ is the complex dielectric permittivity in F/m, $\epsilon_0 = 8.86 \times 10^{-12}$ 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 (mhos/m) which is equivalent to the following:

$$\epsilon_i = \sigma/\omega\epsilon_0$$

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

$$\tan\delta = \epsilon_i/\epsilon_r = \sigma/\omega\epsilon_r\epsilon_0 \quad (2)$$

From Maxwell's equation (21), the current density J in A/m^2 is related to the internal electric field, E_i, by equation 3:

$$J = (\sigma - j\omega\epsilon_r\epsilon_0)E_i \quad (3)$$

thus the rate of internal density of absorbed energy,or power, P, is given by equation 4, where rp = real part of:

$$P = \mathrm{rp}(J \cdot E^*) = \sigma|E_i|^2 \quad (4)$$

or simply,

$$P = \omega\epsilon_r\epsilon_0\tan\delta|E_i|^2 \quad (5)$$

Equation 5 is the practical equation for computing power dissipation in materials and objects of uniform composition adequately described by the simple dielectric parameters.

The internal field is that microwave field which is generally the object for solution when Maxwell's equations are applied to an object of arbitrary geometry and placed in a certain electromagnetic environment. The E_i is to be distinguished from the local field seen by a single molecule which is not necessarily the same (22). The dielectric permittivity as a function of frequency can be described by theoretical models (23) and measured by well-developed techniques for uniform (homogeneous) materials (24).

The dielectric permittivity as a function of frequency may show resonance behavior in the case of gas molecules as studied in microwave spectroscopy (25) or more likely relaxation phenomena in solids associated with the dissipative processes of polarization of molecules, be they nonpolar, dipolar, etc. There are exceptional circumstances of ferromagnetic resonance, electron magnetic resonance, or nmr. In most microwave treatments, the power dissipation or absorption process is described phenomenologically by equation 5, whatever the detailed molecular processes.

The general engineering task in most applications of microwave power to materials or chemicals is to deduce from the geometry of samples and the electromagnetic (EM) environment (applicator), the internal field distribution, E_i(r), and hence the distribution, *P(r)*, of absorbed power. From this, the temperature distribution can be calculated, and processing time and applied power required for the desired result deduced.

The electromagnetic problem is one of solving Maxwell's equations under various boundary conditions (21). If the object is small, the applied EM field may be little perturbed and perturbation theory is adequate (26). If the object is large in terms of penetration depth, quasioptical radiation calculations are valid. If the object is of the order of a wavelength in dimension, geometric resonance can apply using a moderately enhanced absorption cross section. Many calculations for simple models of biological tissue are available (27). There are also many computer programs, software, or codes for the detailed numerical solution for electromagnetic fields. The capabilities and pitfalls of modern computer solutions have been reviewed (28, 29).

Penetration depth, D, at which fields are reduced by a factor of $1/e$, is given by the following formula:

$$D = 0.225\lambda/\epsilon_r^{1/2}\cdot((1+\tan^2\delta)^{1/2}-1)^{1/2} \tag{6}$$

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

$$D \cong \frac{0.318\ \lambda}{\epsilon_r^{1/2}(\tan\delta)} \tag{7}$$

where λ is the free-space wavelength of the microwaveradiation.

For low frequencies or small objects, the components of electrical fields normal to a material boundary are related by equation 8:

$$\left|\frac{E_i}{E_0}\right| \cong (\omega\epsilon_0/\sigma) \tag{8}$$

where E_i and E^0 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^0 is parallel to the surface, then the internal field is equal to E^0. Thus if the applied field is parallel to the long axis, the internal E_i is ca E^0. Otherwise, if E^0 is perpendicular to the long axis, the internal field E_i is given by equation 8 and $E_i < E_0$ for even moderate conductivity ca 1 S/m.

In the typical application of microwave power, the engineering task is to solve for the internal fields of an object for the given system, compute its heating distribution vs time and resulting change of state, and similar problems. The dielectric parameters are key data for such a calculation, particularly the dependence on temperature. Literature references to such dielectric data are available (30, 31). These do not include extensive data on temperature dependence except for water. Because of the concentrated interest in microwave cooking at 2450 MHz, more data are available at this frequency. Temperature dependence of typical food dielectric properties are shown in Figure 1 (32). Table 2 contains information on dielectric properties for foods and other materials. Other references and techniques for measuring dielectric parameters are given in the literature (33).

A basic problem in microwave heating applications is evident in Figure 1**b**. If tanδ increases with temperature, runaway conditions may be created in hot spots, although there are possible mitigating factors. Because water shows the

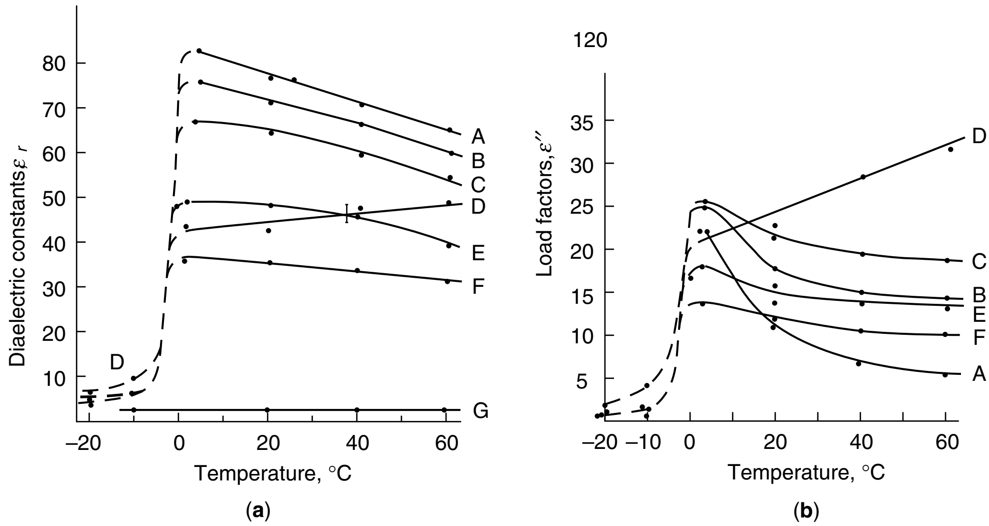

Fig. 1. Properties of foods near 2.45 GHz as a function of temperature, where A represents distilled water; B, cooked carrots; C, mashed potatoes; D, cooked ham; E, raw beef; F, cooked beef; and G, corn oil: (**a**) dielectric constants and (**b**) load factors, $\epsilon = \epsilon\tan\delta$ (32).

opposite behavior above freezing, it is presumably conducive to even cooking. Below freezing, the loss of water is much lower, hence there is a basic conceptual difficulty in designing a process for uniform thawing by microwave heating. Heating to a point short of the melting point, on the other hand, is aided by a negative value of the curve slope and underlies the commercial success of meat tempering. The behavior of ham (Fig. 1**b**) reflects the effect of salts and increased ion conductivity with temperature.

Table 2. **Dielectric Properties of Foods and Other Materials at 2450 MHz and 20°C**

Material	ϵ	tan δ
distilled water	78	0.16
raw beef	49	0.33
paper	2–3	0.05–0.1
wood	1.2–5.0	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

Most demonstrated and useful effects of microwave irradiation of materials are explainable as heating influences. The results may be unique to microwave heating because most conventional heating techniques are not associated with deep penetration of the radiant energy. Speculations on more esoteric, sometimes called nonthermal or field-force, influences have arisen. The only well-demonstrated effect in this category is that of thermoelastic conversion accompanying short pulses or rapid changes of microwave radiation levels (34,35). Other speculative mechanisms, generally considered to be very weak, are those of electrostriction (36), dielectrophoresis (37), and pearl-chain effects. In all these cases the effects are expected to be proportional to $|E|^2$. A review of these mechanisms in biological systems is available (38).

The electromagnetic interactions that make use of the microwave magnetic fields are generally of less interest commercially. There is, however, considerable scientific and possibly medical interest. Magnetic fields, H, play a key role in weak mechanical forces induced by electromagnetic waves (39). The interactions in esr and nmr are of scientific interest and have been successfully developed into the medical imaging technology (qv) called magnetic resonance imaging (mri) (40).

The most widespread applications of interactions with microwave magnetic fields are those of ferromagnetic materials. The dissipation of microwaves in systems of ferromagnets can be quite complicated especially in the presence of nonreciprocal transmission properties in biased ferrite systems (see FERRITES; MAGNETIC MATERIALS) (41). In the simplest cases, eg, linearly polarized or operations far from ferromagnetic resonance, the localized absorption, P^{abs}, in analogy with equation 5, is given by equation 9:

$$P_{\text{abs}} = \omega\mu''|H|^2 \tag{9}$$

where μ'' is the imaginary part of the magneticpermeability and the contributions from the imaginary part of the cross-components of the permeability tensor are negligible. Dissipation is temperature dependent and disappears above the Curie temperature of the material. This is the basis of some browning dishes developed for microwave oven use, designed for browning at a Curie temperature of ca 230°C (42).

The interaction of microwaves with ferrites (qv) has many complicating features. Low field loss mechanism (41), nonlinear effects, and losses at high power levels (41,43) as well as dielectric losses are among these.

The application of microwave power to gaseous plasmas is also of interest (see PLASMA TECHNOLOGY). The basic microwave engineering procedure is first to calculate the microwave fields internal to the plasma and then calculate the internal power absorption given the externally applied fields. The constitutive dielectric parameters are useful in such calculations. In the absence of d-c magnetic fields, the dielectric permittivity, ϵ, of a plasma is given by equation 10:

$$\epsilon = \epsilon_0\left(1 - \frac{Ne^2}{m(\omega^2 + v_c^2)\epsilon_0}\right) \tag{10}$$

and the conductivity, σ, by

$$\sigma = \frac{Ne^2 \upsilon_c^2}{m\left(\omega^2 + \upsilon_c^2\right)} \tag{11}$$

where N is the electron volumedensity, ω is the microwave radian frequency, υ_c is the collision frequency, and e and m are the electron charge, 1.602×10^{-19} C, and mass, 9.11×10^{-31} kg, respectively.

Maximum power transfer to electrons for a given internal field occurs when $\upsilon_c = \omega$. The plasma frequency, ω_p, is the frequency at which $\epsilon = 0$:

$$\omega_p = \left(\frac{Ne^2}{m\epsilon_0}\right)^{1/2} \tag{12}$$

Because the permittivity is negative for $\omega < \omega_p$, transmission through the plasma is cut off and penetration is only by means of evanescent waves.

Various data sources (44) on plasma parameters can be used to calculate conditions for plasma excitation and resulting properties for microwave coupling. Interactions in a d-c magnetic field are more complicated and offer a rich array of means for microwave power transfer (45). The literature offers many data sources for dielectric or magnetic permittivities or permeability of materials (30,31,46). Because these properties vary considerably with frequency and temperature, available experimental data are insufficient to satisfy all proposed applications. In these cases, available theories can be applied or the dielectric parameters can be determined experimentally (47).

3. Instrumentation

3.1. Power Sources. The development of electron tubes, including those for the microwave range, is a mature field (6). It is feasible to generate almost any desired power for most microwave frequencies of practical interest, limited only by costs. Power limits for various devices are shown in Figure 2 (48). Below 500 MHz large power is typically generated by gridded tubes. Above 1 GHz, the feasible power drops roughly as f^{-5}, where f is frequency, because of fundamental limitations on electron beam current density and circuit losses. The boundary is similar for microwave tubes such as magnetrons, klystrons, traveling wave tubes, and backward wave oscillators, except it is at a frequency roughly 30 times higher.

Power sources in the millimeter wave range are mostly in the category of extended interaction klystrons or narrow band backward wave oscillators (49). Power outputs of tens of watts or even more than 100 W are feasible but available tubes are quite expensive and suffer from low life and efficiency compared to what is available at low microwave frequencies. Very high powers of many kilowatts continuous wave (CW), and hundreds of kilowatts low duty cycle, have been generated by gyrotrons (50). These have been developed mostly for fusion energy (qv) at government laboratories and reflect large development costs.

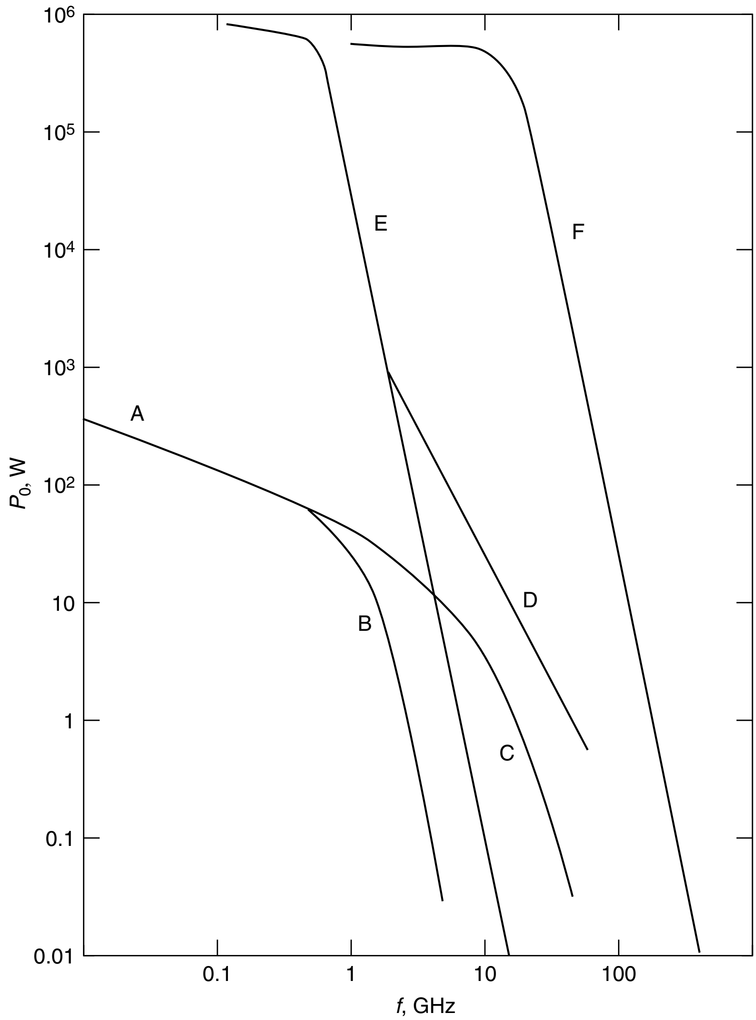

Fig. 2. Maximum limits of average output power *P_0* from power sources at average wattages or continuous wave (CW) where A is the solid state; B, transistors; C, varactors and solid-state avalanche diodes; D, theoretical limit for solid-state devices; E, gridded tubes; and F, microwave tubes.

Because of the unavailability of inexpensive and efficient tubes for millimeter wave frequencies, ISM applications in that range are essentially nil.

Significant power is generated only below 300 GHz. Above this frequency, the expectation has always been that useful laser sources would be eventually developed (51). Thus the most difficult region for power generation appears to be that of submillimeter waves or the far infrared, ie, 300–3000 GHz (1000–100 μm).

The remaining class depicted in Figure 2 is that of solid-state devices, ie, transistors, various types of semiconductor diode amplifiers, etc. At frequencies below 1 GHz, generation of hundreds or even at the lower frequencies, kilowatts, is feasible by solid state. Above 1 GHz power capability of solid-state sources drops. Development of efficient (~50%) sources at about the 50 W level at S-band (2 GHz) has been demonstrated. It is reasonable to expect solid-state sources to replace tubes for low frequency and low (<100 W) power applications (52). For high power or high frequency, however, tube sources should continue to prevail.

The most dramatic evolution of a microwave power source is that of the cooker magnetron for microwave ovens (48). These magnetrons are air-cooled, weigh 1.2 kg, generate well over 700 W at 2.45 GHz into a matched load, and exhibit a tube efficiency on the order of 70%. Application is enhanced by the availability of comparatively inexpensive microwave power and microwave oven hardware (53). The cost of these tubes has consistently dropped (11) since their introduction in the early 1970s. As of this writing (ca 1995), cost is <$15/tube for large quantities. For small quantities the price is <$100/tube.

The availability of a low cost source of microwave power has led to an explosion of work at 2.45 GHz on newer microwave power applications. For many applications at 2.45 GHz, it is feasible to utilize a number of low cost tubes to generate large total powers, eg, 25 or 50 kW. In such cases, multiple feeds or antennas to a heating chamber are used. At 2.45 or 0.915 GHz, it is preferable to use larger power sources at 5, 25, or even 50 kW. Table 3 shows available tubes commonly considered for use at 0.915 or 2.45 GHz. Most of these tubes are magnetrons, although klystrons become competitive at the higher power levels. These tubes are designed to meet the requirements of government agencies on out-of-band spurious emissions. Hence, filter boxes are used around the high voltage terminals of the tubes.

Table 3. **Magnetrons for ISM Applications**[a]

Tube manufacturer and type	Frequency, MHz	Nominal power, kW	Voltage, kV
Hitachi2M107A	2455	0.900	4.2
2M214	2455	0.900	4.25
2M120	2455	1.45	4.5
Toshiba2M172A	2460	0.850	4.0
2M229	2460	0.850	4.0
2M240	2460	0.850	4.0
2M248	2460	1.000	4.35
Matsushita2M167B	2455	0.900	4.1
2M137	2455	1.260	4.5
Samsung2M204	2455	0.900	4.1
OM75S	2460	0.870	4.1
Goldstar2M613	2460	1.420	4.5
RichardsonNL10251	2450	1.50	3.6
YJ1442	2450	3.0	6.0
YJ1191A	2450	6.0	7.3
NL10257	915	1–5	6.5
NL10258-1	915	5–75	17.0
C9460E	915	60	16.1
BurleC9460E	915	60	16.0
CaliforniaCWM-60L	915	60	16.0
Tube Lab. CWM-3L	915	2.5	3.7

[a]ISM = industrial, scientific, and medical.

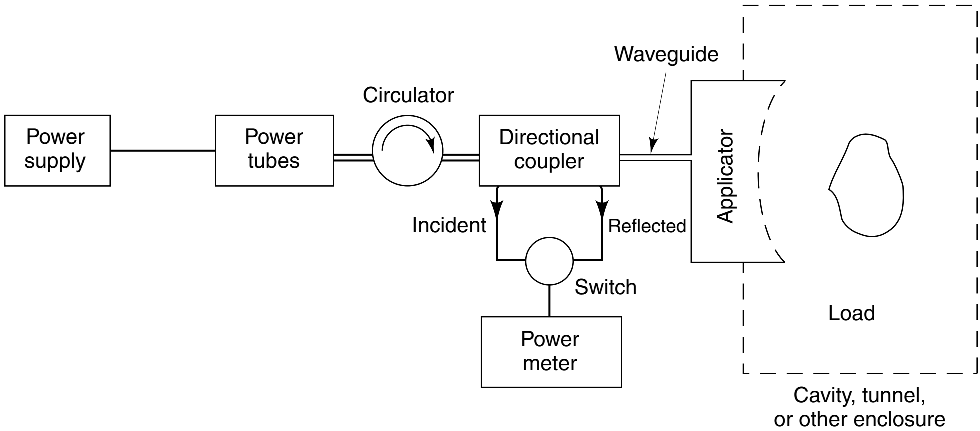

Fig. 3. Basic elements of a microwave power system for processing of materials.

Microwave tubes for other ISM bands are not commonly available as tubes designed specifically for ISM use. Available tubes, generally of military and communications types, are more expensive. Reasonably priced tubes exist at 0.915 GHz at high (>25 kW) power, but not at 5.8 GHz and higher, or at low (<kW) power at 0.915 GHz.

Use of traveling wave tube (TWT) amplifiers at power levels of hundreds of watts has been proposed (54) for power applications, at least when the heating chamber is well shielded. The potential advantage is an improved uniformity of heating when a broad band of frequency is used, ie, excitation of many modes. Disadvantages are high cost and lower (<50%) efficiency of the TWT.

3.2. Applicators and Instruments. The basic elements of a microwave power system for materials processing are indicated schematically in Figure 3. A power supply drives the microwave tubes with an applied d-c voltage or even raw rectified voltage (50 or 60 Hz). The former may be required of klystrons (55), whereas the latter has been perfected in the form of voltage doubler power supplies for microwave ovens (56). The microwave tube source is thus generally operated as a continuous wave (CW), ie, unmodulated signal, except for the possible incidental 60-Hz amplitude modulation for power applications. Only for a few applications is a capability of amplitude or frequency modulation required and these modifications would entail a significant departure from the present low cost sources. The spectrum of typical microwave power sources is not tightly controlled. Considerable frequency drift and signal broadening is tolerable within the most popular designated ISM bands.

Some power tubes can be operated without the need for a protective ferrite isolator. One example is the cooker magnetron (700 W) used in modern microwave ovens (57). At higher power levels, such as 25 kW, it is more common to employ a protective ferrite device, particularly in the form of a circulator (58), as shown in Figure 3. This results in a power loss equivalent to a few percentage points in system efficiency. The ferrite circulator prevents reflected power from returning to the power tube and instead directs it into an auxiliary dummy load. The pulling of tube frequency is thus minimized.

It is common to employ microwave power monitoring by means of a dual-directional coupler in the waveguide transmission system between the power tube and the useful load. Part of the coupled signals may be used for examination with spectrum analyzers, frequency meters, and other microwave instrumentation for special purposes. Generally, this is not necessary in a practical application. Many microwave measurement techniques have been described (59,60). Availability of components, plumbing, and instrumentation is well described in trade journals.

The useful load is the material to be heated by microwave or otherwise affected by exposure to microwave radiation. Some type of applicator, the feed (transmitter), or antenna arrangements that couple microwave energy into the load, is also needed. The object is to maximize the coupling. This is indicated by zero-reflected power in the waveguide monitoring system. Various waveguide components used to produce an effectively matched applicator, $P_{\text{ref}} = 0$, are not indicated in Figure 3 (61). The power transmitted by the applicator is not necessarily all captured by the load, ie, the circuit efficiency in the heating enclosure is not necessarily 100%. Generally it can be designed to be 90% or better, especially for large loads.

The heating system is calculated by taking into account the power supply efficiency (generally $>$90%), tube efficiency (60–90%), waveguide (including circulator) transmission efficiency (generally $>$90%), and circuit efficiency of the heating enclosure. The net efficiency of such systems, ie, useful power into load divided by line input power, varies significantly among systems, but a typical value is ca 50%. The U.S. Department of Energy (DOE) is proposing that manufacturers improve the efficiencies of consumer microwave ovens through improvements in high voltage transformer efficiency, circuit efficiency of oven cavity and waveguide, and the cooling fans (62).

The use of inverter-type power supplies (63) in place of doubler-type 60-Hz supplies results in significant reduction in the weight of microwave ovens. Disadvantages are primarily cost for the consumer market in addition to somewhat less efficiency and increased noise. Their use in commercial or industrial equipment is more attractive.

Different applicator types serve various forms, shapes, and sizes of the material being processed or heated. The latter may be gaseous plasma enclosed in a glass tube passing through a cavity or waveguide, thin films passing through a single cavity, or large-size boxes of frozen meat passing in a conveyor through a long metal enclosure. The aim to achieve efficient and uniform heating (or temperature) in the product is at the heart of the design of microwave power systems, and is reflected in much of the patent literature in this field (1). The number of U.S. patents related to microwave power applications has stayed at about 100/yr since the mid-1980s.

The large variety of possible applicators can be classified in various ways. Most fall into one of the following categories: single-mode cavity; folded guide; slow-wave structures; multimode cavity, batch, and conveyor fed; and radiating antenna. In the single-mode cavity, classical microwave theory and techniques about resonant cavities apply. Generally, the material being heated can be used to calculate the shift in cavity resonance frequency and change in cavity, Q, caused by the insertion of the material. This technique is better suited for measuring dielectric properties than most materials processing. It has been applied in special cases for heating (64) of thin fibers passing along the axis of a cavity of cylindrical symmetry, such that the fiber axis is aligned with the maximum E-field.

The folded guide applicator is formed by bending a rectangular guide in its E-plane to form a meander. Longitudinal slots in the broad walls in the center of the meander permit continuous passage of material in sheet form through the successive portions of guide with the sheets in the E-plane for good coupling. The meandering properties permit efficient heating without resonant cavity properties of high E-field and cavity losses. The folded guide is described in the literature (65).

Slow-wave structures (66,67) are related to the folded waveguide because the phase velocity of waves along an axis passing through all the guides, υ, ie, through the slots where the sheet material is fed, is less than that in free space, c, $\upsilon < c$. A variety of planar structures, meander lines, interdigital lines, and vane lines produce a region of fringing field where E or H vary as $e^{-\gamma x}$ where γ ca β ca ω/υ is the slow-wave propagation constant. In some cases, such structures are suitable for heating sheet material with more space flexibility than the folded guide. Similar slow-wave structures exist in cylindrical form with a fringing field.

It should be possible to achieve greater penetration into a load material using the fringing field of a slow-wave than can be achieved by plane-wave propagation (68). There are, however, no reports of practical application of these principles.

Perhaps the most generally used applicator is the multimode cavity, designed for both batch or conveyor fed processing. The theoretical properties of large loads have never been completely established. A few initial studies were reported (69,70). Earlier developments were marked by the use of waveguide stirrers (dump feeds) having rotating blades somewhere in the cavity acting as mode stirrers (71,72). It was later found that rotating antenna feeds achieve a more uniform heating of the load material (73,74).

A rotating turntable is a simple way to improve heating uniformity (75). A related technique is the use of a linearly moving load-bearing surface, ie, a conveyor belt. In carrying materials through a long cavity, each portion of the load undergoes, in principle, a similar history of field pattern and consequent heating. In Figure 4 a practical conveyor-fed cavity, typical of systems operating at 915 MHz, is depicted. In order to accept substantially sized boxes of material, the conveyor belt passes through long entrance and exit tunnels that are designed to minimize microwave leakage by various techniques, including liquid absorbers along the walls of the tunnels.

In some applications, such as the repair of road surfaces, the load cannot be enclosed in a cavity and radiating applicators must be used. These could be in the form of simple horns (76) or various modified waveguide apertures designed for microwave diathermy (77,78). They can be designed for efficient coupling for a closely spaced load surface as well as minimizing leakage or loss of energy to the sides.

In addition to the measurements of incident and reflected power, measurements related to field strengths, field patterns, and resulting heating may be

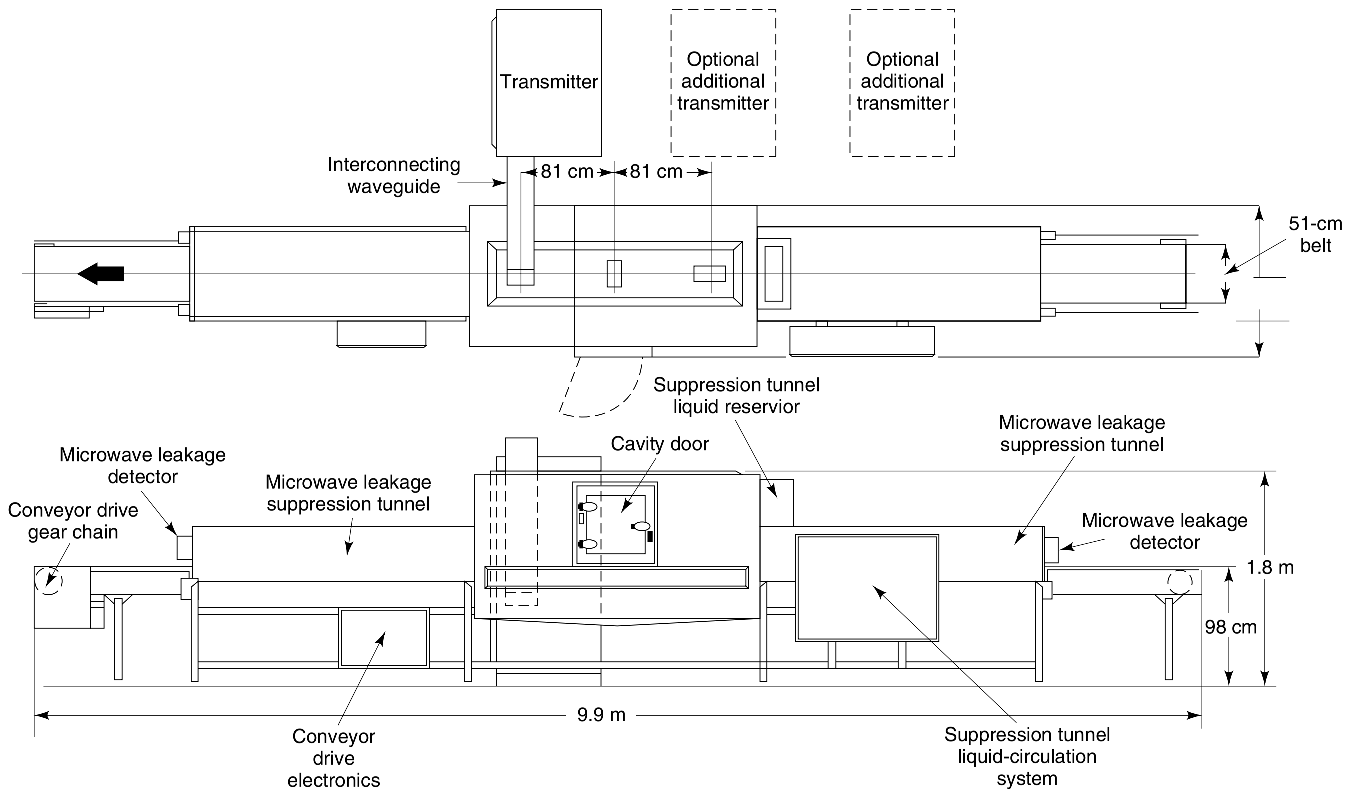

Fig. 4. Top and front views of typical high power conveyor-type industrial microwave equipment.

desired. In simple cavity waveguide or slow-wave systems, perturbation techniques (59) can be used to determine the *E*-field strengths on the load. This is done by measuring cavity resonance or structure-phase shifts. For multimode cavities the use of conventional *E*- or *H*-probes is laborious and not generally valid because of the perturbation of the feed lines for the probes. The electric field can be measured using small-discharge lamps (79). Various techniques, none completely satisfactory, have been used to determine field patterns in a plane or volume of a multimode cavity in the absence of the load (80–82).

The most satisfactory measurement is the determination of fields or temperature distribution in the load. Historically conventional temperature measurements were made at the end of the heating (microwaves off) or during the microwave process by arranging probe leads to be perpendicular to the microwave *E*-field (82). Because this is in general impossible, nonperturbing probes of various degrees of effectiveness have been developed. These include fiber-optic leads with liquid crystal sensors (qv) (83), semiconductors (qv) (84), and fluorescent materials (85). In addition, small thermocouple and thermistor sensors have been used with high resistance leads (86). These techniques permit measurement of internal temperatures during microwave heating and, in conjunction with miniature nonperturbing *E*-field probes (87), are important tools for better design. Commercially available fiber-optic probes have become the preferred means for measuring temperature during microwave heating (see FIBER OPTICS). The most prevalent type (88) works on the basis of the temperature-dependent properties of fluorescence in a small sensor attached to the tip of a fiber. The other type (89) senses the infrared radiation at the tip of the fiber. The fluorescent sensor can also be used as an *E*-field probe in the presence of strong electric fields (90).

The determination of surface temperature and temperature patterns can be made noninvasively using infrared pyrometers (91) or infrared cameras (92) (see INFRARED TECHNOLOGY AND RAMAN SPECTROSCOPY). Such cameras have been bulky and expensive. A practical portable camera has become available for monitoring surface temperatures (93). An appropriately designed window, transparent to infrared radiation but reflecting microwaves, as well as appropriate optics, is needed for this measurement to be carried out during heating (see TEMPERATURE MEASUREMENT).

4. Economic Aspects

The cost of microwave power systems is generally considerably greater than that of conventional heating systems. For example, a 120-kW conveyor system may cost $150,000–200,000. Costs of installation, operating power, maintenance including replacement of power tubes, and financing must be weighed against potential savings in labor, space, yield, productivity, and energy. One additional benefit of increasing worth is the reduction in chemical pollution which accompanies some microwave applications.

A basic choice is that of operating frequency. In principle, operation can take place at any frequency at the cost of suppression of electromagnetic leakage to regulatory limits on RFI, eg, 25 μV/m at 304 m. This cost is avoided, however, by operating within assigned ISM bands. Minimum cost results in bands of considerable use where components are readily available. In the United States, these popular microwave bands are 915 and 2450 MHz.

The price of cooker magnetrons at ca 700 W was in the range of several hundred dollars in the 1960s (11). As of the mid-1990s, this price is $<\$15$. Total sales of microwave ovens worldwide exceed 20×10^6/yr. The majority of homes in Japan and the United States have microwave ovens (94). European homes should follow before the year 2000 (95).

The alternative of lower cost r-f systems, ie, induction and r-f heating systems at 40 MHz and below, should be considered (96) (see also FURNACES, ELECTRIC). More extensive discussions of the economic aspects of microwave systems and payback calculations are available (97,98).

5. Health and Safety Factors

There are some unique safety considerations in microwave systems. Microwave voltage breakdown can occur in microwave systems and waveguides at power levels far below the theoretical values for ideal systems, ie, by a factor of at least 100 below theoretical breakdown (99,100). This is often the result of impurities or dirt particles that overheat and cause a breakdown or a spurious high quality factor, Q, resonance in the system which builds up high fields. In addition, the presence of sharp metal objects, accidental small gaps, and other situations often can induce localized arcing or corona which may or may not lead to a basic system breakdown. In this case, the plasma region of the breakdown travels down the feed waveguide toward the source and may cause failure of the tube through cracking of the output window. Therefore flammable materials should not be processed in microwave systems. Precautions can be taken, however.

In most cases, microwave, like conventional, heating produces the highest temperatures at or near the surface of load objects, except that microwave heating is more penetrating. In special situations, such as the heating of small objects of a few centimeters diameter, microwave frequencies produce rather unique heating patterns where maximum temperatures occur at the center of the object (101,102). This would be a genuine heating from the inside out, a characteristic commonly attributed to microwave heating, but not generally true. Superheating of small volumes of water can occur followed by mild explosions. In principle this phenomenon could occur for any size object if the material dielectric parameters and frequency are at certain values. No reports exist except for small water-like objects.

The most serious hazard that can occur from leakage of microwave energy is interference with other systems (103,104). This could be caused by out-of-band radiation, ie, a violation of RFI regulations, or by high power effects where the offending radiation is out of the band of the affected system, but still effectively interferes because of its intense level (105). An example is the incidental interference with cardiac pacemakers (106). This problem was partly caused by insufficient protection from RFI in the pacemaker unit and has been reduced (107) because of governmental supervision (108). Concern has arisen (109) over potential RFI from cellular phones disrupting medical electronics, both in the hospital and in portable units.

Radiated r-f energy is a hazard to systems containing flammable fuel or electroexplosive devices (EED) used for construction blasting or for military purposes (110). It is recommended that users of large amounts of microwave/r-f energy be aware of guidelines on safe distances of EEDs from sources of radiated power (111).

The hazard of exposure of personnel to microwave energy has been thoroughly reviewed (112,113). Exposure safety limits in Western countries are reasonably similar (Fig. 5), at least in the microwave frequency range. The most advanced standard includes detailed rules dependent on frequency, degree of partial body exposure, exposure time, contact conditions, etc (114). In the microwave range the recommended limits are in the range of 0.3 to 10 mW/cm^2 as averaged over any 6 or 30 minute period depending both on frequency and whether the environment is controlled or uncontrolled. Limits in eastern Europe for many years were much more stringent at microwave frequencies (115).

The nature of potential exposure hazards of low level microwave energy continues to be investigated (116–118). In the United States, leakage emission from microwave ovens is regulated to the stringent limit of 5 mW/cm^2 at 5 cm (119). There is no federal limit on emission from industrial systems but the IMPI has set a voluntary standard which specifies 10 mW/cm^2 at 5 cm (120). Emission values are equivalent to personnel exposures at several meters, well below limits that had previously prevailed in eastern Europe. This conclusion, derived for microwave ovens, should be valid for all microwave systems (121).

Leakage through door-seal areas is reduced through choke techniques (122) as well as absorbing materials (123) described in manufacturers literature on lossy gaskets. Leakage through holes in viewing screens is kept to acceptable limits by well-known limits on hole sizes (124). Generally the technology for minimizing microwave leakage is effectively utilized (125).

6. Uses

6.1. Food. The most successful application of microwave power is that of food processing (qv), cooking, and reheating. The consumer industry surpasses all other microwave power applications. Essentially all microwave ovens operate at 2450 MHz except for a few U.S. combination range models that operate at 915 MHz. The success of this appliance resulted from the development of low cost magnetrons producing over 700 W for oven powers of 500–800 W (Table 3).

The dielectric properties of most foods, at least near 2450 MHz, parallel those of water, the principal lossy constituent of food (Fig. 1). The dielectric properties of free water are well known (30), and presumably serve as the basis for absorption in most foods as the dipole of the water molecule interacts with the microwave electric field. By comparison, ice and water of crystallization absorb very little microwave energy. Adsorbed water, however, can retain its liquid character below 0°C and absorb microwaves (126).

It had been suggested that microwave interaction with foods should be similar to interaction with ionic solutions such as sodium chloride (127,128). Thus the

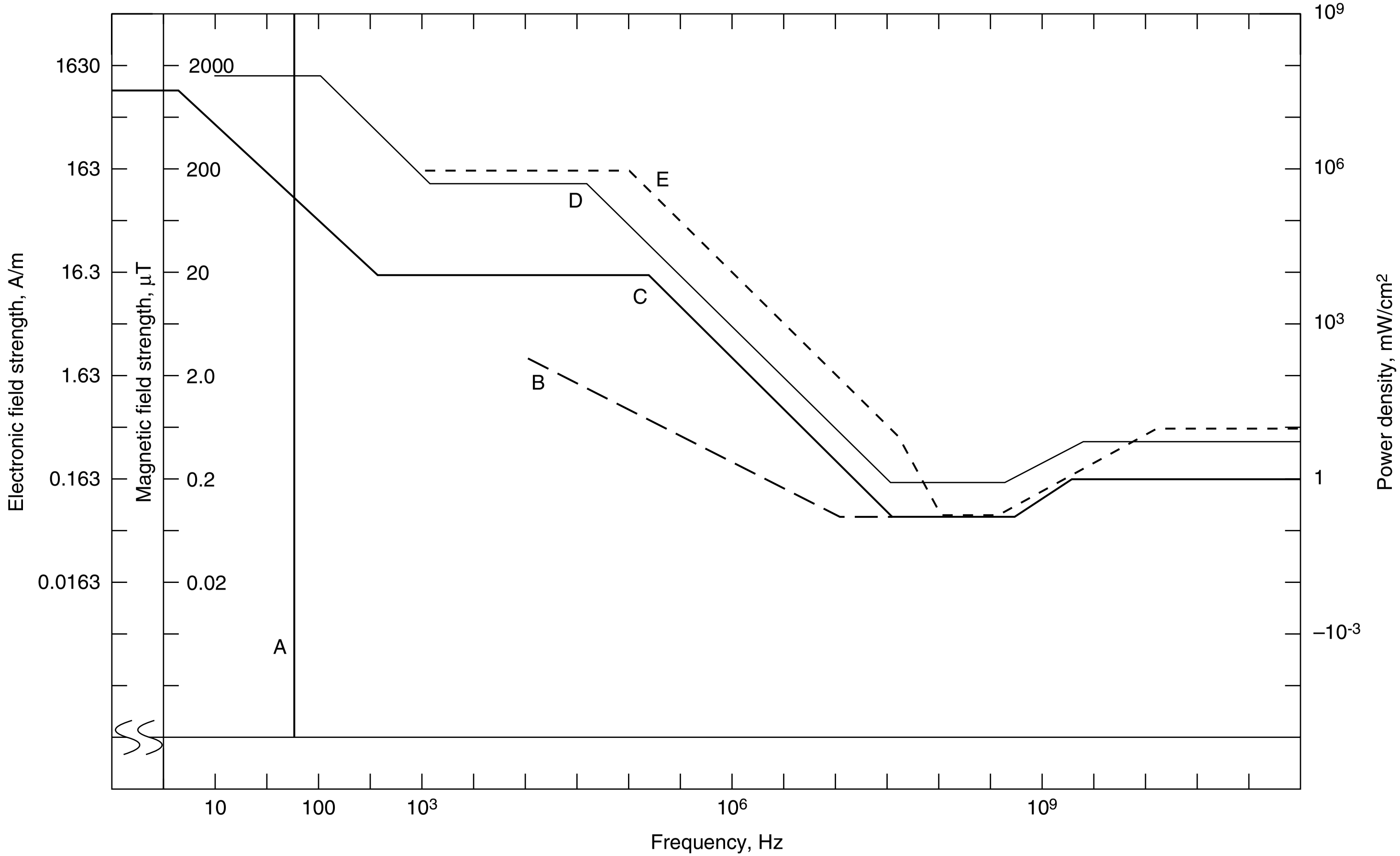

Fig. 5. Long-term magnetic field exposure limits for general public exposures in uncontrolled environment, where A is the 50/60 Hz window, according to B, IRPA; C, VDE (Germany); D, NRPB (U.K.); and E (IEEE C95.1, 1991). To convert T to G, multiply by 10^4.

dielectric loss for a 0.5 N solution below ca 2450 MHz is mostly owing to ionic conductivity, whereas above 2450 MHz the loss results mostly from water dipole relaxation. At low frequencies the dielectric loss increases with temperature, whereas at higher frequencies, but still below the water-relaxation frequency, ca 20 GHz, the dielectric loss decreases with temperature. Increased ionic conductivity in salted products such as ham tend to show increasing dielectric loss with temperature (Fig. 1). Generally the other temperature dependence prevails, however, and is believed to stabilize food heating and avoid runaway heating. The suitability of the higher frequencies for stable heating was one argument put forth in an unsuccessful application for a microwave oven frequency allocation at ca 10.5 GHz (129).

Advances in the technology of microwave ovens include techniques for achieving uniform heating, eg, mode stirrers and turntables (130); temperature (131) and humidity monitoring (132); and the use of microprocessors (133) in programming cooking time, defrost, and variable power levels. In addition, a wide variety of ceramic, glass, and plastic, as well as paperboard products have been developed for utensils, shelves, and food packaging (qv) (134). A growing number of accessory products have been developed (135), eg, browning dishes or utensils, popcorn poppers, coffee-makers, etc. Combination ranges have been developed (136) for microwave electric, microwave gas, and microwave convection, this last in counter-top arrangement.

A unique and successful innovation in food packaging for microwave heating is the microwave susceptor. This is usually the incorporation of a thin vapor-deposited aluminum film in a multilayer construction on paperboard or some other packaging dielectric material (137,138). This susceptor heats up preferentially and contributes browning or enhanced heating. It is used for a variety of foods such as popcorn, pizza, etc. Marketing to consumers of such susceptor paper on rolls, much as the packaging of aluminum foil, plastic wrap, etc, has begun.

The more general food processing applications require data on dielectric and thermal properties (139). Considerable effort has been expended by food companies in the design of food for the microwave oven. These principles have been reviewed (140). The microwave oven at 2450 MHz, used for reheating, cooking, and thawing foods, may also be used for drying (qv), eg, flowers or food materials (141). Commercial microwave ovens are used extensively in restaurants and fast-food establishments.

Food Processing. Only a few industrial food-processing applications are commercialized, although many have been investigated (11,15,142). Some, such as the drying of potato chips, were too costly; others, such as freeze drying (143), encountered technical problems like vacuum breakdown. There have been reports (144) however of the successful resumption of a potato chip processing application. Microwave ovens have been used extensively for thawing. No effective solution has been found for the runaway heating caused by the great increase in dielectric loss at 0°C (144) (see Fig. 1**b**).

Reviews of food processing applications are available in general (10,11,15) as well as in specific reviews (145,146). The most successful food-processing application is that of meat tempering, particularly at 915 MHz (147), although systems exist at 2450 MHz (148) (see MEAT PRODUCTS). Microwave power in the range of 25–120 kW is applied to frozen food conveyed in tunnels so as to achieve a fairly uniform temperature in the range of −5 to −2°C where the product can be cut and otherwise processed mechanically before it is returned to a freezer in its final form. It is estimated that about 200 such installations exist worldwide. Some process over 7000 metric tons of meat or fish annually. Another successful food processing application is that of bacon cooking (149). Precooked bacon is a desirable product for restaurants and institutional kitchens. Bacon fat provides a valuable by-product for the rendering industry.

Nutritional quality of food cooked or heated by microwaves generally does not differ greatly from food cooked or heated by other means (150). Scorching is minimized in microwave heating. Underheating or undercooking can be avoided only in ovens having superior mode-stirrer techniques or through occasional manual rotation.

Studies of food processing by microwave heating include blanching effects on food (151), the processing of stale bread (152), and studies of thawing (153). Most food processing applications involve heating. However, microwaves may be used for oyster shucking (154). This may involve thermal shock to the oyster, thus reducing the mechanical resistance to shucking.

6.2. Biological, Medical, and Agricultural Applications. Diathermy at both 27.33 and 2450 MHz has been extensively used in physical therapy since the 1950s; its popularity has greatly declined in the 1990s (155). An extension of diathermy heating techniques has been investigated for application in hyperthermia as an adjunct to cancer therapy (156). The basis for preferential destruction of tumor cells was studied by hyperthermia alone, and in conjunction with ionizing radiation or chemotherapy. A variety of applicators have been designed, including multiple focused antennas, injected probe antennas, and contact applicators.

Microwaves have successfully been used for rewarming of blood for medical applications (157). Another successful application, not commercialized as of this writing, is the use of microwave heating for rapid tissue fixation (158,159). This procedure appears to reduce the time for tissue sample analysis from many hours to minutes.

Microwaves are also used for the rapid inactivation of brain enzymes in rodents (160). Microwave power at high levels of kilowatts is applied by means of a waveguide applicator to achieve a rapid sacrifice of the rodent.

Most, if not all, microwave biological effects and potential medical applications are believed to be the result of heating, ie, thermal effects. The phenomenon of microwave hearing, ie, the hearing of clicking sounds when exposed to an intense radar-like pulse, is generally believed to be a thermoelastic effect (161). Excellent reviews of the field of microwave bioeffects are available (162,163).

Reports of sterilization (qv) against bacteria by nonthermal effects have appeared, but it is generally believed that the effect is only that of heating (164). Because microwave heating often is not uniform, studies in this area can be seriously flawed by simplistic assumptions of uniform sample temperature.

The use of microwaves has been investigated to affect plant growth by irradiating seeds or to achieve insect control (165). Most useful effects result from heating, however. Studies of agricultural applications of microwaves, eg, the drying of maize (166), exist. There has also been some investigation of the use of microwaves in the processing of pharmaceuticals (qv) (167).

6.3. Chemical Applications. Chemical analysis can be conveniently accelerated by heating of samples in small pressure-tight plastic containers (168–171).

Catalysis can sometimes be improved through the use of microwaves, particularly pulsed microwaves (172). An important component of this process is believed to be an appropriate metallized combination catalyst–susceptor (173). Microwave catalysis is an active area of research (174).

Other chemical applications being studied include the use of microwaves in the petroleum (qv) industry (175), chemical synthesis (176,177), preparation of semiconductor materials (178), and the processing of polymers (179).

Plastics Fabrication and Processing. The application of microwave or r-f energy in various stages of fabrication of plastic products is widespread. Most applications operate at low frequency, ca 27 MHz. The established processes are well known (180).

Microwaves have also been studied for a variety of curing, bonding, and drying applications for plastics and composite materials (qv) (181).

Textiles. Microwave drying of textiles is under investigation, in addition to the possible uses for curing of impregnated and dyed fabrics (182). A microwave clothes dryer for consumer or commercial application is also under discussion (183). Considerable developmental work and media publicity have occurred. Problems remain, however, particularly relating to arcing and resonant heating of metal objects that may be present in a load of clothes. These problems may be alleviated by operation at 915 rather than 2450 MHz (184).

Drying of Castings and Other Products. The use of microwaves in the curing and drying of foundry cores is well established (185). The best example is the use of microwaves for drying water-based core washes at 2450 MHz with up to 150 kW. These applications have not, however, found application in manufacturing. Many similar drying applications have been examined (186,187).

Rubber Products. Microwaves are used in the preheating, curing, and drying of rubber products (188). The most successful applications are those for large products where heating time is greatly reduced because of the penetration properties of microwave energy. Batch oven units at microwave power over 30 kW at 915 MHz are used for preheating of giant tires. Developmental studies continue in this area (189).

6.4. Waste Treatment. Microwave energy has been studied for the desulfurization of coal (qv) and treatment of wastes (190). Developments in microwave incinerators for medical and radioactive wastes have occurred (191,192). Even a consumer unit for consumption of solid household waste has been proposed (193). Economic factors remain a key barrier in these developments.

6.5. Microwave Plasmas. Classical applications of microwave plasmas have been in the areas of torches (194), deposition of organic films (195), fusion energy (196), and plasma chemistry, eg, synthesis or decomposition in nitrogen discharges (197). These developments continue (198), but emphasis has shifted to other areas, in particular the growing of diamond films. Beginning with some early work in the former USSR (199), the investigation of chemical vapor deposition (CVD) of diamond under the assistance of a microwave excited plasma (199, 200) has continued. Commercially available equipment at 2450 MHz (201) is used by a majority of the investigators. The results are impressive and likely to find application for hardening of machine tools, reducing abrasion on the surface of missile domes, and possibly the refinement of diamond as a semiconductor material. In addition diamond is a useful heat-sink material (see CARBON, DIAMOND).

Another development is microwave excited discharges for lamps. The most impressive result is the production of about 500,000 lumens of visible light by the application of 3.6 kW of 2450 MHz energy to a quartz lamp containing some gases and sulfur pellets (202). These lamps are undergoing testing in U.S. government buildings and show promise because of efficiency and pleasing spectral quality of light.

6.6. Ceramics Processing. One of the largest application areas for microwaves is in ceramics (qv) processing. Microwaves are used for sintering, drying, and enhancement of certain materials properties (203–207). Most of this work has been done at 2450 MHz, often in ordinary microwave ovens outfitted with an appropriate casket for the ceramic sample. There is some controversy over the amount of specific improvement offered by microwave heating over ordinary means of heating. Large amount of powers at many frequencies have been employed. Advantages of broad-band sources such as TWTs have been explored for superior uniformity of heating of large ceramic loads (208).

6.7. Other Applications. The use of lower frequency energy (rf) has been explored for *in situ* heating of oil shale (qv) (209). Other power applications address the potential application to electrified roadways (210) and microwave power transmission over large distances on land (211) as well as from space to earth (212). In this latter application the goal would be the generation in space of 10 GW of microwave power and its transmission to earth supplying enough electricity for a city (213).

The field of microwave technology is expected to increase as better and cheaper microwave systems are developed. In particular, uses for 5800 and 2450 MHz and the millimeter wave frequencies await the development of inexpensive efficient sources of power at those frequencies.

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