MICROWAVE TECHNOLOGY AND FOODS

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I. INTRODUCTION

Microwaves and microwave applications for the heating of foods have been the subject of two previous articles in *Advances in Food Research*, in 1951 and 1967. Both these articles were signed by the grand old man of food technology and microwave heating, Professor Samuel Goldblith of MIT.

The time perspective of the subject of this treatise is that the microwave heating technique was only a few years old in 1951 – the first domestic microwave ovens, produced by Litton on a Raytheon license, appearing on the market that same year. Industrial food heating applications of microwave energy began to appear in the US food industry in the early 60s. They were the main subject of the 1967 article.

In those days, little fundamental data on dielectric and thermal properties of foods were available. Tools and methods for temperature and field measurements during microwave heating were not available. Means for computation and modeling of field and temperature distribution were also lacking, which meant that most equipment and application development was empirical. The need for more fundamental data and methods of calculation and measurement was very obvious and the subject of increasing efforts during the 1970s and 80s. Centers for these were MIT in the USA, the Torry Research Station in Scotland and SIK in Sweden.

An overview of microwave applications in the food industry from 1974 gives examples of many different areas for applications both on a commercial and on a laboratory scale (Bengtsson and Ohlsson, 1974). However, the number of industrial installations has only grown slowly. Although many applications have been claimed technically successful, the total number of working installations in the food industry is probably still smaller than 1000. Today, an increase in the interest for industrial applications of microwave technology can be noticed, both in terms of the number of industrial installations and of R&D efforts in industry, research institutes and at universities.

Towards the end of the 1970s the sales of domestic microwave ovens started to grow rapidly in Japan, a couple of years later in the US, and then at the end of the 1980s in western Europe. The domestic microwave oven industry has grown into a worldwide multibillion dollar business, with today about 24 million ovens sold annually. On many markets, the microwave oven is the home appliance with the largest sales volume. It is estimated that there are about 225 million microwave ovens in the homes in Japan, the US and western Europe. User studies have shown that it was predominantly the affluent, "middle-aged parents with kids" families that were the first to own microwave ovens.

This population of microwave oven owners represents a large potential market for food products that can be microwave-heated. The food industry has quickly responded to these market possibilities. The number of new product introductions for the microwave food segment has grown rapidly in many markets; e.g. in the US during the middle and later part of the 1980s.

Microwave and microwavable food today constitute an important segment of the food market in Japan, the US and increasingly in western Europe. The microwave food segment comprises not only prepared food items, such as entrée and side dishes, but also products specially made for microwave heating, the most striking example being the microwave popcorn bag, developed by Golden Valley Microwave Foods in the early 1980s. That alone is today a billion dollar market. The presence of microwave ovens in the homes affects the preparation or cooking instructions for more or less all packed food products, even those not traditionally associated with microwave heating.

The growing number of microwave ovens and microwave foods has also greatly influenced the food packaging industry. Requirements of microwave compatability have greatly changed the way in which the food industry selects food packaging. For prepared foods, microwave-transparent plastic and paperboard packaging has grown at the expense of aluminum packaging. A vast number of packaging designs, specific to microwave heating, have been developed. The most striking example is the so-called susceptor package, in which an extremely thin metalized film on a PET film is heated by the microwaves to temperatures sufficient to crisp or brown pizza or pie crusts, or to pop pop-corn.

The food technology differences between microwave and conventional heating are manifested by differences in development of food flavor and aroma and of food texture and appearance. Thus, modified recipes and special "microwave-adapted" food ingredients have been developed by the industry to overcome at least in part some of the quality problems of microwave-heated foods.

This very substantial development of foods, packaging and ingredients for microwave heating has given an increased general knowledge about microwave heating in the industry (Buffler and Stanford, 1991, 1995). Much of this knowledge is empirical, but a clear trend towards more scientifically based R&D has been seen in later years. There is a steady interest in industrial applications with a number of suppliers of industrial microwave equipment, particularly in Europe. A number of novel applications are being developed by the suppliers, giving interesting additions to the already well-established application areas. An increase in the R&D efforts into drying and pasteurization applications can be noticed in research programs at universities, institutes and large food industry R&D centers.

The objective of this treatise is to reflect the present knowledge on microwave heating fundamentals, methodology and technology – the state of the art – and to outline the problems faced today, the research needs and the expected future development in domestic and industrial microwave heating applications. The basis of the treatise is the more than 30-year-long experience of the authors in R&D of microwave heating of foods at SIK.

II. HEATING MECHANISM

A. WHAT ARE MICROWAVES AND HOW DO THEY HEAT FOODS?

By definition, microwaves are electromagnetic waves in the frequency range from 300 to 300 000 MHz, corresponding to wavelengths from 1 m to 1 mm. For food applications we are, however, limited to the ISM (Industrial and Scientific Medical) band of 2450 ± 50 MHz. In the USA 915 ± 15 MHz is also a recognized ISM frequency, which is not generally available in Europe outside of the UK.

The heating of foods by microwave energy is accomplished both by the absorption of microwave energy by rotation of the dipolar water molecules and translation of the ionic components of the food. This energy is converted into heat. Thus, both the water content and the dissolved ion content (often salt) are dominating factors in the microwave heating of foods. When the dipolar water molecule is subjected to a microwave field that rapidly changes direction, the dipole tries to align itself with the field direction. There is a time lag, as some response time is required for the water molecule to overcome the inertia and the intermolecular forces in the water. The electric field thus provides energy for the water molecule to rotate into alignment. The energy is then lost to the random thermal motion of the water and equivalent to a temperature rise (Fig. 1).

The energy transfer mechanism will be efficient only if the time between the changes of direction of the electric field is so short that the dipolar molecule aggregates can barely follow the changes. If the time is long (frequency low) the alignment will be good and the energy transfer low. If the time is short (frequency high), the aggregates will not move much between field reversals, and energy transfer rate will again be low. Since the statistical number of water molecules that are bound together by hydrogen bonding will decrease with increasing temperature, so the inertia and energy release will be reduced. As the frequency in dielectric heating equipment will be maintained constant and below the energy transfer efficiency optimum, the efficiency will decrease with increasing temperature.

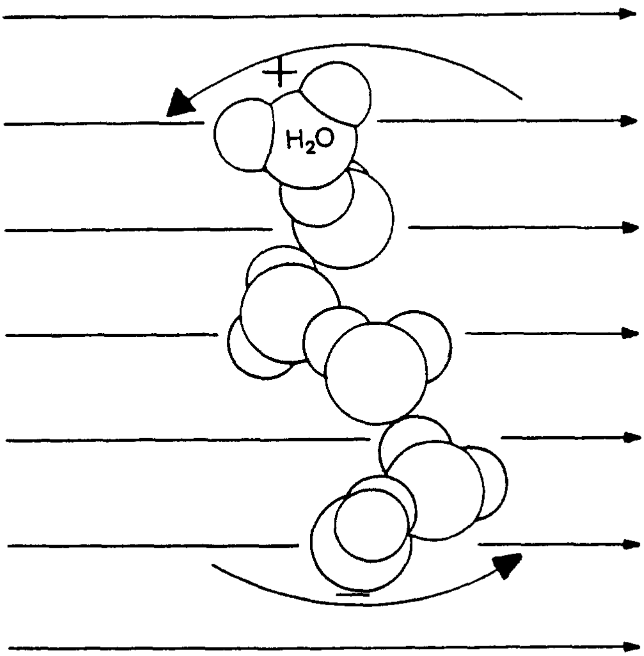


FIG. 1. Water molecules in an electric field (Walker, 1987).

Hydrated ions, such as sodium and chloride from table salt, try to move in the direction of the electrical field, and an electric resistance heating effect is accomplished. The ions are surrounded by water molecules and will in their movement transfer energy randomly to the water molecules (Fig. 2). These are more mobile at higher temperature and not so tightly bound to ions. The ions can then move more freely and absorb and dissipate more energy. The conductive heating due to dissolved ions increases with increasing temperature.

B. DIELECTRIC AND THERMAL PROPERTIES

The macroscopic interaction between a material and a dielectric field is expressed by a complex dimensionless number, the permittivity ε^*. The real component, the dielectric constant, ε^-, expresses the ability to store energy in the material. The imaginary component, ε'', represents the energy losses and is called the dielectric loss factor. The quotient is also often used, called the loss tangent, $\tan \delta = \varepsilon''/\varepsilon'$.

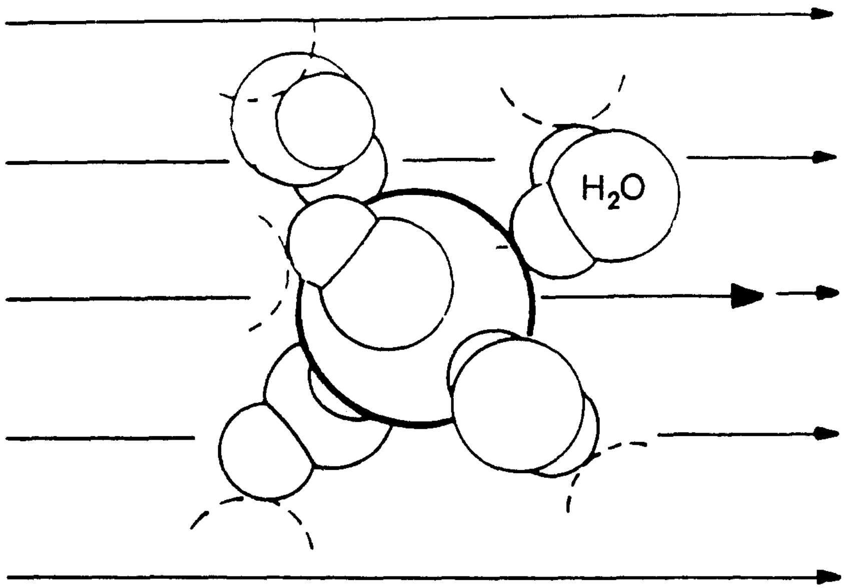


FIG. 2. Dissolved ion (center) and water molecules in an electric field (Walker, 1987).

The dielectric properties are material constants (even though they vary with temperature and frequency) and must be experimentally measured. Data is available to a fairly good extent for basic food components, especially at 2450 MHz. However, very little data is available for formulated foods and ready-made recipe foods. There are few predictive models available by which dielectric properties can be calculated from proximate analysis, and these models have limited applicability (Mudgett, 1985). Predictive equations for dielectric properties of foods have been developed by Calay *et al.* (1995), and Sun *et al.* (1995) where the influence of food composition, moisture content and temperature is included.

For calculating the absorbed microwave power, the so-called power equation is often given:

$$P_v = 2\pi \times f \times \varepsilon_0 \times \varepsilon'' \times E^2$$

where P_v is power released in a given volume
f is the frequency
E is the electrical field strength in V/m inside the food
ε_0 is the permitting in free space ($8.85 \cdot 10^{-12}$ F/m)
ε'' is the dielectric loss factor.

This equation is important for understanding the influence of the dielectric loss factor and the field strength on power absorption. Also it points out the advantages of using very high frequencies for heating; e.g. in comparisons between microwave and high frequency dielectric heating at 27 MHz. At the higher frequency considerably lower field strength is required for a given energy input. The dominating variable, the electric field strength, is unfortunately highly variable and very difficult to estimate or measure when heating in a microwave oven.

When a microwave impinges on a food surface, some of it will be reflected and some will be transmitted and penetrate into the food and gradually be absorbed, while generating heat. Materials can be classified into reflecting, absorbing and transparent according to their interaction with the dielectric field. Reflecting materials are mostly metals, where the electric field creates surface currents that only penetrate some few microns into the material. Transparent materials, on the other hand, do not absorb the energy to any significant extent. Glass and most plastic materials are typical examples of this. Materials that will absorb microwave energy, according to the heating mechanism explained above, are those containing polar constituents, predominantly water.

The rate of power absorption and the extent of penetration will be a function of both frequency and the dielectric properties of the material:

$$P_z = P_o \cdot e^{-z/d\mathrm{p}}$$

where penetration depth d_p is defined as the depth at which only 1/e (roughly 37%) of the surface energy of the wave remains, e being the base of the natural logarithms and z distance from the surface. P_o is the initial power at the surface and P_z the power at depth z.

The penetration depth (as calculated from dielectric data) for water and two food materials is shown in Fig. 3 as a function of temperature. It can be seen that microwave penetration in water rapidly increases with temperature, and that penetration at 915 MHz is markedly higher than at 2450 MHz. For the cooked beef, penetration depth is very high in the frozen state, rapidly decreasing during defrosting and leveling out with further temperature increase, while the penetration depth continues to decrease with rising temperature for salty gravy. The dielectric properties of some common foods of different water content are illustrated in Fig. 4. As seen, the dielectric constant, ε', increases almost linearly with water content, while the loss factor, ε'', only shows a moderate increase, except for higher salt content.

Frozen foods show much lower dielectric properties as compared to thawed foods. Most of the water in frozen foods is present as ice crystals

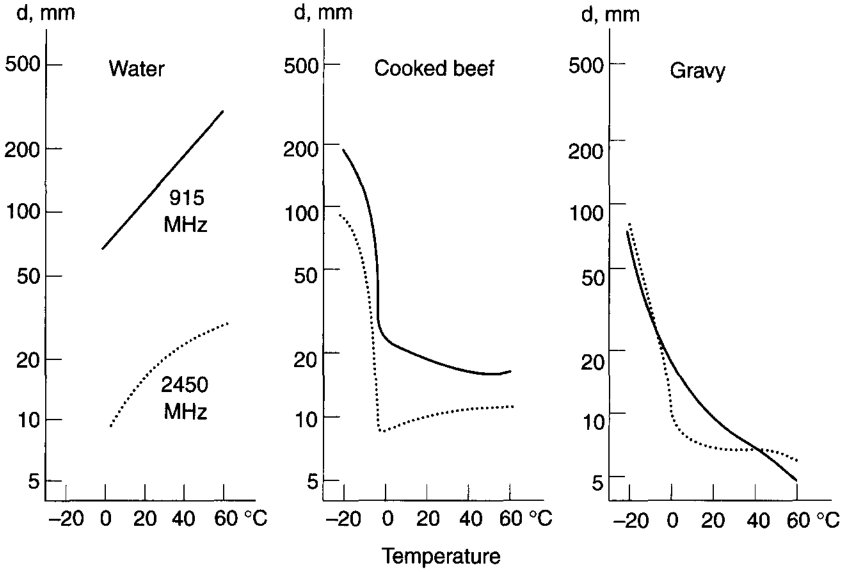


FIG. 3. Microwave penetration depths at 0.915 and 2.45 GHz as a function of temperature (Ohlsson, 1983).

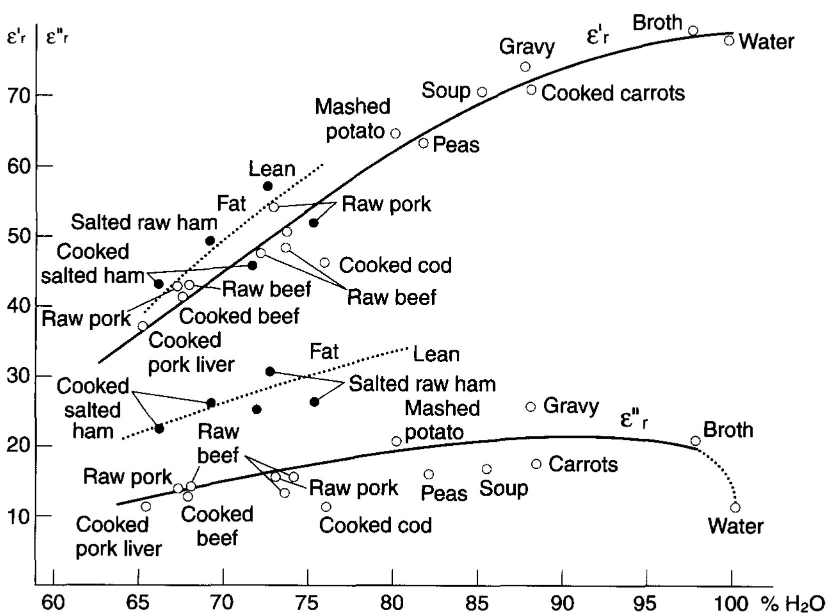


FIG. 4. Dielectric properties of a range of foods as a function of water content at +20°C (Bengtsson and Risman, 1971).

inside the food, and pure ice has very low dielectric properties. However, approximately 10% of the water remains unfrozen as a strong salt solution in the food, explaining why frozen foods absorb microwave energy at all. There is a marked jump in dielectric loss in the melting region, which partly explains the tendency towards so-called runaway heating in microwave thawing of foods, where already thawed parts absorb most of the available microwave energy because of their higher loss factor.

This is illustrated in Fig. 5, which shows the calculated temperature

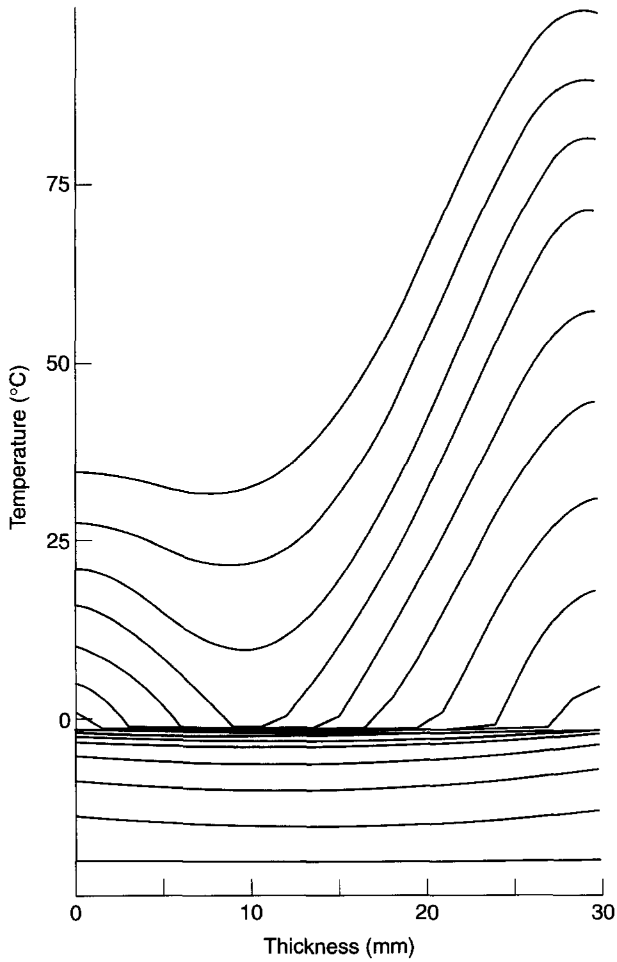


FIG. 5. Temperature profiles during thawing of a 30 mm block of fish. The temperature profiles after every minute are represented by the lines (Ohlsson, 1983).

profiles at one-minute intervals when defrosting a 30 mm thick slab of meat with more microwave energy impinging from one side. It also demonstrates that very even temperature can be maintained as long as the temperature remains below about –2°C and thawing is only partial; tempering instead of complete thawing. In this state, the thermal conductivity of the food is still high, which tends to level out temperature differences.

For non-frozen foods, dielectric loss tends to decrease with increasing temperature, more pronounced the higher the water content and the lower the ionic content. This will tend to slow down runaway heating in thawing such foods. Salty foods, however, demonstrate a pronounced increase in dielectric loss with increasing temperature due to conductive losses. Since most foods contain some ionic material, the reduction in dipolar absorption with increasing temperature tends to be partly balanced by increasing conductive losses.

Since both ε' and ε'' decrease with decreasing water content, penetration depth will increase in the course of a drying operation, most of the microwave energy being absorbed in the inner, moist region of the food. This will help balance moisture transfer to the surface to surface evaporation and counteract tendencies towards case hardening, and accelerate the drying operation. However, for fruits and vegetables, it has been shown (Funebo and Ohlsson, 1998) that the loss factor actually increases during the early stages of drying before tapering off during continued moisture loss.

The actual temperature rise in microwave heating depends not only on the energy released in the food but also on its thermal properties, as apparent from the following energy balance:

$$P \cdot t = m \cdot c_p \cdot \Delta T \text{ or } P \cdot t = m \cdot \Delta H$$

where P is power in W
t is time in s
m is mass in g
ΔT is temperature increase in °C
ΔH is the change in enthalpy corresponding to the temperature rise.

This means that low microwave absorption can still lead to a considerable temperature rise in foods of low specific heat, such as fats and oils.

C. SELECTIVE HEATING EFFECTS

The release of microwave energy in foods is very dependent both on the microwave oven field and the microwave penetration pattern in the particular food material. The field distribution is a function both of the type of microwave applicator and cavity and the manner of introducing the microwaves into it, as well as of the type, shape and distribution of the food inside. This will be discussed further in the section on microwave oven heating uniformity. Here we shall deal with selective heating effects related to the composition and shape of the food material itself. For this discussion we consider the microwave field to be evenly distributed and of a given field strength at the food surface.

1. In-depth heating

In a rectangular slab of food of even thickness, the power level will gradually decrease inwards to an insignificant level if the slab thickness is large in comparison to the calculated penetration depth. The corresponding temperature development is illustrated by Fig. 6. For a thinner slab, the remaining power level from microwaves impinging on the two opposite surfaces will overlap, which can result in more rapid heating of the central part than of the surface regions. This is also taking into account that the surface will be cooled both by heat transfer to the surrounding air space and by evaporative cooling.

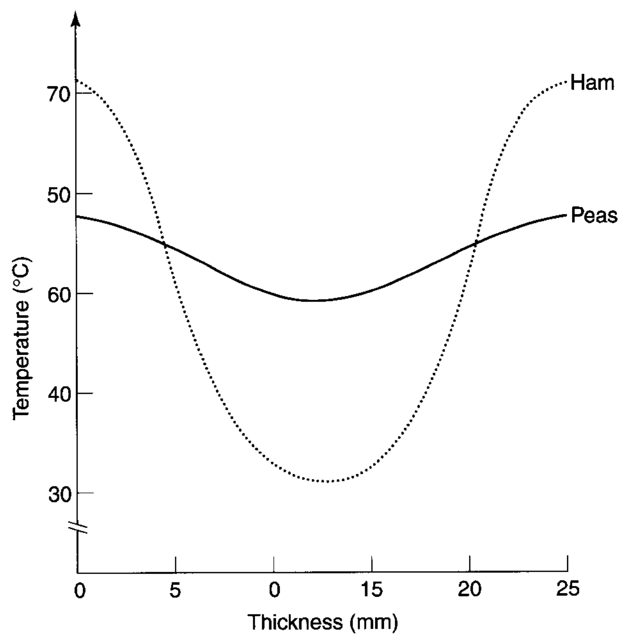


FIG. 6. Temperature profiles after microwave heating of a lossy food (ham) and a normal food (peas) after two-sided microwave heating (Ohlsson, 1983).

For layered materials of different dielectric properties, microwaves will also be reflected and refracted at the interface between these materials, for example between meat and an outer layer of fat. Depending on the thickness and dielectric properties of the layers, standing wave patterns may develop, with maxima and minima. The result can be that the fat layer will be overheated, in spite of its lower dielectric loss factor. A contributing factor will then be the much lower specific heat of the fat material.

If the food is inhomogeneous in composition or if different food materials are heated side by side, temperature differences will result from the combined differences in dielectric and thermal properties when uniform microwave field strength is anticipated.

2. *Concentration effects*

In a slab with sharp corners and edges protruding into the microwave field, energy concentrations will occur causing selective heating, especially at the corners. This is illustrated in Fig. 7 from computer simulation of the

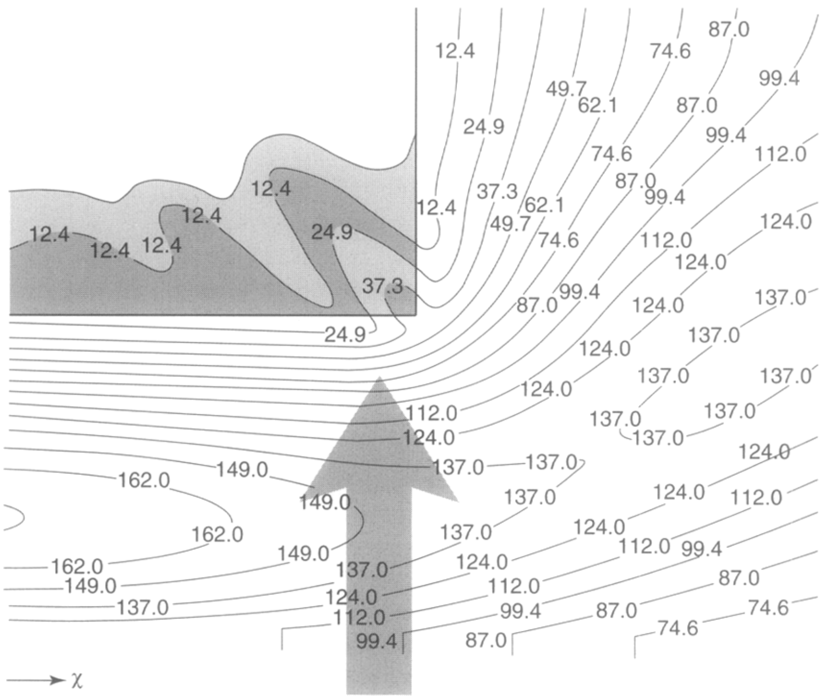


FIG. 7. Power level contours for a microwave heated food edge. Note the strong heating overheating effect diagonally into the food from the sharp corner (Ohlsson, 1990).

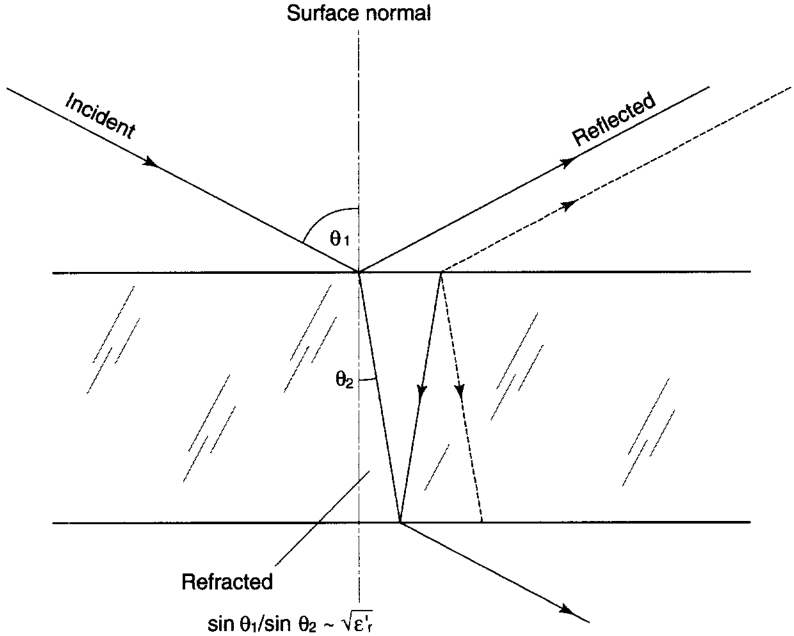
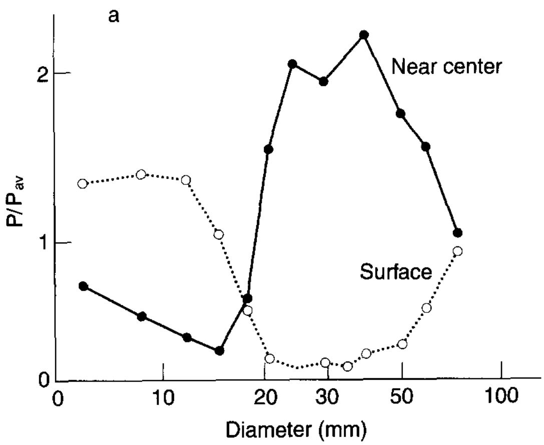


FIG. 8. Reflected and refracted microwave beam at a food surface (Ohlsson, T. 1983).

microwave field distribution for a food corner. A sharp edge or corner will act as an antenna and attract more energy than surrounding areas.

Considering microwaves as radiation and adopting optics terminology, Fig. 8 illustrates microwaves impinging on to a food surface at different angles. Part of the energy is reflected, part refracted. Refracted energy will be partially absorbed, as previously discussed. Most of the remaining energy will be reflected back at the other food surface and so on. Depending on the food geometry, the result can be the focusing of energy on certain areas, which may be part of the explanation for concentration heating effects.

For spherical or cylindrical shapes the result can be a concentration of energy to the center of the food, depending both on the food diameter and its dielectric properties. This central heating effect occurs for diameters approximately one to three times the penetration depth in the material. For cylinders, concentration effects occur when the electrical field is parallel to the cylinder axis. The effect is stronger for foods with high values for its dielectric properties. At 2450 MHz central heating usually happens at diameters between 25 and 55 mm, while the values are correspondingly larger for 915 MHz (Fig. 9).



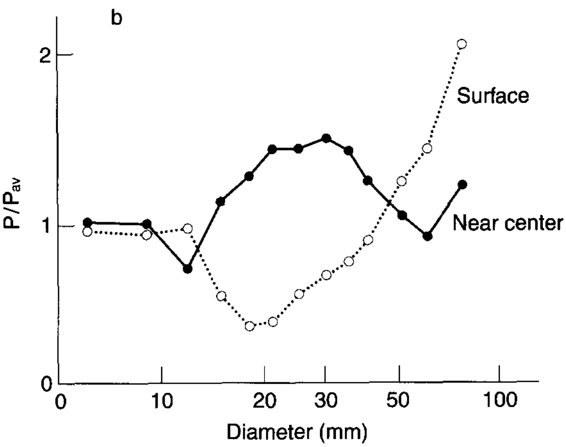


FIG. 9. Relative microwave power levels P/P_{av} for (a) spheres and (b) cylinders near center and at surface (Ohlsson and Risman, 1978).

III. MEASURING METHODOLOGY

A. DIELECTRIC MEASUREMENTS

Microwave reflection and transmission at food interfaces, field distribution inside the food, penetration depth into it and rate of heat development all depend on the permittivity of the food (dielectric constant and loss factor).

Consequently, it is most important to know these properties and their variation with frequency, temperature and food composition, when developing microwave food applications or designing foods for heating in the microwave oven.

Although a fairly impressive bank of dielectric food data has been accumulated over the last 25 years, it is still quite incomplete. Therefore, measurement of the dielectric properties of foods and food components is often a necessary part of the development work. The basic principle in such measurements is to put a homogeneous food sample into some kind of sample holder, at constant temperature, to expose it to a microwave signal of given frequency and to measure how this signal is affected by the food sample. From analyzing the measured change, the real and imaginary parts of the permittivity can then be calculated.

The commonly used method is to place the sample inside or in contact with a coaxial line or waveguide and to measure either both the reflected and the transmitted signal or the reflected signal only. A different technique is to place the sample in a resonant cavity and determine the shift in resonant frequency and the attenuation of the signal in comparison with the empty sample holder.

1. Resonant cavity method

A typical measuring circuit is shown in Fig. 10 together with a measuring cavity (TM012 mode) and sample arrangement (Risman and Bengtsson, 1971). From measurement with empty and filled test tube sample holder the shift in resonant frequency and attenuation are determined, from which the permittivity of the sample is calculated.

Measurements are relative and not absolute, in that a calibration curve is used, based on measurements on samples for which the permittivity is already known with good accuracy from absolute measurements with other technique. Cavity perturbation measurement in a given cavity is limited to one frequency only, and a new cavity has to be built for each additional frequency. On the other hand, permittivity values determined by this technique are quite accurate, even at low permittivities, and a large number of samples can be measured in a short period of time. Also, measurements can be made over a very wide temperature range, from –40°C to +140°C. Sample preparation is very simple for liquids, more time-consuming for solids.

2. Waveguide and coaxial lines

In principle (Fig. 11), a section of waveguide or coaxial line in the form of a sample compartment is filled with the food to be measured, which has to

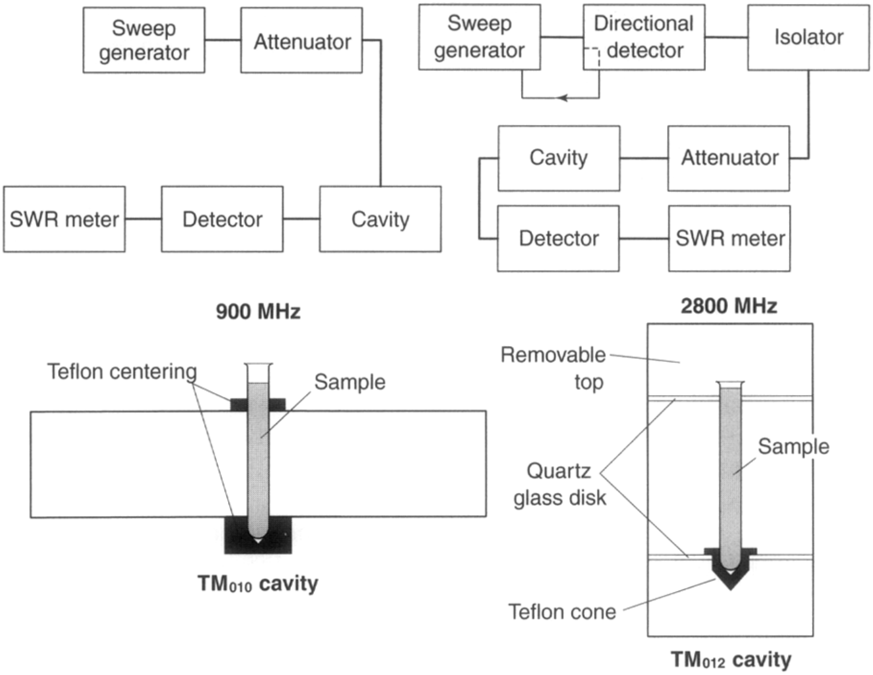


FIG. 10. Cavity perturbation system for measuring dielectric properties (Ohlsson *et al.*, 1974).

accurately fill out the cross-section and be of very precise length. A waveguide line will be more restricted in frequency range, while a coaxial line is truly broad banded from 1kHz to 100 GHz. In a transmission line the signal from the microwave source or generator passes along the line, and both the signals reflected by the sample and transmitted through the sample are picked up by a receiver and analyzed for reflexion and transmission coefficients, from which the permittivity is calculated.

The process is highly simplified by using a modern network analyzer as both source and receiver, coupled to a computer for the calculation, with software taking into account various effects of the measurement arrangement. The sample can also be placed at the end of a short-circuited line, in which case only the reflected signal is of interest.

A very convenient arrangement is the open-ended coaxial probe. The probe (Fig. 12) is put in close contact with the food sample to be measured (by reflected signal only) by immersing it into liquid foods or placing it against a flat surface of a solid food. A necessary requirement is that the food material is homogeneous and the sample size and thickness is sufficient in relation to

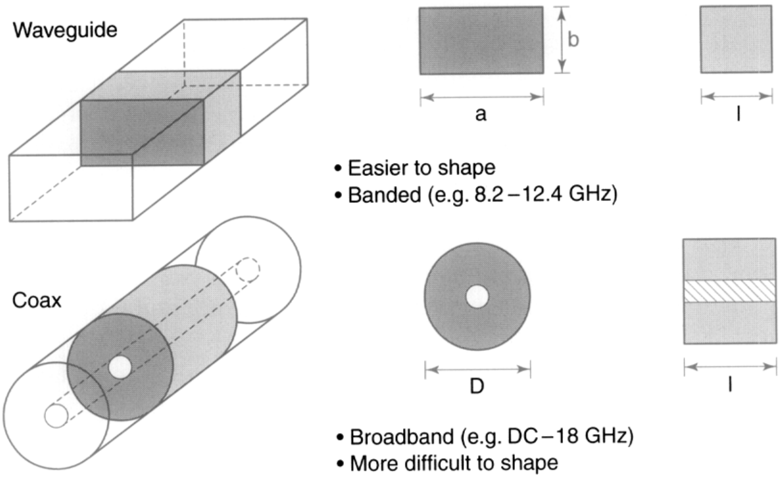


FIG. 11. Transmission line methods for dielectric measurements (Hewlett-Packard, 1990).

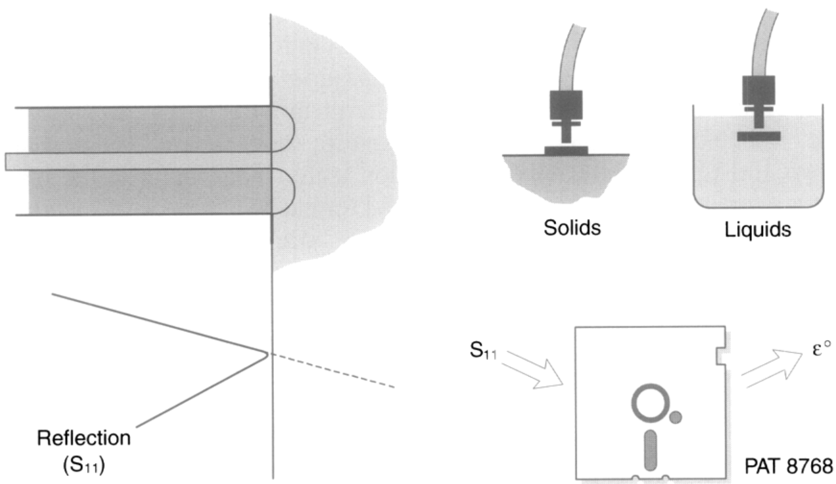


FIG. 12. Coaxial open-ended probe method for dielectric measurements (Hewlett-Packard, 1990).

the microwave penetration depth, so that it can be regarded as being infinite as far as the fringed field from the probe is concerned.

For measurements inside a measuring line, whether waveguide or coaxial, sample preparation is difficult and painstaking and sample holders require high precision. In addition, temperature control over a wide range of temperatures will be complicated. In comparison, the open end-probe is extremely simple to use, requiring very little sample preparation, and can easily be used also inside a thermostated cabinet. The lower accuracy for foods of low permittivity is usually not so important in food development.

Finally, time domain spectroscopy (TDS) methods are also used. They are very expensive and primarily used as tools for advanced research on the interaction of electromagnetic energy and materials over a wide frequency range. TDS determines permittivity from measurements in coaxial lines in the time domain from fractions of Hz to 15 GHz. Signals reflected or transmitted through a sample in the coaxial line are monitored by a sampler connected to a sampling oscilloscope.

Frequency domain spectroscopy (FDS) comprises measurements in the frequency domain by means of a selected monochromatic signal, from a few Hz to 100 GHz.

3. *Measurements in food development*

For dielectric measurements on foods in the course of microwave product and applications development, the choice should be between the coaxial line open-end probe and the cavity perturbation technique.

The open-ended coaxial probe method is simpler in sample preparation and permits a rapid sweep over a wide frequency range. On the negative side, it is more restricted in the temperature range below freezing and above 100°C than the cavity perturbation technique, where on the other hand, a separate cavity has to be designed for each frequency of measurement. Considering that only two frequencies are generally permitted for food heating applications, this may not be an important drawback in regular development work. A negative aspect is that no equipment for cavity perturbation measurements appears to be commercially available.

The measurement over a wide frequency range, possible with the coaxial line open-end sensor, gives important information on polar and ionic responses, from which prediction can be made about how the permittivity of the sample depends on temperature. Also, such measurements reflect the water activity and water-binding conditions in the food sample (Mudgett, 1985).

B. TEMPERATURE MEASUREMENTS

1. *Needs and problems*

Temperature control is of crucial importance in microwave heating, with regard to temperature distribution as well as rate of temperature rise and final or maximum temperature reached. Poor temperature control may lead to substantial quality loss by overheating and even charring and burning of the food. Alternatively, temperatures reached may be too low, leading to microbial hazards. Also, the debate as to whether non-thermal effects of microwaves exist or not cannot be solved unless precise and accurate measurements of temperature and temperature distribution can be made during ongoing microwave heating.

The need, then, is for accurate temperature sensors which:

- are not affected by the microwave field
- do not disturb the field distribution and heating pattern
- can be used to measure surface temperatures as well as in depth temperatures in a representative number of positions.

In a review paper Ofoli (1987) discussed the problem, considerations and methods of temperature measurement in RF and microwave research, with special reference to standard thermometry and optical and fluoroptical techniques.

Metal conductors (such as thermocouples, thermoresistors and thermistors) are normally unsuitable for measurement in microwave fields, since they interact with the field, generating currents which cause false readings. At the same time, they disturb the electromagnetic field and thus may influence the heating pattern in the food.

By using shielded probes, with the shield connected to ground outside the oven, the temperature readings as such will not be affected. However, the field around the probe may still be disturbed. Also, such sensors will not be very convenient for multipoint measurements or for surface temperature measurements. Today many commercial microwave ovens are fitted with shielded thermistor-based temperature probes which may also function for end temperature control (Ramasvamy *et al.*, 1991).

The normal procedure in the past has been to momentarily shut off microwave power and insert a thermocouple probe or multiprobe template for rapid temperature measurement. Unfortunately, surface cooling and equilibration by conduction–convection will be sufficiently fast to cause faulty reading, sometimes by as much as 5–10°C (Bengtsson and Lycke, 1969). By taking a succession of readings and extrapolating back to the moment of power cut-off, a better approximation is reached, but the procedure is rather inconvenient and time-consuming.

2. *Non-interfering methods*

Glass thermometers filled with a "lossless" liquid like toluene or kerosene do not interfere with the microwave field but, even when miniaturized, they are clumsy, slow and difficult to read inside a microwave oven and definitely unsuitable for multipoint measurements.

Miniaturized plastic strips with enclosed circular "windows" containing *white crystals of lossless compounds of very precise melting temperature* can be inserted into or fixed to the surface of foods to indicate what temperature has or has not been reached. They offer a fairly precise method of checking measurements by other techniques but are otherwise not very convenient to use.

Infrared pyrometers, sensing the IR radiation from a defined surface area of the heated object, are being used in continuous industrial microwave equipment for on line surface temperature control. The accuracy can be in the order of ±1–2°C. To determine a surface temperature profile, several IR sensors may be positioned across the tunnel width. However, IR measurements can only give information on the surface temperature pattern, which may not at all reflect the in-depth pattern. IR pyrometers may also be equipped with fiber optic probes.

Infrared imaging by thermography cameras is, in principle, based on an optical IR surface scanner, a detector and a converter, transferring the detected IR signals into amplified video signals, so that an IR video picture can be displayed on a color TV screen. Depending on the intensity of the IR signal, the displayed color on the screen can be varied over a wide range, corresponding to successively increasing scanned surface temperature. A complete color frame is scanned in a fraction of a second, and the picture can be photographed, filmed or stored on disc for computer analysis in a number of ways, to display time–temperature graphs, temperature histograms, individual isotherms etc. (Bows, 1990).

Infrared imaging has the limitation in common with IR pyrometry that only surface temperature patterns can be studied. However, solid phantom foods are now available, offering the same shape and dielectric and thermal properties as real foods, and which can be instantly taken apart along precut planes to study the in-depth temperature distribution by thermography. The accuracy of the heat camera, which has built-in automatic calibration, is in the order of ±1°C, varying with the selected temperature range to be covered in the picture. Limitations for foods are temperatures below freezing and approaching 100°C, where faulty readings may occur depending on surface ice condensation and steam generation, respectively.

Fiberoptic thermometry systems by various sensing principles have been developed to commercial application (Wickersheim and Sun, 1987), and are increasingly being used in microwave food research. The great advantage is that they do not interact with electromagnetic fields and that the sensors have dimension at least comparable to normal thermocouples. They cover the entire temperature range of interest in food research with an accuracy in the order of ±0.5°C. Equipment is available permitting measurement up to 24 points. Lately, also a hand-held, one-channel version has been introduced. Negatives are that the sensors are delicate and that equipment cost is very high in comparison with conventional thermocouple based systems.

Fiber optic techniques can be divided into two-fiber systems, based on transmission of light through probe and to detector, and single-fiber systems based on transfer of light to sensor and reflection of light back to detector, through the same fiber.

The most common type of sensor is based on the rate of decay of fluorescence from a phosphor sensor at the tip of the fiber, exposed to a UV light signal fed into the fiber. The rate of decay is directly related to the temperature of the sensor (Fig. 13).

Another type is based on a luminent GaAs semi-conductor sensor being exposed to incident radiation from an infrared light emitting diode (LED), the absorption of the LED emission being a function of the sensor temperature. A third sensor type relates the change in transmission through a ruby glass filter to temperature, and yet another one utilizes a liquid crystal at the measuring tip, several other principles not to be mentioned.

3. *Future developments*

No doubt the development and improvement of fiberoptic systems will continue, leading to more durable sensors and decreasing equipment cost. At the same time, the efforts will continue to make common thermocouple and thermistor sensors "inert" to electromagnetic fields, for example by using high resistance plastic leads to the sensors. Also, efforts are being made to utilize the temperature dependence of the propulsion of ultrasound to measure temperature.

It has also been speculated that measurements of the microwave spectrum being emitted from heated bodies cannot be utilized to determine the temperature profile through the sample thickness. In a feasibility study of thermometry using multiple frequency-band radiometry, Prionas and Hahn (1985) conclude that it should be feasible to use such a technique for non-invasive sensing of one-dimensional temperature profiles, for example to determine temperature distribution in deep-seated tumors during hypothermia treatments with RF or microwaves.

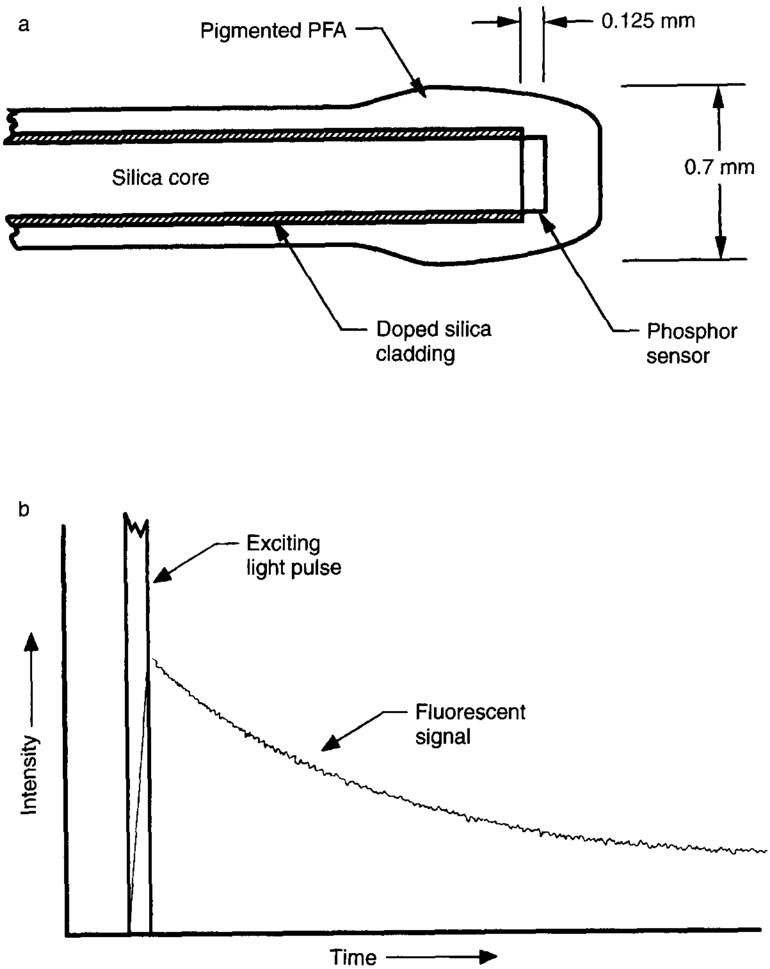


FIG. 13. Fiber-optic probe for temperature measurements in electromagnetic fields: (a) cross-section of typical probe tip; (b) decay time, digital curve fit technique (Wickersheim and Sun, 1987).

IV. HEATING EFFECTS

The basis for the application of microwaves to food is the thermal heating effects caused by a combination of dipole rotation and electrical resistance heating. Over the years, there has been considerable discussion about the possibility of additional, non-thermal or *per se* effects from the exposure of the food to microwave fields.

Let us first assume that non-thermal effects do not exist, at least not at the field strength of practical interest to food processing. The effects of microwaves on foods would then depend entirely on the temperature development with time within the food material, the related mass transfer and the physical and chemical changes dependent on the time, temperature and water activity. Depending on the local microwave field intensity and the thermal and dielectric properties of the food, the rise in temperature may be accompanied by both temperature and pressure gradients that will affect the mass transfer. If the mass transfer resistance is high, pressure build-up may cause volume expansion or structural collapse. If the temperature rises rapidly, superheating may also occur in liquids and in certain solid foods, such as in liver and canned potatoes and mushrooms. When the superheating is broken, the instant steam generation will cause momentary expansion (spluttering, bumping, puffing) and even complete disintegration of the food structure. The phenomenon of exploding popcorns or explosive cooking in reheated coffee in microwave ovens is well known. Rohtla and Risman (1994) studied spluttering in cylindrical samples of liver and cooked eggwhite, heated in a microwave oven under such conditions that focusing of microwave power to the food interior occurred. From direct temperature measurement by fiber optics and observation of color changes, they conclude that superheating above 120°C occurs before splutter starts. The phenomenon is discussed in depth by Buffler and Risman (1996).

In microwave heating of slab-shaped foods, unusual temperature and moisture gradients may develop as a result of concentration effects. In addition, irregularly distributed hot and cold spots are common. Also, the food surface will be colder than in conventional heating, due to a combination of evaporate cooling and a cold oven environment. Many of these thermal effects are difficult to verify experimentally. For a proper understanding of the process, empirical studies must be combined with theoretical analyses and logical explanations.

A. MICROBIOLOGICAL EFFECTS

1. Thermal effects

Microorganisms are affected by heat, irrespective of how it is generated. Depending on the species and strain, there will be an optimal temperature range for growth, and a specific time–temperature relationship for the inactivation or killing of the vegetative organism or its spore. This inactivation will also depend on the composition of the food substrate.

In what ways, if any, will the effects on microorganisms of microwave heating differ from that of conventional heating methods? The literature in this field has been reviewed by Jonsson and Ohlsson (1989), Palaniappan and Sastry (1990), and Finot and Merabet (1991).

The specific properties of microwave heating comprise very rapid in-depth heating and more even temperature profiles through the sample thickness. This means that the temperature range for optimal growth can be reached more rapidly, which is being taken advantage of in applications for dough rising. Another consequence of the rapid and even temperature development with microwaves is that near-HTST (high temperature, short time) processing conditions can be achieved in packaged foods. Since microwave heating of foods exposes them to what could be considered a heat shock, it has been suggested that this could stimulate spore growth that would not occur in conventional heating. Data supporting this assumption have been presented by Bögl (1990).

As previously discussed, microwave heating may give rise to uneven field and temperature distributions. In combination with the short treatment time, this may permit the survival of vegetative, pathogenic microorganisms such as *Salmonella*, *Listeria*, *Clostridia* and *Campylobacter*. This might happen even if the mean temperature reached should represent sufficient heat treatment, had the temperature been achieved by conventional, slower heating methods.

The problems of insufficient microbiological inactivation in microwave reheating of chilled foods were highlighted by a study on survival of *Listeria* in ready meals heated according to recommended cooking instructions in the UK (Walker *et al.*, 1989). The study gave rise to much concern about the microbiological safety of foods heated in microwave ovens. A large number of ovens on the UK market were evaluated in terms of their heating uniformity. A rating system for microwave oven power levels was developed, and was used to some extent in the UK. Also, the requirements that all parts of the food must reach 70°C have been made clear to all parties involved, as a result of the UK microwave oven safety concerns.

In addition, the surface temperatures reached during microwave heating are usually lower and the surface moisture content higher. As microbial contamination is often concentrated to the food surface, this means that the hygiene risk is increased.

Bögl (1990) showed, in a compilation of more than 100 experiments, that conventional heating reduces the microbial count more effectively than microwave heating. He also demonstrated a considerable variation in this effect between different species of microorganisms. It is generally agreed, therefore, that a temperature of at least 72°C should be ascertained in the coldest area, when foods are heated in a microwave oven. On the other hand, the method of reheating foods must not be regarded as a substitute for good hygiene in the earlier stages of handling.

It has been claimed by a number of researchers that non-thermal (or athermal) effects on microorganisms result from exposure to microwave fields. According to others, selective heating of the organisms themselves, due to their higher water and salt content, could explain these observations. Sastry and Palaniappan (1991) analyzed the possible temperature difference between a microorganism and a surrounding liquid medium during microwave heating. They demonstrated that microorganisms would have to possess extremely high loss factors to maintain even a small temperature difference to the surrounding medium. For such small objects, about 1 micron in size, the surface area to volume ratio is extremely high. This would cause very rapid heat dissipation to the surroundings, should indeed any selective heating occur. The energy generation rate within the organism would have to be somewhere between 60 and 1000 times that in the medium, for it to be a 1°C temperature difference! Schwan and Piersol (1954) arrived at the same conclusion forty years earlier!

However, it is also doubtful whether selective power absorption of objects so small in relation to the electromagnetic wavelength within the food is at all possible. Schwan and Piersol (1954) claim that objects smaller than about 1 mm cannot absorb microwave energy at all. This interesting statement has not been sufficiently analyzed as yet. It is certainly a very important issue, also with regard to using microwaves for the killing of small pests such as insects in cereals, by preferential heating.

2. *Non-thermal effects*

It was claimed as long ago as the early 1960s by some researchers (Olsen, 1965) that microwave heating may have special, non-thermal effects on microorganisms, permitting sterility to be reached at considerably lower temperatures and with shorter treatment times than by other means of heat processing. More recent studies (on *Staphylococcus aureus*) by Dreyfuss and Chipley (1980) and Khalil and Villota (1986) have claimed that microwave heating enhanced bacterial kill under "sub-lethal" conditions, due to some athermal effect or possibly to differential heating of the bacteria. They noted differences in specific enzyme activity and cell mobility in microwave heated samples. Khalil and Villota (1986) also reported the survival of *Stearothermophilus* spores in suspension in different media, when heated in test tubes in a water bath maintained at 100°C by microwaves or conventional means. Survival curves and calculated $D_{100°C}$-values were claimed to show consistently higher lethality for the microwave heated samples.

Another kind of non-thermal effect on bacteria was reported by Anderström *et al.* (1983) who claimed a significant stimulating effect on RNA synthesis and cell growth from microwave exposure at 37°C. However, they failed to confirm previous claims in the literature of mutagenic effects of microwave exposure.

On the other hand, a number of comprehensive studies on microorganisms have been reported, for example by Goldblith and Wang (1967), Lechowich *et al.* (1969) and by Welt *et al.* (1994), which demonstrate the *absence* of any other effects than purely thermal.

The conclusion reached in 1989 by an IFT expert panel on Food Safety and Nutrition (Mudgett, 1989) was that it is generally recognized that microwave interactions are solely due to thermal effects. Particularly in work by Welt *et al.* (1994) the temperature control was very well defined and not subject to any doubts. This cannot, however, be said about most of the investigations claiming a *per se* effect of microwave heating. Sometimes no reference method at all has been used, and in most cases the experimental technique has been too insufficiently described to permit repetition of the experiments.

Often, such as in the work by Khalil and Villota (1986), the temperature has been measured with a time delay (after cutting off the microwave power), and temperature differentials, such as those caused by concentration effects, standing wave patterns, etc, have not been taken into account. In 1969 Bengtsson and Lycke demonstrated, by IR thermometry, that a surface temperature drop of more than 5°C could easily occur during the few seconds between cutting off the power and making a thermocouple measurement.

In the literature, non-thermal effects have been claimed not only on microorganisms but also with regard to chemical and biochemical changes in general. Effects causing modification or even the breaking up of weak bonds and, perhaps, the formation of compounds undesirable or even unacceptable in foods have been reported. As pointed out by Rosén (1972), such effects are unlikely, as the quantum energy levels of microwaves are several orders of magnitude lower than those required for breaking up even the weakest hydrogen bond.

Nevertheless, the possibility of greatly accelerating chemical reactions by microwave heating has attracted considerable interest. Two main reaction types have been studied: hydrolysis and organic synthesis. Acid hydrolysis by microwave heating of primarily proteins and peptides have been studied in pressure-resistant glass or Teflon sample holders, and time reduction for complete hydrolysis from 24 hours with conventional methods to below 15 minutes have been observed. Some have attributed this to athermal microwave effects. However, Jahngen *et al.* (1990) studied the hydrolysis of adenosine triphosphate by microwave heating and by conventional heating. Their objective was to determine whether the dramatic rate increase from microwave exposure was in fact due to non-thermal effects. Using a technique based on very accurate temperature measurement, they could demonstrate that the rate increase was solely related to the temperature.

In organic synthesis, both closed, pressure-resistant vessels and open reflux systems at atmospheric pressure have been used – all showing very marked increases, up to a thousandfold, in reaction rates. However, in almost all the cases the experimental design or reporting has not permitted any safe conclusions regarding the existence or non-existence of any athermal effect.

In their overview, Mingos and Baghurst (1991) cite an investigation on polymer synthesis under *low-pressure* conditions, in which the authors explain the 35-time rate increase as being due to either some specific molecular effect (athermal) or a very localized temperature rise in the order of 40–60°C, caused by microwave absorption close to the reaction site. They believe that accelerated rates under reflux conditions can be explained as a result of (a) superheating, (b) more efficient rapid achievement of the reaction temperature or (c) more efficient mixing of reactants together with some localized superheating due to "interfacial polarization".

The only paper that seems to give clear evidence of a special microwave effect in a homogeneous system is that by Berlan *et al.* (1991). Their experimental conditions appear to be well controlled and they compare the microwave and conventional alternatives at equivalent bulk temperature development. Still they find up to a ten-fold increase in reaction rates for the microwave alternative. The authors propose two alternative hypotheses: that the free activation enthalpy is modified (non-thermal effect) or that the bulk temperature measured is not representative because of phenomena similar to sonar cavitation (thermal?). Still, until these findings have been confirmed by other researchers, they have to be regarded with caution.

In 1989, Lubec *et al.* published results from exposure of milk, claiming the formation of unacceptable levels of D-proline and Cis-hydroxyproline, involving a risk of brain damage in infants. However, the experimental conditions were subject to grave doubts, and efforts by other research groups to duplicate his results have been futile, even at the very excessive microwave heating conditions used (Marchelli *et al.*, 1992).

In a critical analysis of the scientific literature on athermal effects of microwaves, Waltz and Schubert (1990) conclude that the existence of athermal effects has so far never been proven. They state, provokingly, that "there is no scientific method by which one can either prove or disprove a non-existing effect".

As far as foods are concerned, at any rate, it remains to be proven that non-thermal effects really exist. Setting up and analyzing such experiments requires expert knowledge of microwave fields and heating physics, and not only expertise in biochemistry or food science and technology! On such lines, Tong (1996) designed a new experimental apparatus and procedure that would allow the study of athermal effects under truly the same time–temperature history for both microwave and conventionally heated samples. Using this equipment for studying microwave effects on *Clostridium sporgenes* spores and thiamin he found the effect to be solely thermal in nature.

In contrast, it seems to be accepted by researchers in the biomedical field that direct, or non-thermal, effects can occur when exposing *living* organisms, tissues and cells to electromagnetic fields (Gandhi, 1990).

B. NUTRITIONAL EFFECTS

There are several good reviews available on the nutritional effects of microwave exposure. In their overview in *CRC Critical Reviews*, Cross and Fung (1982) concluded that no significant nutritional differences exist between foods prepared conventionally and by microwave heating. They also found that many of the early investigations had to be disregarded because of incomplete description of the experimental design, absence of temperature data or doubtful general reliability. They recommended further research on the microwave effects on moisture, protein, carbohydrate and water-soluble vitamin retention, using more standardized experimental procedures, which would allow more meaningful comparisons between investigations.

Ohlsson and Åström (1982) and Jonsson (1989) expressed similar opinions in their reviews. As regards the nutritional quality after comparable degrees of conventional and microwave heating, they concluded that the protein quality is retained in microwave heating of animal foods and improved in vegetables. Since no crust is formed in microwave cooking, the availability of amino acids, especially of lysine, is high. The content of fat in fatty details of meat and pork may decrease. Minerals and vitamins such as potassium and vitamins B1 and C, are better retained in microwave heating as the cooking is done in a minimum of water – provided excessive heating is avoided. On the other hand, data on the effects on carbohydrates (starch and nutritional fibers) and on fat-soluble vitamins were found to be lacking.

In an update, Finot and Merabet (1991) largely confirm the conclusions of the earlier reviewers. They also discuss the possible effects on racemization of amino acids and isomerization of fatty acids. They conclude, on the basis of comprehensive investigations, that there are no such effects of microwave heating that differ from those of conventional heating methods. A positive effect from the rapid microwave heating was a more complete destruction of trypsin inhibitors in beans.

The absence of surface browning in microwave heating is positive in terms of the nutritional content but negative for the organoleptic properties of foods. Investigations on both fat-soluble and water-soluble vitamins have failed to demonstrate any significant differences from conventional heating. The tendency lies rather toward favoring microwave. The reduced surface heating with microwaves is also positive from another point of view. In an investigation by Österdahl and Alriksson (1990) they confirmed that bacon cooked by microwaves yields reduced levels of nitrosamines compared to conventionally pan-fried bacon.

In a number of journals, articles and presentations it was claimed by Hertel (1989) that people who consumed foods cooked by microwave heating showed changes in the chemical composition of their blood, that could be related to cancer. As the reports caused much debate and uncertainty, research was undertaken to study the claims made. Jonker and Til (1995) showed that in feeding trials in rats with diets cooked by microwaves and by conventional heating, no adverse effects of microwaves could be demonstrated. Risman (1993) discusses both the potential hazards of microwave-heating of foods and the misinformation in mass media articles on the safety of microwave-heated foods.

C. SENSORY EFFECTS

Microwave-heated foods demonstrate more or less pronounced differences in appearance, flavor and texture from conventionally heated foods. This is a result of the differences in temperature, moisture and pressure gradients already discussed, and the related changes in structure and binding properties. To the extent that the differences from conventional heating are significant, they will usually be perceived as negative by the consumer. Absence of surface color, low volume and porosity in cakes are examples of such negative differences. In addition, microwave-baked bread, soft cakes and pastries, etc, will often demonstrate a dried-out and hard inner texture and a wet and soggy surface. This can be avoided only by combining microwave heating with other surface heating by hot air or by the use of susceptors.

In conventional cooking, a combination of enzymatic and chemical reactions is given time to develop. These reactions cause textural changes such as softening, firming and tenderizing, and the formation and/or breakdown of flavor substances to give the combined flavor that traditionally is regarded as the normal or optimal. The absence of surface drying and Maillard browning reactions in microwave heating will also mean the absence of flavor notes that are very important to meat and bread.

According to a review on microwave heating and flavor quality by Stöllman (1990), very little is actually known of the effects of microwave heating on flavor substances. In the literature, microwave-related flavor has usually been studied only by sensory and to a very limited extent by chemical analysis.

The most dramatic process-induced flavor differences between microwave and conventional heating are found for cooked beef and for bread and cake products. When beef was cooked to the same degree by microwaves and by conventional heating, major differences, both qualitative and quantitative, in volatiles were found. The rapid microwave heating liberated only one third of the total number of volatiles, but retained greater amounts of alkanes, alkenes, alcohols and pyrazines. The slower conventional heating showed greater proportions of benzenoids, aldehydes and furans. Lack of sensory flavor after microwave heating was associated with the lack of browning reactions.

Similarly, microwave-baked cakes appeared to lack many of the nutty, brown and caramel aromas observed in conventionally baked cakes. While conventionally baked cake was high in isopentenal and furfural, the microwave-baked cakes lacked flavor compounds like methylpyrazine, furan, methanol and acetylfuran, which are normally associated with a baked flavor. On the other hand, it appears that when cooked foods were reheated, rapid microwave heating gave rise to less of a warmed-over flavor (WOF) than did conventional reheating.

The flavor deficiency in microwave-heated foods, resulting from insufficient time for volatile production, loss of volatiles by steam distillation, more effective flavor binding by starch or proteins or chemical breakdown, has to be compensated for in one way or the other in product development. Flavor systems, different from those used for conventionally heated products, have to be specially designed for foods to be microwave-heated. So far, these efforts to increase the resistance to volatilization of aroma and to mask off-notes have been made by trial and error, as the special mechanisms involved in flavor transport and binding in foods during microwave heating are unknown.

According to Steinke *et al.* (1989), the dielectric properties of the food system as a whole and the affinity of the flavor compounds for the different phases of the food medium are primarily responsible for the behavior of the individual flavor compounds. Shaath and Azzo (1988) reported work in which they proposed their so-called Delta-T theory as a tool for selecting flavor materials suitable for foods to be microwave-heated in a more systematic manner. The basis of the theory is that the heating rate in a microwave oven of a test tube sample of the pure flavor material is related to the heating rate of an equivalent sample of water. This ratio should be a measure of the tendency of the flavor material to be *selectively heated* and to diffuse or evaporate from the food during microwave heating.

Unfortunately, the authors have not considered that flavor compounds, which are mixed into or dissolved in a food matrix at a very low concentration cannot have any influence at all on the dielectric or thermal properties of the food. Nor can there be any selective heating of the flavor compounds on the molecular level inside the food. In other words, the Delta-T theory is completely meaningless, unless the flavor is a major component of the food. Another possibility is that the flavor material would be present at a fairly high concentration in emulsion droplets of sufficient size to be selectively heated.

V. HEATING TECHNOLOGY

A. DOMESTIC AND INSTITUTIONAL MICROWAVE HEATING

1. The microwave oven

It is estimated that there are more than 225 million microwave ovens in the homes in the industrialized world today. Penetration into households has reached above 100% in the US, Japan and Australia and above 80% in the UK and the Nordic countries in Europe. There are hundreds of models on the market in a wide range of design, control features, sophistication and price. The basic oven shape and components are illustrated in Fig. 14.

Alternating current from the mains is transformed to around 4 kV and rectified to direct current in the power pack. This is fed to the magnetron tube, in which the electric energy is transformed into microwave energy. This, in its turn, is transferred through a waveguide to the rectangular oven space, the so-called microwave cavity. The cavity is a closed metal box, designed to prevent any external leakage of microwave energy. It is fitted with a door with microwave seals and often has a microwave-tight metal screen for visibility of the oven interior during heating. The food to be heated is positioned on a bottom plate of microwave transparent material or on a rotating plate, or turntable.

Differences can be considerable among the multitude of oven makes and models on the market today, both in generated microwave power and in field distribution. Commonly, microwave output power lies between 500

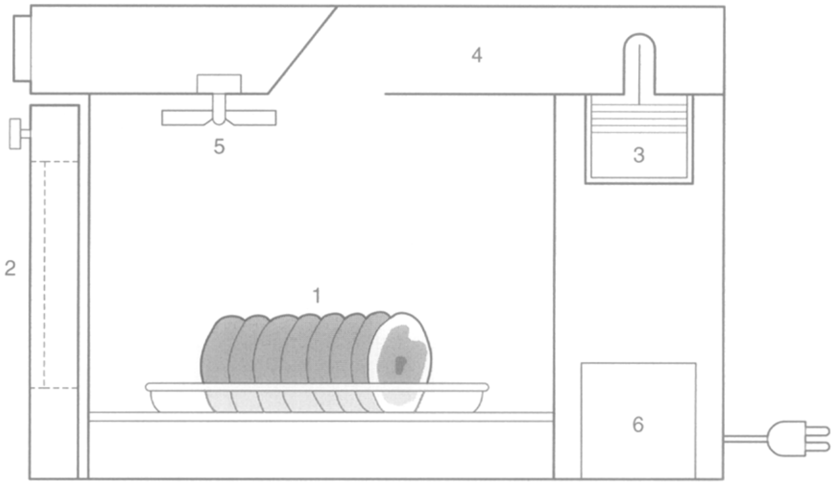


FIG. 14. The principal construction of a microwave oven (Risman, 1989). (1) Food load; (2) door with screen; (3) magnetron; (4) waveguide; (5) stirrer; (6) power supply.

and 1000 watts for domestic ovens and up towards 2 kW for institutional ovens. Control features range from a simple timer and a start-stop button to weight and temperature sensors and microchip based programming. The dimensions of domestic ovens are approximately 30 × 30 × 25 cm, of comparable magnitude to the wavelength in air at 2450 MHz (12 cm), which is the only frequency in use today for domestic and institutional microwave ovens. Institutional ovens usually have a larger cavity and are more robust in order to stand up to the much tougher usage conditions, and they often combine microwaves with a conventional heat source, such as hot air convection heating. Similar combination ovens already enjoy a substantial share of the domestic oven market on the European continent.

Energy is fed into the cavity by means of some kind of waveguide and antenna arrangement or opening slot in the roof or upper side wall of the cavity. The arrangement is designed to efficiently and evenly distribute the energy inside the cavity to make possible rapid and uniform heating of a wide range of food loads.

2. *Oven field distribution*

In the oven space a limited number of standing wave patterns can be generated as a result of multiple reflections at the metal cavity walls. Different mode patterns are illustrated in Fig. 15 for an empty oven. This means that the field is not entirely evenly distributed in the three

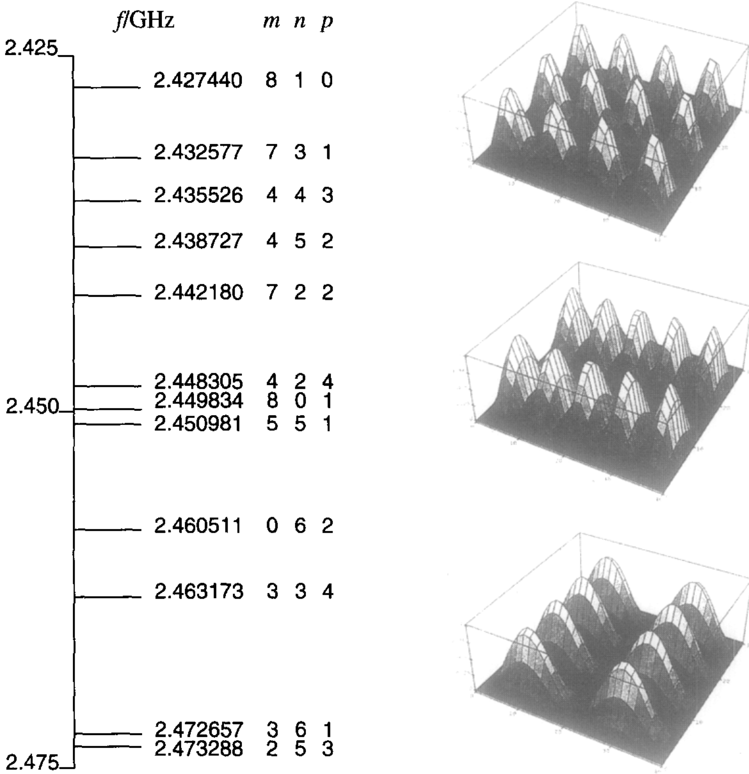


FIG. 15. Mode patterns in an empty microwave oven (Kok and Boon, 1992).

dimensions, but demonstrating a pattern of maxima and minima. At the metal surfaces, the field strength is always zero. The field pattern is continuously modified by using a mode stirrer, a rotating propeller-like device, that will help a number of the possible modes to exist in the oven for certain time intervals. Alternatively, field differences can be compensated for by moving the food through the field on a rotating turntable at the bottom of the oven space. Most ovens use a combination of direct microwave radiation from the in-feed region and a multimode standing wave pattern in the oven.

In addition, ovens are often designed to contain devices that to some extent direct microwaves into the central area of the oven shelf, where foods are placed for heating. These so-called confined modes between the food and the oven bottom have been shown recently to be of great importance for developing ovens with more uniform heating patterns. The major reason for this is a promotion of bottom heating through promotion of the

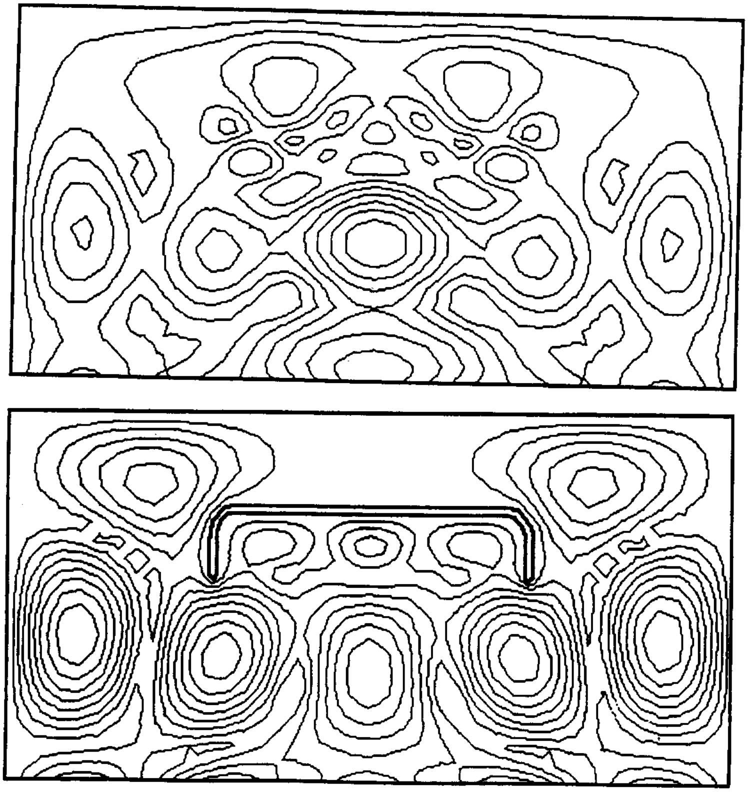


FIG. 16. Computer-simulated electric field pattern in an oven loaded with a food load in a plastic tray (bottom) and an aluminum tray (bottom) (Lefeuvre and Audhuy-Peaudecerf 1993).

propagation of waves with exceptionally long horizontal wavelength (Risman, 1994).

When food material is introduced into the oven cavity, both food composition, geometry of the food and package and the positioning of the food in the oven will affect field distribution compared to that in the empty oven (Fig. 16). Different food components may have widely different dielectric properties and consequently different microwave absorption. The oven field distribution will interact with the microwave field distribution inside the food that the oven field has created. As the wavelength inside moist food is about seven (proportional to $\sqrt{\varepsilon'}$) times smaller than in air, the field distribution in the food will show large variations within short distances (Ohlsson, 1983). Also, the various selective heating effects discussed in the previous section will interact with the basic field pattern in the oven. The resulting oven field pattern will include the effect of the field in the food.

Electromagnetic fields have two different polarities. The polarity determines how much of the energy will be reflected or transmitted into the food. For TM (transverse magnetic) polarity the reflection factor has a minimum at a high degree of incidence. For TE (transverse electric field) the reflection factor gradually increases with degree of incidence, so that more energy is reflected back from the food to the oven walls and back, establishing a resonance mode pattern. This, in its turn, results in less control of the energy distribution and a higher tendency towards edge and corner overheating than for a TM field. This can be demonstrated in computer simulation and has also been borne out in practical oven design. Advanced computer simulation programs have proven to be excellent for studying how to balance different desirable and undesirable microwave fields in order to improve the temperature distribution in microwave-heated foods (Ohlsson and Risman, 1993).

Spluttering or bumbing may occur when heating certain foods like potato, green beans and carrots, at high microwave power level. It is believed to be caused by localized superheating and sudden, explosive water evaporation. Contributing factors are shape and size of container and package and certain dimensions of the solid food pieces (Fu *et al.*, 1994; Buffler and Risman, 1996).

Many methods have been proposed to determine the oven field distribution, ranging from positioning a pattern of glass beakers with water or weak salt solution over the oven bottom plate, to using even layers of homogenous food material (egg white, mashed potato, pancake batter, etc.) or solid food simulants (gels or plastic materials, formulated to match the dielectric and thermal properties of foods). The measured temperature distribution after a given heating time will then be considered to reflect the field distribution in the oven. A convenient but expensive way to map the temperature distribution is by infrared thermography. Changes of state will provide visible indications of field irregularities, such as the coagulation pattern of egg white or melting pattern of agar gel, or temperature-dependent color changes resulting from incorporated chemical systems. Paper sheets moistened with $CoCl_2$ solution have also been used to reflect field distribution by the blue color forming in dehydrated areas. Plastic sheeting covered with a film of temperature indicating liquid crystals has been used for the same purpose.

When the objective of the uniformity measurements is to evaluate the heating performance for a range of prepared food products, it is only relevant to use food test loads that are of similar geometry and composition as the foods. As pointed out in the part on heating uniformity, the microwave power distribution in the oven is strongly affected by the food geometry and composition. A number of glass beakers will not give the same microwave oven power distribution as a prepared food sample, and thus is not considered proper to use (Ohlsson, 1981).

The International Electrotechnical Commission (IEC) has issued an internationally recognized standard performance test for microwave ovens including three cooking tests, one defrosting test and two cup heating tests (IEC Document 705). It has been argued by many, that heating performance testing of ovens should be related to foods or food simulants of a weight and geometry that is really relevant to the normal heating situation in practical use, where one or two trays of food of about 300 g weight are heated in the center of the bottom plate or turntable.

Computer simulation of the microwave field and food temperature distribution has been a tool to evaluate the influence of the many involved product and oven factors since 1971, when Ohlsson and Bengtsson (1971) presented a one-dimensional temperature profile simulation. In recent years, thanks to the vast improvements in computer calculation power, numerical simulations of the three-dimensional microwave field pattern are possible to do even on PCs. Both the FEM (Finite Element Method) (Dibben and Metaxas, 1994 and 1995) and the FDTD method (Sundberg, 1994; Sundberg *et al.*, 1996) is used. The FDTD method offers advantages of lower computer requirements and the simplicity of understanding the method and of "building" models. However, the uniform grid (element) size gives unnecessary large matrices. The simulations primarily give the normalized electric field distribution. The translation to temperature patterns will also require modeling of the power dissipation of the oven, as pointed out by Sundberg *et al.* (1995).

Computer simulations is an important field for research in the future, for improving the understanding of the complex interaction of the variables influencing the microwave field during heating, as well as for the optimization of oven design and microwave foods (Wäppling-Raaholt *et al.*, 1999a).

3. *Power rating and rate of heating*

The rate of heating for a single food component in a microwave oven is primarily a function of the available microwave power, but the sample weight and the dielectric properties of the sample will to some extent affect this available power, as shown in Fig. 17. This figure shows the effective microwave power as a function of oven load for two different microwave ovens. It can be seen that the shape of the curve can differ quite considerably between different oven designs. Normally, available power will diminish with decreasing sample weight. Another factor that influences the available oven power is the line voltage.

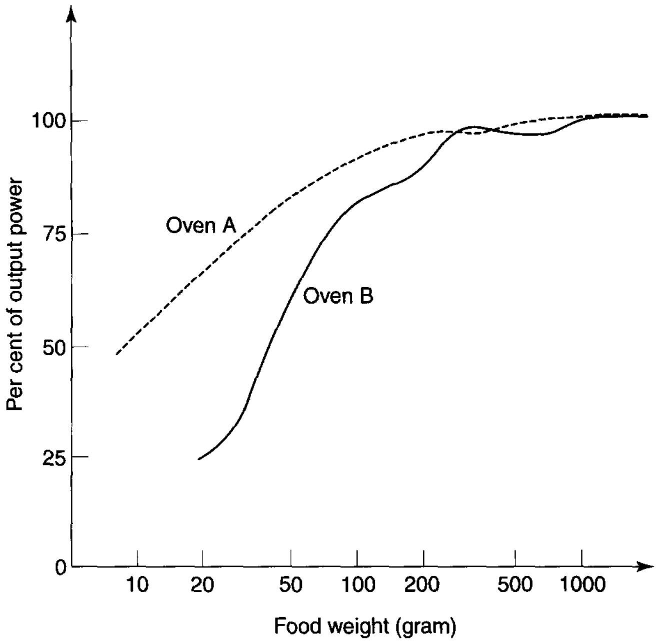


FIG. 17. Output power versus food weight (Ohlsson, 1983).

The recognized standard procedure today for determining oven power output is the IEC (IEC Document 705) standard, which is based on heating a 1000 g water load, from +10 to +20°C under precisely controlled conditions. A five-level grading system for rating the power output of microwave ovens has been proposed in the UK to help reduce the risk of insufficient heating in home microwave ovens. These tests do not take into account several important factors such as the influence of edge overheating and water evaporation (Risman, 1995).

Fig. 18 depicts the temperature rise with heating time for the same sample weight of different food materials. This does not seem to reflect at all the dielectric loss factor of the respective materials. Vegetable oil, which has a very low loss factor, demonstrates a very high heating rate. But this is mainly due to the fact that available microwave power fed into the oven will have to be absorbed by the oil, in the absence of other lossy material. (A contributing factor is the low thermal capacity of the oil.) This also explains why the rate of heating 500 g of water is almost double that for 1000 g. The situation becomes quite different when food components of different dielectric and thermal properties are heated side by side in the microwave oven. Then the rates of energy absorption

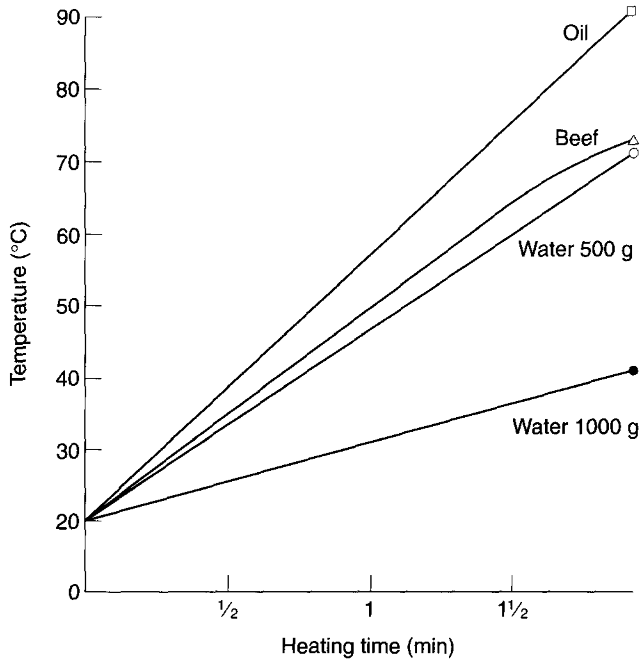


FIG. 18. Temperature rise with time for different foods heated in a microwave oven (Ohlsson, 1983).

and temperature rise will more clearly be reflected by their respective physical properties.

Differential heating can never be entirely avoided either in microwave heating or conventional surface heating, and may sometimes even be desirable. To keep temperature differences within acceptable limits, power input (microwave power or conventional oven temperatures) has to be checked, even if this should mean prolonged heating times. The present trend in Europe and the USA to raise the power rating of microwave ovens is therefore regrettable, as it increases the risks that too high power levels are used for food heating. It has been found in many studies that approximately 600 W is a suitable power level for prepared food reheating.

4. Microwave foods

In microwave cooking, it is expected that the results of conventional heat processing over 20 minutes or so, with heat transfer from a heated surface, should be matched by in-depth microwave heating in a minute or two! This may of course be very difficult to achieve. First of all, microwave heating will not heat the surface to sufficiently high temperature for browning reactions to take place. Secondly, flavor and texture development is depending both on temperature and time for normal, desirable flavor and texture to develop. Thirdly, both temperature and moisture gradients and distributions tend to be different in microwave heating.

a. Effects of geometry and dielectric properties. Granted that microwave ovens are designed to give as even field distribution as possible in the loaded oven and to support TM modes around the food sample for minimal corner and edge overheating, then food composition, geometry and positioning as well as packaging will constitute the main remaining factors that determine heating performance and resulting food quality.

For slab-shaped foods, product thickness should be even, and preferably limited to less than 2.5 times its microwave penetration depth. Rounded edges and corners will limit preferential corner and edge heating tendencies. The hot area is usually protruding diagonally from the edge or corner some 7 mm into the food Ohlsson, 1993). The temperature variations over large, flat surfaces of food, in terms of hot and cold spots, are normally larger than the in-depth temperature variation, and may have greater influence on the overall heating results.

When heating food components of different dielectric and thermal properties together, such as in entrée dishes on trays or compartmented plates, care must be taken in selecting shape and relative arrangement of the components so as to optimize heating uniformity. In this context, advantage can be taken of the central focusing tendencies of rounded (cylindrical or semi-spherical) geometry for thick food samples of limited penetration depth. Food components with high dielectric loss, such as meat stew, can be partially shielded by components of lower loss (such as mashed potato) to even out temperature distribution. Material with low dielectric loss is less susceptible to corner and edge overheating, etc. By adjusting the thickness of material with low dielectric loss, the formation of variable standing wave patterns inside the food can be kept to a minimum (Ohlsson and Thorsell, 1985; Ryynänen and Ohlsson, 1996).

In layered materials, standing wave patterns can develop as a result of microwave reflection at the component interfaces (Risman, 1993). This also offers a certain possibility to "manipulate" energy distribution and heating effects by the choice of layer materials and thickness. Fig. 19 illustrates the situation when a hamburger is heated, sandwiched between two pieces of bun. A standing wave pattern develops between the microwave oven top and bottom walls, the oven shelf and the bread and the meat.

However, the extent to which food geometry and positioning can be

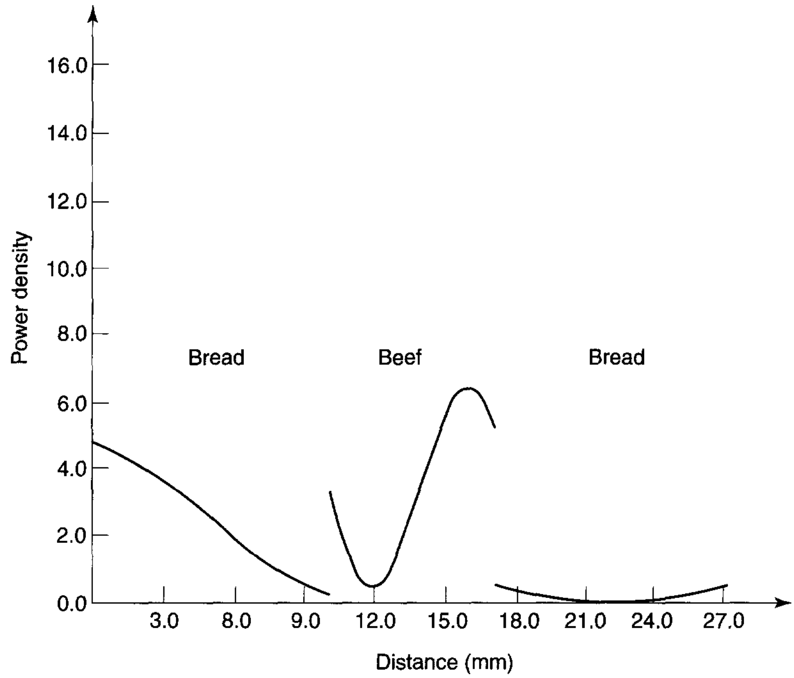


FIG. 19. Power distribution between components of a hamburger bun heated in a microwave oven (Ohlsson, 1991).

modified is fairly limited, since the food or dish must have a "natural" appearance for consumer acceptability.

b. Effect of food composition/formulation. Another means of influencing heating performance is by modifying the food composition or formulation. Lowering the water content and/or mixing with material of low permittivity will tend to reduce microwave absorption as well as raise the microwave penetration depth in the food. Increasing ionic content, such as by salting, will increase dielectric loss and reduce penetration depth without affecting the wavelength in the food. Again, the demands for natural taste, flavor and texture will put rather narrow limits on what changes in dielectric or thermal properties that can be achieved.

To compensate for the lack of flavor development, the addition of flavor substances (natural flavors, spices, etc) may be required, for example micro-encapsulated flavors with controlled release above a certain temperature during reheating.

For foods in which warm swelling starches are being used, the temperature reached during microwave heating may not be sufficient everywhere for these starches to swell, imparting a raw taste and undesirable texture. A combination of warm-swelling and cold-swelling, modified starches is often presented as the answer to this problem (Katt, 1991).

White bread is not very suitable for reheating by microwaves, since a rubbery and tough texture easily develops, for reasons which remain to be clarified (Hoseney and Rogers, 1989). Patented additives are available which may partly prevent such texture changes.

c. Surface browning and crisping. An obvious solution to obtaining surface browning for unpacked products would be to combine microwave heating with hot air convection or radiation – using a combi-oven. Another is to convert part of the microwave energy to conductive or radiant heating in a special browning element, made for example of ferrite material, which absorbs microwave energy.

For packaged foods, extremely thin metal coating can be deposited on temperature resistant polymer film (a susceptor), to absorb part of the impinging microwave energy and convert it into heat to achieve browning and crisping. Or an ingredient susceptor could be attempted, for example consisting of a dry powder or highly concentrated solution of a component or additive that will strongly enhance surface absorption of microwaves. Finally, the food surface can be coated with Maillard reactants, such as amino acids and sugars, or other chemical browning agents in combination with moisture absorbing agents, to give surface browning at a moderate surface temperature. To maintain surface crispness, conventional precooking or baking prior to packaging in combination with strong moisture absorbers (hydrocolloids, fibers, etc) and moisture barriers (edible coatings) near the food surface have been suggested as alternatives to the use of metal susceptor films.

d. Chain of food development. The chain of development for microwave food products will follow three different stages. In the first stage one tests available products for microwave-heating performance. If performance turns out to be acceptable, microwave cooking instructions are added and labeled "microwaveable".

In the second stage, microwave heating is also considered from the start of product development, adopting dual ovenable packaging for reheating both by microwave and conventionally.

In stage three, finally, products are developed from scratch for microwave heating only, taking into consideration all the demands peculiar to this heating form with regard to product formulation, pretreatment, shape, layout and packaging.

5. *Packaging for microwave heating*

In microwave heating, whether in a domestic microwave oven or an industrial tunnel, packaging is an integral part of the food product. Packaging composition, shape and incorporated active functions all contribute to the heating result, in direct interaction with the composition, properties, geometry and positioning of the food inside (Sacharow and Schiffmann, 1992).

a. Materials. Packaging properties of special importance in microwave heating are:

- temperature stability up to 120°C
- microwave transparency (insignificant dielectric loss)
- fat and moisture stability
- form stability in handling
- geometry
- ease of opening.

The packaging material should permit temperatures of at least 120°C without affecting handling stability or food protective properties. For low moisture foods high in oil or sugar, temperature stability may have to extend up to 150°C, because these foods will easily overheat in a microwave field. To permit reheating also in a conventional oven (dual ovenable) temperature resistance up to 200°C is required.

The main packaging alternatives are:

- polymer-coated paperboard
- mono- or multi-layer polymers, laminated or co-extruded
- aluminum foil or foil- and polymer-laminated board
- glass.

Of the polymer materials in use PP (polypropylene) will meet the minimum temperature stability requirement, while APET (polyester) can be used up to 200–250°C.

The ideal food package shape is round or oval with vertical sides and rounded edges to limit sharp corners and edges to a minimum. Rectangular containers may be required for practical reasons, but should have rounded corners and edges to reduce preferential heating tendencies.

A limiting factor in microwave transparent polymer packaging has long been their limited barrier properties and the reduced shelf life of the packaged food compared to foil-laminated packaging. Barrier materials, such as

EVOH (ethylene vinyl alcohol) and silica oxide coatings overcome largely this limitation.

In a closed package, steam will be generated during microwave heating, when part of the food reaches the boiling temperature of water. To avoid bursting or deformed packages, a venting mechanism has to be built into the package (such as a one-way valve), or the package has to be punctured or partially opened before microwave heating. In industrial processing external overpressure may have to be used.

To avoid moisture re-condensation on food surfaces intended to remain crisp, a double layer of moisture-permeable and moisture-absorbing materials may be built into the package, or a susceptor material applied in near contact with the food to prevent condensation and migration of moisture to the food surface.

b. Metal packaging. Metals reflect microwaves completely, and food areas close to a metal surface will not be microwave heated at all. Also, the presence of metal in the package or other metal objects in the microwave oven will markedly influence the microwave field distribution.

Previously, recommendations have been to avoid metal trays or foil laminated packages in microwave heating, because they were likely to cause damage to the magnetron, due to excessive reflection of energy. Since modern magnetrons are considerably less sensitive, aluminum containers, with transparent cover, may now be used safely, provided they are not positioned so close (≤ 2 mm) to the oven wall that electrical discharges or sparks can occur.

The metal will change the mode pattern in the oven, as illustrated previously in Fig. 16, and thus influence the heating result. This may even be improved compared to heating in a transparent package. Because microwaves can now penetrate only from the top and not from the sides, corner and edge overheating is eliminated, even to the extent that these parts may remain cooler than the central parts of the food.

Product thickness will be limited to about half the penetration depth of the food material, to permit sufficient heating of the bottom layer. This is illustrated in Fig. 20, which shows the resulting temperature profiles when microwave heating foods at two thickness in plastic and in aluminum foil containers. Heating time in the Al-container will be prolonged and energy efficiency lowered by a highly variable factor, 10–100% (Ohlsson and Risman, 1991).

c. Active packaging. The property of metal to completely reflect microwaves can be utilized in the design of packages, which minimize heating differences between food components of different physical

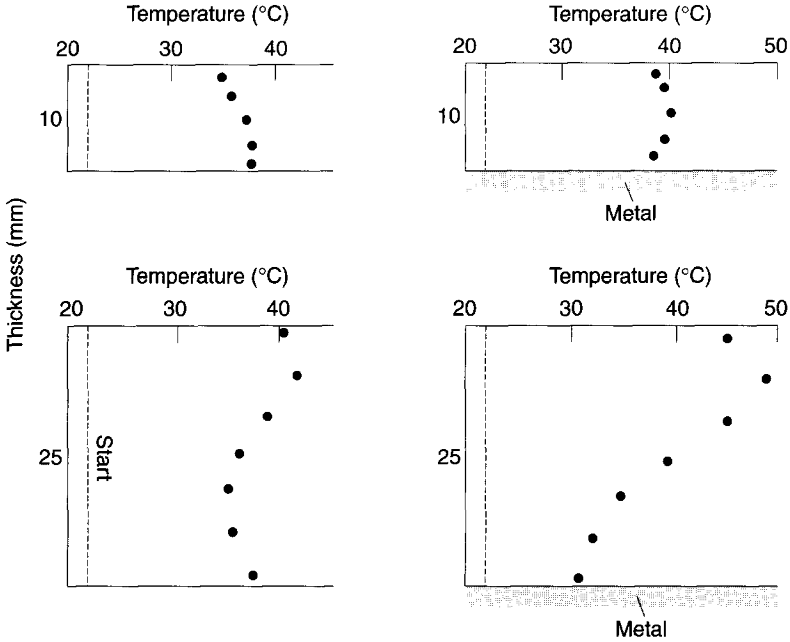


FIG. 20. Temperature profiles through food of 10 and 25 mm thickness, microwave heated in a plastic tray (bottom) and an aluminum tray (top of picture) (Ohlsson, 1983).

properties, shape or thickness. A pattern of aluminum foil can be applied on the package to screen areas that would otherwise overheat, but permit full penetration into areas that would otherwise remain cooler. The best example is the Alcan Micro Match system. Many other forms of package field modification are found in the patent literature.

The use of susceptors was briefly mentioned earlier in this paper. Susceptors, or receptors as they have also been called, are extremely thin films of metal, vacuum deposited on PET-film with paperboard backing. At a metal film thickness of only 25–50 nm, part of the impinging microwave energy is transmitted, part reflected and a substantial part absorbed generating heat and high temperature in the metal film. When such a susceptor film is applied at a few mm distance from the foods surface, the generated heat will rapidly transfer to and heat the food surface (Turpin, 1989). The surface temperature reached will be sufficient to reverse the temperature and moisture profile in the food and to crisp and brown the food surface, as in conventional grilling. Susceptor temperatures will usually not exceed 115–130°C when in close contact with the food, but may otherwise reach temperatures up to and above 250°C (Lentz and Crossett, 1988). At such high temperatures there will be some risk for migration of substances into the food from the plastic film and paperboard backing. Therefore, susceptors are being developed that have a built-in temperature limiting function.

There has been much concern about the migration of hazardous chemical components from susceptor packaging material. Extensive research in USA, UK, Germany, the Netherlands and Sweden has, however, demonstrated that microwave heating itself does not increase migration rates. Also, the short heating times sometimes give lower migration levels compared to conventional heating (Ohlsson *et al.*, 1991).

B. INDUSTRIAL USE

1. Design and equipment

a. General. In principle, the description of the components of the domestic microwave oven is valid also for industrial equipment: a power pack with a magnetron for generating microwave power, a waveguide and a feed arrangement for transferring the energy to an applicator in which the food material is being exposed to the microwave field. A similarity in kind, but with the difference that industrial processing equipment will be designed for power levels between 20 and 200 kW, instead of the 400 to 800 Watts of a domestic oven.

The closed, rectangular cavity applicator typical for domestic ovens is also the most common and versatile type of industrial applicator. However, the industrial units will normally be continuous, the food material being fed through openings in the cavity walls, so designed that leakage of microwaves to the outside is prevented by chokes and absorbers. For high capacity, a succession of standardized or modular cavities will be used.

There are, however, also a number of other applicator designs, often tailored for a specific heating application, while the cavity is an all-purpose applicator.

b. Frequencies and components. Two different microwave frequencies are available for the industrial heating of foods, 2450 MHz and 915 MHz (896 MHz). Of these, the lower one is not yet generally permitted outside Britain and the US. The main differences in heating effect between the two has already been covered earlier in this paper, and will be further commented on in the presentation of some specific heating applications. A very apparent difference is the size of the components and applicators, due to the difference in wavelength: 12.2 cm at 2450 MHz compared to 32.8 cm at 915 MHz.

In the early period of development of industrial applications, klystrons (a type of modified electron accelerator) of very high power rating (25 to 100 kW) were considered for both 2450 and 915 MHz applications in the US. This kind of generator is still being used in the US for 915 MHz, as an alternative to magnetron tubes of 25 to 60 kW rating.

With the mass production for microwave ovens of magnetrons of about 1 kW power rating and other components for 2450 MHz, it has become more economical to use a large number of standardized modules, each with its own plug-in power pack and control devices. However, there is also a small production of 2 and 5 kW 2450 MHz magnetrons for industrial use. Lately, high power 15–30 kW tubes have been developed in the US, reportedly with very high conversion efficiency, as a power source for very high power installations, which would otherwise require hundreds of domestic type magnetrons.

As a rule, the power efficiency of the magnetron will be higher at 915 MHz than at 2450 MHz (75–80% compared to about 65–70%).

c. Applicators. The following are the main types of applicators used for industrial microwave heating applications (Metaxas and Meredith, 1983):

- cavity applicators
- horn or radiator applicators
- periodic structures
- travelling wave applicators
- single mode applicators.

Fig. 21 illustrates an industrial *cavity applicator* and its various functional features. Leakage to the environment is prevented by microwave chokes and special absorbers, and reflection back to the generator can be safeguarded against by circulators, which deflect microwave energy to absorbers.

As in the industrial microwave ovens, there is a variety of ways to feed the microwave energy into the cavity: by antennae, wave guide openings, horns or slots in the cavity walls, supplemented by some kind of mode stirrer or equivalent arrangement. Power may be fed into the cavity or cavities at several points, taking care to avoid interference between different magnetrons or different feed points from the same magnetron.

As for the industrial cavity oven, the field and power distribution will largely depend on the size and shape of the cavity, how the microwave energy is fed into it, the geometry and dielectric properties of the food load and how it is positioned inside the cavity, especially the height above the cavity floor. Field irregularities in the feed direction will be evened out by the continuous movement of the food on the conveyor, just as it is by the

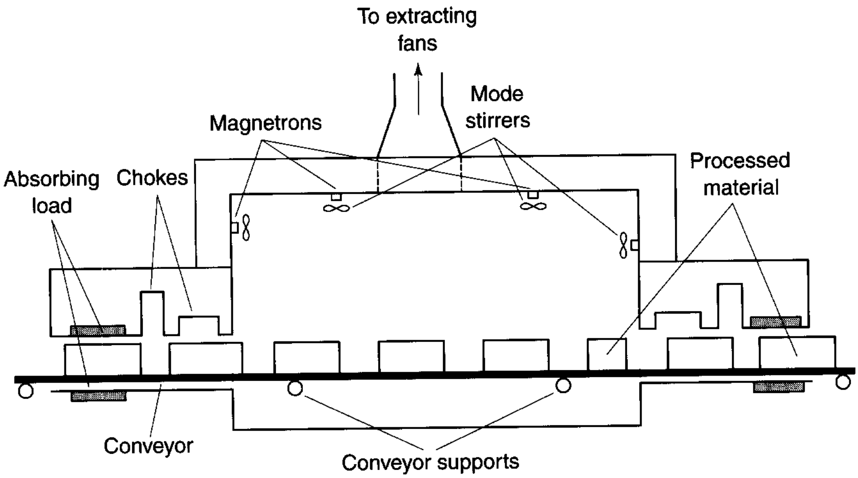


FIG. 21. Cavity applicator (Metaxas and Meredith, 1983).

rotation on a turn table in the domestic oven. Much more sophisticated process control devices can be applied in an industrial unit operating under "steady state conditions", together with better load matching and greater power efficiency. In general, more even field and temperature distribution will also be achieved in industrial microwave applications. Cavity applicators are mostly rectangular in shape, but may also be cylindrical or have some other shape, depending on the application. For vacuum or high-pressure processing, a cylindrical shape is preferable, from the point of view of keeping the wall thickness (and cost) reasonably low.

A *horn applicator* can be considered as a wave guide, the sides of which are gradually widened to form a rectangular horn. One or several horns can be positioned to feed microwave energy close onto the food material from different sides, when fed through a processing tunnel. The horns can be fed from the same magnetron by a power splitting arrangement. (Parabolic radiators and so-called "broadside arrays" have also been used in the past.)

With this type of applicator, corner and edge heating effects are claimed to be reduced and the microwave energy to be more focused to the central part of the (rectangular) food sample. However, the overall field distribution will probably be rather complex in such a hybrid of radiation or plane wave mode and multimode cavity. Figure 22 shows a horn radiator arrangement of the type used in several large tempering installations in Britain.

In a *periodic structure* arrangement, such as seen in the application in Fig. 23, the microwave field is coupled to an intricate regular arrangement

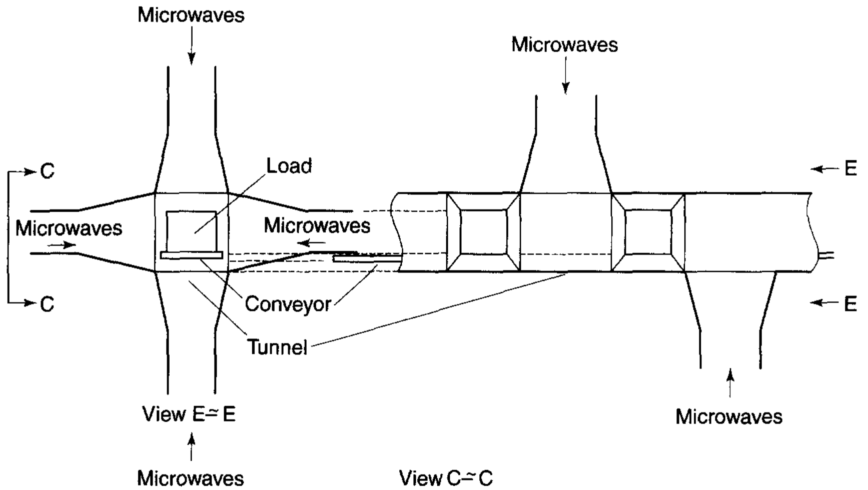


FIG. 22. Ham applicator (Metaxas and Meredith, 1983).

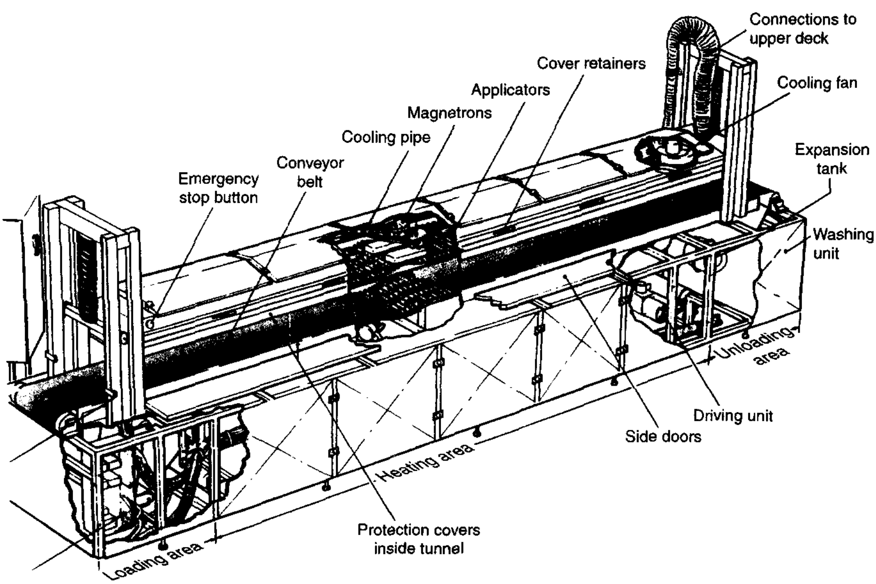


FIG. 23. Periodic structure such as used in this tunnel from the Micro Heat company (Micro Heat Co., 1990).

of metal ridges or rods. In such a near-field kind of applicator, the field distribution will be more independent of the food load than in a multimode cavity. However, when used in a practical conveyorized tunnel with a food load, it will become more of a hybrid system between a nearfield and a resonant cavity.

In principle, in the *travelling wave* applicator microwave energy is fed into a wave guide, where the wave propagates and is gradually absorbed by a food load that is fed either inside and along the waveguide, or straight through slots in the wide side of the waveguide, which is then bent in a Meander fashion as shown in Fig. 24. What little energy remains after the passage of the food is then absorbed by a water load or artificial end load. The Meander-type applicator was fairly popular in 915 MHz applications for thin food materials in the 1970s, but is rarely used today. A 915 MHz wedged waveguide tunnel is still being used in the US for the precooking of bacon slices.

The previously mentioned applicators are characterized by a large or small number of changing electromagnetic field patterns. In contrast, the *single mode* applicator is designed to accommodate only one specific field

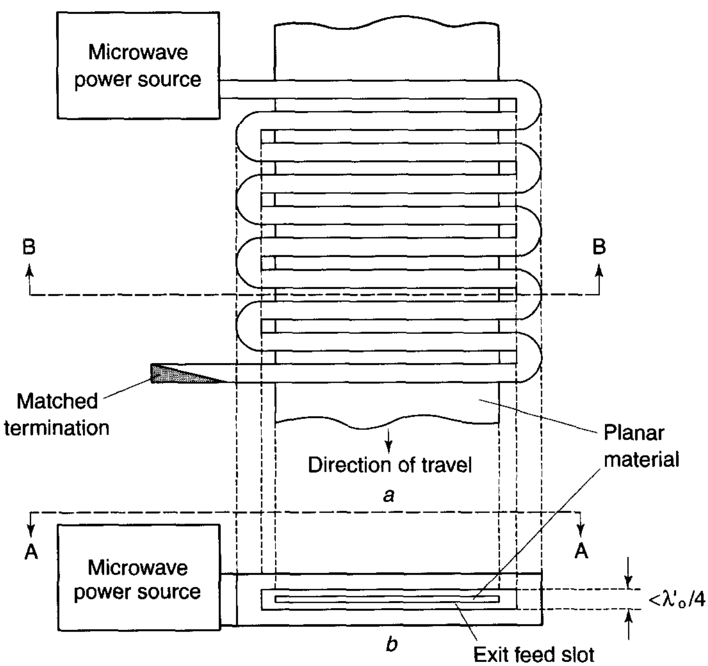


FIG. 24. Travelling wave (Meander) applicator (Metaxas and Meredith, 1983).

pattern. This can be characterized by a set of figures, such as TE 102 or TM 010, the figures indicating the number of half waves in a specific geometric direction inside the empty applicator, TE standing for transverse electric field and TM for transverse magnetic.

The food material introduced into the applicator will have a marked influence on the field distribution, especially in cases where the food takes up a large proportion of the applicator space; the wavelength inside the food being about seven times smaller than in the air space. Single mode applicators, therefore, have to be carefully tailored to a specific food and a specific application, and will not be directly useful for materials of different dielectric properties. In addition, a single mode applicator will often permit very high field strength to be used, provided it is designed to give a very even field inside the food material.

Figure 25 demonstrates the field pattern in a tubular TM020 applicator designed for continuous processing of liquid or semiliquid foods being pumped through a tube of non-absorbing material going through the applicator axis (Risman and Ohlsson, 1975). An important aspect is to choose a suitable tube thickness, as a heating profile can be obtained in the food stream that favors central heating, and thus compensates for the higher central velocity of the food stream and the drag at the tube walls (Ohlsson, 1993). Work is presently in progress using an applicator design optimized by FDTD software to permit a larger workload radie than 10 mm with little axial field variation also at 2450 MHz by superimposing two single modes (Isaksson and Bondeson, 1999).

2. *Heating applications*

Microwave heating applications for the food industry have been considered very promising and novel for well over 30 years. Still, the number of operating microwave lines in the food industry is probably less than a thousand worldwide, although a great many applications have been claimed successful on a laboratory and pilot scale over the years, greatly reducing processing times and improving the yield and product quality. Some of the reasons for this slow growth are the following.

In the enthusiasm over a new microwave application, little consideration was given to what conventional reference method was being used, and whether this was the optimal method or could easily be improved upon, eliminating much of the advantage of the microwave alternative. So, for example, the first large-scale industrial microwave application, the finish drying of potato chips without product darkening, was quickly made obsolete by better handling of the raw material and by vacuum deep-fat frying.

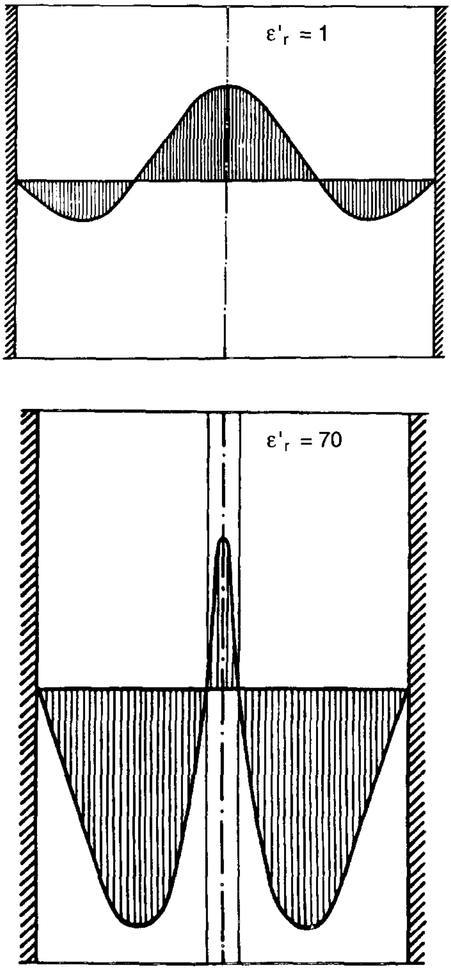


FIG. 25. Field pattern in a single mode TMO20 applicator. Unloaded (top) and loaded (bottom) (Risman, and Ohlsson, 1975).

In other cases, otherwise sound microwave process ideas fell through because of scale-up problems and malfunctioning under factory operating conditions. Uneven field and temperature distribution, poor temperature control and low power efficiency, leakage of microwave to the environment with safety and interference problems and frequent breakdowns were quite common reasons for disappointment in an otherwise promising microwave application.

The microwave equipment manufacturers had no experience of making processing equipment for the food industry. Managers and technical personnel in the food industry lacked knowledge on microwave heating fundamentals, and were often skeptical or even hostile to the new technique, which very definitely was "not invented here".

Considerable R&D efforts were often spent on applications that were very unlikely ever to become cost effective, for example on the blanching of vegetables. This is a typical seasonal application, giving very poor overall utilization of an expensive plant – using a high-cost process for low-cost food produce.

With time, however, it is necessary to realize and live up to some basic requirements for a viable industrial application:

- it must have a high degree of reliability;
- it must have advantages based on some of the unique features of microwave heating, that cannot easily be matched by improved conventional technique;
- it should be cost effective in terms of high power efficiency, and if possible, combine microwave with conventional, cheaper methods of heating for a substantial proportion of the energy required;
- close cooperation must be established between the microwave equipment manufacturer, specialists on process equipment and control systems for the food industry and the technical staff of the food company in the application development and scale-up.

In addition, and partly as a result of the above, the reliability and efficiency of microwave plant equipment and components have been vastly improved, as have the means of process control. Empiricism in design is being exchanged for mathematical modeling and computer simulation, and the use of network analyzers to optimize the matching of the generator and applicator to the food load, and the field and temperature distribution in the food under processing. Process computers and on-line measurement of temperatures, etc. permit improved process control. As a result of this improved performance of microwave equipment, the interest within the food industry and the number of installations are steadily increasing. A contributing factor is that the widespread use of microwave ovens at home has made people in general familiar with microwave heating.

The more specific advantages and disadvantages of microwave heating will first be outlined, followed by an overall tabulation and review of interesting food applications. Finally, those in widest use so far, and with fair prospects for the future, will be reviewed in greater detail.

For a viable commercial application, the advantages have to outweigh the disadvantages by a substantial margin, not only in comparison with the good conventional technique used at present, but also compared to improvements of the conventional techniques that can be foreseen. Therefore, microwave heating applications should be based on some of the unique features of microwave heating. To illustrate the scope and width of application development work done over the years, a list of applications that have been claimed technically successful and economically feasible has been prepared (Table I).

TABLE I
FOOD APPLICATIONS CLAIMED TO BE SUCCESSFUL
(KNOWN COMMERCIAL APPLICATIONS ARE IN ITALIC)

Processing area	Products
Tempering, thawing	*Meat*, fish, *butter*, *berries*, etc.
Melting, rendering	*Fat*, chocolate
Blanching	Corn on the cob, potatoes, etc
Drying	*Pasta*, *onions*
	juices, potato chips and slices, *molasses*, *pet food*
Volume expansion, puffing	*Starchy snacks*
Baking	*dough raising*
	bread baking, *post baking*
Roasting	Peanuts, *coffee*, *cocoa*
Insect killing	cereals, muesli
Preconditioning	*seed*, *grain*, *fish feed*
Cooking, coagulation	*meat*, *chicken*, fish
	sliced bacon, emulsions
Pasteurization	*Bread*, yogurt
Sterilization	*prepared foods*

Of all the applications in the table, those in widest use so far and with fair prospects for the future, appear to be tempering, drying and pasteurization. These will be commented on in greater detail later on, after some general comments on some of the other applications.

Blanching has already been commented on as a microwave application which may be technically interesting, but has poor economical prospects due to the combination of high investment costs and a seasonal, low-cost and high-volume produce. The claimed advantages in nutrient retention and quality from a microwave and steam combination process will probably not suffice to offset the cost disadvantage.

Cooking by a combination of microwave and convection, conduction or radiation is a fairly established but small application, with time reduction and improved yield as the main advantages. In the US, microwave/steam cooking of chicken had already been introduced in the 1970s. The process is now receiving renewed attention with the advent of improved processing equipment and increasing market recognition of the gains possible in yield and sensory quality.

Precooking of sliced bacon is another typical US application, in which microwave processing gives an important advantage in product appearance. It also diminishes the risk of nitrosamine formation and results in greater stability and higher quality of the rendered fat.

In Europe, cooking-coagulation is being used on a limited scale for the texturization of meat and fish emulsions. In a French installation, the emulsion is pumped through a microwave transparent pipe, inside a series of mixed mode or "hybrid" mode tubular applicators (Mimouni *et al.*, 1993). A single mode applicator for the same purpose is seen in Fig. 25, and has been found suitable for the continuous production of skinless sausages, even though no commercial installation has been built.

A Swedish company has been using a combination process of double-sided belt grilling and microwave finish cooking of meat patties for 20 years, with advantages both in processing time, quality and cost.

Promising results in baking of loaves of bread by hot air and microwave at 896 MHz were reported in Britain, but for economic reasons no future is seen today for such an application. In the US, large-scale pilot baking of bread in metal pans was apparently quite successful, but was not commercially introduced. Ovadia and Walker (1995) have presented studies of bread baking using a combination of microwave energy and impingement hot air heating.

In Britain, microwave energy has successfully been introduced into a conventional biscuit baking oven by a special built-in applicator construction, in order to accelerate the baking process without disturbing the conventional heat transfer. In this way the rate of heat input to the dough was substantially increased without exceeding the surface temperature limit, leading to improved process control and savings in energy and floor space (Shute, 1993). Microwaves are uniformly distributed across the conveyor by specially designed applicators. The baking time for biscuits is reduced by 20–40% (Fig. 26).

The leavening and baking of donuts was a technically and economically very successful microwave application in the US in the 1970s, and it is unclear why it is no longer used at all. Application of microwave for rapid raising of dough to optimal yeast growth temperature has met with some success, the main advantage being the substantial savings in production line length and factory space possible.

Volume expansion or "puffing" of partially dried foods has received attention from time to time, the making of pop-corn in the domestic microwave oven being a good example of the principle.

In 1993, a British company announced a process in which a starch-base

FIG. 26. Microwave-assisted baking oven (APV, 1995).

material is being expanded into new types of fat-free snacks in microwave cavities with an extremely high power density. The high power required at 2450 MHz for such production lines made necessary the development of a new 15 kW magnetron tube to keep the number of power modules in a 200 kW plant within reasonable limits, but also in order to achieve much greater power efficiency. In the US a large-scale process for the production of fat-free potato chips was started up in 1993, using a Meander type 915 MHz applicator (Rice, 1993).

Technically successful applications of microwaves for the roasting of coffee and cocoa have been installed for low-volume production of special qualities.

Several microwave plants are in operation for the *preconditioning* of seed, grain and fish feed to improve their functional properties. It is being claimed that microwaves should be used industrially also for the *killing of insects, moulds and bacteria* in dehydrated foods, such as muesli and other breakfast cereals, but no written documentation has been found (Klinger, 1986 and Nakahita *et al.*, 1989).

a. Tempering and thawing. Conventional thawing and tempering is a messy and time-consuming business, requiring 24 hours or more for thick samples, compared to the 5 to 15 minutes needed in microwave processing. Complete thawing is often not necessary or even desirable for uses such as the forming or slicing of meats, de-boning or mincing and blending of emulsions for sausage or meat patty production.

For tempering to temperatures between –5 and –3°C, microwave heating appears to be ideal. The loss factor is still low, the penetration depth, thermal conductivity and specific heat high, combining to level out any temperature differences. In addition, only between 30 and 50% of the energy needed for ice melting has been used, giving a correspondingly lower processing cost and an increase in production capacity.

However, as soon as most of the ice has melted in some part of the food, the loss factor dramatically increases and the penetration depth and thermal properties decrease. The risk of a rapid and uncontrolled temperature rise, so-called "runaway" heating, is now great, unless the energy input is considerably reduced and/or surface cooling introduced. This was illustrated in Fig. 5, a computer simulation of microwave thawing of a 30 mm thick slab of meat in an uneven microwave field. As was seen from Fig. 3, the microwave penetration at low temperatures is much greater at 915 MHz than at 2450 MHz. In addition, the tendency towards corner and edge heating is often lower at 915 MHz, and the difference in loss factor between frozen and thawed smaller. Consequently the lower frequency is to be preferred for tempering and thawing, a drawback being that the frequency is not generally permitted outside of the US and Britain (Bezanson, 1975).

Microwave tempering of meats is the largest industrial application of microwave heating so far, with probably more than 200 lines in operation, batch or continuous, and supplied by half a dozen different equipment manufacturers in the US, Europe and Japan. See also Fig. 27 for an American 915 MHz installation during meat tempering. A British 360 kW installation tempers block-frozen butter at a rate of 20 tons/hr. The time required for conventional tempering of the butter is four days, which can be compared to the five minutes needed for microwave tempering, only occupying one-sixth of the floor space.

Sometimes, however, *complete thawing* with even temperature distribution is also needed for very thick samples, 10–20 cm or more. The requirements are then the following:

- The power level and rate of microwave input must be reduced so that the thermal conduction can level out the temperature gradients.
- Surface overheating must be prevented by circulating cold air of controlled temperature and humidity.

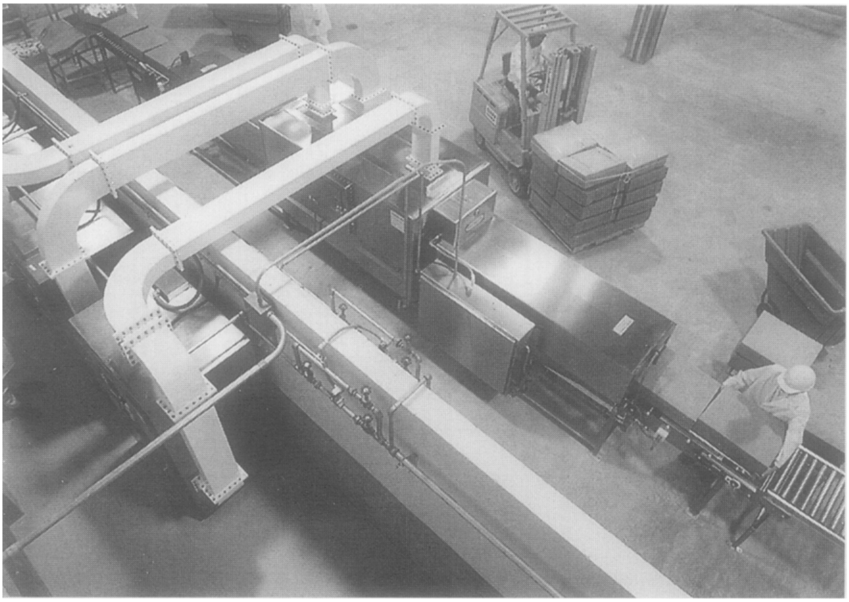


FIG. 27. 915 MHz tunnel for meat tempering (Raytheon, 1975).

The advantages of microwaves as regards thawing time, yield and quality are still so much greater than those of conventional thawing that the higher cost may be well motivated. In Fig. 28 is demonstrated a computer simulation of thawing a 15 cm thick block at 2450 MHz, using very low microwave power in combination with circulating air of +4°C. After 4 hours, the food is uniformly tempered to –2°C. After 8 hours and an additional 2 hours for equilibration at +4°C, a uniform temperature of +2 to +4°C is reached throughout the sample. The thawing time may appear long, but the thawing in cold air only would require about 48 hrs. The microwave power needed for such an installation would be only 10 kW for a 15-ton load, the rest of the energy needed being supplied by the circulating air. If 915 MHz is used, a greater power input and correspondingly shorter thawing time would be possible (Ohlsson, 1983; Virtanen *et al.*, 1997).

Promising results from microwave tempering of meats in a vacuum chamber were reported in Britain at 915 MHz, but so far no commercial installation is known (James, 1984). Microwave tempering is also being used industrially for fruits (before pitting cherries), frozen dough for white bread (bake-off operations) and shrimps (for peeling).

Improvements in conventional techniques for tempering and thawing of foods will limit the number of applications where microwave tempering

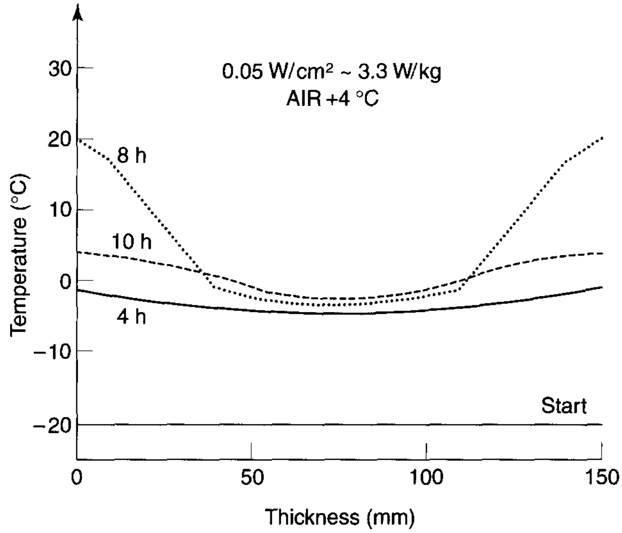


FIG. 28. Simulation of low-power microwave-assisted tempering of 15 cm thick meat blocks (Ohlsson, 1984).

will demonstrate practical advantages worth the extra cost. Another limitation is that raw material suppliers often use dimensions, shapes and packaging materials that are incompatible with any form of controlled and rapid tempering/thawing. An example is the use of big drums for frozen fruit and berries. Strict raw material and packaging specifications will be needed if microwave heating is to be considered.

b. Dehydration. Dehydration and heating of dry foods is probably the most promising application area for microwave heating, especially for granular material and larger, regularly shaped pieces of food (Nijhuis *et al.*, 1996). The penetration depth for microwave is great and increases with decreasing moisture content during drying, while the thermal conductivity decreases, reducing the heat transfer by conventional means (Jolly, 1986).

It is not economical to use microwave heating for the complete drying of high moisture foods, but rather as a complement to conventional heating to greatly accelerate the later stages of the process. Evaporation of water from the surface during the constant rate period of drying is best done by air convection or radiation. However, the constant rate period can be extended by balancing the internal moisture transport, intensified by in-depth microwave heating, to surface evaporation in an optimal way so that case hardening and shrinkage is prevented, while significantly reducing drying time and processing costs (Funebo and Ohlsson, 1998).

Since the loss factor of moist material is higher than that of dry material, microwave heating will also have a moisture leveling effect, important for the quality and shelf life of many dehydrated foods. This is utilized in a French installation for post-baking of biscuits, an application otherwise dominated by RF (HF) heating at 27 MHz.

Modelling and calculation of microwave assisted air drying is very complex, and has, so far, not met any particular success. Khraisheh *et al.* (1995) used a calorimetric technique to model the power absorbed with respect to sample size and oven loading.

Since dielectric heating is selectively absorbed by moist "particles" above 1 mm in size, it can be used also for killing insects, eggs and larvae without overheating the surrounding dry material.

The reversed temperature profile developing during the later stages of microwave drying, will give rise to a vapor pressure gradient from the interior, increasing the moisture transport rate. Pressure build-up and evaporation in the interior of the food may also cause structural expansion and fissures that will facilitate both water transport to the surface and water uptake in reconstitution of the dried food. The new concept for snacks production has already been mentioned. The Japanese *cup noodle* product, which has grown into a major snack product already, is based on microwave expansion drying of egg noodles, offering very rapid reconstitution when hot water is added to a cup.

Of two spectacular drying applications in the US during the early application period (1960s and 1970s), finish drying of potato chips and drying of pasta, only the latter has survived. While drying of chips could soon be matched more economically by improved conventional techniques, pasta drying was based on some of the unique properties of microwave heating and has survived and spread into both Europe and Japan. In the US application of pasta drying, a combination with hot air is used in a three-stage process to bring the moisture content down from 30% to 13% in half the time needed in the conventional hot air process, and with improved process control, product quality and plant hygiene. The space requirements are smaller, and the economical efficiency much greater. Figure 29 presents a typical diagram for moisture reduction in the three-stage drying process (Anon., 1981). Similar concepts are being used on a more limited scale for drying chopped onions, wild rice, bacon bits and extruded snacks.

Vacuum drying was introduced in France for semi-continuous drying of juice concentrates in a 2450 MHz cavity-vacuum chamber. Substantial reductions are claimed in both drying time and aroma losses, and a product quality comparable to that of freeze-dried juices at considerably lower cost. About a dozen microwave-vacuum dryers of different makes are thought to be installed in the food industry at present.

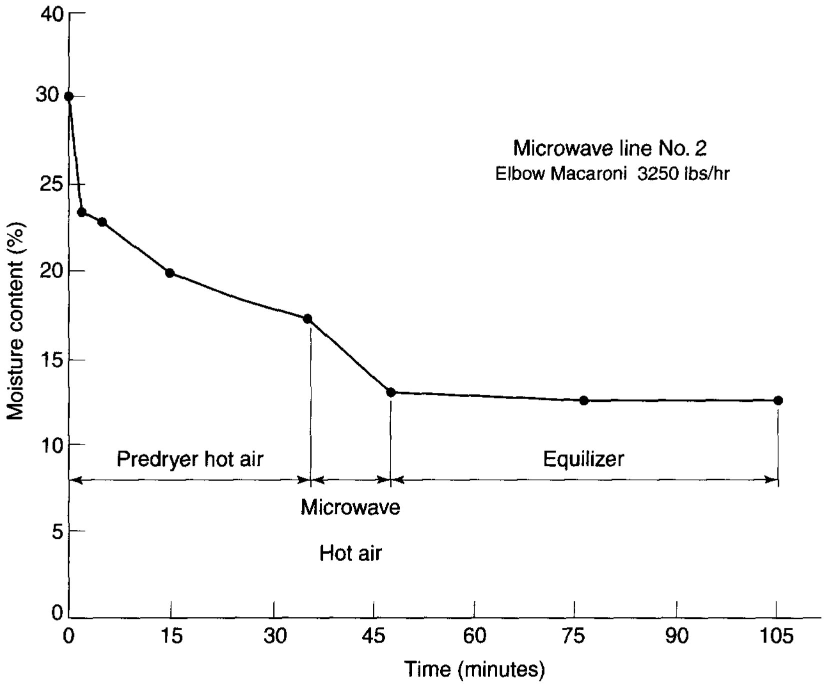


FIG. 29. Drying rate curve for microwave assisted pasta drying (Anon., 1981).

Vacuum microwave drying has been studied for drying of granular materials (Heindl, 1993). In Japan, promising results have been published for drying both chicken pieces and potato slices by a combination of cool air and low-power microwave, claiming a quality and reconstitution ability comparable to that of freeze-dried foods (Akahoshi and Matashige, 1990).

At California State University in Fresno a dried foods technology laboratory has been installed, using microwave-vacuum drying on a large pilot scale. Pre-drying of fruits and vegetables is done by vegetable oil immersion, followed by two-stage microwave drying and moisture equilibration by radiant heat. All operations are performed under vacuum.

Research in Germany at the Fraunhofer Institute in Munich on the application of microwave in fluidized bed drying of particulate foods, have shown that the heat and mass transfer are limiting factors. It is also known that such applications have been investigated by major food companies, and a British company claims to be making such equipment. For both spray drying and rotating drum drying, combinations with microwave heating have been claimed to give significant improvements in both drying time and quality.

c. *Pasteurization and sterilization.* The relationships established in the scientific literature between time, temperature and the killing of microorganisms, inactivation of enzymes and sensory and nutritional loss clearly demonstrate that a HTST (high temperature, short time) process should result in quality advantages with maintained safety, both in the pasteurization and sterilization of packaged foods.

Microwave heating is the only heating method by which HTST-like processing can be achieved for solid foods of several cm thickness. Important limitations to such a microwave process are what minimum temperature spread can be controlled, and that the cooling rate will have to depend on conventional cooling techniques and the thermal conductivity of the food material.

To avoid excessive overheating of corners and edges of packaged, slab-shaped foods, the Swedish Multitherm process used water of controlled temperature as the surrounding medium. Japanese, Italian and German processes use air or steam around the food package, but have developed special, hybrid applicator and screening devices to prevent edge overheating. They all claim a temperature spread within 5°C. The temperature profile developing in pasteurization by the Multitherm process is seen in Fig. 30, based on computer modeling (Ohlsson, 1991b; Brody, 1992). Van Loock (1996) described a number of equipment designs for pasteurization and sterilization and their respective advantages and disadvantages.

In *pasteurization*, sterility is not the objective, only elimination of vegetative bacteria, yeast and molds. The requirements for temperature control are thus less stringent than for sterilization, except that temperatures near or above 100°C are not permissible, unless overpressure is applied to avoid internal steam development and bursting of packages.

Microwave plants have been in commercial use for many years for the pasteurization of packaged bread, cakes and confectionery, especially in countries where chemical mold inhibitors are not permitted, or where their effect on the bread volume and aroma is not deemed acceptable.

The focus of interest for the last 5–10 years, however, has been on the processing of packaged, precooked foods, the first trials (for microwave sterilization) being reported by the US Army as early as in 1971. Today, plants for commercial pasteurization of ready-made meals are being offered by several European companies.

Experimental work at SIK with finish cooking and pasteurization of packaged pre-browned meat patties by microwave processing showed that a shelf life of five to six weeks in chilled temperature storage was obtainable by two minutes of microwave heating to reach 80°C. The microbial development during storage at different temperatures after microwave heating to 70 and 80°C respectively is shown in Fig. 31 (Ohlsson and Rask, 1983).

In Europe alone, over a hundred pasteurization plants of at least four different equipment manufacturers are claimed to have been installed over the last 5 years, primarily for processing packaged sliced bread and pasta dishes. They all claim microwave heat processing times of about five minutes, after pre-heating by conventional means to some 40°C below the desired final temperature of 80–85°C. Some extent of air overpressure or mechanical constraints seems to be applied also in pasteurizing units to safeguard against package rupture by localized overheating. A typical pasteurization plant for two tons/hr will consist of up to eight hybrid-wave guide/cavity chambers, with a total of some 200 low-power magnetron modules.

In a report by Burfoot (1990), comparative studies have demonstrated a higher potential for 915 MHz than for 2450 MHz in the pasteurization of ready-made meals, offering superior temperature uniformity.

A British company claims to achieve corresponding or better results by mixing the two frequencies 896 and 2450 MHz in the same cavity tunnel, in combination with hot air. They also claim to be able to use package thicknesses of up to 10 cm with satisfactory results. After holding for temperature equilibration and sufficient heat treatment, liquid nitrogen spray or cooled water is used for rapid cooling, all inside a pressurized chamber (Gordon, 1991).

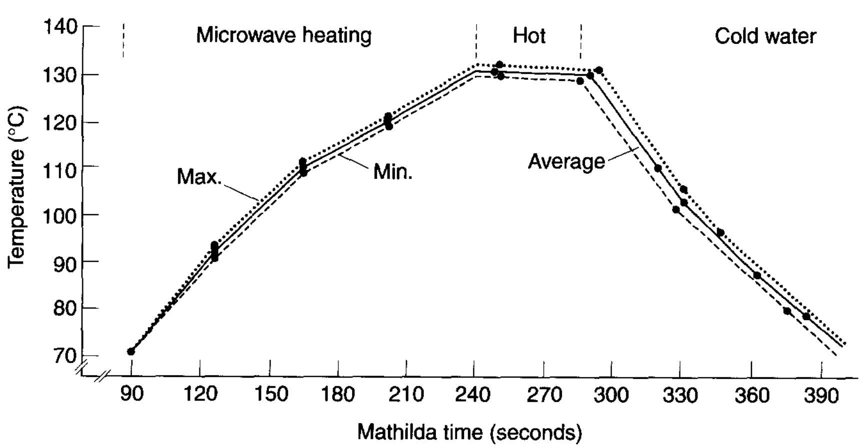


FIG. 30. Time-temperature distribution curve during microwave sterilization with the Multitherm concept (Ohlsson, 1991).

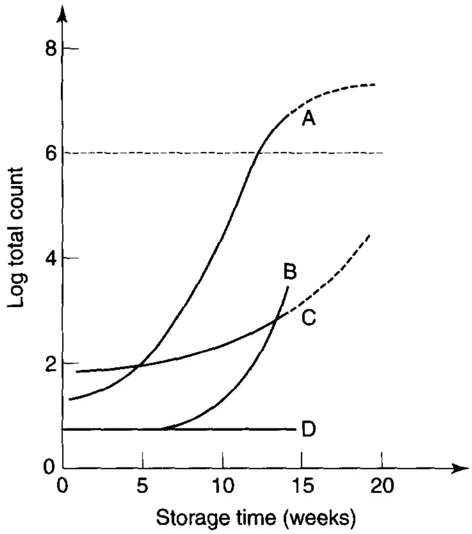


FIG. 31. Bacterial development during storage of microwave pasteurized meat patties (Ohlsson and Rask, 1983).

From its description in a trade journal (Anon., 1991), a commercial microwave *sterilization* plant operated by a Belgian food company appears to be a very sophisticated and complex system, with computer control of each magnetron and food sample to safeguard the correct heat processing of each individual package. It is claimed that their pasta dishes will have a shelf life at ambient temperature of 9–12 months, combining the use of a modified atmosphere with high-barrier seven-ply co-extruded plastic trays. A similar equipment is also installed in Japan processing packs of cooked rice.

The Multitherm concept for sterilization has been based on many years of fundamental and applied research on microwave sterilization at the Alfa Laval Company and SIK. This has comprised the determination of dielectric data in the high temperature region, computer simulation work and experimental pasteurization and sterilization work. It has included quality studies on sensory and nutritional aspects as well as inoculated pack work to ascertain microbiological safety.

Figure 32 presents sensory data for carrots, comparing microwave sterilization with pouch sterilization and can sterilization with steam and preservation by deep freezing over a storage period. The quality of the microwave-sterilized sample is significantly higher than that of the conventionally processed sample, and equivalent to the frozen one. For green peas, a similar advantage was obtained initially, but was followed by rapid deterioration of the microwave-processed product during storage. Clearly,

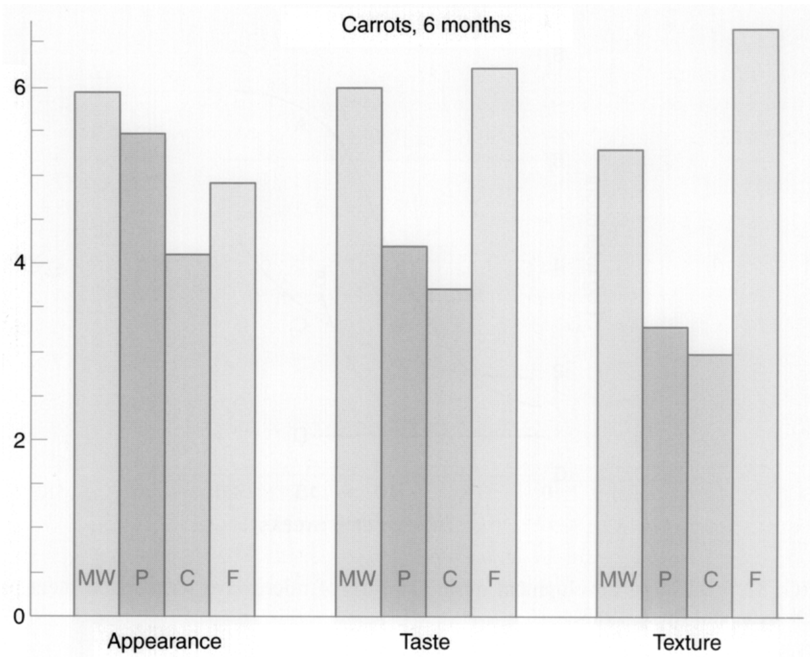


FIG. 32. Sensory scores for carrots comparing microwave sterilization (MW) with in-pouch steam sterilization (P), in-can steam sterilization (C) and deep freezing (F) (Ohlsson, 1991).

there is variation from product to product as regards the quality and stability resulting from HTST microwave processing.

For more complex foods, the temperature spread is larger, leading to higher average heat treatment levels, with less pronounced HTST-product advantages. A high degree of uniformity of heating is needed to achieve a superior quality in microwave sterilization (Ohlsson, 1991b; Sundberg, 1998). Sundberg reports sophisticated computer simulation work, permitting the optimization of industrial applicators for more uniformly held distribution and heating.

VI. SAFETY ASPECTS AND INTERFERENCE

Another issue of great importance is to what extent human exposure to microwave fields may occur during microwave heating of foods, and what effects such exposure may have on the organism. What safety regulations should apply?

Research on non-ionizing radiation in the biomedical field over the years has been keyed to the development of a scientific basis for defining safety limits for the exposure of the human body to electromagnetic fields. The objective is to clarify the interactions between field and living biological material and the mechanisms involved.

A. EMISSION AND EXPOSURE

It is important to make a clear distinction between emission (leakage) standards for microwave equipment, and exposure standards for human exposure to microwaves. The permissible *leakage* from equipment in use has been set at 5 mW/cm^2, as measured at a distance of 5 cm from the point of the greatest leakage. The power intensity of this field diminishes in proportion to the square of the distance from the source.

The human *exposure* limit is the power in mW/cm^2 of body surface that is generally considered safe for people working in the environment surrounding the microwave source. In most countries, this limit is set at 1 mW/cm^2. It is becoming more common, however, to express the exposure as the specific absorption rate, SAR, in W/kg body weight instead. Thus the IRPA (International Radiation Protection Association) international guidelines from 1988 set a specific absorption rate of 0.4 W/kg as the safety limit for whole body exposure.

There is often confusion in the literature between emission, which relates to the equipment, and exposure, which relates to people. The permissive emission leakage of 5 mW/cm^2 at a 5 cm distance from the leak will decay to a power level of 0.05 mW/cm^2 at a distance of 50 cm, which is far less than the exposure limit for humans.

The basis for the exposure standards is the *thermal* effects that a microwave field may cause in different parts of the human body, particularly in organs with a reduced thermal balancing mechanism, such as the eyes, and taking into account possible geometrical focusing effects. There are, however, also a number of reports and ideas to the effect that prolonged exposure, even to very weak microwave fields, could cause *non-thermal* effects detrimental to health. Claims have been made that such exposure may cause leukemia in children, certain genetic effects and nerve interactions, such as evidenced by the perception of light or sound, and behavioral irregularities.

However, plausible explanations for such effects are lacking, as well as conclusive evidence of their existence. Attempts to reproduce claimed effects by other researchers have generally failed. Nevertheless, it is an area requiring more research in order to prove or disprove the alleged existence of these effects, particularly at low frequencies and low frequency modulated microwave carrier frequencies.

Critical reviews of the literature in this field have been presented by Osepchuk (1990) and by Jauchem (1991). Research on biological effects of electromagnetic fields is presented in a reference book by Gandhi (1990).

B. INTERFERENCE

Three microwave frequencies, 433, 915 and 2450 MHz, have been reserved for industrial, scientific and medical use, the so-called ISM frequencies. These have been selected so as not to interfere with other applications, primarily in telecommunications. Unfortunately, the 915 MHz has not been generally permitted on the European continent. As it does offer some considerable advantages for industrial applications, actions are being taken in Continental Europe to have an ISM-band around 960 MHz opened (Van Loock, 1992). As long as a recognized ISM frequency is maintained within its narrow limits, leakage from the microwave equipment does not create any disturbance, and no maximum leakage is therefore defined.

However, outside of the permitted frequencies, including their harmonics, leakage over the power lines or through the air is very restricted, roughly to a value of less than 25 μV/m at 1000 ft from the emission source (or 60 dBμV/m at a distance of 30 m).

The standards for interference may vary from country to country, both as regards the measuring techniques and the distance from the source of the interference.

The explosive developments in microwave communication, e.g. for GSM cellular phones, has led to the development of a project (Bloodtooth) oriented on using the "free" 2450 MHz band for local wireless communication networks. It is not fully clear how strongly these new developments will be influenced by the (omni-)presence of microwave ovens.

VII. FUTURE OUTLOOK AND RESEARCH IMPLICATIONS

The market for *domestic microwave ovens* will continue to grow worldwide, even if a near-saturation point has already been reached in a few countries, like the United States and Japan, where all households already have one or more ovens.

The *heating performance* and consistency of microwave ovens will gradually improve as a result of the ongoing international standardization of performance and output power testing methods. At the same time, the growth in fundamental knowledge on field distribution and the interactions between oven design, microwave field and food will lead to improved oven performance.

Packaging development continues in materials, shape, shielding, susceptors and other forms of active packaging, in combination with a product development that increasingly takes into account dielectric and thermal properties of foods and their interaction with the microwave field. Tailor-made aluminum foil shielding and susceptors are in use on the UK and USA food market.

There will also be important improvements in oven components, such as solid state components, which will substantially lower oven weight, size and production costs. In Europe at least, the proportion of combination ovens, combining microwaves with heat by convection or radiation, will continue to grow.

Industrial microwave processing has been considered very promising for decades, but practical application has been slow to develop. Several factors now speak for accelerated growth in the years to come. The reliability of microwave equipment is now easily comparable to that of alternative processing equipment, making the special advantages inherent in microwave heating more attractive. With the strong trend in today's food industry towards continuous processing lines and on-line process control, there will be a growing need for microwave heating as a unit operation for very rapid and in-depth heating. A contributing factor will be the advent of more sophisticated applicators based on computer assissted design, giving more even power distribution and improved process control, both for the continuous heating of packaged solids on conveyors and for the heating in bulk of pumpable liquids in pipes.

The dominating applications will probably continue to be tempering, pasteurization, drying and snacks production, but with a steadily growing number of specialty applications. For industrial processing it will be very important that 915 MHz be generally recognized as an ISM frequency, because of its advantages in penetration depth and generator power and efficiency.

In *research*, further development of mathematical models and computer simulation will be invaluable tools in studying how field distribution and heating patterns in foods are influenced by oven or applicator design, and by food shape and composition. It will also greatly facilitate studies of how combinations of microwaves with other forms of heating will affect both performance and costs and reduce the need for empirical, experimental work.

REFERENCES

Introduction

Bengtsson, N. E., and Ohlsson, T. 1974. Microwave heating in the food industry. *Proc. of the IEEE* **62**(1), 44–55.

Buffler, C. R. 1993. Microwave cooking and processing. *In* "Engineering Fundamentals for the Food Scientist". AVI, Van Nostrand Reinhold, New York.

Heating Mechanisms

Bengtsson, N., and Risman, P. 1971. Dielectric properties of foods at 3 GHz as determined by a cavity perturbation technique. II. Measurements on food materials. *J. Microwave Power* **6**(2), 107–123.

Buffler, C. R., and Stanford, M. A. 1991 and 1995. Effects of dielectric and thermal properties on the microwave heating of foods. *Microwave World* **12**(4), 15–23, and **16**(1), 5–10.

Cheng, V., Sakai, N. and Hanzawa, T. 1997. Effects of dielectric properties on temperature distributions in food model during microwave heating. *Food Sci. Technol. Int. Tokyo* **3**(4), 324–328.

Kent, M. 1987. "Electrical and dielectric properties of food materials". Science and Technology Publishers, Hornchurch, UK.

Lorenson, C. 1990. The why's and how's of mathematical modelling in microwave heating. *Microwave World* **11**(1), 15–23.

Mudgett, R. 1985. Dielectric properties of foods. *In* "Microwaves in the Food Processing Industry" (R. Decareau, ed.), pp. 15–37. Academic Press.

Ohlsson, T., and Risman, P. 1978. Temperature distribution of microwave heating-spheres and cylinders. *J. Microwave Power* **13**(4), 303–310.

Ohlsson, T. 1983. Fundamentals of microwave cooking. *Microwave World*, March-April, 4–9.

Ohlsson, T. 1990. Controlling heating uniformity. The key to successful microwave products. *Eur. Food and Drink Review*, Summer, pp. 1–5.

Walker, J. 1987. The secret of a microwave oven's rapid cooking is disclosed. *Scientific American* **2**, 98–102.

Dielectric Properties

Calay, R. K., Newborough, M., Probert, D., and Calay, P. S. 1995. Predictive equations for the dielectric properties of foods. *Int. J. Food Sci. and Techn.* **29**, 699–713.

Engelder, D. S., and Buffler, C. R. 1991. Measuring dielectric properties of food products at microwave frequencies. *Microwave World* **12**(2), 6–15.

Funebo, T., and Ohlsson, T. 1999. Dielectric properties of fruits and vegetables as a function of temperature and moisture content. *J. Microwave Power and Electromagnetic Energy* **34**(1), 42–54.

Gabriel, C., and Grant, E. H. 1989. Dielectric sensors for industrial microwave measurement and control. *Proc. of High Frequency/ Microwave Conference at Arnhem*, KEMA, Netherlands.

Hewlett-Packard, 1990. *Dielectric Materials Measurements*. Network Measurements Division, Hewlett-Packard, Santa Rosa, CA, USA.

Ohlsson, T., Bengtsson, N. E. and Risman, P. O. 1974. The frequency and temperature dependence of dielectric food data as determined by a cavity perturbation technique. *J. Microwave Power* **9**(2), 129–145.

Risman, P. O., and Bengtsson, N. E. 1971. Dielectric properties of foods at 3 GHz as determined by a cavity perturbation technique I. Measuring technique. *J. Microwave Power* **6**(2), 101–106.

Sun, E., Datta, A., and Lobo, S. 1995. Composition-based prediction of dielectric properties of foods. *J. Microwave Power* **30**(4), 205–212.

Temperature Measurements

Anon. 1991. Data file on thermovision: High definition thermography for advanced R&D applications. AGEMA Infrared Systems.

Bengtsson, N., and Lycke, E. 1969. Experiments with a heat camera for recording temperature distribution in foods during microwave heating. *J. Microwave Power* **4**(2), 46–54.

Bows, J. R. 1990. Automating the data acquisition process for the Luxtron 755 fibre optic thermometer with special reference to microwave applications. Technical memo No. 570, Campden Food & Drink Research Association. 11 pp.

Gundersen, L. C. 1989. Fiber optic sensors. *Optic News*, November, 43–47.

Mullin, J., and Bows, J. 1993. Temperature measurements during microwave cooking. *Food Additives and Contaminants* **10**(6), 663–672.

Ofoli, R. Y. 1987. Thermometric consideration for RF and microwave research in food engineering. *J. Microwave Power* 85–94.

Prionas, S. D., and Hahn, G. M. 1985. Noninvasive thermometry using multiple frequency-band radiometry: A feasibility study. *Bioelectromagnetics* **6**, 391–404.

Ramasvamy, H., van de Voort, F. R., Raghavan, G. S. V., Lightfoot, D.,and Timbers, G. 1991. Feed-back temperature control system for microwave ovens using a shielded thermocouple. *J. Food. Sci.* **56**(2), 550–555.

Wickersheim, K. A., and Sun, M. H. 1987. Fiberoptic thermometry and its applications. *J. Microwave Power* **22**(1), 85–94.

Heating Effects

Anderström, B. *et al.* 1983. Studies of possible genetic effects in bacteria of high frequency electromagnetic fields. *Hereditas* **98**, 11–32.

Berlan, J., Giboreau, P., Lefeuvre, S., and Marchard, C. 1991. Synthese organique sous champ microondes: premier example dắctivation specifique en phase homogene. *Tetrahedron Letters* **32**(21), 2363–2366.

Buffler, C. R., and Risman, P. O. 1996. Microwave super-heating and splutter of beverages and foods. *Microwave World* **17**(2), 8–13.

Bögl, H.W. 1990. Possible health risks from consumption of microwave heated milk. View of the Federal Republic Health Office. *Bundesgesundheitsblatt* **33**(8), 342–344.

Cable, D.W., and Saaski, E. 1990. Fiberoptic pressure measurement of spontaneous bumping/spluttering of foods during microwaving. *Food Techn.* **44**(6), 120.

Chen-Shui-Tein *et al.* 1987. Rapid hydrolysis of proteins and peptides by means of microwave technology and its application to amino acid analysis. *Int. J. of Peptide and Protein Res.* **30**, 572.

Cross, G. A., and Fung, D. Y. C. 1982. The effect of microwaves on nutrient value of foods. *CRC Critical Reviews in Food Science and Nutrition* **16**(4), 355–381.

Dreyfus, M. S., and Chipley, J. R. 1980. Comparison of effects of sublethal microwave radiation and conventional heating on metabolic activity of *Staphylococcus aureus*. *Appl. and Env. Microbiology* **39**(1), 13–16.

Engelhart, W. G. 1990. Microwave hydrolysis of peptides and proteins for amino acid analysis. *American Biotechnology Laboratory* **8**, part 15, pp. 30, 32, 34.
Finot, P. A., and Merabet, M. 1991. Heat treatment of foods – necessity and consequences. Role of microwave heating. *Proc. Int. Congress Microwave and High Frequency*, Nice, 8–10 October, 1991, I. Addendum.
Gandhi, P. (ed.) 1990. "Biological Effects and Medical Applications of Electromagnetic Energy". Prentice-Hall, Engelwood Cliffs, NJ. Advanced Reference Series of Physical and Life Sciences.
Gedye, R., Smith, F., and Westaway, K. 1991. Microwaves in organic and organometallic synthesis. *J. Microwave Power and Electromagnetic Energy* **26**(1), 3–17.
Goebel, N. K., Grider, J., Davis, E. A., and Gordon, J. 1984. The effects of microwave energy and convection heating on wheat starch granule transformations. *Food Microstructure* **3**, 73–82.
Goldblith, S. A., and Wang, D. I. C. 1967. Effects of microwaves on *Escherichia coli* and *Bacillus subtilis*. *Appl. Microbiol.* **15**, 1371–1375.
Gombos, J. 1990. Mikrowellen aus bakteriologischer Sicht. *Ernährung* **14**(9), 527–530.
Hertel, H. U. 1989. Death lurks also in the microwave oven. *Journal Franz Weber* **8**, 18.
Hollywood, N.W., Naidoo, R. I., Mitchell, G. E., and Dommett, T.W. 1991. Effect of microwave heating on microbial flora of frozen convenience foods. *Food Australia* **43**(4), 160–163.
Hoseney, R. C., and Rogers, D. E. 1989. Problems and solutions in the microwave reheating of bread. Contribution No 90-94-A. Kansas Agric. Exp. Station, Manhattan, KS 66506.
Jahngen, E. G. E. *et al.* 1990. Hydrolysis of adenosine triphosphate by conventional or microwave heating. *J. Org. Chem.* **55**, 3406.
Jonker, D., and Til, H. P. 1995. Human diets cooked by microwave or conventionally: Comparative sub-chronic (13WK) toxicity study in rats. *Food Chem. Toxic.* **33**(4), 245–256.
Jonsson, A., and Ohlsson, T. 1989. The effect of microwaves on microorganisms (in Swedish, with figure captions in English). *Vår Föda* **41**(4), 181–187.
Jonsson, L. 1989. Nutritional changes through microwave cooking (in Swedish, with English summary). *Vår Föda* **41**(4), 188–194.
Jullien, S. C., Delmotte, M., Loupy, A., and Jullien, H. 1991. Theoretical hypothesis on wave-molecule interaction to interpret microwave chemical reactions (in French). *Proc. Int. Congress Microwave and High Frequency*, Nice, 8–10 October 1991, pp. 397–400.
Katt, J. L. 1991. The effect of starches and sugars on microwave cooking. *Microwave World* **12**(2), 19–23.
Khalil, H., and Villota, R. 1986. A comparative study on the thermal inactivation of *B. Stearothermophilus* spores in microwave and conventional heating. *Proc. 4th Int. Congress on Engineering & Food*, July 1985. *In* "Food Engineering and Process Applications" (M. Le Maguer and P. Jelen, eds), Vol. 1, p. 583. London.
Koertner, B., and Lampe, D. 1990. Microwave flavours. *European Food & Drink Review*, Summer, pp. 47–48.
Lechowich, R. V., Beuchat, L. R., Fox, K. I., and Webster, F. H. 1969. Procedure for evaluating the effects of 2450 megahertz microwaves upon *Streptococcus faecalis* and *Saccaromyces cerevisiae*. *Applied Microbiology* **17**(1), 106–110.
Lefeuvre, S., and Audhuy-Peaudecerf, M. 1993. Le couple emballage-produit dans un four microonde. *JAA*, June, pp. 384–388.
Lin, W., and Sawyer, C. 1988. Bacterial survival and thermal responses of beef loaf after microwave processing. *J. Microwave Power and Electromagnetic Energy* **23**(3), 183–194.
Lubec, G., Wolf, C., and Bartosch, B. 1989. Amino acid isomerization and microwave exposure. *Lancet* **II**(8676), 1392–1393.
Lund, B. M., Knox, M. R., and Cole. M. B. 1989. Destruction of *Listeria monocytogenes* during microwave cooking. *Lancet* **I** (8631), 218.

Marchelli, R., Dossena, A., Palla, G., Audhuy-Peaudecerf, M., Lefeuvre, S., Carnevali, P., and Freddi, M. 1992. D-amino acids in reconstituted infant formula: A comparison between conventional and microwave heating. *J. Sci. Food Agric.* **59**, 217–226.

Mingos, D. M., and Baghurst, D. R. 1991. Application of microwave dielectric heating effects to synthetic problems in chemistry. *Chem. Soc. Rev.* **20**, 1–47.

Mudgett, R. E. 1989. Microwave Food Processing. A scientific status summary by the IFT's expert panel on food safety and nutrition. *Food Techn.* **43**(1), 117–126.

Ohlsson, T., and Åström, A. 1982. Sensory and nutritional quality in microwave cooking. *Microwave World*, Nov.–Dec., pp. 15–16.

Österdahl, B. G., and Alriksson, E. 1990. Volatile nitrosamines in microwave cooked bacon. *Food Additives and Contaminants* **7**(1), 51–54.

Palaniappan, S., and Sastry, S. K. 1990. Effects of electricity on microorganisms: A review. *J. Food Proc. Preserv.* **14**, 393–414.

Pszczola, D. E. 1988. Applications of the delta T theory in the design of microwaveable flavours. *Food Techn.* **42**(9), 102–103.

Risman, P. O. 1993. Microwave food hazards. *Microwave World* **14**(2), 21–23.

Rohtla, M., and Risman, P. O. 1994. Splutter of foods during microwave heating. *Proceedings of 29th IMPI Congress*, Chicago, 25–27 July.

Rosén, G. 1972. Effects of microwaves on food and related materials. *Food Techn.* **26**(7), 36–40.

Sastry, S. K., and Palaniappan, S. 1991. The temperature difference between a microorganism and a liquid medium during microwave heating. *J. Food Process. Preserv.* **15**(3), 225–230.

Schiffman, R. F. 1991. Major problems in heating foods in microwave ovens. *Proc. Int. Congress Microwave and High Frequency*, Nice, 8–10 October 1991, Vol. II, p. 91.

Schwan, H. P., and Piersol, G. M. 1954. The absorption of electromagnetic energy in body tissues. A review and critical analysis. *Int. Rev. Phys. Med. and Rehab. Am. J. Phys. Med.*, 371–404.

Shaath, N., and Azzo, N. R. 1988. Design of flavours for the microwave oven. The Delta T theory. Presented at the *First Int. Conference on Formulating Food for the Microwave Oven*, Chicago, IL, March 1988.

Steinke, J. A., Frick, C. M., Gallagher, J. A., and Strassburger, K.J. 1989. Influence of microwave heating on flavour. *In* "Thermal Generation of Aromas" (T. H. Parliment, ed.), ACS Symposium Series **409**, 519–525.

Stöllman, U. 1990. Microwave heating and flavour quality. *In* "Flavour Science and Technology", 6th Weurman Symposium. J.Wiley & Sons, pp. 297–313.

Tong, C. H., Fu, Y. C., and Lund, D. B. 1991. Understanding microwave bumping. From art to science. *Proc. Int. Congress "Microwave and High Frequency"*, Nice, 8–10 October, 1991 Vol, II. p. 83.

Tong, C. H. 1996. Effect of microwaves on biological and chemical systems. *Microwave World* **17**(2), 14–23.

Unda, J. R., Molins, R. A., and Walker, H.W. 1991. *Clostridium sporogenes* and *Listeria monocytogenes*: Survival and inhibition in microwave-ready beef roasts containing selected antimicrobials. *J. Food. Sci.* **56**(1), 198–205, 219.

Walker, S.J., Bows, J., Richardson, P., and Banks, J. G. 1989. Effect of recommended microwave cooking on the survival of *Listeria monocytogenes* in chilled retail products. *Tech. mem.* **548**, Campden Food & Drink Res. Ass., Jan.

Walker, S.J., Bows, J., Richardson, P., and Banks, J. G. 1991. Listeria survival in chilled retail products: Effects of recommended microwave cooking. MAFF, Food Safety Directorate, Ministry of Agriculture, Fisheries and Food. Microwave Science Series, No. 1.

Walz., E., and Schubert, H. 1990. Review of publications regarding the question of thermal effects by microwave heating. Bundesforschungsanstalt für Ernährung, Karlsruhe, Jahresbericht, A37.

Welt, B. A., Tong, C. H., Rossen, J. L. and Lund, D. B. 1994. Effect of microwave radiation on inactivation of *Clostridium sporogenes* spores. *Appl. and Envir. Microbiology* **60**(2), 482–488.

Yeo, H. C. H., and Shibamoto, T. 1991. Chemical comparison of flavours in microwaved and conventionally heated foods. *Trends in Food. Sci.& Techn.* Dec., 329–332.

Zagon, J. Dehne, L. I., and Bögl, K. W. 1991. Effects of microwave heating on the nutritive and sensory value of food. Part 1. Changes in meat and meat products. *Food Tech.* **2**, 2–10. Part 2. Changes in food of vegetable origin. *Lebensmitteltechnologien* **3/4**, 14–15.

The Microwave Oven

Decat, G., Wouters, G., and Kretzschmar, J. G. 1993. Energy efficiency of domestic microwave ovens. *Proc. Int. Conf. Microwave and High Frequency*, 28–30 September, Göteborg, Sweden.

Dibben, D. C., and Metaxas, A. C., 1994. Finite-element time-domain analysis of multimode applicators using edge elements. *Int. J. Microwave Power and Electromagnetic Energy* **29**(4), 242–251.

Fu, Y. C., Tong, C. H., and Lund, D. B. 1994. Microwave bumping: Quantifying explosions in foods during microwave heating. *J. Food Science* **59**(4), 899–904.

IEC 1988. Methods for measuring the performance of microwave ovens for household and similar purposes. CEI IEC 705, 2nd edn Bureau Central de la Commission Electrotechnique Internationale, Geneva, Switzerland.

ILSI 1995. Europe helps evaluate the biological safety of microwave ovens. *ILSI Europe Newsletter*, (19), February.

Kok, L. P., and Boon, M. E. 1992. "Microwave Cookbook for Microscopists: Art and Science of Visualization". Coulomb Press, Leyden.

Ohlsson, T. 1981. Methods for measuring temperature distribution in microwave ovens. *Microwave World* **2**(2), 14–17.

Ohlsson, T. 1991. More uniformity in heat from microwave ovens. *Food Technology International – Europe*, 77–81.

Ohlsson, T., and Risman, P. O. 1993. Temperature distribution in microwave oven heating – The influence of different cavity modes. Paper presented at *Int. Congress on Food and Engineering*, 23–27 May, Chiba, Japan.

Ohlsson, T., and Thorsell, U. 1985. Wiederwärmen gekühlter Lebensmittel und Speisen mittels Mikrowellen. *Ernährungs-Umschau* **32**(4), 104–108.

Peyk, F., Datta, A., and Seyleri, C. 1997. Influence of the dielectric property on microwave oven heating patterns: Application to food materials. *J. Microwave Power* **32**(1), 3–14.

Risman, P. O. 1989. How does the microwave oven work. Var Foda 89(4), 172–180.

Risman, P. O. 1992. Different types of microwave oven cavity modes and their interaction with food loads. *Presentation at the 27th IMPI Symposium.*

Risman, P. O. 1994. Confined modes between a lossy slab and a metal plane as determined by a waveguide trough model. *J Microwave Power* **29**(3), 161–170.

Risman, P. O. 1995. Microwave oven efficiency: Effects towards standardized test methods. *Microwave World* **16**(2), 20–23.

Risman, P. O., Ohlsson, T., and Wass, B. 1987. Principles and models of power density distribution in microwave oven loads. *J. Microwave Power* **E2**, 193–198.

Risman, P. O., Ohlsson, T., and Lignert, H. 1993. Model substances and their use in microwave heating studies. SIK – Report 588.

Wäppling-Raaholt, B., Galt, S., and Ohlsson, T. 1999a. FDTD simulation of a microwave heating process: effects of food parameters. *Proc. 7th Int. Conf. on Microwave and High*

Frequency Heating, 13–17 September, Valencia, Spain, pp. 3–6.
Wäppling-Raaholt, B., Galt, S., and Ohlsson, T. 1999b. Development of a model food substance with temperature profiles indicated by colours for the validation of microwave heating processes. *Proc. 7th Int. Conf. on Microwave and High Frequency Heating*, 13–17 September, Valencia, Spain, pp. 145–149.

Microwave Foods

Blenford, D. 1993. Reformulating for microwaves. *Food Ingredients and Analysis International*, June/July, pp. 24–25.
Brain, S. M., and Zallie, J. P. 1990. Role and function of starches in microwaveable food formulation. *Food Australia* **42**(11), 523–524.
Buffler, C. R., and Stanford, A. 1995. Effects of dielectric and thermal properties on the microwave heating of foods. *Microwave World* **16**(1), 5–10.
Dibben, D. C., and Metaxas, A. C. 1995. Time domain finite element analysis of multimode microwave applicators loaded with low and high loss materials. *Proc. Int. Conf. Microwave and High Frequency Heating*, 17–21 September. St John's College, Cambridge, UK, A 3.1–A 3.4.
Fu, Y. C., Tong, C. H., and Lund, D. B. 1994. Microwave bumping: Quantifying explosions in foods during microwave heating. *J. Food. Sci.* **59**(4), 899–904.
George, R. M., and Burnett, S-A. 1991. General guidelines for microwaveable products. *Food Control*, January, pp. 35–43.
Hoseney, R. C., and Rogers, D. E. 1989. Problems and solutions in the microwave reheating of bread. Department of Grain Science and Industry, Kansas State University. Contribution No. 90-94A, Kansas Agricultural Experiment Station, Manhattan, KS 66506.
Katt, J. L. 1991. The effect of starches and sugars on microwave cooking. *Microwave World* **12**(2), 19–23.
Keefer, R. M., and Ball, M. D. 1993. Improving the final quality of microwaveable foods. *ZFL* **44**(7/8), 420–422.
Koertner, B., and Lampe, D. 1990. Microwave flavours. *European Food & Drink Review*, Summer, p. 47.
Ohlsson, T., and Bengtsson, N. 1971. Microwave heating profiles in foods. A comparison between heating experiments and computer simulations. A research note. *Microwave Energy Applications Newsletter*, Vol. IV, Nov.–Dec., No 6, pp. 1–8.
Olsen, C. M. 1965. Microwaves inhibit bread mold. *Food Eng.* **37**(7), 51–53.
Ryynänen, S., and Ohlsson, T. 1996. Microwave heating uniformity of ready meals as affected by placement, composition and geometry. *J. of Food Eng.* **29**, 13–21.
Sundberg, M. 1994. Simulation of sterilization and pasteurization in multimode applicators. Paper presented at the 29th Microwave Symposium, 25–27 July, Chicago, USA. SIK Service Series No. 908.
Sundberg, M., Risman, P. O., and Kildal, P. S. 1995. Quantification of heating uniformity in multi-applicator tunnel ovens. *Proc. Int. Conf. Microwave and High Frequency Heating*, 17–21 September, St John's College, Cambridge University, Cambridge, UK, pp. A5.1–A-5.4.

Packaging

Lentz, R. R., and Crossett, T. M. 1988. Food/susceptor interface temperature during microwave heating. *Microwave World* **9**(5), 11–16.

O'Donnell, C. D., and Swientek, B. 1994. Formulating and packaging microwavable foods. *Prepared Food*, June, pp. 36–38.

Ohlsson, T., and Risman, P. O. 1991. Temperature distribution in microwave oven heating – the influence of packaging material. *Proc. Microwave and High Frequency Symposium*, Nice, 8–10 October, 1991, pp. 199–202.

Ohlsson, T., Stöllman, U., and Erlöv, L. 1991. Migration from packaging intended for use in microwave ovens (in Swedish with English summary). *Vår Föda* **43**(6), 317–327.

Sacharow, S., and Schiffmann, R. F. 1992. "Microwave Packaging". Pira International, Leatherhead, UK. Reprinted 1995.

Turpin, C. 1989. Browning and crisping. The function, design and operation of susceptors. *Microwave World* **10**(6), 8–12.

Industrial Equipment and Applications

Akahoshi, R., and Matashige, E. 1990. Drying of sliced potatoes by microwave heating and flowing air. *Jap. Soc. for Food Sci. and Techn.* **37**(8), 581.

Anon. 1986. Microwave food processing – an industrial overview. *Food Techn.* June, pp. 82–116.

Anon. 1991. Breakthrough: World's first commercial microwave sterilization system. *Food Eng.*, March, pp. 98, 101–102, 106–107.

APV. 1995. Microwave equipment. APV Baker, Peterborough, England.

Bezanson, A. 1975. Microwave tempering of frozen foods. *Trans. Int. Microwave Power Inst.* **5**, 89–100.

Brody, A. L. 1992. Microwave food. Pasteurization, sterilization and packaging. *Food Techn. Internat. Europe*, 67–71.

Burfoot, D. 1990. Microwave processing of prepared meals. *In* "Microwaveable Product Technology". *Symposium Proc. No. 44*, Leatherhead Food RA, UK, pp. 77–95.

Decareau, R. V. 1985. "Microwaves in the Food Processing Industry". Academic Press Inc.

Eves, G. 1996. Industrial microwave food processing. *Microwave World* **17**(1), 15–18.

Feng, H., and Tang, J. 1998. Microwave finish drying of diced apples in a spouted bed. *J. Food Sci.* **63**(4), 679–683.

Funebo, T., and Ohlsson, T. 1998. Microwave assisted air dehydration of apple and mushroom. *J. of Food Eng.* **38**, 353–367.

Goldblith, S. A. 1967. Basic principles of microwaves and recent developments". *Advances in Food Research* **15**, 277–301.

Gordon, A. 1991. Safe foods by microwaves. *Food Man.* July, pp. 25–26.

Heindl, A. 1993. Mikrowellenunterstützte Vakuumkonvektionstrocknung. Entwicklung eines kombinierten Trocknungsverfahrens zur Verbesserung der Qualität getrockneter, stückiger Lebensmittel. Mainburg: Eigenverlag, 189 Seiten.

Isaksson, S., and Bondeson, A. 1999. Aspects of Continuous Tubular Microwave Heating. *Proc. 7th Int. Conf. on Microwave and High Frequency Heating*, September 13–17, Valencia, Spain, pp. 209–212.

James, S. J. 1984. Thawing meat blocks using microwaves under vacuum. *Proc. European Meeting of Meat Res. Workers.*

Jolly, P. G. 1986. Temperature controlled combined microwave-convection drying. *J. Microwave Power* **21**(2), 65–74.

Khraisheh, M. A. M., Cooper. T. J. R., and Magee, T. R. A. 1995. Investigations and modelling of combined microwave and air drying. *Trans I Chem* **E73(c)**, 121–126.

Klinger, R.W. 1986. Mikrowellenbehandlung von Müsli im Labor- und Technikumsmasstab. *Getreide Mehl und Brot* **40**(9), 277.

Koch, K. 1993. PC Controlled microwave systems for the preservations of ready meals in sealed plastic trays. *Proc. Microwave and High Frequency Conference*, Göteborg, Sweden, 28–30 September. Paper H3.

Laguerre, J. C., Tauzin, V., and Grenier, E. 1999. Hot air and microwave drying of onions: a comparative study. *Drying Technology* **17**(7/8), 1471–1480.

Mermelstein, N. 1998. Microwave and radiofrequency drying. *Food Techn.* **52**(1), 84–86.

Metaxas, A. C., and Meredith, R. J. 1983. "Industrial Microwave Heating". IEE Power Engineering Series 4. Peter Peregrinius Ltd.

Microheat Co. 1990. Commercial information. Microheat Co., Stockholm, Sweden.

Mimouni, M., Bartholin, G., and Germain, A. 1993. Continuous sterilization of food products by using the microwave thermo-star processing. *Proc. Microwave and High Frequency Conference*, Göteborg, Sweden, 28–30 September, Paper H4.

MIVAC. Dried Food Technology Laboratory, California State University, Fresno, Presentation booklet.

Mudgett, R. E., and Schwartzberg, H. G. 1980. Microwave food processing: Pasteurization and sterilization of liquids and semi-solids. *Paper presented at 89th National Meeting of AIChE*, Portland, Oregon, 17–20 August.

Nakahita, H., Imura, O., Nabetani, H., Watanabe, A., Watanabe, S., and Chikubu, S. 1989. Application of electromagnetic waves for control of stored-product insects. I. Effects of microwaves on susceptibilities of insects and quality of rice. *J. Jap. Soc. Food Sci. & Techn.* **36**(4), 267–273.

Ohlsson, T. 1984. Low power microwave thawing of animal foods. *In* "Thermal Processes and Quality of Foods". *Proc. Concluding COST Seminar*, Athens, 14–18 November, Elsevier Appl. Sci. Publ., pp. 579–584.

Ohlsson, T. 1991a. Microwave processing in the food industry. *Eur. Food & Drink Review*, Spring, pp. 7–11.

Ohlsson, T. 1991b. Development and evaluation of a microwave sterilization process for plastic pouches. *Paper presented at the 8th World Congress of Food Science and Technology*, Toronto, 29 September–4 October.

Ohlsson, T. 1999. In-flow microwave heating of pumpable foods. *Paper presented at Int. Congress on Food and Engineering*, 23–27 May, Chiba, Japan.

Ohlsson, T., and Rask, Ö. 1983. Microwave pasteurization of prebrowned meat patties. *Proc. 6th Int. Congress of Food Science and Technology*, Dublin 1983. Vol. 1, pp. 212–213.

Ovadia, D. Z., and Walker, C. E. 1995. Microwave baking of bread. *J. Microwave Power* **30**(2), 81–89.

Raytheon Co. 1975. Commercial information. Raytheon Co., Waltham, Mass., USA.

Rice, J. 1993. Harnessing microwave technology for no-fat and low-fat snacks. *Food Processing*, July, pp. 26–28.

Risman, P. O., and Ohlsson, T. 1975. Theory for and experiments with a TMO2n applicator. *J. Microwave Power* **10**(3), 271–280.

Rosenberg, U., and Bögl, W. 1987. Microwave thawing, drying and baking in the food industry. *Food Techn.* **41**(6), 85–91.

Rosenberg, U., and Bögl, W. 1987. Microwave pasteurization, sterilization, blanching and pest control in the food industry. *Food Techn.* **41**(6), 92–99.

Schiffman, R. F. 1992. Microwave Processing in the U.S. Food Industry. *Food Techn.* December, pp. 50–52.

Shute, M. 1993. Continuous biscuit production assisted by microwave. *Proc. Int. Conf. on Microwave and High Frequency*, 28–30 September, Göteborg, Sweden, Paper J 2.

Skjöldebrand, C. 1994. Dough thawing by microwaves and baking by infrared radiation. Paper presented at *VACro-Day Technology Transfertag, Lebensmitteltechnologien Seminar*,

in Dresden-Radebeul, 24 June.
Smith, F. J. 1979. Microwave hot air drying of pasta, onions and bacon. *Microwave energy Applications Newsletter*, 12(6), 6–11.
Sundberg, M. 1998. Analysis of industrial microwave ovens. Doktorate Thesis, Dept. of Microwave Technology, Chalmers University of Technology and SIK – The Swedish Institute for Food and Biotechnology, Göteborg, May 1998, 55 pages.
Sundberg, M., Risman, P. O., Kildal, P-S., and Ohlsson, T. 1996. Analysis and design of industrial microwave ovens using the finite difference time domain method. *J. Microwave Power* **31**(3), 142–157.
Van Loock, W. 1996. Electromagnetic energy for pasteurization and sterilization. Another viewpoint. *Microwave World* **17**(1), 23–27.
Virtanen, A.J., Goedeken, D. L., and Tong, C. H. 1997. Microwave assisted thawing of model frozen foods using feed-back temperature control and surface cooking. *J. Food Sci.* **62**(1), 150–154.

Safety and Interference

Jauchem, J. 1991. Alleged health effects of electromagnetic fields: Misconceptions in the scientific literature. *J. Microwave Power and Electromagnetic Energy* **26**, No 4.
Osepchuk, J. M. 1990. Some misconceptions about electromagnetic fields and their effects and hazards. *In* "Biological Effects and Medical Applications of Electromagnetic Energy" (P. Gandhi, ed.), pp. 530–554. Prentice-Hall, Engelwood Cliffs, NJ.
Van Loock, W. 1992. Operating 900 MHz, ISM equipment within the regulation limits. *Presented at IMPI Symposium*, 2–5 August, Washington, DC.

Future Outlook

Nijhuis, H. H., Torringa, E., Luyten, H., René, F., Jones, P. , Funebo, T., and Ohlsson, T. 1996. Research needs and opportunities in the dry conservation of fruits and vegetables. *Drying Technology* **14**(6), 1429–1457.
Rubbright, H. A. 1990. Looking into the future of microwave technology. *Microwave World* **11**(4), 19–23.