On-line measurements in microwave ovens

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ABSTRACT *There are various ways to measure food temperatures in the oven during microwave heating. While conventional electrical sensors are inadequate, the feasible methods include infrared and fiber optic thermometry techniques. Measurements of moisture, microwave fields, and power can be made in the oven. While the probes to measure microwave fields are still under development, detailed mapping of field and power distributions in the oven should be possible soon. Even continuous monitoring at discrete points within the food may be possible in the near future. Computer modeling should be used to optimize the design of a specific type of microwave food product.*

KEYWORDS
Analysis
Computer modeling
Microwaves
Moisture
Packaging
Temperature

Microwave ovens are now in the majority of U.S. homes, and the percentages of working wives and single-parent families are growing (*1*). The convenience of using microwave ovens to produce quick meals has brought about the rapid development of new food products designed for microwave use. The business economic opportunities are outstanding, with only a small percentage of prepared foods having been optimized for this purpose. The competition is intense between food companies to introduce new and better microwaveable products to ensure their share of this rapidly growing market.

The role of the microwave oven in the home has been principally to rewarm leftovers or for quick thawing of frozen foods. With the exception of fresh vegetables cooked in the microwave by using it as a "steamer," consumers have not found foods prepared in the microwave oven as appealing as meals prepared by traditional techniques using a conventional stove or oven. Hence, developers of microwaveable foods have begun to emphasize food "aesthetics." This emphasis has led to a focus on the problems of obtaining well-controlled, uniform heating in the oven. At the same time, we are seeing a variety of specialty products that make use of novel techniques for obtaining deliberately nonuniform heating.

These developments have taken considerable ingenuity on the part of the food product designer, both in modified food formulations (*2*) and in specialized food packaging (*3*). Food packaging has been elevated to a more prominent place in the development of the microwave food product.

In optimizing its products for the microwave oven, the food company has to fight several difficult battles at once. While the microwave oven can heat food quickly, it does not heat it uniformly. The very speed of heating further limits the equilibration of food temperatures. Home ovens differ widely in size, power, and power distribution, with the trend being towards smaller and less expensive ovens with more limited capability. Many properties of the food product affect the way it is heated in the oven. In addition to the effects of special packaging, the size of the food, its shape, orientation in the oven, homogeneity, moisture content, and electrical conductivity all play a role in determining the outcome.

In today's competitive market, the food company needs to be certain that its products will at least equal but preferably "win" over those of its competitors. While guidelines are emerging to help the microwave food designer, quantitative measurements are essential throughout product development and testing stages. Many measurements must be made on the product after it is prepared in the oven. Some of the most fundamental measurements, however, are best made in the oven during cooking. These include measurements of heating rates, uniformity of temperatures achieved, and times at temperature. Ideally, similar measurements also should be made during taste testing to guarantee that each of several product variations has been prepared optimally. When the cooking characteristics of a particular product have been optimized, these data may form the basis for cooking instructions to the customer.

Temperature measurement problems and techniques

The microwave oven is an unusually

hostile environment for making reliable temperature measurements. Traditional instrumentation techniques fail because of the interaction of the powerful microwave fields with electrical sensors and their conducting metal leads. This difficulty causes the sensor to be heated more than the food. The probe and leads also distort the microwave fields as they are being measured. Both of these effects lead to invalid measurements.

The conducting lead wires can also produce electrical arcing in the oven and the pickup of electrical noise unless careful shielding and filtering precautions are taken. If thermistors are buried in heavily shielded probes to avoid some of these problems, the measurement becomes that of the average temperature of the metal shield, which is not the same as that of the food in the absence of the probe. The result is that electrical sensors are difficult to use, yielding inaccurate and unreliable results.

Because of these difficulties, we turn to measurement techniques that are not electrical. Both of the two best techniques available today are optical. The first is infrared radiometry. A radiometer measures from a distance the thermally generated infrared radiation from a warm object to allow its surface temperature to be measured remotely. **Figure 1** shows the spectral distribution of infrared emission from a "black body," or perfect emitter, as a function of temperature. The total radiant energy emitted increases as the fourth power of the absolute temperature. The radiometer uses a sensitive infrared detector to sense a portion of this radiation (*4*). With calibration, the radiometer can determine the temperature of the emitting surface.

Scanning a warm surface with the radiometer produces a complete thermal image, or temperature map, that lets us visualize heating patterns (*5*). A variety of infrared cameras, or "thermographs" as they are sometimes called, are now available commercially (*6*). **Figure 2** is an infrared image of a person's hands before and after smoking. It illustrates the sensitivity of such systems in measuring small changes in surface temperature.

The thermal imaging technique can be used in the oven if the oven is modified to allow viewing through an open-mesh metal screen such as that typically found in the oven door. (Note that long-wave infrared radiation is not transmitted by the glass window of the oven door, so the glass must be removed.) The strengths of the infrared imaging system are its ability to obtain data without contact and to produce quickly a recognizable image from which temperatures can be derived. Its disadvantages are that it can only measure surface temperatures and that it requires careful calibration for measuring absolute temperatures.

There are several problems in this regard. First, materials vary widely in their infrared emission efficiency (emissivity). Water has a high emissivity. As a moist surface dries, its emissivity will decrease, causing it to appear cooler even if its temperature is unchanged. Plastic packaging materials absorb and obscure portions of the infrared emission from the food. Similarly, viewing through a wire mesh in the oven wall or door physically obstructs portions of the infrared radiation from the object being viewed, so in-the-oven calibration is required (*7*). Finally, metals typically have very low emissivities, so substantial corrections are required when metallic or metalized surfaces (such as susceptors) are measured.

While the infrared imager can be used to measure food surface temperatures in an appropriately modified oven, its primary value is to determine *where* on-line measurements within the product should be made. For this purpose, the infrared imager can be used conveniently to scan the food product immediately after it is removed from the oven at any stage in the cooking cycle.

The other optical technique involves the use of fiber optic temperature probes. These are probes constructed from optical fibers that carry sensors at their tips and operate on optical principles. Since all materials in these probes are by design good electrical insulators, the probes are transparent to microwave radiation. They do not alter the microwave field patterns, and the measurements are not perturbed by the microwave fields. The sensors can be implanted in the food at locations of interest, such as hot or cold spots detected by the infrared imager. The sensors can be used also to monitor heating rates during microwave cooking.

Because the sensors are quite small, they exhibit rapid thermal response, so temperatures can be monitored during actual microwave heating. This technique is now becoming more widely employed in microwave food and packaging development, but the principle of operation may not be known generally. More complete explanations can be found elsewhere (*8-10*), but let us examine this principle briefly.

Fluoroptic thermometry

Our company's fiber optic technology is known as Fluoroptic® thermometry, where "Fluoroptic" is coined from the term "fluorescent, fiber optic."

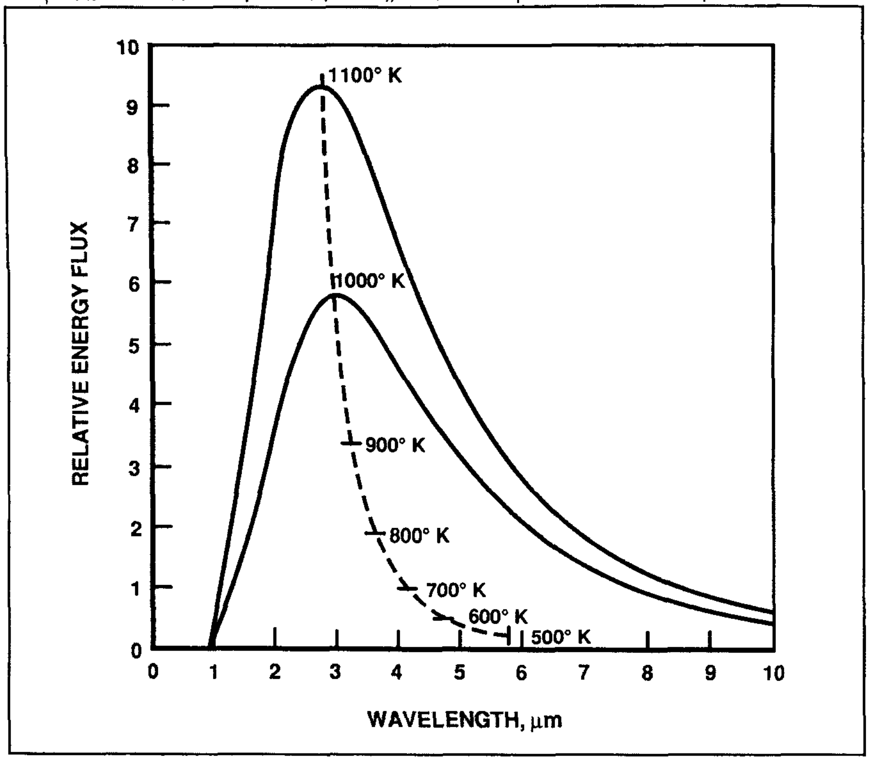
The fluorescent sensor is formed from phosphor. Phosphors are widely used in fluorescent lamps, X-ray screens, and in the light-emitting screens of television tubes. These materials emit light of a useful wavelength (color) when excited by radiation of a shorter wavelength. Not only are photons of a different wavelength created, but there is also a delay that gives us an after-glow with a measurable fluorescent decay time. This decay time is a function of temperature, so we can determine temperature by measuring the decay time.

In the fluoroptic thermometer, the phosphor utilized is manganese-activated magnesium fluorogermanate. This is a stable phosphor developed originally as a color corrector for mercury vapor street lamps. It is prepared by a solid-state reaction at high temperature (*11*). When excited by blue or ultraviolet radiation, this material emits light in the deep red region of the spectrum.

The instrument sends a short flash of blue light down the fiber to the sensor at the tip and then measures the rate of decay of the returning red fluorescence, as **Fig. 3** shows. In the figure, a reading, S_1, of the red fluorescent signal, is taken at time t_1, approximately 1 ms after the blue-violet excitation pulse has terminated. The time from t_1 to the crossover of the decaying fluorescent signal with the S_1/e reference level is τ, the exponential decay time of the phosphor.

The decay time (**Fig. 4**) decreases monotonically from about 5.3 ms at

1. Spectral distribution of infrared energy emitted by a perfect radiator (black body) at various temperatures. At room temperature (300°K), the emission peak falls at about 10μm.



2. High-performance infrared thermographs showing hands during and after smoking. During smoking (left), the finger temperatures are 31±1°C. Five minutes after smoking (right), finger temperatures have decreased to 27.5±1°C. While the ΔT scale is 4°C for both photos, the base level has been lowered from 29°C to 26°C in the photo on the left.

-200°C to about 0.5 ms at +450°C. Once the decay time is known, the temperature can be determined from a digital reference table stored in the instrument.

The optical fibers used are multimode fibers with a high-purity fused silica core for good transmission of the excitation radiation. These fibers may have either a plastic cladding or a doped silica cladding depending on the temperature range. (The cladding is a layer of material surrounding the core that traps light.) All silica fibers have superior transmission at all temperatures and are the most hardy with regard to high temperatures and resistance to oils and chemicals. They are more expensive, however, than plastic-clad fibers.

The fibers are jacketed with black-pigmented perfluoroalkoxy (PFA), which has the highest melting point of the Teflon® series of compounds. Most probes are cabled for extra strength with a wrap of Kevlar fiber over which a second PFA outer jacket is extruded. The black pigment used in the jacket is not carbon, but is a pigment that insulates against electricity and is not heated by the microwaves.

Measurements typically are taken at a 1-s output rate and are accurate to within about 1°C with no calibration. With calibration, accuracy at a single point can be improved to within 0.1–0.2°C. Data can be displayed, recorded, and used for analysis or control purposes. A 4-channel system is shown in **Fig. 5**.

Methods of use

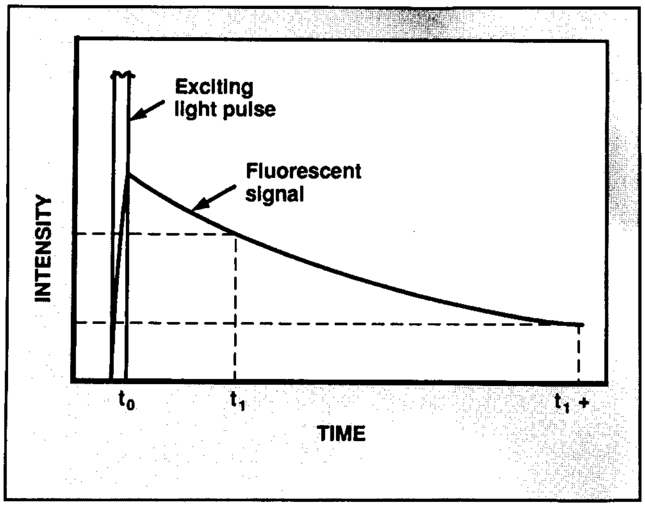
As with the infrared technique, the oven may have to be modified somewhat to allow for the insertion of the fluoroptic probes. The modification required, however, is quite simple. If no opening is available, it is necessary to drill a small hole in the oven wall, just large enough to accommodate the probes. If the hole is less than 0.5 cm in diameter, no significant microwave leakage is likely to occur. For larger holes, a metal tube that is at least twice as long as the hole diameter and that makes good metal-to-metal contact with the oven wall should be added to block microwave leakage.

Since the probes consist of single strands of fused silica, they can be broken by sharp bending or kinking but are quite hardy when handled correctly. Probes are also available with replaceable tips so that if breakage does occur, the entire probe need not be discarded.

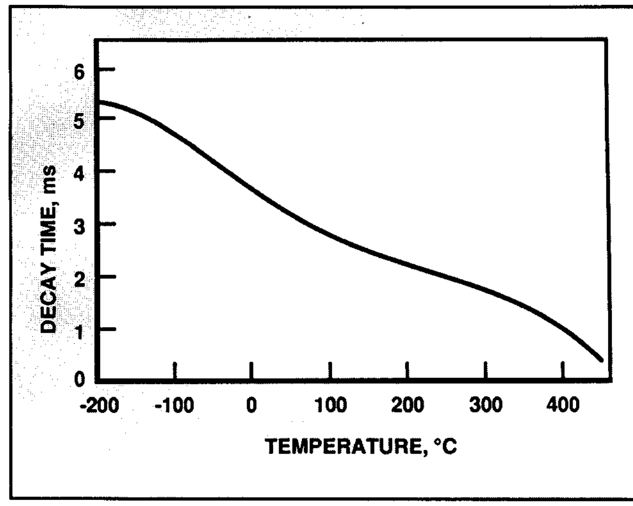
Each type of food presents its own problems. To insert the probe into firm foods or through resistive packaging, a hole will first have to be punctured or drilled. In monitoring the thawing of a frozen food, it may even be necessary to freeze the probe tip into the product.

One suggested technique for better control of probe position in the product during cooking is to first implant a plastic catheter, or a piece of tubing of a suitable insulating material, to

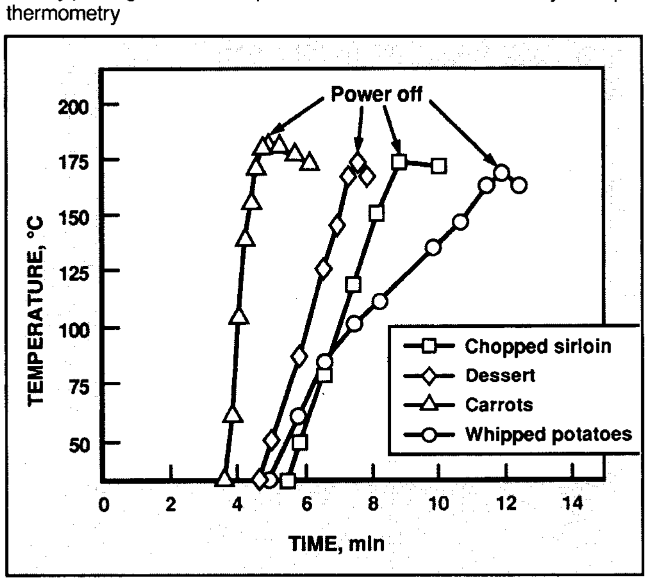
3. The method of measuring the fluorescent decay time of the phosphor temperature sensor used in the fluoroptic thermometer



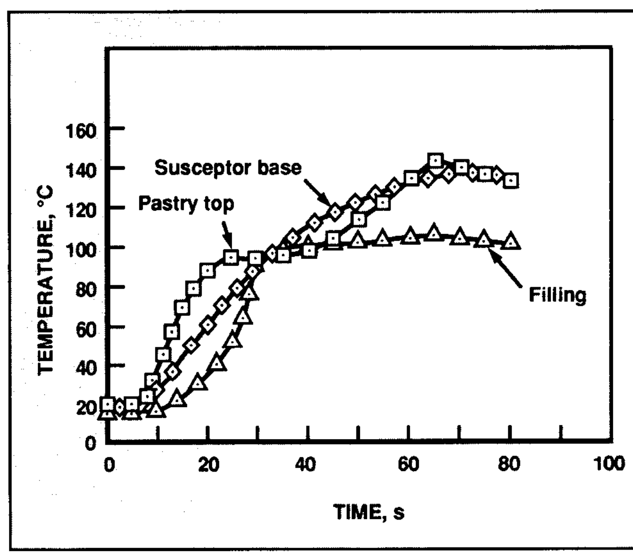
4. A plot of the decay time τ vs. temperature for the magnesium fluorogermanate phosphor sensor used in the fluoroptic thermometer



6. Measured heating rates of the individual components in a conventionally packaged, multi-component TV dinner as determined by fluoroptic thermometry



7. Temperature vs. time at critical locations in a sausage roll undergoing microwave heating, as determined by fluoroptic thermometry



form a track through which to insert the fiber optic probe (*12*). This also provides a track along which temperatures can be "mapped" by controlled withdrawal of the probes. Medical catheters of appropriate dimension, equipped either with a push-rod or with a disposable, breakaway hypodermic needle, have been developed for medical hyperthermia purposes. Unfortunately, not all of these catheters are made of plastics that can withstand the higher temperatures of cooking.

Using fiber optic probes with a rotating oven carousel is difficult, particularly if more than one probe is used. As a result, the carousel is normally stopped during measurements. If only one sensor is used, simple rotating couplers can be constructed. For certain types of research ovens, there are also special oscillating carousels that rotate 180° in one direction and then reverse their rotation.

While there may be problems with probe placement and position maintenance, these are not much different than would be encountered with any other type of temperature measurement system. Because the probes are more fragile than thermocouple probes, however, good planning and preparation are advised.

Typical in-the-oven applications

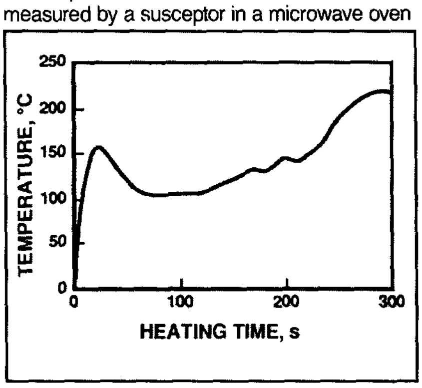
Most companies keep secret their activities in developing new food products. Consequently, it is difficult to obtain current information, but a few historic examples may suffice to illustrate the value of in-the-oven measurements.

Heating rate measurements in multi-component meals

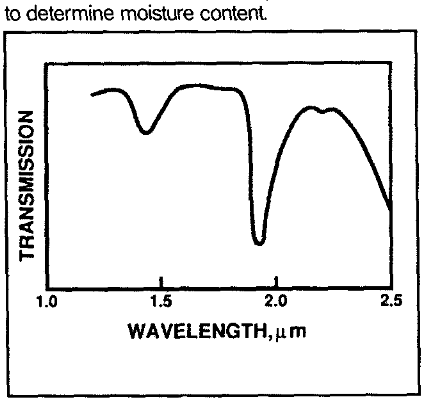
"Active" packaging techniques have been developed to alter the heating behavior of the microwave oven. An "active" package is a package used to improve heating uniformity or to alter

5. Fluoroptic thermometer with four fiber optic probes attached

8. Temperatures in a breaded cod fillet as measured by a susceptor in a microwave oven



9. Near infrared transmission of a 10-μm-thick film of water. The 1.9-μm absorption can be used to determine moisture content



the rates of heating of individual components of a multi-component meal so that all the foods reach the eating temperature at more or less the same time.

In the development of active packaging, infrared techniques were used to observe overall heating uniformity (*13*). On the other hand, fiber optic techniques were used to monitor heating rates in multi-component meals. As **Fig. 6** shows, the heating rates of each food component must be "adjusted" significantly.

Heating rates in inhomogeneous foods

Figure 7 shows another example of the value of being able to measure the local temperatures in a food product during microwave heating. These data (*14*) illustrate the entire process of the heating of a packaged sausage roll in the microwave oven. The pastry top, being of low thermal mass, is heated rapidly by steam from the moist filling. The filling heats more slowly because of its greater thermal mass and specific heat.

Initially, the temperature of the filling and pastry top are limited to 100°C (the boiling point of water). Then as the pastry top dries, its temperature rises above that of the filling. The metal susceptor in the base heats strongly throughout. Its temperature continues to rise above that of the filling as the filling levels off at 100°C. Thus, the susceptor is able to drive moisture from the pastry layer at the base of the product. The final result is a fully heated roll with dry crust on top and bottom.

Susceptor temperature measurements

Another example of in-the-oven measurements comes from the work of Lentz and Crossett, who recently studied the maximum temperatures reached by susceptors in contact with various types of food products (*7*). Metallic susceptors represent another type of "active" food packaging used to produce intense local heating in the food immediately adjacent to the susceptor (*3*). The susceptor is made from a low-mass film of an electrically conducting metal. As shown in **Fig. 8**, it absorbs microwave energy and is heated strongly, initially rising to a temperature above that of the adjacent fish fillet. As the heat is conducted into the fish, the susceptor comes to equilibrium with the fish, whose temperature is constrained to the boiling point of water. As the fish dries, the susceptor temperature again begins to rise, eventually reaching more than 200°C.

In another experiment (*7*), Lentz and Crossett studied the temperatures achieved in a bare susceptor like the type used in a microwave popcorn bag. In this experiment, it was possible to use both infrared and fiber optic techniques. The infrared camera proved superior to the fiber optic thermometer for this measurement, despite the anticipated calibration problems. The infrared measurement followed more rapidly the susceptor temperature changes than did the fiber optic sensor, because the encapsulated fiber optic sensor was handicapped by poor thermal contact with the surface. (In fairness, however, the phosphor technique does allow good surface measurements if the phosphor sensor is brought into more intimate contact with the surface.) Because of the low thermal mass and rapid cooling of the susceptor film, this measurement could be made in the oven only with the microwave power on.

Food sterilization studies

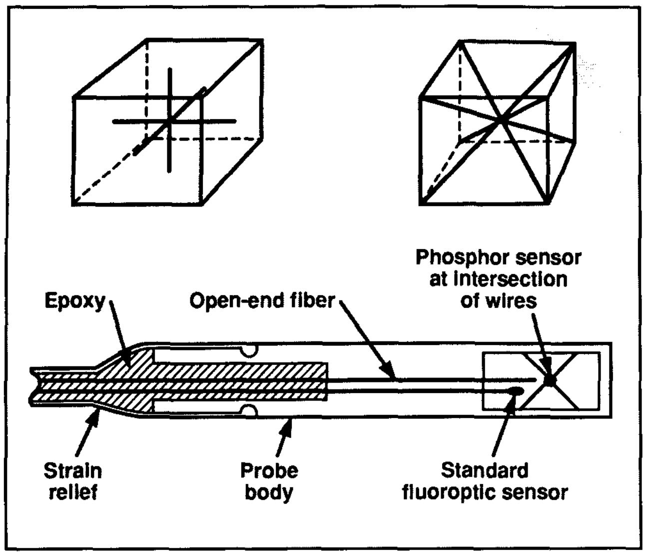
Finally, there have been a number of in-the-oven measurements to monitor the cooking of various types of meat products to determine the effectiveness of sterilization during microwave cooking. Potential contaminants include trichina in pork, fishborne parasites, and a variety of types of bacteria (*2*).

In an early study, Gerling demonstrated the problems of cooking a pork roast in a microwave oven (*15*). Only by controlling evaporation from the surface of the roast with a microwave transparent bag was it possible to achieve the temperatures necessary at the surface to guarantee the destruction of the trichina larvae. Since the surface is constantly cooled by evaporation, it was only possible to establish reliably the maximum surface temperatures achieved by in-the-oven measurements.

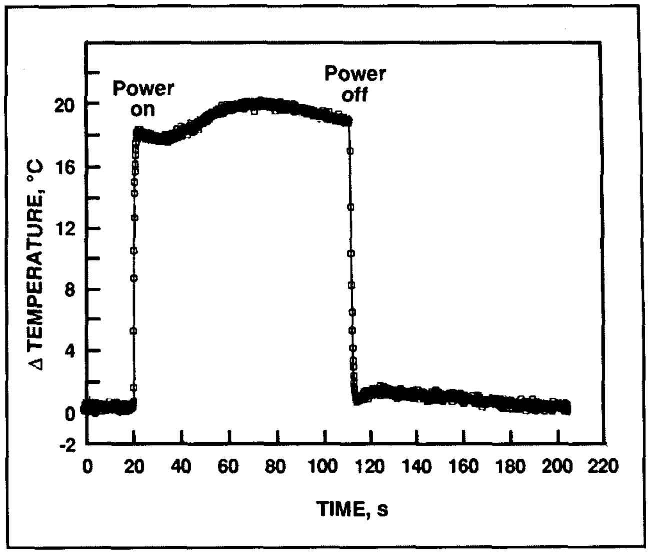
Recently, Lin and Sawyer have shown that microwave exposure reduces the survival of bacteria in beef loaf wrapped in PVDC (polyvinylidine chloride) film (*16*). They also monitored temperatures throughout the cooking cycle using a fiber optic probe.

Other possible in-the-oven measurements

There are other areas where quantitative measurements during microwave cooking could be of value in helping us understand the behavior of



10. Design of a minimally perturbing electric field sensor. Either of the isotropic structures, formed from thin, resistive wires, can be mounted in a cylindrical fiber optic probe. The central optical fiber illuminates and collects fluorescence from the phosphor sensor at the intersection of the wires. A second fiber optic sensor is used to record and correct for ambient temperature changes.



11. Differential response of an electric field probe of the type shown in Fig. 10. The momentary kinks observed when the power is turned on and off are thought to result from response time differences between the electric field and reference temperature sensors. However, the broader, more gradual change after the power is turned on is believed to represent a real change in power output.

food products, thereby providing guidance to improved product design.

Moisture

One parameter of interest is moisture content. Ignoring for the moment the use of metal susceptors, it is water molecules that are most responsible for the heating of food in microwave cooking. In microwave cooking, internal water is converted rapidly to the vapor phase and driven towards the surface of the food. In conventional cooking, conversely, the surface tends to dry, while the interior stays moist. An important aesthetic parameter is how moist the food is, and since a great deal of the energy is consumed in evaporating water, changes in the moisture content of the food are worth studying.

Presently, there is no satisfactory technique for measuring localized moisture. To obtain a measure of the rate of the loss of water from the product, the best that can be done is to measure the humidity of the effluent air from the oven or to monitor the total weight change during cooking.

Infrared measurements using optical fibers soon may provide the solution to localized moisture monitoring. Infrared systems already are available to measure the surface moisture content of various materials. These systems utilize filter spectrometers that operate in the near infrared region. Light from an infrared source is passed first through a filter that transmits 1.9-μm radiation, and this radiation is focused onto the food surface. The intensity of the radiation reflected from the surface is compared with the reflection of a second beam of 1.7-μm radiation. As shown in **Fig. 9**, water has a strong absorption band at 1.9 μm, but there is no water absorption in the 1.6–1.8-μm region, where we should see only the normal reflection of the food, whether dry or wet. We can determine surface moisture by comparing the intensity of the two reflections (*17*).

Durable optical fibers that transmit in the near infrared spectral range have been developed recently. Hence, it should be possible to fashion a fiber optic probe which, when implanted in a food in the oven, would allow us to measure localized moisture at depth.

Microwave fields

To better understand the origins of heating nonuniformities, we also need to measure the intensity of the local microwave fields in the oven. Our company has recently undertaken the exploratory development of probes that can measure by thermal techniques the local intensity of either the electric or magnetic fields and the corresponding microwave power distribution.

Figure 10 shows the design of a thermal electric field probe, the outer diameter of which is approximately 7 mm. In this probe, a miniature crossed-dipole antenna is formed from fine resistive wires. Because the wires are much shorter than the wavelength of 2450-MHz microwaves, coupling with the antenna is by design very weak. Nonetheless, the microwave frequency currents generated in the wires by the oscillating electric fields are sufficient to produce a measurable temperature rise.

Figure 11 shows the ΔT obtained when a probe of this type is mounted at the electric field maximum in a waveguide connected to a 500-W microwave power source. This ΔT measurement uses one sensor to read the rise in temperature at the intersection of the crossed-dipole antenna and a second bare (unencapsulated) temperature sensor to record variations of ambient temperature. Ambient temperature changes must be subtracted to accurately measure the rise in temperature produced by the microwave power absorbed in the resistive wire antenna. As can be seen, the response of this experimental probe is quite rapid.

Lentz recently has obtained a patent on a design for an electric field probe in which a small piece of susceptor material is attached to a fiber optic sensor (*18*). In his design, a second reference sensor also is used.

While the development of such field-measuring probes is not complete, early results are encouraging. Detailed mapping of field and power distributions in the oven should be possible, and continuous monitoring may even be possible at discrete points within the food during cooking.

Future developments

The food industry has not been noted in the past for its investment in sophisticated measurement equipment for use in routine product development. However, the surge in microwaveable food development is now bringing microwave engineers and physicists into the field of food and packaging research. As this trend continues, the use of sophisticated measurement techniques seems likely to become more common.

A particularly intriguing possibility is that of optimizing the design of a specific type of microwave food product by means of computer modeling. This possibility may be closer to being realized than we think. For several years, bioengineers and medical physicists working in the field of induced hyperthermia, a cancer therapy that holds promise (*19*), have been working to model and predict the temperatures produced within a human cancer tumor by electromagnetic energy beamed into the body from a microwave applicator. This is an extremely difficult problem to solve because of the many factors involved. These include:

1. The microwave radiation pattern produced by the applicator and further modified by the materials through which the radiation passes
2. The natural inhomogeneities of the human body in terms of fat, muscle, bone, and air
3. The highly variable cooling effects of blood flow.

Despite these problems, considerable progress has been made.

By contrast, predicting food temperatures should be much more straightforward, presuming the fields in the food are known and the thermal and electric properties of the product materials are measured as a function of temperature. Techniques have been developed for measuring the complex permitivities of materials at microwave frequencies as a function of temperature (*20, 21*). Thermal properties are also needed, and these can be estimated or measured.

A major complication in microwave food modeling is simulating the fields in the microwave oven. For initial calculations, the complex oven mode structure would have to be constructed as a superposition of many waves. This especially is difficult for a chamber whose dimensions are not too different from that of the microwaves themselves.

If, however, the actual microwave power distribution within the product can be mapped, the problem should be solvable, at least for a product of a particular type, shape, and location within a given oven. For a specific product, conductivities can be varied by changing ion content. Product size, shape, and orientation also can be varied, and various packaging layers, including reflectors or susceptors, can be introduced. Finally, the model can be tested by comparing predicted heating patterns with measured results.

While this approach may seem futuristic, it is close enough to being practical for one to begin to think seriously about computer-aided-design (CAD) systems for food and packaging optimization. In this event, the cost of sophisticated measuring systems for producing the necessary input parameters and for confirming predicted results could easily be justified by eliminating trial-and-error experiments.

Summary

What are the techniques that are available or potentially available for measuring food parameters during microwave cooking? Most easily measured are food temperatures, heating rates, and time at temperature. Infrared imagers and fiber optic sensors can be used to advantage for such measurements. Other evolving techniques include localized measurements of moisture and of microwave fields and power, also using fiber optic probes.

The use of such measurement techniques should allow more complete and more accurate understanding of the microwave food heating process on a component-by-component basis. Better measurements in turn should allow more systematic product improvement, including the possibility of computer modeling.□

Literature cited

1. Messenger, B., Prepared Foods (Oct.): 66(1987).
2. Best, D., Prepared Foods (Oct.): 20(1987).
3. Lingle, R., Prepared Foods (Oct.): 76(1987).
4. Smith, R. A., Jones, F. E., and Chasmar, R. P., The Detection and Measurement of Infrared Radiation, Oxford University Press, Oxford, England, 1957.
5. Lloyd, J. M., Thermal Imaging Systems, Plenum Press, New York, 1975.
6. Masi, C. G., Test and Measurement World (Mar.): 109(1989).
7. Lentz, R. R. and Crossett, T. M., Microwave World 9(5): 11(1988).
8. Wickersheim, K. A., Second generation fluoroptic thermometer, presented at Digitec '85, Northeastern Conference on Industrial Instrumentation and Control, Digitec, Boston, Mass., 1985.
9. Wickersheim, K. A. and Sun, M. H., Resource and Development, (Nov.): 114(1985).
10. Wickersheim, K. A. and Sun, M. H., J. Microwave Power 22(4): (1987).
11. Thorington, L., J.O.S.A., 40(9): 579(1950).
12. Berek, H. E. and Wickersheim, K. A., J. Pack. Tech. 2(4): 164(1988).
13. Ball, M. D., Techniques for evaluating the performance of microwave food packaging systems, presented at the 21st International Microwave Power Symposium, IMPI, Clifton, Va. 1986.
14. Turner, P., Van Leer Packaging, private communication.
15. Gerling, J. E., Gerling Laboratories, private communication.
16. Lin, W. and Sawyer, C., J. Microwave Power 23(3): 183(1988).
17. Anderson, J. H., Jr., and Wickersheim, K. A., Surface Science 2: 252(1964).
18. Lentz, R., U.S. pat. 4,816,634 (March 28, 1989).
19. Hahn, G. M., Hyperthermia and Cancer, Plenum Press, New York, 1982.
20. Ollivon, M., Thermochimica Acta 125: 141(1988).
21. Jow, J., Rev. Sci. Instrum. 60(1): 96(1989).

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