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Unlocking Potentials of Microwaves for Food Safety and Quality

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Abstract: Microwave is an effective means to deliver energy to food through polymeric package materials, offering potential for developing short-time in-package sterilization and pasteurization processes. The complex physics related to microwave propagation and microwave heating require special attention to the design of process systems and development of thermal processes in compliance with regulatory requirements for food safety. This article describes the basic microwave properties relevant to heating uniformity and system design, and provides a historical overview on the development of microwave-assisted thermal sterilization (MATS) and pasteurization systems in research laboratories and used in food plants. It presents recent activities on the development of 915 MHz single-mode MATS technology, the procedures leading to regulatory acceptance, and sensory results of the processed products. The article discusses needs for further efforts to bridge remaining knowledge gaps and facilitate transfer of academic research to industrial implementation.

Keywords: food quality, food safety, microwave, pasteurization, sterilization

Introduction

On October 8, 1945, Percy L. Spencer of Raytheon Co. (Mass., U.S.A.) filed a patent application in which he described a device using electromagnetic (EM) energy with wavelengths of about 10 cm to heat foods (Spencer 1950). This invention initiated a fundamental breakthrough from traditional methods for heating and cooking foods in kitchens. The devices, now known as microwave ovens, reduce heating time to a few minutes, thus providing great convenience to consumers. In spite of certain misunderstanding in the general public about possible adverse effects of microwave heating on food nutrients and concerns about microwave radiation to users, microwave ovens have been increasingly used in homes. A recent report reveals that in the U.S.A., microwaving is the 3rd most popular domestic heating method (after baking and grilling) for cooking and heating foods (Sloan 2013). To leverage the advantages of microwave ovens, food manufacturers now produce wide varieties of microwavable shelf-stable, refrigerated, and frozen meals for retail markets. Microwave heating has also been used in the food industry to reduce waste, increase throughputs and improve food safety in various processing operations, including thawing frozen meat and fish blocks, pre-cooking bacon for fast food chains, and pasteurizing pre-packaged foods (Decareau 1985). Additional advantages in using microwave systems to replace some of the conventional heating methods in the food industry include a cleaner work environment, reduced use of plant space, and shortened process time. Given the public and industrial interests in microwaveable foods, and the intrinsic advantages of microwave heating over conventional heating methods, the future use of microwave heating devices will continue to grow.

Microwave heating involves complex multi-physics phenomena that include interaction between the heated materials and microwaves, conversion from electric energy into thermal energy, and heat transfer driven by temperature gradients. Since the classic essay Dielectrics and Waves written by Von Hippel (1954), extensive research has been published on microwave heating for a wide range of food and non-food applications. These efforts have been aided by the recent sharp increase in computational power, advancements in instrumentation, and better design of microwave equipment. The number of peer-reviewed papers on microwave heating applications has also increased steadily, for example, from 50 in 1990 to over 500 in 2013, according to the Web of Science Core Collection (Thomson Reuters, December 2014). This paper will review important properties of microwaves in connection with heating uniformity and design of domestic and industrial microwave heating systems. It will provide an overview of important activities over the past 40 y in advancement of microwave sterilization and pasteurization technologies for pre-packaged foods in U.S.A. and Europe, and present major outcomes from our 20 y activities in developing 915 MHz single-mode microwave sterilization technology. It will also discuss needs for future research.

Basic Characteristics of Microwave Heating

Microwave frequency and wavelength

Microwaves are EM waves at frequencies between 300 MHz and 300 GHz (Decareau 1985), or 300×10^6 to 300×10^9 Hz (cycles per second). Like all EM waves, microwaves propagate in free space at the speed of light (Figure 1). The wavelength is related to frequency by:

$$\lambda = c/f \tag{1}$$

where λ is wavelength (m), c is speed of light (3×10^8 m/s), and f is frequency (Hz).

Microwaves are used for air-traffic control, weather forecasting, global positioning, cellular video systems, and other telecommunication and remote ranging applications (Pozar 1998). To avoid interference with these uses, a limited number of frequency bands are

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Table 1–Important microwave frequencies allocated for industrial, scientific, and medical (ISM) use (Decareau 1985; Metaxas and Meredith 1993; Buffler 1993).

Frequency (MHz)	Frequency tolerance (MHz)	Wavelength in air (m)	Application examples	Countries
896	±10	0.335	Industrial applications: for example, tempering of frozen products	Great Britain
915	±13	0.328	Industrial applications: precooking of bacon, tempering of frozen products	North and South America, China
2375	±50	0.126	Domestic microwave ovens	Albania, Bulgaria, Hungary, Romania, Czechoslovakia, former USSR
2450	±50	0.122	Domestic microwave ovens, industrial precooking of bacon, pasteurization and sterilization of packaged foods	Worldwide, except where 2375 MHz is used
5800	±75	0.052	No food heating applications	Worldwide

assigned by the US Federal Communications Commission (FCC) for industrial, scientific, and medical (ISM) applications. Table 1 lists the microwave frequencies and the corresponding wavelengths for ISM heating applications. In the U.S.A., 2450 MHz microwaves (wavelength in air, 0.122 m) are used in domestic microwave ovens and in industrial systems, whereas 915 MHz (wavelength in air, 0.327 m) are only used in large-scale industrial food processing systems. Wavelengths are critical parameters in the design of microwave systems; they also determine the depth of microwave penetration into foods, as will be discussed later. Although no specific microwave frequencies were specified in Spencer's 1st patent application (Spencer 1950), based on the suggested wavelengths (0.1 m), he most likely worked with microwave devices using frequencies close to 2450 MHz.

Propagation of microwaves

When microwaves propagate from air to foods, a portion of the waves is reflected; the rest enters the foods. The direction of the entered waves differs (refracted) from the original direction (Figure 2). The frequency of those waves in foods remains the same as that of the incident waves, whereas the wavelength is shortened by a factor of 6 to 9 in high moisture foods (Tang and Resurreccion 2009).

The propagation direction of the refracted waves is determined by the intrinsic impedances of air and foods according to Snell's law (Mudgett 1985):

$$\sin\psi = \frac{\eta \sin\phi}{\eta_0} \tag{2}$$

where ψ is the angle of refraction, ϕ is the angle of incidence, η_0 $(= \sqrt{\mu_0}/\sqrt{\varepsilon_0})$ is the intrinsic impedance of air (377 Ω). μ_0 (=4π x 10^{-7} H/m) is the permeability (determining material's ability to support a magnetic field) of free space, and ε_0 (=8.854×10^{-12} F/m) is the permittivity (measuring reaction of a material to formation of an electric field) of free space.

The intrinsic impedance, η, in a material is defined as (Sadiku 1995):

$$\eta = \frac{\sqrt{\mu}}{\sqrt{\varepsilon\varepsilon_0}} = \frac{\eta_0}{\sqrt{\varepsilon}} \tag{3}$$

where μ and ε are the permeability and permittivity of foods, respectively. Foods do not interact with magnetic fields. Thus, in the above equation, we assume $\mu = \mu_0$.

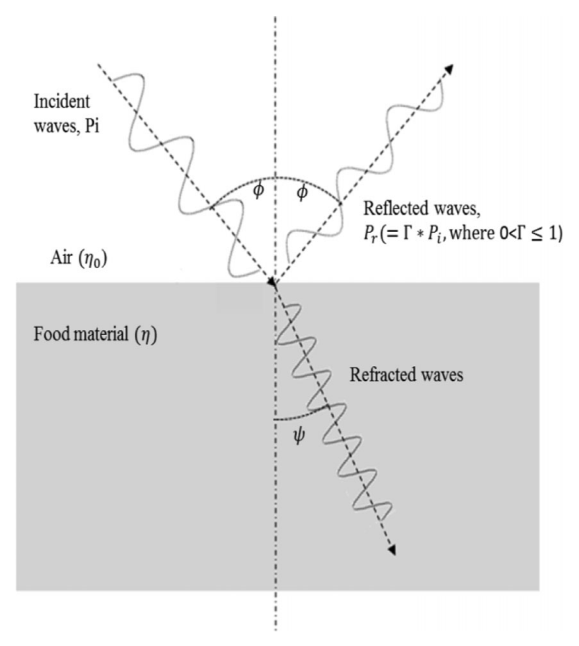


Figure 2–Upon touching the surface of food, a portion of waves is reflected, and the rest enters the food. ψ is the angle of refraction and ϕ is the angle of incidence and reflection. The arrows show the directions of wave propagation.

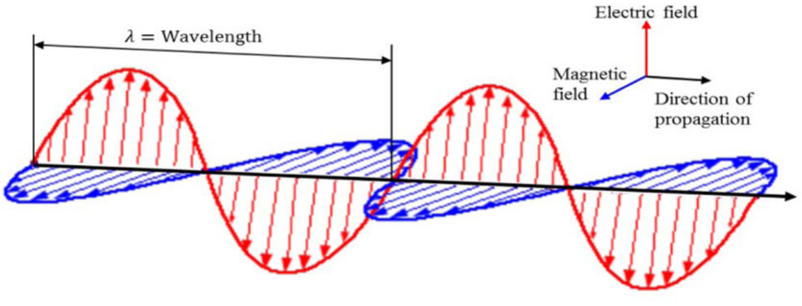


Figure 1–An EM wave consists of 2 components: electric field and magnetic field, oscillating in phase and in planes perpendicular to the direction of wave propagation.

Table 2–Refraction angle and percent power reflection at a flat interface between air and ice or water as a function of the incident angle in the direction of microwave propagation.

Material	Intrinsic impedance η	Incident angle ϕ	Refracted angle ψ	Reflected power in %
Ice	188Ω	0	0	33.5%
		30°	14.4°	38.3%
		90°	29.9°	100%
Water (at 25 °C)	42Ω	0	0	80.0%
		30°	3.2°	82.4%
		90°	6.4°	100%

The reflected portion of the waves at the food surface is in turn determined by the reflected and refracted angles, as well as the intrinsic properties of the air and the food (Mudgett 1985):

$$\Gamma = \frac{P_r}{P_i} = \frac{\eta_0 \cos\psi - \eta\cos\phi}{\eta_0\cos\psi + \eta\cos\phi} \tag{4}$$

where P_r is reflected power and P_i is incident power.

The intrinsic impedances of water and ice, and calculated reflected power for different incident angles over a flat surface of those materials are shown in Table 2. More microwave power is reflected from water than from ice because of the larger difference between the intrinsic impedances of water and of air. High moisture foods have impedance similar to that of water, whereas frozen foods have intrinsic impedance similar to that of ice. Thus, in a single pass, more microwave power is reflected from moist foods than from frozen foods. In a microwave oven, microwaves are reflected back to foods from metal walls. High microwave field intensity may be created between foods and oven walls in high power ovens, causing possible arcing at the pointed parts of foods. The large differences between the impedance of air ($\eta_0 = 377$) and that of moist foods ($\eta < 60$) are also responsible for the edge heating of packaged foods when heated in domestic microwave ovens.

When spherical and cylindrical high moisture foods are exposed to microwaves, the entering microwaves are refracted toward the center. High moisture foods at room temperature have dielectric constants $\varepsilon' > 40$ (see examples in Table 3). From Eq. 3, the intrinsic impedance, η, of those foods are smaller than 60. According to Eq. 2, all incident microwaves in high moisture food are refracted to within an angle of 9° of the internal normal and travel toward the center of the spheres (Buffler 1993), as illustrated in Figure 3. For relatively small sized foods, for example, when the sphere diameter is less than 2.5 to 3 times the microwave penetration depth, the focused microwave field would cause central heating (Lu and others 1997). Calculated microwave penetration depths of microwave in selected foods included in Table 3 will be discussed in a later section.

In a microwave oven, not all microwave energy is absorbed by foods. The amount of microwave energy converted to thermal energy in foods follows approximately the following empirical relationship (Mudgett 1985):

$$P_0 = P_m(1 - e^{-b\,V}) \tag{5}$$

where P_0 is the total microwave power absorbed by food, P_m is the microwave power generated by the oven magnetron, V is the volume of the food, and value of b depends upon geometry and dielectric properties of foods and design of the oven. This relationship states that the larger the food volume, the more microwave energy is used for heating.

Dielectric properties of foods

As stated earlier, the magnetic component of microwaves does not interact with foods; only the electric component causes heating. Thus, dielectric properties (electric permittivity) are among the most important characters of foods related to microwave heating. These properties are described by the complete relative electric permittivity ε^* (relative to that of air):

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{6}$$

where $j = \sqrt{-1}$. Dielectric constant ε' expresses the ability of the material to store electric energy. Dielectric loss factor ε'' determines conversion of microwave energy into thermal energy:

$$Q = 2\pi\varepsilon_o\varepsilon'' f\, E^2 \tag{7}$$

where Q is the converted thermal energy per unit volume (w/m^3) and E (V/m) is the electric field instantaneous intensity.

Dielectric properties of foods are affected by food composition, in particular moisture content, salt, and fat contents. They also depend on temperature and frequency. Table 3 provides representative dielectric properties of selected materials to illustrate the wide range of values.

As shown in Table 3, moisture and salt contents particularly affect the values of loss factor, and thus the conversion of microwave energy to thermal energy in foods, according to Eq. (7).

Within the spectrum of microwaves, dipolar water molecules and ions are agitated in alternating electric fields to generate thermal energy. The contributions of these 2 elements to the total value of loss factor of a food material are expressed as (Ryynänen 1995):

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma = \varepsilon''_d + \frac{\sigma}{2\pi f\varepsilon_0} \tag{8}$$

where σ (S/m) is ionic conductivity. The 1st term on the right hand side of Eq. (8), ε_d, represents the dielectric loss factor due to dipole rotation of water molecules. The resonance frequency, which corresponds to the peak value of loss factor over EM frequency spectrum, of water molecules at room temperature is about 20000 MHz. This frequency increases with increasing temperature (Figure 4). The 2nd term, ε_σ, represents the contribution of ionic conductivity. Its value increases with increasing ionic conductivity and decreasing frequency. Ionic conductivity in foods, in turn, increases with increasing amount of dissolved salts and with increasing temperature. The values of loss factors of different foods listed in Table 3 are the combined results of the two contributors discussed above. For example, the loss factor of deionized water at 2450 MHz is larger than that at 915 MHz because 2450 MHz is closer to the resonance frequency of water molecules (that is, ~20000 MHz at room temperature). Ice has a very low loss factor because water molecules are locked in rigid structure when frozen. Thus, frozen foods have very low loss factors. It is interesting to note that increasing temperature reduces loss factors of tap water at 2450 and 915 MHz. This is because the resonance frequency of water shifts further away from 2450 and 915 MHz as temperature increases (Figure 4). Adding 0.5% salt to ionized water increases the loss factor of water at both frequencies, but more so at 915 MHz (Table 3). For foods with added salt, for example, mashed potatoes with 1.5% salt, increasing temperature increases the value of the loss factor (Table 3), as a result of increased ionic conductivity at higher temperatures as shown in Figure 4.

Table 3–Dielectric properties of selected foods and calculated penetration depth, dp, (Tang 2005).

		915 MHz			2450 MHz		
Foods	**Temperature (°C)**	ε'	ε''	**dp (mm)**	ε'	ε''	**dp (mm)**
Air		1.0	0		1.0	0	
Water							
Distilled/deionized	20	79.5	3.8	122.4	78.2	10.3	16.8
0.5% Salt	23	77.2	20.8	22.2	75.8	15.6	10.9
Ice	−12	–	–	–	3.2	0.003	11,615
Tap water[a]	20	78	4.1	112.4	80.0	14.0	12.5
	80	62	2.6	158.0	61.2	4.0	38.0
	120	56	2.5	156.2			
Corn oil	25	2.6	0.18	467	2.5	0.14	220
Fresh fruit and vegetables							
Apples	22	60	9.5	42.6	57	12	12.3
Potatoes	25	65	20	21.3	54	16	9.0
Asparagus	21	74	21	21.5	71	16	10.3
Pasted potatoes[b]	20	64	20	18.8	65	13	12.1
86% moisture, 0.8% salt	80	60	28	15.0	58	12	12.4
	120	55	38	10.6	53	18	8.0
86% moisture, 1.8% salt	20	55	28	14.1	54	16	9.0
	80	46	52	7.7	45	24	5.6
	120	48	95	4.6	49	46	3.2
High protein products							
Yogurt (pre-mixed)	22	71	21	21.2	68	18	9.0
Cooked ham[c]	25	61	96	5.1	60	42	3.8
Cooked beef[c]	25	76	36	13.0	72	23	9.9
Salmon fillets[d]	20	57	23	17.6	53	16	8.9
Middle section, 1.7% fat, 75.0% moisture	80	52	52	9.8	47	20	6.8
	120	51	60	7.0	46	28	4.9
Belly, 2.0% fat	20	54	20	19.5	50	14	9.9
75.7% moisture	80	49	35	11.0	44	20	6.6
	120	47	51	7.8	41	26	5.0

[a] From Komarov and Tang (2004).
[b] From Guan and others (2004), the 2450 MHz data were extrapolated from trends between 915 and 1800 MHz.
[c] From Mudgett (1986).
[d] From Wang and others (2008), the 2450 MHz data were extrapolated from trends between 915 and 1800 MHz.

Over a broad range of EM frequency spectrum, other mechanisms also contribute to the overall values of loss factor as illustrated in Figure 4. Detailed discussion on those mechanisms and influence of frequency and temperature can be found in Tang and Resurreccion (2009).

Penetration depth of microwaves in foods

Upon entering foods, microwave energy is partially converted to thermal energy. The power of the microwave is reduced along its path, according to the following relationship:

$$P(z) = P_0 e^{-2\alpha z} \tag{9}$$

where P_0 is microwave power entering the food, $P(z)$ is microwave power in food at distance z from surface. α is a constant calculated from von Hippel (1954):

$$\alpha = \frac{2\pi}{\lambda_0}\left[\frac{1}{2}\varepsilon'\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon''}\right)^2}-1\right)\right]^{\frac{1}{2}} \tag{10}$$

where λ_0 is the wave length in free space, ε' and ε'' are dielectric constant and loss factor, respectively, of food materials.

The microwave penetration depth (dp) is defined as the distance at which microwave power is reduced to $1/e$ ($e = 2.718$) from the strength at the point of entry (Figure 5). That is:

$$P(\mathrm{dp}) = \frac{P_0}{e} \tag{11}$$

From Eq. (9) and (10), dp is calculated as:

$$\mathrm{dp} = \frac{1}{2\alpha} = \frac{\lambda_o}{2\pi\sqrt{2\varepsilon'\left[\sqrt{1+(\frac{\varepsilon''}{\varepsilon'})^2}-1\right]}} \tag{12}$$

The value of microwave penetration depth in a specific food is a good indicator of the ability of the food material to convert microwave energy to heat. It is also a useful parameter when deciding food package thickness for proper microwave heating. For a flat profile food package and when microwaves come from the top and the bottom of the food package, ideally we should select a package thickness of 2 to 3 times the penetration depths of the foods.

As shown in Table 3, the penetration depths of microwaves in foods of different moisture and salt contents vary widely with temperature and frequency. Microwave penetration depths are small in foods with added salt. For example, the penetration depth of 2450 MHz microwave is 3.8 mm in cooked ham at room temperature, as compared with 9.9 mm in cooked beef. The penetration depths in foods also decreased with increasing temperature as shown with mashed potatoes having 1.8% salt (Table 3), that is, 9.0 mm at 20 °C and 5.6 mm at 80 °C for 2450 MHz microwaves. In general, 915 MHz microwaves have deeper penetration depth in foods than 2450 MHz. For the same mashed potatoes, the penetration depth of 915 MHz microwaves increased to 14.1 mm at room temperature and to 7.7 mm at 80 °C.

Microwaves at 915 MHz penetrate deeply in tap and deionized water, in particular at elevated temperatures (for example, >150 mm at 120 °C) (Table 3). This suggests that tap water at elevated temperature is relatively transparent to 915 MHz microwaves. Such a unique feature is used in the design of 915 MHz single mode microwave-assisted sterilization and pasteurization systems at Washington State Univ. (Tang and others 2006) which will be discussed in a later section.

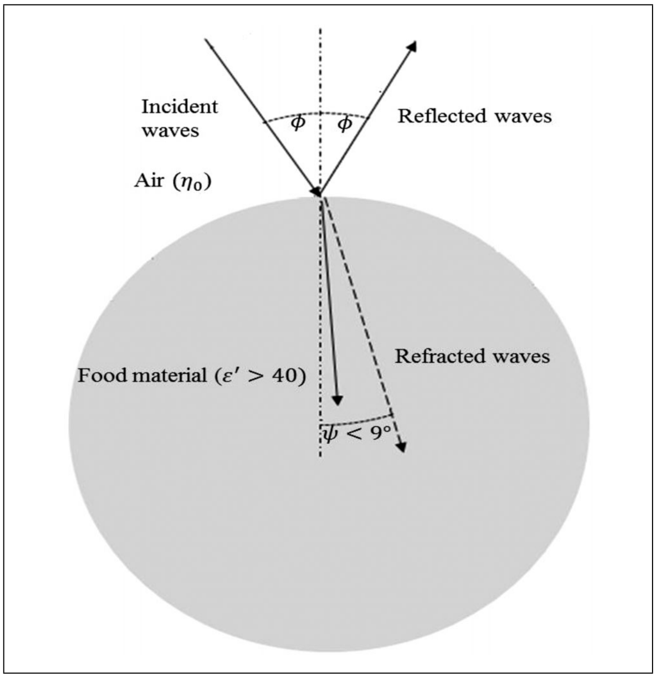


Figure 3–Microwaves entering a sphere are directed to the core (adapted from Buffler and Stanford 1991).

Microwave cavities

A simple microwave system consists of four main components: a magnetron that converts electric energy to microwave energy, a microwave cavity for holding and heating foods, waveguides that lead microwaves from the magnetron to the cavity, and a control system. In addition to penetration depths discussed in the previous section, standing waves in microwave cavities play a major role in determining heating uniformity.

Standing waves. Microwaves reflect at a metal wall. For a simple case in which the incident angle $\phi = 0$ in Figure 2 (that is the incident waves propagate vertical to a wall), the reflected waves are 180° out of phase with the incident waves at the wall, and travel in the opposite direction with the same wavelength and frequency as the incident waves. The incident and reflected waves form standing waves that have zero strength at the wall and have antinodes (maximum strength) and nodes (minimum strength) alternatively ¼ wavelength apart. Those antinodes and nodes create hot and cold spots in foods. Complex 3-dimensional standing waves are formed in a microwave cavity because of the reflection of microwaves off 6 metal walls.

Multi-mode cavities. The magnetron in a domestic microwave oven does not generate microwaves exactly at 2450 MHz, rather over a certain bandwidth (for example, between 2425 and 2475 MHz, as in a case described in Chan and Reader 2000). In a microwave cavity with dimensions similar to or larger than the wavelengths of the microwaves, several standing wave patterns can simultaneously form; each corresponds to a resonance frequency and each pattern is referred to as a resonant mode. This type of cavity is called a multi-mode cavity. For example, in an empty $360 \times 350 \times 260$ mm^3 microwave cavity, 10 different microwave standing wave patterns (thus 10 resonant modes) can form within a microwave spectrum between 2425 and 2475 MHz (Chan and Reader 2000). Figure 6 shows only one of several possible field patterns in a domestic microwave oven with load.

The locations of the high and low microwave field zones created by the superimposed multiple standing wave patterns in an microwave oven depend on cavity dimension, the entry port of the microwave, the frequency spectrum of the microwaves from the magnetron, and the geometry, dimension, dielectric properties, and location of the food.

As discussed in Resurreccion and others (2015), the peak frequency of a microwave generator changes with age and power setting. Our recent tests with multiple new microwave ovens also show that the peak frequency changes with size and location of

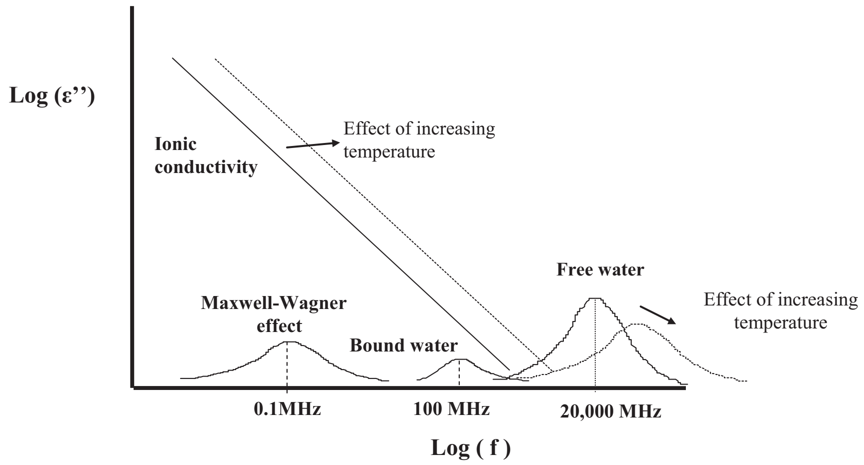


Figure 4–Contributions of various mechanisms of the loss factor (ε'') of foods as a function of frequency, in MHz (Tang 2005).

the food in the cavity. Thus, it is extremely difficult to predict and control microwave standing wave patterns in a multi-mode microwave cavity.

Single-mode cavity. When at least 1 dimension of a microwave cavity is much smaller than the wavelength of the microwaves from the magnetron, it is possible to create a single predictable and stable wave pattern. These cavities are referred to as single-mode cavities. Figure 7 illustrates the design of a 915 MHz single-mode cavity for sterilization or pasteurization of pre-packaged food. In this design, microwaves from a generator is split 50% into each of the 2 horns. The synchronized waves from the 2 horns enter the rectangular section to form a standing wave pattern. This single-mode cavity is able to provide a stable heating pattern over a reasonable bandwidth applicable to industrial 915 MHz generators and for foods of different dielectric properties (Resurreccion and others 2013, 2015). Nine hundred fifteen MHz single-mode microwave cavities are also designed for in-pipe processing of pumpable foods (Coronel and others 2003, Steed and others 2008).

The dimension of single-mode cavities is proportional to the wavelength of microwaves. For example, single-mode cavities for 2450 MHz microwaves are about 1/3 the size of 915 MHz cavities. 2450 MHz single-mode cavities are too small for heating foods in single meal sized packages. They are often used in bench-top research devices, such as in CEM units (CEM, Mathews, N.C., U.S.A.), for studies of chemical reactions in well-controlled microwave fields.

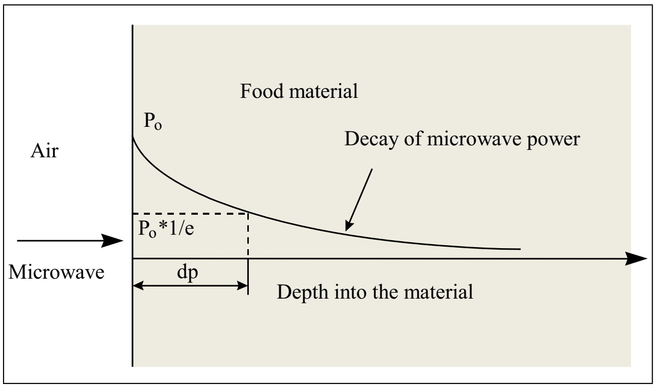


Figure 5–Definition of penetration depth of microwave.

An important consideration in designing a single-mode cavity is efficient coupling of microwave energy from the microwave generator to the cavity. A single-mode cavity has its own intrinsic resonance frequency determined by the geometry and dimension of the cavity. Maximum coupling occurs when the resonance frequency of the cavity matches the peak frequency of the generator. But the resonance frequency of an empty cavity shifts when loaded with a dielectric material such as food; the degree of the shift depends on the size, geometry, and dielectric properties of the material. Tuning devices (such as 3-stub tuners) are installed in the waveguides that connect cavities for fine tuning of resonance. It is critical to design single-mode microwave cavities having resonant frequencies that match or are close to the peak frequencies of the microwave generators. It is also important that the efficiency of the coupling is not sensitive to possible variations in food composition and package geometries. Computer simulation models are often used to aid the design of single-mode cavities.

Safety concerns in using microwaves

Microwave heating devices have been extensively used in homes, by food services and in the food processing industry. Yet, some consumers associate microwave heating with radioactivity and are seriously concerned about possible harmful chemical reactions caused by microwaves. This concern can be eased by considering a relationship derived from experimental data by Max Planck in 1900 who assumed that the total energy absorbed by a black body when exposed to a thermal radiation source was the sum of discrete quantities, each having the value of e (Tipler 1991):

$$e = hf \tag{13}$$

where h is Planck's constant, $h = 6.626 \times 10^{-34}$ J*s or 4.136×10^{-15} eV*s (eV stands for electron volt). For visible light, e is the energy of a photon, as demonstrated by Albert Einstein in 1905.

Using Eq. (13), the energy quantum is calculated to be: 6.063×10^{-25} J (or 3.784×10^{-6} eV) for 915 MHz and 1.623×10^{-24} J (1.013×10^{-5} eV) for 2450 MHz. These values are more than 5 orders of magnitude smaller than that of visible light and UV light (see corresponding frequencies and

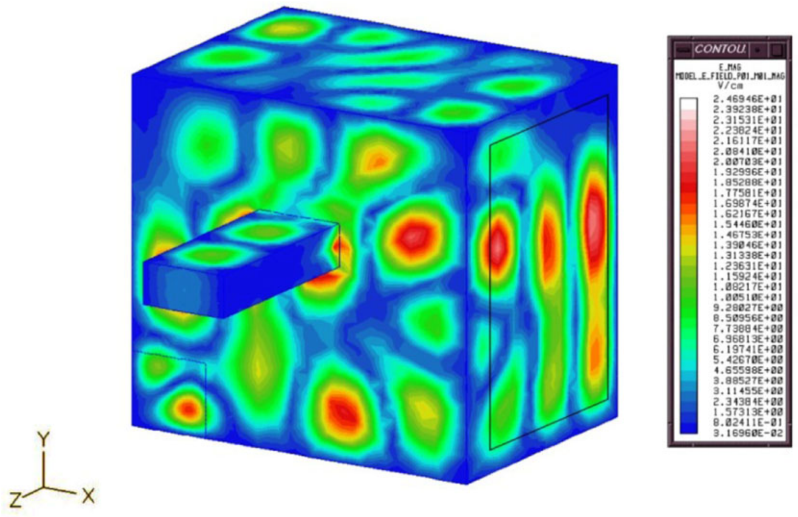


Figure 6–Electric field intensity in a multi-mode cavity that corresponds to a resonant frequency of 2430 MHz (Chan and Reader 2000). The red color indicates high intensity, blue for low intensity. The diagram includes a section of waveguide (in *Z* direction) that leads the waves to the entry port of the oven.

wavelengths in Figure 8), and more than 7 orders of magnitude less than that of X-rays (see Table 4). In addition, microwave wavelengths (0.12 to 0.33 m as shown in Table 4) are about 10 orders (10000000000 times) longer than the lengths of chemical bonds (that is, 1 to 2 × 10^{-11} m) (Haynes, 2014). Because of these factors, microwaves, unlike X-rays, are not able to create free radicals or disrupt molecular bonds in biological materials. The only effects on foods are the results of thermal energy converted from microwave energy.

Datta and Davison (2000) conducted an extensive literature review and consulted experts about possible non-thermal inactivation of foodborne micro-organisms by microwave energy. They concluded that "microbial inactivation kinetics for MWs are essentially the same as the inactivation kinetics of conventional thermal processing" (IFT 2000).

Another concern by users of microwave heating systems, including domestic microwave ovens, is exposure to microwaves leaking from those heating devices. The Food and Drug Administration (FDA) strictly regulates manufacture of domestic microwave ovens (FDA 2008). Microwave power decays with distance from the source by a factor of $1/r^2$ (r represents the distance from the source). According to FDA regulations (FDA 1991), microwave ovens should be designed with emission at time of manufacture of less than 1 mW/cm^2 measured 5 cm from a new microwave oven, and less than 5 mW/cm^2 measured 5 cm from ovens over their lifetime (Buffler 1993). Industrial microwave systems are also designed with similar considerations; microwave leakage detectors can be installed to monitor possible worker exposure in food plants (Decareau 1985; Baron 2009).

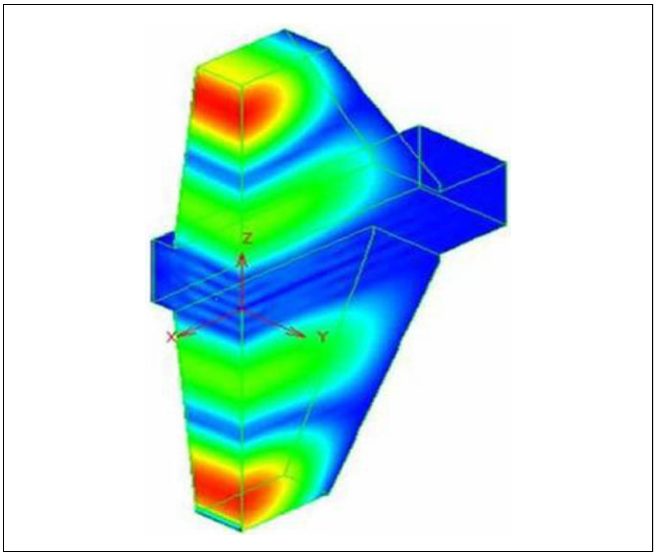


Figure 7–A single mode heating cavity formed by two horn applicators and a rectangular heating section filled with water at elevated temperature (Tang and others 2006).

Industrial Microwave Technologies for Packaged Foods

Microwave energy has been intensively studied worldwide over the past 40 y by food companies, government research institutions, and research communities for use in sterilization and pasteurization of pre-packaged foods, as an alternative to traditional canning. To understand the motivation for these efforts, it is appropriate to discuss fundamental factors that limit the potential of canning processes for production of high quality heat sensitive foods.

Drawbacks of conventional canning

The history of canning traces back to Nicholas Appert in France who patented a process in 1810 for preserving food in sealed containers. Over the past 200 y, the canning (or retorting) has evolved from art to science-based industrial operations that have been designed with thermal death kinetic data for pathogenic and spoilage microorganisms and refined methods for engineering calculations (Goldblith 1971; Stumbo 1973; Downing 1996; Holdsworth 1997). Yet the principle remains the same: holding packaged foods in a pre-heated medium (water or steam) for a sufficient time allowing transfer of thermal energy from container surface to interior to inactivate target bacteria.

Fundamentally, all current industrial sterilization and pasteurization processes are developed using the following equation to ensure that the least heated portion of the foods in containers achieves a desire reduction in the population of the target bacterium:

$$F = \int_0^t 10^{\frac{T(t)-T_{\text{ref}}}{z}}\,dt \tag{14}$$

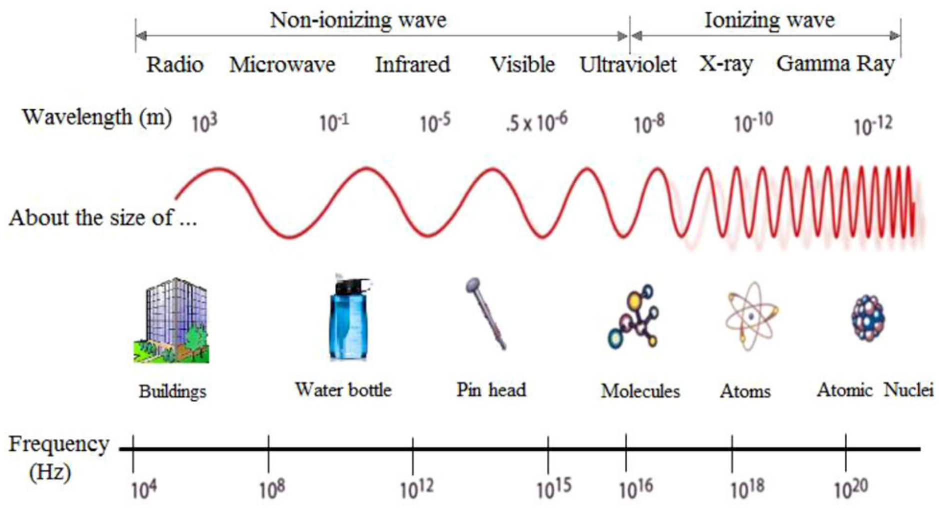


Figure 8–Frequency and wavelength of microwaves compared with that of visible light, UV lights and X Rays (adapted from http://mynasadata.larc.nasa.gov/science-processes/electromagnetic-diagram/).

Table 4–Energy quantum of selected EM waves.

	Frequency Hz	Wavelength in air meter	Energy quantum	
			J	eV
Microwaves	915×10^6	0.326	6.063×10^{-25}	3.784×10^{-6}
	2450×10^6	0.122	1.623×10^{-24}	10.13×10^{-6}
Visible light spectrum				
Red	400 to 480×10^{12}	6.3 to 7.5×10^{-7}	2.65 to 3.18×10^{-19}	1.65 to 1.99
Yellow	508 to 526×10^{12}	5.7 to 5.9×10^{-7}	3.37 to 3.49×10^{-19}	2.10 to 2.18
Blue	606 to 668×10^{12}	4.5 to 4.9×10^{-7}	4.03 to 4.43×10^{-19}	2.51 to 2.76
UV lights	700×10^{12} to 10^{17}	4.3×10^{-7} to 3×10^{-9}	4.64×10^{-19} to 6.62×10^{-17}	2.89 to 413.6
X-rays	10^{16} to 10^{20}	3×10^{-8} to 3×10^{-12}	6.63×10^{-18} to 6.63×10^{-14}	41.4 to 413,600

where F stands for the accumulative time (in minutes) exposure of food to a reference temperature of T_{ref}, $T(t)$ represents the history of the temperature at the least heated location inside food packages, z value, in °C, indicate how the thermal resistance of a bacterium changes with temperature.

For commercial canning of low acid ($\text{pH} > 4.6$, water activity > 0.85) shelf-stable foods, *Clostridium botulinum* type A and B (proteolytic) spores are the target bacteria; the corresponding z value is 10 °C (Stumbo 1973), T_{ref} is taken as 121.1 °C, and the symbol F_o for F. Industrial canning processes are designed to achieve $F_o \geq 3$ min, corresponding to a minimum of 12 log reduction in *C. botulinum* type A and B spores. For pasteurization, the targeted bacteria may be a vegetative pathogen, for example, *Listeria monocytogenes*, and T_{ref} may be a selected temperature between 65 and 90 °C (Holdsworth 1997). Six log reductions are often used in process calculation.

Heat transfer is slow in solid or semi-solid foods due to their relatively low thermal diffusivities, as compared with metals and other solid non-food materials. For example, in a still retort, tuna in 401 × 211 cans (103 mm diameter × 68 mm height) should be held for 100 min at 121.1 °C to produce a shelf-stable product (Downing 1996). The lengthy exposure times of foods, in particular near the container surface, to high temperature could cause severe thermal degradation in food quality. This limits nutritional values and market appeal of heat sensitive products from canning processes.

Cook value C, in minutes, is used to evaluate the impact of a thermal process on food quality:

$$C = \int_0^t 10^{\frac{T(t)-100}{z}}\, dt \qquad (15)$$

where z value, in °C, measures sensitivity of quality change rate with temperature; it varies from 16 to 34 °C, depending upon the type of food and cook criteria (for example, taste, texture, or appearance) (Lund 1986). C values are often calculated by volumetric integration of quality losses throughout the whole volume of the containers, or for the most heated portion of the foods.

Based on the intrinsic kinetics for thermal kills of food pathogens and thermal degradation of food qualities illustrated in the above 2 equations, high-temperature-short-time (HTST) thermal processes have been developed for liquid foods that use heat exchangers followed by aseptic filling and packaging to reduce adverse thermal degradation while still ensuring food safety. The possibility of HTST processing for solid and semi-solid foods is limited by slow heat conduction which often causes overheating at the solid surface during the time needed for the heat to be transferred to the center (least processed spot). Several early studies used computer simulation models to minimize food quality losses in canning processes by varying processing temperatures (for example, 113 to 145 °C) and package geometries (Teixeria and others 1969, 1975; Lund 1977; Ohlsson 1980a,b). Those studies demonstrated that high temperatures did not necessarily lead to overall higher quality of solid or semi-solid foods because of the slow internal heat transfer within food packages. Unless using very slim food package geometries, high processing temperatures might cause more overall product losses. Teixeira and others (1975) and Lenz and Lund (1977) stated that for those products raising steam temperature much beyond 121.1 °C in retorts does not help. After reviewing these results Lund (1977) concluded, "Heat transfer, not reaction kinetics, is controlling the process. Changing the heat transfer characteristics or changing the geometry of the container is the only alternative to increasing nutritional retention."

For liquid foods or foods consisting of particulates and low viscosity sauces, agitations in containers in thermal processes can facilitate in-container heat transfer and reduce processing times (Dwivedi and Ramaswamy 2010; Rattan and Ramaswamy 2014). But for processing pre-packaged solid or semi-solid foods, it is impossible to create effective internal agitation. The fundamental limitation of conventional canning technology has been the main motivation for developing in-package microwave sterilization and pasteurization technologies.

Early R&D research on microwave sterilization

The earliest research on in-package microwave sterilization processes in the U.S. was conducted at U.S. Army Natick Solider Center (Natick, Mass., U.S.A.) in its search for novel technologies to produce high quality shelf-stable ready-to-eat meals for soldiers (Kenyon and others 1971; Ayoub and others 1974). A pilot-scale system, designed to prove the concept, had an air-tight plastic pipe running through a 2450 MHz multi-mode cavity. The pipe was pressurized with compressed air. Foods in flexible packaging materials were heated in the cavity on a conveyor. But the food suffered from severe edge heating. The temperature difference between the edge and center of a beef slice ($5.2 \times 14.6 \times 0.5$ cm^3) was 5 to 17 °C, measured by paper thermometers (±5 °C) after the cold spot reached 120 °C (Ayoub and others 1974). The research activities were later moved to the USDA-ARS Western Research Center (Albany, Calif., U.S.A.). Researchers there reported similar severe edge heating (O'Meara and others 1976, 1977).

In Europe, researchers in Alfa-Laval (Sweden) designed a different 2450 MHz pressurized system (Stenstrom 1972, 1974) in which packaged foods were heated with microwaves while being immersed in water. This design reduced edge and surface overheating. The improved heating uniformity made it possible to design high temperature and short-time thermal processes. Scientists at the Swedish Inst. for Food Preservation Research (SIK) used a system similar to that of Alfa-Laval to study the influence of short time microwave sterilization processes on food quality (Ohlsson 1992). HTST microwave processes (that is, 128 °C final product temperature, 3 min cooking time for $F_0 = 6$) resulted in superior texture in carrots compared with controls retorted in cans (120 °C retort temperature and 45 min holding) or in foil pouches (125 °C retort temperature and 13 min holding) measured after 24 mo of storage at 25 °C Ohlsson (1987, 1989). But there has not been a report on scaling up of the Alfa-Laval design for commercial applications.

Major challenges reported in early research on microwave sterilization technologies included non-uniform and often unpredictable EM fields in multi-mode microwave cavities, as well as a lack of high-barrier microwave transparent packaging materials and reliable means to monitor product temperature, in particular in moving packages (Decareau 1994). In addition, 2450 MHz microwaves could only process foods of shallow thicknesses (Ohlsson 1992), due to limited penetration in foods (see section *Penetration Depth of Microwaves in Foods*).

Commercial systems

In spite of the above challenges in research and development activities, 2 European designs of commercial 2450 MHz microwave sterilization systems were reported in early 1990s, that is, from OMAC (Harlfinger 1992) and Berstorff (Schiegel 1992). The OMAC design was later improved for in-package sterilization operations in Tops Foods plant (Olen, Belgium) and in a processing plant of Otsuka Chemical Co. (Osaka, Japan) (DeCareau 1996). In both operations, compressed air was used to provide over-pressure. A detailed description of the microwave sterilization processes in Tops Foods can be found in Tang and Chan (2007). Briefly, the Tops Foods microwave system consists of 4 gated and linearly connected metal tunnel sections. Dozens of 2450 MHz magnetrons are mounted in each of the first 2 sections to provide microwave heating. The 3rd section is connected to heated air for holding, whereas the last section is for cooling with chilled air. In operation, batches of packaged foods are transported in a single file on a conveyor belt into the 1st section, the gates are closed, and the tunnel is pressurized via compressed air. After a pre-determined microwave heating time, gates are opened, the heated foods are moved to the 2nd section for further microwave heating, and then to the 3rd section for holding, before moving to the cooling section. The residence time for each section is about 7 min. More recently, new microwave sterilization operations are reported by Gustosi in Italy in which food packages arranged in multi-lanes are processed in 2450 MHz systems (http://www.gusto-si.it/engnew/tecnologia.html). When heated in compressed air, edge microwave heating is inevitable. Low microwave powers are often used to prevent busting of food packages and allow adequate time for heat transfer within food packages.

Interest in microwave sterilization has been high in the U.S. food industry over the past 30 y. Between the middle 1980s and late 1990s, many large U.S. food companies allocated internal resources to develop their own microwave sterilization systems or attempted to adopt from European systems. In 1996, Food Engineering Magazine reported a survey that asked top US executives to forecast food manufacturing trends in the 21st century. Among the 10 emerging food processing technologies, microwave cooking/sterilization was rated "High Potential" by the highest percentage of the respondents (28.6%) followed by gamma radiation (22.6%) (Morris 1996). But so far, no commercial operations have been reported for microwave sterilization of in-packaged foods in the U.S.A. at time of writing this article. One of the main likely reasons is the rigorous food safety assurance requirements of the FDA for low-acid foods in hermetically sealed containers.

Commercial operations using microwave pasteurization systems, on the other hand, have been reported in the U.S., as well as in Europe and Japan (Schiffmann 1992; Ohlsson 1989). These reported systems operate at 2450 MHz with 10 to 40 kW total power; the pasteurized products include cakes, breads, pasta, and refrigerated ready-to-serve meals (Giese 1992). Recently, Micvac (Sweden) introduced a new concept in commercial production of microwave pasteurized meals. A re-closeable valve is installed in each food package. Microwave energy (2450 MHz) heats foods in sealed trays; internally generated steam helps transfer thermal energy in the headspace to reduce non-uniform heating. When internal vapor pressure reaches a certain point, the valves open and vent the steam. The valves are closed upon cooling, creating a vacuum in the containers (http://www.micvac.com/food-technology/method). This design significantly reduces the thermal impact of edge heating and improves food quality.

All reported commercial microwave sterilization and pasteurization systems use 2450 MHz multi-mode heating cavities.

915 MHz Single-Mode Microwave Sterilization Technology Development in the U.S.A

Research on in-package microwave sterilization and pasteurization started at Washington State Univ. in 1997, partially financed by the U.S. Army Natick Soldier Center and Kraft Foods. Recognizing the limitations of 2450 MHz microwaves, the team selected 915 MHz microwaves in the system design. Preliminary research on 915 MHz microwave pasteurization and sterilization of food in containers yielded promising results in terms of food quality and microbial safety (Herve and others 1998; Lau and others 2002; Guan and others 2002 and 2003). In 2001, with a grant support from the US Department of Defense Dual Use Science and Technology (DUST) program, the Washington State Univ. team formed a microwave consortium consisting of 7 food processing, packaging, and equipment companies and the U.S. Army Natick Soldier Center. The goal was to develop a microwave in-package sterilization technology for production of high quality shelf stable read-to-eat meals for the U.S. Army and the retail market. Research and development efforts were focused on 5 areas of activities: (1) designing microwave cavities that could provide predictable and stable heating patterns, the system should be scalable for industrial implementation; (2) developing an effective method to determine heating patterns and identify cold spots in food packages; (3) evaluating effective devices to accurately measure temperature at cold spots of food in continuous microwave heating systems for process development; (4) developing procedures to file for FDA and USDA-FSIS acceptance; (5) studying food quality changes during processing and in storage. The following sub-sections discuss details of the outcomes.

System design

Compared with the reported 2450 MHz microwave sterilization systems in Europe and Japan, our system includes two unique design features: (1) 915 MHz single-mode cavities and (2) water immersion. 915 MHz microwaves have adequate wavelength (Table 1) for single-mode cavities to accommodate single-meal portion food packages. This is impossible with 2450 MHz microwaves. In addition, microwaves at 915 MHz penetrate deeper into foods (Table 3), thus allowing heating of thicker packaged foods. Instead of heating packaged foods in air which causes severe microwave edge heating, as discussed in section *Propagation of Microwaves*, food packages in our system is heated in a shallow bed of water at high temperatures. As shown in Table 3, microwaves at 915 MHz can penetrate deeply into water at 80 to 120 °C. Yet the similarity between the dielectric constant of water and of foods reduces reflection and refraction of microwaves at the interface between water and foods, thus reducing or eliminating edge heating of the foods.

As discussed in section *Microwave Cavities*, the geometry and size of a single mode cavity determine its resonance frequency and electric field pattern. A 3-dimensional computer simulation model based on a finite-difference-time domain (FDTD) method was developed to guide the design of the cavity (Pathak and others 2003). The final ranges of cavity geometry and dimensions were decided after tests with several versions of mock-up cavities made of aluminum sheets (Tang and others 2006; Chen and others 2007). The 1st pilot-scale system with two inter-connected pressure cavities was built to prove this design concept (Chen and others 2008). But this system could only process foods in a batch mode (Tang and others 2008). A 2nd generation pilot-scale system (shown in Figure 9) was later built to simulate a continuous process (Resurreccion and others 2013), and used to develop protocols to file for FDA and USDA FSIS acceptance.

The 2nd generation WSU pilot-scale system consists of four zones, that is, for preheating, microwave heating, holding, and cooling, each has its own water circulation and external temperature control system. Compressed air connected to the buffer tanks of the water circulation systems provides overpressure during processing. The microwave heating section has four 915 MHz microwave single-mode cavities connected via a pressurized tunnel (Figure 10). Relatively high microwave power (~5 kW each) was provided to the first 2 cavities. Lower power was used for the other 2 cavities (~3 and ~2 kW, respectively) to allow a good control of the final product temperature. In operation, up to 48 single meal packages are moved on a microwave transparent conveyor from the pre-heating zone through the 4 cavities in a single file. The packages then move through the holding zone and, in the end, into the cooling zone. Special transition devices are installed between 2 adjacent zones to minimalize exchange of circulating water, while allowing food packages to pass through. The residence time of food packages in each zone is controlled by the belt speed. Since microwaves were used in combination with surface heating with circulating water, we refer to our system as a microwave-assisted thermal sterilization (MATS^{TM}) system.

The core of the innovation is the 915 MHz single-mode cavity design illustrated in Figure 11. In operation, microwaves propagate from a generator though the main waveguide (*f*, *e*). The waves are equally split at the tee-junction (*d*) into two branch waveguides, one is connected to the upper horn applicator, and another to the lower horn applicator. The microwave transparent windows at the base of the two horn applicators (*b*) are built as part of a pressurized rectangular metal tunnel in which food packages move in circulating water. A three stub tuner installed in the main waveguide helps increase coupling efficiency from the generator to the cavity. Measured reflected power from these cavities with moving foods in circulating water was about 10%. A major advantage of the design is stable heating patterns in foods over a wide range of food properties. Our recent studies show that variations in the peak frequency of microwaves within the FCC allocated frequency bandwidth (902 to 928 MHz) around 915 MHz do not influence heating patterns in the tested foods (Resurreccion and others 2015).

Chemical marker method for heating pattern determination

U.S. food safety regulations require that a thermal process is developed based on the temperature history at the least heated portion in food packages (FDA 1977). Thus, it is necessary to have an effective measurement method for determining the cold spots in foods during a microwave sterilization process. In an attempt to develop non-invasive temperature mapping methods for advanced thermal processing technologies, scientists at the U.S. Army Natick Soldier Center identified 3 possible intrinsic chemical markers (M-1, M-2, and M-3) formed in different food matrices during thermal processing. Those markers were used to assess accumulative time–temperature effects in different processing technologies (Kim and Taub 1993; Kim and others 1996a and b; Ramaswamy and others 1996; Prakash and others 1997). In those studies, marker precursors were added in natural foods to enhance marker formation.

After studying formation kinetics of those three markers, we found that the M-2 marker is particularly suited for short-time microwave sterilization processes (Lau and others 2003; Wang and others 2004). Figure 12 shows M-2 yield changes in whey protein gels consisting of 20% whey protein and 1% D-ribose. At temperatures from 116 to 131 °C, the chemical marker M-2 yield increases sharply with time within 10 min heating. The formation of M-2 follows 1st order kinetics, which is similar to thermal inactivation kinetics of foodborne microbial pathogens (Lau and others 2003). The 1st order reaction kinetic was also reported for M-2 formation in mashed potatoes made from dehydrated flakes (Pandit and others 2006).

Based on these results, standard whey protein gels and mashed potatoes with chemical marker precursors for M-2 were developed that cover the range of dielectric and thermal properties similar to those of different types of foods. The color of those model foods are pale white before thermal processing. When heated in a package with microwaves, localized brown color develops. The color intensity depends upon the intensity of heating.

Positive correlations were established between local thermal lethality F_o value, as calculated from Eq. (14), and color intensity as a result of M-2 formation from microwave sterilization (Pandit and others 2007a). This led to the development of a computer aided vision method for rapid heating pattern determination after each microwave sterilization run (Pandit and others 2007b). For example, when using HPLC to determine M-2 yields from multiple points in different layers, it took 3 d to map the heating patterns in 3 different layers in a single tray. The computer vision method only takes a few minutes. This method has been used to identify cold spots in model foods as a critical step in developing microwave sterilization processes for a wide range of products. The vision method has also been used to verify 3-D transient computer simulation models based on equations for microwave propagation, microwave heating, and heat transfer (Resurreccion and others 2015; Luan and others 2015). An example of experimental verification of computer simulation is shown in Figure 13. The intensity of brown color developed in a whey protein gel during the microwave sterilization process was converted to values in the RGB (red, green, and blue) scale to help visualize heating pattern (Pandit and others 2007b). It is interesting to note that both computer simulation and chemical maker results from experiments confirm no edge heating in food (Figure 13). This is a unique feature of our system design compared with the commercial 2450 MHz multi-mode microwave systems in Europe where no water immersion is used during microwave heating.

Temperature measurement for process development

Microwave sterilization processes are developed by measuring temperature at the cold spots. In our early studies, we used fiber optical temperature sensors to avoid interference from microwave fields (Tang and others 2008; Guan and others 2003; Lau and others 2002). But this method does not work for continuous processes in which food packages move from one end of the system to the other end under pressure. It is impractical to connect sensors embedded in moving packages to the light sources outside the pressurized system over long distances, in particular in industrial operations. Thus, we explored the possibility of using metallic mobile temperature sensors that are commercially available for conventional continuous canning operations (Tang and Liu 2015). Systematic studies were conducted to compare temperature readings from pre-calibrated fiber optic sensors and small mobile metallic sensors embedded in foods in the microwave sterilization processes. In addition, a 3-D computer simulation model was used to study the influence of insertion of a mobile metallic temperature sensor in foods on the electric field patterns in our four cavity pilot-scale system (Luan and others 2013). Simulation results were verified with the chemical marker method described above. Figure 14 compares simulated temperature histories at the cold zones in a tray, with and without probes, and shows the influence of probe orientation with respect to the dominant electric field direction.

Further simulation was conducted to evaluate the influence of high power electric fields (up to 24 kW per cavity) potentially used in industrial systems on temperature measurement errors when using mobile temperature sensors (Luan and others 2015). It is concluded from these studies that: (1) the slim metal probe of mobile temperature sensors do not influence overall heating patterns, and thus the locations of cold spots, (2) when the probes are properly oriented, the measured temperature history can be used for thermal lethality calculation.

Regulatory acceptance of MATS processes

FDA acceptance. The WSU team, its partners, and representatives from the National Food Processors Association (NFPA, consultant to microwave sterilization consortium on regulatory filing) met with scientists of the FDA Low Acid Food Team in 2004

Figure 9–2nd generation pilot-scale microwave sterilization system at Washington State University.

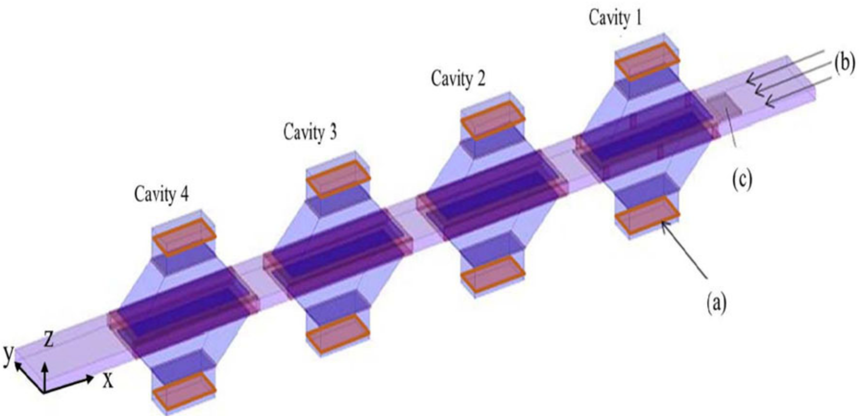


Figure 10–Schematic diagram for 4 cavity microwave sterilization system; (a) entry port of microwaves, (b) movement direction of a mesh belt carrying food packages, (c) food packages immersed in circulating water at over 121 °C (Resurreccion and others 2015).

to seek advice on necessary steps and information required to file for FDA acceptance. After discussions with the FDA team, the consortium decided to support the development of a 2nd generation pilot system (described in section *System Design*) to simulate continuous operations, so that filing protocols could be easily extrapolated to industrial systems. Thermal processing authorities of the Seafood Products Association (SPA, a former regional laboratory of NFPA) submitted the 1st filing in October 2008 on behalf of Washington State Univ. Supplemental data were provided to the FDA in May 2009, after two rounds of feedback and a new set of tests based on recommendations from the FDA. The filing was finally accepted in October 2009. The 1st filing was for a homogeneous food, mashed potatoes in 10.5 oz. trays; the attention was focused on system calibration, cold spot determination, process development procedures, and the microbial validation methods. A 2nd filing, for salmon fillets in Alfredo sauce in 8 oz. pouches, was made in September 2010. It was accepted in January 2011. A 3rd process filing was made by Ameriqual Foods (Evansville, Ind., U.S.A.), a military ration producer, for a 915 MHz single mode microwave pilot-scale system based on the design of Tang and others (2006), following a similar filing protocol for mashed potatoes developed at Washington State Univ. It was accepted in 2014.

Each of those filings was made electronically on the FDA website, along with a supporting document that provided scientific information and related experimental data to comply with 21 CFR 108 and 113 (FDA 1979) for thermal production of low acid (pH > 4.6, water activity > 0.85) shelf-stable foods. The supporting document consisted of 10 sections: (1) a general description of the system, (2) description and calibration of microwave power and temperature measurement devices, (3) heat distribution test results, (4) dielectric property data, as function of temperature, of the food or its main ingredients, (5) model foods containing chemical marker precursors, and their dielectric properties, (6) location of cold spots determination by the chemical marker method, and verification with direct temperature measurement using mobile sensors, (7) heat penetration test results using mobile temperature sensors, (8) microbial validation

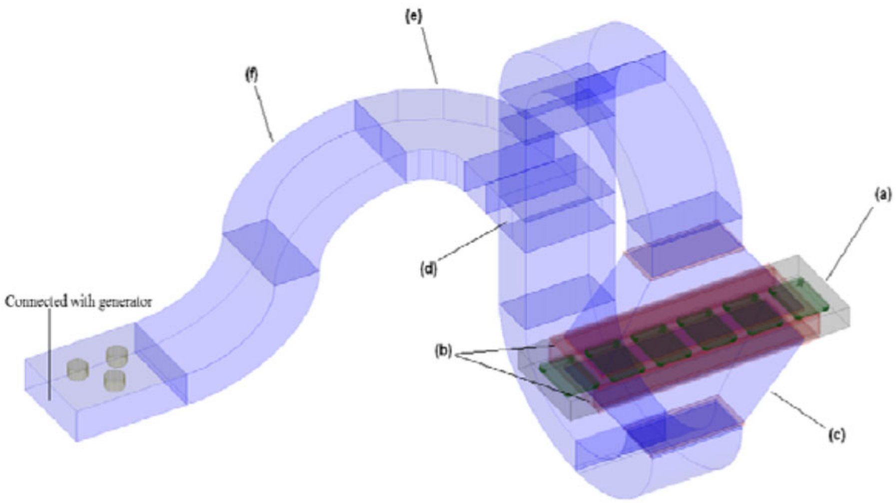


Figure 11–915 MHz single mode cavity: (a) food packages immersed in circulating water, (b) microwave transparent windows as parts of a pressurized tunnel, (c) horn applicator, (d) Tee waveguide splitter, and (e) and (f) waveguides (Resurreccion and others 2015).

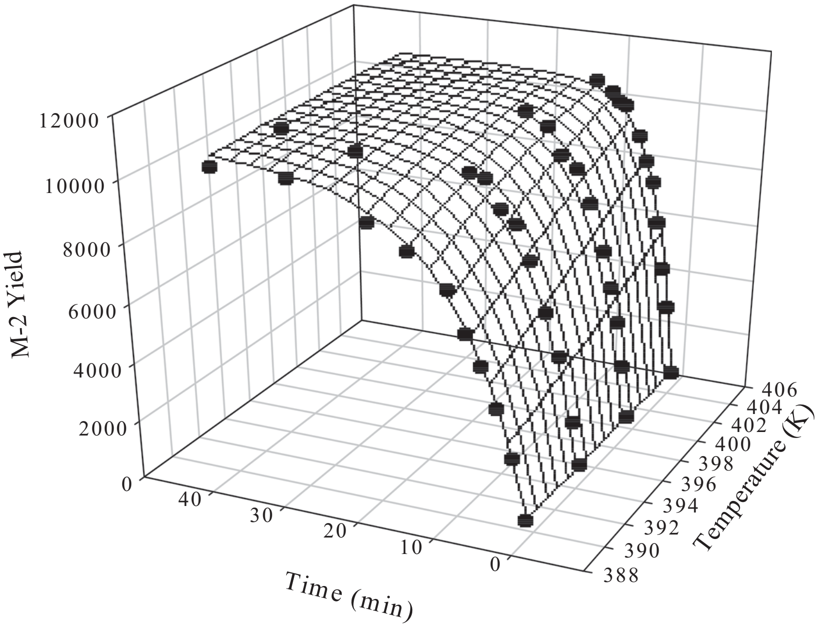


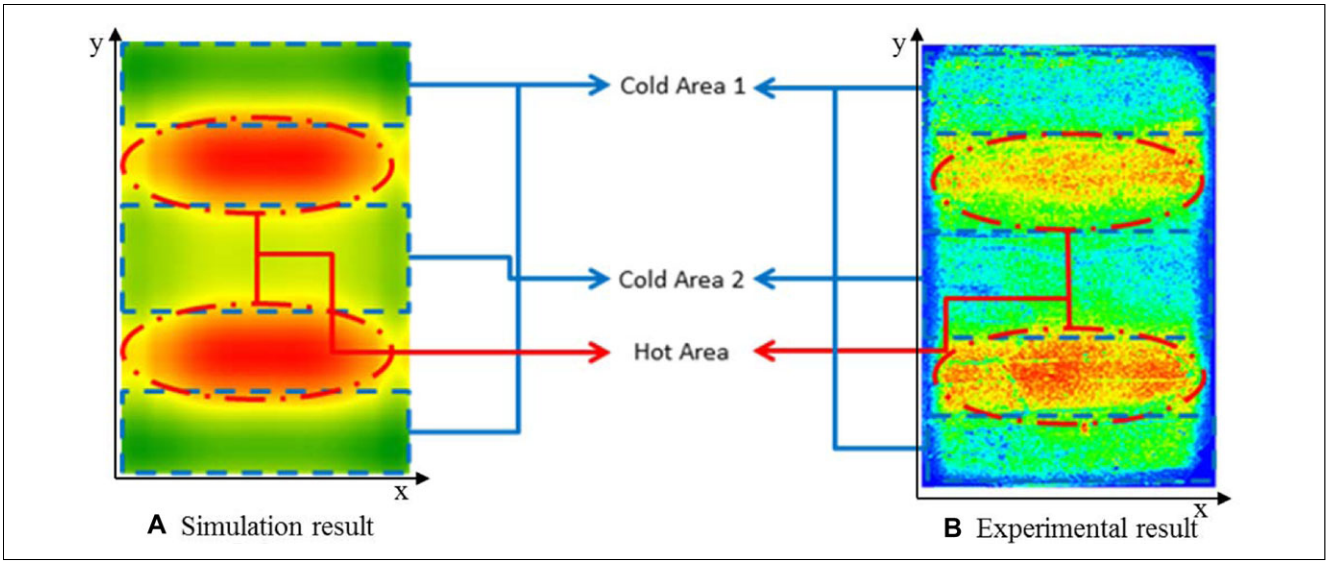
Figure 12–M-2 yield in whey protein gels increased with time and temperature (Lau and others 2003).

for $F_0 = 6$ min using *Clostridium sporogenes* strain PA 3679 spores as surrogates for C. *botulinum* spores type A and B, (9) critical factor considerations and limit determination, and (10) process deviation detection and corrective action measures.

For non-homogeneous foods, dielectric properties of main ingredients were determined. Several standard whey protein gels were prepared to cover the range of the dielectric properties of the food. These gels were simultaneously processed in the same system to identify possible cold spots using chemical markers for computer-assisted visual identification of cold spots. Direct temperature measurements were made with mobile temperature sensor tips inserted in different food components at and in the vicinity of the cold spots to determine temperature histories. These tests were followed by formal heat penetration runs with packaged foods. For our previous filings, we conducted 12 individual processing runs, spread over 1 mo. In each run, multiple food packages were monitored at the cold spot using mobile temperature sensors. These sensors measured the temperature of the largest pieces of solid food at the previously determined cold locations in the food packages. The most conservative data were used for process calculation and for selection of belt speed to achieve desired F_0.

Microbial validation was conducted using PA 3679 spores (Guan and others 2003). Thermal resistance (D- and z-values) of PA 3679 cultures was 1st determined in M/15 Sorensen's phosphate buffer (pH 7.0) (Mah and others 2008, 2009). This step is referred to as calibration of surrogates. Only spore crops with a z value close to 10 °C (the same as *C. botulinum* type A and B spores) and $D_{121.1\,°C}$ (D value at 121.1 °C) values over 0.6 min (about 2.5 times more than that of *C. botulinum* spores type A and B) were used for microbial validation tests. Further tests were conducted to determine thermal resistance of the selected spore crop in different food components (for example, sauce and salmon fillets) to be processed in the same packages. The food component in which the calibrated PA 3679 spore crop had the highest $D_{121.1\,°C}$ value and also had the slowest heating at cold spots was inoculated for microbial validation tests.

For the 3 previous filings, we used 5 different levels of microwave sterilization processes, 1 at the target level of $F_0 = 6$ min, 3 levels



A Simulation result

B Experimental result

Figure 13–Heating pattern comparison between (A) computer simulation result and (B) experimentally determined heating pattern based on chemical marker M-2. The pattern was for the center layer of whey protein gel 84 × 127 × 16 mm^3 in a pouch (Resurreccion and others 2015).

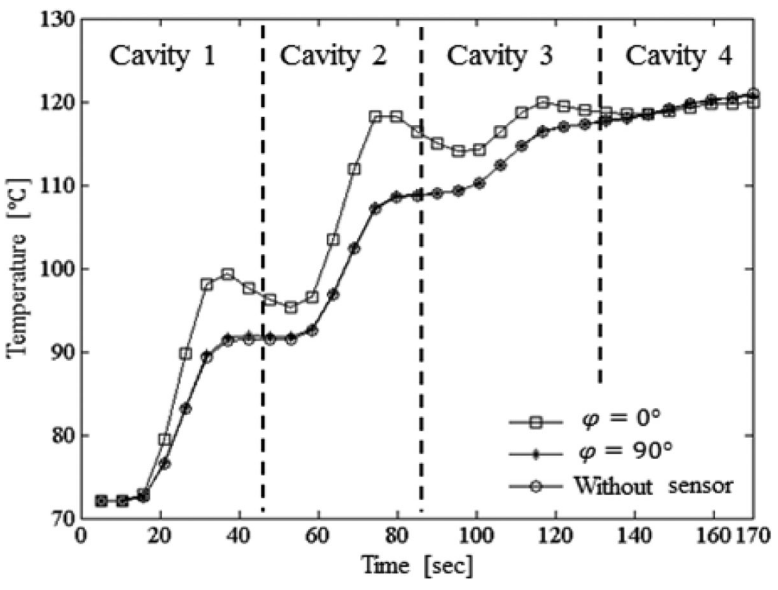


Figure 14–Temperature profiles at the cold spot. φ is the angle between the length of sensor probe and that of the dominating electric field component (Luan and others 2013).

below and 1 level above the target level. The initial inoculum spore count was calculated based on the determined $D_{121.1\ °C}$ for the inoculated food component, to allow survival of spores in the 3 under-target processes. This was to ensure that the inoculated PA 3679 spores had the same thermal resistance as determined from the prior thermal resistance tests. Inoculated packages were then processed at the above stated 5 levels, and stored at 36.5 °C, along with controls (inoculated but not processed foods). The samples were observed over 90 d for sign of bulging as an indication of survival of PA 3679 spores (PA 3679 is a gas producer). After 90 d, 25% of the packages that showed no sign of bulging were randomly taken for enrichment tests to detect possible injured spores. Description of the enrichment test procedure can be found in Luechapattanaporn and others (2004).

For foods under the jurisdiction of the FDA, each new process and product requires separate filing for FDA acceptance.

USDA FSIS non-objection. Foods containing meat (>3% raw or 2% cooked), poultry and egg products are not under the jurisdiction of the FDA. Novel processing technologies for these products require clearance from the U.S. Dept. of Agriculture Food Safety and Inspection Service (USDA-FSIS). In addition to assuring that food safety is consistent with related regulations (for example, 9CFR 318 and 381), USDA-FSIS examines how the new technologies would affect in-plant inspection procedures, and if they could create any safety concerns to FSIS inspectors. After positive review, USDA FSIS would provide non-objection letters for general use of the technologies in commercial production, but they will examine case by case how the technologies are implemented in specific food plants.

On behalf of Washington State Univ. (WSU), the Seafood Consulting Service Incorporated (SCSI, Seattle) submitted a new technology notification in July 2011 to USDA-FSIS for use of Microwave Assisted Thermal Sterilization (MATS) technology in production of packaged foods intended to be stored under refrigerated conditions (pasteurized) and for shelf-stable foods (sterilized). Supporting documents included data used in the 2 previous filings for FDA acceptance (mashed potatoes, and salmon fillets in sauce) and a complete set of new data for chicken and dumplings in 8 oz. pouches. This product consisted of three main components: sauce, pieces of chicken breast, and dumpling dough. The overall procedures for process development and validation were the same as for salmon fillets in sauce and for mashed potatoes. Additional heating pattern and temperature measurement tests were conducted to study the influence of random distribution of 3 main components in chicken and dumpling pouches, so that the final design of the process would produce a safe product. We received FSIS review comments in Oct. 2011. After several conference calls with the USDA-FSIS review team and providing them with two formal response letters, we received a non-objection notification in March 2012 from the Division of Risk, Innovation, and Management (RIMD) in the USDA-FSIS Office of Policy and Program Development. This clears the path for food companies to implement this technology for commercial production for foods under the jurisdiction of USDA-FSIS.

Food quality and shelf-life studies

In addition to food safety, food quality and market potential of the new products are the main interests expressed by food companies in our technology development. It is generally believed that short-time processes should produce better quality foods compared with lengthy processes, when food ingredients are heat-labile. Before our studies, the only published food quality data from testing on a pilot-scale microwave sterilization system are from SIK (Ohlsson and others 1992). A fundamental question is how much improvement the microwave sterilization technology could potentially provide over conventional canning processes. To answer this question, we conducted a set of heat penetration tests using a model food in 10.5 oz. trays. The trays were processed either in our pilot-scale microwave system or in a pressurized tunnel with circulating water (under pressure) at 121.1 or 125 °C. The latter represented the best case scenario in conventional canning because packages were individually exposed to flow of heated water. All the processes were designed to achieve $F_0 = 6$ min. The temperatures at the cold spot and close to the surface lid (hot spot) were recorded for calculation of cook values using Eq. (15). Those values are compared in Table 5.

Table 5–Comparison of cook values[a] in foods from different processes achieving the same thermal lethality F_0 = 6 min at the cold spot in 10.5 oz. trays.

Process	Process time (min)	Cook value at hot spot[a] (min)	Cook value at cold spot[a] (min)
Processing temperature: 121.1 °C			
Ideal	6	39	39
Retort	33	212	93
MATS	9	58	50
Processing temperature: 125 °C			
Ideal	2.4	22	22
Retort	27	279	78
MATS	3.9	36	32

[a]Cook values were calculated using Eq. (15), with $z = 26$ °C, hot spot cook values were calculated at product surface close to lid film, minimum cook values were calculated for cold spots.

Also included in the Table 5 are cook values calculated from Eq. (15) for ideal processes in which products are hypothetically heated with no thermal delay to the process temperature, maintained at that temperature to achieve $F_0 = 6$ min, and instantaneously cooled to room temperature. No practical thermal process could provide this fast, uniform heating and cooling. Thus, those calculated cook values are the minimums for practical thermal processes of $F_0 = 6$ min. A cook value, expressed in min, can intuitively be interpreted as a measure of the thermal impact of a process on food quality after that many minutes of cooking at 100 °C. As shown in Table 5, the minimum cook value for a $F_0 = 6$ is 39 min when using a processing temperature of 121.1 °C. That level of thermal impact on food quality is inevitable regardless of what thermal processes are used to attain $F_0 = 6$.

Compared with the hypothetical idea processes, the cook values were 212 min (5.4 times) at the hot spot and 93 min (2.4 times) at the cold spot when using a conventional thermal process. This explains the severity of the thermal effect of conventional thermal processes on food quality. The cook value for the hot spot is 2.3 times that of the cold spot, reflecting a high level of non-heating uniformity. In the microwave process used in this study, the cook value was 58 min at the hot spot, 1.5 times the cook value for the ideal process, and about 1.2 times that at the cold spot. Therefore, microwave short-time processes theoretically should produce better quality products containing ingredients that are heat-sensitive.

Raising the processing temperature to 125 °C reduced processing time to 2.4 min for the ideal process, resulting in a cook value to 22 min. This confirms the concept of HTST in increasing product quality. The processing time for the conventional process was reduced to 27 min (compared to 33 min when using

Table 6–Panel scores for chicken breasts processed by microwave or retorting after storage at 100°F (Courtesy of Tom Yang from the US Army Natick Solider Center).

	Microwave				Retorting			
	Storage time, in month							
Quality attributes	0	2	4	6	0	2	4	6
Appearance	6.5	6.5	6.8	6.3	6.3	6.4	6.2	5.8
Odor	6.9	6.6	6.4	6.3	6.5	6.3	6.3	5.9
Flavor	6.7	6.4	6.3	5.7	5.5	6.0	5.3	4.9
Texture	6.4	6.4	6.3	5.8	5.9	5.2	5.0	5.2
Overall quality	6.7	6.6	6.3	5.9	5.5	5.9	5.1	4.8

Table 7–Panel scores for chicken and dumplings processed by microwave or in retort after storage at 120°F (Courtesy of Tom Yang from US Army Natick Solider Center).

	Microwave		Retorting	
	Storage time, in month			
Quality attributes	0	4	0	4
Appearance	7.1	6.8	5.8	5.9
Odor	6.9	6.7	6.2	6.0
Flavor	7.0	6.7	6.0	6.2
Texture	6.9	6.6	6.2	6.3
Overall quality	7.0	6.8	5.9	6.1

121.1 °C). But the corresponding cook value at the hot spot increased to 279 min, 1.3 times the cook value of 212 min when processed at 121.1 °C. Thus, using a higher processing temperature did not lead to better quality.

When using 125 °C as the target processing temperature, microwave processes could reduce the cook values at the hot and cold spots by 1/3, as compared with processing at 121.1 °C. Microwave sterilization technology, thus, could possibly provide better quality at processing temperatures higher than 121.1 °C. But this could only be achieved with good heating uniformity. Microwave processing at too high a temperature may result in bursting of sealed packages, caused by generation of extremely high internal vapor pressure in the event of localized heating.

Our earlier work with pilot-scale microwave systems documented the influence of microwave processing on pasteurized and sterilized asparagus (Lau and Tang 2002; Sun and others 2005) and macaroni and cheese (Guan and others 2002). Independent kinetics studies, under isothermal conditions, suggest that short processing times indeed reduce product degradations, in particular in terms of texture and color (Peng and others 2014; Kong and others 2007, 2008). But those studies did not investigate changes in quality attributes during storage.

Systematic shelf-life studies were conducted at the U.S. Army Natick Soldier Center over the past few years on several food products processed in our pilot-scale microwave system. The 1st product was chicken breast, vacuum sealed in 10.5 oz. polymeric trays with lid films. The trays contained a layer of EVOH and the lid film had PVDC as oxygen barrier. Both the polymeric trays and the lid films had been extensively used by the food industry in production of low-acid shelf-stable foods for the retail market with expected 1 y shelf-life. Microwave processing for $F_0 = 6$ min was conducted in the food processing pilot plant of Washington State Univ. For comparison, the same product in aluminum pouches was retort-processed to the same lethality level in a commercial plant. The aluminum pouches were designed for a 3-y shelf-life for ready-to-eat meals. They were provided by the U.S. Army Natick Soldier Center.

The processed products were shipped to the U.S. Army Natick Solder Center, and stored at ~38 °C (100 °F) over a 6 mo period to simulate quality changes over 3 y at ~27 °C (80°F). Samples were randomly taken out of storage every 2 mo and evaluated by a trained panel on a 9-point quality scale, following a standard protocol for accelerated shelf-life studies of ready-to-eat U.S. military meals. A score of 6 and higher reflects good acceptance by the panel. Results are summarized in Table 6.

This was our 1st attempt at shelf-life studies; we used very simple food matrices to compare the influence of microwave sterilization and retorting. The data in Table 6 show much higher scores for overall quality (1.2 difference) and flavor (1.2) in the microwave processed product before storage, as compared with retorted counterparts. Over the course of 6 mo at 100 °F, which is equivalent to 3 y at 80 °F, product quality deteriorated. But at the end of storage, the sensory score for the overall quality and flavor of microwave sterilized product was still 1.1 and 0.8 points, respectively, above that of the retorted control.

A more interesting set of data was obtained for a new product, chicken and dumplings. Several preliminary test runs were conducted on our microwave system. The product formulation and ingredient selection were finalized after evaluating the processed products and through discussion among product development teams from several food companies involved in the microwave sterilization consortium. The food made from the selected formula was vacuum packed in 8 oz. polymeric pouches specially developed by Print-Pack, Inc. (Ga., U.S.A.) for high oxygen barrier properties. Microwave processing was conducted at Washington State Univ. Retorting was conducted in the pilot plant of a military ration producer and co-packer. The samples were shipped to the U.S. Army Natick Soldier Center, stored at 120 °F for 4 wk to simulate storage of 3 y at 80 °F. Sensory results obtained for both processes are shown in Table 7. The scores for appearance, flavor, and overall quality were very high (7.0 to 7.1) on day 0 of storage. After the simulated 3-y storage at 80 °F, the sensory scores dropped slightly, but still remained in the high range of 6.7 to 6.8. The influence of storage on chicken and dumplings processed in retort was not significant.

Package Considerations

Plastic polymer food packages are increasingly used in retail markets. Combining layers of polymers with special functionalities provides flexibility in designing rigid containers or flexible pouches for thermally processed shelf-stable foods. Typical polymers used in those packages include polypropylene, polyethylene terephthalate, and Nylon 6. The dielectric constant (ε') of those materials varies between 2.0 and 3.5, and dielectric loss factor (ε'') between 0.01 and 0.0001 (Mokwena 2010), much smaller than that of foods (see Table 3). According to Eq. (7), those materials are transparent to microwaves and, thus, are suited for in-package microwave sterilization and pasteurization processes. The exposure time of food package materials in microwave sterilization processes are less than 1/3 of the time needed for conventional thermal processes. From limited studies, we have found less thermal degradation in food packages during microwave sterilization processes (Mokwena and others 2009, 2011; Dhawan and others 2014a,b). In our microwave sterilization systems, food packages are immersed in water. The temperature of the packages during in-package microwave sterilization would not exceed that of the food and the circulation water. Thus, we expect that polymer packages designed for conventional thermal processes in compliance with FDA regulations (Marsh and Bugusu 2007) are also suited for in-package microwave sterilization processes.

One concern is the limited shelf-life provided by polymer materials used in pouches and lid films for trays. Food companies generally expect a 1 y shelf-life at room temperature for meals processed in polymer packages. Military rations are designed for a 3 y shelf-life; NASA space foods for future Mars missions require minimum shelf-life of 3 to 5 y at ambient conditions (Catauro and Perchonok 2012). Flexible films containing aluminum foil laminate have ideal oxygen and moisture barrier properties, and are used as packaging materials for military ready-to-eat meals and for certain foods in retail markets. But those films do not allow penetration of microwave energy and, thus, are not suitable for in-package microwave heating processes. We are collaborating with U.S. Army Natick Soldier Center and food packaging companies to explore use of high barrier polymers, including EVOH (Dhawan and others 2014a,b; Mokwena and Tang 2012; Mokwena and others 2011), as alternatives to aluminum foil based packaging films for shelf-lives between 3 and 5 y.

Polymeric trays for retorted products are designed with thick walls to sustain lengthy heating in high pressure water or steam environment. We hypothesize that short microwave-assisted thermal processes reduce thermal degradation to tray properties, making it possible to use thinner walls. This would reduce package costs and environmental loads. Future research is needed to test the hypothesis.

Current Research and Future Needs

Microwave sterilization

Our past efforts have primarily been focused on developing and evaluating sound processing system design concepts and on creating effective tools and methodologies for process development and validation. Those are the necessary 1st step for commercialization. It is now possible to produce shelf-stable low-acid foods in packages by exposing products to high temperature in a few minutes, as compared with 40 to 90 min. The shortened processing time starts to show unintended benefits. For example, our team and industrial partners consistently observed that MATS short-time processed foods taste much saltier than the counterparts processed in retorts, using exactly the same formulations. We were able to cut salt by 20% to 50% to bring down the saltiness to a desirable level. We 1st attributed this to the reduced salt diffusion from sauce into solids in short processing time at high temperature. But detailed analyses with controlled tests revealed that within a few days of storage at ambient temperature, salt continues to migrate until reaching the equilibrium (Bornhorst 2013). Thus, reduced processing time does not make products appear to be more salty after storage. A possible explanation is the sensory perception. Salt is an effective flavor enhancer (Nachay 2013). Extra salt is added in conventionally retorted foods to compensate for the loss in flavor. It is our hypothesis that the high retention of flavor in microwave processed foods as shown in Table 6 and 7 elevates the contrast of saltiness, allowing possibilities to remove the extra salt. Future research is highly desirable to prove the above hypothesis. If true, this should be a great news for food companies that have attempted to reduce salt contents in thermally processed foods in order to meet the new guidelines for daily salt intake, while still maintaining consumer satisfaction of product sensory quality (USDA 2015). It is also very likely that we will see other positive surprises that deserve in-depth research to unlock the full potential offered by short-time microwave sterilization.

Systematic studies (including kinetic studies) are needed to evaluate the influence of short processing on retention of heat sensitive nutrients and quality (including sensory) attributes. Such information should allow the food industry to produce a wide range of food products with excellent consumer appeal and nutritional values that could not have been possible with conventional thermal processes. The food industry is also very interested in technologies that have minimum environmental footprint. Life-cycle analyses on uses of water, energy and food packaging associated with MATs technology are necessary to assess impacts to the environment as compared with conventional retorting. Further engineering research is required to optimize system design and process conditions for best product quality, least energy uses, and minimal environmental impacts.

Microwave pasteurization

At Washington State Univ. we have started developing a 915 MHz single-mode in-package pasteurization technology to help food companies in compliance with the Food Safety Modernization Act (FSMA). With support of a USDA-NIFA grant, we have built a pilot-scale 915 MHz microwave pasteurization system, and developed new model foods for heating pattern determination in the 70 to 90 °C temperature range (Zhang and others 2014, 2015). The system also combines surface water heating with center microwave heating, which we refer it to as microwave-assisted pasteurization system (MAPS$^{\text{TM}}$). The microwave pasteurization system typically takes 1.5 to 2 min to raise products temperature to 70 °C for control of *Listeria monocytogenes* for shelf-life of 7 d under refrigeration or to 90 °C for control of non-proteolytic *C. botulinum* for shelf-life of 9 wk under refrigeration. The process temperatures of between 70 and 90 °C are adequate for control of viruses (Bozkurt and others 2013, 2014a, b, c). We are exploring its use as an effective intervention operation for production of frozen and chilled meals. Our early results demonstrated the ability to produce safe meals containing heat sensitive spices with excellent appearance, texture, and flavor. A shelf-life study on 3 microwave pasteurized pasta products have been completed at the U.S. Army Natick Soldier Center after storage at a normal temperature of 7 °C and abused temperature of 12 °C over a 9-wk period. The sensory scores were consistently high over the tested storage period. Further research and development efforts are required to scale-up systems to different capacities for commercial applications. Systematic food quality and nutrition studies are also needed to study and capture the full benefits of short-time in-package pasteurization processes.

Future outlook

Both continuous microwave sterilization and pasteurization systems can be designed to minimize adverse environmental impacts through efficient use of energy and water. Multi-international food companies are interested in large-scale sterilization systems with capacities typically between 100 and 150 meals per min. Medium capacity systems producing 50 to 100 meals/min can also be designed for smaller food companies and co-packers. The long shelf-life of sterilized foods allows distant distributions from centralized processing plants. Pasteurization systems are more suited for small and medium sized food companies. Short yet adequate shelf-life of the products under refrigerated conditions should allow food companies to provide a wide range of chef-inspired, nutritionally formulated, and/or ethnic meals free of pathogens to consumers in homes, schools, and nursing homes, or even during international airline flights. Refrigerated meals eliminate the need for freezing and thawing. This should sharply reduce energy uses, improve product quality, and shorten reheating time. Thermally pasteurized foods also do not require chemical preservatives, allowing for cleaner food labels.

Microwave pasteurization systems do not require over-pressure, and can operate economically at a wide range of capacities. The operations can be easily scheduled to process different products with little downtime. This gives small and medium size food companies the flexibility to produce a wide range of meals for communities within a reasonable travel distance though refrigerated distribution chains.

Compared to the 200 y history for conventional retorting, development, and application of microwave-assisted thermal processing technologies is still in its infancy. Enhanced efforts are required to bridge the remaining knowledge gaps and facilitate technology transfer. When fully integrated with state-of-art automation and process control and guided by new knowledge of influence on food qualities and nutrition, it is possible to develop precision processes based on microwave energy to satisfy special needs of different consumers while providing clean work environment to the operators.

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