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Non-Chemical Disinfestation of Food and Agricultural Commodities with Radiofrequency Power

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1. Introduction

The presence of microbial and insect/mite pests in foods and agricultural commodities, particularly in fresh produce, dried foods, nuts, grains, seeds, nursery plants, ornamental flowers and in wood products (i.e. pallets), continues to be a major factor affecting their condition for safe distribution and use in local, regional and international markets. As a mean to reduce the potential of propagating non-indigenous pests, postharvest (mandatory) treatment modalities and quarantine barriers have been imposed to regulate transportation and distribution of many of these products worldwide. These regulations define strategies for the detection, control, or eradication techniques for controlling quarantine insect and mite pests.

Today, more than 6,500 nonnative species are already established in the United States and approximately 15% of these species are either economically or environmentally harmful (Pimentel, Lach, Zuñiga et al., 1999). Control or eradication practices for arthropod pests are mostly based on chemical pesticides, although host removal, adequate agricultural production practices, biological control agents, and sterile insect release are often techniques applied in place off or in conjunction with pesticides.

Among the most important quarantine plant pests, various exotic fruit flies have been identified in the USA as threats to more than 250 crops. On the other hand, the presence of moths in stored products represents important and unacceptable risks to many growing and expanding agricultural regions worldwide. If detected, affected commodities must be processed with effective control or eradication techniques. If unattended, losses in product's quality represent unacceptable economic losses.

Chemical pesticides, waxes, coatings, thermal treatments (heated air; hot water immersion), modified atmospheres, cold storage (refrigeration), and irradiation are some of the processes that have helped industry meet current challenges and demands. Lately, however, new consumer preferences, trends and regulatory interventions have increased the needs for minimally processed foods with low or no residual chemicals. This new trend requires that less invasive or chemical-free alternatives become available to replace or minimize the use of pesticides. Furthermore, recent concerns associated with potential terrorist threats using microbial contaminants or other pests, have increased the need to develop alternatives to

assure the safety of the food supply while minimizing economical risks associated with production and export agriculture. These combined challenges are now familiar to affected governments as well as to industry and regulators worldwide.

Historically, and with a few exceptions, pesticides have provided an ample spectrum of effective techniques to control pests and there is a continual industry trend to maintain and improve their use. However, this practice and its effects and limitations have partially fueled the emergence of organic agriculture. This in turn has prompted conventional agriculture to review its practices, its traditional processes, and to investigate new types of pesticides as well as to develop new disinfestation techniques. The incorporation of fluorine in agrochemicals to enhance stability and bioavailability is the latest attempt to increase their effectiveness while reducing their secondary impact (Jeschke, 2004). Nevertheless, their invasiveness and persistence in all environs surrounding agricultural practices continues to be resisted by consumers and by increased limiting regulations.

Past and even present industry reliance on methyl bromide fumigation for quarantine pest controls is the best and most recent example of the changing attitude that exists today with respect to invasive chemical processes. The existing ban and the new restrictions on production levels have forced agriculture to look for new and better alternatives. Fumigation, vacuum techniques and controlled atmospheres (CA) for insect (quarantine) control are marginally successful and restricted to long-storage commodities (i.e. grains, nut products, raisins) (Bond, 2007; Calderon, 1990). For perishable fresh commodities, these techniques have failed to provide the required and timely disinfestation level. Nevertheless, while somewhat successful, the needed long processing times (days or weeks) increases cost and is inadequate to fit with the logistics of marketing fresh agricultural products.

The use of low-level doses of ionizing radiation (i.e. food irradiation) is another effective and approved technique providing an alternative to disinfestation and disinfection of many commodities (Urbain, 1986). However, while technically useful and approved for certain applications, this approach prompts many public concerns and is usually and effectively resisted. Furthermore, because irradiation facilities require a high capital investment to install and operate in order to remain economically viable, it also forces the irradiation industry to operate as major centralized facilities located near high productivity agricultural areas. The seasonal nature of agriculture, however, forces the irradiation industry to meet the peak demands with excess processing capacity and to broaden off-season applications (i.e. disinfection of medical supplies) to remain viable. Consequently, the handling and distribution of to-be-treated food and agricultural commodities imposes new and severe logistical and cost adjustments to the user community. As a result, few if any agricultural export areas rely on irradiation facilities and those operating represent a small and stagnant resource for insect control.

Despite the above limitations, ionizing radiation also provide means to sterilize insects that once released in specific areas can reduce the impact of local/regional infestations.

As of today, with the exception of food irradiation, few attempts to fulfill the need for new alternatives to pesticides have been investigated using single or combined physical processes. If effective, these processes are inherently safer, eliminating the risks associated with the presence of pesticides in products and ultimately easing the current concerns with disposal issues, worker safety, and environmental impacts. Non-chemical or residue-free alternatives also provide opportunities to yield products with attributes closer to their natural sensory and nutritional properties. Furthermore, because physical processes are

solely based on the use of energy, they are naturally free of residues and therefore can serve the needs of both conventional and organic agriculture.

Since 2002, research at the University of California, Davis established the use of RF power for disinfestation as well as for many novel sanitation and preservation purposes for a variety of food, non-food and agricultural commodities. Since then, RF processing has been established as a novel methodology able to provide new alternatives for chemical-free disinfestation, disinfection and enzyme deactivation effects on various commodities (Lagunas-Solar, 2003; Lagunas-Solar, Zeng & Essert, 2003; Lagunas-Solar, Zeng, Essert et al. 2005a; Lagunas-Solar, Cullor, Zeng, et al. 2005b; Lagunas-Solar, Zeng, Essert et al. 2006a). RF disinfestation, in particular, was proven as an effective, rapid, and a reliable chemical-free alternative to pesticides and capable of large-scale processing.

Radiofrequency waves using designated, single frequencies are approved for industrial, scientific and medical uses by national (US Federal Communication Commission, FCC) and international organizations. Currently, limited but increasing commercial use in all these areas to heat-treat and dry a variety of commodities is underway. Radiofrequency power provides well-controlled, volumetric (internal) and rapid heating of a diverse variety of food and non-food commodities. Appropriate food and non-food products to be processed and heated with RF power are generally known as dielectrics (poor electric conductors) and include pests, microbes, foods and non-food agricultural commodities such as soil, packaging and wood (pallets) products.

Dielectric properties are directly related to the material's chemical (molecular) composition and due to the presence and relative abundance of dipoles like water and/or induced dipoles like proteins, lipids, and carbohydrates. Therefore, the material's ability to absorb RF power and convert it to thermal power resides at the molecular level. Because molecules are well distributed and organized within and on the surface of dielectric materials, the effect of absorbing RF power occurs throughout its volume and to a lesser extent on its surface (lower concentrations) where temperatures are slightly lower than its internal volume (< 1°C). For this reason, RF processing is said to be a volumetric process, comparable to microwave heating, but in contrast with any other conventional surface thermal process known today. By comparison, the volumetric nature of RF processing provides with unique opportunities to reduce the needed thermal load (i.e. temperature over time) required for an intended effect as heat losses by radiation are larger at the surface. This volumetric property applies equally to arthropod and microbial pests as well as to the host commodity and its package.

The RF disinfestation process is rapid (seconds to minutes) and proven effective when reaches lethal thermal levels (50-60°C). These levels are sufficient to provide thermal loads able to irreversibly disrupt essential and common metabolic pathways and to affect all biological stages of arthropod (and other) pests. Furthermore, as the interaction of RF photons with molecules is frequency dependent, at specific frequencies insect pests exhibit a higher heating rate than the host commodity allowing a somewhat selective heating process to be realized. This selective process minimizes processing time and lowers the overall thermal load applied to the commodity thus decreasing the potential for any adverse effects on its quality attributes.

The fundamental physical concepts and the rationale behind the RF disinfestation process, including the interactive energy-transfer and conversion mechanisms (RF to thermal power) with arthropod pests are explained below.

2. Physics of RF power

2.1 RF photons and the electromagnetic spectrum

Radiofrequency photons belong to the electromagnetic spectrum of radiant energy. The electromagnetic spectrum covers a very large range of wave photons with frequencies ranging from 10^6 to 10^{20} Hz (1 Hz = 1 cycle/sec) and wavelengths from 10^3 to 10^{-12} m. As shown below in Figure 1, this range covers radiowaves ($\sim 10^6$ to 10^{10} Hz), microwaves ($\sim 10^{10}$ to 10^{12} Hz), infrared, visible and ultraviolet radiation ($\sim 10^{12}$ to 10^{16} Hz) and soft, hard X rays and gamma rays (10^{16} to 10^{20} Hz).

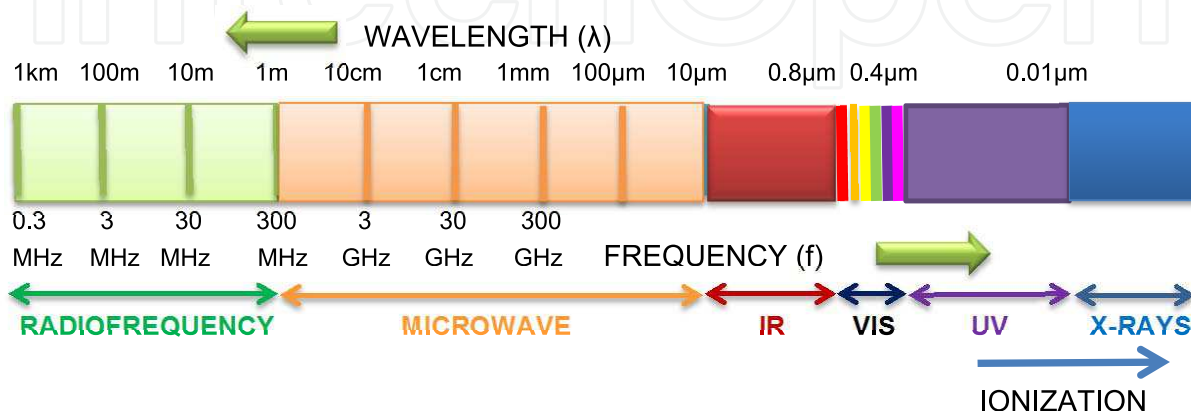


Fig. 1. Electromagnetic spectrum (simplified).

Radiofrequency power is, however, a small segment of the radiowaves region with an arbitrarily defined range of frequencies between ~ 1 MHz (300 m wavelengths) to 300 MHz (1 m wavelengths). In the defined frequency range, the RF photon energy is in the 6.6×10^{-28} to 6.6×10^{-26} J/photon (or 4.1×10^{-9} to 4.1×10^{-7} eV/photon). Therefore, RF processing involves photons of very low energy and long wavelength and therefore absorbing dipole or induced dipole molecules can only experience excitation effects (i.e. vibrational and rotational) but will not lose electrons to cause ionization or the formation of free radicals.¹

Radiofrequency waves are produced by rapid electrical oscillations and generally are able to penetrate deep into various materials, but are reflected by electric conductors and by the ionized layers in the upper atmosphere. Like all other photons in the electromagnetic spectrum, RF photons consist of electric and magnetic waves oscillating at right angles to the direction of propagation (i.e. transverse waves) and moving through space at the speed of light ($c = 2.998 \times 10^8$ m/sec). The combination of electric and magnetic fields originates an electromagnetic field.

The relationship between the RF photon energy and its frequency is given by Einstein's classical expression as:

$$E = hf \quad (1)$$

where: E is the photon energy (Joules);

¹ Chemical bond energies are in the range of 1 to 10 eV per bond. Therefore, RF photons (1 to 100MHz) carry one billionths to 100 millionths less energy than is required to break a single bond. Free radicals are extremely reactive (short lived) chemical species capable of inducing chemical reactions. Their formation is associated exclusively with sources of ionizing radiation (> 1 eV/photon).

h is the Planck's constant (6.626×10^{-34} Joules sec or 4.136×10^{-15} eV sec); and
 f is the photon frequency (Hz or cycles/sec).

This expression indicates that all photons in the electromagnetic spectrum come as discrete quantities named "quanta" and moving at the speed of light. It also indicates that photon energy is always a multiple of Planck's constant times its frequency (cycles/sec).

Because frequency (f in Hz) and wavelength (λ in m) of an electromagnetic wave are related to the speed of light as

$$c = f\lambda \quad (2)$$

formula 1 can also be expressed as

$$E = hc / \lambda \quad (3)$$

indicating that photon energy E is inversely proportional to its wavelength λ .

2.2 Interactions of RF photons with matter

Biological materials - including foods, microbes, arthropods and many agricultural products, are non-magnetic in nature, therefore, only the electric field component of an electromagnetic wave is able to interact and strongly affect the polar and induced polar molecules in the product.

In the presence of an oscillating electric field (changing polarity at a set frequency), the interactive mechanisms of the electric field with RF active molecules (i.e. dielectrics or poor electric conductors) include: (1) reorientation of permanent dipoles (i.e. water); (2) inducing dipoles by polarization of bound charges (proteins, carbohydrates, lipids); and (3) forcing the drift (displacement) of electronic and ionic conduction charges (mineral nutrients) (Klaunberg & Miklavcic, 2000).

The above interactive mechanisms only act at the molecular level and thus the effects of RF processing is based solely on the material's chemical composition in which permanent dipoles (i.e. water) play a major role while other lower concentration non-polar or weakly polar molecules are activated in proportion to the magnitude of the electric field. Initially, and without an electric field, polar and non-polar molecules in any material are randomly oriented due to thermal excitation, which forces their multi-directional movement and spatial distribution.

When an electric field is applied, dipole (polar) molecules tend to re-orient and become aligned according to the direction of the electric field in a phenomenon known as "orientation polarization". Still, orientation is opposed by thermal excitation and therefore, the net orientation effect is proportional to the intensity of the electric field once it overcomes the random distribution of the active molecules in the RF field.

In non-polar molecules, the electric forces separate positive and negative charges a small distance thus inducing temporal dipoles. This type of induced dipole exists only when the electric field is present and occurs via electronic (displacement of electrons) or atomic (displacement of charged atoms) mechanisms known collectively as "distortion polarization".

In both cases with orientation or distortion polarization, the charges in dipoles or in induced dipoles do not cancel and, therefore, new internal electric fields are formed. Distortion polarization is temperature dependent while orientation polarization is inversely

proportional to temperature as RF active molecules must overcome the randomness from thermal excitation.

Furthermore, all polarization effects can only operate up to a limiting frequency after which if frequency increases, orientation polarization effects tend to disappear as the inertial effect of permanent polar molecules prevent reversal of their direction of motion and thus their inertial movement (i.e. momentum) cannot be overcome. The RF process is thus frequency dependent and can be optimized at certain selective frequencies matching the dielectric properties of a material (Lagunas-Solar, Zeng & Essert, 2003).

In arthropod pests, as in all biological systems, water (free and bound) and to a lesser extent proteins, lipids, carbohydrates are the major chemical constituents while mineral nutrients are at trace levels. Water is a natural permanent dipole but its degree of freedom depends on its chemical environment with free (unbound) water being the most active dipole to interact with oscillating electric fields. Bound water, on the other hand, because of its binding (coordination) with other molecules, may still be active but is somewhat restricted to respond to electric field oscillations. Proteins, including enzymes, lipids and carbohydrates are polarizable under a voltage difference and therefore become temporal induced dipoles able to experience electric field interactions and be actively involved in generating thermal energy within the material. Inorganic ions (i.e. mineral nutrients) are always charged and can be displaced by the electric fields and generate small electric currents which convert to heat through resistance (Ohm's law). Overall, although at different levels, all constituents may be actively re-oriented or displaced generating thermal energy by combination of the above different interactive mechanisms.

Although most permanent and induced dipoles are not free to drift, displacements of conduction charges or free ions under the influence of an electric field is a classical phenomenon known as ionic conductivity. Conduction effects (J_c in Amperes/m²) are related directly to both conductivity (σ in Siemens/m²) and the net electric field E (Amperes/Siemens) (Lea & Burke, 1998).

2.3 Mechanisms of RF heating

The ability to induce polarization effects in a material by an applied electric field and the creation of new, transient electric fields and currents within the material is characterized by a quantity noted as ϵ and called "dielectric constant" or "permittivity" (Klaunberg & Miklavcic, 2000). Therefore, the dielectric constant measures how easily a material is polarized to store electric energy.

However, dielectric constants are measured in relation to vacuum or air ($\epsilon_0 = 1.00000$ and 1.00054 , respectively) as they represent the ability of a material to store electric energy (i.e. capacitance) at a given voltage as compared to vacuum or air. Therefore, relative dielectric constants for a material are given by

$$\epsilon' = |\hat{E}_a| / |\hat{E}| \quad (4)$$

where ϵ' is the relative dielectric constant and \hat{E}_a and \hat{E} are the applied and the net electric field strengths (vectors), respectively.

In real practice, the ratio by which each mechanism intervenes in storing electric energy is accompanied by effective dissipation losses due to thermal excitation, inertial motions and due to the different binding forces in lattices or accompanying the RF active chemicals. These losses force molecules to lag behind the frequency of the oscillating electric field or

restrict drifting and thus resist movements of electric currents. These types of losses are represented by a relative complex dielectric constant (ϵ^*) which is given by the expression (Metaxas & Meredith, 1983):

$$\epsilon^* = \epsilon' - j \epsilon'' \quad (5)$$

In this expression, ϵ'' is a measure of the dissipation losses per cycle and is known as the “dielectric loss factor” and j is the imaginary unit. The dielectric loss factor measures the ability of a material to convert electric energy to thermal energy purely based on polarization effects (i.e. no resistance heating) and is always positive and much smaller than the relative complex dielectric constant (ϵ^*) (Mudgett, 1986; Nyfors & Vainikainen, 1989).

Both relative complex dielectric constant and dielectric loss factors are related to the absolute dielectric constant in vacuum ($\epsilon_0 = 8.85 \times 10^{-12}$ F/m). For clarity, the use of the word “relative” is omitted from this point and therefore ϵ^* , ϵ' and ϵ'' will be known simply as complex dielectric constant, dielectric constant and dielectric loss factor, respectively.

While most products have small dielectric loss factors, it increases rapidly with temperature but only slightly with pressure. However, these factors can vary drastically with operating frequencies but are independent of the applied electric-field magnitude.

Finally, dielectric constants are the factor by which a dielectric material increases the capacitance of a parallel-plate RF system (i.e. RF cavity, see section 3.1 below) in relation to its capacitance in vacuum or air under the same electric field conditions. Examples of ϵ^* values for selected materials are given in Table 1, below (Clarke, 2006). Worth noting is that ϵ^* values for codling moth (71.5; 84.5) and Mexican fruit fly (90; 141) are exceptionally high and similar to water and much larger than values for some host materials (i.e. nuts). Thus, RF disinfestation applications with nuts or similar products, selective (higher) heating of insects - as compared with heating of the host commodity, can be realized and is advantageous for effective insect control while lowering overall thermal loads applied to the host commodity. This phenomenon is further explained in section 3.5.2, below.

Material (Moisture %)	Temperature (°C)	Frequency	ϵ^*
Water	100	> 1MHz	80
Ethanol	20	10 MHz	24
Sand (dry)	20	1	2.5
Walnut (0%)	20	10 MHz	2.0
Walnut (17%)	20 (60)	10 (27) MHz	5.0 (4.9)
Almonds (5%)	20 (60)	27 MHz	5.9 (6.0)
Codling moth	20 (60)	27 MHz	71.5 (84.5)
Mexican fruit fly	20 (60)	27 MHz	90 (141)
Douglas fir (11%)	15	1 MHz/10 MHz	3.2
Compressed	15		4.3
Paper Fiber	20	1 MHz	4.5
Polyethylene (non polar)	20	50 Hz/1 GHz	2.3
Polycarbonate (polar)	20	1 MHz	3.0

(*) From: National Physical Laboratory (www.kayelaby.npl.co.uk/general_physics/2_6/2_6_5.html) and Wang et al., (2003)

Table 1. Values of complex dielectric constants for selected materials (*).

2.4 RF power dissipation as thermal power

The ability of molecules within a material to store electric energy from an operating RF system is the first step towards an effective heating process able to induce a desirable biological effect (i.e. disinfection). As indicated above, this is expressed by the complex dielectric constant which combines dielectric properties defined by molecular composition. Therefore, the conversion of RF power into thermal power is directly related to the polarization and ionic conduction mechanisms described above. However, the fractional contribution of each interactive mechanism is determined by the frequency (Hz) of the oscillating electric field.

At low frequencies, all dipole molecules (permanent and induced) have sufficient time to follow and adjust to the reversal cycles of the oscillating electric fields. In this case, no or negligible energy dissipation losses occur due to orientation polarization effects. Under this condition, the dielectric constant is at its maximum value and the dielectric material is capable of storing a maximum energy from the applied electric field. The RF heating is then mostly due to combined polarization and ionic conduction effects.

As frequency increases, dipoles gradually lose their ability to fully adjust to the oscillations in polarity of the electric field and polarization effects lag behind and contribute less to the total polarization. To minimize this lagging, the electric field transfers its energy to the dipoles forcing them to respond faster. However, this electric-field forced adjustment reaches a limit at which no further corrections occur. At this point, lags in dipolar polarization become larger forcing the dielectric constant to fall in value while dielectric loss factors increases. Under this scenario, RF heating depends less on polarization effects but more on ionic conduction effects (displacements or drifting of charged molecules and ions) leading to resistance heating. This variation in mechanism is therefore highly influenced by commodity temperature.

The total RF power dissipation into a sample is derived from the fundamental laws of electromagnetism. For a steady-state sinusoidal electric field, the time-average of RF thermal power dissipation per unit volume of the sample is given by:

$$P_v = 2\pi\epsilon_0 f \epsilon''_{\text{eff}} E_{\text{rms}}^2 \quad (6)$$

where P_v is in watt per cubic meter (W/m^3 ; or $[\text{Joules}/\text{sec}]/\text{m}^3$); f is the frequency of the oscillating electric field (Hz); ϵ'' is the dielectric loss factor and E_{rms} is the root-mean-square of the applied electric field in Volts per meter (V/m) (Metaxas & Meredith, 1983).

The total amount of heat Q (Joules) needed for a mass m (kg) of a dielectric material to increase its temperature from an initial value (T_i) to a final temperature (T_f) (i.e. $\Delta T = T_f - T_i$) is given by the classical expression

$$Q = mC_p(T_f - T_i) \quad (7)$$

where C_p is the specific heat of the material ($\text{Joules}/\text{kg}^\circ\text{C}$).

Power per unit volume in formula 6 can be combined with the energy required as given in formula 7 to provide a combined formula (formula 8) leading to RF throughput as determined with RF processing parameters:

$$mC_p(T_f - T_i)/Vt = 2\pi\epsilon_0 f \epsilon''_{\text{eff}} E_{\text{rms}}^2 \quad (8)$$

which can be expressed as

$$\Delta T/t = (2\pi\epsilon_0 f \epsilon''_{\text{eff}} E_{\text{rms}}^2)/d \quad (9)$$

where the ratio $\Delta T/t$ is the rate of heating expressed as a function of processing parameters (f , E) and the other factors are associated with the product properties (ϵ'' and d), where d (kg/m^3) is its density.

2.5 Temperature distribution and depth of penetration in RF processing

Reaching all pests in a volume of material to be disinfested is an important feature of RF disinfestation as the process must be effective over large volumes of material to assure reliable control with adequate throughputs. Temperature distribution and depth of penetration are thus important aspects that need to be considered for RF disinfestation of large volumes of commodities.

In standard volumes of boxed or palletized materials processed with a parallel-plate capacitor (see section 3, below), the intensity of the electric field is largely unaffected by the load and it contributes to similar energy absorption throughout the material. In addition, depth of penetration is an important added factor.

An electromagnetic wave incident on the surface of a dielectric material can either be reflected (i.e. reflected wave) or be transmitted into the material (i.e. transmitted wave).

In good dielectrics (including its package), a great fraction of the wave energy is transmitted but is gradually attenuated as it is converted to thermal energy. The extent (length) of the wave transmitted into the material is known as "penetration depth" (D_p) and is arbitrarily defined as the distance from the surface to the point (plane) at which its energy is reduced to e^{-1} (1/2.71 or 37%).

Because the effective loss tangent ($\tan \delta_{\text{eff}} = \epsilon''_{\text{eff}}/\epsilon'$); the penetration depth can be approximated by

$$D_p = \frac{c}{2\pi f (\epsilon')^{1/2} \tan \delta_{\text{eff}}} = \frac{c(\epsilon')^{1/2}}{2\pi f \epsilon''_{\text{eff}}} \quad (10)$$

Penetration depth (D_p in meters) is therefore proportional to the dielectric constant (ϵ') and inversely proportional to the dielectric loss factor (ϵ''_{eff}) and to the frequency of oscillation of the electric field. In general, at frequencies below 100 MHz, penetration depth is of the order of meters unless the dielectric loss factors are exceedingly high (Metaxas & Meredith, 1983). Despite its penetration, however, the energy distribution and thus the thermal profiles of the RF heated material must be taken into account when the process's efficacy requires a pre-defined or a narrow temperature range.

For disinfestation applications, however, the threshold temperature to assure lethal effects in all insects and mites at any biological stage is rather small (50-60°C) and requires a short time (< 1 min). This allows the use of RF disinfestation in large-volume containers (i.e. pallets at 2 x 2 x 2.2 m high) as material handling techniques can also be applied to improve temperature homogeneity to narrower ranges (but assuring reaching a threshold thermal load) as some limitations are expected by penetration depth factors.

However, as explained above, changes in the dielectric behavior of the load due to increased temperature (i.e. increased dielectric loss factors) induce rapid and significant changes in the fraction of the electric energy being absorbed and converted to thermal power. Unattended, these factors could lead to severe localized, uneven heating of the packaged commodity with potential loss of quality. Therefore, process controls need to be focused into

maintaining adequate RF power densities to be applied and by controlling product temperatures during the process. Besides, product geometry, package material and its geometry, and air gaps within the material clearly contribute further to different power densities being generated in their volumes and thus temperature variations are to be expected. As lethal thermal loads in insects and mites are low (50-60°C; ~ 1 min), process effectiveness is assured by reaching the relatively low lethal thermal loads needed. This occurs at levels below than those affecting quality in the host commodity and is due to the higher metabolic complexity of arthropod pests as compared with the much simpler metabolism of the host food (i.e. insects in grains) or agricultural commodity (i.e. insects in pallets).

Heat transfer and temperature distribution across a material in RF disinfestation is critical to assure effectiveness and both phenomena have been studied intensively (Giles, Moore & Bounds, 1970). In the absence of any significant mass transfer (e.g. evaporation), the temperature distribution in the medium obeys the heat diffusion law and is given by:

$$\frac{\partial T}{\partial t} = \alpha_T \nabla^2 T + \frac{\delta P}{dc_p} \quad (11)$$

where α_T is the thermal diffusivity of the medium (m^2/s), T is temperature, δP is the localized power density (W/m^3), ∇ is the Laplacian operator, d is density and c_p the specific heat (Metaxas & Meredith, 1983). The thermal diffusivity measures the ability of a material to conduct thermal energy relative to its ability to store thermal energy. Materials of large α_T will respond quickly to changes in their thermal environment, while materials of small α_T will respond more sluggishly and take more time to reach a new temperature equilibrium condition.

In RF processing, materials are usually heterogeneous, and therefore α_T plays an important role because different parts absorb RF power at different rates. For homogenous materials, α_T is less important in temperature distribution, and δP can be approximated as P_v (formula 6) for the temperature analysis. However, thermal diffusivity (or thermal mass effect) of insects and mites is not known despite the many reported studies on thermoregulation of common habitats with its surroundings. However, the rapid heating of insects with RF power (Nelson & Charity, 1972) suggests an appreciable value of thermal diffusivity for insects.

Finally, due to its direct heating effects at molecular levels, RF heating is independent of temperature differences and heat transfer coefficients, although both these factors will influence the subsequent dynamic distribution of thermal energy within the volume of the material (Hill et al., 1969).

3. Principles of RF processing

3.1 The RF cavity – A parallel-plate capacitor

In order to best realize and apply the above mechanisms in a controlled and safe RF disinfestation process, a parallel-plate capacitor is used with materials to be treated placed in between and named the “load”. The process can be performed either statically (batch mode) or continuously (conveyorized mode). This type of capacitor is known as a “RF cavity” and is shown schematically in Figure 2, below.

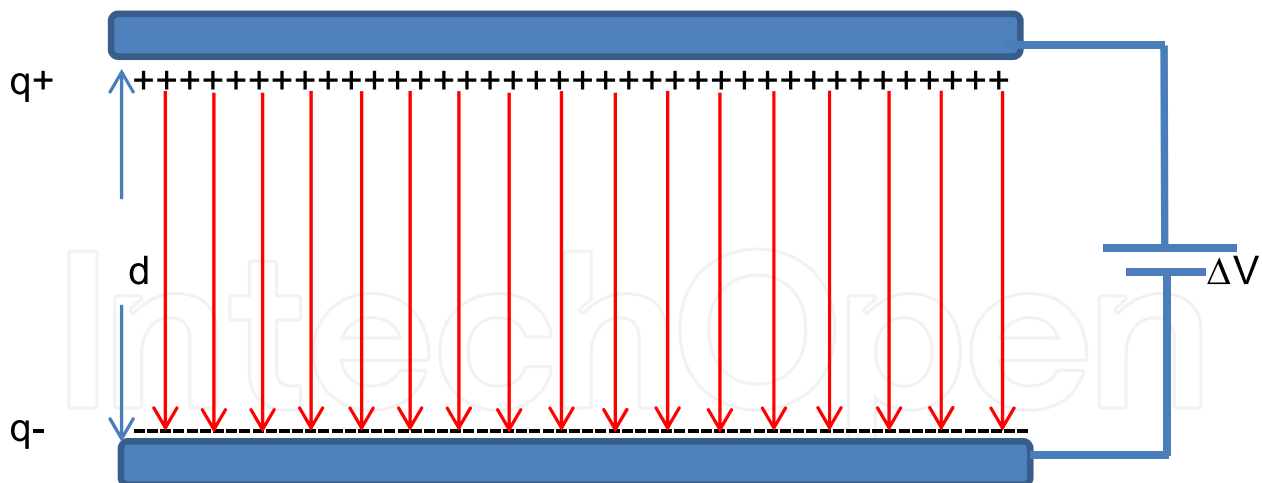


Fig. 2. A static parallel-plate capacitor (RF cavity).

The RF cavity operates with equally charged plates (top positive and bottom negative) formed when a voltage difference is applied. Electric field lines (red) are directed towards the negative (ground) plate and are equally spaced and parallel to each other. Transverse waves (not shown) are perpendicular to the electric field. When activated, however, by placing a material (load) in between, the electric field geometry is changed as field lines are distorted (i.e. fringe effects especially at low frequencies) due to the load and its package, and its intensity is decreased because of new charges created in the load. The presence of air gaps in between and on top of the packaged dielectric load also contributes to field distortion and localization effects. Therefore, an active RF cavity needs to be properly designed and managed in order to minimize the above effects and maintain field homogeneity and thus treat with adequate uniformity.

A schematic of the major features of a RF power system is shown in Figure 3, below, while a version of an operating commercial-scale prototype is shown in Figure 4.

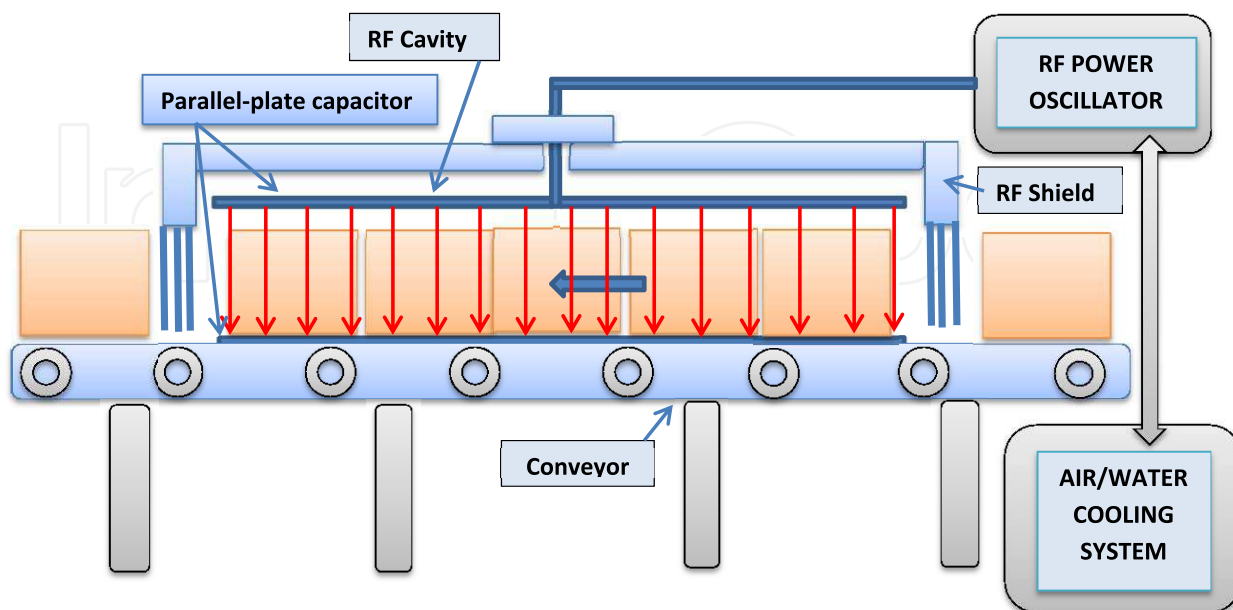


Fig. 3. Schematics of a conveyorized RF processing system.



Fig. 4. RF system for batch processing (13.15 MHz, 10 kW). Designed by UC Davis & RF Biocidics Inc.

In this latter system, the RF cavity is shielded in all directions with a metallic enclosure (shown in light blue) so as to prevent propagation or reflections of RF waves outside its boundaries and thus eliminate the potential to expose workers, the surrounding environs or interfere with other radiowaves. This basic configuration, singly or in modules, is able to operate and meet the conditions to generate and delivery RF energy safely and efficiently to food and agricultural commodities at commercial-scale levels.

The parallel-plate configuration shown in Figure 2 (above) is said to be in a static condition in which no material (other than air or vacuum) is placed in between and therefore the electric field lines are equally spaced and parallel to each other while the overall electric field is uniform except at the edges. However, when a product (load) (i.e. a dielectric) is introduced and the electric field is rapidly oscillated (changing electric polarities at every cycle) with a certain frequency, the dielectric product (load) is now capable of absorbing RF energy by a combination of the above mentioned molecular mechanisms and convert it to thermal power.

The main characteristic of RF processing (RF heating) is therefore, based on the high frequency alternating oscillating electric fields interacting with the dielectric medium (dipoles and induced dipoles) in between the plates and generating thermal energy (heat). RF heating is therefore, also known as “high frequency capacitive heating” (Piyasena et al., 2003), although as the medium in between the plates is also a dielectric material, the process is often referred as “high frequency dielectric heating” (Zhao et al., 2000).

The generation of thermal energy is due to the ability of the applied oscillating electric field to polarize and re-orient internal electric fields of charges formed in the load (material). The rotating electric field exerts torques on permanent and induced dipoles to force them into flip-flop motions. During the rapid cycling, friction and heat is generated between polarized molecules (permanent or induced dipoles) and their neighbors including lattice losses as they move. The higher the frequency of oscillations the greater is the energy available or

created to be converted to heat. However, due to lattice limitations, when the frequency is at the maximum equilibrium between rotation and inertial restrictions, it is said to be at a "Debye resonance" at which there is maximum conversion to heat. If operating frequency is beyond the ability of the molecules to react due to inertial motion, the process loses overall energy-conversion efficiency. This suggests that specific materials, due to their own unique chemical composition will present an optimal frequency at which to operate with maximum energy-use efficiency. In materials with complex or different composition (i.e. pest and host) is therefore possible to establish selective RF heating effects and establish a process with minimal energy input to the lesser dielectric component (Lagunas-Solar et al. 2006).

In addition to polarization mechanisms, a dielectric material can also be heated by the resistance to direct ionic conduction or drift mechanism as given by Ohm's law and that states that the current (I in Amperes) through a conductor between two points is directly proportional to the voltage difference (V in volts) across the two points and inversely proportional to the resistance (R in Ohms). The heating level through these mechanisms depends on the electric conductivity of the material which is generally low as dielectric (i.e. poor conductor) properties prevail.

Finally, because these mechanisms occur with equal intensity between the RF cavities (i.e. same electric field intensity) and are only dependent on the material's chemical composition, RF heating is in principle homogeneous and a volumetric (internal) method in contrast with all other surface heating methods known today. However, at a microscopic scale within biological materials, some differences do occur due to variations in chemical composition and moisture levels. These differences allow for the enhancement of the rate of heating with distinct materials and are the basis for selective RF heating effects (Zimmerman, Pilwat & Riemann, 1974).

3.2 Advantages of RF disinfestation

For disinfestation purposes, RF power provides a unique mean to heat an arthropod pest (small mass or volume) inside a host commodity (large mass or volume) volumetrically (internally) and with penetrating RF waves. This behavior is opposite to the use of conventional surface-heat methods such as infrared, dry and wet steam, or hot water where the host's surface becomes a physical barrier to the applied thermal energy. In all latter cases, the distribution of the applied heat to reach the entire volume depends on heat-transport mechanisms and time. In addition, heat is only applied at its surface. Furthermore, under these conditions, many commodities experience undesirable changes that lower product value. In contrast, because of its penetration, RF waves are effective in reaching deeply internalized pests such as eggs and larva deposited in internal cavities by borer insects, a situation in which the effectiveness of fumigants is restricted by the presence of air-locks impeding penetration of fumigants.

Radiofrequency processing is volumetric heating and its energy transfers directly to the product without the need of intermediate transfer mechanism such as conduction, radiation, or convection. This allows RF energy to be transfer to the load much faster and more effectively. The amount of input energy can be controlled by reducing the input power or switching the system on and off in order to achieve precisely the final temperature. These characteristics allow the RF process to be operated within low and high thermal boundaries, called "thermal windows". Thermal windows for RF disinfestation as compared with other biological effects (i.e. pasteurization and enzyme deactivation) are given in Figure 5, below.

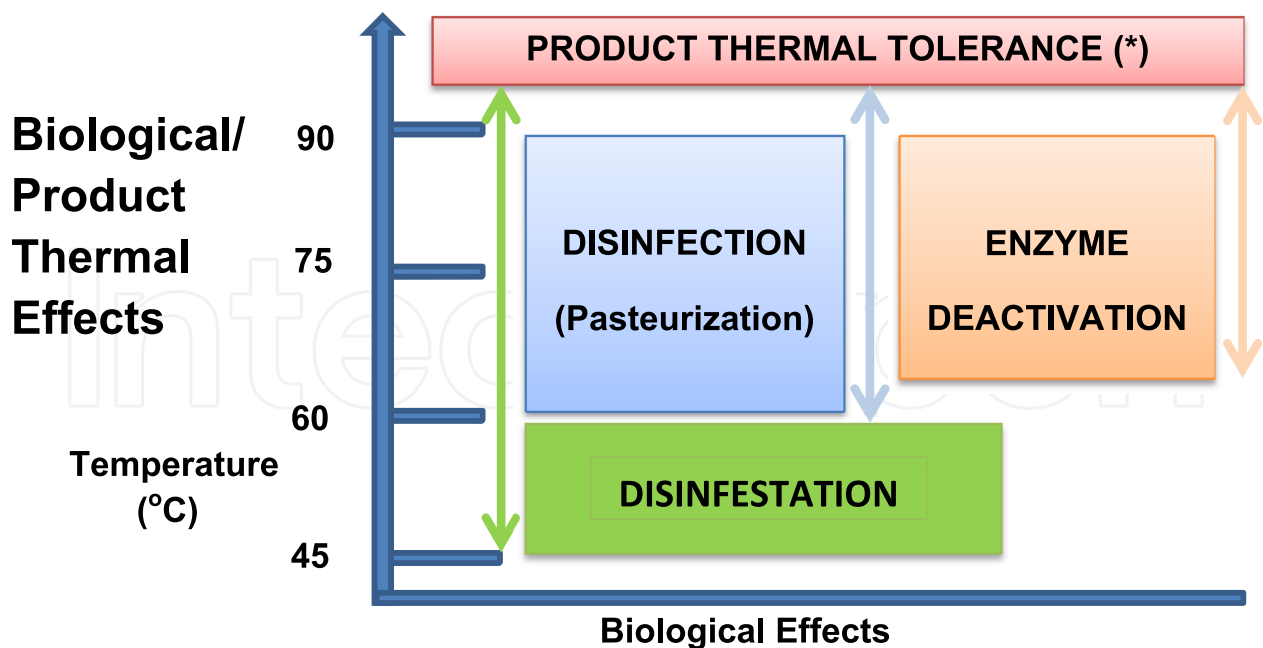


Fig. 5. Thermal Windows (colored arrows) for RF processing effects.

A thermal window represents the differential thermal sensitivity between living organisms (highly-heat sensitive) and the more heat-tolerant properties of agricultural products. Therefore, operating within a product's thermal window minimizes the impact on the host commodity. This is a critical advantage of RF processing over any conventional (surface) heating method as disinfestation effects can be well controlled because of the high sensitivity of arthropod pests to thermal energy and the higher heat tolerance of most affected foods and agricultural commodities.

By comparison with conventional heating processes, overheating the surface is very common because energy is first applied to the surface and then is conducted to its interior. Because energy loss from the surface (by radiation and/or convection) is unavoidable, significant and fast, these processes often require additional heat input on the surface in order to produce internal temperatures high enough to achieve a uniform biological effect. The host, however, received higher and usually damaging thermal loads on its surface.

As a result, the upper boundary of the thermal window (especially for the surface) is frequently exceeded causing unacceptable changes in the physiological, sensory, and quality of foods. In RF disinfestation, the surface temperature is usually lower than the internal temperature due to the heat loss from surface radiation and due to evaporation. This can be effectively prevented during RF processing by reducing evaporation (e.g. high humidity inside the chamber), by adding moisture before processing and by providing good radiation reflectors in the RF cavity design.

3.3 RF and microwave processing

Frequently, microwave heating is confused with RF heating. While fundamentally similar, microwave heating (also an energy source in the electromagnetic spectrum) is operated at 915 MHz ($\lambda = 0.3$ m) and 2,450 MHz ($\lambda = 0.1$ m), that is with higher frequency and shorter waves than RF. For most commercial scales (i.e. large amounts) of foods and agricultural products, microwave heating is not adequate also has many disadvantages in aspects of heating homogeneity, energy penetration, and energy-use efficiency. First, it does not

produce homogeneous heating because of the limited penetration of the shorter wavelength and the complex non-uniform standing wave patterns. The penetration depth of microwave is in the order of 5 cm to 10 cm for bodies with high water content, and may be higher (in several tens of centimeters) for other drier materials (Orfeuil, 1987). In addition, the electric field inside the microwave oven is not uniform due to the nature of standing waves. In fact, the enclosed electric field and power density vary with the location and the sample's shape and size. Non-uniform electric field patterns and variable power densities often lead to local (or uneven) heating in the material. Besides, the power density in microwave heating are much higher than in RF heating (due to much higher operational frequencies) and is associated with non-uniform electric fields. Therefore microwave heating normally causes local hot spots to the commodity.

In contrast, the RF process is operated at frequencies much lower than conventional microwaves hence the penetration of RF energy is greater, usually higher than 1 m and even several tens of meters at low frequencies (Orfeuil, 1987). Furthermore, the electric fields generated between two parallel plates are very uniform; therefore, RF transversal waves interact and heat the material more homogeneously (Wig *et al.*, 1999; Mitcham *et al.*, 2004).

3.4 Comparison with conventional disinfestation technologies

Today, conventional or emerging alternatives face several restrictions or their use is associated with many safety concerns many of which prompted the development of RF disinfestation as well. The contributing factors from the industry perspective are summarized below.

3.4.1 Chemical pesticides issues and concerns

Methyl bromide fumigation was for many decades the preferred treatment applied to many stored food commodities. It was used worldwide to meet quarantine and phytosanitary restrictions and quality requirements as mandated by global agriculture markets. Current alternative methods used to control insects in grains include the use of insecticides (e.g. Malathion), fumigants (e.g. phosphine, carbon dioxide) and temperature treatment (Bond, 2007).

Malathion (American Cyanamid Co., USA) is one of the safest organophosphate insecticides. Nevertheless, existing regulations demands that the treated grains should not be sold for at least 7 days nor should be eaten within 60 days after treatment to avoid potential toxic effects from residues left.

Phosphine gas is very toxic to human therefore its application requires strict controls, even though there is no residue left to the treated grains.

Other pesticides in use include Chloropicrin, 1,3-dichloropropene, Telone/Vapam, sulfaryl fluoride and hydrogen cyanide.

However, all pesticides available and those mentioned in particular are of global concern due to the potential for causing detrimental effects on animals, air, water and soil as well as potentially impacting public health and workers safety.

Conventional carbon dioxide fumigation of grains usually referred as modified atmospheres requires a lengthy treatment (i.e. days to weeks) therefore its cost is high as well as its impact on the logistics of product distribution to markets.

3.4.2 Conventional heat processing

Conventional high-temperature treatments of grains, such as hot air or hot water immersion and dry or wet steam are usually less effective to internally hidden eggs or pupae inside grain kernels. As adequate lethal temperature for insect pests need to be applied throughout the volume of the commodity, surface overheating and diminishing quality attributes usually occurs due to slow dynamics of heat transport from the outside to the core of grain kernels. Overheating also leads to the deterioration of grain quality and viability.

Because of the above, there is a clear need to develop and establish better, less or non-invasive alternatives to disinfect grains and other commodities to overcome safety concerns associated to invasive methods (leaving residues). Highly desirable is the long-stated need to reduce risks to consumers, workers and the environment as indicated by international organizations (UNEP 1998; WMO 2003).

3.5 Mechanisms of RF Disinfestation

As RF disinfestation is to initiate energy-transfer mechanisms at the molecular level, there are two possible mechanisms for the inactivation/control of insect and mites using RF power: thermal and non-thermal effects. The thermal effect of RF power is essential to the destruction of microorganisms and many studies have proven its validity (Goldblith & Wang, 1967; Fujikawa et al., 1992; Kozempel, Annous, Cook et al., 1998). The energy absorption from RF power can raise the temperature of contaminant organisms high and fast enough to induce irreversible (i.e. non repairable) biochemical damage to cells such as the denaturation of enzymes, proteins, DNA, RNA, or of other vital cellular components, as well as disruption of cell membranes (Heddleson & Doores, 1994). Reports of potential non-thermal effects (effects unrelated to heat stress) with higher-frequency dielectric heating (basically at microwave frequencies) are still controversial. While some researchers have announced these effects (Burton, 1949; Olsen, 1965; Fung & Cunningham, 1980; Cross & Fung, 1982), other researches have concluded there is little or no non-thermal effect on cells (Goldblith & Wang, 1967; Carroll & Lopez, 1969; Rosenberg & Bögl, 1987; Knutson *et al.*, 1987). However, using high-peak power RF technologies capable of delivering ultra-short pulses with very high instant power (>MW/pulse) remain as a potentially successful approach for disinfestation and in particular for fresh produce and other high-thermally sensitive commodities (Lagunas-Solar, Zeng & Essert, 2003).

3.5.1 RF disinfestation thermal effects

The cell is the fundamental unit of all living matter. Living cells (prokaryotes and eukaryotes) are basically composed of high-molecular-weight polymeric compounds (macromolecules) such as proteins, DNA, RNA, polysaccharides, lipids, and storage materials such as fats, glycogen, polyhydroxybutyrate, etc. (Madigan, Martinko & Parker, 2000). These macromolecules are only functional in the proper three-dimensional structures. The structural property is affected by thermal energy and is especially important for enzymes as they are very effective biological catalysts and involved in most of cellular reactions (Shuler and Kargi, 1992).

Because RF power generates heat at the molecular level, RF energy can effectively increase the kinetic energy of molecules and make these molecules vibrate more rapidly and violently. These molecular vibrations, up to a point, are strong enough to disrupt weak intermolecular forces, such as hydrogen bonds, salt bridges, disulfide bonds, and non-polar hydrophobic interactions in secondary, tertiary and quaternary structures of

macromolecules and denature their normal biological order and function. The most essential thermal damage that leads to cell death is the denaturation of enzymes, especially some critical enzymes responsible for DNA and RNA replications in the cell (Roti Roti, 1982). Thermal energy or heat can cause non-repairable denaturation of DNA, RNA, and sometimes create structural DNA lesions (sections of DNA contain elementary damage sites) that cause the loss of cellular genetic information (Ward, 1985).

Heat also transfers its energy to make molecules more energetic which leads to weaker hydrogen bonds and hydrophobic interactions sustaining the cell membrane, and eventually causes its disruption or collapse. The disruption of cell membrane leads to uncontrollable material exchange between the cell and its environment, which causes the cell to lose its optimum microenvironment required for its metabolisms and the cell dies eventually (Bowler & Fuller, 1987). Heat can also destroy storage materials in cells such as lipids, fats, and carbohydrates by oxidation.

Thermal energy from RF power can increase insect body temperature high enough to be lethal and destroy them (disinfestation) by causing cellular damages (i.e. cell death or dysfunctional) or body dehydration. The thermal death due to cellular damages of this multi-cellular organism is not usually the consequence of massive cell death per unit time, but it may due to the loss or disruption of cells in a certain critical tissues (Denlinger & Yocum, 1998).

Differences in species and developmental stages are also likely to influence the site of lethal thermal wounding. The more complex the biological system, the more susceptible it is to high thermal stress. Therefore, it is expected that macromolecules (e.g. proteins, DNA, RNA, lipid, fat, etc.) are more resistant to thermal stress than cellular organelles (e.g. mitochondria, nucleus, Golgi complex, etc.), cellular organelles are more resistant than cells, cells are more resistant than tissues, and tissues are more resistant than the whole organism (Ushakov, 1964; Prosser, 1986). Hence for a multi-cellular organism, lethal wounding may be inflicted from cellular damages of an organization with a high level of complexity.

The above concepts explains the prevalence of the concept "living dead" in the insect control, which means organisms are still alive but will not survive and reproduce due to cellular thermal injuries (Bowler, 1963; Chen, Lee & Denlinger, 1990). Therefore, as insect's biology is more complex than unicellular organisms (e.g. bacteria, fungi), they are expectedly more susceptible to thermal stress.

High temperature can also be lethal to insects by causing dehydration and promoting desiccation. Above a certain temperature, the critical transition temperature, the rates that insects lose water from their bodies increase dramatically (Yoder & Denlinger, 1991). Critical transition temperature values commonly range from 30 to 60°C for different species and developmental stages (Hadley, 1994). Most insects contain about 60 to 70% water in their body weights, and many can tolerate a loss of 20 to 30% of water for brief periods. The loss of water will increase the osmotic stress and concurrently increase the solute concentration within the body, presumably leading to irreversible cell damages. This also increases RF-induced ionic conduction effects in insects thus enhancing thermal energy production and thermal stress favoring lethality.

3.5.2 RF selective heating of insects

The main mechanism of disinfestation in RF selective heating is also thermal stress (i.e. heat). In the selective RF heating, a proper operating frequency is selected so that the effective dielectric loss factor (ϵ'') of the target material is close to its maximum value and

the load (material) can be heated fast. Because different materials have different dielectric properties (i.e. dielectric constant [ϵ'] and effective dielectric loss factor [ϵ'']) - both of which depend on the composition and frequency, they interact and convert RF energy into heat at different rates at the same frequency.

This leads to the potential that different materials in the same load can have different heating rates, depending on the values of their effective loss factor (ϵ'') at that frequency. If an appropriate frequency is chosen so that contaminant organisms (e.g. arthropods, arachnids) can absorb RF energy faster than host material, those organisms can be heated much faster than other components in the same load (Lagunas-Solar *et al.*, 2006; Lagunas-Solar *et al.*, 2008). As a result, insects/mites are destroyed by heat while the host commodity is unaffected. This treatment is proposed for somewhat thermally resistance fresh products (i.e. tomatoes, avocados, apples, grapes, and broccoli) which can tolerate some low thermal loads but sufficiently high to be effective for disinfestation applications using a controlled- thermal RF treatment.

While theoretically applicable to selective RF heating of microorganisms, their small size prevents adequate absorption of the penetrating RF energy waves and thus there is no evidence today for the availability of this selective mechanism for microorganisms.

Finally, the above and other technological and consumer factors prompted the investigation on the use of RF power for disinfestation of various commodities by several authors (Ikediala *et al.*, 2000; Wang *et al.*, 2003; Mitcham *et al.*, 2004; Wang *et al.*, 2007a; Wang *et al.*, 2007b). Results and conclusions of all these studies corroborated the advantages of RF disinfestation over available techniques and also helped identify remaining challenges (Prakash & Rao, 2002).

4. Case study: RF disinfestation of rough (paddy) rice

During long-term storage, insects can cause considerable damage to grains (and to other products, i.e. nuts), with weight and nutritional losses reducing yields and quality which reduces market values. Furthermore, deterioration of grains intended for seedling purposes may cause further losses in quality and viability (germination) thus affecting future yields in crop production.

Under current storage (bulk) conditions over long periods of time, the presence of even a few viable colonies of insect pests may result in the emergence of much larger populations as the storage conditions are favorable to insect reproduction and propagation due to the abundant presence of nutrients and lack of antagonistic organisms. In rough (paddy) rice, two major insects Angoumois grain moths (*Sitotroga cerealella* [Oliver]) and lesser grain borers (*Rhyzopertha dominica* [F.]) represent major threats as primary grain insects whose larvae feed entirely inside the kernel of the grain and eat from inside becoming more tolerant to fumigation as diffusion of gas into kernels is severely restricted or blocked by the presence of air locks (pockets). Therefore, infestation with primary insects are critically more damaging to stored grains than secondary insects that eat grains from outside and are more easily controlled with conventional fumigation or heat treatments.

As explained above (see section 3.5.2), selective heating of arthropod pests is feasible via a differential heating mechanism based upon the higher ionic conductivity in pests (see Table 1). Therefore, all biological stages of arthropod pests do heat faster than the host commodity leading to their effective biological inactivation (Wang *et al.*, 2003). As shown in table 1 (above), insects such as codling moths and Mexican fruit flies have large dielectric constants (ϵ'' 71.5-84.5 and 90 to 141; respectively at 27 MHz). Therefore, when treated with RF power

these pests can absorb a larger proportion of the available RF energy delivered. By comparison, the host commodity is expected to have complex dielectric constants in the range of 3 to 6 for low-moisture foods (nuts, seeds, grains) or up to 60 to 70 for high-moisture foods (i.e. fruits) although considerable higher dielectric loss factors (>200) for insects have been reported under the same processing conditions (frequency) (Ikediala et al., 2000). The difference in dielectric properties between insects and host generates lower thermal effects on the commodity (Kunze, 1979).

As arthropods (arachnids as well) have similar chemical composition, selective heating effects have been demonstrated with ants, aphids, beetles, borers, bugs, fruit flies, moths, thrips, mites and arachnids confirming the validity of the selective heating process in different food hosts as well as soil and wood products (unpublished results).

Therefore, disinfestation appears as an effective RF application that can heat arthropod pests rapidly (45 to 65°C; 3-4 min) inducing lethal conditions that are well tolerated by a large variety of foods. As proven in various laboratory-scale experimentations, this approach is being developed for commercial-scale applications with RF systems designed and engineered for full optimization.

4.1 Experimental results of RF disinfestation of rough (paddy) rice

A full control of all life cycles of Angoumois grain moths (*Sitotroga cerealella* [Oliver]) and lesser grain borers *Rhyzopertha dominica* [F.], in laboratory-scale experimentation with rough (paddy) rice as host was reported (Lagunas-Solar et al., 2008).

Samples of rough rice (13.5% and 11.0% moisture) were obtained from Pacific International Rice Mills Inc., (Woodland, CA) and were infested in separate batches (~ 10 kg each) with adult grain moth *Sitotroga cerealella* (13.5% batch) and with both *Sitotroga cerealella* and adult lesser-grain borer *Rhyzopertha dominica* (11.0% batch).

After approximately one month at 28-30°C (35-40% relative humidity) both colonies were well established showing abundant populations of all biological stages. RF disinfestation was conducted at the University of California, Davis using several processing conditions with 500 W of RF power at 20.3 MHz (Lagunas-Solar et al., 2008). Samples were treated at the same temperature (60°C) but with different times (5 and 30 min; 1 and 2 h) so as to vary thermal loads (temperature x time) delivered. Effectiveness of the RF disinfestation process was determined by assaying the emergence of adult insects found over ~40 days of periodic observations. However, as no adult insects survived any of the initial treatments, adult emergence was assumed to be due to the presence of surviving eggs, larva and/or pupas. Results from replicates in triplicate (control and treated) are shown in Figures 6 and 7, below.

The response of grain moth *Sitotroga cerealella* and lesser-grain borer *Rhyzopertha dominica* to the same RF processing conditions were different indicating that other parameters need to be considered in establishing an optimized process.

As expected, *Sitotroga cerealella* was found to be more sensitive to the RF disinfestation process as these insects are normally on the outside surface of the grain. While disinfestation effects were observed at all conditions (Figure 6), some adult emergence (~ 16%) was observed in the 60°C/5 min samples after ~40-day incubation and observation period. This was attributed to the partial survival of eggs at different eclosion stages prompting a delayed emergence of adult insects. In all other treatments (60°C/30min; 60°C/1h; 60°C/2h) the thermal loads were sufficiently high to cause a full control of all stages of *Sitotroga cerealella*, as no adult emerged in the treated samples.

Rhyzopertha dominica showed higher tolerance under the same processing conditions.

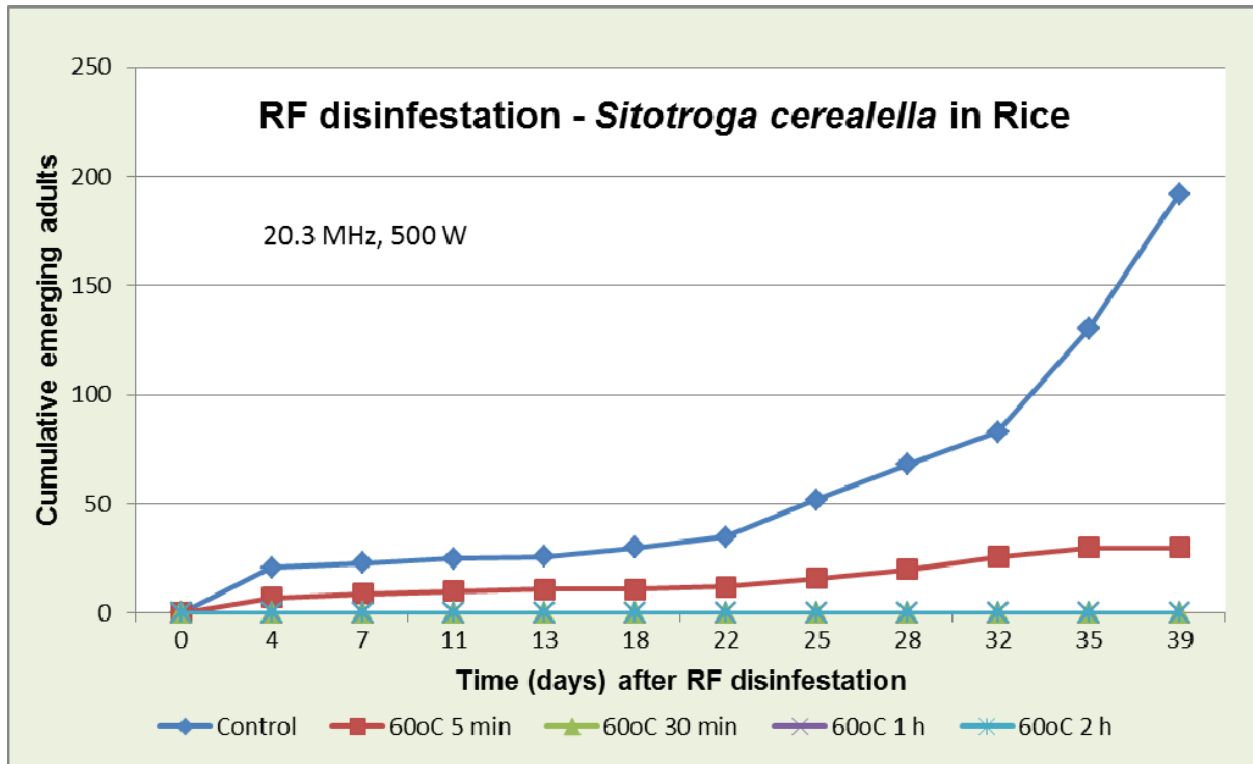


Fig. 6. RF disinfestation of *Sitotroga cerealella* grain moths in rough (paddy) rice.

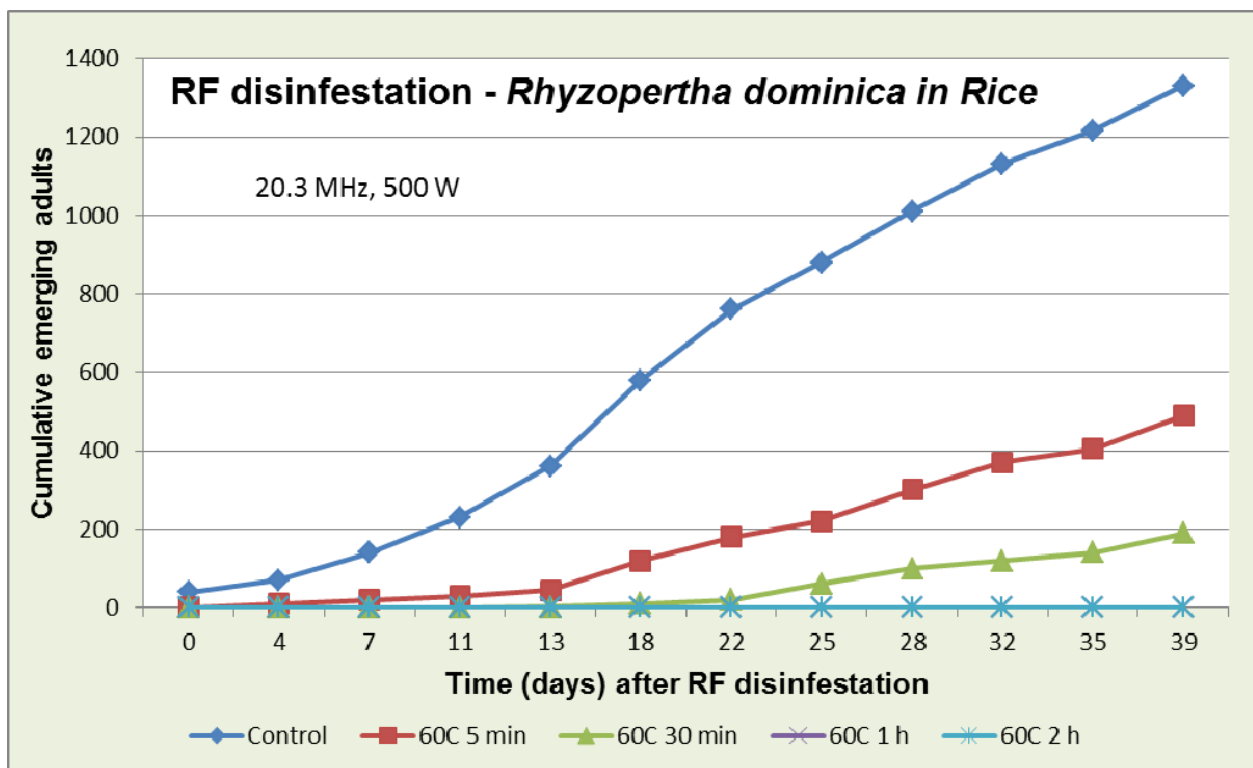


Fig. 7. RF disinfestation of *Rhyzopertha dominica* (lesser grain borers) in rough (paddy) rice.

As compared with controls (1330 adults/40 days); in the 60°C/5min batch 490 adults/40 days were observed for ~37% emergence (~63% control). As thermal load was increased, the 60°C/30 min batch showed only 190 adults/40 days (~14% emergence; 86% control). With either 60°C/1h and 60°C/2h processes, a 100% control were observed as no adults emerged during the 40-day observation period. It was concluded that the ability of *Rhyzopertha dominica* to bore into grains and deposit eggs from which larva emerged, provided additional barriers and protection due to the internalized condition of the pest.

As stated earlier, RF disinfestation is applicable under similar conditions to all arthropod pests as the interactive mechanisms utilized operate with similar molecules present in all arthropods and thus is independent from the biological speciation, developmental stages, or behavioral patterns. Optimization of the RF disinfestation process is also straightforward as thermal loads required for full control (i.e. 60°C/1h for both insects) can be achieved rapidly by increasing RF power. As only 500 W were used in previous experimentation, an operation at 10 kW would only require a 5-min processing time. Other commercial-scale conditions with increased RF power (i.e. 25-50 kW) are also possible and available (www.rfbiocidics.com) for processing larger throughputs (> 2-4 tons/h) while taking full advantage of this emerging chemical-free alternative.

4.2 Quality attributes of host commodity

The application of RF power in disinfestation applications should also consider the potential effects of the applied thermal load to the host commodity. Therefore, the potential for changes of quality attributes in RF treated rough (paddy) rice was also studied and the results are summarized in Table 2, below. These measurements were conducted using standard commercial laboratory tests and indicated no adverse effects.

Rough (paddy) rice samples				
Quality attributes (%)	Controls	Batch 1 (50°C)	Batch 2 (60°C)	Batch 3 (70°C)
Moisture	13.5 ± 0.1	13.5 ± 0.1	13.5 ± 0.1	13.5 ± 0.1
Whole kernel	79.3 ± 1.1	81.1 ± 7.9	78.3 ± 0.1	77.9 ± 0.8
Total rice	68.1 ± 0.3	68.3 ± 0.1	68.2 ± 0.1	68.0 ± 0.1
Dockage	16.9 ± 4.8	11.7 ± 1.0	12.4 ± 1.6	13.2 ± 1.7
Brown rice	81.1 ± 0.4	81.1 ± 0.4	81.3 ± 0.2	81.3 ± 0.1
Whiteness	44.2 ± 0.2	44.1 ± 0.2	44.2 ± 0.2	44.3 ± 0.3
* Mean values and standard deviations for triplicate measurements with 1-kg samples. Data courtesy of California Rice Association.				

Table 2. Quality attributes of RF disinfested rough (paddy) rice*

5. RF process economics

Commercial application of RF disinfestation is already taking place on various commodities and is combined with simultaneous disinfection (pasteurization) and enzyme deactivation effects.² This combination of desirable and simultaneous sanitation effects is unique to RF processing and is only dependent on the applied thermal loads (see Figure 5, above). In

² RF Biocidics Inc., Vacaville, CA 95688 USA (www.rfbiocidics.com)

addition, and because of its penetration, RF power is capable of processing commodities in its package (boxes, bags) thus avoiding recontamination and facilitating logistics of operation. Therefore, due to its chemical-free nature and to the combined effects, RF processing offers many advantages over single-effect technologies including those based upon applications of conventional surface-heat sources (i.e. dry or wet heat, vapor, steam, etc.). Despite its unique advantages and multiple controlling effects, the current commercial application of RF disinfestation is priced competitively in comparison with the cost of using chemical pesticides or any other physical process.

As a new and emerging option for sanitation of foods and agricultural commodities, RF operating facilities are being established to operate at or near high agriculture production areas or near key distribution centers and facilities in which RF processing can be part of the overall chain of production and distribution for local, regional and overseas markets.

6. Conclusions

The application of RF power to disinfestation provides a rapid and effective chemical-free alternative capable of replacing the use of chemical and biological pesticides and as alternative to other conventional heating processes during post-harvest management of various foods and agricultural commodities. As a physical, electricity-based process, its operation is based on well-known, designed and engineered systems capable of safe and large-scale applications. Disinfestation efficacy requires reaching a relatively low thermal-load level as RF is a volumetric heating process with interactions and heating effects starting at the molecular level and somewhat selectively. It can be readily applied to arthropods and arachnids with equal effectiveness using thermal loads well below the threshold for impacting host's quality.

The RF process - with similar and even higher thermal loads, has been demonstrated at a commercial scale for various different commodities including nut products (no effects on free fatty acids, peroxide values), other grains (Quinoa, edible seeds (Chia, pumpkins, sunflower), spices (paprika, cumin, cardamom, nutmeg, coriander, etc.) and flours (brown rice, oat, wheat, flaxseed). Therefore, RF disinfestation is an emerging process with broad applications to many potentially infested commodities and can even be extended to disinfest some heat-tolerant fruits and vegetables as the required thermal load is low and the RF disinfestation process is rapid.

Furthermore, additional energy-use savings can be realized as less RF energy would be needed to control insects (a very small load) as compared with the larger mass (load) represented by the commodity. It is postulated that this approach would result in significant operational cost reductions for RF-based disinfestation applications of a variety of foods such as grains, nut products, flours, beans, spices, and agricultural commodities such as wood products (pallets), soil and soil amendments, and tobacco.

As the needs for non-chemical (residue-free), non-thermal technologies for disinfestation (and disinfection as well) continues to be a goal in production agriculture, a new non-thermal, residue-free process named metabolic stress has recently emerged and is soon to initiate commercialization (Lagunas-Solar, Essert, Piña et al., 2006b; Lagunas-Solar & Essert, 2011). Metabolic stress, singly or in combination with RF processing, is expected to overcome some of the limitations of RF disinfestation and be able to treat commercial levels of thermally-sensitive commodities in particular fresh fruits and vegetables.³

³ RF Biocidics Inc., (www.rfbiocidics.com)

Finally, because of its nature, RF disinfestation can be applied to conventionally- and organically-produced food commodities.

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It is our hope that this book will be of interest and use not only to scientists, but also to the food-producing industry, governments, politicians and consumers as well. If we are able to stimulate this interest, albeit in a small way, we have achieved our goal.

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