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**Review Paper**

# RADIO FREQUENCY AND MICROWAVE ALTERNATIVE TREATMENTS FOR INSECT CONTROL IN NUTS: A REVIEW

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## Abstract

A major problem in the production, storage and marketing of nuts is the infestation of insect pests such as codling moth, naval orangeworm and Indian meal moth. Present and potential quarantine treatments for both domestic and international nut markets include chemical fumigation, ionizing radiation, controlled atmosphere, cold treatment, conventional hot air or water heating and dielectric heating using radio frequency (RF) and microwave (MW) energy. Based on the brief review of the above six methods, a comparison about their properties was carried out. An innovative technique using RF and MW heating treatments was proposed as an alternative quarantine treatment in nuts. The practical future application in industry should be possible after solving their problems of high cost, non-uniform heating and quality damage.

***Keywords***: *Radio frequency, microwave, quarantine, nut disinfestation, insects*

## 1. INTRODUCTION

Nuts growers in the United States (U.S.) play an important role in the world nut production, supplying approximately two-thirds of the world nut trade. Almonds, walnuts and pecans are the three major nuts grown in the continental U.S. California is the leading state in U.S. producing more than 99% nuts with a value of $1.47 billion per year (USDA, 1999). Nuts have become increasingly popular products for consumers due to nutrition advantages over cereal products.

A major problem in the production, storage and marketing of nuts is the infestation of insect pests, such as the codling moth (*Cydia pomonella*), navel orangeworm (*Amyelois transitella*), and Indian meal moth (*Plodia interpunctella*). Larvae of codling moths are targeted by quarantine regulations in Japan and South Korea, and navel orangeworm is of phytosanitary concern for Australia. The Indian meal moth is a common pest of stored nuts and is the insect most often responsible for consumer returns and complains. These three pests reduce the product quality by direct damage through feeding and by producing web and textile.

Postharvest control of insects in nuts is essential for quarantine regulations in many countries. The traditional treatment is chemical fumigation due to low cost, fast speed in processing and ease of use. Because of concerns about the health hazards of chemical pesticides and its environment pollution, research has been conducted on the ionizing radiation, controlled atmosphere, cold treatment, conventional hot air or water heating and novel radio frequency (RF) and microwave (MW) dielectric heating for controlling nut insects. Currently, the use of chemical fumigation continues and efficient uses of RF and MW methods for nut insect control are still to be accepted. The objectives of this review were to increase the systematic information on the insect control for nuts, to analyze the different properties of chemical, ionizing radiation, controlled atmosphere, cold treatment, conventional heating and dielectric heating methods by detailed comparisons and to prospect a tendency of possible practical application of RF and MW methods for nut insect control in the future.

# 2. TREATMENT METHODS

## 2.1 Chemical Fumigation

Chemical fumigation has two distinguish advantages for postharvest control in nuts, including ease of use and low cost. Most postharvest pest management programs, therefore, rely heavily on fumigants, and most processing systems are designed to allow for fumigant treatments. Since hydrogen phosphide fumigation takes a relatively long time (Yokoyama et al., 1993), methyl bromide (MeBr) fumigation has become a common phytosanitation treatment because its treatment is usually under 3 hours, and it is used to control codling moths in cherries (Guance et al., 1981; Maindonald et al., 1992; Moffitt et al., 1992), in nectarines (Yokoyama et al., 1987; 1990), in watermelons (Cowley et al., 1991) and in unshelled walnuts (Hartsell et al., 1991).

When used in commodity fumigation, MeBr gas is injected into a chamber or under a tarp containing the commodities. About 80 to 95% of the MeBr used for a typical commodity treatment eventually enters the atmosphere (USEPA, 1998). However, MeBr is identified by the U.S. Environmental Protection Agency (EPA) as having high ozone depletion potential (Anonymous, 1995). The U.S. has signed an international accord, known as the Montreal Protocol, to ban the MeBr use to protect the earth's atmosphere. The EPA has mandated the removal of MeBr from chemical registration and the phase out of its production in U.S. by December 31, 2005. Therefore, an alternative quarantine treatment is urgently required to replace this chemical fumigation.

## 2.2 Ionizing Radiation

Irradiation treatment is a process to expose infested commodities to ionizing radiation so as to sterilize, kill, or prevent emergence of insect pests by damaging their DNA. This method includes three types of ionizing radiation used on foods: gamma rays from radioactive cobalt-60 and cesium-137, high energy electrons, and x-rays. The gamma ray method is one of most commonly used in postharvest pest control because of the gamma ray's ability to deeply penetrate pallet loads of food (Morrison, 1989). Some researches showed that irradiation levels as low as 0.30 kGy were effective in controlling plum curculio, blueberry maggot, cherry fruit flies and codling moths, without altering overall fruit quality (Johnson and Vail, 1988; Drake et al., 1994). Because these doses do not cause immediate kill of treated insects, a particular concern for radiation treatments is the possibility of inspectors or consumers finding live insects in treated product.

Major problems for irradiation begin with the substantial initial investment per site to establish irradiation facilities, including a radiation shield control system and other auxiliary equipment. Such an investment requires continuous operation of the facility to remain economically feasible, but the seasonal nature of commodity treatments prevents efficient use of facilities. Consumers also have concerns for disposal of radioactive wastes, the safety of the irradiation technology and its effect on food.

## 2.3 Controlled Atmosphere Treatments

Controlled atmosphere (CA) has been used for many years to extend commodity shelf life. CA has been used for many years for the control of stored product insects in grains and nut crops (Fleurat-Lessard, 1990), and research has demonstrated its efficacy for fresh commodities (Mitcham et al., 1997). In general, $O_2$ concentrations must be below 1% and $CO_2$ concentrations must be above 20% for insect control (Zhou et al., 2000). For most applications, however, CA treatments require long exposures. For example, Johnson et al. (1998) used a 2 day purge time followed by a 6 day exposure to 0.5% $O_2$ to disinfest walnuts of navel orangeworm. This long treatment time may not be acceptable for some markets. To be able to certify and ship the quantities needed for the vital European market, optimal treatment time should be 24 hour. In addition, prolonged exposure to low $O_2$ has detrimental effect on some fresh fruits.

## 2.4 Cold Treatments

Chilled aeration has been used as a means to slow the development of insect pest populations within stored grains, and given sufficient exposure times, may effectively disinfest the product (Maier, 1994). Cold storage treatments have also been developed for quarantine purposes and for use against exotic fruit flies and other insects (Gould, 1994). Cold treatments may take several weeks to be effective, and thus work best when incorporated into existing storage or shipping regimes. Cold storage has been combined with other treatments such as hot air and water heating, and is an important component in existing quarantine treatments for codling moth on apple. While effective in some situations, its use is limited because of the lengthy treatment times required to kill insects, and the high costs associated with building and maintaining refrigerated storage.

## 2.5 Conventional Heating

Conventional heating methods are increasingly being used to provide an alternative treatment of the chemical fumigation, which include forced hot air and hot water treatments. Since the heat mechanism is simple and the process can be easily controlled, many studies on different fruit types and insect species have been carried out using different thermal treatments alone or in combination with cold or controlled storage conditions (Sharp et al., 1991; Toba and Moffitt, 1991; Moffitt et al., 1992; Sharp, 1993; Neven, 1994; Neven and Rehfield, 1995). To be effective, the fruit core must reach certain temperatures so that the treatment is effective even in the most insulated areas, such as inside nuts or into the center flesh, seeds and kernels. Slow heating rates by forced hot air or water result in a long treatment time (Hansen, 1992).

Table 1 shows the heating time to reach the core temperature obtained by experiments with different medium temperatures, heating methods, and fruit types. Forced hot air is usually used to treat nuts because hot water heating results in unacceptable moisture content, greater than 6% for storage (Tang et al., 2000). The core temperature is lower than the medium temperature and is close to the medium value at maximum after a long heating time. The heating duration for the core to reach the medium temperature reported in Table 1 varies from 23 min to 360 min, which is mainly dependent on the fruit size (Wang et al., 2001b). Such heating methods are limited due to heat convection from the medium to the surface and heat conduction from the surface to the fruit core. The heating time can be slightly decreased by increasing the air speed and using small fruits. The slow heating process takes long treatment times to kill the insects. For example, Soderstrom et al. (1996) showed that a 39°C treatment took about 730 h to obtain probit 9 quarantine security which provides 99.9968% insect mortality. Furthermore, external and internal damage caused by heat over long exposure times included peel browning, pitting, poor color development and abnormal softening (Lurie, 1998) and prolonged heating may not be practical in industry applications. Therefore, RF and MW heat treatments have been proposed to reach the same level of insect mortality at a shorter time.

Table 1: Temperature characteristics of conventional heating methods

| Medium temp., °C | Heating methods | Fruit types | Speed, $ms^{-1}$ | Core temp., °C | Needed time, min | Sources |
|---|---|---|---|---|---|---|
| 40 | Hot air | Apple | 1 | 40 | 360 | Whiting et al. (1999) |
| 44 | Moist air | Apple | 2 | 42 | 97 | Neven et al. (1996) |
| 45 | Hot air | Tangerine | 2 | 44 | 60 | Shellie & Mangan (1996) |
| 45 | Hot air | Cherry | 2 | 44 | 23 | Neven & Mitcham (1996) |
| 48 | Hot water | Small Potato | 2 | 48 | 140 | Hansen (1992) |
| 48 | Hot water | Large Potato | 2 | 48 | 220 | Hansen (1992) |
| 48 | Hot water | Grapefruit | 2 | 48 | 155 | Hansen (1992) |
| 50 | Hot air | Mango | 2 | 48 | 150 | Mangan & Ingle (1992) |
| 52 | Hot air | Mango | 2.5 | 39 | 75 | Sharp et al. (1991) |
| 52 | Hot air | Grapefruit | 2 | 48 | 90 | Shellie & Mangan (1996) |

## 2.6 Dielectric Heating

Dielectric heating is a term that covers both RF and MW systems which are high frequency electromagnetic waves generated by magnetrons and klystrons. When the material with water molecules is subjected to an electromagnetic field that rapidly changes direction, the water molecules rotate into alignment with the direction of electrical field. The water molecular friction produces the internal heat of the material. The frequency in a range of 12 MHz-2450 MHz is usually used in food engineering. Dielectric materials, such as most agricultural products, can store electric energy and convert electric energy into heat. The increase in temperature of a material by absorbed electromagnetic energy can be expressed by (Nelson, 1996):

$$\rho\, C_p \frac{\Delta T}{\Delta t} = 55.63 \times 10^{-12} f\, E^2 \varepsilon'' \qquad (1)$$

where $C_p$ is the specific heat of the material ($J.kg^{-1}.°C^{-1}$), ρ is the density of the material ($kg.m^{-3}$), E is the electric field intensity ($V.m^{-1}$), f is the frequency (Hz), ε'' is the dielectric loss factor (-) of the material, Δt is the time duration (s) and ΔT is the temperature rise in the material (°C). From Eq. (1), the raise in temperature depends on the power, frequency, heating time and the material's dielectric loss factor. Higher temperatures in commodities can be achieved by long heating duration and high power input. If the dielectric loss factor is relatively constant, rapid dielectric heating using higher frequencies can be achieved with much lower field intensities. However, the frequency interacts with the dielectric loss factor where the latter variable is a function of the frequency, temperature and water content of the material.

Electromagnetic energy has been studied to control insects in commodities for many years. Initial investigations using RF heating to control pests of grain and nuts were conducted by Frings (1952), Thomas (1952) and Nelson (1966; 1973). Hirose et al. (1970) studied the use of dielectric heating (2450 MHz) for controlling tobacco moth larvae. A recent study demonstrated the possibility of using 2450 MHz MW to destroy woodworms by heating the larvae to 52-53 °C for less than 3 minutes (Andreuccetti et al., 1994). Hallman and Sharp (1994) summarized RF and MW treatments that destroyed selected pests in many postharvest food crops. Nelson (1996) summarized more than five decades of research on the susceptibility of various stored grain insect species to RF and MW treatments.

Table 2 briefly presents main RF and MW treatments under different conditions and insects at different temperatures. Since the congested bands of RF and MW have already been used for communication purposes, the Federal Communications Commissions (FCC) allocated five frequencies for industry, scientific and medical (ISM) applications: 13.56, 27.12 and 40.68 MHz for RF, 915 and 2450 MHz for MWs. Higher temperature was used for stored grain than for fruits. The product quality after RF and MW treatments was rarely examined. More recently, Ikediala et al. (1999) and Wang et al. (2001a) reported that MW and RF treatments might have particular advantages over conventional heating methods in treating cherries and walnuts, because the desired level of insect mortality was achieved without quality damage.

Table 2: Reported radio frequency and microwave heat treatments for different products and insects at various temperatures

| Frequency, MHz | Temp., °C | Product (Insect) | Quality | Sources |
|---|---|---|---|---|
| 27 | 56 | Wheat (weevil) | No | Anglade et al. (1979) |
| | 53 | Walnut (codling moth) | Yes | Wang et al. (2001a) |
| 40 | 80 | Pecan (weevil) | No | Nelson and Payne (1982) |
| 915 | 55 | Cherry (codling moth) | Yes | Ikediala et al. (1999) |
| 915 & 2450 | 50-60 | Cheese (microorganism) | Yes | Herve et al. (1998) |
| 2450 | 45 | Papaya (D. dorsalis) | No | Hayes et al. (1984) |
| | 50 | Fruit (Fruit fly) | Yes | Sharp et al. (1999) |
| | 57 | Wood (woodworm) | No | Andreuccetti et al. (1994) |
| | 80 | Cereal (weevil) | No | Shayesteh & Barthakur (1996) |
| 12000-55000 | 43-61 | Wheat (weevil) | No | Halverson et al. (1996) |

RF energy penetrates deeper than MWs in fresh fruits and nuts because of its longer wavelength. Based on RF heating theory and dissipated power calculations in Eq. (1), the absorption of RF energy is proportional to the dielectric loss factor of the materials. The dielectric loss factor is clearly different between codling moth larvae and walnut kernels, especially in the RF range (Fig. 1). The dielectric loss factor of the insects was much higher than that of walnuts, as found by Nelson (1991) for weevil and wheat. Codling moth larvae might absorb more energy than walnuts when subjected to the same electromagnetic fields, which may lead to preferential heating of insects (Ikediala et al., 2000a). The unexpected complete kill with 3 min RF treatment can be explained by preferential heating of codling moth larvae infesting the walnuts (Wang et al., 2001a). An attractive feature of the insect control using the electromagnetic field is the possibility that the insects may be heated at a faster rate than the product they infest. If this phenomenon can be proved, the insects would reach a high lethal temperature while the product would be heated only to temperatures below the quality limit.

RF and MW treatments have particular advantages over conventional hot air heating in treating walnuts in shells. The shell and the void (air spaces) in the shell act as layers of insulation and slow down heat transfer with conventional heating methods, while electromagnetic energy directly interacts with the kernel inside the shell to generate heat. Fig. 2 shows typical temperature-time profiles for in-shell walnut kernel during hot air treatment (53°C at 1 m/s air velocity) followed by forced room air cooling (22°C at 1 m/s air velocity). With hot air treatment, the heating rates decreased as the product temperature approaches the medium temperature, resulting in prolonged heating time of more than 40 min. The kernel temperature lags significantly behind that of the void and hot air temperatures, increasing very slowly with treatment time once it reaches within about 10°C of the air temperature. The small thermal conductivity of the porous walnut shell and the in-shell void hinders the transfer of thermal energy from the hot air outside of the walnut shell. The walnut kernel temperature can reach 52°C approximately 10 fold faster when they are exposed to RF than to hot air.

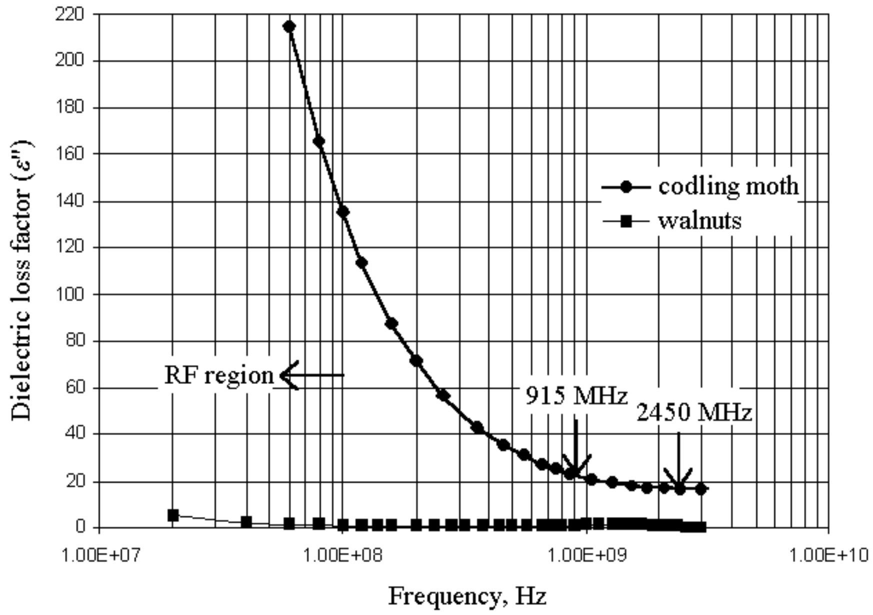

Fig. 1: Dielectric loss factor (ε'') of codling moth larvae and walnuts as a function of frequency.

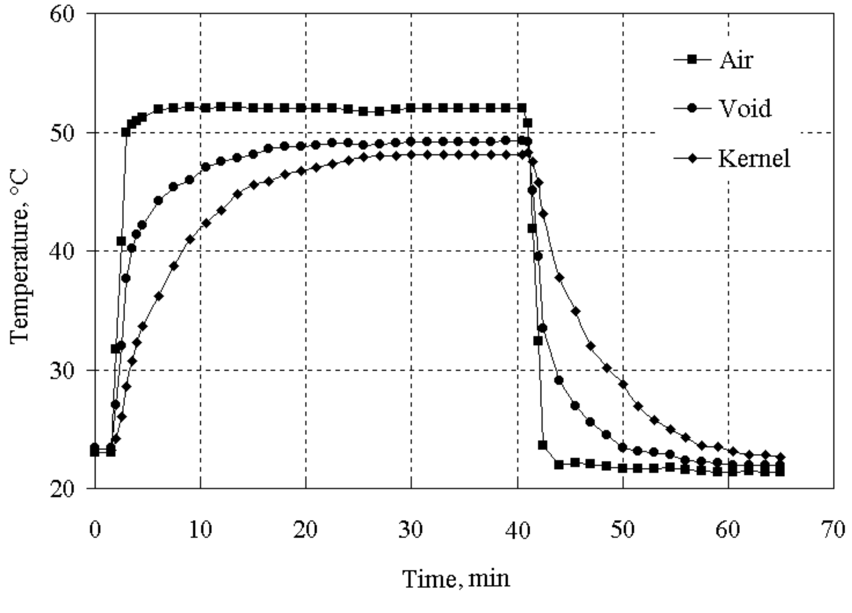

Fig. 2: Heating and cooling curves for in-shell walnut kernel when subjected to forced hot air (air temperature, 53 °C; air velocity, 1 m/s) treatment.

The short treatment time makes it possible to design continuous treatment processes to allow processing of large quantities of products in a short period of time, a tremendous advantage over batch-type fumigation or conventional heating. Continuous processes also reduce labor cost and use of space, and cause less mechanical damage to the commodities as a result of significantly reduced handling steps, as compared to traditional batch fumigation processes. RF can also be used in combination with other operations to reduce treatment times and modernize handling processes. For example, in-shell walnuts are currently fumigated by MeBr in tanks upon arrival to a storage facility or processing plant. The walnuts are then washed and dried in bins. These processes take 10-12 hrs, and walnuts are dropped into bins several times, which leads to cracking of shells. It is possible to combine RF treatment for control of insect pests with RF drying to reduce the whole process time to 15-20 min in a continuous process, thus, significantly reducing process time, space, and quality loses.

RF and MW energies leave no chemical residues on products. These processes are safe to operators and have little impact on the environment. However, dielectric heating treatments for practical industry applications have a long way to go due to the high energy cost, the uneven heating and the quality damage. Therefore, further studies should be performed to solve these problems.

# 3. TENDENCY TOWARD FUTURE RESEARCHES

## 3.1 Combination of RF and MW Treatments with Controlled Atmosphere

RF and MW treatments are similar to other conventional heat treatments in that the targeted insects in host commodities are killed thermally. An important key to the development of acceptable alternative thermal treatments is to identify a delicate balance between minimized thermal impact on product quality and complete killing of insects. A clear understanding of the thermal resistance of treated insects is essential.

Codling moth larvae are the main insects found in walnuts. The 5th instar is the most heat resistant stage of codling moths (Yokoyama et al., 1991). Table 3 shows a summary of reported 5th instar codling moth mortality. Different experimental methods were used to test the thermal resistance of codling moths. Water bath methods could not truly reflect the intrinsic insect resistance to heat due to insect drowning. Heating rate was not given in most studies but was believed to have a significant effect on insect mortality (Neven et al., 1996). It is observed that higher temperatures need generally shorter time to reach 100% mortality.

It is reasonable to describe a 100% mortality curve and a safe quality curve as a function of temperatures for different agricultural products (Fig. 3). The treatment region between the two curves may exist though they will be non-linear. The suggestion can be proposed to make the mortality carve as low as possible. CA environment is also believed to have significant effects on insect mortality at high temperatures (Soderstrom et al., 1990; 1996; Toba and Moffitt, 1991; Whiting et al., 1991; Neven et al., 1996). This is because reducing $O_2$ and increasing $CO_2$ reduces the vitality of insects and increasing temperature increases insect metabolism and demand for $O_2$, further reducing the thermal resistance of insects in CA. The treatment region between the quality and mortality curves will be increased by means of optimal heating rate and controlled atmosphere.

Table 3: Thermal tolerance of 5th instar codling moths

| Temp., °C | Medium | Heating method | Time, min for 100% mortality | Heating rate, °C/min | Sources |
|---|---|---|---|---|---|
| 45 | 15 ml vials | Water bath | >55 | No report | Yokoyama et al. (1991) |
| | 0.48 l jars | Walk-in chamber | 1440 | No report | Soderstrom et al. (1996) |
| | Infested cherry | Test chamber | 60 | 4.4 | Neven & Rehfield (1995) |
| | Infested cherry | Test chamber | 124 | 1.66 | Neven & Mitcham (1996) |
| 46 | 15 ml vials | Water bath | >55 | No report | Yokoyama et al. (1991) |
| | Apples | Test chamber | 480 | 4 | Neven & Rehfield (1995) |
| | 7.5 vials | Water bath | 97 | No report | Neven et al. (1996) |
| 47 | 15 ml vials | Water bath | 25 | No report | Yokoyama et al. (1991) |
| 48 | 15 ml vials | Water bath | 10 | No report | Yokoyama et al. (1991) |
| | 7.5 ml vials | Water bath | 177 | No report | Neven et al. (1996) |
| | 7.5 ml vials | Water bath | 73 | No report | Neven et al. (1996) |
| 49 | 15 ml vials | Water bath | 7.5 | No report | Yokoyama et al. (1991) |
| 50 | 15 ml vials | Water bath | 4 | No report | Yokoyama et al. (1991) |
| 51 | 15 ml vials | Water bath | 3 | No report | Yokoyama et al. (1991) |
| 52 | Metal surface | Heating block | 2 | 20 | Ikediala et al. (2000b) |

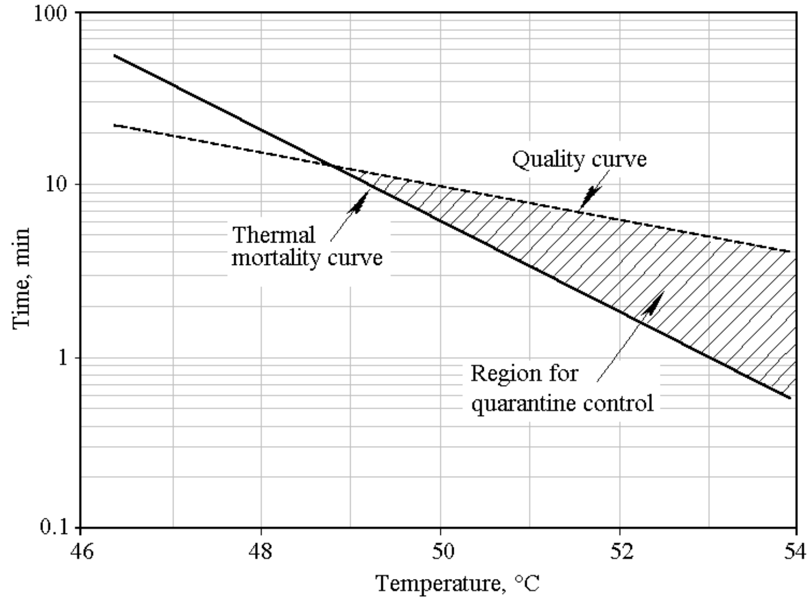

Fig. 3: Acceptable time-temperature treatment area obtained from different mortality and quality curves

## 3.2 Prediction of Temperature Fields

Experimental data for different commodities and insect species are essential using RF and MW treatments and experimental results are very important to validate simulation models. Compared to the simulation methods, laboratory experiments using RF and MW systems take a long time to obtain individual information and are difficult to repeat under the same conditions. A clear and systematic understanding of RF and MW treatments may rely on the theoretical solution (Burfoot et al., 1996; Fleischman, 1999). On the other hand, improving the design procedures for RF and MW heating systems should lead to an efficient engineering approach to optimize design parameters based on the prediction of electric and magnetic fields and temperature distributions in commodities.

Maxwell's equations are usually used to predict the three components of electromagnetic fields. Navier-Stokes equations are successfully used to predict temperature and gas component distributions in the three-dimensional domain based on the mass and energy conservation. Up to now, large differences between measured and predicted temperatures were found at some locations in RF treatments. To solve such a problem, experimental data about the dielectric properties of commodities, geometry definitions of the simulated space and boundary conditions should be primarily required to validate the simulation results. The most important thing is to combine effectively the Maxwell's equations with Navier-Stokes equations. By using highly developed computing facilities, simulation models can help design practical RF and MW treatments.

## 3.3 Practical Industry Applications

Laboratory and pilot-scale RF and MW test systems are essential for developing treatment protocols. Optimal information can be found easily using small-scale experiments, however, this phase of study should be in close collaboration with the nut industry and equipment manufacturers. It is important to transfer from laboratory research to large-scale industrial implementation. Rapid RF and MW treatments can be designed as a continuous flow process to allow large quantities of products passing in a short period of time. Since the nut quantity is limited to reach the fast heating rate by the designed power for RF oscillators, the treated nut layer thickness should be taken into account. Enough coupled power has to be obtained to maintain the treatment speed.

The well-established commercial RF and MW operations for textile and wood drying may be extended for nut insect control. Over four hundred continuous industrial process lines have been installed in U.S. Such a technology can serve as a basis to design a continuous operation with conveyor belts transporting multi-layer products through a MW cavity or between two RF plate electrodes. Since the specific heat capacity of nuts is small (about 2 $kJ.kg^{-1}.K^{-1}$), the energy requirement for heating these products from room temperature to 55°C will be relatively small (0.025 $kW\ h.kg^{-1}$). Typical RF and MW systems have an overall energy efficiency of 60 to 80%. The energy efficiency can be increased by using the waste heat from generators for concurrent surface heating of nuts to kill surface pests on the outside of the shell.

Therefore, it is possible to provide the industry with an effective, rapid and environmental friendly nut insect control process.

## 4. Conclusions

Quarantine security for international markets is very important for nut industry in U.S. Current and alternative quarantine treatments involve chemical fumigation, ionizing radiation, controlled atmosphere, cold treatment, conventional hot air or water heating and dielectric heating. Because of MeBr chemical fumigation being phased out by 2005 in U.S. and the disadvantages of the other potential methods, RF and MW heat methods are proposed as an alternative to control insects in nuts during a short time period without product quality damage. This method is an attractive quarantine treatment because it is quick and safe, and operation costs are comparable to chemical fumigation.

Three future research projects were suggested to make potential RF and MW heating methods practical in nut industry. The acceptable heat treatment region should be extended by optimal heating rates and controlled atmospheres which may be used to make the mortality curve as low as possible. Accurate simulation methods for full-scale temperature fields have to be developed so as to produce a clear and systematic understanding of RF and MW treatments. It is useful to improve and optimize design parameters for RF industry and manufacturers so that laboratory and pilot-scale RF and MW test systems are transferred to large-scale industry implementation. With careful design and the background about well-established commercial RF and MW processing lines in food industry, it is possible to provide the nut industry a rapid, viable, efficient and competitive treatment that meets quarantine security needs.

## LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| KGy | A unit of absorbed irradiation dose which is defined as the gray (Gy).<br>So 1 kGy=1000 Gy= 1000 Joule per kilogram. |
| $C_p$ | Specific heat of the material, $J.kg^{-1}.°C^{-1}$ |
| ρ | Density of the material, $kg.m^{-3}$ |
| E | Electric field intensity, $Vm^{-1}$ |
| f | Frequency, Hz |
| ε″ | Dielectric loss factor of the material |
| Δt | Time duration, s |
| ΔT | Temperature rise in the material, °C |
| CA | Controlled Atmosphere |
| DNA | Deoxyribonucleic Acid |
| EPA | Environmental Protection Agency |
| FCC | Federal Communication Commission |
| ISM | Industrial, Scientific, and Medical applications |
| MeBr | Methyl bromide |
| MW | Microwave |
| RF | Radio frequency |

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