WHEAT DISINFESTATION USING MICROWAVE ENERGY

BY

VADIVAMBAL RAJAGOPAL

A Thesis
Submitted to the Faculty of Graduate Studies in
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ABSTRACT

Infestation of grain by insects is usually controlled using insecticides. Use of insecticides results in chemical residues left in the food which may have adverse effects on humans. Another limiting factor for using an insecticide is that insects develop resistance to them. Microwave disinfestation offers an alternate way to disinfest grain. The use of microwaves to kill insects is based on the dielectric heating effect produced in grain which is a relatively poor conductor of electricity

An industrial microwave system operating at 2.45 GHz was used to determine the mortality of three common types of stored-grain insects namely *Tribolium castaneum* (Herbst), *Cryptolestes ferrugineus* (Stephens) and *Sitophilus granarius (L.).* Wheat samples (50 g each) at 14 and 16% moisture content (wet basis) were infested with 5, 10 and 15 adult insects. The infested samples were then exposed to microwave energy at four different power levels 250, 300, 400 and 500 W for two exposure times of 28 and 56 s. Mortality of 100% was achieved for all the three adult insects at 500 W for an exposure time of 28 s and at 400 W for an exposure time of 56 s for both 14 and 16% moisture content wheat. The mortality was lower at the lower power levels. For instance, for *T. castaneum* at 250, 300 and 400 W and exposure time of 28 s, the mortality was 45, 58 and 85% for 14% moisture content wheat. There was a significant difference in the mortality of *T. castaneum* and *C. ferrugineus* at 14 and 16% m.c wheat but there was no significant difference in the mortality of *S. granarius*. For all the insects mortality increased with increasing power and exposure time. Larval and pupal stages of *T. castaneum* were also treated with microwave energy. There was no significant difference

between the mortality of larvae and pupae of *T. castaneum* but the mortality of adult is significantly different from larval and pupal stages

Germination tests were conducted for samples treated at different power levels and exposure time. Germination of wheat kernels were lowered after treatment with microwave energy. Milling and baking test were done for the samples at which 100% mortality was obtained. There was no significant difference in the quality of grain protein, flour protein, flour yield, flour ash and loaf volume of the wheat treated with microwave energy.

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1. INTRODUCTION

1.1 Canadian wheat production and wheat loss

Canada is the largest producer of high protein milling wheat in the world although it is only the seventh largest wheat producing country. Wheat continues to be Canada's largest crop in terms of both area seeded and production. Wheat is the single largest earner of export revenue of all agricultural products, with annual exports worth about $3.8 billion. Most Canadian wheat is grown in the prairie provinces of Saskatchewan, Alberta and Manitoba (Agriculture and Agri-Food Canada 2004). In western Canada, wheat production is dominated by Canada Western Hard Red Spring (CWHRS) and Canada Western Amber Durum (CWAD) with smaller production of Canada Prairie Spring (CPS), Canada Western Red Winter (CWRW), Canada Western Soft White Spring (CWSWS) and Canada Western Hard White (CWHW).

Most of Canada's production of hard red spring wheat is used for the production of pan breads. Approximately 1.5 Mt of medium and high protein CWHRS wheat is used domestically (Agriculture, Food and Rural Development 2001). Over the five year period from 1997-2001, CWHRS production averaged 15.4 Mt, making up 62% of all wheat produced in Canada. The Canadian domestic milling and baking industry is the single largest market for CWHRS wheat, accounting for over 2.5 Mt annually, as all bread flour produced in Canada is from CWHRS wheat (Agriculture and Agri Food Canada 2002).

Harvested crops are stored on-farm or in commercial grain handling facilities, like primary and terminal elevators. In Canada, grain is mainly stored on-farm (Sode et al. 1995). Maintaining quality and quantity are the main criteria for safe storage. Canada has a zero tolerance for pest insects in stored-grain for human consumption. If a stored product insect is detected in a wheat sample, the grain is termed infested and the grain must be treated to kill the insects (Canada Grain Act 1975).

It is estimated that annual losses of cereal grains due to insects and rodents are about 10% in North America and 30% in Africa and Asia, but higher losses and contamination often occur locally (Hill 1990). Economic losses due to insects and microorganisms in grain have been estimated to be around one billion dollars per year in the United States (Brader et al. 2000). Since losses of grain due to insect infestation are very high, disinfestation of grain is very important for the safe storage of grain.

The stored-grain insects affect not only the quantity of grain but also affect the quality of grain. Insects consume grain and also contaminate it with their metabolic by-products and body parts. Insect infested flours are unacceptable in the baking industry for aesthetic reasons and health concerns to the consumers. Changes in chemical compositions such as increase in moisture, non-protein nitrogen content, and a decrease in pH and protein contents in the wheat are caused by insect infestations (Venkatrao et al. 1960).

1.2 Various methods of insect control

The various methods of insect control can be grouped as physical, biological and chemical methods. The implementation of an insect-control program requires a thorough appreciation of all the elements of an infestation problem: the insects; their age, species and distribution; their survival and developmental rates under different environmental conditions; and the various chemical and non-chemical methods available.

1.2.1 Physical methods

Insects in stored grain can be controlled by manipulating the physical environment or applying physical treatments to the grain and insects. Physical methods to control insects include different types of traps (probe traps, pheromone traps), manipulation of physical environment (Sinha and Watters 1985), mechanical impact, physical removal, abrasive and inert dusts and ionizing radiation (Muir and Fields 2001). The physical variables that are usually manipulated are temperature, relative humidity or grain moisture content, and relative composition of atmospheric gases in the intergranular air spaces. Low temperatures are usually obtained by aeration with cool ambient air. Methods to obtain high grain temperatures are more diverse, including: microwaves, infrared, hot air and dielectric heating. Controlled atmosphere techniques involve changing the carbon dioxide, oxygen and nitrogen content of storage atmospheres to render them lethal to insects (Banks and Fields 1995). Physical control methods tend to be slow and some may not give high levels of mortality even when well managed. They can be used where the infestation is low. Microwave disinfestation is a physical method to control insects in stored-grain.

There is a renewed interest in physical control methods even though most of these methods may be more expensive and not as effective in eliminating or preventing an infestation as chemical treatments (Muir and Fields 2001). The resurgence in interest in physical control is a result of the increasing restrictions on the use of chemically-based control programs.

1.2.2 Biological methods

The biological method is to use living beneficial organisms, as natural enemies, to control pests. There are many approaches to biological control of pests in stored products, including the use of predatory insects and mites, parasitoids and species specific pathogens. Unlike chemicals that need to be applied to a wide area, natural enemies can be released at a single location and they find and attack the pests in a grain mass. There are no chemicals involved and these methods do not pose serious risk to the consumers or to the environment. But the biological method also has some disadvantages.

1.2.2.1 Drawbacks of biological control methods

Biological control agents are usually species specific. Since most infestation comprises multiple species, several different isolates or species of biological control agents may be needed. Biological control methods act slowly and consequently much damage may occur before control is effective. It is not usually suitable for dealing with heavy infestations (Subramanyam and Hagstrum 2000). Currently, little expertise or infrastructure exists to supply control agents or support the use of biological control methods.

1.2.3 Chemical method

The chemical method uses insecticides and pesticides to kill the insects. Pesticides are among the most commonly used chemicals in the world, and among the most dangerous to human health. The chemicals used to control insects in the bulk stored-grains and cereal processing industries comprise two classes namely, contact insecticides and fumigants. Contact insecticides kill insects when they contact treated surfaces or respire gas molecules. Some of the commonly used insecticides are malathion, pirimiphos-methyl, chlorpyrifos-methyl (Sinha and Watters 1985). Fumigants are gaseous insecticides applied to control insects in grains and processed foods that are inaccessible by contact insecticide. Some of the commonly used fumigants are methyl bromide and phosphine (Sinha and Watters 1985). Methyl bromide is involved in the depletion of the atmospheric ozone layer. Hence it has been banned effective 2005 in developed countries, except for quarantine purposes (Fields and White 2002). Many alternatives have been tested as replacements for methyl bromide, from physical control methods such as heat, cold and sanitation to fumigant replacements such as phosphine, sulfuryl fluoride and carbonyl sulfide (Fields and White 2002).

Among the physical, chemical and biological control methods, the chemical method is widely used to control insects (Sinha and Watters 1985). Chemical control methods are essential for efficient production and preservation of food products. For the past three decades, efforts have been devoted to the study of possible alternative insect control methods that might be helpful in minimizing the environmental hazards associated with chemical insecticides (Nelson and Stetson 1974). Many effective insecticides have been banned for health and environmental reasons and only a few new insecticides have been developed to replace them.

1.2.3.1 Drawbacks of chemical control methods

A major limiting factor for using insecticide is that insects develop resistance to insecticides. A world-wide survey of stored-product insects revealed that 87% of 505 strains of the red flour beetle, *Tribolium castaneum*, collected from 78 countries were resistant to malathion (Sinha and Watters 1985). In several countries where malathion resistance is a severe problem, other control methods such as alternative insecticides, fumigants or physical control methods have to be substituted. Even though insecticide and fumigants are applied with care and in limited quantity, there is a possibility of these chemicals remaining in the food grains and having adverse effects on humans. These chemicals also have a hazardous effect on the environment. Phosphine is increasingly used as a treatment to replace methyl bromide but the major drawback with phosphine is the rapid increase in insect resistance to this compound (Taylor 1994, Fields and White 2002).

1.3 Objectives

The objectives of this research were:

1. To determine the mortality of the adult rusty rain beetle, *Cryptolestes ferrugineus* (Stephens) and granary weevil, *Sitophilus granarius* (L.) in wheat at two different moisture content 14 and 16%, four different power levels 250, 300, 400 and 500 W, at two exposure time 28 and 56 s, and at three levels of infestation 5, 10 and 15 insects per 50 g of sample.
2. To determine the mortality of the larvae, pupae and adult stages of red flour beetle, *Tribolium castaneum* (Herbst) at different variables cited above.
3. To conduct a germination test on wheat subjected to microwave energy to determine the effect of microwave power on germination.
4. To perform a quality analyses on wheat subjected to microwave power to determine if there are any detrimental effects on the flour quality.

2. LITERATURE REVIEW

2.1 Biology of stored grain insects

The most common stored-grain pests in Western Canada are *T. castaneum* and *C. ferrugineus* Other stored-grain insects are *Sitophilus oryzae* (L.), *Sitophilus granarius*, *Plodia interpunctella* (Hubner) and *Oryzaephilus. surinamensis* (L.), *Rhyzopertha dominica* (Fabricius) (Sinha and Watters 1985). Most stored-product insects have a wide range of food habits and they can feed on several different dry food products. This wide range allows them to move from one food product to another during storage and transportation leading to cross-infestations and residual infestations. The distribution of insects in bulk grain is typically non-uniform and is determined by gradients of temperature and moisture, distribution of dockage and broken grain, and insects inter and intra-species interactions (Muir and White 2001).

2.1.1 *Tribolium castaneum*

Tribolium castaneum is commonly called the red flour beetle and it is a secondary grain feeder. *Tribolim castaneum* feeds on grain germ, broken kernels, grain products, and grain flour (Lhaloui et al. 1988). The red flour beetle is found across Canada, mainly in bins where grain is stored for long periods, such as farm silos and country elevators. It prefers damaged grain, but will attack whole wheat, feeding first on the germ and then on the endosperm (Agriculture Canada 1981 Sheet No.75). The red flour beetle lays eggs in the grain bulk and it spends its entire cycle outside the grain kernels.

Each female lays 300 to 400 eggs and egg-laying occurs when the temperature is over 20°C. Development from egg to adult takes 15 to 20 d under optimum conditions, a temperature of 35°C and relative humidity ranging between 70 and 90%. The red flour beetle will fly when the temperature is 25°C or higher, so the infestations can spread quickly.

2.1.2 *Cryptolestes ferrugineus*

Cryptolestes ferrugineus is called the rusty grain beetle and it is a common pest in farm granaries and storage elevators in Canada. They are secondary grain feeders and cannot penetrate sound grain kernels. Hence, they feed on exposed germ, broken, and damaged seeds. Heavy infestations of the insects also contribute to other damage by causing the grain to heat and spoil and by spreading fungal spores in the stored grain.

Each female is capable of laying 200-500 eggs which are deposited loosely on or among the grain kernels and hatch in 3 to 5 d in a temperature of 30°C. Under conditions of 15% grain moisture content and temperature of 32°C, the transition from egg to adult beetle takes about four weeks (Agriculture Canada 1981 Sheet No.78). The optimum temperature and relative humidity for the development of *C. ferrugineus* is 32-35°C and 70-90%, respectively (Smith 1965). Rusty grain beetles can tolerate very cold temperatures of -15°C for 2 weeks and low relative humidity (Sinha and Watters 1985).

2.1.3 *Sitophilus granarius*

Sitophilus granarius is called the granary weevil and attacks small grains and hard cereal products. The insects feed on the kernels, leaving only the hulls, and a severe infestation can reduce stored grain to a mass of hulls and frass. The female lays about 150 eggs during its life time of 7 to 8 mo. The female drills a small hole in the kernel, deposits an egg in the cavity and seals the hole with a gelatinous secretion. The legless larva completes its growth, pupates and develops into an adult weevil within the kernel. Because most of the insect's life cycle occurs inside the kernel, an initial infestation is difficult to detect. Infestation can start at temperatures as low as 15°C but optimum development takes place at about 30°C and at a relative humidity of 70% (Agriculture Canada 1981 Sheet No.80)

2.2 Microwaves

2.2.1 Properties of microwaves

Microwaves are electromagnetic waves with frequencies ranging from about 300 MHz to 300 GHz and corresponding wavelength from 1 to 0.001 m (Decareau 1985). Microwaves are invisible waves of energy that travel at the speed of light, 3×10^8 m/s. In the electromagnetic spectrum, microwaves lie between radio frequencies and infrared radiation. From the broad range of microwave frequencies available, a few are designated for industrial, scientific and medical applications (ISM). As a result, utilization of specific microwave frequencies comes under the regulations of the Federal Communications Commission (Copson 1962). For all practical purposes industrial applications are carried out at 915 MHz in the USA, 896 MHz in the UK and 2450 MHz worldwide (Mullin

1995). Since early 2002, a higher frequency of 5.8 GHz is available for industrial purposes (Linn and Moller 2003; Suhm et al. 2003). Microwaves are reflected by metals, transmitted through electrically neutral materials such as glass, most plastics, ceramics and paper, and absorbed by electrically charged materials (Decareau 1972; Mullin 1995).

2.2.2 Principle of microwave heating

Microwave heating is based on the transformation of alternating electromagnetic field energy into thermal energy by affecting polar molecules of a material. All matter is made up of atoms and molecules and some of these molecules are electrically neutral but many are bipolar. When an electric field is applied the bipolar molecules tend to behave like microscopic magnets and attempt to align themselves with the field. When the electrical field is changing millions of times per second (915 or 2450 million times per second), these molecular magnets are unable to withstand the forces acting to slow them. This resistance to the rapid movement of the bipolar molecules creates friction and results in heat dissipation in the material exposed to the microwave radiation (Brygidyr 1976). Biological material placed in such radiation absorbs an amount of energy which depends on the electrical characteristics of the material and heat is produced. In general, the higher the moisture and oil content the more energy is absorbed and the more heat is generated.

Microwaves are not heat. Microwave fields are a form of energy and microwaves are converted to heat by their interaction with charged particles and polar molecules, their agitation is defined as heat (Buffler 1993). The most important characteristic of microwave heating is volumetric heating which is different from conventional heating

(Xiaofeng 2002). Conventional heating occurs by conduction or convection where heat must diffuse from the surface of the material. Volumetric heating means that materials can absorb microwave energy directly and internally and convert it into heat. The conversion of microwave energy to heat is expressed by the following equation (Mullin 1995; Linn and Moller 2003):

$$P = 2\pi E^2 f \varepsilon_0 \varepsilon'' V$$

Where P = power, W

E = the electric field strength, V/m

f = the frequency, Hz

ε_0 = the permittivity of free space, F/m

ε'' = the dielectric loss factor

V = volume of the material, m^3

2.2.3 Advantages of microwave heating

The most important advantage of microwave heating is the shortening of processing time by 50% and more. The quality of product is good compared to conventional heating. The processing capacity is greater. Microwave heating requires smaller floor space when compared to other methods (Dench 1973, Mullin 1995). Better hygiene of the working environment is maintained. Heating can be immediately started or stopped by automatic control. In microwave heating operational cost is lower and also easier and faster maintenance is possible (Dench 1973, Thuery 1992). Conventional heating using coal or fossil fuel may give out smoke which affects the environment by causing pollution. By using microwave heating, environmental stress is reduced (Dench 1973). Heat generated by microwave energy occurs principally in the product, not in the oven walls or atmosphere. Therefore, heat losses from the oven to the surroundings are much lower, making for more comfortable working temperatures (Dench 1973, Mullin 1995). Fast start-up and shut-down and precise process control are possible in microwave heating (Mullin 1995).

2.3 Application

The applications of microwaves fall into two categories, depending on whether the radiation is used to transmit information or just energy. The first category includes terrestrial and satellite communication links, radar, radio astronomy, microwave thermography, material permittivity measurements and so on. In all cases, the transmission link incorporates a receiver whose function is to extract the information that in some way modulates the microwave signal. In the second category of applications, there is no modulating signal but the electromagnetic wave interacts directly with certain solid or liquid materials known as lossy dielectrics, among which water is of particular interest (Thuery 1992). The second category of applications as related to agricultural industries is discussed.

2.3.1 Microwave grain drying

Microwave drying of grain is fundamentally different from either convection or conduction drying (Shivare et al. 1993). The microwaves have the distinct advantage in drying as the heat is generated within the food material by reorientation of the dipoles which in turn cause molecular friction and generate heat (Decareau 1985). Microwave drying helps to remove the moisture content from the food products without the problem of case hardening (Schiffman 1986 cited by Walde et al. 2002).

Campana et al. (1986, 1993) studied the effect of microwave energy on wheat and the physical, chemical and baking properties of dried wheat. They reported that the total protein content was not affected even by heating to 91°C in a microwave dryer, but germination and wet gluten content were progressively affected by temperatures above 60 and 66°C, respectively. They concluded that protein content was not affected, but the functionality of gluten was altered gradually with increasing exposure time.

Walde et al. (2002) conducted studies on the effect of the microwave power supply on drying and grinding, and microwave power was found to have an effect on grinding characteristics. The structural and functional characteristics of wheat protein-gluten were changed. The functionality of gluten was altered which was observed by the absence of elasticity and stretchability of the dough made from the grain. This showed that microwave drying of wheat would not be suitable where the final products made out of the flour were required to be soft in textural characteristics.

2.3.2 Microwave drying of fruits and vegetables

Drying is one of the oldest methods of food preservation and it is a difficult food processing operation because of undesirable changes in the quality of the dried product. High temperature and long drying times, required to remove the water from the sugar-containing fruit material in conventional air drying, may cause serious damage to the flavor, color, and nutrients, and a reduction in bulk density and rehydration capacity of the dried product (Lin et al.1998; Drouzas et al. 1999). Major disadvantages of hot air drying of foods are low energy efficiency and lengthy drying time during the falling rate period (Maskan 2000).

In recent years, microwave drying has gained popularity as an alternative drying method for a wide variety of food products such as fruits, vegetables, snack foods and dairy products. Several food products have been successfully dried by the microwave-vacuum application or by a combined microwave assisted-convection process: cranberries (Yongsawatdigul and Gunasekaran 1996a), carrot slices (Lin et al. 1998), model fruit gels (Drouzas et al. 1999), potato slices (Bouraout et al. 1994), carrots (Prabhanjan et al.1995), grapes (Tulasidas et al. 1996), apple and mushroom (Funebo and Ohlsson 1998), and banana (Maskan 2000).

A combination of hot air and microwave energy improves the heat transfer compared to hot air alone. Several experiments have reported microwave-assisted hot-air drying experiments with foodstuffs, where considerable improvements in the drying process have been evident: apple and potato (Huxsoll and Morgan 1968), banana (Garcia et al. 1988), carrot (Torringa et al. 1993 cited by Funebo and Ohlsson 1998). The improvements are described as better aroma, faster and better rehydration than hot-air drying, and much shorter drying times (Funebo and Ohlsson 1998).

Microwave drying is rapid, more uniform and energy efficient compared to conventional hot air drying. Microwave drying requires only 20-35% of the floor space as compared to conventional heating and drying equipment. However microwave drying is known to result in a poor quality product if not properly applied (Yongsawatdigul and Gunasekaran 1996a; Adu and Otten 1996). It has also been suggested that microwave energy should be applied in the falling rate period or at low moisture content for finish drying (Prabhanjan et al. 1995; Funebo and Ohlsson 1998). The reason for this is essentially economic. Due to high cost, microwave can not compete with conventional air drying. However, microwaves may be advantageous in the last stages of air drying.

Maskan (1999) studied the drying characteristic of 4.3 mm thick banana slices by using the following drying regime: convective (60°C at 1.45 m/s) until equilibrium was reached, microwave (350, 490, and 700 W) until the material reached a constant weight, and convection until the point where drying slowed down followed by microwave (at 350 W) finish drying. The drying of banana slices took place in the falling rate drying period. Higher drying rates were observed with the higher power level. Microwave finish drying reduced the convection drying time by about 64.3%.

Hot air, microwave and hot air-microwave drying characteristics of kiwi fruits were studied by Maskan (2000). Drying rates, shrinkage and rehydration capacities for these drying regimes were compared. The drying took place in the falling rate period. Shrinkage of kiwifruits during microwave drying was greater than during hot air drying. Less shrinkage was observed with hot-air microwave drying. Microwave-dried kiwifruit slices exhibited lower rehydration capacity and a faster water absorption rate than when the hot air and hot-air microwave drying methods were used.

Vacuum microwave drying offers an alternative way to improve the quality of dehydrated products. The low temperature and fast mass transfer conferred by vacuum (Yongsawatdigul and Gunasekaran 1996a), combined with rapid energy transfer conferred by microwave heating, generates very rapid, low temperature drying. Moreover, the absence of air during drying may inhibit oxidation, and therefore, color and nutrient content of products can be largely preserved. Yongsawatdigul and Gunasekaran (1996b) reported that vacuum microwave dried (VMD) cranberries had redder color and softer texture as compared to the hot air dried cranberries. Petrucci and Clary (1989 cited by Lin et al. 1998) also indicated that the contents of vitamin A, vitamin C, thiamin, riboflavin, and niacin in dried grape were largely preserved during vacuum microwave drying.

Lin et al. (1998) made a comparative study of vacuum microwave drying of carrot slices to air drying and freeze drying on the basis of rehydration potential, color, density, nutritional value, and textural properties. Vacuum microwave dried carrot slices had higher rehydration potential, higher alpha-carotene and vitamin C content, lower density, and softer texture than those prepared by air drying. Carrot slices that were air dried were darker, and had less red and yellow hues. Less color deterioration occurred when vacuum-microwave drying was applied. Although freeze drying of carrot slices yielded a product with improved rehydration potential, appearance, and nutrient retention, the

VMD carrot slices were rated as equal to or better than freeze dried samples by a sensory panel for color, texture, flavor and overall preference, in both the dry and rehydrated state.

2.3.3 Seed germination enhancement

Some seeds do not germinate even under optimum conditions. This can be ascribed to the permeability of the shell, the immaturity of the embryo, the presence of inhibitors, and a lack of heat or light. These factors allow the seed to remain in the dormant state until all conditions for growth are favorable. Exposure to 650 W, 2.45 GHz microwaves for about 30 s is sufficient to ensure a high rate of germination by some mechanism that is not as yet fully understood. The microwaves seem to act on the strophiola, a sensitive part located on the ventral side of the seed, which may thus become more water permeable. The effect of the radiation varies according to the species: clover, peas, beans, and spinach respond favorably whereas wheat, corn, and cotton are less sensitive (Thuery 1992).

2.3.4 Soil treatment

Vegetable tissue is very sensitive to the thermal effect of microwaves. The use of microwaves instead of herbicides for the destruction of unwanted seeds and parasitic plants has been under investigation since the early 1970s by the USDA Agricultural Research Center (Welasco, Texas). The aim was to destroy, before sowing, all undesirable grain and shoots. The first prototype applicator for soils "Zapper", could be described as a four wheel trailer carrying four 1.5 kW generators operating at 2.45 GHz and connected by means of flexible guides to four antennas forming a square shaped assembly. The first trial with the zapper produced very good results for grass, parasitic fungi and nematodes (Thuery 1992).

Effect of microwave radiation on soil nitrification and respiration was studied by Wainwright et al. (1980). According to them a 20 s exposure to 2.45 GHz microwave radiation had a marked differential effect on the viable count of soil micro-organisms, had little influence on numbers of heterotrophic bacteria, but reduced fungal colonies. The growth of fungi from soil particles was reduced following treatment. Microwave radiation was investigated as a controlled biocidal treatment which could selectively kill microbial biomass. Fungi were more susceptible to irradiation than bacteria (Speir et al. 1986).

The advantages of using microwaves for soil disinfestation are rapid heat transfer, selective heating, compactness of the equipment, speed of switching on and off and a pollution-free environment as there are no products of combustion. A major obstacle prohibiting the use of microwaves for soil disinfestation is the large amount of energy required to obtain sufficient results. Mavrogianopoulos et al. (2000) conducted an experimental study on the effect of initial soil temperature and soil moisture on energy consumption by application of microwaves for soil disinfestation. It was concluded that humidity of the soil and the initial soil temperature are critical for a low-cost use of microwaves for soil disinfestation and a combination of solarization and microwaves was proposed as an energy efficient technique of using microwaves for soil disinfestation.

2.3.5 Crop protection

Experiments on crop protection by microwaves have been carried out on the McGill University experimental farm, Ste. Anne de Bellevue, QC. A 2.4-kW generator operating at 2.45 GHz was kept on top of a 2-m high tower and the field was irradiated. The study was conducted when there was a cold northerly wind and the temperature was between -1 and -5° C. The storm resulted in the deposition of snow on the plants to a depth of 1.3 cm in certain parts of the plant. After 60 h, 10% of the plants were dead, but on the whole the crop had been remarkable well protected. Though this trial was not repeated, this was potentially a very interesting application. An increase in temperature by just a few degrees, produced by this technique, could prevent crop losses worth several millions of dollar (Thuery 1992).

2.3.6 Microwave disinfestation of grains

Stored grain is often infested with different insects whose larvae develop at the expense of the grain, reducing its quality and leading to significant mass loss. Microwave disinfestation is possible because insects do not readily tolerate high temperatures. For disinfestation of grain by microwaves, the radiation must penetrate the grain without significant attenuation and that the dielectric loss factor of the insects be significantly greater than that of the medium (Thuery 1992).

2.3.6.1 Principle of microwave disinfestation

The use of microwaves for killing insects is based on the dielectric heating of insects present in grain, which is a relatively poor conductor of electricity. Since this heating depends upon the electrical properties of the material, there is a possibility of advantageous selective heating in mixtures of different substances (Hamid et al. 1968, Nelson 1972). In a mixture of dry food stuffs and insects, it is possible to heat the insects to a lethal temperature because they have high moisture content while leaving the drier foodstuff unaffected or slightly warm (Hurlock et al. 1979). Insects that infest grain, cereal products, seed and other stored products, can be controlled through dielectric heating by microwave or lower radio frequency energy. Raising the temperature of infested materials by any means can be used to control insects if the infested product can tolerate the temperature levels that are necessary to kill the insects.

2.3.6.2 Earlier experiments on microwave disinfestation

Hamid et al. (1968) conducted experiments for detection and control of *Tribolium confusum, Sitophilus granarius and Cryptolestes ferrugineus* in samples of wheat and flour. The penetration and mortality tests were conducted in a screened room with microwave absorbing material placed such as to absorb power not dissipated in the sample. The required exposure times for 90% mortality of the three species in wheat were approximately 30, 30 and 18 s, respectively. The corresponding exposure time for 90% mortality of *T. confusum* in wheat flour was 37 s. They concluded that bulk heating is not feasible when the depth is greater than 0.1 m (4 inches). However, if wheat is passed in thin layers on a conveyor belt, then a satisfactory mortality of insects can be achieved in a reasonable time and at a reasonable cost.

Hamid and Boulanger (1969) presented a method for the control of *Tribolium confusum* by microwave heating with an output power of 1.2 kW at 2.45 GHz. Samples of insects were scattered in small plastic containers filled with wheat and allowed to pass through the wave guide. Temperature measurements were made inside the container of bulk wheat. For *Tribolium confusum*, 70% mortality was obtained when the grain temperature was 55°C and 100 % at 65°C. To determine the effects of high frequency radiation on the milling and baking qualities of wheat, three samples were heated to 55, 65, and 80°C and compared with control samples. There was no effect on the milling quality or protein content of the wheat. But the bread making quality was affected deleteriously and progressively, as the treatment temperature was increased. The effects were similar to those produced by improper drying of grain. They suggested the use of lower-frequency power source to improve the efficiency of drying and disinfestation of grain.

Boulanger et al. (1969) compared the design, operation and cost of a microwave and a dielectric heating system for the control of moisture content and insect infestations of grain. Due to the highly effective penetration of high frequency and microwave energy, more uniform drying as well as efficient insect control was simultaneously achieved with the electrical drying technique. They concluded that microwave and dielectric heating systems are highly efficient with marginal advantages over each other and significant advantages over conventional hot air dryers.

Watters (1976) studied the susceptibility of *Tribolium confusum* to microwave energy by irradiating vials of infested wheat. Wheat samples at 8.5, 12.5 and 15.6% moisture content were infested with ten *T. confusum* adults. After irradiation, each block was removed from the radiation source and the wheat sample was allowed to cool to 32°C. The samples were then stored at 27.5°C and 70% relative humidity for 2 d, when mortality was assessed. After 105 s, in wheat at 15.6, 12.5, and 8.5% moisture contents mortality was 100, 90 and 68%, respectively. *T. confusum* larvae were more tolerant than eggs or pupae. Complete mortality of eggs and pupae were obtained at 75°C, but 21% of the larvae completed development.

Hurlock et. al. (1979) conducted experiments on bags of wheat at 13.7% moisture content containing 50 adult beetles of saw-toothed grain beetle, *Oryzaephilus surinamensis* (L.), *Tribolium castaneum* or *Sitophilus granarius*. These insects were exposed to microwave generated from 896 a MHz generator and subjected to a variety of exposure times and power settings. Another test was conducted on coca crumbs of 18% moisture content containing ten larvae of warehouse moth *Ephestia cautella* (Walker) or fifty adult *Tribolium castaneum*. When the samples from cocoa crumbs were examined, there were more survivors in samples that comprised predominantly powdery material than those that contained a large proportion of lumps (irregular shaped mass). Samples of treated coca beans examined in the laboratory showed no change in fat or moisture content. But exposure to microwave radiation progressively lowered the peroxide level indicating that some chemical changes occur due to microwave radiation and no food should be treated without first ensuring that its quality is not impaired.

2.3.6.3 Advantages of microwave disinfestation

The major advantage of using microwave energy is that no chemical residues are left in the food and hence no adverse effects on human beings (Hurlock et al.1979). Microwave energy has no adverse effect on the environment as chemical method's do. Insects are unlikely to develop resistance to this treatment (Watters 1976). High frequency radiation may not only kill insects by the dielectric heat induced within them but may also affect the reproduction of the survivors (Hamid et al. 1968).

3. MATERIALS AND METHODS

3.1 Grain samples

CWHRS (Canada Western Hard Red Spring) wheat (*Triticum aestivum L.*) was selected for the experimental study. CWHRS is well known for its excellent milling and baking qualities with minimal protein loss during milling. The top grades of CWHRS wheat are characterized by hard texture, high protein and high gluten content. The term 'hard' refers to kernel texture and hard wheat often has a vitreous endosperm.

3.2 Moisture Content

Moisture content of the samples was determined by an oven drying method by drying 10 g of ungrounded grain at 130 ± 2°C for 19 h (ASAE 2001) and was expressed in percent wet mass basis.

After determining the initial moisture content of the sample, the grain was then conditioned to 14 and 16% by adding a calculated quantity of distilled water and rotating the grain mixture for about 30 min. The samples were then kept in polythene bags and stored in a refrigerator for 72 h for uniform moisture distribution. Samples were mixed within the bag every 3 h during the day to ensure uniform distribution of moisture. The moisture content was then verified with five replicates by drying 10 g of sample at 130 ± 2°C for 19 h. The moisturized grain was then kept in air tight plastic bags until used for the experiments.

3.3 Experimental apparatus set-up

All the experiments were conducted in an Industrial Microwave dryer (Model No: P24YKA03, Industrial Microwave Systems, Morrisville, NC). The frequency of the dryer is 2450 MHz. The microwave dryer consists of a conveyor belt, an applicator, fan and heater assembly and a control panel (Fig. 2). The speed of the conveyor can be adjusted by turning the conveyor speed knob on the control panel. The maximum speed of the conveyor is 3 m/min. The power output of the generator is adjustable from 0 – 2 kW. A plastic, microwavable rectangular box of specification 30 cm x 3 cm x 1 cm was made in the lab to hold a 50 g sample of wheat. All the experiments were conducted by placing the sample in this box and subjecting it to microwave power by allowing it to pass on the conveyor belt.

3.4 Experimental design

The experiments were conducted with samples at 14% and 16% moisture content. Three common stored-grain insects, namely, *T. castaneum, C. ferrugineus* and *S. granarius* adults were selected for the experiments. The experiments were carried out at three different infestation levels: 5, 10 and 15 insects per 50 g of sample. The experiments were conducted at two different conveyor speeds, 3 m/min which is the maximum speed of the conveyor and 1.5 m/min. At the maximum speed it takes 28 s for the sample to pass the applicator and at the speed of 1.5 m/min the sample is exposed to microwave energy for 56 s. The power is adjustable and the experiments were conducted at four different power levels: 250, 300, 400 and 500 W.

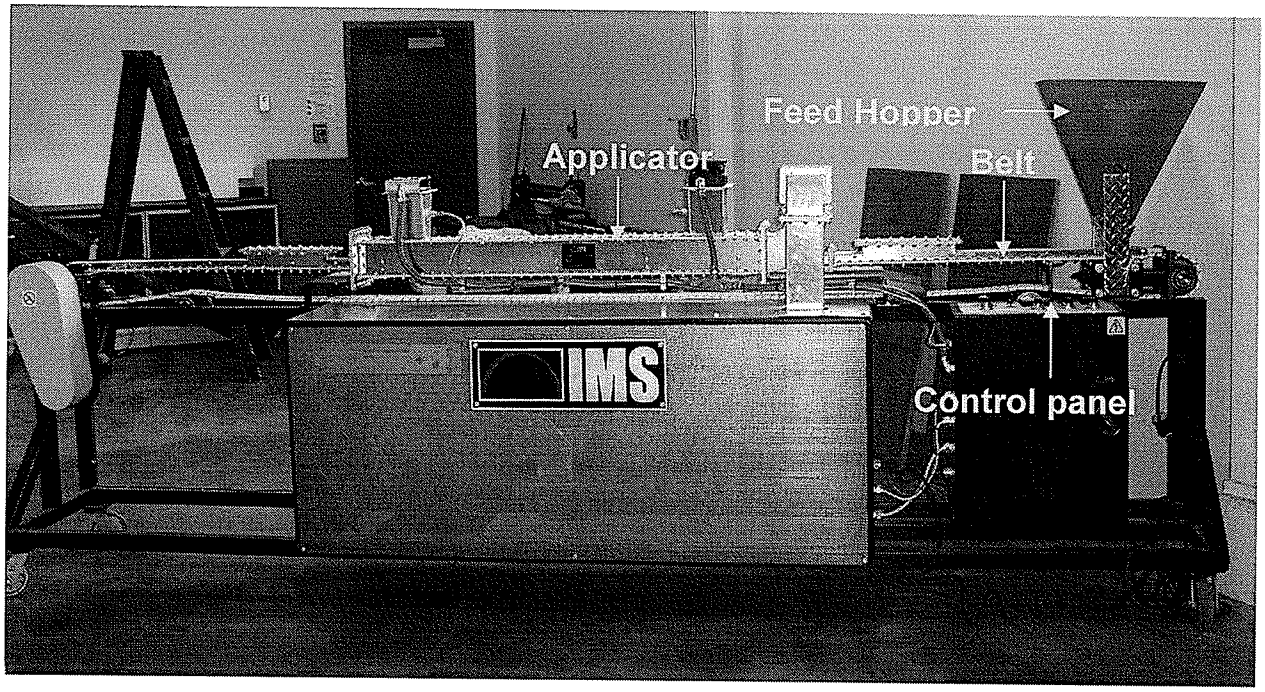

Fig. 1. Industrial Microwave Dryer

3.5 Experimental procedure

3.5.1 Determination of mortality

Fifty gram of sample was placed in the box and insects were added to the sample. The conveyor was switched on and ensured that it was running at its maximum speed. The power was adjusted to the desired level. The grain, along with the insects was then kept on the conveyor belt and the sample was subjected to microwave power. When the box came out of the conveyor it was gently taken out from the conveyor and the sample was spread on a sheet of paper. The number of live and dead insects was counted. The insects were considered dead if they failed to respond to gentle rubbing with a small brush.

The sample was allowed to cool and the insects were checked for mortality again after 15 min. When the final count of the insect was less than the initial count or when the insects were missing, the experiment was repeated again until the final count was the same as the initial count. The sample was then weighed again and from the weight of the sample before and after treatment moisture loss was calculated

For *T. castaneum,* experiments were conducted for the larvae, pupae and adult stages. For the larval stage the experiments were conducted in a manner similar to that used for adult insects. The pupae were subjected to microwave energy at different power levels and exposure time. All the pupae were then returned to a favorable environment. The treated pupae were kept in wheat flour and placed in an environment chamber maintained at 35°C and 70% relative humidity. After one week the total number of adults that emerged from pupae was counted. Three replicates were done for all the mortality experiments.

3.5.2 Determination of Germination

Germination of the wheat seeds subjected to different levels of microwave power was assessed by plating 25 seeds on Whatman no. 3 filter paper in a 9-cm diameter Petri dish saturated with 5.5 mL of distilled water (Wallace and Sinha 1962). The plates were covered with a plastic bag to prevent desiccation of filter paper and kept at 25°C for 7 d. On the seventh day the germinated seeds were counted and the germination percentage was calculated.

3.5.3. Quality analysis

Three samples of one kg each were treated at 500 W for an exposure time of 28 s and at 400 W for an exposure time of 56 s for milling and baking tests. These are the two combinations where we achieved 100% mortality for all the three insects. Three replications were done for the control sample. Various quality analyses like, flour protein, flour yield, flour ash, and loaf volume were done for the microwave treated samples. Grain protein was determined by a grain protein analyzer (Grainspec, Foss Electric, Brampton, ON) and expressed as percentage.

Flour protein was determined according to AACC method 46-30 (Model No. Instalab 600, Dickey-John, Auburn, IL) and expressed as percentage.

Flour yield was determined using a Buhler laboratory flour mill (Model: MLU-202, Uzwil, Switzerland) and expressed as percentage. The mill was equipped with three corrugated break rolls, three smooth reduction rolls and sifting apparatus to produce flour.

Flour ash was determined according to AACC method 08-01. 3 g of flour was kept in ashing dish and placed in a muffle furnace at 575° C for 8 hrs.(Model No: BF51828C, Asheville, NC). The sample was then cooled in a desiccator and weight of residue was measured. Ash percentage was determined using the formula:

Ash percentage = (wt. of residue / wt. of sample) x 100

Farinograph was determined according to the AACC approved method 54-21 (Model No: S-50, 982151, CW, Brabender Instruments Inc, Hackensack, NJ). Constant flour weight procedure was followed.

The baking formula was100 g of flour, 1 g of salt, 5 g of sugar, 3 g of yeast, 0.1 g of malt and water. Mixing was performed in a National 200 g mixer (National Mfg. Co., Lincoln, NE). After a fermentation period of 2 hr, the dough was hand punched and then sheeted, molded and proofed for 70 min at 37.5° C and baked at 225° C for 25 min. The loaf volume was then determined by rapeseed displacement method.

3.5.4 Statistical analysis

A t-test and analysis of variance was done to check the difference between the mortality of insects at different moisture content, power level and exposure time and also the mortality between the insects. Statistical analysis was also done to check the significance between the germination percentage of wheat at difference moisture content and power level and also to check the quality of control and treated sample (SAS version 9.1, Statistical Analysis Systems, Cary, NC).

4. RESULTS AND DISCUSSION

4.1 Mortality of adult insects

4.1.1 Mortality of *Tribolium castaneum*

The mortality percentages for adult *Tribolium castaneum* at various power levels and for 14 and 16% m.c. wheat are shown in Table I. At a power level of 250 W and an exposure time of 28 s, the mortality percentage for adult *T. castaneum* is 45% at a moisture content of 14%. As the power was increased to 300, 400 and 500 W, the mortality also increased to 58, 85 and 100%, respectively. The mortality increased as power level and exposure time was increased.

Table I. Mortality (mean ± standard error) of *Tribolium castaneum* adults exposed to microwave radiation in wheat at 14 and 16% moisture contents.

Power, W	Moisture content			
	14 %		16%	
	Exposure time, s		Exposure time, s	
	28	56	28	56
250	45±11.6	77±2.9	56±2.9	81±4.9
300	58±1.1	90±1.7	68±7.2	95±4.2
400	85±5	100	86±2.5	100
500	100	-*	100	-*

* Since 100% mortality was achieved at 400 W, experiments were not performed at 500 W for 56 s.

At the same power level, higher mortality was obtained for higher exposure time. As exposure time was increased, higher mortality was achieved at lower power levels. For example, at 500 W, 100% mortality was obtained for an exposure time of 28 s. When the exposure time was increased to 56 s, 100% mortality was obtained at a power of 400 W.

An independent t-test between the means of mortality at 14 and 16% m.c. wheat showed that mortality was not significantly different at $p<0.05$ except at 300 W power and 28 s exposure time. Analysis of Variance between the mortality of *T. castaneum* at 16% and 14% m.c. wheat showed that mortality was significantly different at $p<0.05$. The mortality was significantly different at different power levels and exposure time.

4.1.2. Mortality of *Cryptolestes ferrugineus*

The mortality percentage for adult *Cryptolestes ferrugineus* at various power levels and for 14 and 16% m.c. wheat are shown in Table II. For *C. ferrugineus*, the mortality was 23% at 250 W power and an exposure time of 28 s for the 14% moisture content wheat. Similar to *T. castaneum*, mortality was higher at 16% moisture content. Effect of power level and exposure time on mortality was same for *C. ferrugineus* as for *T. castaneum.*

Table II. Mortality (mean ± standard error) of *Cryptolestes ferrugineus* adults exposed to microwave radiation in wheat at 14 and 16% moisture contents.

Power, W	Moisture content 14 %		Moisture content 16%	
	Exposure time, s		Exposure time, s	
	28	56	28	56
250	23±4	61±8.3	34±3.3	72±5
300	43±11.3	75±6.5	47±5	91±2.8
400	69±8.7	100	73±2.3	100
500	100	-*	100	-*

* Since 100% mortality was achieved 400 W, experiments were not performed at 500 W for 56 s

An independent t-test between means of mortality of *C. ferrugineus* at 14 and 16% m.c. wheat showed that mortality was significantly different at 56 s exposure time for 250 and

300 W at $p<0.05$. But mortality was not significantly different at 28 s exposure time at $p<0.05$. Analysis of variance showed that mortality was significantly different at 14 and 16% m.c wheat at $p<0.05$

4.1.3 Mortality of *Sitophilus granarius*

The mortality percentage for adult *S. granarius* at various power levels and for 14 and 16% moisture content wheat is shown in Table III. The mortality of *S. granarius* was 100% at 500 W at an exposure time of 28 s, similar to the other two insects. But at the higher exposure time of 56 s, 100% mortality was obtained at 300 W instead of 400 W. This shows that *S. granarius* was more susceptible at lower power level for greater exposure time. An independent t-test and analysis of variance between the mortality of *S. granarius* at 14 and 16% m.c showed that they were not significantly different at $p<0.05$.

Table III. Mortality (mean ± standard error) of *Sitophilus granarius* adults exposed to microwave radiation in wheat at 14 and 16% moisture contents.

Power, W	Moisture content			
	14 %		16%	
	Exposure time, s		Exposure time, s	
	28	56	28	56
250	41±12.8	73±4	44±12	78±7.6
300	64±5	100	70±10	100
400	84±7.4	100	87±7.4	100
500	100	-*	100	-*

* Since 100% mortality was achieved at 300 W, experiments were not performed at 500 W for 56 s.

When the mortality of the three insects was compared, the mortality of *C. ferrugineus* was significantly different from the mortality of other two insects. This shows that *C. ferrugineus* was more heat resistant compared to other two insects.

Hamid et al. (1968) conducted experiments to control *Tribolium confusum, Sitophilus granarius* and *Cryptolestes ferrugineus* and determined that 90% mortality of the three species can be obtained at 30, 30 and 18 s, respectively with an input power of 600 W. A similar result was obtained from our experiments, for *S. granarius* which requires an exposure time of 28 s for 100% mortality at 500 W. But the exposure time for 100% mortality varies for C. *ferrugineus*. Hamid et al. (1968) concluded that bulk illumination was not possible when the depth was greater than 0.1 m (4 inches) but satisfactory mortality can be achieved when wheat was passed in thin layers on a conveyor belt. This is in agreement with our results, because we achieved 100% mortality at 500 W when wheat was passed in thin layers on the conveyor belt.

The variability in mortality between tests at each power level can be attributed to the location of the insects in the container. By using an infra red thermal camera, hot and cold spots were detected in the samples. There is a possibility that insects may escape from the hot spot and remain in the cold spot.

4.2 Mortality of *Tribolium castaneum* larvae

The mortality percentage for *T. castaneum* larvae at 14 and 16% moisture content wheat is shown in Table IV. The mortality increased as power level and exposure time was increased. One hundred percent mortality was achieved at 500 W for an exposure time of 28 s and at 400 W for an exposure time of 56 s, similar to the adult insects.

Table IV. Mortality (mean ± standard error) of *Tribolium castaneum* larvae exposed to microwave radiation in wheat at 14 and 16% moisture contents.

Power, W	Moisture content 14 % Exposure time, s 28	56	16% Exposure time, s 28	56
250	53±3.6	78.9±2.2	61.1±5.1	77.4±4.2
300	71.8±4.4	92.9±1.3	73.7±5.6	94.8±0.7
400	90.7±4.6	100	93±6.3	100
500	100	-*	100	-*

* Since 100% mortality was achieved at 400 W, experiments were not performed at 500 W for 56 s.

An independent t-test between the means of the mortality of adult and larvae showed that they were not significantly different at $p<0.05$ except at 300 W power, 28 s exposure time for the 14% m.c wheat. Analysis of variance showed that mortality of adult is significantly different from larvae.

This result differs from the results of Mahroof et al. (2003a, 2003b). Mahroof et al. (2003a) reported that during heat treatment of mills using gas heaters to 50-60° C, old instars and pupae appeared relatively heat tolerant compared with other life stages. Mahroof et al. (2003 b) conducted experiments to study time-mortality relationships for life stages of *T. castaneum* exposed to elevated temperature of 50-60°C. They concluded that young larvae were the most heat –tolerant stage. Hamid and Boulanger (1969) concluded that the mortality of larvae was the same as the adult *T. confusum* at different temperatures.

4.3 Mortality of *Tribolium castaneum* pupae

The mortality percentage for *T. castaneum* pupae at 14 and 16% moisture content wheat are shown in Table V. At a power level of 250 W and an exposure time of 28 s, the mortality percentage for *T. castaneum* pupae was 43% and at an exposure time of 56 s, mortality was 74%. An independent t–test between the means of the mortality of *T. castaneum* adult and pupae at all power levels and exposure time showed that the mortality of pupae was not significantly different from the adults at $p<0.05$ except at 250 W power, 28 s exposure time at 16% m.c. Analysis of variance showed that mortality of adult is significantly different from pupae.

From our experiments we can conclude that mortality of larval and pupal stages of *T. castaneum* are significantly the same but different from the adults

Table V. Mortality (mean ± standard error) of *Tribolium castaneum* pupae exposed to microwave radiation in wheat at 14 and 16% moisture contents.

Power, W	Moisture content 14 % Exposure time, s 28	56	16% Exposure time, s 28	56
250	43.3±1.1	73.7±3.4	43.7±1.7	77.8±5.1
300	54.8±9.4	86.3±2.3	67.4±1.7	94.1±2.8
400	75.5±3	100	77.8±4.5	100
500	100	-*	100	-*

* Since 100% mortality was achieved at 400 W, experiments were not performed at 500 W for 56 s.

In all larvae, pupae and adult stages, the mortality increased as the power level was increased. Also the mortality was higher at higher exposure time. Our experiments were conducted at a frequency of 2450 MHz. Based on our experimental results, it can be concluded that selective heating of insects has not occurred at microwave frequency because the wheat was heated to a lethal temperature when the power level was increased from 250-500 W. For example, temperature of wheat was in the range of 55-58°C when the power applied was 250 W. When the power applied was increased to 500 W, the temperature of wheat was around 93-96°C. As a result of increase in temperature due to increase in power level, higher mortality was obtained.

Nelson and Charity (1972) compared the dielectric properties of different cereals and cereal products at different frequencies and concluded that selective heating of insects in a cereal was less likely to occur at microwave frequencies but it may occur at radio frequencies. The experiments of Baker et al. (1956) also support this conclusion. Nelson and Stetson (1974) studied the dielectric heating treatments of rice weevils in wheat at 39 and 2450 MHz and showed that the lower frequency was much more effective in killing the insects. Wang et al. (2003) studied the differential heating of insects in dried nuts and fruits at microwave and radio frequencies. They concluded that differential heating of insects in walnuts does occur at 27 MHz but not at 915 MHz. Thuery (1992) has stated that irradiation at frequencies in excess of 1GHz has almost no selective effect on insects.

4.4 Temperature measurement

Thermocouple and thermistor are mainly used in heat transfer studies, as they are readily available and inexpensive. These conventional temperature measurement systems are not very suitable for measuring the heating process in microwave due to high electric fields, which cause interference or even failure of a sensor (Richardson 1989). It is possible to obtain temperature data by infrared imaging. The main advantage is that it makes it possible to look at complex heating patterns. Although it measures only the surface temperature, Bows (1992 cited by Ryynanen 2002) claims it can be used to infer internal heating patterns too. The IR imaging is also a non-invasive method (Mullin and Bows 1993).

Initially the temperature of the treated sample was measured with a K-type thermocouple, a temperature variation up to few degrees was noted. At 500 W, the temperature was in the range of 93-96°C. At 400 W, the temperature varied between 81- 87°C. At 300 W, the temperature varied between 62- 68°C. At 250 W, the temperature varied between 55-58°C. When the surface temperature of the wheat was measured using an infra-red thermal camera (Model: ThermaCAM ™ SC500 of FLIR systems, Burlington, Ontario), a large variation in the temperature was noticed. At 500 W, the temperature was in the range of 61-109°C. At 400 W, the temperature was in the range of 53-101°C. At 300 W, the temperature was in the range of 48-78°C. There were clear hot and cold regions on the treated sample.

This kind of non uniform heating was observed in poultry meat (Goksoy et al. 1999), ready meals (Ryynanen et al. 2001), commercially refrigerated and frozen foods (Fakhouri and Ramaswamy 1993), and prepared meals (Burfoot et al. 1988). Goksoy et al (1999) conducted experiments on poultry meat using a domestic microwave oven and concluded that an average temperature difference of up to 61°C was obtained between different points on the carcass. Ryynanen et al. (2001) studied the temperature effects on ready meals and concluded that large differences in temperature existed but it did not have a major impact on the overall pleasantness of the meal. Burfoot et al. (1988) studied the microwave pasteurization of prepared meals. They measured a temperature difference up to 66 and 36°C in the product after heating in the domestic microwave oven and 2450 MHz tunnel, respectively.

There is no clear literature explaining the reasons for non-uniformity of temperature during microwave heating of grain. Hot and cold spots are produced because the microwaves form standing waves inside the microwave cavity. Standing waves are produced whenever two waves of identical frequency interfere with one another when traveling in opposite directions along the same medium. These standing wave patterns are characterized by certain fixed points which undergo no displacement and these points are called nodes. Midway between every node point, there are points which undergo maximum displacement and they are called antinodes. Nodes are caused by destructive interference of two waves and these spots are 'cold spots'. Antinodes are caused by constructive interference of two waves and these spots are 'hot spots' (Henderson 1998).

It is probable that because of this wave pattern, hot and cold spots are formed during microwave heating.

4.5 Moisture loss

At the lower power of 250 W, the moisture loss was around 0.85 and 1.5 percentage points for an exposure time of 28 s and 56 s, respectively. The moisture content of a 16% sample was reduced to around 15.15 and 14.5% after treatment. At 500 W, the moisture loss was around 2 percentage points for exposure time of 28 s and around 3 percentage points for an exposure time of 56 s. The moisture loss corresponding to 100% mortality varied between 2-3 percentage points.

Hamid et al. (1968) has shown in his experiments that the moisture content in wheat drops by less than 1% for exposure times greater than that corresponding to total mortality of the three wheat insects. Boulanger et al. (1969) achieved a moisture reduction around 1-3% in their experiments. In the present study, we obtained a moisture loss of around 2-3% corresponding to the mortality of the insects.

4.6 Germination

The results of the germination test conducted for 14 and 16% moisture content wheat at various power levels is shown in Figs. 3 and 4, respectively. The results indicate that germination percentage was lowered by treatment with microwaves.

At 250 W, 81% of seeds germinated at 14% moisture content and 77% of seeds germinated at 16% moisture content. As the power was increased the germination percentage was lowered. At 500 W, the germination was zero for an exposure time of 56 s. The germination of the control sample was around 96-97%. As the power and exposure time were increased, the germination was lowered significantly. Hence we can conclude that with increasing power and exposure time of microwave energy, the germination of the seed was lowered significantly.

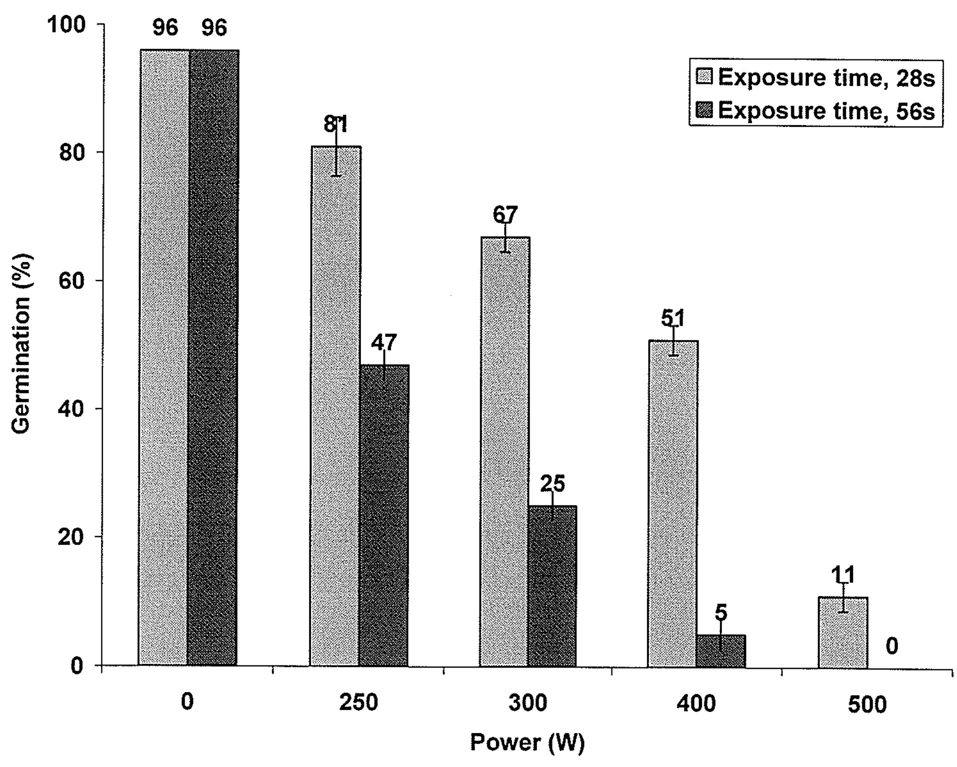

Fig. 2. Germination of 14% m.c. wheat at different power levels and exposure time.

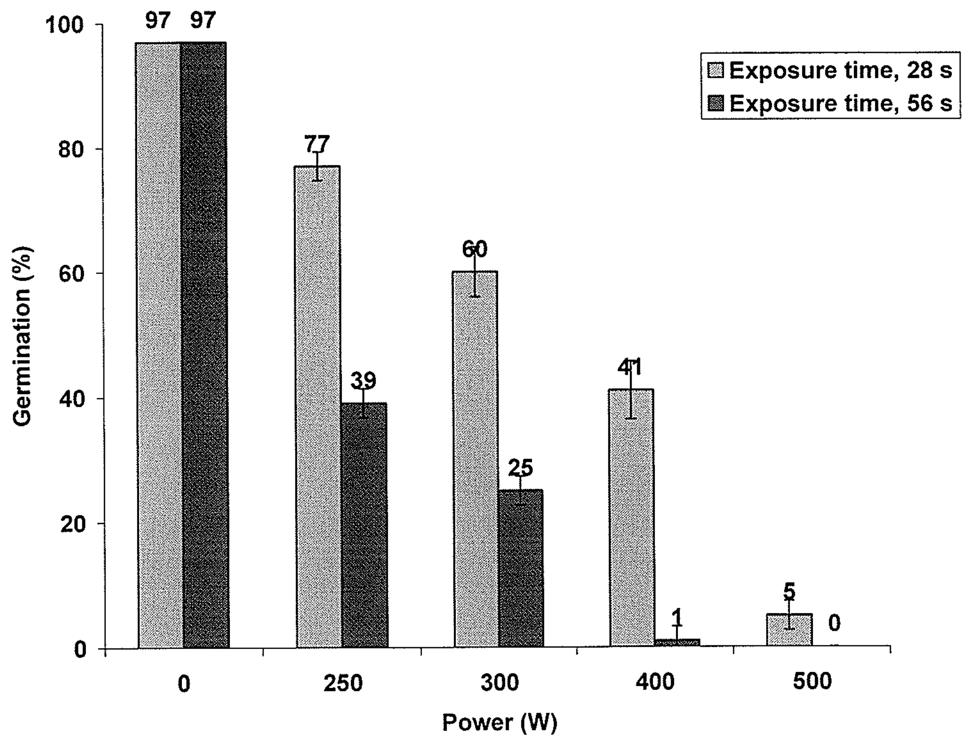

Fig. 3. Germination of 16% m.c. wheat at different power levels and exposure time.

An independent t-test between means of germination percentage of seeds at 14 and 16% m.c. wheat showed they are not significantly different when $p<0.05$ except at 500 W, 28 s exposure time and 250 W, 56 s . Analysis of variance between the germination showed that they are significantly different at 14 and 16% m.c, different power levels and exposure time.

Similar kind of results was obtained by Campana et al. (1993) and Bhaskara et al. (1998). Campana et al. (1993) studied the physical, chemical and baking properties of wheat dried with microwave energy. They concluded that germination capacity was affected by exposure to microwave energy. The decrease in germination capacity was related to the final temperature and the initial moisture content of the grains.

Bhaskara et al. (1998) studied the effect of microwave treatment on quality of wheat seeds infected with *Fusarium graminearum.* Their results showed that eradication of the pathogen increased with the total microwave energy, but the seed viability and seedling vigour decreased accordingly.

4.7 Quality analysis

The quality analysis for the grain protein, flour protein, flour ash, stability and loaf volume are shown in Table VI. The flour protein for the control sample varied between 12.8-13%. The flour protein for the sample exposed to 500 W and 28 s varied between 12.6-13.5% and the sample exposed to 400 W for 56 s varied between 12.5-13%. Flour yield for the control sample varied between 77-77.4%. Flour yield for the sample exposed to 500 W for 28 s was between 76.6-77.4% and the sample exposed to 400 W for 56 s was between 75.3-77.8%. Flour ash content for the control sample was between 0.48-0.52%. For the sample exposed to 500 W for 28 s flour ash varied between 0.45-0.53% and for the sample exposed to 400 W for 56 s varied between 0.46-0.54%. The loaf volume for the control sample varied between 975-1045 cc. The loaf volume of the sample treated at 500 W and 28 s varied between 955-1085 cc and the loaf volume of the sample treated at 400 W and 56 s varied between 945-1035 cc.

A t-test and analysis of variance test between the means of the control sample and treated sample was performed for flour protein, flour yield, flour ash, stability and loaf volume. The results showed that the treated samples are significantly the same as the control sample.

Boulanger et al. (1969) determined the effects of high frequency and microwave radiation on the quality of wheat, for a maximum grain heating temperature of 45°C. The results indicated that there were no damaging effects on the milling properties, bread-making quality, and the protein content of the grain but the loaf volume was reduced slightly for the microwave system.

Macarthur and d'Appolonia (1979) studied the effects of microwave radiation and storage on hard red spring wheat flour. They examined the physical dough properties and baking characteristics immediately and at definite time intervals after radiation treatment. Analysis of the flour and bread indicated that exposing the flour to high levels of microwave radiation produced an abnormal farinograph curve exhibiting two peaks, whereas low levels produced bread with loaf volumes and overall bread characteristics equal to or better than those of the control flour.

Campana et al. (1993) studied the physical, chemical and baking properties of wheat dried with microwave energy. They stated that the protein content was not affected but the functionality of gluten was altered gradually with increasing time of exposure.

Based on our experimental results, it can be concluded that there was no significant difference in the quality of grain protein, flour protein, flour yield, flour ash, and loaf volume of the wheat subjected to microwave energy.

Table VI. Quality aspects (mean of 3 replicates ± standard error) of wheat subjected to microwave energy

Power W	Exposure time s	M.C %	Grain protein %	Flour protein %	Flour yield %	Flour ash %	Stability min	Loaf volume cc
Control			13.9± 0.11	12.9±0.10	77.2±0.21	0.51±0.02	18.2±0.23	1018±37.8
500	28	14	13.8±0.05	12.7±0.11	76.9±0.35	0.50±0.03	18.0±0.25	1022±65.1
500	28	16	14.1±0.11	13.1±0.35	77.3±0.23	0.47±0.03	16.4±0.92	1050±13.2
400	56	14	13.8±0.11	12.8±0.23	76.5±1.06	0.51±0.03	18.0±0.26	992±40.4
400	56	16	14.1±0	12.9±0.11	77.4±0.40	0.47±0.02	16.6±0.83	992±45.1

5. CONCLUSIONS

1. For all the three adult insects, 100% mortality was achieved at 500 W for an exposure time of 28 s, for both the 14% and 16% moisture content wheat.
2. For *T. castaneum* and *C. ferrugineus*, 100% mortality was achieved at 400 W for an exposure time of 56 s, and for *S. granarius* 100% mortality was achieved at 300 W for an exposure time of 56 s.
3. For the larval and pupal stages of *T. castaneum*, 100% mortality was achieved at 500 W and 400 W for an exposure time of 28 s and 56 s, respectively.
4. There was a significant difference in the mortality of *T. castaneum* and *C. ferrugineus* at 14 and 16% moisture content wheat.
5. There was no significant difference in the mortality of *S. granarius* at 14 and 16% moisture content wheat.
6. Mortality of *T. castaneum* larvae and pupae are significantly the same but different from the adults.
7. Germination was affected by subjecting to microwave energy and as the power level and exposure time were increased, germination was lowered.
8. The quality aspects of microwave treated wheat were not significantly affected compared to the control sample.

6. RECOMMENDATIONS FOR FUTURE RESEARCH

1. Life stages of all the stored-product insects can be treated with microwave energy and their susceptibility to microwave treatment should be studied.
2. Non-uniform temperature distribution during microwave heating needs further research. Possible ways to minimize large temperature variation occurring in a wheat sample during microwave treatment need to be developed and evaluated.
3. Possibility of low frequency radio waves for disinfesting grains should be studied and compared with the microwave disinfestation results.

7. REFERENCES

Adu, B. and L. Otten. 1996. Microwave heating and mass transfer characteristics of white beans. *Journal of Agricultural Engineering Research* 64(1): 71-78.

Agriculture and Agri-Food Canada. 2002. Canadian wheat classes. AAFC No.2081/E. Vol. 15(7) Winnipeg, MB: Market Analysis Division

Agriculture and Agri-Food Canada. 2004. Profile of the Canadian wheat industry. AAFC Reference No.2081/E.Vol 17(11). Winnipeg, MB: Market Analysis Division.

Agriculture Canada. 1981. Red flour beetle. Insect Identification Sheet No.75. Ottawa, ON.

Agriculture Canada. 1981. Rusty grain beetle. Insect Identification Sheet No.78. Ottawa, ON.

Agriculture Canada. 1981. Granary weevil. Insect Identification Sheet No.80. Ottawa, ON.

Agriculture, Food and Rural Development. 2001. Wheat Utilization. Edmonton, Government of Alberta.

ASAE. 2001. *ASAE Standards 2001*. St. Joseph, MI: American Society of Agricultural Engineers.

Baker, V.H., D.E. Wiant and O. Taboada. 1956. Some effects of microwaves on certain insects which infest wheat and flour. *Journal of Economic Entomology* 49(1): 33-37.

Banks, J. and P. Fields. 1995. Physical methods for insect control in stored-grain ecosystems. In *Stored-Grain Ecosystem*, eds. D.S. Jayas, N.D.G. White and W.E. Muir, 353-410. New York, NY: Marcel Dekker, Inc

Bhaskara, M.V., G.S.V. Raghavan, A.C. Kushalappa and T.C. Paulitz. 1998. Effects of microwave treatment on quality of wheat seeds infected with *Fusarium graminearum*. *Journal of Agricultural Engineering Research* 71(2): 113-117.

Boulanger, R.J., W.M. Boerner and M.A.K. Hamid. 1969. Comparison of microwave and dielectric heating systems for the control of moisture content and insect infestation of grain. *Journal of Microwave Power* 4(3): 194-207.

Bouraout, M., P. Richard and T. Durance. 1994. Microwave and convective drying of potato slices. *Journal of Food Process Engineering* 28: 203-209

Bows, J. 1992. Infrared imaging feels the heat in microwave ovens. *Physical World* 5: 21-22.

Brader, B., R.C. Lee, R. Plarre, W. Burkholder, G.B. Kitto, C. Kao, L. Polston, E. Dorneanu, I. Szabo, B. Mead, B. Rouse, D. Sullins and R. Denning. 2000. A comparison of screening methods for insect contamination in wheat. *Journal of Stored Products Research* 38(1): 75-86.

Brygidyr, A.M. 1976. Characterization and drying of tomato paste foam utilizing hot air and microwave energy. Unpublished M.Sc. thesis. Winnipeg, MB: University of Manitoba, Department of Food Science.

Buffler, C.R. 1993. *Microwave Cooking and Processing*. Glenview, IL: Van Nostrand Reinhold.

Burfoot, D., W.J. Griffin and S.J. James. 1988. Microwave pasteurization of prepared meals. *Journal of Food Engineering* 8(3): 145-156.

Campana, L.E., M.E. Sempe and R.R. Filgueria. 1986. Effect of microwave energy on drying wheat. *Cereal Chemistry* 63(3): 271-273.

Campana, L.E., M.E. Sempe and R.R. Filgueria. 1993. Physical, chemical, and baking properties of wheat dried with microwave energy. *Cereal Chemistry* 70(6): 760-762.

Canada Grain Act. 1975. Canada Grain Regulations. Canada Gazette, Part II, Vol.109, No.14.

Copson, D.A. 1962. *Microwave Heating In Freeze-Drying, Electronic Ovens and Other Applications.* Westport, CT: The AVI Publishing Company Inc.

Decareau, R.V. 1972. ABC's of microwave cooking. *Journal of Microwave Power* 7(4): 397-409.

Decareau, R.V. 1985. *Microwaves in the Food Processing Industry*. Natick, MA: Academic Press Inc.

Dench, E.C. 1973. Advantages of microwave processing. IMPI Paper No.1. Edmonton, AB: Industrial Microwave Power Institute.

Drouzas, A.E., E. Tsami and G.D. Saravacos. 1999. Microwave/ vacuum drying of model fruit gels. *Journal of Food Engineering* 39(2): 117-122.

Fakhouri, M.O. and H.S. Ramaswamy. 1993. Temperature uniformity of microwave heated foods as influenced by product type and composition. *Food Research International* 26(2): 89-95.

Fields, P.G. and N.D.G. White. 2002. Alternatives to methyl bromide treatments for stored-product and quarantine insects. *Annual Review of Entomology* 47: 331-359.

Funebo, T. and T. Ohlsson. 1998. Microwave assisted air dehydration of apple and mushroom. *Journal of Food Engineering* 38(3): 353-367.

Garcia, R., F. Leal and C. Rolz. 1988. Modelling of dielectrically assisted drying. *International Journal of Food Science and Technology* 23: 73-80.

Goksoy, E.O., C. James and S.J. James. 1999. Non-uniformity of surface temperatures after microwave heating of poultry meat. *Journal of Microwave Power Electromagnetic Energy* 34(3): 149-160.

Hamid, M.A.K. and R.J. Boulanger. 1969. A new method for the control of moisture and insect infestations of grain by microwave power. *Journal of Microwave power* 4(1): 11-18.

Hamid, M.A.K., C.S. Kashyap and R.V. Cauwenberghe. 1968. Control of grain insects by microwave power. *Journal of Microwave Power* 3(3): 126-135.

Henderson, T. 1998. Multimedia Physics Studios. http://www.glenbrook.k12.il.us/gbssci/phys/mmedia/waves/swf.html (accessed 2005/04/20).

Hill, D.S. 1990. *Pests of Stored Products and their Control*. Boca Raton, FL: CRC Press.

Hurlock, E.T., B.E. Llewelling and L.M. Stables. 1979. Microwaves can kill insect pests. *Food Manufacture* 54(1): 37-39.

Huxsoll, C.C and A.I. Morgan. 1968. Microwave dehydration of potatoes and apples. *Food Technology* 22: 47-51.

Lhaloui, S., D.W. Hagstrum, D.L. Keith, T.O. Holtzer and H.J. Ball. 1988. Combined influence of temperature and moisture on the red flour beetle (Coleoptera: Tenebrionidae) reproduction on whole grain wheat. *Journal of Economic Entomology* 81(2): 488-489.

Lin, T.M., T.D. Durance and C.H. Scaman. 1998. Characterization of vacuum, microwave, air and freeze dried carrot slices. *Food Research International* 31(2): 111-117.

Linn, H. and M. Moller. 2003. Microwave heating. In *Thermprocess Symposium*, Dusseldorf, Germany. June 16-21

Macarthur, L.A. and B.L. d'Appolonia. 1979. Effects of microwave radiation and storage on hard red spring wheat flour. *Cereal Chemistry* 58(1): 53-56.

Mahroof, R, B. Subramanyam and D. Eustace. 2003a. Temperature and relative humidity profiles during heat treatment of mills and its efficacy against *Tribolium castaneum* (Herbst) life stages. *Journal of Stored Products Research* 39: 555-569.

Mahroof, R., B. Subramanyam, J.E. Throne and A. Menon. 2003b. Time-mortality relationships for *Tribolium castaneum* (Coleoptera: Tenebrionidae) life stages exposed to elevated temperatures. *Journal of Economic Entomology* 96(4): 1345-1351.

Maskan, M. 1999. Microwave/air and microwave finish drying of banana. *Journal of Food Engineering* 44(2): 71-78.

Maskan, M. 2000. Drying, shrinkage and rehydration characteristics of kiwifruits during hot air and microwave drying. *Journal of Food Engineering* 48(2): 177-182.

Mavrogianopoulos, G.N., A. Frangoudakis and J. Pandelakis. 2000. Energy efficient soil disinfestation by microwaves. *Journal of Agricultural Engineering Research* 75: 149-153.

Muir, W.E. and P.G. Fields. 2001. Miscellaneous methods for physical control of insects. In *Grain Preservation Biosystems*, 319-329. Winnipeg, MB: Department of Biosystems Engineering, University of Manitoba.

Muir, W.E. and N.D.G. White. 2001. Insects and mites in stored grain. In *Grain Preservation Biosystems*, 43-53. Winnipeg, MB: Department of Biosystems Engineering, University of Manitoba.

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

Mullin, J. 1995. Microwave processing. In *New Methods of Food Preservation,* ed. G.W. Gould, 112-134. Bishopbriggs, Glasgow: Blackie Academic and Professional.

Nelson, S.O. 1972. Possibilities for controlling stored-grain insects with RF energy. *Journal of Microwave Power* 7(3): 231-237.

Nelson, S.O. and L.F. Charity. 1972. Frequency dependence of energy absorption by insects and grain in electric fields. *Transactions of the ASAE* 15: 1099-1102.

Nelson, S.O. and L.E. Stetson. 1974. Possibilities for controlling insects with microwaves and lower frequency RF energy. *IEEE Transactions of Microwave Theory and Techniques* 22(12): 1303-1305.

Petrucci, V.E. and C.D. Clary. 1989. Vacuum microwave drying of food products. Final Report (No.2897-3). Fresna , CA: California State University.

Prabhanjan, D.G., H.S. Ramaswamy and G.S.V. Raghavan. 1995. Microwave assisted convective air drying of thin layer carrots. *Journal of Food Engineering* 25(2): 283-293.

Richardson, P. 1989. Measuring the temperature in a microwave oven. *Food Manufacture* 64(6): 45-46.

Ryynanen, S., H. Tuorila and L. Hyvonen. 2001. Perceived temperature effects on microwave heated meals and meal components. *Food Service Technology* 1: 141-148.

Ryynanen, S. 2002. Microwave heating uniformity of multi-component prepared food. Unpublished Ph.D thesis. Department of Food Technology: University of Helsinki. Helsinki, Finland

Schiffmann, R.F. 1986. Food product developments for microwave processing. *Food Technology* 40(6): 94-98.

Shivare, U.S., G.S.V. Raghavan and R.G. Bosisio. 1993. Modelling the drying kinetics of maize in a microwave environment. *Journal of Agricultural Engineering Research* 57(3): 199-205.

Sinha, R.N. and F.L. Watters. 1985. *Insect Pests of Flour Mills, Grain Elevators, and Feed Mills and their Control.* Winnipeg, Manitoba: Agriculture Canada

Smith, L.B. 1965. The intrinsic rate of natural increase of *Cryptolestes ferrugineus* (Coleoptera: Cucujidae). *Journal of Stored Products Research* 1: 35-49.

Sode, O.J., F. Mazaud and F. Troude. 1995. Economics of grain storage. In *Stored Grain Ecosystems*, eds. D.S. Jayas, N.D.G. White and W.E. Muir, 101-122. New York, NY: Marcel Dekker, Inc.

Speir, T.W., J.C. Cowling, G.P. Sparling, A.W. West and M. Corderoy. 1986. Effects of microwave radiation on the microbial biomass, phosphatase activity and levels of extractable N and P in a low fertility soil under pressure. *Soil Biology and Biochemistry* 18(4): 377-382.

Subramanyam, B. and D.W. Hagstrum. 2000. *Alternatives to Pesticides in Stored-Product IPM.* Boston, MA: Kluwer Academic Publishers

Suhm, J., M. Moller and H. Linn. 2003. New development for industrial microwave heating. In *International Scientific Colloquium.* Hannover, Prussia. March 24-26.

Taylor, R.W.D. 1994. Methyl bromide-Is there any future for this noteworthy fumigant?. *Journal of Stored Products Research* 30(4): 253-260.

Thuery, J. 1992. *Microwaves: Industrial, Scientific and Medical Applications.* Norwood, MA: Artech House.

Torringa, E.M., H.H. Nijhius, H.H.J. Remmen and P.V. Bartles. 1993. Electromagnetic drying of vegetable produce. In *Proceedings of the Fourth International Congress on Food Industry*, 331-344. Cesme, Turkey.

Tulasidas, T.N., G.S.V. Raghavan and E.R. Norris. 1996. Effects of dipping and washing pre-treatments on microwave drying of grapes. *Journal of Food Process Engineering* 19: 15-25.

Venkatrao, S., R.N. Nuggehalli, S.V. Pingale, M. Swaminathan and V. Subrahmanyan. 1960. The effect of infestation by *Tribolium castaneum* on the quality of wheat flour. *Cereal Chemistry* 37: 97-103.

Wainwright, M., K. Killham and M.F. Diprose. 1980. Effects of 2450 MHz microwave radiation on nitrification, respiration and S-oxidation in soil. *Soil Biology and Biochemistry* 12(5): 489-493.

Walde, S.G., K. Balaswamy, V. Velu and D.G. Rao. 2002. Microwave drying and grinding characteristics of wheat (*Triticum aestivum*). *Journal of Food Engineering* 55(3): 271-276.

Wallace, H.A.H. and R.N. Sinha. 1962. Fungi associated with hot spots in farm stored grain. *Canadian Journal of Plant Science* 42: 130-141.

Wang, S., J. Tang, R.P. Cavalieri and D.C. Davis. 2003. Differential heating of insects in dried nuts and fruits associated with radio frequency and microwave treatments. *Transactions of the ASAE* 46(4): 1175-1182.

Watters, F.L. 1976. Microwave radiation for control of *Tribolium confusum* in wheat and flour. *Journal of Stored Product Research* 12: 19-25.

Xiaofeng, W. 2002. Experimental and theoretical study of microwave heating of thermal runaway material. Unpublished Ph.D.thesis. Blacksburg, Virginia: Department of Mechanical Engineering, Virginia Polytechnic Institute and State University.

Yongsawatdigul, J. and S. Gunasekaran. 1996a. Microwave vacuum drying of cranberries: Part I: Energy use and efficiency. *Journal of Food Processing and Preservation* 20(1): 121-143.

Yongsawatdigul, J. and S. Gunasekaran. 1996b. Microwave vacuum drying of cranberries: Part II: Quality evaluation. *Journal of Food Processing and Preservation* 20(1): 121-143.

APPENDIX A: Mortality data

Table A1. Mortality of adult *Tribolium castaneum* at 14% m.c.
Replication 1

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	1	4	50.0079	49.7266
	28	10	3	7	50.0085	49.6888
	28	15	7	8	50.0154	49.6623
	56	5	4	1	49.9983	49.4592
	56	10	7	3	49.9884	49.4817
	56	15	13	2	50.009	49.4743
300	28	5	2	3	50.0121	49.5898
	28	10	7	3	50.0125	49.6105
	28	15	9	6	49.9829	49.5328
	56	5	4	1	49.9951	49.2283
	56	10	10	1	50.0126	49.2953
	56	15	13	2	50.0172	49.3729
400	28	5	5	0	49.9976	49.2817
	28	10	8	2	49.9758	49.2179
	28	15	11	4	50.0074	49.3011
	56	5	5	0	50.0068	48.5218
	56	10	10	0	50.0196	48.5967
	56	15	15	0	49.9912	48.4982
500	28	5	5	0	50.0048	48.9845
	28	10	10	0	50.0171	49.0411
	28	15	15	0	49.9912	48.8991

Table A2. Mortality of adult *Tribolium castaneum* at 14% m.c.
Replication 2

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	3	2	49.9901	49.6583
	28	10	5	5	50.0174	49.7426
	28	15	8	7	50.028	49.6146
	56	5	4	1	49.9853	49.3073
	56	10	6	4	49.9989	49.3718
	56	15	12	3	50.0039	49.2561
300	28	5	3	2	50.0216	49.4691
	28	10	7	3	50.0075	49.4518
	28	15	7	8	50.0221	49.4597
	56	5	5	0	50.0015	49.0794
	56	10	9	1	50.013	49.0333
	56	15	13	2	49.9953	49.1146
400	28	5	5	0	50.0152	49.345
	28	10	9	1	49.9882	49.1978
	28	15	12	3	50.0302	49.2589
	56	5	5	0	50.0073	48.5274
	56	10	10	0	50.0208	48.4592
	56	15	15	0	50.0019	48.4917
500	28	5	5	0	50.0147	49.0914
	28	10	10	0	50.0092	49.0572
	28	15	15	0	49.9813	48.9791

Table A3. Mortality of adult *Tribolium castaneum* at 14% m.c.
Replication 3

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	3	2	50.0179	49.6397
	28	10	4	6	50.0016	49.6814
	28	15	7	8	50.1028	49.7013
	56	5	4	1	49.9912	49.5104
	56	10	8	2	49.9892	49.4891
	56	15	11	4	50.0191	49.4377
300	28	5	3	2	50.0006	49.4910
	28	10	6	4	50.0075	49.5261
	28	15	8	7	50.0151	49.5814
	56	5	5	0	49.9819	49.2192
	56	10	9	1	50.0209	49.3099
	56	15	12	3	50.0037	49.2362
400	28	5	4	1	50.0073	49.2792
	28	10	8	2	50.0191	49.3515
	28	15	12	3	49.9971	49.3091
	56	5	5	0	49.9815	48.7168
	56	10	10	0	50.0008	48.6819
	56	15	15	0	50.0064	48.5919
500	28	5	5	0	49.9794	48.9812
	28	10	10	0	50.0134	48.9744
	28	15	15	0	50.0097	49.0182

Table A4. Mortality of adult *Tribolium castaneum* at 16% m.c.
Replication 1

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	3	2	50.0141	49.6470
	28	10	5	5	50.0219	49.5546
	28	15	7	8	50.0284	49.5955
	56	5	4	1	50.0086	49.1417
	56	10	7	3	50.0007	41.2306
	56	15	13	2	50.0073	49.1568
300	28	5	3	2	50.0233	49.6044
	28	10	7	3	49.9906	49.5829
	28	15	11	4	50.0010	49.5988
	56	5	5	0	50.0155	48.9772
	56	10	10	0	50.0205	49.0219
	56	15	15	0	50.0047	49.0398
400	28	5	5	0	50.0268	49.2100
	28	10	7	3	49.9943	49.2882
	28	15	12	3	49.9973	49.2952
	56	5	5	0	50.0108	48.1531
	56	10	10	0	49.9929	48.1679
	56	15	15	0	50.0146	48.1733
500	28	5	5	0	50.0263	48.9623
	28	10	10	0	50.0213	48.9285
	28	15	15	0	50.0000	48.7711

Table A5. Mortality of adult *Tribolium castaneum* at 16% m.c.
Replication 2

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	3	2	50.0105	49.7456
	28	10	6	4	49.9854	49.5784
	28	15	8	7	49.9770	49.6386
	56	5	4	1	49.9872	49.3961
	56	10	8	2	49.9859	49.4146
	56	15	11	4	50.0084	49.4385
300	28	5	3	2	50.0287	49.4639
	28	10	7	3	50.0030	49.463
	28	15	8	7	50.0300	49.6918
	56	5	5	0	50.0091	49.1186
	56	10	8	2	49.9917	49.1713
	56	15	15	0	49.9979	49.2041
400	28	5	4	1	50.0028	49.3839
	28	10	10	0	50.0124	49.4877
	28	15	13	2	50.0001	49.4632
	56	5	5	0	50.0178	48.3012
	56	10	10	0	50.0092	48.2744
	56	15	15	0	50.0211	48.1917
500	28	5	5	0	49.8994	48.8897
	28	10	10	0	49.9762	48.9715
	28	15	15	0	50.0294	48.7933

Table A6. Mortality of adult *Tribolium castaneum* at 16% m.c.
Replication 3

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	3	2	50.0029	49.5698
	28	10	5	5	50.0148	49.5172
	28	15	9	6	50.0075	49.5927
	56	5	5	0	49.9978	49.2008
	56	10	8	2	50.0214	49.1799
	56	15	12	3	50.0019	49.1291
300	28	5	4	1	50.0121	49.5572
	28	10	8	2	50.0092	49.6097
	28	15	10	5	50.0009	49.5319
	56	5	5	0	49.9891	49.0792
	56	10	9	1	49.9916	48.9112
	56	15	13	2	50.0015	48.9059
400	28	5	4	1	50.0192	49.1987
	28	10	9	1	50.0090	49.2562
	28	15	13	2	50.0210	49.2219
	56	5	5	0	50.1009	48.1899
	56	10	10	0	50.0078	48.2078
	56	15	15	0	4909954	48.2311
500	28	5	5	0	49.9177	48.7798
	28	10	10	0	49.9432	48.8187
	28	15	15	0	50.0019	48.9932

Table A7. Mortality of *Cryptolestes ferrugineus* at 14% m.c.
Replication I

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	1	4	50.0192	49.7569
	28	10	2	8	50.0160	49.7631
	28	15	4	11	50.0091	49.6891
	56	5	4	1	50.0236	49.5916
	56	10	6	4	49.9934	49.5206
	56	15	10	5	49.9978	49.4529
300	28	5	1	4	49.9989	49.647
	28	10	3	7	50.0080	49.5978
	28	15	6	9	50.0037	49.5762
	56	5	4	1	50.0068	49.2603
	56	10	7	3	49.9977	49.3976
	56	15	10	5	49.9987	49.2023
400	28	5	2	3	50.0058	49.3673
	28	10	7	3	49.9870	49.3465
	28	15	10	5	50.0055	49.3044
	56	5	5	0	50.0022	48.7647
	56	10	10	0	50.0134	48.8197
	56	15	15	0	50.0110	48.6209
500	28	5	5	0	50.0009	48.8765
	28	10	10	0	49.9874	48.9621
	28	15	15	0	50.0114	49.1005

Table A8. Mortality of *Cryptolestes ferrugineus* at 14% m.c. Replication 2

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	0	5	49.9948	49.7779
	28	10	2	8	50.0073	49.7712
	28	15	6	9	49.9941	49.7450
	56	5	3	2	50.0177	49.4975
	56	10	5	5	50.0197	49.5001
	56	15	7	8	50.0304	49.4694
300	28	5	2	3	49.9946	49.7114
	28	10	6	4	50.0070	49.7215
	28	15	8	7	49.9912	49.7014
	56	5	3	2	50.0010	49.2585
	56	10	7	3	49.9941	49.2893
	56	15	12	3	50.0143	49.2742
400	28	5	5	0	50.0157	49.6042
	28	10	6	4	50.0048	49.5511
	28	15	9	6	50.0058	49.5876
	56	5	5	0	50.0218	48.7262
	56	10	10	0	50.0104	48.5411
	56	15	15	0	50.0077	48.6714
500	28	5	5	0	49.9714	48.8971
	28	10	10	0	50.0221	48.8186
	28	15	15	0	50.0087	48.9341

Table A9. Mortality of *Cryptolestes ferrugineus* at 14% m.c.
Replication 3

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	1	4	50.0172	49.6481
	28	10	3	7	50.0009	49.7012
	28	15	5	10	50.0218	49.6825
	56	5	3	2	49.9811	49.5144
	56	10	7	3	49.9932	49.3994
	56	15	8	7	50.0214	49.4543
300	28	5	2	3	49.9822	49.5461
	28	10	5	5	49.9987	49.4811
	28	15	8	7	50.0045	49.5199
	56	5	4	1	50.0074	49.1992
	56	10	8	2	50.0192	49.2974
	56	15	13	2	50.0077	49.2482
400	28	5	4	1	50.0112	49.1989
	28	10	7	3	50.0044	49.2744
	28	15	11	4	50.0095	49.2333
	56	5	5	0	50.0198	48.6382
	56	10	10	0	50.0225	48.5994
	56	15	15	0	49.9898	48.5365
500	28	5	5	0	50.0217	49.0373
	28	10	10	0	50.0184	48.7992
	28	15	15	0	49.9382	48.8571

Table A10. Mortality of *Cryptolestes ferrugineus* at 16% m.c.
Replication I

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	2	3	50.1097	49.6708
	28	10	3	7	49.9952	49.5097
	28	15	5	10	50.0206	49.5755
	56	5	4	1	50.0071	49.1019
	56	10	9	1	50.0027	49.9798
	56	15	9	6	49.9870	49.1420
300	28	5	2	3	49.9944	49.5925
	28	10	5	5	49.9999	49.4069
	28	15	8	7	50.0165	49.5704
	56	5	5	0	49.9916	48.9275
	56	10	8	2	50.0348	48.9809
	56	15	13	2	49.9853	48.9704
400	28	5	4	1	49.9901	49.2838
	28	10	6	4	50.0112	49.2691
	28	15	11	4	50.0009	49.1992
	56	5	5	0	50.0128	47.9906
	56	10	10	0	49.9838	48.2722
	56	15	15	0	50.005	48.1603
500	28	5	5	0	50.0355	48.9465
	28	10	10	0	50.0119	48.7673
	28	15	15	0	50.0050	48.8643

Table A11. Mortality of *Cryptolestes ferrugineus* at 16% m.c. Replication 2

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	1	4	50.0011	49.5853
	28	10	5	5	49.9922	49.5439
	28	15	6	9	50.0108	49.5501
	56	5	3	2	50.0009	49.1401
	56	10	8	2	50.0179	49.1687
	56	15	9	6	50.0043	49.1861
300	28	5	3	2	50.0065	49.5077
	28	10	5	5	50.0178	49.5265
	28	15	7	8	50.0022	49.4797
	56	5	5	0	50.0147	48.9466
	56	10	9	1	50.0144	48.9116
	56	15	14	1	50.0000	48.9422
400	28	5	4	1	50.0009	49.2972
	28	10	8	2	50.0113	49.2847
	28	15	10	5	50.0162	49.2888
	56	5	5	0	50.0070	48.3787
	56	10	10	0	50.0241	48.2994
	56	15	15	0	50.0093	48.3276
500	28	5	5	0	50.0242	49.1332
	28	10	10	0	50.0178	48.9817
	28	15	15	0	50.0024	49.0712

Table A12. Mortality of *Cryptolestes ferrugineus* at 16% m.c.
Replication 3

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	1	4	50.0021	49.5432
	28	10	3	7	50.0135	49.6091
	28	15	6	9	49.9689	49.5239
	56	5	4	1	50.0047	49.2177
	56	10	7	3	50.0019	49.1592
	56	15	10	5	50.0217	49.1409
300	28	5	2	3	50.0191	49.5583
	28	10	4	6	49.9982	49.5172
	28	15	7	8	49.9891	49.4091
	56	5	4	1	50.0314	48.9808
	56	10	10	0	50.0073	49.0411
	56	15	14	1	50.0019	48.9715
400	28	5	4	1	50.0097	49.2573
	28	10	7	3	50.0055	49.2166
	28	15	10	5	49.9914	49.2917
	56	5	5	0	50.0182	48.1664
	56	10	10	0	49.9847	48.3005
	56	15	15	0	50.0078	48.1849
500	28	5	5	0	50.0142	48.8491
	28	10	10	0	50.0079	48.9714
	28	15	15	0	50.0181	48.8019

Table A13. Mortality of *Sitophilus granarius* at 14% m.c.
Replication 1

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	1	4	50.0213	49.7111
	28	10	3	7	49.9838	49.744
	28	15	5	10	49.9955	49.6808
	56	5	4	1	49.9905	49.5454
	56	10	7	3	49.9979	49.4773
	56	15	12	3	49.9835	49.4794
300	28	5	3	2	50.0095	49.6176
	28	10	5	5	50.0058	49.6009
	28	15	10	5	50.0012	49.6034
	56	5	5	0	49.9936	49.1953
	56	10	10	0	50.0095	49.2146
	56	15	15	0	49.9877	49.2649
400	28	5	4	1	49.9791	49.3471
	28	10	8	2	50.0137	49.2838
	28	15	11	4	49.9839	49.3118
	56	5	5	0	49.9971	48.4172
	56	10	10	0	50.0072	48.4994
	56	15	15	0	50.0135	48.5591
500	28	5	5	0	49.9779	48.8805
	28	10	10	0	50.0087	48.8315
	28	15	15	0	50.0155	49.0611

Table A14. Mortality of *Sitophilus granarius* at 14% m.c.
Replication 2

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	3	2	50.0109	49.7126
	28	10	6	4	50.0063	49.8016
	28	15	6	9	50.0029	49.7212
	56	5	4	1	50.0171	49.4858
	56	10	7	3	50.0136	49.4466
	56	15	11	4	50.0104	49.5189
300	28	5	3	2	50.0051	49.6500
	28	10	8	2	50.0003	49.6199
	28	15	10	5	50.0008	49.5286
	56	5	5	0	49.9935	49.3315
	56	10	10	0	50.0024	49.3004
	56	15	15	0	50.0157	49.2468
400	28	5	5	0	50.0111	49.4126
	28	10	9	1	49.999	49.3456
	28	15	13	2	50.0011	49.4266
	56	5	5	0	50.0214	48.5172
	56	10	10	0	50.0007	48.4111
	56	15	15	0	50.0178	48.5448
500	28	5	5	0	49.8949	48.7515
	28	10	10	0	50.0045	48.9223
	28	15	15	0	50.0173	48.8914

Table A15. Mortality of *Sitophilus granarius* at 14% m.c.
Replication 3

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	2	3	50.0214	49.7112
	28	10	4	6	50.0092	49.6382
	28	15	7	8	50.0147	49.6671
	56	5	3	2	50.0198	49.5098
	56	10	8	2	50.0046	49.4462
	56	15	10	5	49.9991	49.4814
300	28	5	3	2	49.9895	49.5781
	28	10	6	4	50.0033	49.5114
	28	15	11	4	50.0128	49.5588
	56	5	5	0	50.0027	49.2815
	56	10	10	0	50.0214	49.1971
	56	15	15	0	50.0194	49.2554
400	28	5	4	1	49.9964	49.3271
	28	10	8	2	50.0166	49.2448
	28	15	13	2	49.9794	49.2819
	56	5	5	0	50.0065	48.5844
	56	10	10	0	50.0188	48.6615
	56	15	15	0	50.0075	48.6114
500	28	5	5	0	50.0273	49.0188
	28	10	10	0	50.0194	48.8493
	28	15	15	0	49.9914	48.9162

Table A16. Mortality of *Sitophilus granarius* at 16% m.c.
Replication 1

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	1	4	49.9975	49.5391
	28	10	3	7	50.0276	49.6269
	28	15	6	9	49.9780	49.4542
	56	5	4	1	49.9896	49.0840
	56	10	8	2	49.9918	49.1797
	56	15	10	5	50.0078	49.1892
300	28	5	3	2	50.0141	49.4139
	28	10	5	0	49.9966	49.5221
	28	15	10	5	50.0017	49.4981
	56	5	5	0	50.0303	49.0301
	56	10	10	0	50.0123	48.9723
	56	15	15	0	50.0297	49.0114
400	28	5	4	1	49.9809	49.2578
	28	10	7	3	50.0057	49.2751
	28	15	13	2	50.0008	49.2899
	56	5	5	0	50.0032	48.0052
	56	10	10	0	50.0178	48.0557
	56	15	15	0	50.0201	48.1471
500	28	5	5	0	50.0367	48.9948
	28	10	10	0	49.9919	48.8588
	28	15	15	0	50.0027	48.9523

Table A17. Mortality of *Sitophilus granarius* at 16% m.c.
Replication 2

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	3	2	50.0042	49.5807
	28	10	5	5	50.0149	49.5462
	28	15	7	8	50.0014	49.6132
	56	5	5	0	50.0211	49.1696
	56	10	8	2	49.9971	49.1941
	56	15	12	3	50.0084	49.1511
300	28	5	3	2	50.013	49.4584
	28	10	8	2	50.0009	49.4650
	28	15	14	1	50.0081	49.4765
	56	5	5	0	49.9875	48.9814
	56	10	10	0	50.0044	49.0221
	56	15	15	0	50.0171	49.0614
400	28	5	5	0	50.0000	49.3768
	28	10	9	1	49.9953	49.3556
	28	15	13	2	50.0070	49.3192
	56	5	5	0	50.0078	48.3217
	56	10	10	0	50.0112	48.2466
	56	15	15	0	50.0018	48.2970
500	28	5	5	0	50.0014	48.8917
	28	10	10	0	49.9877	48.9633
	28	15	15	0	50.0162	48.8283

Table A18. Mortality of *Sitophilus granarius* at 16% m.c. Replication 3

Power, W	Exposure time, s	No: of Insects	Dead	Alive	Initial wt, g	Final wt, g
250	28	5	3	2	50.0049	49.5782
	28	10	4	6	50.1210	49.6514
	28	15	7	8	50.0094	49.6046
	56	5	4	1	49.9891	49.4462
	56	10	7	3	49.9911	49.3578
	56	15	10	5	50.0019	49.4194
300	28	5	4	1	50.0135	49.5377
	28	10	7	3	50.0008	49.5914
	28	15	11	4	50.0174	49.4541
	56	5	5	0	49.9798	49.1926
	56	10	10	0	50.0034	49.2178
	56	15	15	0	50.0176	49.1689
400	28	5	5	0	50.0089	49.4289
	28	10	8	2	50.0214	49.4914
	28	15	14	1	50.0178	49.3994
	56	5	5	0	49.9946	48.3398
	56	10	10	0	50.0078	48.3114
	56	15	15	0	50.0116	48.2898
500	28	5	5	0	49.9811	48.9115
	28	10	10	0	50.0144	48.8994
	28	15	15	0	50.0072	48.8432

Table A19. Mortality of *Tribolium castaneum* larvae at 14% m.c. Replication 1

Power, W	Exposure time, s	No: of Insects	Dead	Alive
250	28	5	3	2
	28	10	4	6
	28	15	7	8
	56	5	3	2
	56	10	9	1
	56	15	12	3
300	28	5	4	1
	28	10	7	3
	28	15	11	4
	56	5	5	0
	56	10	9	1
	56	15	14	1
400	28	5	5	0
	28	10	9	1
	28	15	14	1
	56	5	5	0
	56	10	10	0
	56	15	15	0
500	28	5	5	0
	28	10	10	0
	28	15	15	0

Table A20. Mortality of *Tribolium castaneum* larvae at 14% m.c.
Replication 2

Power, W	Exposure time, s	No: of Insects	Dead	Alive
250	28	5	3	2
	28	10	5	5
	28	15	8	7
	56	5	4	1
	56	10	7	3
	56	15	13	2
300	28	5	3	2
	28	10	6	4
	28	15	12	3
	56	5	5	0
	56	10	9	1
	56	15	13	2
400	28	5	4	1
	28	10	9	1
	28	15	13	2
	56	5	5	0
	56	10	10	0
	56	15	15	0
500	28	5	5	0
	28	10	10	0
	28	15	15	0

Table A21. Mortality of *Tribolium castaneum* larvae at 14% m.c.
Replication 3

Power, W	Exposure time, s	No: of Insects	Dead	Alive
250	28	5	2	3
	28	10	6	4
	28	15	10	5
	56	5	4	1
	56	10	9	1
	56	15	11	4
300	28	5	4	1
	28	10	7	3
	28	15	11	4
	56	5	5	0
	56	10	9	1
	56	15	13	2
400	28	5	5	0
	28	10	9	1
	28	15	13	2
	56	5	5	0
	56	10	10	0
	56	15	15	0
500	28	5	5	0
	28	10	10	0
	28	15	15	0

Table A22. Mortality of *Tribolium castaneum* larvae at 16% m.c.
Replication 1

Power, W	Exposure time, s	No: of Insects	Dead	Alive
250	28	5	2	3
	28	10	6	4
	28	15	10	5
	56	5	4	1
	56	10	7	3
	56	15	11	4
300	28	5	3	2
	28	10	7	3
	28	15	11	4
	56	5	5	0
	56	10	9	1
	56	15	14	1
400	28	5	5	0
	28	10	10	0
	28	15	15	0
	56	5	5	0
	56	10	10	0
	56	15	15	0
500	28	5	5	0
	28	10	10	0
	28	15	15	0

Table A23. Mortality of *Tribolium castaneum* larvae at 16% m.c. Replication 2

Power, W	Exposure time, s	No: of Insects	Dead	Alive
250	28	5	3	2
	28	10	7	3
	28	15	10	5
	56	5	3	2
	56	10	8	2
	56	15	13	2
300	28	5	4	1
	28	10	7	3
	28	15	13	2
	56	5	5	0
	56	10	9	1
	56	15	14	1
400	28	5	4	1
	28	10	10	0
	28	15	14	1
	56	5	5	0
	56	10	10	0
	56	15	15	0
500	28	5	5	0
	28	10	10	0
	28	15	15	0

Table A24. Mortality of *Tribolium castaneum* larvae at 16% m.c.
Replication 3

Power, W	Exposure time, s	No: of Insects	Dead	Alive
250	28	5	3	2
	28	10	6	4
	28	15	10	5
	56	5	4	1
	56	10	8	2
	56	15	13	2
300	28	5	4	1
	28	10	7	3
	28	15	11	4
	56	5	5	0
	56	10	10	0
	56	15	13	2
400	28	5	5	0
	28	10	8	2
	28	15	14	1
	56	5	5	0
	56	10	10	0
	56	15	15	0
500	28	5	5	0
	28	10	10	0
	28	15	15	0

Table A25. Mortality of *Tribolium castaneum* pupae at 14% m.c.
Replication 1

Power, W	Exposure time, s	No: of Insects	Dead	Alive
250	28	5	3	2
	28	10	4	6
	28	15	5	10
	56	5	4	1
	56	10	7	3
	56	15	11	4
300	28	5	3	2
	28	10	7	3
	28	15	10	5
	56	5	4	1
	56	10	8	2
	56	15	14	1
400	28	5	3	2
	28	10	8	2
	28	15	12	3
	56	5	5	0
	56	10	10	0
	56	15	15	0
500	28	5	5	0
	28	10	10	0
	28	15	15	0

Table A26. Mortality of *Tribolium castaneum* pupae at 14% m.c.
Replication 2

Power, W	Exposure time, s	No: of Insects	Dead	Alive
250	28	5	2	3
	28	10	5	5
	28	15	6	9
	56	5	3	2
	56	10	7	3
	56	15	12	3
300	28	5	2	3
	28	10	5	5
	28	15	8	7
	56	5	5	0
	56	10	8	2
	56	15	13	2
400	28	5	4	1
	28	10	7	3
	28	15	11	4
	56	5	5	0
	56	10	10	0
	56	15	15	0
500	28	5	5	0
	28	10	10	0
	28	15	15	0

Table A27. Mortality of *Tribolium castaneum* pupae at 14% m.c. Replication 3

Power, W	Exposure time, s	No: of Insects	Dead	Alive
250	28	5	2	3
	28	10	4	6
	28	15	7	8
	56	5	4	1
	56	10	7	3
	56	15	12	3
300	28	5	2	3
	28	10	6	4
	28	15	8	7
	56	5	5	0
	56	10	7	3
	56	15	13	2
400	28	5	3	2
	28	10	9	1
	28	15	13	2
	56	5	5	0
	56	10	10	0
	56	15	15	0
500	28	5	5	0
	28	10	10	0
	28	15	15	0

Table A28. Mortality of *Tribolium castaneum* pupae at 16% m.c.
Replication 1

Power, W	Exposure time, s	No: of Insects	Dead	Alive
250	28	5	2	3
	28	10	5	5
	28	15	7	8
	56	5	4	1
	56	10	8	2
	56	15	13	2
300	28	5	3	2
	28	10	7	3
	28	15	11	4
	56	5	5	0
	56	10	9	1
	56	15	15	0
400	28	5	4	1
	28	10	8	2
	28	15	11	4
	56	5	5	0
	56	10	10	0
	56	15	15	0
500	28	5	5	0
	28	10	10	0
	28	15	15	0

Table A29. Mortality of *Tribolium castaneum* pupae at 16% m.c.
Replication 2

Power, W	Exposure time, s	No: of Insects	Dead	Alive
250	28	5	2	3
	28	10	4	6
	28	15	7	8
	56	5	4	1
	56	10	7	3
	56	15	13	2
300	28	5	3	2
	28	10	7	3
	28	15	10	5
	56	5	4	1
	56	10	10	0
	56	15	14	1
400	28	5	3	2
	28	10	8	2
	28	15	12	3
	56	5	5	0
	56	10	10	0
	56	15	15	0
500	28	5	5	0
	28	10	10	0
	28	15	15	0

Table A30. Mortality of *Tribolium castaneum* pupae at 16% m.c. Replication 3

Power, W	Exposure time, s	No: of Insects	Dead	Alive
250	28	5	3	2
	28	10	3	7
	28	15	6	9
	56	5	3	2
	56	10	7	3
	56	15	13	2
300	28	5	3	2
	28	10	8	2
	28	15	10	5
	56	5	5	0
	56	10	9	1
	56	15	14	1
400	28	5	4	1
	28	10	8	2
	28	15	13	3
	56	5	5	0
	56	10	10	0
	56	15	15	0
500	28	5	5	0
	28	10	10	0
	28	15	15	0

APPENDIX B: Germination data

Table B1. Germination (%) of 14% m.c. wheat exposed to microwave energy for 28 s

Power, W		Control	250	300	400	500
Replicate	a	92	76	64	52	12
	b	100	84	68	48	8
	c	96	84	68	52	12

Table B2. Germination (%) of 14% m.c. wheat exposed to microwave energy for 56 s

Power, W		Control	250	300	400	500
Replicate	a	92	48	28	4	0
	b	100	44	24	4	0
	c	96	48	24	8	0

Table B3. Germination (%) of 16% m.c. wheat exposed to microwave energy for 28 s

Power, W		Control	250	300	400	500
Replicate	a	100	76	56	44	4
	b	96	80	64	36	4
	c	96	76	60	44	8

Table B4. Germination (%) of 16% m.c. wheat exposed to microwave energy for 56 s

Power, W		Control	250	300	400	500
Replicate	a	100	40	24	0	0
	b	96	36	28	4	0
	c	96	40	24	0	0