Microwave external decontamination of sea containers

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By S. Hinni, J. Holdem, D. McClary
Golder Associates (NZ) Ltd

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Requests for further copies should be directed to:

Strategic Science Team
Policy and Risk Directorate
MAF Biosecurity New Zealand
P O Box 2526
WELLINGTON

Telephone: 0800 00 83 33
Facsimile: 04-894 0300

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Abstract

Shipping containers imported to New Zealand are a potential vector for a range of non-native species, including spiders, insects and snails. This project investigated the possible application of microwave technology to heat invertebrate contaminants on the external surfaces of containers to lethal temperatures, to replace the current practice of using water blasters.

A 5 kilowatt (kW) 915 megahertz (MHz) and a 0.8 kW 2,450 MHz microwave generator were utilised to conduct direct and indirect heating trials of test invertebrate contaminants on a Corten A steel plate. Corten A steel is used in sea container construction. Garden snails (*Cantareus aspersus*), wax moth (*Galleria mellonella*) caterpillars and diamond back moth (*Plutella xylostella*) eggs were used. These organisms were selected to represent the types of organisms found on the outsides of containers, and also to provide a range of sizes which would enable heating effects to be explored. The two microwave generators were not directly comparable, as they had different physical configurations as well as different power outputs.

Initial experiments were conducted with the 915 MHz generator. The direct application of microwave energy to the metal surface for 60 seconds using this machine did not result in an increase in temperature in euthanized snails. It was also found that most of the microwave energy was reflected from the steel surface back into the wave guide that was potentially damaging to the equipment. Experimentation with direct application of microwaves to the metal surface was therefore stopped and work continued using a water layer or heat-conducting media (HCM) applied to the steel surface. This was to test if the microwaves would heat these materials to a level where lethal temperatures could be reached and which would kill organisms on the metal surface.

In initial indirect heating experiments with the 915 MHz generator, some heating of euthanized snails on a water layer was observed. For this an open arrangement was used which allowed the microwaves to escape into the surroundings. A non-lethal maximum flesh temperature of 44.4 ˚C was achieved on a horizontal surface with water layer.

Following these initial results, consideration was given to possible adjustments which might enhance performance. These included running experiments with a 2,450 MHz generator and exploring the use of Faraday cages to provide closed systems without microwave leakage. The use of Faraday cages enhanced performance, but this was not very marked for the 915 MHz machine. With the 2,450 MHz generator, substantial heating of euthanized snails was observed and a maximum temperature of 88.6 ˚C was attained in snails on a water layer. Euthanized caterpillars were, however, only heated to a maximum temperature of 40.8 ˚C. Mortality of the live moth eggs was not significantly different from controls at either frequency (915 MHz and 2,450 MHz) tested. These results were consistent with theoretical predictions, which indicated that small organisms would not be heated as, due to the interaction of the microwaves with the highly conductive steel surface, they reside in an area of low field strength.

Three important principles relate to the feasibility of deploying microwaves for decontaminating containers:

- the field strength is zero immediately at the steel metal surface;
- heating efficiency is directly related to the point of maximum field strength; and,
- the point of maximum field strength usually occurs at a distance from a steel surface which is inversely proportional to the frequency.

Calculations indicated that maximum field strength would not be encountered until 107 mm from the surface for the 915 MHz generator, and 40 mm for the 2,450 MHz machine. The highest commercially available microwave frequency is 5,800 MHz, which would deposit significant heat into organisms of around 17 mm in height, the point of maximum field strength. These calculations indicated that microwaves, while they will be effective against larger organisms such as snails (20 – 29 mm shell diameter), will not be suitable for this application as they are unable to deliver lethal temperatures to small risk organisms, such as ants, caterpillars, moth pupae and moth eggs. Direct heating of such contaminants on the metal surface is not feasible, and it is unlikely that cost effective HCM with appropriate physical properties, particularly their ability to hold the necessary thickness, could be formulated.

The above indicates that microwave technology is unsuitable for the decontamination of sea containers in its current form. One other possible means of application was examined, which was the generation of steam using microwave absorbing Silar® ceramics. The overall cost of this system was, however, considered to be more expensive than when using the standard steam cleaning method.

Electromagnetic radiation may, however, still be an option for decontaminating sea containers. Medium-wave infrared radiation, for example, is of higher frequency than microwaves and may therefore offer some advantages in treating small organisms adhering to the external surfaces of sea containers.

Keywords: Sea containers, external decontamination, microwave technology.

1. General Introduction

1.1 BACKGROUND

Shipping containers imported to New Zealand are a potential vector for a range of non-native species, including spiders, insects and snails, on their external surfaces as well as inside. Some of these may be pests which could have a detrimental effect on the New Zealand economy. For example, Goldson et al. (2005) estimated potential economic impacts from losses in pasture and forage production of $800 million to $2 billion. MAF commissioned this research in order to determine if microwaves have potential application as an improved method for managing external biosecurity contaminants on containers compared with the current practice of using water blasters.

1.2 MICROWAVE TECHNOLOGY

Microwaves are electromagnetic waves with frequencies between 0.3 - 300 gigahertz (GHz) (Figure 1). Microwave energy is generated by a magnetron and these waves are directed to the target via a waveguide (Aymerich et al. 2008). Heating is caused by friction of dipolar components in the target under an oscillating electric field (Fakhouri & Ramaswamy 1993). Water is one of the best sources for microwave interactions due to its dipolar nature and, as a result, microwave radiation tends to be most effective on organisms with high water content (Oliveira & Franca 2002). Microwaves are also particularly effective against organisms with calcareous tubes and shells, as the shell matrix is transparent to this wavelength.

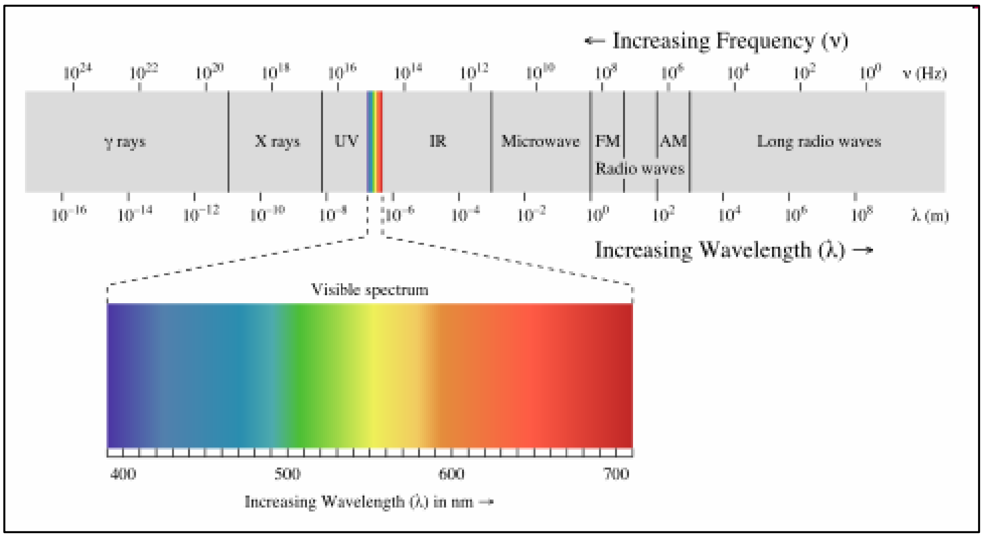

Figure 1: The electromagnetic spectrum. (Source: www.answers.com).

Utilisation of microwaves can, however, be problematic, as their application can result in uneven heating of certain products, due to variations in their dielectric (poorly conducting) properties (Fakhouri & Ramaswamy 1993).

Materials can be classified into three groups based on their dielectric properties and interaction with a microwave field (Shang et al. 2007):

1. Transparent or low dielectric loss materials: microwaves pass through the material with little absorption (e.g. sand, quartz, mollusc shells);
2. Opaque or conductors: microwaves are reflected by the material and do not penetrate (e.g. metals); and

3. Absorbing or high dielectric loss material: microwave energy is absorbed based on the electric field strength and the dielectric loss factor (e.g. water and activated carbon).

It has been shown the dielectric properties of a given material vary with the frequency of the microwaves used (Nzokou et al. 2008), and are considerably dependent on temperature variations when using low frequencies (Oliveira & Franca 2002).

Microwave technology has been employed since the 1940s, particularly in the food industry for cooking, thawing, drying, heating, re-heating, pasteurisation, decontamination and sterilisation (Ayappa et al. 1991, Aymerich et al. 2008, Boldor et al. 2005). Microwave technology was introduced in the 1990s to the fields of chemical engineering (including the polymer and ceramics industry), and medicine (Oliveira & Franca, 2002). More recent investigations have also examined the application of microwave technology to soil and sand decontamination (Kawala & Atamaczuk 1998, Shang et al. 2007), drying and heating of wood products and vulcanisation of rubber (Oloyede & Groombridge 2000, Rattanadecho 2006).

The concept of using microwave radiation as a means of killing pest species has been tested previously, particularly in the timber industry for the eradication of pest organisms in wood and wood products (Fleming et al. 2003, 2004, 2005; Nzokou et al. 2008). Trials using a commercial 2,450 MHz microwave apparatus proved effective at killing long-horned beetle larvae and pine wood nematodes in red pine, as well as Asian longhorn beetles in wood packaging material. These studies identified microwaves as a feasible alternative to conventional heat treatment or methyl bromide fumigation (Fleming et al. 2003, 2004, 2005).

Microwave radiation has also been trialled as a method for the sterilisation of ships ballast water, but initial treatment success was considered to be too variable and the cost too expensive to apply on a commercial scale (Vinograd & Sytsma 2002). More recently, laboratory studies using a 5 kilowatt (kW), 915 megahertz (MHz) microwave generator have resulted in the complete inactivation of microalgae, zooplankton and bivalve larvae when subjected to continuous microwave treatments at power levels of 2.5 kW and 4.5 kW and flow rates of between 1 - 2 L of water/min (Balasubramanian et al. 2008, Boldor et al. 2008).

A series of laboratory experiments conducted by Hinni & McClary (2008) demonstrated that microwave radiation may be suitable for the eradication of non-native infaunal marine organisms living no deeper than 3 cm from the surface. Mortality rates of the shellfish *Nucula* spp. were, however, quite variable and ranged from 0 – 100% after 60 s of radiation when a 5 kW microwave generator was utilised.

1.3 SCOPE OF REPORT

The Ministry of Agriculture and Forestry Biosecurity New Zealand (MAFBNZ) commissioned Golder Associates (NZ) Limited (Golder) to evaluate the practical utility of microwave heating as a tool for the decontamination of external surfaces of sea containers. Sea containers are a potential vector for a variety of exotic species. The results of a recent survey by MAFBNZ suggest nearly 20% of low-risk containers released into circulation from Auckland and Tauranga may harbour risk species on their external surfaces. An improved method of managing this risk is required. Current practice uses water blasting.

This report presents the results of a series of proof of concept trials aimed at determining a suitable method for delivering microwave energy for decontaminating a surface comprised of the same steel used in containers.

The suitability of a method was based on:

- whether lethal temperatures (~ 100 ˚C) could be achieved at the surface of a sea container during microwave exposure;
- the amount of time required to achieve these temperatures; and
- efficacy of the application and removal of a heat conducting medium (HCM), if one was used.

An indirect means of generating steam using a microwave absorbing Silar® ceramics was also assessed. The relative running costs of decontaminating the surface of a sea container using steam by a boiler or by microwave heated Silar® ceramics were examined.

2. Methods

2.1 INTRODUCTION

Two different approaches were assessed during the proof of concept trials: direct heating of biological contaminants and indirect heating. These were chosen due to the interaction of microwaves with metal surfaces. As a near-perfect conductor, the steel surface of a sea container will reflect and dissipate microwaves; the field strength at the metal surface is effectively zero (Figure 2A) (Rizzi 1988). An indirect means of heating the surface was therefore tested by application of a heat conducting medium (HCM), in the form of a gel or foam, to the metal surface prior to exposure to microwave energy. In theory, the HCM would absorb microwave radiation and conduct heat energy to the contaminant on the metal surface (Figure 2B).

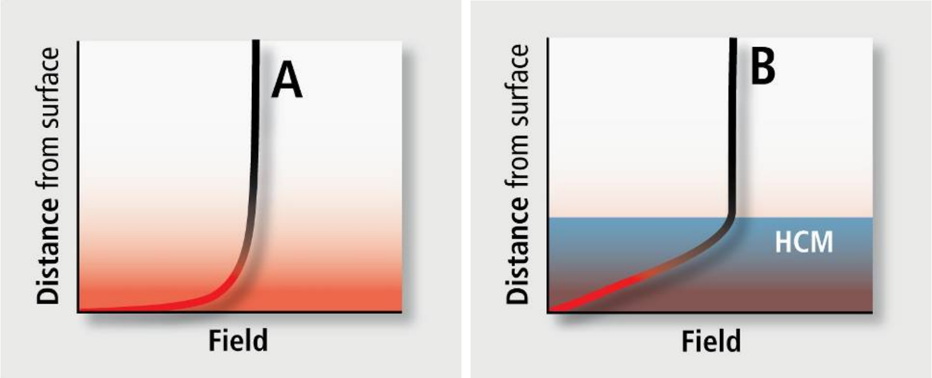

Figure 2: Microwave field strength on surface without (A), and with (B) a HCM.

The HCM tested had to fulfil a number of technical and operational requirements, including:

- low heat capacity (i.e. the amount of heat energy required to increase the temperature of a unit quantity of a substance by a unit of temperature);
- good heat conductor;
- ability to maintain structure and high build (i.e. thickness) during microwave radiation;
- easy and fast production of HCM;
- inexpensive;
- Non-toxic for staff members handling containers;
- adhesive to metal surfaces from all orientations; and
- fast and easy application and removal from the container surface after treatment.

Initial experiments were conducted on the common garden snail (*Cantareus aspersus*) (shell diameter ranging from 20 - 29 mm). Further experiments also included euthanized wax moth (Lepidoptera: *Galleria mellonella*) caterpillars (15 – 22 mm long) and live eggs of the diamond back moth (Lepidoptera: *Plutella xylostella*) (approximately 0.5 mm diameter). Snails and caterpillars were euthanized by freezing at -15 °C and thawed to ambient temperature prior to heating. These organisms were selected to represent the types of organisms found on the outside of containers, and also to provide a range of sizes which would enable heating effects to be explored.

2.2 EXPERIMENTAL SET-UP

The microwave generator used for the proof of concept trials had a power output of 5 kW and operated at a frequency of 915 MHz (Figure 3a). This frequency corresponds to a wavelength of 327 mm in air. Microwave energy was provided to the target on a 500 mm x 500 mm piece of unpainted 3 mm thick Corten A steel via a 280 mm x 160 mm rectangular waveguide/antenna. The generator was manually power controlled and a three-stub impedance tuner was used in the waveguide section to ensure a good match between the generator and the steel surface, which was measured using a calibrated waveguide dual directional coupler that indicated forward and reflective power (Figure 3b). A good match in impedance was obtained when forward power was maximised and reflective power minimised, which resulted in optimum heating of the target.

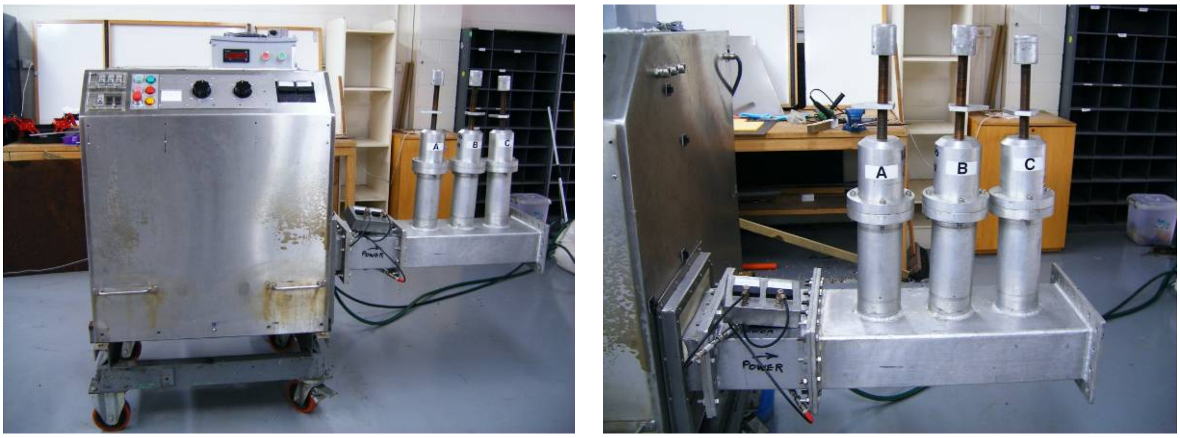

Figure 3: a) Five kW Microwave generator, and b) three-stub impedance tuner (labelled A, B, C) on waveguide with waveguide dual directional coupler.

To minimise the microwave radiation in the surrounding environment while operating the generator, bags of damp sawdust were placed around the waveguide treatment area at approximately 1m distance from the generator as a protective shield (Figure 4). Prior to conducting any experiments, the microwave generator was activated and radiation near the waveguide was measured using a field strength meter (EMF Strength Meter, Extech Instruments) to ensure microwave leakage was within compliance levels (New Zealand Standard 2772). Measurements were taken in a 180º radius and at 1.5 m distance from the waveguide, and at 1 m and 2 m height from the floor.

Figure 4: a) Screen of sawdust bags, and b) Elbow attachment to treat horizontal surfaces.

2.3 TEMPERATURE MEASUREMENT

A k-type thermocouple (Digitech QM-1600) was used for all temperature measurements. The thermocouple, which was calibrated prior to use, was threaded from behind through a 3 mm aperture in the steel plate. The aim was to continuously measure and record the temperature on the metal surface, or contaminant, during radiation; however, microwave radiation was found to interfere with the electronics of the meter and no temperature was displayed while the generator was operating. Thus, the meter was disconnected from the thermocouple while the generator was running.

To record the temperature change over time, the generator was stopped after every 10 s of heating, the thermocouple was connected to the meter and the temperature was recorded. The thermocouple was then disconnected from the meter and microwave radiation applied to the steel plate for another 10 s. The time required to take each measurement was approximately 5 s, during which time the medium was likely to cool down. To determine whether higher temperatures were achieved through continuous heating, measurements were only taken after 60 s of heating in a second trial.

2.4 DIRECT HEATING

To establish whether direct heating was feasible a thawed snail was placed directly over the aperture in the steel plate and microwave radiation was applied for 10 s. Most of the microwave radiation reflected back into the waveguide, measured using the waveguide directional dual coupler; even after adjusting the three-stub impedance tuner in the waveguide, it was not possible to obtain a good match (i.e. low reflective power) between the generator and the steel plate. Further experiments using this method were not conducted, due to the likelihood of the magnetron being damaged by reflected radiation.

2.5 INDIRECT HEATING

2.5.1 Water Layer

A spray bottle was used to apply a layer of water to the steel surface. Temperature was measured as described in Section 2.3. The first measurement was taken in the water layer, ensuring the thermocouple protruded approximately 1 mm from the surface of the metal plate while still remaining in the water. The second temperature measurement was taken in the snail by inserting the thermocouple directly into the flesh. Three replicate exposures each followed by temperature measurement were conducted. Testing was performed on vertical, angled and horizontal surfaces.

2.5.2 Heat Conducting Media

Gelatine was initially chosen as HCM due to its non-toxicity, availability and low cost. Davis Gelatine (GELITA NZ Ltd.) was used for the experiments and several consistencies (7%, 14% and 21%) were tested. To prepare the gelatine, 125 mL of boiled water was poured into a glass beaker and the powder was added (e.g. 3.5 g for 7% consistency) and briskly stirred. After the powder was completely dissolved, another 375 mL of hot water was added to the liquid. The liquid was cooled at room temperature and placed into the fridge at 5 °C for at least 4 h. Depending on the consistency of the gel, it was either sprayed onto the metal surface using a spray bottle, or applied with a spatula. Temperature measurements were either taken by threading the thermocouple through the aperture in the metal, until it protruded around 1 mm while still remaining in the HCM, or by inserting the thermocouple into the flesh of the snail. Three replicate exposures followed by temperature measurements were conducted on vertical, angled and horizontal surfaces.

Initial results indicated that the gelatine lost its textural stability within a short period of heating; further and more suitable HCM were hereafter investigated and those trialled are listed below:

- gelatine with starch (cornflour) added (2%, 4% and 6%);
- agar (melting temperature of 88 °C, 10%);
- water spray between waveguide and steel plate; and
- carpet foam.

2.6 FARADAY CAGE EXPERIMENTS

Experiments with the open system showed that insufficient heating of the contaminant was achieved and therefore, the use of a Faraday cage was tested to increase the effective field strength from the microwave generator. A Faraday cage is an enclosure that prevents the entry or escape of electromagnetic radiation. By minimising the loss of microwaves from the enclosure improved heating of the contaminant was expected. The Faraday cage consisted of an aluminium rectangular funnel (260 mm x 460 mm) attached to the waveguide opening with flexible metal teeth to allow a tight electrical seal between the cage and the metal surface to be treated (Figure 5a). The dimensions of the cage were chosen to encourage several electromagnetic modes, allowing the formation of at least one antinode (the point of maximum amplitude of the microwave) near the steel plate. A perspex transparent window screened with metal mesh from an old microwave oven was built into the cage to enable direct observation of the impact of the microwaves on the targets and HCM.

For this set of experiments, a circulator was installed into the microwave generator to allow direct heating of the contaminant without damaging the magnetron. The circulator ensures that all microwave radiation that is reflected back into the waveguide is directed into a fully absorbing water load (Figure 5a).

Tests using the Faraday Cage were conducted using euthanized (frozen and thawed to ambient temperature) wax moth (Lepidoptera: *Galleria mellonella*) caterpillars and live eggs of the diamond back moth (Lepidoptera: *Plutella xylostella*). Tests on Lepidopteran caterpillars and eggs were conducted using two microwave generators: the 915 MHz generator which was set up as described in Section 2.2 and a 2,450 MHz microwave generator operating at 0.8 kW (Figure 5b). The length and weight of each caterpillar used was recorded. The thermocouple was inserted into the flesh of the caterpillar, microwave radiation was applied and the temperature reached in the caterpillar was measured and recorded. Three replicate tests were conducted on horizontal plates.

The effect of microwave radiation on lepidopteran eggs was tested by irradiating 12 eggs placed on a metal surface with a layer of water for 60 s for both microwave frequency. Three replicate experiments were conducted at each frequency. Survival of the treated eggs was assessed based on the number of eggs that hatched into caterpillars. Statistical analyses were conducted to compare egg hatching rates between control and treatment eggs.

As viability controls, 12 eggs were left untreated on the cabbage leaves. For the two microwave frequencies treatment controls, an additional 12 eggs each were handled in the exact same manner as for the microwave treatments described above except for the application of microwave radiation. All treatment and treatment control eggs were placed in appropriately labelled petri dishes with moist paper towels and maintained at ambient room temperature of between 19 - 20 °C until hatching.

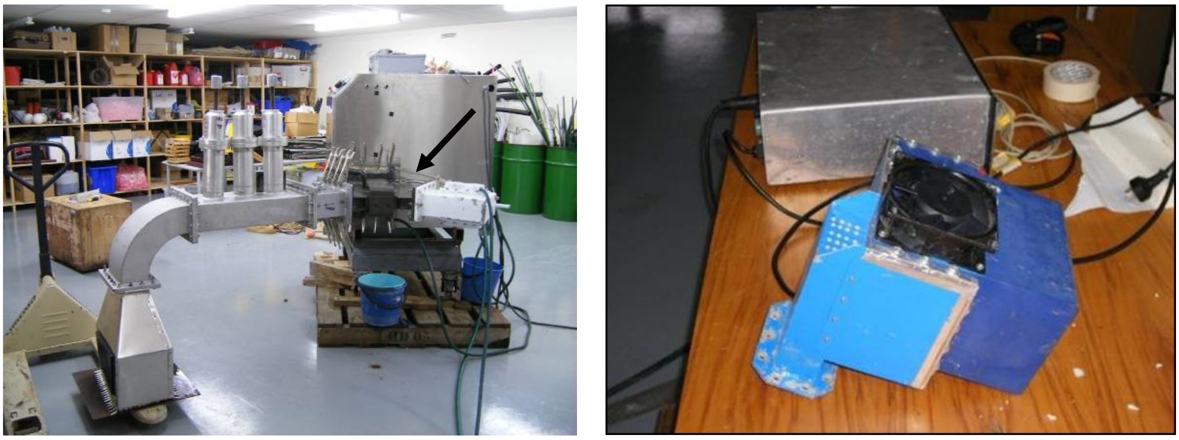

Figure 5: a) Circulator in the 915 MHz generator (indicated by arrow) with Faraday cage attached to the waveguide, and b) 2,450 MHz microwave generator.

The Faraday cage in the 2,450 MHz generator simply consisted of the waveguide flange (internal dimensions: 100 mm x 50 mm) of the generator which was placed directly on the metal surface to prevent loss of microwave radiation from any gaps. Radiation was applied to the contaminant for 60 s for both generators. Three replicate experiments were also conducted on snails to compare heating rates between the two microwave generators. Snails were placed on the centre of the steel plate and irradiated for 60 s each.

Tests were also conducted on known volumes of water in open and closed systems to directly compare the efficiency of the two microwave generators. A small plastic cup (42 mm high and 42 mm radius) was filled with water (55 mL), placed in the centre of the metal surface and heated for 60 s. The open system had a gap of 140 mm between the opening of the waveguide and the metal plate, while in the closed system, the Faraday cage was placed directly on the steel. After heating, the temperature was measured immediately below the water surface and at the bottom of the cup, as well as after stirring the water.

3. Results

3.1 MICROWAVE EXPOSURE LEVELS

The field strength at 1.5 m distance from the waveguide and at a height of 1 m and 2 m ranged from 1 to 8.4 W/m^2. Behind the screen of sawdust bags, radiation measured at 1 m height was 3.6 W/m^2 and at a height of 2 m was 8.3 W/m^2. The microwave field directly in front of the waveguide could not be measured during operation due to health and safety reasons, but would likely have been above maximum exposure levels in the absence of sawdust bags. Under the New Zealand Standard (NZS) 2772 Radiofrequency Fields, Part 1: 1999 Maximum Exposure Levels 3 kHz to 300 GHz, the maximum occupational level of exposure is 22.9 W/m^2. The levels measured around the microwave generator were therefore well within compliance limits. During operation of the microwave generator, all personnel remained at a minimum distance of 1.5 m from the waveguide.

3.2 DIRECT HEATING

This method proved to be unsuitable for the heating of the metal surface due to the high reflection of microwave radiation back into the waveguide, as indicated by the waveguide dual directional coupler. Continuing the experiments could have potentially damaged the magnetron and further trials using direct heating were therefore halted.

3.3 INDIRECT HEATING

3.3.1 Water Layer

There was no appreciable increase in the temperature of a layer of water on a metal surface irradiated with microwaves for 60 s (Figure 6**)**. The highest temperature, after 60 s of continuous heating, of a water layer was measured on a horizontal surface (mean: 25.0 °C, standard deviation (SD) 0.8 °C)

A maximum temperature of 44.4 ºC was recorded when heating a snail on a water layer on a horizontal surface. This temperature was achieved after 40 s of irradiation (Figure 7). No appreciable temperature rise (26.3 ºC, SD 0.3 ºC after 60 s) in the snail was recorded when microwave radiation was applied to a vertical surface. The highest average temperature achieved in the snail after 60 s of continuous irradiation was on a horizontal surface (mean: 44.3 °C, SD 2.7 °C).

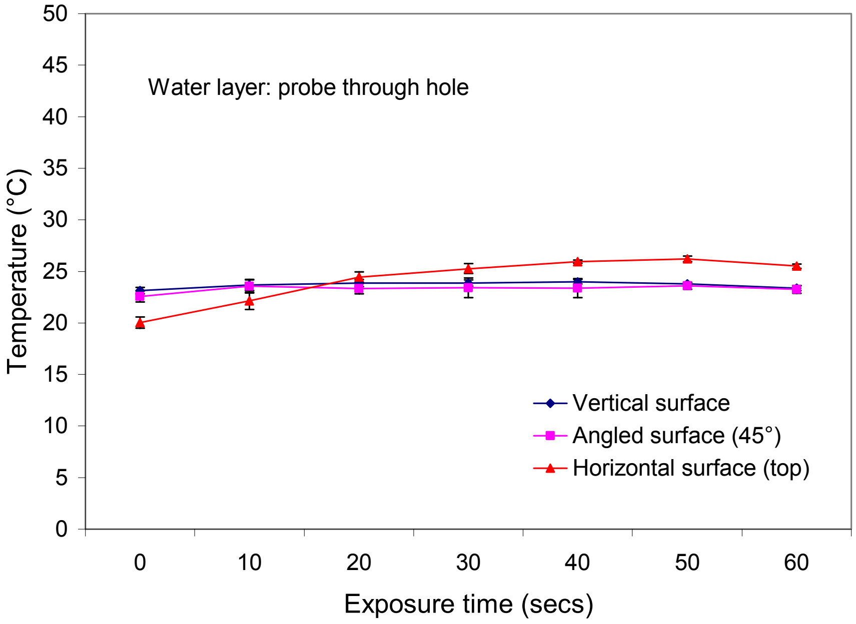

Figure 6: Mean temperature of a water layer following microwave exposure (± 1 SD, n = 3).

3.3.2 Heat Conducting Media

The 7% solution of gelatine was applied to the metal surface using a spray bottle. The 14% gelatine solution had a thicker consistency, but did not remain on the vertical and angled surfaces when applied with a spatula without sliding off the plate.

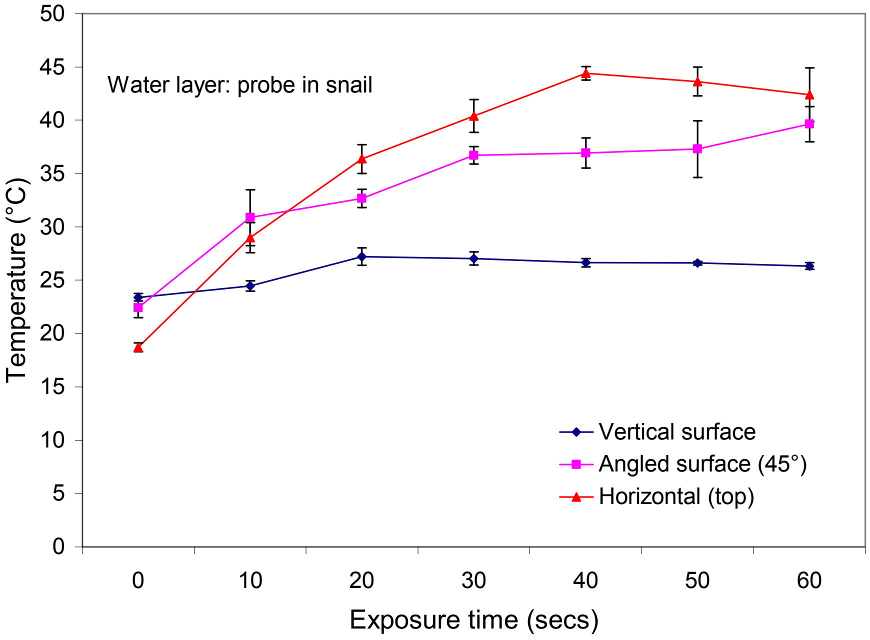

Figure 7: Mean temperature of the flesh of a snail on a water layer following microwave exposure (± 1 SD, n = 3).

The gelatine with the thickest consistency (21% solution) remained on the angled plate when a 10 mm layer was applied with a spatula. It did not, however, remain on the vertical plate and simply slid off the metal surface. On a horizontal surface, the gelatine started to melt within a short period of heating (Figure 8). Average temperatures obtained by heating the gelatine never exceeded 30 ºC (Figure 9). The highest temperature of 41.3 ºC was measured in the flesh of the snail after 50 s of irradiating gelatine on an angled surface (Figure 10). Temperatures measured after 60 s of continuous heating were similar, with the maximum temperature obtained on an angled surface (Mean: 39.3 ºC, SD 0.7 ºC).

Figure 8: a) Gelatine layer on a horizontal surface before heating, and b) after heating.

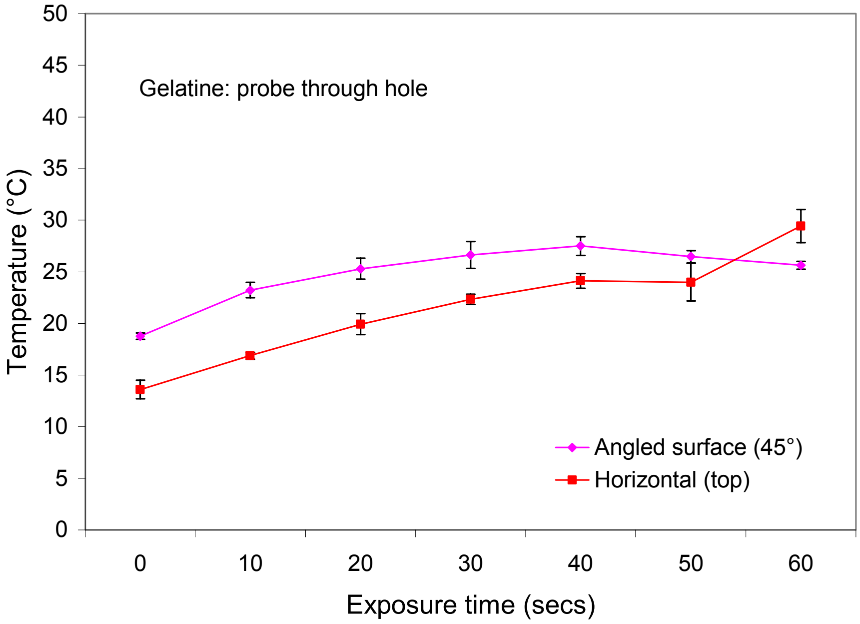

Figure 9: Mean temperature of a gelatine layer following microwave exposure (± 1 SD, n = 3)

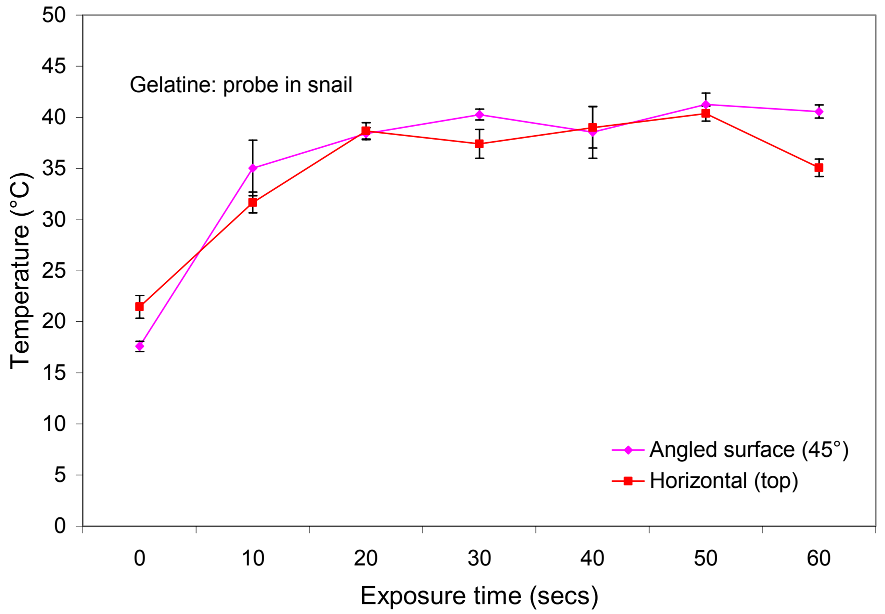

Figure 10: Mean temperature of the flesh of a snail on a gelatine layer following microwave exposure (± 1 SD, n = 3).

A number of HCM were considered and tested to establish whether heating rates could be improved. The justification for their use and the results obtained are outlined in Table 1.

Table 1: Other HCM tested and outcomes achieved.

Medium used	Justification for use	Outcome
Gelatine with starch added	Starch could potentially polymerise and gel the gelatine to reduce melting upon heating.	Similar to the gelatine without starch added, melting of gelatine set in after a short period of heating.
Agar	Agar has a melting point of around 88 ºC and was thus tested to determine whether higher temperatures could be achieved.	Agar was more heat stable than gelatine. A maximum temperature of 32.2 °C was recorded.
Water spray	A spray of water between the waveguide and the steel plate was tested due to its potential to reduce reflection from the metal.	A continuous water spray was applied between the waveguide and the metal steel plate using a garden fertiliser sprayer. No heating was recorded when both, a thermocouple alone was used for temperature measurement, and when using a thermocouple inserted into a snail.
Carpet foam	Foam maintains its structural integrity when applied to the surface and when heated.	The temperatures measured in the inside of the foam reached 55.1 ˚C and 44.6 ˚C after 30 s and 60 s of heating, respectively. The fact that temperature decreased after ongoing radiation is likely due to the changing composition of foam, mostly air, which is considered to have a low heat capacity. Air pockets expanded upon initial heating but collapsed after ongoing heating, thus preventing further temperature rise of the foam. Given the limited testing performed with carpet foam, the results do not appear promising. Other foams that were considered include agricultural marker foam and fire retardant foam. These foams are, however, unlikely to provide better results due to their composition being similar to the carpet foam, i.e. gas bubbles trapped in a liquid.

3.4 FARADAY CAGE

Table 2 details temperatures and hatching success achieved during the Faraday cage experiments at both microwave frequencies. No increase in temperature was observed when using the Faraday cage on the 915 MHz generator; a maximum temperature of 21.5 ˚C was reached after 60 s of radiation (Table 2). The mean weight of the caterpillars used was 0.20 g (± 1 SD 0.03 g) and length was 19.7 mm (± 1 SD 1.2 mm).

Mean hatching of eggs treated at 915 MHz was 51%, while of the treatment controls, 52% of caterpillars hatched. The difference between control and treatment hatching rate was not statistically significant (ANOVA F-Ratio 0.0014, p = 0.97). Of the viability control, where eggs were left untreated on the cabbage leaves, 75% of caterpillars hatched from the eggs.

Some heating in caterpillars was achieved after 60 s of exposure to the microwaves on the 2,450 MHz generator. The maximum temperature measured was 40.8 ˚C and the mean temperature was 39.3 ˚C (Table 2). The mean weight of the caterpillars used was 0.20 g (± 1 SD 0.02 g) and length was 17.7 mm (± 1 SD 1.5 mm). There was no statistical difference between percentage hatching in controls and treatments, at 53% and 52% respectively (ANOVA F-Ratio 0.0023, p = 0.96).

Table 2: Mean temperatures (˚C) in the contaminants with the 915 and 2,450 MHz generators and percentage of eggs hatched (± 1 SD) (n = 3).

Microwave generator	Contaminant	Max Temperature (˚C)	Mean Temperature (˚C)	Percentage of eggs hatched
915 MHz	Eggs	-	-	51.5 (0.15)
	Caterpillars	21.5	21.4 (0.2)	-
2,450 MHz	Eggs	-	-	52.8 (23.2)
	Caterpillars	40.8	39.3 (2.2)	-
	Snails	88.6	53.8 (12.2)	-
Treatment Control	Control eggs	-	-	51.9 (9.1)
Viability Control	Control eggs	-	-	75 (N/A)

Irradiation of garden snails with microwaves for 30 s resulted in a maximum temperature of 88.6 ˚C in one single trial, which was the highest temperature achieved among all experiments. The mean temperature reached was 78.5 ˚C and mean temperature increase after 30 s was 53.8 ˚C. A fizzing sound of water evaporating was heard after 5 - 10 s of heating, indicating temperatures of at least 100 ˚C were reached. After 60 s of radiation, the flesh of the snails was dry and appeared to be cooked.

The water heating experiments, which were conducted to directly compare the energy efficiency of the two microwave generators, showed that maximum heating (94.5 ˚C) was obtained on the water surface with the 2,450 MHz generator in a closed system (Table 3). It was observed that the water in the cup boiled over during the heating and therefore concluded that boiling point was reached with 2,450 MHz.

Table 3: Mean temperatures (˚C) in water (in open and closed systems, i.e. without and with Faraday cage, respectively) (± 1 SD) (n = 3).

Microwave generator	System	Temperature surface	Temperature bottom	Temperature stirred
915 MHz	Open	41.0 (2.4)	34.9 (0.5)	38.2 (2.1)
	Closed	47.7 (1.2)	42.8 (1.4)	45.3 (1.3)
2,450 MHz	Open	33.2 (0.8)	28.9 (0.1)	31.3 (0.8)
	Closed	94.5 (0.1)	72.2 (0.3)	84.3 (0.1)

4. Discussion

4.1 INTRODUCTION

The aim of the current project was to conduct a series of trials to determine the suitability of delivering microwave energy to a steel surface for decontamination. The proof of concept trials demonstrated that a microwave frequency of 2,450 MHz achieved near-lethal temperatures in larger contaminants (i.e. snails). Heating of smaller contaminants (5 mm high), such as caterpillars and very small moth eggs (0.5 mm diameter) was however, problematic in both the 2,450 MHz and 915 MHz frequency generators; using a circulator (in the 915 MHz generator) and Faraday cages resulted in little improvement. Irrespective of the use of microwave frequency, however, field strength at a conducting metal surface is always zero (Rizzi 1988), thus a number of intermediary HCM were assessed.

4.2 EXPERIMENTAL CHALLENGES

The measurement of temperatures during the trials proved an operational challenge, as microwave radiation interfered with the electronics of the thermometer equipment. As such, thermocouples were used for all the experiments. The temperature measured during microwaving underwent a rapid rise and then fall immediately after the thermocouple was connected to the meter. Only when the thermocouple was inserted into the snail tissue after microwaving was completed a stable temperature was observed, which was around 5 - 10 °C higher than if the thermocouple remained in the snail during irradiation. This effect is believed to result from the "temperature waves" (called "slugs" of heat in classical thermodynamics) in the snail flesh, which occurred as a result of the shielding of the part of the snail tissue close to the metallic thermocouple during microwave radiation.

The proof of concept trials indicated that direct heating of contaminants on a steel plate, in the absence of an intermediate heating medium, is not feasible due to the high reflection of the waves. In addition, some results were limited by the difficulty in tuning the antenna to handle the large amount of this power reflected from the steel plate. As a near-perfect conductor, the steel plate simply dissipated microwave energy away from the target point. This was particularly evident with the direct heating trials, where microwave radiation was applied directly to the metal surface.

The reflection of an incident wave from a conducting surface is a basic physical phenomenon and results in currents being induced in the surface, thus increasing the magnetic field at the surface and cancel (in the case of normal incidence) the non-tangential electric field. The tangential electric field is always zero at the surface, for normal and oblique incidence (Rizzi 1988).

As most sea containers have wooden floors, consideration must be made of the effects of microwave irradiation of wooden materials. In comparison to metal, wood provides a different and quite variable substrate for microwave radiation. Wooden materials do not fully reflect the waves (one of the issues when treating metal surfaces), thereby allowing any contaminants to be subjected to a potentially high and lethal microwave field.

In the absence of a resonant structure (the metal surface), a direct wave is necessary for the treatment of wood. This may propagate into the floor or contents of the container with minimal energy loss, depending on container contents, floor moisture level and likely geometry (e.g. thickness of wood, gaps between wooden boards). The incident field required to heat the contaminant on the lower surface of the floor may thus unacceptably heat, or in some cases even ignite, the floor or contents of the container.

When using gelatine as a HCM in experiments involving indirect heating of a metal surface, melting occurred soon after applying microwave radiation. This was followed by a characteristic metallic pinging sound, indicative of destructive heating of the magnetron as a result of an increase in power reflecting back into the waveguide system. In these instances the experiment had to be halted to prevent damage to the magnetron. The installation of a circulator reduced the degree of destructive heating by directing any reflected microwaves into an absorbing water load; heating rates with the circulator were, however, lower. This suggests higher magnitude (more resonant) fields were obtained when the magnetron was subjected to the reflected waves. In other words, without the circulator, waves reflecting back into the waveguide were partially being re-reflected by the magnetron.

4.3 FARADAY CAGE

Initial experiments showed that insufficient heating of the contaminant was achieved and therefore, the use of a Faraday cage was tested to increase the effective field strength from the microwave generator. The use of a Faraday cage with the 915 MHz generator did improve heating to a small extent. The temperature of caterpillars on a steel plate did not increase following exposure to microwave radiation. The use of the 915 MHz generator with the Faraday cage on known volumes of water resulted in water temperatures that were, on average, 6 °C higher with the Faraday cage than when an open system was used. In contrast, temperatures achieved with the 2,450 MHz generator were two to three times higher in the closed system (with a Faraday cage) than in an open system.

The relatively low temperature rise achieved with the 915 MHz frequency can partially be explained by energy loss from the Faraday cage. It is possible there was significant energy leakage from the multiple points used to make electrical contact between the walls of the 915 MHz Faraday cage and the steel surface, despite efforts to form a good electrical “seal” with the steel plate. Occasionally, arcing with localised heating was observed at some points, indicating a loss of energy in the contained field. While a better containment system could theoretically be devised, there is considerable difficulty in forming an efficient electrical contact with a moving steel surface, particularly where HCM fluids are present.

Furthermore, the 915 MHz Faraday cage was large enough to contain multiple electromagnetic modes; multiple modes ensure “hotspots” are widely spread. Thus, heating is homogenised and larger areas can be treated simultaneously. The electromagnetic mode(s) interacting with the known volume of water, however, may not contain a high proportion of the total energy. This was the case when other loss mechanisms were present in the cage, namely contact point arcing. Energy distribution between modes is not controlled by analytic process and can vary strongly during operation, which was reflected in the greater variation in the temperatures achieved when using this system.

Heating with a 2,450 MHz generator, on the other hand, was single-modal only; therefore, stronger heating at a particular antinode (the point of maximum amplitude of the microwave) was obtained, resulting in high temperatures in the contaminant and water layer. In addition, the Faraday cage of the 2,450 MHz generator had flat flanges which provided good conduction on the end wall of the cage. A disadvantage with single-mode heating is that only a small area would be subjected to this higher field.

The use of a higher frequency and therefore shorter wavelength would result in higher field strength closer to the surface. Frequencies of about 50 GHz would be necessary to achieve some heating near a conducting surface. Generators at these frequencies are, however, not currently available and are unlikely to become available in the near future. The difficulties in heating contaminants near the surface without the presence of a suitable HCM are deemed to be insurmountable and it is not considered that adjustments to cage size and shape or "tuning" the generator would overcome the problems encountered. The use of microwave technology is therefore not considered suitable in achieving heating at the boundary of a conducting surface such as steel.

4.4 MICROWAVE FREQUENCY

Tests using the different generators indicated a change in frequency may be as important, or more important, in achieving lethal temperatures as the power input. Higher temperatures were achieved with the higher frequency generator, using a more effective containment system, despite its lower power output. Theoretical considerations indicate microwave generators operating at different frequencies may be suitable for differently sized targets, since frequency is inversely proportional to wavelength (e.g. Metaxas and Meredith 1988).

The field strength is greatest at a distance equivalent to a quarter of the wavelength ($\lambda/4$) (Figure 11), where wavelength $(\lambda)_{Air}$ = speed of light in air (c) / frequency (915 MHz) (Marcuvitz 1951). This diminishes with decreasing distance to the surface and is zero immediately at the metal surface. An increase in the microwave frequency results in the maximum field strength moving closer to the metal surface. For instance, in the 915 MHz generator, it is at a maximum approximately 107 mm from the metal surface. This distance was calculated using:

Wavelength $(\lambda)_{Guide} = \lambda_{Air} / \surd(1 - (\lambda_{Air} / 2 * \text{guide width})^2\ )^{0.5}$

Since all the physical distances are proportional to the wavelength of the electromagnetic wave, the point of highest field strength for the 2,450 MHz generator is thus at 40 mm above the surface. This explains the improved heating observed with the 2,450 MHz generator in snails (to a maximum of 88.6 °C), which ranged from 21 - 29 mm height and were therefore closer to the area of maximum field strength than when using the 915 MHz frequency.

Magnetrons for industrial microwave heating at the higher frequency of 5,800 MHz have recently become commercially available. The maximum field strength for such a generator would be approximately 17 mm above the metal surface. To deposit significant energy into a contaminant or HCM at 5 to 10 mm above the surface, a frequency of approximately 20 GHz would be necessary.

The field strength applied to any organism or HCM is proportional to the square root of the magnetron power (Metaxas & Meredith 1988), indicating the "industrial rate" of eradicating contaminants is controlled by the maximum magnetron power as well as the effectiveness of the coupling of the energy to the organism. Currently, the maximum power output for 915 MHz and 2,450 MHz industrial magnetrons is 100 kW and 20 kW, respectively; a 5,800 MHz magnetron has a maximum power output of 0.7 kW.

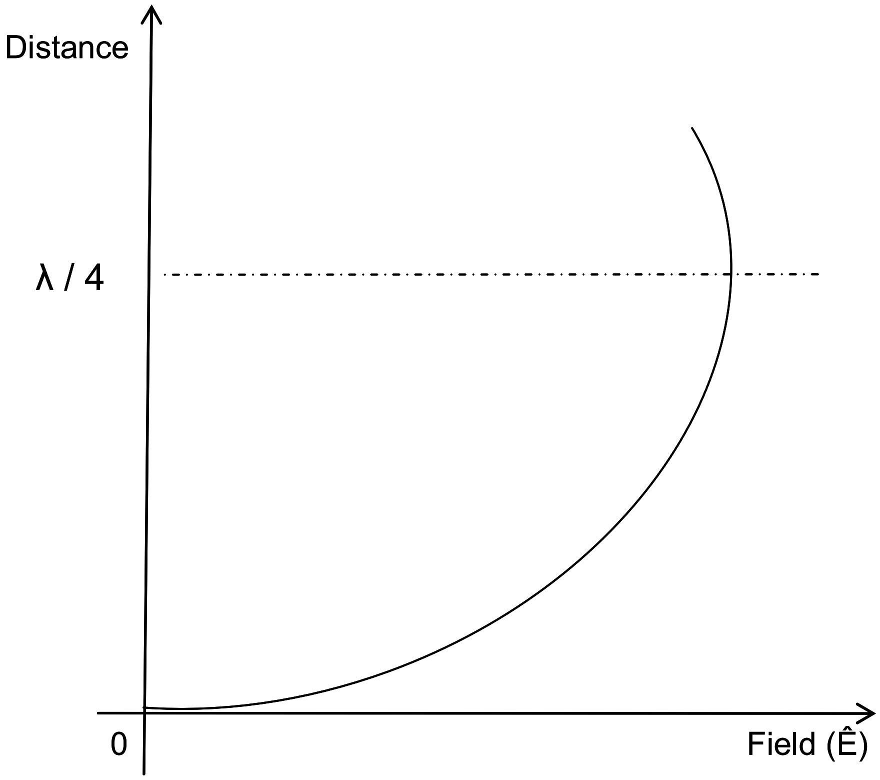

Figure 11: Microwave field strength with distance from the metal surface.

4.5 HEAT CONDUCTING MEDIA

Irrespective of the microwave frequency used for the experiments, field strength is equal to zero at the metal surface. The possible use of HCM were, therefore explored to bridge the gap between the point of maximum field strength several millimetres above the surface and the location of the contaminant on the surface. Ideal HCM would absorb microwave radiation, transform it to heat, and conduct this heat to the contaminant on the surface, thus exposing the contaminant to potentially lethal temperatures. Furthermore, the application of a HCM might temporarily immobilise mobile organisms such as spiders and insects on the container surface and prevent their escape during the treatment process.

A range of HCM were trialled, all of which proved unsuitable. As mentioned in Section 3.3.2, gelatine melted into a thin layer of liquid upon heating, before sliding off the metal plate. In addition, adhesion of solid gelatine was limited, as increasing the angle of the steel plate from 45° to 90° resulted in the gelatine sliding off. As a result, other HCM were tested. Agar, with a melting point of 88 °C, retained its form when microwaving; however, the maximum temperature attained following microwave radiation was 35.5 °C.

Further research into more suitable HCM was, therefore, conducted (including those with thixotropic properties) and discussions were held with experts from related chemical industries. Unfortunately, the many conditions that a suitable HCM had to fulfil resulted into the exclusions of most of the HCM considered. A non-replicated experiment on carpet cleaning foam was conducted. The foam, unlike gelatine, maintained its form of 10 mm in height, but could not be heated to lethal temperatures. Foam is primarily air and is, thus, not able to absorb a significant amount of energy from microwaves. Consequently, foam was also discarded as a HCM.

Microwave eradication has been demonstrated on pest organisms enclosed or surrounded by microwave absorbing materials such as wood, wood packaging material or seawater

(Balasubramanian et al. 2008; Boldor et al. 2008, Fleming et al. 2004, 2005); however, there appear to be no reports relating to experiments involving biological contaminants on metal surfaces. In studies involving wood, wood packaging material or seawater, the contaminants treated were of a similar upper size to those used in this work, but organisms much smaller than the moth eggs employed in the current study were also eradicated successfully. The larger organism treated, the cottonwood borers (*Plectrodera scalator*), which ranged in size from 25 - 38 mm (Fleming et al. 2004), while organisms as small as 1 - 2 µm (the microalgae *Nannochloropsis oculata*) were inactivated in ballast water using microwave radiation (Boldor et al. 2008).

The successful eradication of such small organisms is likely attributable to the microwaves heating the seawater in the vicinity of the organisms to a lethal temperature. Boldor et al. (2008) demonstrated the complete inactivation of microalgae (*N. oculata*), zooplankton (*Artemia* nauplii and adults) and bivalve larvae (*Crassostrea virginica*) after 200 s of exposure to 55 °C seawater. Microwave heating is known to be very effective in water due to its polar nature (Kamala & Atamaczuk 1998). In this current project, water was also considered to be a good basic component of HCM due to its low heat capacity and good heat conductivity. To achieve maximum heating, the water layer would need to have a relatively high volume to reach the region of maximum field strength above the steel plate, which is dependent on the microwave frequency utilised, as discussed in Section 4.4. It was not feasible, however, to apply a thick layer of water on metal surfaces.

4.6 SILAR® TECHNOLOGY

The results of this research indicate that practically-obtainable microwave fields cannot produce lethal heating effects on organisms located on a steel surface.

Another potential approach would be to use Silar® ceramics to provide an indirect means of generating steam and thus decontaminate the external surface of a sea container. Silar® ceramics are a class of chemically inert, stable materials that rapidly absorb microwaves and convert them into heat at any frequency (ACM-USA 2009). Application of microwaves to the Silar® ceramics could, in theory, convert water running over the ceramics into steam which could then be directed to the container surface (Figure 12).

The projected operational costs of a Silar® steam generation system were evaluated. The relative running costs of decontaminating the surface of a sea container using steam by a boiler (Method A), or by microwave heated Silar® ceramics (Method B), were examined.

Generally, there are three main factors which will affect the cost of using steam to treat shipping containers. These are the source cost, the transfer efficiency and the application efficiency. These factors will be evaluated individually and then combined to give overall relative costs.

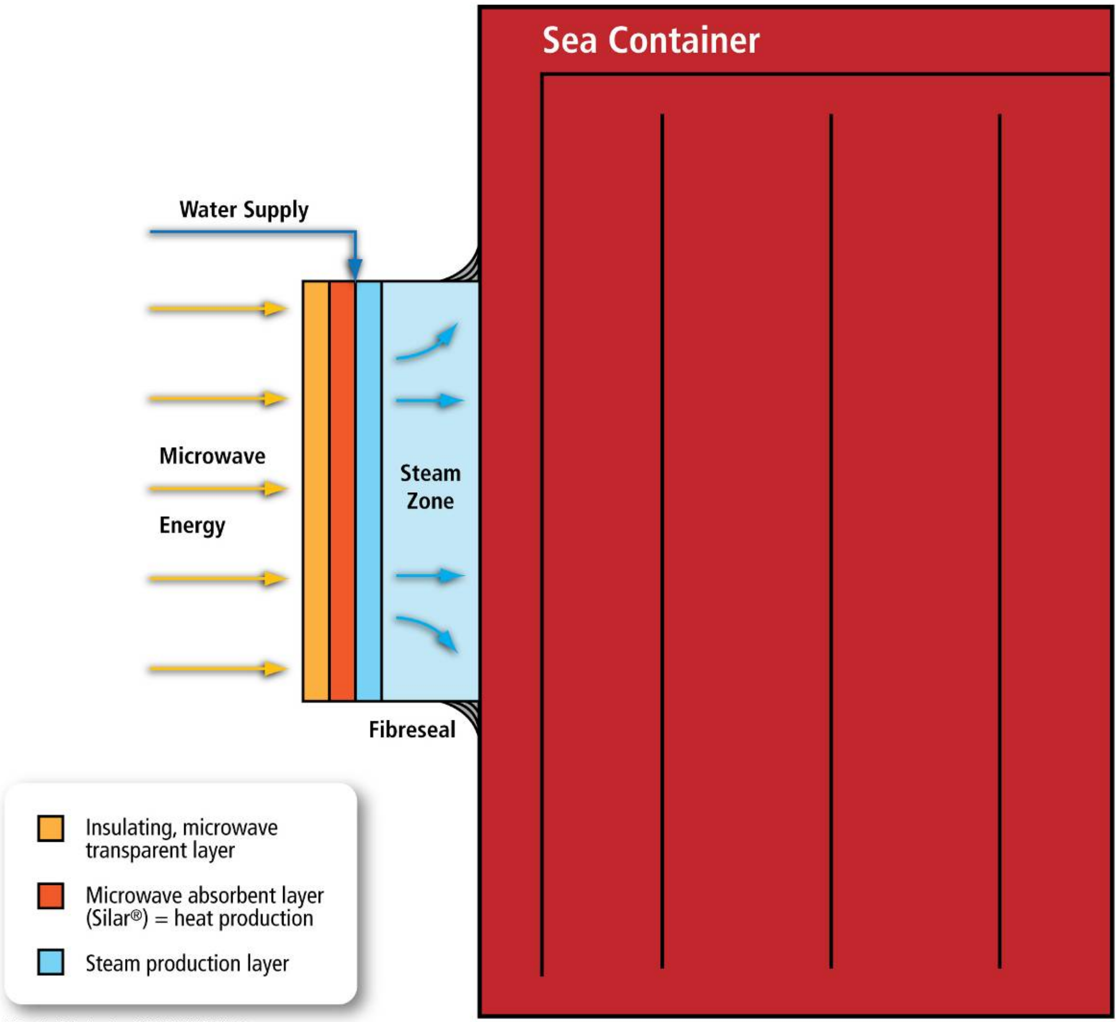

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Figure 12: Silar® lined steam generator system.

4.6.1. Source Cost

The source costs would be significant in both methods if electricity was used in Method A to produce steam; however, gas or oil could be used in Method A, which would reduce the supply costs if these fuels could be procured at a reduced rate. At present:

- Electricity costs about $0.20/kW/h, giving an energy cost of $0.057/MJ (megajoule);
- Gas costs approximately $0.065/kW/h giving an energy cost of $0.018/MJ; and
- Oil (diesel) costs about $1.00/L giving an energy cost of $0.27/MJ, assuming 36.4 MJ/L.

The costs associated with electricity and gas are based on residential retail. Given the efficiencies of producing steam using oil or gas would be expected to be similar, it seems oil would be an option only if the process was required at a location remote from a gas supply (either fixed line or bottled). Thus, the methods to be considered are:

A1 Steam generated by a boiler using gas;
A2 Steam generated by a boiler using electricity; and
B Steam generated by a microwave and Silar® using electricity.

4.6.2 Transfer Efficiency

Transfer efficiency is defined as the efficiency with which the source energy is transferred to heat. The transfer efficiency of Method A1 depends on the efficiency of the gas boiler, which is considered relatively low. Given that the efficiencies of the best combined cycle electricity generating plant is approximately 60% (Power Technology 2009), and an average US plant has an efficiency of ~ 35% (Climate Change 2007), a figure of 40% efficiency is used as a reasonable estimate. The transfer efficiency of Method A2 also depends on the efficiency of the boiler, which can be improved by insulating the boiler properly; efficiencies of up to 95% can be achieved in this manner. The transfer efficiency when using microwaves to generate steam (Method B) depends on the efficiency of converting electricity to a microwave field (about 75%) and the amount of the field that can be absorbed at the container surface (about 90%) giving an overall transfer efficiency of 68%.

4.6.3 Application Efficiency

Application efficiency is defined as the efficiency with which the heat is applied to organisms. It is considered appropriate to assume heat will be transferred most efficiently to an organism when the velocity of the steam is low and the vapour condenses on the organism. The heat or enthalpy of condensation, which is equivalent to the heat liberated by a unit mass of gas at its boiling point as it condenses into a liquid, is 2,257 J/g, while heat liberated when the temperature of a liquid decreases from 99 ˚C to 80 ˚C (for example) is 80 J/g. Since the contaminants comprise a small fraction (approximately 1%) of the treatment volume and/or the treatment surface, the heat will be transferred to the container wall as well as the organism. This applies to all three methods discussed herein.

For Methods A1 and A2, there will be a wide range of application efficiencies obtainable, controlled by a number of factors, including steam nozzle design, steam temperature, target organism size and shape, and nozzle scanning rate, all of which presumably can be optimised. Similarly, there will be a range of application efficiencies obtainable for Method B, assuming the entire microwave field can be gathered by the Silar® ceramic. These application efficiencies are controlled by several factors, including thickness of the Silar® ceramic, distance of the Silar® ceramic from the container wall, effectiveness of constraint of the steam to the volume being treated, rate of water delivery, and target organism size and shape.

If the application of steam generated by Method A1 or A2 and the geometry and rate factors used in Method B are optimised, the resultant application efficiencies will be low, since there is no preferential heating of the organism over the container wall in either case. Also, since there are probably fewer degrees of design freedom for Method B (e.g. position of Silar® ceramic is determined by optimal distance from irradiating microwaves) there is no reason to expect improved application efficiency from Method B than from either Methods A1 or A2. On balance, it is considered (under optimised conditions) that application efficiencies similar to the fraction of the surface occupied by the organism (1%) will be obtained for all methods.

4.6.4 Overall Relative Efficiencies

The costs of each method are presented in Table 4. It is evident that without a significant running cost advantage, the higher projected overall cost of a microwave system may negate any other putative benefit.

Table 4: Overall treatment costs of the three methods.

Method	Source Cost	Transfer Efficiency	Application Efficiency	Overall Relative Cost (per MJ deposited into contaminant)
A1: Steam from gas	$0.018/MJ	0.40	0.01	$4.5
A2: Steam from electricity	$0.057/MJ	0.95	0.01	$6
B: Microwave / Silar®	$0.057/MJ	0.68	0.01	$8.4

4.7 SUMMARY

The proof of concept trials undertaken in this study demonstrated that a microwave frequency of 2,450 MHz can be used to achieve near-lethal temperatures in larger contaminants (i.e. snails). Heating of smaller contaminants, such as caterpillars (height <5 mm), and very small moth eggs (0.5 mm diameter) was, however, problematic.

An increase in microwave frequency is expected to improve heating in smaller contaminants. A higher frequency will generate a field strength maximum closer to the metal surface than a lower frequency, although the field strength at the surface will always be zero. Thus, several heat conducting media (HCM) were assessed; an HCM will absorb microwave radiation and conduct heat energy to the contaminant on the surface. Due to the many requirements such an HCM had to fulfil, however, suitable materials to fulfil this function could not be found in this study.

The HCM and Silar® methods are somewhat inefficient since they heat the container wall as well as the contaminant. It is considered that none of these methods have sufficient promise for the decontamination of containers and no further experiments, even using the higher microwave frequency of 5,800 MHz, are recommended.

4.8 FUTURE DIRECTIONS

The results of this investigation suggest it is not possible to decontaminate a metal surface using readily available microwave technology. Magnetrons with a higher frequency, but initially at a low power (e.g. 1 kW at 20 GHz) may become available in the future, and these may be used for specific small organism decontamination, provided the organism is heated preferentially to the metal surface.

There are other methods of delivering electromagnetic energy to the organism and not the container wall that should be considered. The “normal field” method is one such method, in which an electrode, energised by electromagnetic frequencies, would scan along a steel surface while generating a strong component field normal to the wall surface and in the region between the wall and the electrode. The electric field vector would point from the electrode to the container wall, with the same field strength (V/m) at all points on this path, emitting a significant field in the unwanted organism.

The “normal field” method would not have to heat the container wall, but would probably have to operate at a lower frequency to avoid radiating power away from the treatment area, which would require higher field strength. The higher field strength needed, as a result of the lower frequency, would, however, increase the risk of arcing. Furthermore, it would not be feasible to maintain this field at internal corners (in two or three dimensions) and on nonconducting surfaces (e.g. wood or plastic). This method would need to be used in combination with another method to ensure these problems were overcome.

The efficiency analysis for the Silar® method presented in Section 4.5 demonstrated the main loss of efficiency occurs during the application stage. A medium-wave infrared radiation system would appear to offer a significant advantage in this regard, as it would preferentially heat the moist organism rather than the container, which may improve overall energy efficiency. Infrared radiation is non-ionising electromagnetic radiation with wavelengths between those of microwaves and visible light (rather nearer to visible light). Medium-wave infrared radiation has wavelengths of between 5 - 10 µm; thus offering some advantages in treating smaller organisms, which were shown to be unaffected by microwave radiation. Efficiency of use is achieved by matching the wavelength of the infrared heater to the absorption characteristics of the materials.

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