

# Quarantine treatment of cherries using 915 MHz microwaves: temperature mapping, codling moth mortality and fruit quality

J.N. Ikediala<sup>a</sup>, J. Tang<sup>a,\*</sup>, L.G. Neven<sup>b</sup>, S.R. Drake<sup>c</sup>

<sup>a</sup> Department of Biological Systems Engineering, Washington State University, 213 L.J. Smith Hall, Pullman, WA 99164-6120, USA

<sup>b</sup> USDA-ARS Fruit and Vegetable Insect Research Laboratory, 5230 Konnowac Pass Road, Wapato, WA 98951, USA

<sup>c</sup> USDA-ARS Tree Fruit Quality Laboratory, 1104 North Western Avenue, Wenatchee, WA 98801, USA

Received 12 October 1998; accepted 16 February 1999

## Abstract

Sweet cherries (*Prunus avium* L.) were treated by 915 MHz microwaves in a pilot-scale multimode microwave system with an auxiliary hot air heater to determine heating characteristics and the effect of treatments on insect mortality and fruit quality. Quality parameters of the microwave-treated 'Bing' cherries were compared with control fruit and those subjected to methyl bromide fumigation. When heating cherries to average pit temperatures of 45, 50 and 55°C, the cherry pits heated faster than the surface, and larger cherries heated more quickly than smaller ones. Cherry temperature increased linearly with time with heating rates dependent on the microwave power, sample weight, cherry size and radial location inside the cherry. With a 2 min holding and 5 min hydrocooling protocol after microwave treatments, adjusted percentage 3rd instar codling moth (*Cydia pomonella* L.) mortality ranged from 5 to 62% and 39 to 98% without and with 1–2 days cold storage, respectively. A higher mortality rate was obtained for insects in 'Bing' than 'Rainier' fruit. Firmness, percentage soluble solids content, titratable acidity, fruit weight, and objective fruit colour of microwave-treated 'Bing' fruit were comparable with these properties of control fruit and to those of cherries fumigated with methyl bromide. Stem greenness colour was reduced after the microwave and dry hot air combined treatments. Microwave energy may provide an alternative non-chemical quarantine treatment against codling moth in export cherries, but further study is needed to optimize the treatment protocol for insect control and fruit quality. © 1999 Elsevier Science B.V. All rights reserved.

**Keywords:** Quarantine; Codling moth; Cherries; Heat treatment; Microwave; Quality

## 1. Introduction

Codling moth (*Cydia pomonella* L.) is a quarantine pest of US cherry (*Prunus avium* L.) and other stone and pome fruits and requires unique

\* Corresponding author. Tel.: +1-509-3352140; fax: +1-509-3352722.

E-mail address: jtang@mail.wsu.edu (J. Tang)

postharvest treatments for markets such as Japan and South Korea (Anon., 1950, 1982). Although fumigation with methyl bromide (MeBr) is still the accepted treatment against codling moth (Guance et al., 1981; Anon., 1983; Yokoyama et al., 1990; Moffitt et al., 1992), MeBr has been identified by the US Environmental Protection Agency (EPA) under the Federal Clean Air Act (Anon., 1990) and by the Montreal Protocol (Anon., 1995) as having a high ozone depletion potential. EPA has mandated the removal of MeBr from the chemical register and the phase-out of the production and import into the United States (similar legislation passed in other industrialized countries) by December 31, 2005. Although phytosanitary and quarantine use of MeBr were recently exempted by the US Congress, an alternative quarantine treatment protocol is still needed for cherries and other export pome and stone fruits and nuts because the cost of MeBr may become prohibitive after 2005. With worldwide interest in reduced pesticide use, effective non-chemical quarantine treatment alternatives are urgently required.

Different thermal treatment methods have been investigated as an alternative to MeBr fumigation (Yokoyama et al., 1991; Sharp et al., 1991; Neven, 1994; Neven and Rehfield, 1995; Neven and Mitcham, 1996). Varying degrees of efficacy were reported with different time–temperature heat treatments alone and in combination with cold or controlled atmosphere storage conditions (Sharp, 1993; Neven, 1994; Neven and Rehfield, 1995; Neven and Mitcham, 1996; Neven et al., 1996; Soderstrom et al., 1996). Work by these researchers has shown that prolonged heat treatments of up to 4 days (vapour, moist and dry forced hot air, hot water dips) and temperatures ranging from 38 to 51°C were promising in achieving codling moth control. Soderstrom et al. (1996) showed that it would take about 730 h to obtain probit 9 quarantine security for codling moth at 39°C. Prolonged heating could be detrimental to quality of fresh produce. Rapid volumetric heating by microwave energy may be a viable alternative to maintain fruit quality. The use of high temperature/short time processes in commercial pasteurization and sterilization to kill

or reduce counts of undesirable biochemical and pathogenic microorganisms in foods results in better quality retention (Lund, 1977; Ohlsson, 1980). Yokoyama and Miller (1987) also mentioned the need for short exposure periods if heat treatments are to be incorporated in packing-house handling procedures.

Microwave technology is increasingly used in the food industry. The heating method leaves no chemical residues on the fruit and has minimal impact on the environment. Since certain developmental stages of the codling moth larva reside and feed in the fruit core, targeted heating due to the microwave energy's centre-focusing effect in near spherical objects could be exploited to advantage. Thus, the core of the fruit, which takes much time to heat up by conventional methods, could be raised quickly to the desired temperature, leaving the total fruit volume average temperature below the critical temperature that might cause quality loss.

Feasibility of microwave disinfestation of insect pests has been explored by Andreuccetti et al. (1994) for woodworms and by Halverson et al. (1996) for wheat, maize and flour weevils. Nelson (1996) reviewed and summarized more than five decades of research on the susceptibility of various stored grain insect species to radio frequency and microwave treatments. Hallman and Sharp (1994) also summarized research on the application of radio frequency and microwave heat (electromagnetic energy) treatments to kill different pests on many postharvest food crops. Most of the reported research, however, concentrated on using radio frequency (between 13 and 40 MHz), 2450 MHz microwave frequency, or much higher frequency (10.6–55 GHz) electromagnetic energy against stored grain weevils (*Tribolium* spp.). Little is reported on the use of 915 MHz microwaves to achieve quarantine security and the quality of microwave-treated fresh produce. The two microwave frequencies approved by the US Federal Communications Commission for heating applications are 915 and 2450 MHz. The 915 MHz microwaves are characterized by longer penetration depths in fruits and vegetables and a higher energy efficiency than 2450 MHz microwaves (Giese, 1992). Using 915 MHz microwaves, there-

fore, may have the advantage of better core heating in large and small fruits.

The objective of this research was to determine the 915 MHz microwave heating pattern and temperature distribution in cherry fruits and to study the behaviour and mortality of codling moth larvae in infested cherries during microwave heat treatments. This study also examined the impact of the treatments on cherry quality.

## 2. Materials and methods

### 2.1. 915 MHz microwave system

A pilot-scale 915 MHz microwave system was used for the treatments (Fig. 1). The 915 MHz microwaves were generated by a 5 kW power generator (Model IV-5, Microdry Inc., Crestwood, KY) with a multimode stainless steel microwave cavity ( $1.07 \times 1.22 \times 1.47$  m). The power

unit transformed a 480 V power supply to 7500 V required by the microwave generator (magnetron). The magnetron converted electric energy into microwaves that were directed to the cavity via rectangular wave guides and a circulator. The generator provided microwave power from 0.2 to 5 kW. Stability and control of the power output was maintained by the feedback of a 4–20 mA control signal from the magnetron anode current. Power meters and other control instrumentation monitored microwave power input to, and reflected power from, the cavity. The reflected waves from the cavity were directed to a matched water load by the circulator, thus preventing it from damaging the magnetron. Uniformity of the microwaves in the cavity was enhanced by a stirrer (0.87 m diameter, 15 rpm) and a turntable (0.61 m diameter, 1 rpm). The microwave unit incorporated an auxiliary hot air heating unit with an electric heater capable of delivering up to 10 kW. A variable speed fan blew the hot air

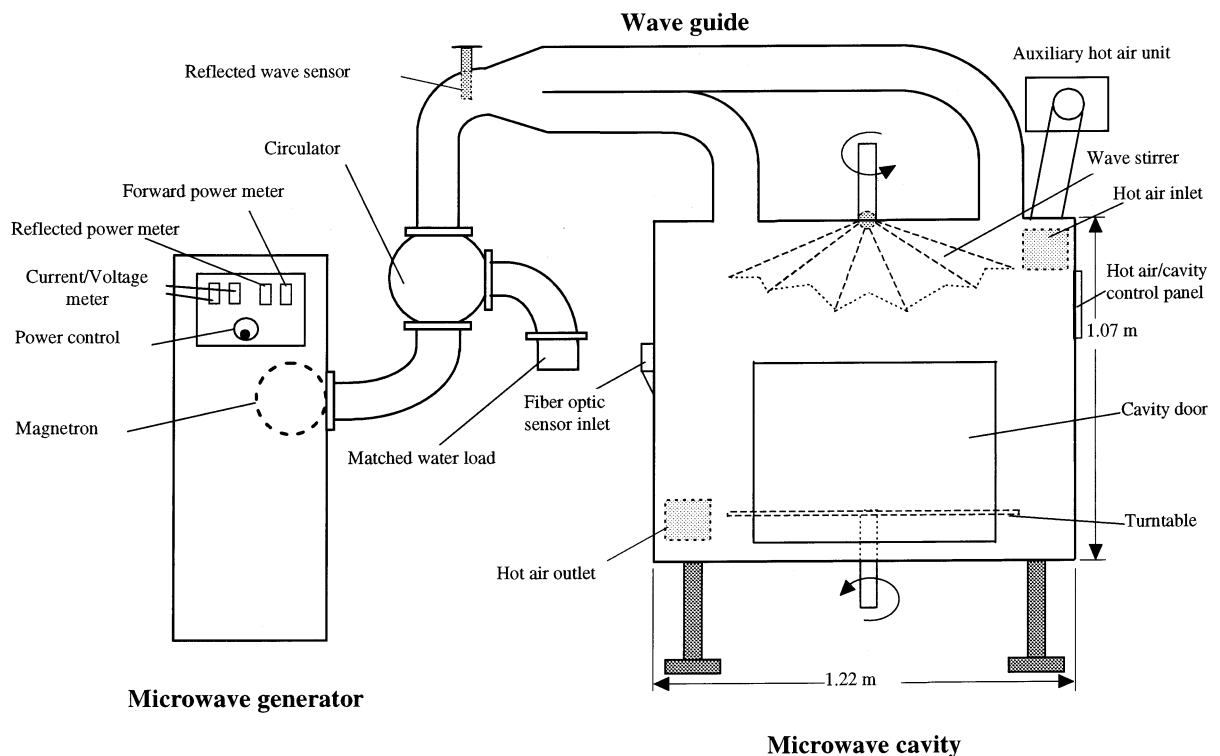


Fig. 1. Schematic diagram of the pilot-scale 915 MHz microwave heating/drying system at Washington State University.

across the cavity. The discharged hot air can be re-circulated by closing an external outlet air duct window. The auxiliary hot air was operated independent of the microwave unit. With a control panel and instrumentation, the temperature of the hot air delivered to the oven cavity was controlled at the set point temperature with a steady state stability of  $\pm 1^\circ\text{C}$ .

## 2.2. Temperature mapping and insect mortality tests

Cherries were procured from Wenatchee or Wapato, WA and held at room temperature ( $\sim 23^\circ\text{C}$ ) before mapping tests. Cherry sample temperatures were measured using four fiber optic sensors and a Photonetic data acquisition system (Photonetics Inc., MetriCor Div., Wakefield, MA) at 1 s intervals. Probes were placed close to the pit or close to the surface of cherries to determine heating characteristics before the mortality tests. Due to the low flexibility of the probe cables, the microwave turntable was not used during temperature profile mapping tests in which temperature–time data were recorded using the data acquisition system, to prevent the sensors from shifting in the cherries. The turntable was, however, used in average fruit temperature mapping, insect mortality and cherry quality tests. Separate tests were conducted with ‘Bing’ fruit to confirm average cherry temperatures using the turntable. In these tests, fruit temperature was measured immediately after the microwave heating using a type T thermocouple thermometer (Barnant 115; Barnant Co., Barrington, IL) with a response time of 0.8 s. While establishing the protocol for the treatments, it was observed that final temperature attained depended on cherry fruit size. Cherries ranged in size from 3.1 to 13.5 g and the size variation and differences derived from the source or the batch. This effect was later investigated, but cherries from one source and of fairly uniform and average size (7–9.5 g) were used in the mapping for mortality and quality tests. Furthermore, we noted that some of the insect larvae remained on the surface of the fruit. Thus, to enhance the heat treatment of these with the microwave, hot air was blown across the samples in the cavity for 2

min. The hot air unit, with set point temperature the same as the targeted microwave treatment temperature level, was started at the maximum blower power ( $\sim 9 \text{ m s}^{-1}$  air flow rate) 1 min before the end of microwave heating and continued for 1 more min. At the end of the microwave treatment, samples were left on the turntable for 2 min (1 min after termination of the complementary hot air treatment) to allow the heat to redistribute by conduction in the cherries and impart added lethality, before being transferred into nylon mesh bags and placed in iced water at  $0^\circ\text{C}$  for 5 min, to minimize possible prolonged heat damage due to slow cooling by natural convection.

Carton boxes containing 100 ‘Bing’ or ‘Rainier’ cherries were infested overnight with 3rd instar codling moths at a ratio of one larva per cherry. The insects were reared at the USDA-ARS Fruit and Vegetable Insect Research Laboratory in Wapato, WA on artificial diet developed by Toba and Howell (1991). The larvae were transferred with a camel’s hair paint brush onto the cherries. The boxes containing the infested cherries were covered with nylon mesh and shipped to Washington State University, Pullman the following day for microwave treatment. Six separate batches of infested cherries (four batches of ‘Bing’ and two of ‘Rainier’ fruit) were shipped to Pullman for treatment in June and July 1997. Each batch had between 6 and 15 boxes of infested (100 per box) fruits. For each test, the 100 fruits initially at room temperature ( $23^\circ\text{C}$ ) were placed on the periphery of the microwave cavity turntable and treated to core temperatures of 45, 50 or  $55^\circ\text{C}$ , held for 2 min and hydrocooled for 5 min. The treatment at each temperature level was repeated 2–5 times. Treatment temperatures of 45 and  $50^\circ\text{C}$  are within the lower and upper ranges employed in conventional thermal treatments, respectively, while  $55^\circ\text{C}$  is a bit higher than reported in the literature for cherries. However, up to  $55^\circ\text{C}$  has been employed for other crops and insects. Based on preliminary investigations with ‘Bing’ cherries, the corresponding heating times at 1 kW power output of the microwave (with  $\sim 0.11 \text{ kW}$  or about 10% reflected power) ranged between 2 and 5 min to achieve the above temperatures.

Each batch was accompanied by a box (100 fruits) of infested cherries as the control which was also hydrocooled for the same time as the treated samples. The hydrocooled samples were left for 15 min at room temperature to remove surface water before being transported back to USDA-ARS Insect Research Lab in Wapato, WA for subsequent analyses. Samples to be placed in cold storage later were first put in coolers with ice packs and then transferred into normal commercial cherry storage rooms ( $\sim 1^{\circ}\text{C}$ ) on arrival at Wapato, for 1–2 days. Although 100 instars were infested in each box of 100 fruits before shipping, only 65–89 (control) and 78–91 (treated) larvae were recovered during analysis. In six batches of tests and three temperature levels, a total of 466 larvae in the control and 4883 larvae in the microwave treatments (3560 for ‘Bing’ and 1323 for ‘Rainier’ fruit) were recovered. Mortality was calculated based on the total number of recovered insects, and assessed on half the treated fruit after 24 h and on the rest 24 h after cold storage to reduce the effects of cold stupor and allow easy assessment of mortality by examining for surviving larvae. Dead larvae were determined as those that showed no movement, while moribund larvae showed very little or sluggish movement when prodded with a blunt instrument. Moribund larvae were held for 7 additional days at room conditions on thinning apples and then assessed for survival (Neven and Mitcham, 1996). Adjusted mortality was obtained by correcting for natural mortality in the controls according to Abbott (1925).

### 2.3. Cherry quality parameters

Freshly harvested ‘Bing’ cherries were transported from Wenatchee, WA to Washington State University, Pullman, WA for the study of fruit quality after microwave treatment. ‘Bing’ cherries and controls were treated similarly to the infested cherries. Treated samples and control fruit were then put back into cold storage at the USDA-ARS Tree Fruit Quality Laboratory in Wenatchee, WA for quality analysis. In order to compare the quality of the microwave-treated cherries with cherries treated with MeBr fumiga-

tion, samples from the same batch were treated with microwave and with MeBr in the fumigation chamber at USDA-ARS lab, Wapato. To simulate commercial practice, cherries were also stored at  $1^{\circ}\text{C}$  for up to 2 weeks to determine the impact of storage on the quality of the treated fruit. Firmness, percentage soluble solids content (SSC), titratable acidity (TA), fruit weight, and fruit and stem colours (Hunterlab values) were determined as described by Drake et al. (1991), after 0, 7 and 14 days in storage. The GLM procedure of SAS (SAS Institute Inc., 1990) was used for analysis of variance. The Least Squares Difference (LSD) and Duncan’s Multiple Range Tests were used to determine differences between means of treatments for each storage period.

## 3. Results and discussion

### 3.1. Temperature mapping and heating characteristics

Due to the small size of cherries and the batch nature of the microwave unit, samples had to be matched to the microwave power/load input. Although theoretically there is an infinite combination of power input settings and sample sizes, 100 cherries were used because this number provided an average rate of heating and load matching for the selected 1 kW power setting. The 1 kW power setting provided a fairly high heating rate as well as sufficient time for the turntable to complete at least one rotation to improve uniformity of heating. A representative plot of the heat treatment protocol used in the quality and insect mortality tests is shown in Fig. 2. The ratio of heating rates at the pit and close to the fruit surface was about 1.5. A centre-focused heating was, therefore, evident during 915 MHz microwave heating of cherries. This phenomenon was expected, confirming reports by Ohlsson and Risman (1978) and Ohlsson (1983) that a pronounced microwave centre heating effect occurs for spheres of diameters 25–60 mm (cherry diameters ranged from 19 to 30 mm). Temperature increased linearly with time at about  $6.5^{\circ}\text{C min}^{-1}$  with the sample size and power setting. The heating rate was quite high,

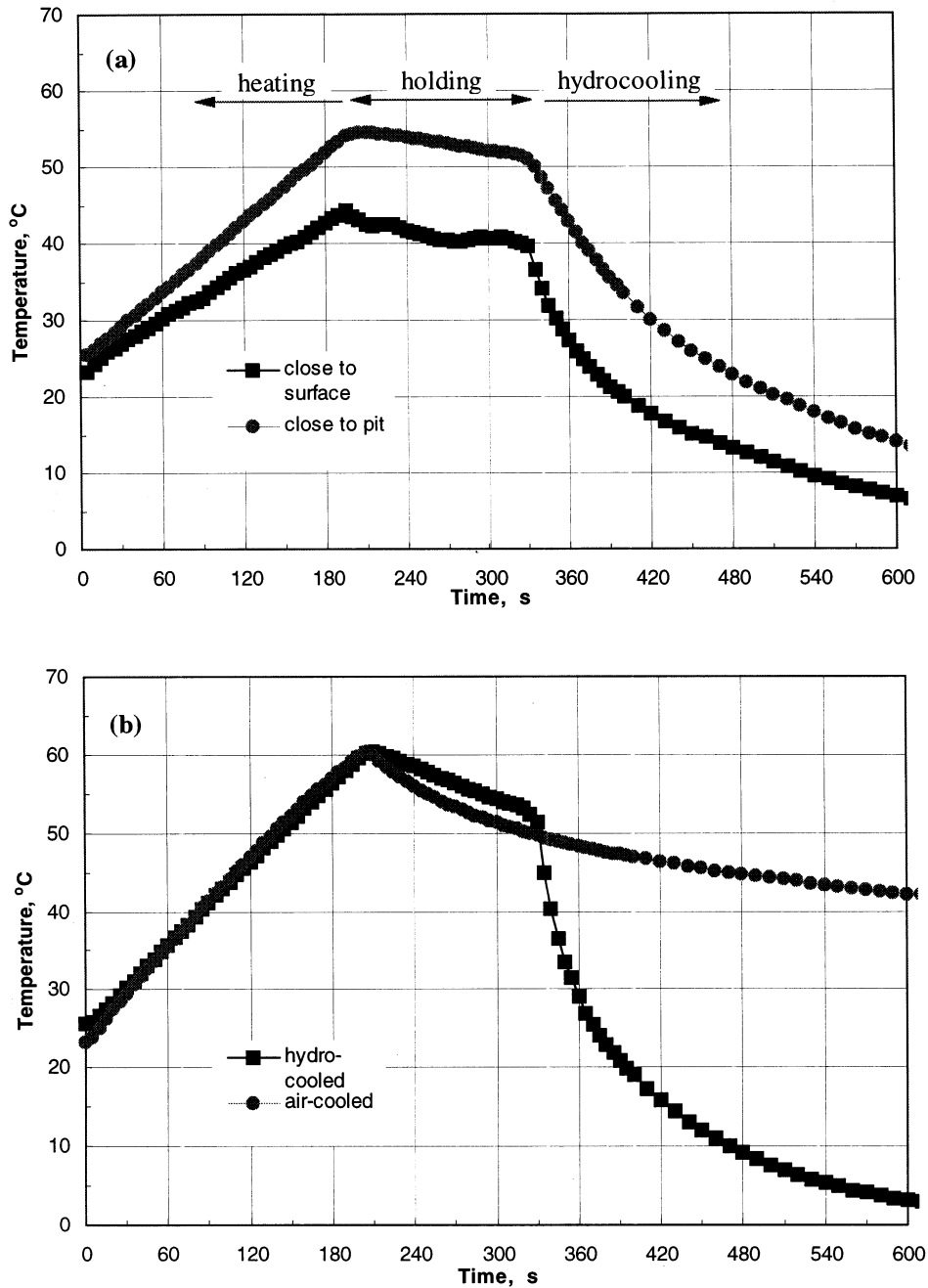


Fig. 2. Temperature mapping in sweet cherries during 915 MHz microwave treatment: (a) 'Bing' cherry showing temperature distribution between pit and surface, and protocol used in insect mortality and quality tests; (b) 'Rainier' cherry pit temperature profile showing effect of air and hydrocooling after heat treatment.

which may be preferable to conventional heating methods, and even higher heating rates are obtainable with increased microwave power. Neven and Mitcham (1996) and Neven (1998a) reported heating rates from 0.067 to 6.5°C min<sup>-1</sup> using simulated heat treatments of codling moth larvae in 7.5 ml glass vials in a computer-controlled hot water bath. The effect of heating rate on insect metabolism and physiological adjustment to the heat treatment has been shown to affect insect mortality (Evans, 1986; Neven, 1998a,b). Neven (1998a) reported that at slower heating rates, larvae must be exposed longer to the final treatment temperature to achieve 95% mortality.

Microwave heating did not produce the usual asymptotic pattern of fruit centre temperature that develops when the fruit is heated with hot air or warm water and results in prolonged heating (Hansen, 1992). The linear temperature changes in microwave heating may be advantageous for insect disinfection because the fruit can be brought quickly to the desired lethal temperature, held long enough to kill the insects, and cooled quickly. Hansen (1992) reported that times required for the centre temperature of several fruits and vegetables to attain a quarantine temperature of 48°C during incremental or constant hot air or water dip treatments ranged between 25 and 560 min. Exposure of fruits to high temperatures using conventional heating methods to kill insect pests may have adverse effects on fruit quality due to the prolonged duration required to raise the fruit core temperature. Similarly, hydrocooling removes the heat faster than convection air cooling of cherries and reduces the overall time fruit remained at the elevated temperature, further minimizing heat damage (Fig. 2b).

There was marked temperature variation among individual cherry fruits during microwave heating. Large cherries heated faster than small ones in the same batch, which is quite contrary to conventional heating. When 100 'Rainier' cherries sorted into size categories of 3–6 g (mean 4.4 g) and 9.5–13.5 g (mean 10.8 g) were heated separately in the microwave at 1 kW for 3 min, their mean core temperature reached 36 ± 2 and 46 ± 4°C, respectively. The smaller cherries required 6 min to reach a core temperature of about 49 ±

4°C. In another preliminary temperature mapping test on 40 'Bing' cherries of two-size categories (4.2 and 8.8 g) mixed together and heated at 0.5 kW for 7 min, the recorded mean temperatures for the small and large cherries were 44 and 58°C, respectively. In these tests, turntable rotation was used but not hot air, and all cherries temperatures were measured within 2 min after heat treatment. The measurements showed that temperature variation was mainly due to size differences. We attribute these differences in part to the nominal microwave energy absorption capacity of the fruit. Microwave output power absorption is known to vary with weight of material (Ohlsson, 1983) and it is probable that the larger cherries may absorb more of the incident energy due to the larger surface area and sample volume. It is also likely that the microwave absorption per unit surface area may be relatively uniform. Because of the 'centre-focusing effect,' however, the core of larger cherries receives more energy than the smaller ones due to the larger surface area. Sorting into size classes is a normal packing-house practice and will assist in obtaining more even heating.

During the holding phase, fruit final temperatures could not be maintained constant but generally dropped by as much as 5°C due to heat redistribution within the fruits and convective heat loss to the environment. This may be overcome by employing moist hot air in combination with the microwave heating.

### 3.2. *Insect mortality*

During microwave heating of infested cherries, some larvae moved to the surface of the cherries and some resided close to the surface (partially inside the cherry). At the beginning of the heating phase, insects close to the surface were able to quickly leave the cherry as they sensed the heat, while others inside were unable to do so due to the short heat up time. Some cherries were cracked due to larvae burrowing. The surface temperature of the exposed moist flesh might be lower than the desired temperature due to evaporative cooling.

Table 1 shows codling moth mortality in ‘Bing’ and ‘Rainier’ cherries after different treatments. When corrected for natural mortality in the control (18–57.5%), the percentage codling moth larvae killed ranged from 5 to 98%. Generally, increasing treatment temperature resulted in increased larvae mortality. This agrees with Neven and Rehfield (1995) and Neven and Mitcham (1996). With a computer-controlled hot water bath treatment of codling moth larvae at a temperature ramp rate of  $6.25^{\circ}\text{C min}^{-1}$ , Neven (1994) obtained 50% mortality following a 30 min exposure at  $45^{\circ}\text{C}$ . For infested sweet cherries treated with forced hot air at 45 and  $47^{\circ}\text{C}$ , Neven and Mitcham (1996) reported that 99% mortality required 124 and 72 min, respectively.

The control mortality was inexplicably high; handling during transportation may have contributed to this high mortality. Insect mortality was generally low with microwave and hot air only treatments, especially with ‘Rainier’ cherries. This may have resulted from the use of small sized ‘Bing’ and ‘Rainier’ fruits for this treatment while the mapping was done using medium to large sized ‘Bing’ fruit. Thus, the cherries may have attained lower average temperature than the expected treatment temperatures. Furthermore, some larvae that were on the surface of the fruit during the microwave treatment may not have been affected by the microwave heat. In addition, the hot dry air heater unit required more than 1 min heat up time to reach the set point and steady

state since the system is a batch process. The dry air may have caused evaporative cooling of the infested fruits. Mortality may also have been affected by the wide variation in cherry fruit sizes, which ranged from 3.1 to 13.5 g.

A total of 1–2 days cold storage markedly improved percentage mortality. For both cherry cultivars and in all the treatments, percentage mortality was more than doubled when the microwave treatment was combined with cold storage. This agreed with the findings of Neven (1994) and Neven and Rehfield (1995) that mortality of heat-treated codling moth 5th instars greatly increased with cold storage. They reported that complete mortality was achieved after exposure of infested immature apples or fresh artificial diet to  $46^{\circ}\text{C}$  for 8 h, followed by 28 days of cold storage. The authors concluded that the increased mortality resulted from the combination of metabolic stress induced by the heat treatment alone followed by the subsequent cold storage which exacerbated the condition. Neven (1998b) also noted that while heat treatments increased insect metabolic demands, subsequent cold storage suppressed respiration and metabolism, which together may inhibit repair of damage that occurs to cells during exposure to high temperature. In our study, however, maximum total heat treatment times were  $\leq 7$  min (including 5 min heat up and 2 min hold). Thus, compared with the heating times reported above, results obtained in this test appear very promising.

Table 1  
Corrected insect mortality in ‘Bing’ and ‘Rainier’ cherries after 915 MHz microwave and hot air heat treatment with cold storage<sup>a</sup>

Treatment levels	Mortality of 3rd instar codling moth in ‘Bing’ cherries (%)	Mortality of 3rd instar codling moth in ‘Rainier’ cherries (%)
45°C	14–17	5
50°C	37–38	9
55°C	38–62	7
45°C+CS	47–67*	54 <sup>†</sup>
50°C+CS	61–95*	39 <sup>†</sup>
55°C+CS	98*	72 <sup>†</sup>

<sup>a</sup> CS = cold storage.

\* A total of 1 day in cold storage after microwave treatment.

<sup>†</sup> A total of 2 days in cold storage after microwave treatment.



Table 2  
Effects of MeBr fumigation and 915 MHz microwave and hot air treatments on 'Bing' cherry quality parameters as a function of treatment and days in cold storage

Treatments	Firmness (N)	Soluble solids (%)	Titratable acidity (% malic)	SS/TA ratio	Weight (for 30 cherries) (g)	Fruit colour (Hunterlab values)		Stem colour (Hunterlab, <i>a</i> )
						( <i>L</i> )	( <i>a</i> )	
<i>0 day</i>								
Control	5.2 <sup>b*</sup>	17.9 <sup>a</sup>	0.71 <sup>a</sup>	25.8 <sup>a</sup>	190.1 <sup>ab</sup>	42.2 <sup>a</sup>	6.0 <sup>ab</sup>	−4.3 <sup>a</sup>
MeBr	5.2 <sup>b</sup>	16.3 <sup>b</sup>	0.86 <sup>c</sup>	18.6 <sup>b</sup>	181.2 <sup>ab</sup>	44.9 <sup>a</sup>	7.3 <sup>ab</sup>	−4.8 <sup>a</sup>
Microwave 45°C	5.7 <sup>a</sup>	17.2 <sup>ab</sup>	0.85 <sup>bc</sup>	20.2 <sup>b</sup>	209.2 <sup>ab</sup>	41.2 <sup>a</sup>	6.4 <sup>ab</sup>	−3.3 <sup>b</sup>
Microwave 50°C	5.4 <sup>ab</sup>	17.9 <sup>a</sup>	0.84 <sup>bc</sup>	21.3 <sup>b</sup>	215.7 <sup>a</sup>	32.8 <sup>b</sup>	8.5 <sup>a</sup>	−2.4 <sup>b</sup>
Microwave 55°C	5.4 <sup>ab</sup>	16.6 <sup>ab</sup>	0.79 <sup>b</sup>	21.2 <sup>b</sup>	169.5 <sup>b</sup>	46.1 <sup>a</sup>	5.3 <sup>b</sup>	−2.9 <sup>b</sup>
<i>7 day</i>								
Control	5.4 <sup>a</sup>	18.2 <sup>ns†</sup>	0.82 <sup>c</sup>	22.2 <sup>b</sup>	206.2 <sup>ns†</sup>	26.0 <sup>bc</sup>	9.5 <sup>a</sup>	−2.6 <sup>a</sup>
MeBr	5.0 <sup>b</sup>	17.7	0.81 <sup>bc</sup>	21.9 <sup>b</sup>	202.7	31.1 <sup>a</sup>	8.5 <sup>ab</sup>	−2.1 <sup>ab</sup>
Microwave 45°C	4.9 <sup>b</sup>	17.8	0.78 <sup>ab</sup>	22.8 <sup>ab</sup>	200.2	28.8 <sup>abc</sup>	7.9 <sup>ab</sup>	−1.0 <sup>bc</sup>
Microwave 50°C	5.1 <sup>b</sup>	18.3	0.77 <sup>a</sup>	24.0 <sup>a</sup>	202.2	29.4 <sup>ab</sup>	6.8 <sup>b</sup>	−1.0 <sup>bc</sup>
Microwave 55°C	4.3 <sup>c</sup>	17.5	0.77 <sup>a</sup>	22.8 <sup>ab</sup>	186.1	25.5 <sup>c</sup>	6.9 <sup>b</sup>	−0.1 <sup>c</sup>
<i>14 day</i>								
Control	5.5 <sup>a</sup>	17.7 <sup>b</sup>	0.79 <sup>bc</sup>	22.4 <sup>b</sup>	227.7 <sup>a</sup>	29.4 <sup>b</sup>	9.2 <sup>ab</sup>	−0.1 <sup>b</sup>
MeBr	4.9 <sup>b</sup>	16.9 <sup>c</sup>	0.83 <sup>c</sup>	20.5 <sup>c</sup>	188.5 <sup>b</sup>	32.8 <sup>a</sup>	10.1 <sup>a</sup>	−1.1 <sup>a</sup>
Microwave 45°C	5.2 <sup>ab</sup>	17.8 <sup>b</sup>	0.78 <sup>b</sup>	22.9 <sup>b</sup>	212.9 <sup>ab</sup>	32.4 <sup>a</sup>	7.7 <sup>bc</sup>	0.2 <sup>b</sup>
Microwave 50°C	5.0 <sup>b</sup>	18.8 <sup>a</sup>	0.72 <sup>a</sup>	26.5 <sup>a</sup>	227.7 <sup>a</sup>	32.5 <sup>a</sup>	6.8 <sup>c</sup>	0.3 <sup>b</sup>

\* Within each storage period, means with different letters are significantly different ( $P < 0.05$ ).

† ns = not significantly different.

### 3.3. Cherry quality characteristics

The effect of microwave treatments on the quality parameters of 'Bing' sweet cherry were compared with that of control and MeBr-fumigated cherries (Table 2). It must be noted that a different batch of fruit was used for each storage period. Statistical analyses showed that there were differences among batches, particularly in sample weight ( $P > F = 0.0220$ ) and colour ( $P > F = 0.0001$ ). Therefore, the effects of treatments on the quality factors were analyzed and compared within the same storage period.

There were significant differences ( $P < 0.05$ ) in firmness, soluble solids content (SSC), titratable acidity (TA) and weight of cherries due to the treatments, although the changes were slight. Firmness of fruit after microwave treatment apparently was either higher or similar to that of the control and MeBr-treated samples at the different days in storage. SSC was consistently lowest and TA highest for the MeBr-fumigated cherries. However, after 7 days in storage, there were no significant differences in SSC and fruit final weight among the treatments. SSC and TA are indicators of the degree of sweetness and tartness, respectively, while lower weight suggests probable desiccation of fruit due to the treatment. The microwave treatments resulted in SSC/TA ratios similar to or higher than those of control and MeBr-treated fruit. This ratio was reported to be a good descriptor of flavour generation or perceived sweetness/tartness (Boylston et al., 1994). Although there were apparent significant differences among the treatments and storage periods, the data did not reveal any consistent lower Hunterlab 'L' (lightness) or higher 'a' (redness) colour values at all storage periods for a particular treatment. It appeared, however, that the microwave treatments gave lower stem 'a' (greenness) values as storage period increased. Drake et al. (1991) noted that the cherry stem condition greatly influences consumer perception of the overall cherry quality. Our tests revealed that 'a' (greenness) colour values for the stem generally decreased with increased temperature during the microwave treatments. Fruit stems were observed to be drier after microwave treat-

ment. This stem drying was mainly attributed to the hot dry air employed during the treatments. In future studies, vapour moist or humid hot air should be used to overcome this drying and to improve heat transfer to the surface of the fruit, thus providing enough heat to kill larvae residing on the surface of the fruit. Care should be taken to avoid moisture condensation on the fruit since that may conflict with microwave energy coupling.

In general, microwave treatments at 45 and 50°C appear more promising because they affected fruit quality only slightly. But, microwave treatment at 45°C gave low insect mortality, and thus may require prolonged holding to achieve desired mortality. Fruit quality attributes with the microwave treatment at 55°C were either worse or about same as with the other two microwave treatments. Assessment of the fruit with this treatment was discontinued after the 7th day of the storage, because the fruits were visually judged not acceptable.

### Acknowledgements

This research was supported by the IMPACT Centre at Washington State University, and partially by the Washington State Tree Fruit Research Commission.

### References

- Abbott, W.S., 1925. A method of computing the effectiveness of an insecticide. *J. Econ. Entomol.* 18, 265–267.
- Andreuccetti, D., Bini, M., Ignesti, A., Gambetta, A., Olmi, R., 1994. Microwave destruction of woodworms. *J. Microwave. Power Electromagn. Energy* 29, 153–160.
- Anon., 1950. Plant protection law enforcement regulations. Ministerial Ordinance No. 73, annexed I. Ministry of Agriculture, Forestry and Fisheries, Tokyo, Japan.
- Anon., 1982. Plant protection law enforcement regulations. Ministerial Ordinance No. 848, Article 3, annexed table. Ministry of Agriculture, Forestry and Fisheries, Seoul, Korea.
- Anon., 1983. International plant quarantine treatment manual. Plant production and protection paper 50. Food and Agriculture Organization of the United Nations. FAO, Rome, Italy.

- Anon., 1990. Public law 101–549, Federal Clean Air Act enacted 15 November, 1990. Washington DC.
- Anon., 1995. Montreal protocol on substances that deplete the ozone layer. Report of methyl bromide technical options committee: 1995 Assessment. United Nations Environmental Program, Ozone Secretariat, Nairobi, Kenya.
- Boylston, T.D., Kupferman, E.U., Foss, J.D., Buering, C., 1994. Sensory quality of gala apples as influenced by controlled and regular atmosphere storage. *J. Food Qual.* 17, 477–494.
- Drake, S.R., Moffitt, H.R., Kupferman, E.M., 1991. Quality characteristics of 'Bing' and 'Rainier' sweet cherries treated with gibberellic acid, following fumigation with methyl bromide. *J. Food Qual.* 14, 119–125.
- Evans, D.E., 1986. The influence of rate of heating on the mortality of *Rhyzopertha dominica* (L.) (Coleoptera: Bostrychidae). *J. Stored Prod. Res.* 23, 73–77.
- Giese, J., 1992. Advances in microwave food processing. *Food Technol.* 46, 118–123.
- Guance, A.P., Madsen, H.F., McMullen, R.D., 1981. Fumigation with methyl bromide to kill larvae and eggs of codling moth in Lambert cherries. *J. Econ. Entomol.* 74, 154–157.
- Hallman, G.J., Sharp, J.L., 1994. Radio frequency heat treatments. In: Sharp, J.L., Hallman, G.J. (Eds.), *Quarantine Treatments for Pests of Food Plants*. Westview Press, San Francisco, CA, pp. 165–170.
- Halverson, S.L., Burkholder, W.E., Bigelow, T.S., Nordheim, E.V., Misenheimer, M.E., 1996. High-power microwave radiation as an alternative insect control method for stored products. *J. Econ. Entomol.* 89, 1638–1648.
- Hansen, J., 1992. Heating curve models of quarantine treatments against insect pests. *J. Econ. Entomol.* 85, 1846–1854.
- Lund, D.B., 1977. Design of thermal processes for maximizing nutrient retention. *Food Technol.* 31, 71–78.
- Moffitt, H.R., Drake, S.R., Toba, H.H., Hartsell, P.L., 1992. Comparative efficacy of methyl bromide against codling moth (Lepidoptera: Tortricidae) larvae in 'Bing' and 'Rainier' cherries and confirmation of efficacy of a quarantine treatment for 'Rainier' cherries. *J. Econ. Entomol.* 85, 1855–1858.
- Nelson, S.O., 1996. Review and assessment of radio-frequency and microwave energy for stored-grain insect control. *Trans. ASAE* 39, 1475–1484.
- Neven, L.G., 1994. Combined heat treatments and cold storage effects on mortality of fifth-instar codling moth (Lepidoptera: Tortricidae). *J. Econ. Entomol.* 87, 1262–1265.
- Neven, L.G., 1998a. Effects of heating rate on the mortality of fifth-instar codling moth (Lepidoptera: Tortricidae). *J. Econ. Entomol.* 91, 297–301.
- Neven, L.G., 1998b. Respiratory response of fifth-instar codling moth (Lepidoptera: Tortricidae) to rapidly changing temperatures. *J. Econ. Entomol.* 91, 302–308.
- Neven, L.G., Rehfield, L.M., 1995. Comparison of pre-storage heat treatments on fifth-instar codling moth (Lepidoptera: Tortricidae) mortality. *J. Econ. Entomol.* 88, 1371–1375.
- Neven, L.G., Mitcham, E.J., 1996. CATTs (Controlled Atmosphere/Temperature Treatment System): A novel tool for the development of quarantine treatments. *J. Am. Entomol.* 1996, 56–59.
- Neven, L.G., Rehfield, L.M., Shellie, K.C., 1996. Moist and vapor forced air treatment of apples and pears: Effects on the mortality of fifth instar codling moth (Lepidoptera: Tortricidae). *J. Econ. Entomol.* 89, 700–704.
- Ohlsson, T., 1980. Temperature dependence of sensory quality changes during thermal processing. *J. Food Sci.* 45, 836–839, 847.
- Ohlsson, T., 1983. Fundamentals of microwave cooking. *Microw. World* 3, 4–9.
- Ohlsson, T., Risman, P.O., 1978. Temperature distribution of microwave heating-spheres and cylinders. *J. Microw. Power* 13, 303–309.
- SAS Institute Inc., 1990. SAS/STAT® User's Guide, Version 6, 4th ed. Vol. 2. SAS Institute Inc., Cary, NC.
- Sharp, J.L., 1993. Heat and cold treatments of post-harvest quarantine disinfestation of fruit flies (Diptera: Tephritidae) and other quarantine pests. *Fla. Entomol.* 76, 212–218.
- Sharp, J.L., Gaffney, J.J., Moss, J.I., Gould, W.P., 1991. Hot-air treatment device for quarantine research. *J. Econ. Entomol.* 84, 520–527.
- Soderstrom, E.L., Brandl, D.G., Mackey, B.E., 1996. High temperature alone and combined with controlled atmospheres for control of diapausing codling moth (Lepidoptera: Tortricidae) in walnuts. *J. Econ. Entomol.* 89, 144–147.
- Toba, H.H., Howell, J.F., 1991. An improved system for mass-rearing codling moths. *J. Entomol. Soc. Br. Columbia* 88, 22–27.
- Yokoyama, V.Y., Miller, G.T., 1987. High temperature for control of Oriental fruit moth (Lepidoptera: Tortricidae) in stone fruit. *J. Econ. Entomol.* 80, 641–645.
- Yokoyama, V.Y., Miller, G.T., Hartsell, P.L., 1990. Evaluation of a methyl bromide quarantine treatment to control codling moth (Lepidoptera: Tortricidae) on nectarine cultivars proposed for export to Japan. *J. Econ. Entomol.* 83, 466–471.
- Yokoyama, V.Y., Miller, G.T., Dowell, R.V., 1991. Response of codling moth (Lepidoptera: Tortricidae) to high temperature, a potential quarantine treatment for exported commodities. *J. Econ. Entomol.* 84, 528–531.