HEAT TREATMENTS FOR CONTROL OF HUHU BEETLE (*PRIONOPLUS RETICULARIS*) LARVAE IN LOGS

PETER R. DENTENER, SONYA E. LEWTHWAITE, DAVID J. ROGERS, XENIA MEIER, DIANA C. WHITING and ROD M. McDONALD

The Horticulture and Food Research Institute of New Zealand Limited, Mount Albert Research Centre, Private Bag 92 169, Auckland, New Zealand.

(Received for publication 7 March 2001; revision 14 August 2001)

ABSTRACT

Experiments were carried out to determine the effect of quarantine heating conditions on temperature distribution inside logs of varying diameter. When 20-cm-diameter *Pinus radiata* D. Don logs were heated using a 3.5-hour ramp from 20°C to 65°C air temperature and this air temperature was maintained, internal temperatures at 10 cm depth inside the logs reached an average of 45°C 6 hours from start. This temperature had previously been shown to be lethal to huhu (*Prionoplus reticularis* White) larvae treated outside logs. Mortality of all huhu larvae heat-treated in logs was achieved using the 6-hour heat treatment. Huhu mortality in the insect-infested logs may have been further aided by the fact that internal temperatures continued to rise for more than 1 hour after treatment was completed, and that the average temperature remained above 40°C for more than 3.5 hours from completion of treatment.

As log diameter increased, longer treatment duration was required. The treatment time to reach 45°C at 10 cm depth had to be extended from 6 hours for a 20-cm-diameter log to an average of 10.5 hours for a 30-cm log and 13.5 hours for a 40-cm log.

Heat treatments may be cost-effective compared to the currently used methyl bromide disinfestation treatments, and could also improve wood quality (reducing the incidence of surface checks, warping, or discoloration).

Keywords: huhu beetle larvae; temperature; logs; quarantine; Coleoptera; Cerambycidae; *Prionoplus reticularis*; *Pinus radiata*.

INTRODUCTION

New Zealand is the third largest exporter of forestry products in the world, with NZ$2.4 billion [US$1.1 billion] export earnings (4% of GDP) contributing to about 11% of total New Zealand exports (Anonymous 1999). In the year ending June 2000, 32% of forestry products exported consisted of logs with an export value (f.o.b.) of NZ$642 million [US$257 million] (NZFOA 2000). Access for logs to markets such as the United States requires methyl bromide treatment pre-export against pests such as the native New Zealand huhu beetle (*Prionoplus reticularis* White) (Coleoptera: Cerambycidae), one of five major

insect pests identified as a quarantine risk if present on New Zealand *Pinus radiata* D. Don logs imported into the United States (USDA 1992). Although it is not mandatory, substantial volumes of logs are also fumigated with methyl bromide for disinfestation purposes on arrival in North Asian markets (Maud 1995).

Due to world-wide concerns over the effects of chemicals and their residues on the environment and human health, there is an urgent need to develop alternative disinfestation methods which are practical, cost-effective, and environmentally sustainable, while providing a high level of quarantine security and not affecting commodity quality. Treatments effective against insects and nematodes in wood include heat (USDA 1991; Dwinell 1997; Morrell 1995), controlled atmospheres (Schroeder & Eidmann 1986; Paton & Creffield 1987), gamma irradiation (Lester *et al.* 2000), and radio-frequency/vacuum applications (Dwinell *et al.* 1994).

In previous research we tested a range of disinfestation methods for huhu control (off logs) including controlled atmospheres and heat treatments (Dentener *et al.* 1999). Our investigations showed that 99% of huhu larvae were killed after a 3-hour heat treatment at 45°C. Although there is a wealth of data on kiln-drying round wood for fungal or insect control, its effectiveness is based mainly on treatment of poles rather than unprocessed logs (Morrell 1995). Here we present the second part of this study which determined the tolerance of huhu larvae, contained within *P. radiata* logs, to heat treatments. Studies were also carried out to determine heat transfer into *P. radiata* logs. In this paper we discuss:

(1) temperature profiling in small-diameter logs, and validation of a heat transfer model;
(2) huhu larval mortality in small-diameter heated logs, and expected treatment times for huhu larval mortality in logs of varying diameter; and
(3) incorporating heat treatments into a commercial process.

METHODS

Insect numbers and treatment conditions presented are described as mean ± standard error of the mean (SEM), with the number of observations used for analysis in parentheses.

Treatment Procedures

Heat treatment facility

Heat experiments were carried out using the high air-flow controlled atmosphere and temperature treatment facility (hereafter referred to as HAFCAT) based at HortResearch, Auckland. This facility was designed to precisely control treatment conditions to develop accurate time-mortality data for pests (Dentener *et al.* 1996). The HAFCAT was purpose-built for large-scale experiments, and measures 6 × 2.4 m at the base and 3.2 m at the highest point, with a 2.9-m^3 treatment chamber. Air temperature can be maintained to within 0.1°C of target temperature. A centrifugal fan was used to provide a 1.62 m/s air recirculating flow in the treatment area and to maintain temperature homogeneity throughout the treated logs. Temperature homogeneity was further improved by reversing the air flow every 0.5 hours using automatic switching gates in the air ducts. Air temperature measurements were made using calibrated PT100 platinum-resistance temperature probes. Humidity was measured using a Rotronic I128RD11FF001V1 sensor and was set at 85% RH during heating. The

facility was controlled by a Macintosh LCIII computer running LabView version 2.0 software to create virtual instruments, allowing time-varying set points for temperature, humidity, and air flow velocity.

Logs of 20 and 30 cm diameter were supported on rectangular open frames, placed inside the HAFCAT treatment area. The 40-cm-diameter logs were too heavy to be supported by frames, and instead were placed inside plywood bins measuring 118.5 × 117.5 × 48 cm, with a very coarse, open (6 × 6 cm) mesh, metal floor. Two bins could be accommodated inside the treatment area.

Treatment conditions

Initial temperature profiling trials along the length of the log, and all subsequent huhu disinfestation trials were carried out with logs which had been cut in half longitudinally, and were strapped together again for trials (*see below*). Further temperature profiling of logs to depths of 1 to 15 cm were carried out with intact logs varying in diameter from 20 to 40 cm. All logs were debarked, and moisture content (MC) was determined by oven drying using 3-cm-thick segments cut from both ends of each log. Moisture content was calculated using the formula:

$$MC\% = \frac{\text{Wt (original)} - \text{Wt (oven dry)}}{\text{WT (oven dry)}} \times 100 \text{ (Kininmonth1991)}$$

and was on average 99.3 ± 6.6% (n=16).

Logs used for temperature profiles — Initial temperature profile trials were carried out with logs 110 cm long with an average diameter of 22.8 cm (± 0.33 cm; average volume 44.8 ± 1.3 litres; n=7), hereafter referred to as small-diameter logs. Subsequent temperature profile experiments were carried out with logs 110 cm long and varying in diameter from an average 19.9 cm (± 0.45 cm; average volume 34.2 ± 1.8 litres; n=3) to 29.3 cm (± 0.34 cm; average volume 74.2 ± 2.5 litres; n=3) and 39.7 cm (± 0.5 cm; average volume 136.1 ± 6.6 litres; n=3). Hereafter they will be referred to as logs with nominal diameters of 20, 30, and 40 cm respectively.

Small-diameter logs for huhu disinfestation — Huhu larvae hatching from eggs laid underneath the bark of logs usually create an establishment gallery which extends about 0.2 cm into the wood, perpendicular to the surface. The larvae then turn into the longitudinal axis of the wood for the first moult after which galleries can be quite irregular during subsequent larval stages (Edwards 1960). The fully grown larvae make a pupal cell which can be found anywhere from just beneath the bark to 10 cm below the wood surface (Hosking 1978). Based on this information, it was decided to carry out disinfestation research with huhu larvae to a depth of up to 10 cm into the logs.

All huhu treatments were carried out in logs as described above with an average diameter of 22.8 cm, and halved along the longitudinal axis (Fig. 1). A total of two rows consisting of 12 holes each were cut in each top and bottom log half, starting 4.5 cm from the short edge of the log. Each hole measured 7 (L) × 2 (W) × 2 (D) cm and was spaced 1.5 cm from the previous hole (at 8.5-cm centres; Fig. 1A–B). Holes in the top part of the log were spaced in such a way that they did not overlap the holes in the bottom part of the

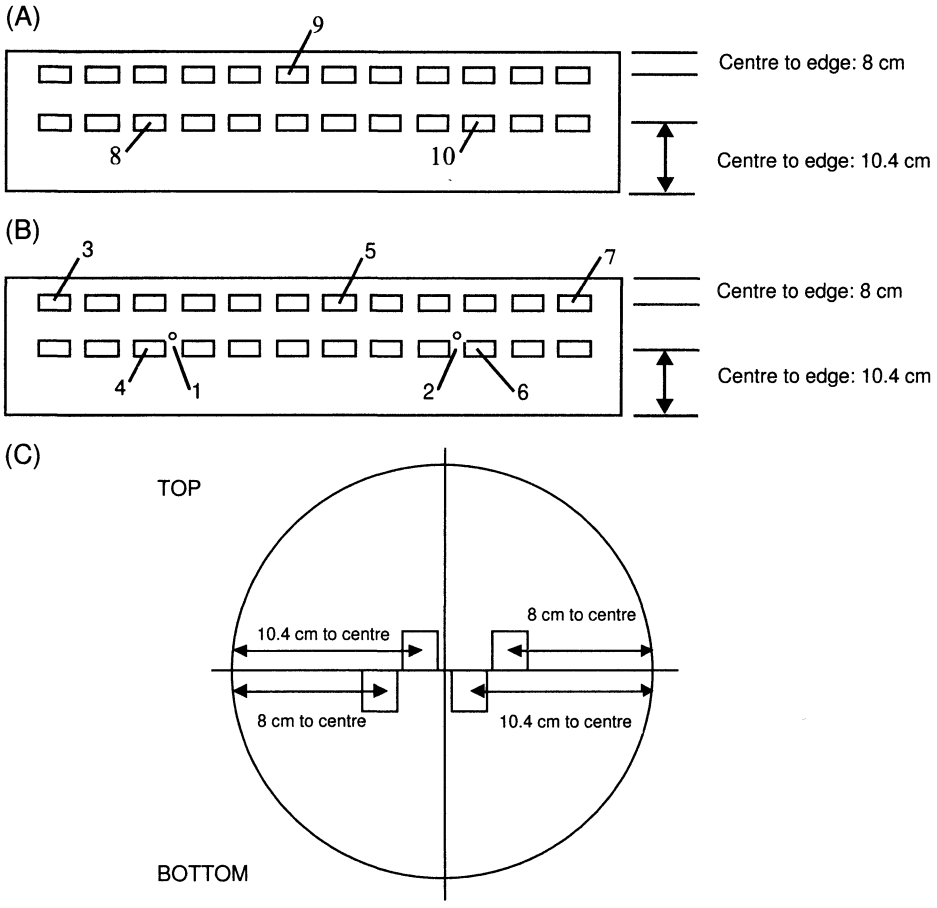

FIG. 1–Schematic longitudinal top (A), bottom (B), and frontal views (C) of log halves used for initial temperature profiles, and huhu disinfestation studies. Numbers indicate position of temperature probes in circular (1–2) and rectangular (3–10) holes. Rectangular holes held huhu larvae during disinfestation trials. Drawing not to scale.

log (Fig. 1C). Measured from the centre of the hole to the outside of the log, holes were positioned on average 8 cm (±0.15 cm; n=42) or 10.4 (±0.17 cm; n=42) from either edge of the log. All holes containing insects were covered with 1 ply natural cellulose paper towel which was secured to the log with double-sided sticky tape to prevent the insects falling out when the log halves were joined together. Log halves were strapped tightly together using 1.9-cm heavy duty wire buckles, and straps.

Temperature observations — Temperature recordings inside the logs during the temperature profiling treatments were collected with a Grant Squirrel data logger with calibrated thermistor catheter probes with a 0.2-cm-diameter tip. During initial temperature profile research with the small-diameter logs, two probes were placed in circular holes close to the longitudinal centre of the log, 28.5 cm from either end of the

log. An additional eight probes were positioned as follows (measured from the short end of the log): two probes, each at 8 cm from either side of the log ; four probes, two in each row 25 cm from either side; and two probes, each 50 cm from either side (Fig. 1A–B). During subsequent huhu disinfestation trials temperature was measured inside the circular holes in each log.

Observations of temperatures inside logs of 20, 30, and 40 cm diameter were made at depths of 1, 3, 6, 10 (all log diameters), and 15 cm (30- and 40-cm-diameter logs only). All probes were inserted perpendicular to the longitudinal axis of the logs, and evenly distributed within a 90-degree span in the middle of the log. Three logs were used for each temperature profiling trial and all trials were carried out twice (30-cm-diameter logs) or three times (20- and 40-cm-diameter logs).

Heating rates used—Initial temperature profile trials were carried out to determine the effect of different ramp rates on temperatures inside the logs. Ramp rates from ambient (about 20°C) to an air temperature of 65°C of 0 hours (no ramp, i.e., static temperature of 65°C), 3.5, 4.5, or 6 hours were used. On completion of the treatment, logs were removed from the HAFCAT and placed at 20°C and 70% RH. Huhu disinfestation treatment conditions were based on results obtained during the initial temperature profile trials to reach a temperature of 45°C inside the log. Insects and logs during time-mortality trials were therefore exposed from ambient (20°C) rising to an air temperature of 65°C in 3.5 hours, and held at 65°C air temperature for up to an additional 2.5 hours (to achieve an internal log temperature of approximately 45°C). After this they were placed at 20°C and 70% RH until assessed. Sub-samples, each of one log with insects, were removed from the HAFCAT at 4, 4.5, 5, 5.5, and 6 hours from the start (including the 3.5-hour ramp time) to determine progressive huhu mortality. In subsequent insect tests to confirm treatment efficacy, all logs were heated for the maximum exposure time carried out during the sub-sample experiments (i.e., 6 hours from start). Confirmatory tests were carried out with huhu larvae in four logs, and experiments were replicated three times. Larvae were removed from the logs when internal log temperatures fell to about 22°C (16–18 hours after completion of the heating component).

In subsequent trials, logs of various diameters were heated from ambient (about 20°C) to an air temperature of 65°C in 3.5 hours, and held at 65°C air temperature until probes at a depth of 10 cm in the three logs reached an average of 45°C. After this the logs were removed from the HAFCAT and placed at 20°C and 70% RH. The measurement depth of 10 cm was based on the huhu disinfestation trials reported in this paper, in which insects were inoculated inside the logs at depths of 8 to 10.4 cm.

Insects

Huhu larvae ≥ 100 mg were collected from *P. radiata* logs and stumps in Riverhead and Woodhill Forests north of Auckland, transported to the laboratory individually in insulated containers, and sorted individually into size classes (100–500 mg; 500–1500 mg; >1500 mg) for equal distribution to treatment logs. Larvae were held overnight at 20°C, 70% RH, and a photoperiod of 16:8 (L:D) h before being placed inside the holes in the log halves. These were strapped together and held overnight at 20°C before treatment the next day. After

treatment, all insects were transferred from the logs into glass tubes with 1 ply paper towel inserts and held for 3 days at 20°C, 70% RH, and a photoperiod of 16:8 (L:D) h until assessment (Dentener *et al.* 1999). Control larvae were treated similarly (i.e., placed in a control log) but not exposed to the treatment. All experiments were carried out three times.

Determination of Mortality

Larvae were recorded as "live" (movement) or "dead" (no movement) when gently prodded with blunt forceps and observed by binocular microscope (20× magnification) or naked eye.

Statistical Analysis

Time-mortality data for each experiment were analysed with a complementary log-log model $\log(-\log(1-p)) = a + bt$, where p = expected mortality and t = time (Preisler & Robertson 1989). This gave approximate linearity and determined the estimated times for 50% (LT_{50}) and 99% mortality (LT_{99}). These estimates were calculated after allowance for the control mortality as the time to achieve a mortality of $c + (1-c) \times d$, where c = control mortality and d = required level of mortality (0.50 or 0.99, for LT_{50} and LT_{99} respectively).

The model was fitted using a robust version of the generalised linear model procedure in S-PLUS (Statistical Sciences 1995). Mortality was the dependent variable, with time as the explanatory variable. This model assumes that variance is proportional to that of a binomial distribution. The robust version reduces the weight given to points lying away from the body of the data (Waddell *et al.* 1997).

RESULTS

Initial Temperature Profiling with Small-diameter Logs

When logs were placed immediately at 65°C air temperature (0 hour ramp), it took an average of 3.7 hours for the inside of the logs to reach 45°C. This increased to 5.9 hours (3.5 hour ramp), 6.6 hours (4.5 hour ramp), and 7.5 hours (6 hour ramp) (Table 1). Thus, as the ramp time from 20°C to 65°C was increased, the time for the inside of the logs to reach target temperature also increased.

TABLE 1–Average heating times (± SEM) to reach 45°C* inside logs using a range of heating times from ambient (20°C) to 65°C air temperature, followed by a 65°C holding period.

Ramp rates (hours)	Average time (hours)	Average temperature (°C)		
		All probes†	Probes‡ in circular holes	Repl.
0	3.7 ± 0.02	44.9 ± 0.8	42.2 ± 0.3	2
3.5	5.9 ± 0.08	45.2 ± 0.8	42.5 ± 0.4	2
4.5	6.6 ± 0.02	44.7 ± 0.7	42.4 ± 0.3	2
6	7.5 ± 0.02	44.8 ± 0.7	42.6 ± 0.4	2

* Average temperature based on 10 probes per log
† n=10
‡ n=2

Huhu Disinfestation Trials

The estimated LT_{50} values for the three replicates in the time-mortality trials varied between 5.5 and 5.6 hours with LT_{99} values between 6.1 and 6.2 hours (Table 2). The geometric mean of the three estimated LT_{99} values was 6.2 hours with fiducial limits of 6.1 to 6.3 hours. Complete mortality of all huhu larvae treated in logs was achieved in each of three confirmatory trials using a ramp of 3.5 hours to 65°C air temperature which was maintained for a further 2.5 hours before logs were removed and stored at 20°C (Table 3). Temperatures in the circular hole position inside the logs (Fig. 1B) had reached an average of 41.1°C (± 0.7; n=9) when insects in the logs were removed from the HAFCAT. Based on observed temperature differences between the circular holes and the insect locations (Table 1) in initial trials with small-diameter logs, this temperature is similar to an extrapolated average temperature of 43.5°C in the insect locations.

TABLE 2–Time (hours) required for 50% (LT_{50}) and 99% (LT_{99}) mortality of huhu larvae in logs exposed to heated air at 65°C. Larval control mortality: 5.8 ± 2.2% (n=3; 137 insects)

Repl. No.	LT_{50} (h)	LT_{99} (h)	Insects used for analysis (n)
1	5.5	6.2	221
2	5.6	6.1	275
3	5.6	6.2	285

TABLE 3–Mortality of huhu larvae in logs exposed to heated air at 65°C during confirmatory trials. Larval control mortality: 6.7 ± 1.7% (n=3; 133 insects)

Repl. No.	No. of logs used	Insects		
		Live	Total	Mortality (%)
1	4	0	184	100
2	4	0	184	100
3	4	0	183	100

Temperature Profiling of Logs with Various Diameters

Based on heating three logs (30 cm diameter) per trial using a 3.5-hour ramp rate, it took on average 5.4 hours, 8 hours, 9.9 hours, and 10.8 hours to reach 45°C at 3, 6, 10, and 15 cm depth respectively inside the logs. This can be represented by:

$$y = 3.466\text{Ln}(x) + 1.6844 \ (R^2 = 0.9916)$$

with y = time (in hours) to 45°C for a 30-cm diameter log, and
x = depth of probe (in centimetres).

Heat treating logs of 20, 30, and 40 cm diameter showed that it took on average 6.4 hours (20 cm diameter), 10.4 hours (30 cm diameter), and 13.5 hours (40 cm diameter) for the temperature to reach 45°C at a 10-cm depth in the log (Table 4) which is the approximate depth in the log used during the huhu disinfestation trials. In general, temperature gradients (1 to 10 or 15 cm depths) were similar, regardless of log diameter. After removal from the

HAFCAT, internal temperatures at 10 cm depth continued to rise for up to 1.7 hours, with the highest average temperature recorded at 49.3°C (Table 5). Subsequent log cool-down to 40°C in a controlled-temperature room at 20°C took 3.8 hours (20 cm diameter), 6.0 hours (30 cm), and 8.1 hours (40 cm). A further reduction in temperature to 30°C extended the cool-down period to 7 hours, 13.7 hours, and 18.3 hours for log diameters of 20, 30, and 40 cm respectively.

TABLE 4–Average heating times to reach 45°C* at 10 cm depth inside logs of various diameter using a 3.5-hour ramp time, and associated temperatures at other depths

Average heating time (hours)	Associated temperatures at different depths (mean ± SEM)					Repl.
	1 cm	3 cm	6 cm	10 cm	15 cm	
20-cm-diameter logs						
6.4 ± 0.03	58.9 ± 0.1	55.1 ± 0.3	49.4 ± 0.1	44.6 ± 0.6	N.A.†	3
30-cm-diameter logs						
10.4 ± 0.47	59.7 ± 0.4	54.4 ± 0.9	50.0 ± 1.6	45.1 ± 2	42.9 ± 1.8	2
40-cm-diameter logs						
13.5 ± 0.22	60.3 ±0.1	57.1 ± 0.1	50.9 ± 0.1	45.0 ± 0.3	39.5 ± 0.3	3

* Average temperature at 10 cm depth was 44.8 ± 0.42°C (n=24). Results based on three logs per replicate

† N.A. Not applicable for 20-cm-diameter log

TABLE 5–Average highest temperatures measured at 10 cm depth in logs of various diameters after completion of heating, and times taken to reduce temperatures at this depth to 40°C and 30°C during cooling in a 20°C environment. Three logs per trial. All measurements mean ± SEM.

Highest temperature measured (°C)	Time (hours) taken during cooling phase to reach			Repl.
	Highest temperature	40°C	30°C	
20-cm-diameter logs				
49.3 ± 0.4	1.2 ± 0.07	3.8 ± 0.07	7.0 ± 0.12	3
30-cm-diameter logs				
47.5 ± 1.8	1.6 ± 0.23	6.0 ± 0.05	13.7 ± 0.85	1
40-cm-diameter logs				
47.1 ± 0.3	1.7 ± 0.05	8.1 ± 0.30	18.3 ± 0.33	3

DISCUSSION

Dentener *et al.* (1999) established that 3 hours at 45°C were needed to achieve 99% predicted mortality (LT_{99}) of unprotected huhu larvae. In the study reported here, we showed that a temperature of 45°C inside a small (22.8-cm) diameter log can be achieved for such a duration (3 hours) using a 3.5-hour ramp from ambient (20°C) to 65°C air temperature, followed by a 2.5-hour holding period at this air temperature. These heat treatment conditions, followed by log removal to 20°C once the heat treatment component was

completed, also provided complete kill of huhu larvae inoculated up to 10 cm deep inside small-diameter logs. Comparing temperature profiles at 10 cm depth in logs of varying diameter, it took 6.4 hours to reach 45°C inside a 20 cm diameter log, increasing to 10.5 and 13.5 hours for a 30 and 40 cm diameter log respectively. Treatment times for control of huhu larvae in logs of varying diameter therefore need to be adjusted accordingly. Similar effects of diameter on internal temperature changes have been reported by Sahle-Demessie *et al.* (1992). Siau (1984) described methods to calculate the temperature within a pole based on a given initial log temperature, outside temperature, and a thermal diffusion coefficient of 1.62×10^{-3} cm^2/sec. His calculations were based on MacLean's (1952) graphical solutions of the unsteady-state differential equations applied to the heating of wood. While his calculations do not allow a ramping of the air temperature, the calculations predict with reasonable accuracy (within 0.8 to 1.9°C) the temperature inside the logs used in our "0 hours" ramp trials (Table 6). His calculations were based on a 25.4-cm-diameter log and the formulas were adjusted pro rata to 22 cm for our experiments.

TABLE 6–Actual and predicted (after Siau 1984) temperatures in a 22-cm-diameter log at various times during a non-ramped 65°C heat treatment.

Temperature (°C)	Time from start of treatment (hours)				
	1.5	2	2.5	3	3.5
Observed (our research)					
Repl. 1	24.2	28.4	32.8	37.2	41
Repl. 2	23.8	28	32.6	37	41
Predicted (after Siau 1984)	23.2	27.2	30.8	35.4	39.3

In their pest risk assessment study of New Zealand *P. radiata* logs imported into the United States, the USDA (1992) considered mitigation measures such as steam and hot water "highly effective" against *Platypus apicalis* White, *P. gracilis* Broun, and *Kalotermes brouni* Froggatt. In addition, these treatments were considered "Probably effective but needs research" against huhu and *Sirex noctilio* Fabricius. Although data about the efficacy of steam or hot water are limited, it was suggested that raising the centre temperature of the log to 49°C for at least 24 hours, or to 71°C for a minimum of 75 minutes may be satisfactory for insect control (USDA 1992). The time required to reach the specified temperature depends on log size, density, and moisture content, but for softwoods is typically 33 hours for a 60-cm-diameter log (MacLean 1930).

Woodrow & Grace (1998) reported complete control of *Cryptotermes brevis* (Walker) (Kalotermitidae) nymphs in 2.46- and 4.65-litre wooden blocks heated to 46°C and 49°C using 60- and 90-minute treatment times. However, a temperature of 45°C to achieve complete kill of huhu larvae inside logs is low when compared with research on other insects. A corewood temperature of 53°C for 0.5 hours killed *Monochamus* spp. (Cerambycidae) woodborers in naturally infested Virginia pine (*Pinus virginiana* Mill.), and 60°C for 0.5 hours eliminated the nematodes and wood-colonising fungi (Dwinell 1997). Morrell (1995) reviewed heat treatment options and stated for lumber that "...a wealth of data support the ability of kiln-drying to eliminate fungi, insects and nematodes from wood...". However,

"...relative effectiveness of various heating regimes for unprocessed logs is primarily determined from data developed for treatment of wood poles and timbers with preservatives..." (*see*, for example, Wenlong He *et al.* 1997; Dost 1984).

When specifying a minimum temperature and time combination for pest or fungal control in materials which have a large mass, it is important to consider the temperature profile post-treatment. In our research, internal log temperatures rose up to 4°C above target temperature after completion of the heat treatment component, and remained above 40°C for another 4 to 8 hours (dependent on log diameter) during 20°C storage. The use of accumulated hourly temperatures above a minimum threshold (similar to degree-hour modelling developed to calculate insect developmental rates (Got *et al.* 1996) or insect population dynamics (Lerin & Koubaiti 1997)) may also provide additional information on treatment security. When combined with our knowledge of maximum development or lethal temperatures for that pest species, this may potentially reduce the need for long treatment conditions.

Heating and drying processes of lumber have been extensively studied and modelled (Pang & Dakin 1999; Milota & Tschernitz 1994; Couture *et al.* 1996). Yoshizawa *et al.* (1999) tested smoke-heating of logs with increased far-infrared radiation to improve wood quality, and Kreber *et al.* (1998) tested the effect of velocity and relative humidity on reduction of kiln brown stain in *Pinus radiata*. Heat treatment may also assist with further processing of the timber (Haslett 1998). Kiln drying is an established process in timber industries world-wide, and since 1996 approximately 60% of sawn *P. radiata* in New Zealand has been kiln dried (Haslett 1998). Combination treatments for the preservation of wood are common (Burton *et al.* 1991; Wenlong He *et al.* 1997), and could further assist with the acceptance of the incorporation of heat-based disinfestation into industry processes. Heat can be applied by a range of methods (Milota & Wengert 1995) including far-infrared radiation (Yoshizawa *et al.* 1999), hot moist air or steam under vacuum (Pang & Dakin 1999), and hot water (Jones 1973). New Zealand ranks sixth world-wide in the use of geothermal energy (Lund 1998), and low-temperature resources (<100°C) can be successfully and economically developed for a wide range of commercial applications (Hunt 1998). Low-grade thermal energy has also been identified as a potentially very valuable heat source for use in timber drying kilns (Scott 1998) and its use could be extended to treatment of logs for quarantine purposes.

Heat treatment is often seen as an economically desirable process for wood processing, irrespective of disinfestation benefits (Patterson *et al.* 1988; Jones *et al.* 1989). It reduces the incidence of surface checks, warping, uneven moisture content, and discoloration. Jones *et al.* (1989) stated that "...Lumber drying has long been identified as a vital link between primary and secondary manufacturing...", and concluded that, given an adequate scale of operation (5 million board feet per year) and integration with a sawmill, a steam kiln costing $US1.4 million (in 1989) would give an acceptable return on investment (>15%).

Heat treatment also aids the preservation of the wood. MacLean (1930) reported of the United States timber industry that "...It is common practice at various plants treating green southern pine timbers, such as poles and piling, to apply a preliminary steam and vacuum treatment in order to partially season the material...".

If the additional value due to heat treatment can be captured, heat treatment can potentially be carried out at zero or even negative cost, because the value of the timber can be increased

30–50% by the heat treatment. An illustration of how net gains can result from sterilising logs and lumber with heat rather than methyl bromide is given in Table 7, which is derived from the United States Environmental Protection Agency's "Methyl Bromide Alternative Case Study" (EPA 1996). In these estimates, the costs include labour, tarpaulin, and chemical costs for methyl bromide treatment, and labour, energy, and equipment costs for the heat treatments.

TABLE 7–Timber treatment cost comparison (derived from EPA 1996). Wood value untreated $US500/1000 bdft.

	Softwood treatment method		
	Methyl bromide	Hot air	Steam
Treatment time (days)	1	3–5	1–2
Treatment cost ($US/1000 bdft)	1–3	85–155	35–60
Increase in wood value ($US/1000 bdft)	0	155	150
Net gain ($US/1000 bdft)	–1 to –3	–5 to 65	90 to 115

Heat treatment is considered by the EPA to be more effective than methyl bromide for pest and pathogen control, because of the unreliable penetration of methyl bromide into logs with a high moisture content. The EPA studies go further to say that "...Because wood treated with methyl bromide must be dried and cured via heat treatment anyway and because heat treatments provide similar pest control benefits compared to methyl bromide, methyl bromide treatments may be superfluous...".

One option is to carry out heat treatment on-board ship during transportation to the market. This removes the need, common to onshore treatment with heat or methyl bromide, to protect the treated material from renewed infestation. Seidner has patented (1996) a method and equipment for treatment in-transit, where re-infestation would be extremely unlikely. He reported (Seidner 1997) that the cost is lower than all other treatment methods, including methyl bromide.

It is important that alternative quarantine treatments are found to replace current fumigation practices with methyl bromide. Continued access to overseas markets is vital for New Zealand export earnings, and lack of access for New Zealand logs to markets such as the United States can be costly (NZFIC 2000).

In our research we have demonstrated the potential of using dry heat to control huhu larvae inside logs. Further research will be required, in collaboration with the New Zealand Forest Industry and using commercial treatment facilities, to test the quarantine security and economic feasibility of applying these treatment conditions to insects in logs.

ACKNOWLEDGMENTS

We thank Lisa Jamieson and Rob Petry for assistance with insect collection; Patrick Connolly for statistical analysis; John Curtain and Don Hancock (all HortResearch) for the design and manufacture of probe insertion and log frame loading units; Carter Holt Harvey for allowing us access to Riverhead and Woodhill Forests; Timbersales Ltd, Helensville, for supply and cutting of logs; and Jill McLaren, Libby Burgess, and Chris Hale for comments on the manuscript. This research was funded by the New Zealand Foundation for Research Science and Technology (C06634).

REFERENCES

ANONYMOUS 1999: New Zealand Forest Industries Council, Quarterly Report. *Focus 8*. 4 p.

BURTON, R.; BERGERVOET, T.; NASHERI, K.; VINDEN, P.; PAGE, D. 1991: Vapour phase preservation of wood. *The Institute of Professional Engineers New Zealand, Transactions 18(1/EMCh)*: 40–44.

COUTURE, F.; JOMAA, W.; PUIGGALI, J.R. 1996: Relative permeability relations: a key factor for a drying model. *Transport in Porous Media 23*: 303–335.

DENTENER, P.R.; ALEXANDER, S.M.; LESTER, P.J.; PETRY, R.J.; MAINDONALD, J.H.; McDONALD R.M. 1996: Hot air treatment for disinfestation of lightbrown apple moth and longtailed mealy bug on persimmons. *Postharvest Biology and Technology 8*: 143–152.

DENTENER, P.R.; LEWTHWAITE, S.E.; ROGERS, D.J.; MILLER, M.; CONNOLLY, P.G. 1999: Mortality of huhu (*Prionoplus reticularis*) subjected to heat and controlled atmosphere treatments. *New Zealand Journal of Forestry Science 29(3)*: 473–483.

DOST, W.A. 1984: Internal temperature during ACA treatments of utility poles. *Proceedings of the American Wood-Preservers' Association 80*: 26–38.

DWINELL, L.D. 1997: The pinewood nematode: regulation and mitigation. *Annual Review of Phytopathology 35*: 153–166.

DWINELL, L.D.; AVRAMIDIS, S.; CLARK, J.E. 1994: Evaluation of a radio-frequency/vacuum dryer for eradicating the pinewood nematode in green sawn timber. *Forest Products Journal 44(4)*: 19–24.

EDWARDS, J.S. 1960: Observations on the biology of the immature stages of *Prionoplus reticularis* White (Col. Ceramb.). *Transactions of the Royal Society of New Zealand 88(4)*: 727–731.

ENVIRONMENTAL PROTECTION AGENCY 1996: Heat treatments to control pests on imported timber. Methyl bromide alternative case study. Part of EPA 430-R-96-021, 10 case studies, Volume 2. Available: http://www.epa.gov/spdpublc/mbr/heatlog2.html [February 2001]

GOT, B.; LABATTE, J.M.; PIRY, S. 1996: European corn borer (Lepidoptera: Pyralidae) development time model. *Environmental Entomology 25(2)*: 310–320.

HASLETT, A.N. 1998: Drying radiata pine in New Zealand. Research and commercial aspects. *New Zealand Forest Research Institute, FRI Bulletin No. 206.*

HOSKING, G.P. 1978: *Prionoplus reticularis* White (Coleoptera: Cerambycidae). Huhu beetle. *New Zealand Forest Service, Forest Research Institute, Forest and Timber Insects in New Zealand No. 35.*

HUNT, T.M. 1998: Geothermal resources in New Zealand. An overview. *In* "Business Opportunities Involving Direct Use of Geothermal Energy". New Zealand Geothermal Association, 2–3 July, Rotorua.

JONES, K.D.; ARMSTRONG, J.P.; ZINN, G.W. 1989: Feasibility of an integrated manufacturing system for kiln-drying hardwood lumber. *Forest Products Journal 39(9)*: 59–63.

JONES, T.W. 1973: Killing the oak wilt fungus in logs. *Forest Products Journal 23*: 52–54.

KININMONTH, J.A. 1991: Wood-water relationships. Pp. 1–23 *in* Kininmonth, J.A.; Whitehouse, L.J. (Ed.) "Properties and Uses of Radiata Pine. Volume One — Wood Properties". New Zealand Ministry of Forestry, Forest Research Institute, Rotorua.

KREBER, B.; HASLETT, A.N.; NORRIS, M.G.C. 1998: High air velocity and relative humidity reduce development of kiln brown stain in *Pinus radiata*. *New Zealand Journal of Forestry Science 28*: 400–407.

LERIN, J.; KOUBAITI, K. 1997: Modelling winter oilseed rape plant infestation by *Baris coerulescens* (Coleoptera: Curculionidae). *Environmental Entomology 26(5)*: 1031–1039.

LESTER, P.J.; ROGERS, D.J.; PETRY, R.J.; CONNOLLY, P.G.; ROBERTS, P.B. 2000: The lethal effects of gamma irradiation on larvae of the huhu beetle *Prionoplus reticularis*: a potential quarantine treatment for New Zealand export pine trees. *Entomologia Experimentalis & Applicata 94*: 237–242.

LUND, J.W. 1998: Geothermal resources in New Zealand. An overview. *In* "Business Opportunities Involving Direct Use of Geothermal Energy". New Zealand Geothermal Association, 2–3 July, Rotorua.

MacLEAN, J.D. 1930: Studies on heat conduction in wood—results of steaming green round southern pine timbers. *Proceedings of the American Wood-preservers' Association 26*: 197–219.

———1952: Preservative treatment of wood by pressure methods. *USDA Handbook 40*. 160 p.

MAUD, J. 1995: Methyl bromide. The race to replace. *New Zealand Pine International August/September*: 30–32.

MILOTA, M.R.; TSCHERNITZ, J.L. 1994: Simulation of drying in a batch lumber kiln from single-board tests. *Drying Technology 12(8)*: 2027–2055.

MILOTA, M.R.; WENGERT, E.M. 1995: Applied drying technology, 1988 to 1993. *Forest Products Journal 45(5)*: 33–41.

MORRELL, J.J. 1995: Importation of unprocessed logs into North America: a review of pest mitigation procedures and their efficacy. *Forest Products Journal 45(9)*: 41–50.

NZFIC 2000: "New Zealand Forest Industries Council Annual Report. 1998/1999 Financial Year". New Zealand Forest Industries Council, Wellington, New Zealand.

NZFOA 2000: "NZ Forest Industry Facts & Figures 2000/2001". Joint publication by the New Zealand Forest Owners Association Inc., the New Zealand Forest Industries Council, and the Ministry of Agriculture and Forestry. 24 p.

PANG, S.; DAKIN, M. 1999: Drying rate and temperature profile for superheated steam vacuum drying and moist air drying of softwood lumber. *Drying Technology 17(6)*: 1135–1147.

PATON, R.; CREFFIELD, J.W. 1987: The tolerance of some timber insect pests to atmospheres of carbon dioxide and carbon dioxide in air. *International Pest Control, January/February*: 10–12.

PATTERSON, D.W.; ARMSTRONG, J.P.; WALTON, D.R. 1988: Factors for economic analysis of installing hardwood kilns. *Forest Products Journal 38(2)*: 38–40.

PREISLER, H.K.; ROBERTSON, J.L. 1989: Analysis of time-dose-mortality data. *Journal of Economic Entomology 82*: 1534–1542.

SAHLE-DEMESSIE, E.; LEVIEN, K.L.; MORRELL, J.J.; NEWBILL, M. 1992: Modeling internal temperature changes of timber poles during ACA treatment. *Wood Science and Technology 26*: 227–240.

SCHROEDER, L.M.; EIDMANN, H.H. 1986: The effects of pure and blended atmospheric gases on the survival of three bark beetle species. *Journal of Applied Entomology 101*: 353–359.

SCOTT, J.W. 1998: Geothermal resources in New Zealand. An overview. *In* "Business Opportunities Involving Direct Use of Geothermal Energy". New Zealand Geothermal Association, 2–3 July, Rotorua.

SEIDNER, M.A. 1996: Shipboard apparatus for heat-treating wood and wood products. *US Patent 5578274*.

———1997: Method for heat-treating wood and wood products. The clean kill. Pp. 82-1 – 82-2 *in* "Annual International Conference on Methyl Bromide Alternatives and Emissions Reductions", 3–5 November, San Diego, California.

SIAU, J.F. 1984: "Transport Process in Wood". Springer series in wood science, Springer-Verlag, New York. 245 p.

STATISTICAL SCIENCES 1995: "S-PLUS Guide to Statistical and Mathematical Analysis, Version 3". StatSci, a Division of MathSoft Inc., Seattle, WA.

USDA 1991: An efficacy review of control measures for potential pests of imported Soviet timber. *USDA Animal and Plant Health Inspection Service, Miscellaneous Publication No. 1496.*

———1992: Pest risk assessment of the importation of *Pinus radiata* and Douglas-fir logs from New Zealand. *USDA Forest Service, Miscellaneous Publication No. 1508.*

WADDELL, B.C.; CLARE, G.K; MAINDONALD, J.H. 1997: Comparative mortality responses of two Cook Island fruit fly (Diptera: Tephritidae) species to hot water immersion. *Journal of Economic Entomology 90(5)*: 1351–1356.

WENLONG HE; SIMONSON, W.J.; HUA CHEN; MORRELL, J.J. 1997: Evaluation of the efficacy of selected thermal boron treatments in eliminating pests in freshly peeled Douglas-fir logs. *Forest Products Journal 47(3)*: 66–70.

WOODROW, R.J.; GRACE, J.K. 1998: Laboratory evaluation of high temperatures to control *Cryptotermes brevis* (Isoptera: Kalotermitidae). *Journal of Economic Entomology 91(4)*: 905–909.

YOSHIZAWA, N.; ANDOH, M.; ISHIGURI, F.; YOKOTU, S.; FURUNO, T. 1999: Rupture of pit membranes in Sugi (*Cryptomeria japonica* D. Don) logs by a smoke-heating system with increased far-infrared radiation. *Holzforschung 53*: 9–15.