ERADICATION OF PINEWOOD NEMATODES IN SOFTWOOD LUMBER

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Abstract

Forintek Canada Corp. was commissioned by the Canadian Federal Government Task Force on Pasteurization of Softwood Lumber to lead a research initiative to examine heat treatment (pasteurization) as an alternative to kiln drying for the eradication of pinewood nematode (PWN) and a sawyer beetle *(Monochamus)* from green, unseasoned softwood lumber.

Pasteurization of unseasoned coniferous wood using wet heat at 56.1°C resulted in total mortality for PWN with a reliability of 99.994% and confidence of 95%.

The successful use of pasteurization was then demonstrated at three different locations across Canada using a conventional (Vancouver), high temperature (Sudbury) and dehumidification (Fredericton), kiln at a slightly increased temperature of 59°C for 30 minutes. The longest times for any board to reach 59°C at these three locations, using 2 x 4 inch boards of infested ponderosa pine, were 5.3, 4.3 and 30.3 hours respectively.

To pasteurize lumber it is essential that the core temperatures for all lumber of all species, specific gravities, moisture contents and thicknesses, has reached the required 59°C for 30 minutes. It was generally found that heating times increased with increasing specific gravity and moisture content of the lumber, whereas the effect of species, by itself, was not clear. Differences in heating times between the nine species tested could be at least double and heating times increased with increasing lumber thickness, being at least trebled between 100 mm (4 inch) and 254 mm (10 inch) thick lumber.

The use of chemicals to kill PWN in lumber showed little promise, apart from the use of boron on thin boards. Irradiation at 7 KGy could be used to eradicate PWN and *Monochamus* from lumber. Radio frequency heating could be used to heat lumber to 59°C, however inconsistencies due to variable moisture contents could make the method impractical.

Introduction

The pinewood nematode (PWN), *Bursaphelenchus xylophilus* (Steiner and Buhrer) Nickle, is a very small, elongated worm, about three quarters of a millimetre long (13) (Figure 1). It

occurs in wood very rarely in Canada (25, 12) where it has never been known to kill a single native tree. In Canada PWN occurs in coniferous trees weakened, dying or freshly killed, by other pests or diseases, where it feeds on the ray parenchyma or resin duct cells. The pinewood nematode also feeds on fungi (Figure 2), which explains why it frequently occurs in sapwood which is heavily discoloured by sapstaining fungi.

The PWN is heterosexual and reproduces by producing eggs which then hatch to form the worm (larva). In the propagative phase, under ideal growing conditions, at 25-30°C, females reproduce and begin laying eggs about four days after hatching. These eggs then hatch within one to two days thereby rapidly multiplying the population of nematodes. During the dispersal phase the PWN goes through three larval stages before passing into the final (adult) larval stage (dauerlarva), when it attaches itself to the breathing tubes of its vector, the sawyer beetle (*Monochamus* spp.). The *Monochamus* beetle then transmits the PWN to a fresh host tree, or log, during its shoot feeding or egg laying activities (Figure 3). The cycle of nematode multiplication then continues in the fresh host.

In Japan the PWN has been shown to be responsible for pine wilt disease (13), resulting in destruction of some plantation grown pine species. Pine wilt disease has never been recognised as occurring in Canada's forests, where the necessary conditions for the development of this disease do not seem to occur (17). The PWN also occurs in China (2), Taiwan and Korea.

The European Community (EC) believes that PWN does not occur in Europe. Since the EC is very dependent on the importation of lumber and timbers, particularly from North America, they have become very concerned about the potential introduction of PWN to Europe. Canada has been very responsive to the EC concerns and has, over the years, implemented measures to dramatically reduce the risk of exporting PWN. A very strict lumber grading inspection program known as the Mill Certification Program for Bark and Grubhole Control (MCP), has been implemented. Through this program, sawmills and shippers guarantee that all bark and grubholes have been eliminated from the lumber. It is worth noting that following close to 100 years of lumber shipments and over 200 years of roundwood shipments such as masts and spars, from North America to the EC, even without the MCP in place, no evidence of pine wilt disease has been found in Europe.

At a meeting called by Forestry Canada on April 27, 1990, involving members from federal departments, the provinces, industry and research organizations, it was decided to establish a Task Force on Pasteurization of Softwood Lumber under the direction of Mr. J. Carette. The mandate of this Task Force was to develop a technical proposal to evaluate the potential use of pasteurization technology in Canada for the eradication of PWN from exported, unseasoned, Canadian softwood lumber.

Forintek Canada Corp., as a scientific research organization, was then commissioned to lead a research initiative to examine pasteurization as an alternative to kiln drying for the PWN from lumber. The use of heat for the sterilization of materials has been applied for many centuries and found to be both practical and reliable. The boiling of drinking water was even advocated by Aristotle about the year 344 BC for the protection of Alexander the Great's armies on the march. However the first introduction of a steam pressure vessel did not occur until 1859, following the researches of Koch and Pasteur.

The principles of heat sterilization are described in the literature (18, 3) and are widely used for the sterilization of many materials, including hospital goods and microbiological growth media. Pasteurization was developed following the researches of Louis Pasteur in the middle of the last century on the prevention of spoilage of wine. The method uses temperatures lower than those required for sterilization, resulting in the killing of selected organisms. It can be used where higher temperatures may be detrimental to the materials being heated, as for example in the pasteurization of milk or in the brewing industry. It has been used to control a range of microorganisms in various materials, including nematodes in soil (21). The use of simple and clean, wet heat, is very attractive and presents no direct environmental problems. It is a well established fact that PWN (7) and beetles (16), like most organisms, can be killed by moderate heat, but for Canadian lumber species little data exists on what temperature would be required, or for how long.

In developing the Canadian initiative, the necessity to include some testing of the vector sawyer beetle, *Monochamus* sp. was established, both by the Canadian and EC participants. The use of heat treatments to control insect pests on lumber has been demonstrated by several workers. Hopping and Jenkins (1933) recommended heating to control ambrosia beetles in western hemlock, while Ostaff and Cech (1978) demonstrated complete kill of sawyer larvae and beetles in infested spruce-pine-fir lumber that had been heated for one hour, thereby achieving a maximum core temperature of about 54°C. A useful wood information sheet (24) was put out by the Timber Research and Development Association in England, which describes the use of kiln treatments for the control of insect pests in lumber, specifically *Lyctus* beetles. Here it is suggested that a temperature of 50°C at 100% relative humidity will be suitable to kill wood-destroying insects and that at any temperature, the higher the relative humidity the more lethal it is. The practice of heat treatment for wood products has already been established by the Australian Quarantine Service (1986), although this was not connected to the PWN, nor was the process used, pasteurization.

The mandate for this research program, agreed to between the Canadian and EC research teams, was to establish time and temperature (pasteurization) schedules required to kill PWN and

its vectors in unseasoned Canadian softwood lumber. The work would be done in such a way that the data could be used to support reliability requirements yet to be agreed upon between Canada and the EC. Alternative technologies to pasteurization would also be briefly evaluated. The Canadian research initiative on PWN eradication also included a preliminary examination of other alternative technologies, including gamma irradiation, radio frequency heating and treatment with borates and the antisapstain chemical didecyldimethylammonium chloride (DDAC).

The Canadian research team for the PWN initiative consisted of scientists from Forintek's Vancouver and Ottawa Laboratories, Forestry Canada's Pacific Forestry Centre in Victoria, the University of New Brunswick's Wood Science and Technology Centre and Simon Fraser University in Burnaby, B.C. The present paper reviews the results produced by this team of scientists which has been reported in detail elsewhere (22).

Biological Studies

The objective of these studies was to determine temperature and time parameters required to kill PWN in wood.

The initial two experiments were done *in vitro* to evaluate the general range of temperatures that would be expected to kill PWN and also to see if different isolates of PWN would have different thermal death points. Cultures of PWN were obtained from Mr. Jack Sutherland of the Forestry Canada, Pacific and Yukon Region, Pacific Forestry Centre and represented a selection of five isolates from five different regions of Canada (Table 1). These cultures were then multiplied by growing the PWN on agar Petri dishes inoculated with a non-sporulating strain of *Botrytis cinerea* pers. ex Fr. Exposure studies were done in multi-well microplates floated on the surface of a water bath.

The initial experiment done on the Alberta PWN isolate showed 100% mortality at 50°C after 60 minutes. Comparing the five isolates at this temperature the St. John and B.C. Isolates to be the most heat resistant (Figure 4). Because of St. John isolate could be multiplied more rapidly than the other isolates and because it was more pathogenic than the B.C. Isolate in seedling mortality studies (20), all further biological studies were done on this isolate.

To determine which wood species and moisture content would provide the "worse case" situation for pasteurization, the next series of experiments were done on PWN cultured in small wood blocks that had a prior infection with the sapstain fungus *Ophiostoma piceae* (Münch) H. and P. Syd. The infested blocks were then heated in an oven to the required target temperatures. Sampling of the blocks both before and after heating was done by splitting them into several pieces and using a modified Baermann

thermocouples inserted at mid-length and width to the geometric centre of the board. All boards were heated in a dry kiln set for 75°C dry bulb, with steam injection to ensure a wet bulb depression of no less than 3°C during heat up and 1°C upon reaching set point. Temperature in all boards were recorded every three minutes until all 60 boards in a run had reached a core temperature of 70°C. Runs were done on lumber from both ambient and frozen conditions (Figures 8 and 9).

From the results it was concluded that differences in heating time do exist between species, even after correction for moisture content and specific gravity, but a consistent relationship could not be found for all species. For example double the heating time would be required for hem-fir than for Sitka spruce. Also the heating times increased with increasing moisture content and specific gravity in Douglas fir, balsam fir, hem-fir, white pine, spruce/pine (frozen only), larch (frozen only). There was also a considerable difference between the fastest and slowest board to reach the target temperature in any run. It was shown that this variability could be reduced when the difference between the chamber temperature and wood target temperature was increased.

Wood Thickness

The objective here was to determine the effect of wood thickness over a range of 25 - 254 mm on the rate of heating of lumber. Amabilis fir was used for boards 108, 152 and 254 mm thick and white pine for boards 25, 50 and 75 mm thick. Each kiln charge was 60 boards and specific gravity and moisture content of each board were taken. Thermocouple temperature measuring devices were used as in the previous study. The results showed about a 15 times increase in time to target temperatures between the range 50 to 90°C tested, when board thickness increased from 25 to 254 mm (Figure 10).

It was concluded that as well as average heating times increasing with wood thickness, the variability between replicate boards increased with increasing wood thickness. Also, for the 75 mm Douglas fir and white pine tested, heating times were longer with a 5° depression than when the kiln was operated near saturated conditions. This is in agreement with the known enhanced heat transfer properties of saturated steam.

Field Testing

The objective of this phase of the study was to ensure that pasteurization schedules would be practicable in selected industrial kiln installations and to confirm that both PWN and Monochamus would be killed by the schedules. Project leaders from both the EC and Canadian teams participated in this phase.

funnel technique.

The results, although not clear-cut, pointed to Jack pine as being one of the worse-case wood species. Further experiments to evaluate Jack pine at various moisture contents, suggested that PWN infested samples would be more difficult to pasteurize at lower wood moisture contents of about 20%.

Having established the appropriate lethal temperature for the worse case of PWN isolate, wood species and moisture content, the critical development of a mortality curve was undertaken. By this technique a dose-response curve could be developed from which the lethal temperature could be derived at any required reliability. The EC had suggested that a reliability of 99.994% would be required.

The experiment was done using a replicate of 60 blocks infected with *O. piceae* and infested with PWN, held at eight separate temperatures for 30 minutes encapsulated in plastic in a water bath (Figure 5). The blocks were sampled before and after heating by splitting and using a modified Baermann funnel technique (Figure 6). The results were used to construct an excellent mortality curve (Figure 7). This was used to show that at a reliability of 99.994% and with 95% confidence, a thermal death time of 56°C for 30 minutes was applicable.

Heating of Lumber

The objective of this phase of the project was to determine the temperature and time treatments (pasteurization) required to ensure the eradication of PWN from Canadian softwood lumber. This could be expected to vary according to wood species, specific gravity, moisture content and lumber dimension.

Wood Species, Moisture Content, and Specific Gravity

The following nine wood species from across Canada were tested:

- Douglas fir *(Pseudotsuga menziesii)*
- Sitka spruce *(Picea sitchensis)*
- Spruce/Pine *(Picea glauca, Pinus contorta)*
- Hem-fir *(Tsuga heterophylla, Abies amabilis)*
- Eastern hemlock *(Tsuga canadensis)*
- White pine *(Pinus strobus)*
- Balsam fir *(Abies balsamea)*
- Larch *(Larix laricina)*
- Eastern spruce *(Picea mariana)*

Ninety six pieces of freshly sawn green lumber of size 75 mm x 150 mm x 3.6 M were used for each species or species group. The moisture content and specific gravity was determined for each piece. Temperature measurements were made on each piece using

Pasteurization runs were done in three different types of kilns at different locations:

1. Conventional kiln: Vancouver, B.C.
2. High temperature kiln: Sudbury, Ontario
3. Dehumidification kiln: Fredericton, New Brunswick

A replication of 30 boards of nominal 2 x 4 inch ponderosa pine, heavily sapstained and infested with the St. John isolate of PWN was used at each location. Also, in Vancouver, 30 boards of 4 x 4 inch amabilis fir infested with *Monochamus*, and in Sudbury and Fredericton, 30 boards of 2 x 6 inch Jack pine infested with *Monochamus* was included (Figure 11). Sampling of the boards for PWN both before and after pasteurization was done by drilling wood shavings from the centre of the boards and using the Baermann funnel method. Sampling for *Monochamus* was done by repeated splitting of the boards after pasteurization and counting any live larvae and adults. The target lethal conditions chosen for all the locations was 59°C for 30 minutes for the slowest heating board in the total replication. This was based on the previously obtained mortality curve temperature and time of 56.1°C for 30 minutes, but adding a small temperature factor for thermocouple and other experimental errors. The total treatment times to target temperature varied for each location and were as follows:

1. Conventional kiln: 5.8 Hr.
2. High temperature kiln: 4.8 Hr.
3. Dehumidification kiln: 30.8 Hr.

No PWN were recovered from any of the boards heat treated in the dehumidification, high-temperature, or conventional kilns (Table 2). Clearly the selected regime of 59°C for 30 minutes had successfully pasteurized all the test lumber and rendered it free of living PWN. This result agrees with the findings of Dwinell (1990) who states that a temperature of 60° in lumber is sufficient for nematode eradication.

Also, no live *Monochamus* (larvae, pupae, or adult) were recovered from heat treated lumber at any of the three demonstration sites. All *Monochamus* infested samples in the Fredericton and Sudbury tests reached or exceeded 60°C. The 4 x 4-inch amabilis fir used in the Vancouver test heated at a slower rate but still reached at least 57.5°C. The successful kill of all *Monochamus* supports the previous work of Ostaff and Cech (1978) where 100 percent mortality was achieved in boards heated in a kiln to a maximum core temperature of 54°C.

This phase of the project served two purposes. Firstly, it demonstrated that the conditions found to be effective in causing complete mortality of PWN in the laboratory are also effective when applied in industrial dry kilns. Secondly it demonstrated that the conditions required to obtain mortality can be achieved in a wide range of dry kilns.

It should be remembered that the chambers used for these demonstrations were not designed to operate as heat treatment chambers. They were initially designed to create conditions for the drying of lumber. Operating at conditions less than full saturation will slow the heating rate. It is therefore realistic to assume that heating rates would be faster in a purpose-built chamber designed to operate a close to full saturation and capable of maintaining a large difference between air and wood temperature.

Alternative Technologies

The objective of this phase was to review the use of RF heating, gamma irradiation, borates and DDAC as alternate potential methods to eradicate PWN from softwood lumber.

RF Heating

Nominal 2 x 4 inch boards, 2.4 M long of heavily sapstained ponderosa pine, were infested with the St. John isolate of PWN. Two replicate sets of 30 boards were then treated by RF heating using a raytherm radio-frequency generator, one set to 40°C and the other to 60°C. A further set of 30 boards was kept as a control.

After treatment it was found that RF heating to 60°C killed PWN in 44% of the boards, while heating to 40°C killed PWN in only 4% of the boards (Table 3). Temperatures measured within the boards showed considerable variation, ranging from 54° to 80°C in the target 60°C set. This treatment appears to have some potential for PWN control, however, the board target temperature would have to be higher than 60°C to overcome the considerable temperature variations occurring. It is possible that this variation, resulting from internal variations in board moisture content, would always make the method unreliable.

Gamma Irradiation

Irradiation using either gamma rays or electron beam has the potential of being a rapid and clean method for disinfecting lumber from PWN. Cultures of the Alberta isolate of PWN were suspended in water in eppendorf tubes and irradiated at a commercial facility with gamma rays. A similar technology has been used for food processing and could readily be adapted to treat lumber.

Results demonstrated that a dosage of 0.7 Mrad dosage will eliminate PWN in an aqueous solution (Table 4). This observation is in rough agreement with results obtained by Eichholz and Dwinell (1991), who gamma irradiated PWN infested wood samples and found 0.9 Mrad to be the lethal dose.

However, it is considerably lower than the 2.5 Mrad found by

Smith and Sharman (1971) to be necessary to kill bacteria and fungi in wood. These authors also found wood moisture content would affect the required dosage level to achieve sterilization, a factor that would also need testing for PWN in lumber.

Borates

Borates are effective fungicides and insecticides. They offer an environmentally benign preservative treatment for protected environments and are readily applied to certain wet Canadian wood species using diffusion treatment. (4, 10). Their potential as nematicides against PWN has already been demonstrated by Morris and Clark, 1990. High retentions of boron (1.55 % Bae) were shown to effect mortality over short time periods (4 weeks) and it was postulated that lower retentions might give 100% mortality over longer time periods.

In this study fresh lodgepole pine sapwood blocks, 30 x 10 x 5 mm, were infested with *O. picea* and then infested with the B.C. isolate of PWN. Following a period of colonization, the blocks were then diffusion treated with various strengths of Timbor®. After various time periods the blocks were then removed from test and evaluated for PWN using the baermann funnel method.

The results showed that a retention of 0.42% Bae in wood achieved 100% mortality of PWN in eight weeks (Table 5), whereas 0.92% Bae achieved 100% mortality in four weeks. A level of 0.42% Bae would be achievable in the core of nominal 2 inch lumber, although the cost may not be recoverable unless used as an added-value incentive because of the resulting decay resistance of the lumber.

DDAC Treatment

DDAC is a major component of three of the seven main antisapstain formulations currently in use by the Canadian lumber industry. As such it was an ideal candidate to exemplify the effect of antisapstain chemicals on PWN.

Fresh sapwood block infested with PWN ere prepared similarly to those used in the borate tests. These were then dipped for three seconds in several strengths of aqueous DDAC solutions up to 4% and stored for four weeks at 25°C.

After four weeks storage all of the blocks exposed to 4% DDAC did not have any detectable PWN, while the blocks exposed to 0.25% DDAC had a greatly reduced number (Table 6). Clearly DDAC is toxic to PWN at 4%; however, since in commercial use DDAC penetrates little more than 1 mm into lumber (14), its use as a PWN irradicant would seem limited.

Conclusions

The pasteurization of unseasoned coniferous wood under laboratory conditions using wet heat at 56.1°C for 30 minutes, resulted in total mortality for PWN with a reliability of 99.994% with 95% confidence. This conclusion was derived for the worst conditions of PWN isolate, wood species and moisture content of those tested.

To apply pasteurization to lumber it is essential to ensure that core temperatures for lumber of all species, specific gravities, moisture contents and thicknesses, have reached at least the required 56.1°C for 30 minutes. It was generally found that heating times increased with increasing specific gravity and moisture content of the lumber, whereas the effect of species by itself, was not clear. Differences in heating times between the nine species tested could vary by a factor of at least two. As expected, heating times increased with increasing lumber thickness, the time being at least trebled in going from 108 mm (4¼ inch) to 254 mm (10 inch) lumber, for example.

Pasteurization at higher temperatures was much more rapid than at lower temperatures. For example raising kiln temperatures from 70 to 90°C, for 254 mm (10 inch) amabilis fir, reduced the estimated time for pasteurization by 44%.

Pasteurization of unseasoned lumber, using an operational temperature of 59°C for 30 minutes, was demonstrated at three different locations across Canada using a conventional, high temperature, and dehumidification kiln. No surviving PWN or *Monochamus* beetles were found in the lumber treated at any of the three locations. This clearly demonstrated the applicability of pasteurization under mill conditions using a temperature slightly above that found to be necessary under laboratory testing. However it should be remembered that before pasteurization can be applied to industrial lumber production its deleterious effect on the antisapstain formulations used to protect lumber in transit and storage would have to be evaluated. A recent study by Byrne and Minchin (1992) clearly shows the magnitude of this problem and its specificity to individual formulations.

Alternate technology using irradiation showed some promise, and the use of chemicals such as boron may be suitable for PWN control in wet lumber of thin dimensions.

Acknowledgements

The success of any scientific endeavour always depends upon the intelligence, ability and effort put into it by the individual contributors. Of crucial importance is the functioning of these people as one whole team dedicated to produce a quality product. In turn this scientific effort must be supported by a sound financial infrastructure and time must be allowed for data to be developed. This pasteurization project,

planned and done in little over seven months, reflects the very best in scientific endeavour from a large team of scientific and technical people from a number of laboratories across Canada. They were presented with a complex problem, of enormous importance to our lumber industry, and expected to provide a practical solution. This was to be done speedily and under the constant scrutiny of scientific experts from EC. This present document is a measure of this collective scientific effort and I congratulate and salute every person who worked so hard to make it possible. The challenge was accepted, the work completed on time, and a practical result has been prepared for our lumber industry.

In particular I would like to acknowledge the expert support of this project provided by Mr. Jacques Carette from Forestry Canada, who really did make it all possible. Technically the program was driven hard by the project leaders, Paul Morris, Graham Mackay, Peter Garrahan, Mary Mes-Hartree, John White and Jean Cook, who conceived and gave scientific substance to the pasteurization of lumber.

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Table 1. Isolates of PWN Used in Experiments

Isolate	Substrate	Locality	Form
St. John	Wood Chips	St. John, New Brunswick	M
Alberta	*Pinus Banksiana*	Smokey Lake, Alberta	R
B.C.	Wood Chips	Clinton, B.C.	M
St. Will	*Pinus Nigra*	St. Williams, Ontario	R
Q52	Wood Chips	Mappin, Quebec	M

Table 2. Mortality of PWN and *Monochamus* from 30 Infested Boards Pasteurized in Three Different Heat Chambers Across Canada.

Kiln Type	% Mortality PWN	% Mortality *Monochamus*
Dehumidification	100	100
Conventional	100	100
High-Temperature	100	100

Table 3. Mortality of PWN from Infested Ponderosa Pine Boards Exposed to RF Heating to Target Temperatures of 40° and 60°C.

Heat Treatment Target Temperature	PWN Mortality %
Controls	0
40°C	4
60°C	44

Table 4 Mortality of PWN in Water Following Gamma Irradiation

Sample Tube #	Dosage (KRAD)	Assay Culture Plate Response	
		Plate 1	Plate 2
1	1	+	+
2	1	+	+
3	1	+	+
4	1	+	+
5	1	+	+
6	2.5	+	+
7	2.5	+	+
8	2.5	+	+
9	2.5	+	+
10	2.5	+	+
11	4	+	+
12	4	+	+
13	4	+	+
14	4	+	+
15	4	+	+
16	5	+	+
17	5	+	+
18	5	+	+
19	5	+	+
20	5	+	+
21	6	-	-
22	6	-	-
23	6	+	-
24	6	-	-
25	6	-	-
26	7	-	-
27	7	-	-
28	7	-	-
29	7	-	-
30	7	-	-

Table 5. Pine Wood Nematode Viability After Exposure to Borates.

Treating Solution (%BAE)	Block Retention Analyzed	Mean PWN Numbers in Blocks			
		0 Week	4 Weeks	8 Weeks	12 Weeks
0.0	0.0	641 (251)	205 (72)	131 (53)	124 (61)
0.37	0.07	535 (184)	243 (138)	205 (95)	252 (96)
0.76	0.125	704 (493)	177 (87)	231 (224)	105 (36)
1.5	0.27	629 (255)	91 (40)	13 (12)	5 (6)
3.0	0.42	703 (376)	1 (2)	0 (0)	0 (0)
6.0	0.92	979 (376)	0 (0)	0 (0)	0 (0)

Table 6. Numbers of PWN Isolated from Infested Wood Test Blocks Dipped in DDAC and Inoculated for Four Weeks at 25°C.

Solution	Exposure	Mean PWN Numbers in Blocks			
% DDAC	Time (Weeks)	Split Block		Whole Block	
0.0	0	641	(318)	552	(251)
0.0	4	205	(72)	148	(34)
0.25	4	21	(13)	15	(9)
1.0	4	0	(0)	2	(4)
4.0	4	0	(0)	0	(0)

Numbers within parenthesis are standard deviations.

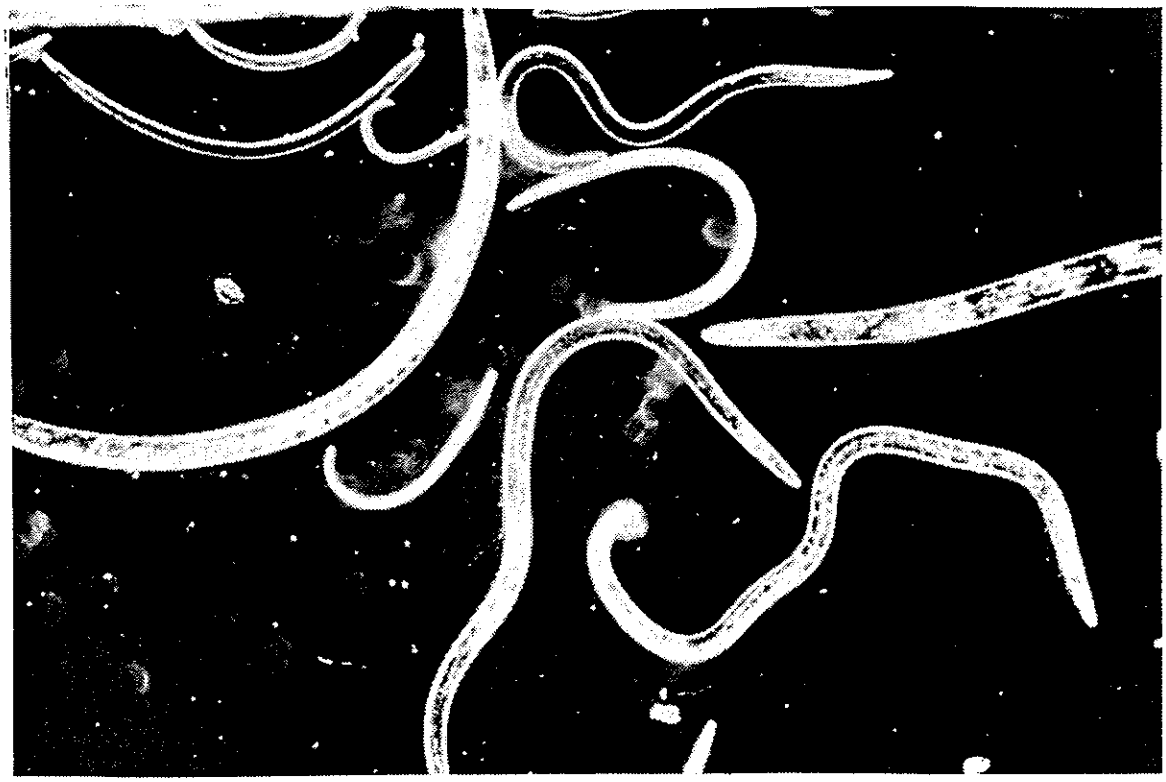

Figure 1 Pinewood nematodes (*Bursaphelenchus xylophilus*), in liquid culture: magnification x 500.

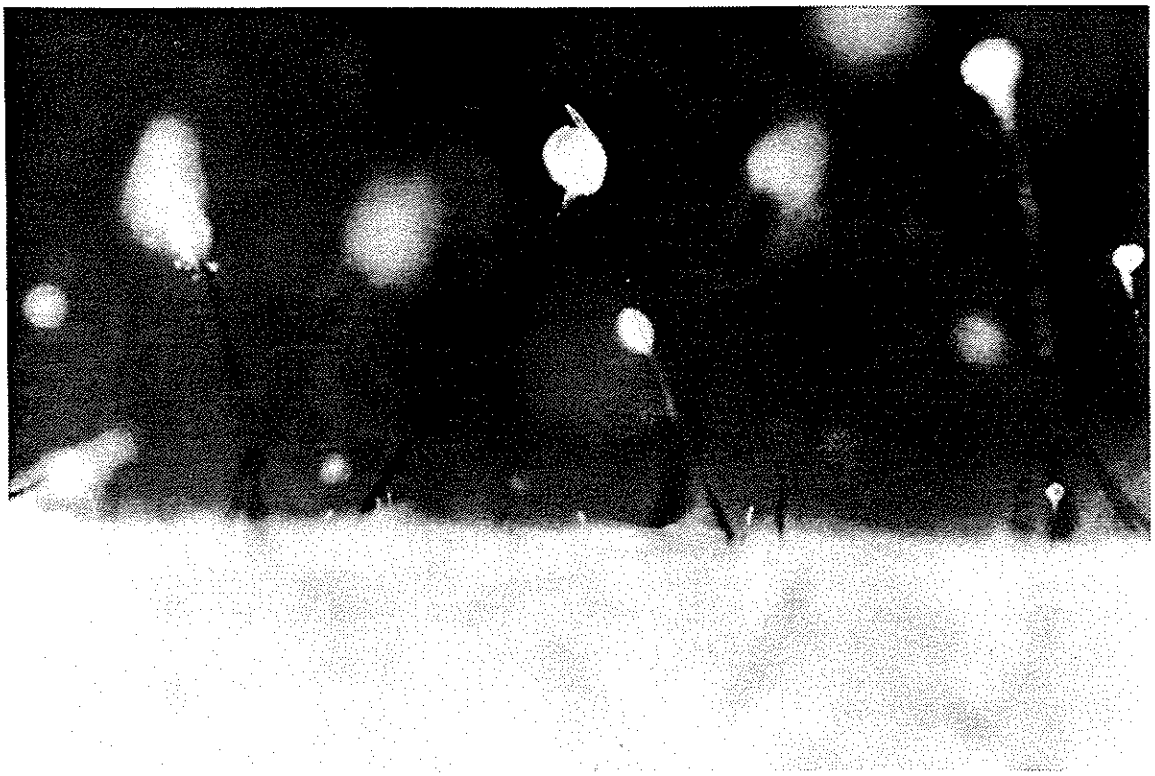

Figure 2 Pinewood nematode feeding on the "head" (coremium) of sapstain fungus (*Ophiostoma* sp.): magnification x 50.

Figure 3 Sawyer beetle adult (*Monochamus scutellatus*) on log adjacent to round emergence hole: magnification 1.4 x life size.

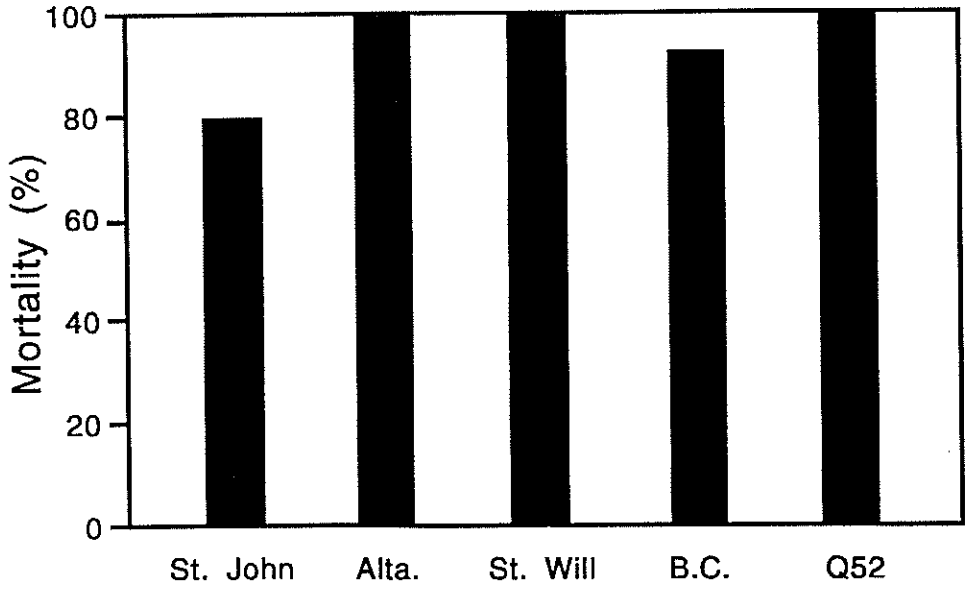

Figure 4 Percent mortality of five isolates of PWN heated in liquid culture for 30 minutes at 50°C.

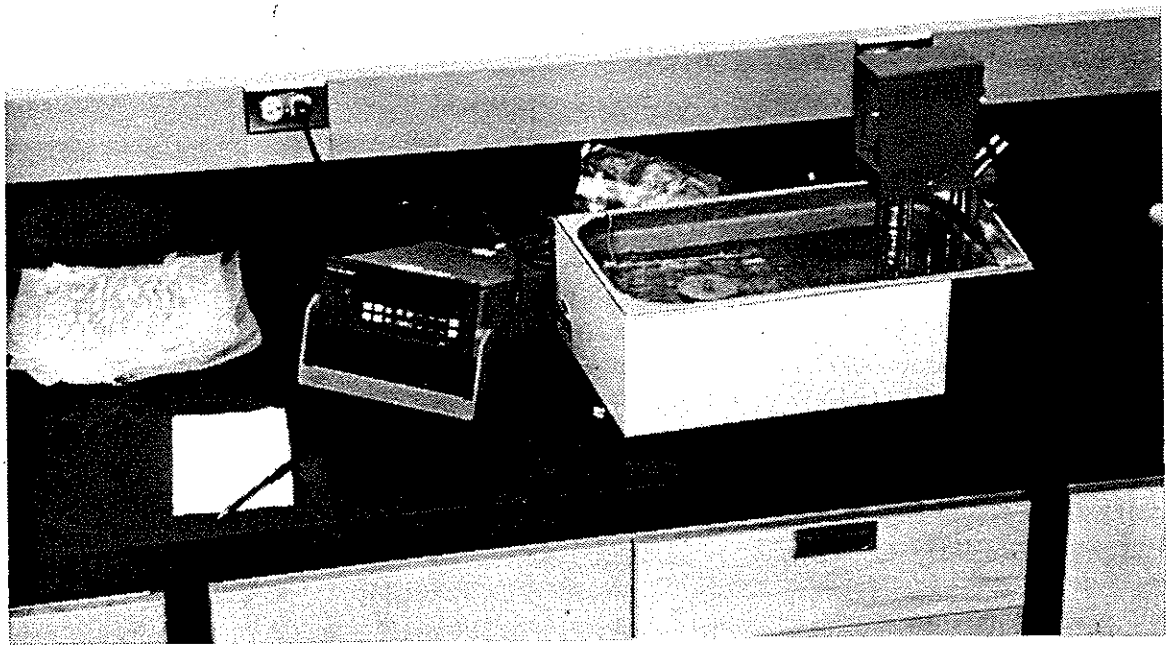

Figure 5 Water bath and heater unit containing PWN infested blocks submerged in sealed bags sandwiched between metal grids.

Figure 6 Baermann funnels containing wood shavings wrapped in Kimwipes and covered with water. Nematodes in solution obtained by opening pinchcock clamp on rubber tube.

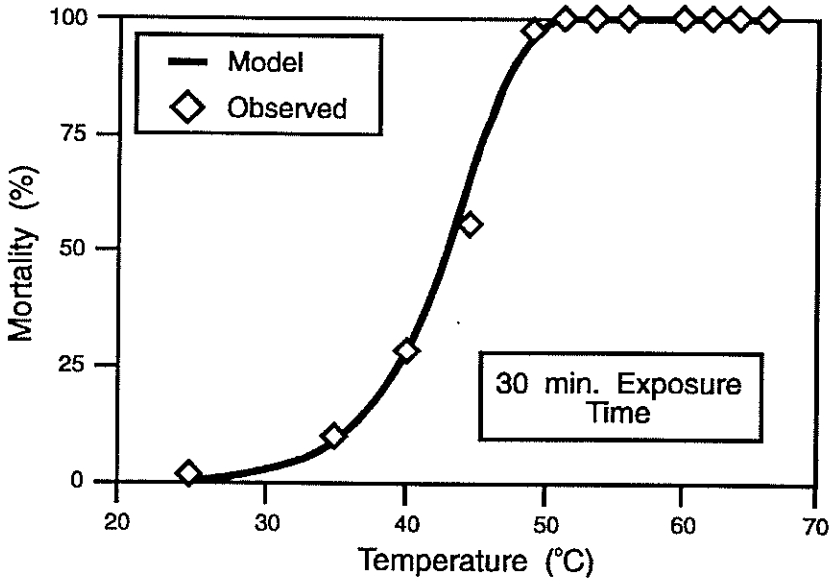

Figure 7 Temperature mortality curve for PWN in unseasoned wood following 30 minutes exposure.

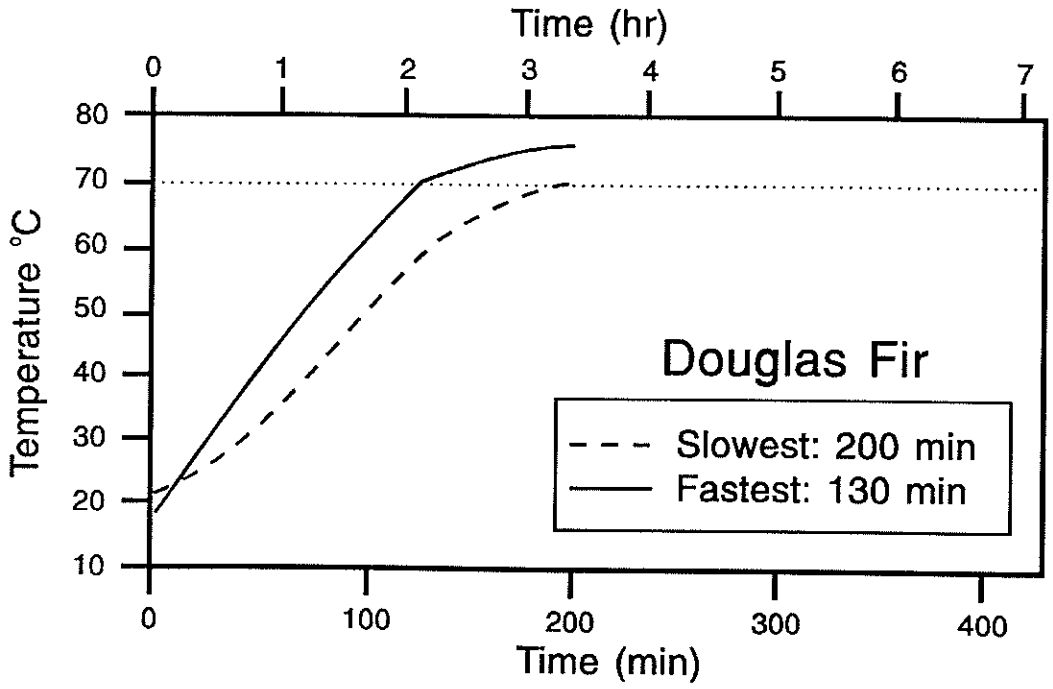

Figure 8 Heating rate curves for the fastest and slowest 75 x 150 mm x 2.4 m Douglas fir specimens heated from ambient conditions to 70°C in a pasteurization chamber operated at 75°C.

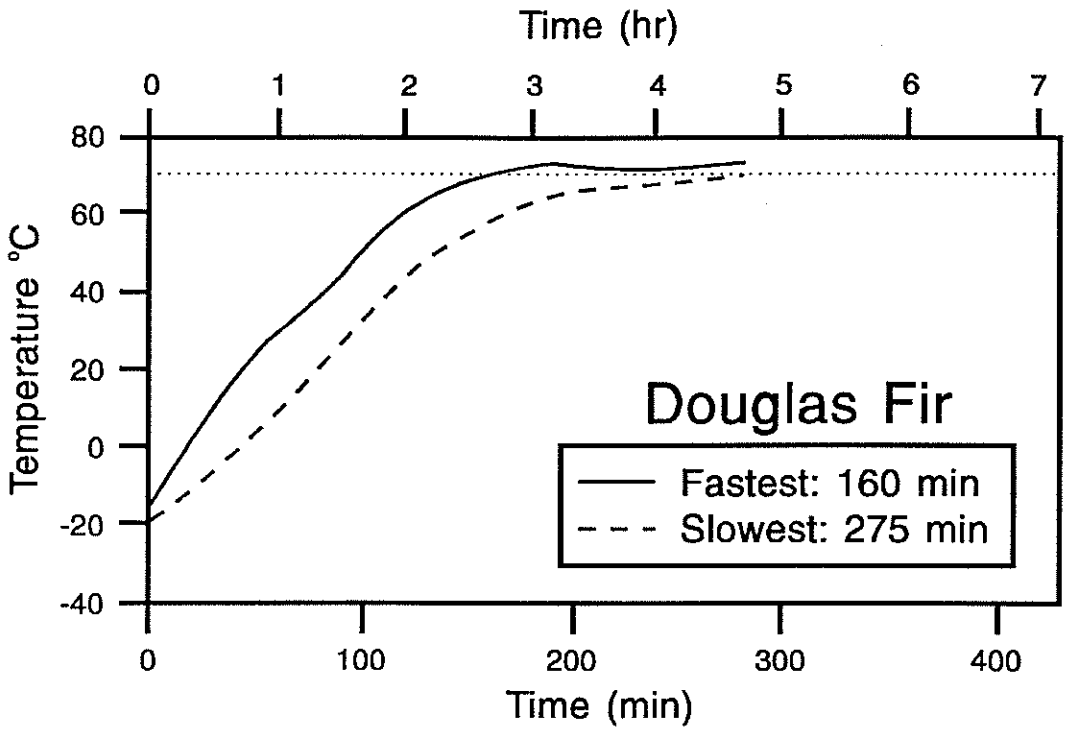

Figure 9 Heating rate curves for the fastest and slowest 75 x 150 mm x 2.4 m Douglas fir specimen heated from frozen condition to 70°C in a pasteurization chamber operated at 75°C.

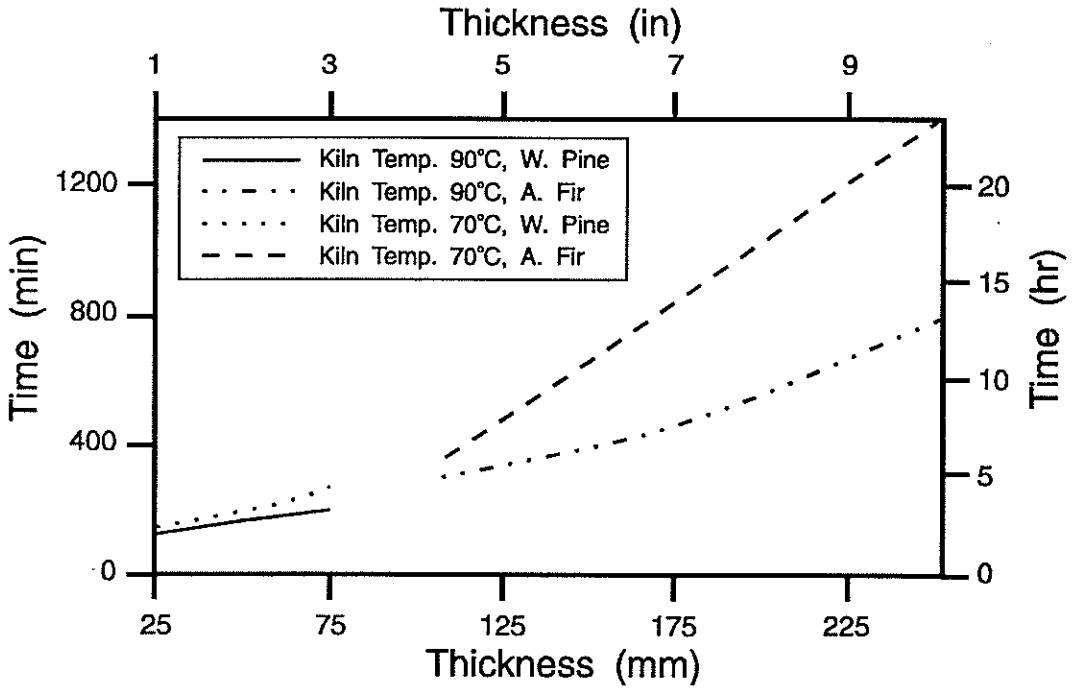

Figure 10 Effect of wood thickness on heating times for western white pine and amabilis fir placed in a pasteurization chambers at 70° and 90°C.

Figure 11 Experimental package of sapstained and PWN infested, ponderosa pine (dark boards), surrounded by *Monochamus* infested boards of white pine (light boards), all wired with thermocouples, at dehumidification kiln of Ashley Colter Ltd.