TREATABILITY OF CANADIAN WOOD SPECIES WITH BORATES

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Summary

Forintek has conducted a series of studies designed to develop rapid, but readily useable, borate treatment processes for Canadian wood species. The work centred around pressure plus diffusion treatment. Pre-steaming, solution additives and various diffusion periods were studied. Not all variables have been evaluated on all species but the information generated in these studies should be sufficient to allow the industry to develop commercially viable treating processes for the species of their choice.

Not surprisingly, initial uptakes were generally higher in dried rather than green material for Douglas fir, lodgepole pine, alpine fir, white spruce, jack pine, and white pine, however, the reverse was true for balsam fir and black spruce. Green western hemlock showed the best rate of diffusion. Diffusion was not as fast as expected in the true firs which also have wet heartwood. Species with low heartwood moisture contents, around 30%, such as Douglas fir, and the pines showed the lowest rates of diffusion. As might be expected, there was no discernable diffusion in kiln-dried lodgepole pine and alpine fir (20 and 25 % mc respectively) and very little in partially air-dried Douglas fir (20.3%). With eastern SPF, there was some movement during storage in the air dried material with average moisture contents between 17 and 21%.

Presteaming was found to be highly effective in enhancing uptake in green western hemlock. After steaming a 30-minute vacuum was better than 60 minutes or no vacuum. Presteaming also had a highly beneficial effect in green Douglas fir but not in dry material. In contrast, presteaming did not provide any discernable benefit with either western or eastern spruce-pine-fir or white pine. White pine was so treatable with the basic pressure treatment that it was impossible to distinguish any improvement in treatment with any of the process modifications.

The addition of 0.5% DDAC to the solution provided some improvement in uptake in some of the more refractory species wood such as one source of western hemlock, white spruce, and particularly in Douglas special fir. There was no similar effect with lodgepole pine, alpine fir, jack pine, balsam fir or black spruce. In western hemlock there was also a significant effect of DDAC on rate of penetration of borate during storage, possibly due to a surfactant action. The combination of presteaming and DDAC addition was particularly effective in increasing uptake and subsequent penetration in green Douglas fir but not in eastern SPF.

By selecting the right moisture content, treatment process and diffusion period most Canadian species can be borate treated to meet American Wood Preservers' Association standards.

Introduction

Over the past six years a number of factors have come together to revive interest in treatment of Canadian softwoods with borates (Byrne 1990a,b). These include opportunities in overseas markets where termites are a problem and the recognition of borate-treated framing as an environmentally acceptable alternative to soil poisoning and house fumigation (Williams 1990). If Canadian sawmills are to take advantage of these new market opportunities they must be able to effectively treat a broad range of Canadian species. A series of studies was therefore designed to investigate process options for borate treatment. These studies evolved over time as more experience was gained and different species were used. Consequently, not all the process variables have been evaluated on all species. Before discussing the approach to this work, a review of some background information is appropriate.

Borates are highly effective against both wood-rotting fungi and wood-boring beetles (Drysdale 1994). Borate-treated Douglas fir is now being used routinely for framing in Hawaii where the Formosan subterranean termite (*Coptotermes formosanus* Shiraki) is the most serious wood deterioration problem (Grace and Yamamoto 1994a,b). Effectiveness of borates against termites is still a matter of debate (Drysdale 1994) but recent work suggests borates may prove effective provided that high enough retentions are used (Grace, Tsunoda, Byrne and Morris 1994). Borates commonly used as wood preservators are colourless, odourless and water-soluble. They also have very low mammalian toxicity, comparable to that of table salt. The one major drawback to borates is that they are leachable under continuously wet conditions thus borate-treated wood is only suitable for use in protected environments. Suitable uses include framing lumber and exterior millwork with a three-coat paint finish. Borates have proven effective in these applications over 40 years of use in New Zealand (Drysdale 1994).

In the 1960s and early 1970s, coastal British Columbia sawmills treated hem-fir, a mix of western hemlock (*Tsuga heterophylla* Raf. Sarg.) and Pacific silver fir (*Abies amabilis* Dougl. Forbes), via dip-diffusion for export to the United Kingdom (Byrne 1990b). This process was effective, but it took seven weeks to achieve through treatment in nominal two inch lumber (Maclean 1962). Diffusion proceeded well in saturated sapwood but less rapidly in hem-fir heartwood which has a lower moisture content (Maclean 1962, Smith and Williams 1969), around 50% (Nielson, Dobie and Wright 1985). Based on experience with pine in New Zealand (Vinden 1988), 100 mm-thick lumber was expected to take 16 weeks diffusion, including a second dip after 8 weeks, for complete penetration. The recent revival of interest in borate treatment has led to a search for more rapid treatment processes (Morris, Byrne and Minchin 1996).

Methods developed in New Zealand for speeding up the treatment process, were reviewed by Vinden Fenton and Nasheri (1985). One of these methods, pressure treatment followed by diffusion, has been evaluated for treatment of green hemlock and Douglas fir (*Pseudotsuga menziesii* Mirb. Franco.). Lebow and Morrell (1989) achieved mean penetrations of up to 12 mm in green 100 x 100 mm western hemlock immediately after treatment with a one-hour pressure period using a variety of solution strengths. Thirty days' diffusion storage gave mean penetrations of up to 40 mm. Uptakes and diffusion rates were much lower in Douglas fir, especially when dry (Morrell and Lebow 1991). Morris *et al.* (1996) found Pacific silver fir to be relatively easily pressure treated with borates to virtually complete penetration but western hemlock was more difficult to treat. Since it is usual for the two species to be marketed together, methods of enhancing penetration into western hemlock were needed. The methods developed for this species were also expected to be useful for other, more refractory, Canadian species.

It was anticipated that, with borates, there might be a wider range of process options for increasing penetration than are available with chromated copper arsenate (CCA). Unlike CCA, borate treating solutions are heat stable allowing the wood or solution to be heated. CCA reacts with many potential solution additives limiting the use and effectiveness of penetration-enhancing surfactants (Kumar and Morrell 1992). In refractory species, CCA may block penetration pathways through deposition of fixation products during the treatment process. Borates, not having a fixation mechanism, would not be expected to do this. Furthermore, unlike CCA, borates can continue to penetrate the wood during storage after pressure treatment. A moisture content of 50% or more is needed for diffusion to occur at a reasonable rate (Maclean 1962, Smith and Williams 1969). Finally, pressure treatment with borates does not require an initial kiln drying of the lumber. The moisture content (m.c.) of lumber normally has to be reduced substantially to provide space for solution to enter during pressure treatment. Since relatively high concentrations of borate can be used and diffusion is expected, initial uptake is less important.

Part of the energy saved in not drying prior to treatment could be employed to presteam the lumber. Considered as a highly practical option, pre-steaming can potentially provide at least four benefits. First, with green pine sapwood, pre-steaming, followed by evacuation or a few days storage, can reduce the moisture content and create voids to be filled with preservative (McQuire 1962, Vinden, Fenton and Nasheri 1985, Vinden 1987). Murphy and Dickinson (1986) and Vinden (1987) found that the wetter sapwood lost considerable amounts of water while the drier heartwood did not. Second, steam/evacuation blows out ray tissue in pine sapwood creating pathways for preservative penetration (McQuire 1975). Similar increases in permeability have also been seen in pine heartwood, although removal of resin deposits from pits or resin canals was suggested as the primary mode of action (Bergervoet 1983). Third, expansion of the gases and boiling of the water in the wood creates a partial vacuum in the wood as it cools. This effect has been used more commonly in combination with diffusion (McQuire and Goudie 1972, Murphy and Dickinson 1986, Barnes, Landers and Williams 1993) rather than pressure treatment. Fourth, if the solution does not cool the wood too much, a higher temperature at the end of the pressure treatment process will speed up diffusion into untreated wood.

Very little work has been done with pre-steaming and borate pressure treatment on wood species containing a high percentage of heartwood. Lebow and Morrell (1993) tried a range of pre-steaming and equilibration-storage periods on green and dry Douglas fir prior to pressure treatment with borates. They achieved the best results with a one hour steaming and a one hour equilibration period, the shortest times for each process. Similarly, with Sitka spruce (*Picea sitchensis* Bong. Carr.), Murphy and Dickinson (1986) achieved their best results with pre-steaming followed immediately by dipping in the treating solution. These results suggested that equilibration storage after steaming would not be of benefit. In earlier studies didecyldimethyl ammonium chloride (DDAC) has been added to the borate solution to protect the lumber against stain and mould during the short diffusion storage or on rewetting in service (Morris *et al.* 1996). Since DDAC is a surfactant which decreases surface tension and improves the wettability of wood it could also increase penetration of borate.

The research described in this paper consisted of investigations in five areas. The focus of the first two studies described here was the treatment of larger dimension western hemlock. Preliminary work at Forintek (unpublished) suggested that improvements in heartwood penetration of 40% could be achieved by pre-steaming western hemlock. The first study described in this paper was undertaken to optimize the process for western hemlock baby squares (dodai). The second study was done to evaluate the effect of surfactants in improving borate penetration.

The third study was set up to compare the treatability of western SPF with CCA and borates and to examine ways to improve borate treatment of western SPF. Process parameters considered were wood moisture content, pre-steaming and surfactant additives.

Combinations of pressure treatment plus diffusion had proven reasonably successful for Douglas fir in laboratory experiments (Lebow and Morrell 1989, 1993) but further improvements were required (Manning 1995). The fourth study was therefore designed to investigate process options to meet standards for borate treatment. Process parameters considered were again: wood moisture content, pre-steaming and surfactant additives. Pressure treating in the partially air dried condition was evaluated because this is the condition that Douglas fir commonly reaches the treater.

The fifth and final study extended the work to eastern Canadian species. Rather than pre-steaming in a kiln, in-retort pre-steaming was evaluated.

Materials and Methods

General

Disodium octaborate tetrahydrate (DOT) was obtained from US Borax Inc. DDAC was obtained from Huntington Laboratories Inc. Treating solutions were analysed for borate by mannitol titration (Johnson and Ingram 1992, Winters undated) and for DDAC by high performance liquid chromatography (Daniels 1992) modified with a fully characterized DDAC standard, a smaller column (150 x 3 mm) and a slower flow rate (0.4 ml/min). Lumber for use in these experiments was selected on the basis of minimal checking and knots and in the case of Douglas fir, for maximum heartwood. All samples were end sealed with three coats of a two-part epoxy resin. Pre-steaming is known to adversely affect the strength of wood and Douglas fir is particularly susceptible (Maclean, 1953). Steaming times were kept within the limits set in AWPA C2 (AWPA 1995).

The basic pressure treatment process used was as follows:

- bring retort to full vacuum (740 mm Hg)
- 30-minute vacuum
- fill retort under vacuum
- bring retort to full pressure 1035 kPa (150 psi)
- two hrs under pressure
- empty retort
- 15-minute vacuum (740 mm Hg)

Each sample was weighed before and after treatment to determine solution uptake. Immediately after the second weighing a 50-mm sub-sample was removed. The remaining parts of the samples were end sealed with one coat of epoxy resin, wrapped, and stored wet. Further sub-samples were removed at various time intervals. The 50-mm subsample was oven dried to constant weight at 50° C then further cut into three slices. The centre 10-mm slice was retained for chemical analysis if required. One of the outer slices was sprayed on the freshly cut face with two-part curcumin indicator. A red or pink colour indicated the presence of boron. Part A was 0.28g curcumin in 100 ml of ethanol and part B was a saturated solution of salicylic acid in 90% ethanol / 10% concentrated hydrochloric acid. The cut face was sprayed with part A and, after two minutes, with part B. After waiting 30 minutes for the colour to fully develop, the boundary of the treated zone was marked with a felt-tip pen. The penetration of borate was measured, at the centre of the heartwood face, from the block surface to the edge of the line nearest the surface of the block. This procedure was used to avoid the redistribution of borate associated with the use of an increment borer in wet wood (Morris, Byrne and Minchin 1996).

Chemical analysis was done to AWPA specifications. The 20 samples from the 16 mm analysis zone were combined and ground into one composite sample. The AWPA retention is given in terms of pounds per cubic foot or kg/m^3. For the purpose of a wider international audience the data have been presented here as percent boric acid equivalent (% BAE). CCA analysis was carried out using x-ray spectroscopy (AWPA 1994a). The borate samples were extracted, using hot water extraction, at 95°C for 4 hours. The leachate was then titrated using a mannitol titration method (Johnson and Ingram 1992, Winters, undated).

Differences between penetration measurements were evaluated using analysis of variance for complete block designs, the t-test for other experiments using non-end-matched samples and using the paired t-test for end-matched samples.

Western Hemlock Study 1

Green western hemlock dodai, 105 mm x 105 mm x 6 m, were obtained from a sawmill on Vancouver Island. Two end-matched 2.52 m-long samples were cut from each of 50 pieces. This provided two sets of 25 end-matched pairs for the four processes given in Table 1. End matching was between treatments 1.1 and 1.2 and treatments 1.3 and 1.4. DDAC was included here only as a mould inhibitor.

Table 1
Preservatives and Processes used for Study 1 on Western Hemlock

Treatment #	%BAE	%DDAC	Steam	Vacuum. min.
1.1.	1.8	0.10	no	30
1.2.	1.9	0.10	yes	30
1.3.	1.9	0.10	yes	0
1.4.	1.8	0.10	yes	60

The presteaming was done in Forintek's pilot-scale kiln. Samples were presteamed for four hours in a kiln, to a maximum core temp. of 82 - 84° C. The kiln was ramped to a maximum temperature of 94°C-dry bulb and 89°C-wet bulb. The air velocity was approximately 800 linear feet/min. One day after pressure treatment the dodai were put outside under cover to reduce their temperature and induce internal vacuum. The core temperature of the pre-steamed samples one day after pressure treatment was 15-16° C. The outside air temperature was around 7 - 8° C. Sampling was done immediately after treatment and after one and two weeks storage.

Western Hemlock Study 2

Green western hemlock dodai 105 x 105-mm were obtained from a sawmill on Vancouver Island. Four 250-mm-long end-matched samples were cut from each of 20 dodai. In experiment A, one set of 20 end-matched samples was treated with each of the solutions in Table 2.

Table 2

Preservatives, Additives and Processes used for Study 2A on Western Hemlock

Treatment #	% BAE	% DDAC	%SDDS	Presteaming
2A1	4.0	-	-	No
2A2	4.0	0.05	-	No
2A3	4.0	0.50	-	No
2A4	4.0	-	0.50	No

* Sodium dodecyl sulphonate

For preservative penetration determination, sampling was done immediately after treatment and after one and two weeks storage. Borate retention was not considered in this study since retention requirements for Formosan subterranean termites are still under discussion (Grace and Yamamoto 1994a,b) and, if through-treatment is achieved, the target retention can normally be reached by adjusting the solution strength.

To confirm the results obtained in experiment 2A and to identify the minimum effective concentration of DDAC, the experiment was repeated with minor modifications. In experiment 2B, 105-mm western hemlock squares were obtained from a different sawmill on Vancouver Island and cut in a similar manner to that described above. The solutions are listed in table 3. Sampling was done immediately after treatment and after one and two weeks storage.

Table 3

Preservatives, Additives and Processes used for Study 2B on Western Hemlock

Treatment #	% BAE	% DDAC	Presteaming
2B1	1.8	0.00	No
2B2	1.8	0.10	No
2B3	1.8	0.20	No
2B4	1.8	0.50	No

Western SPF

Spruce, pine, and alpine fir nominal 2 x 6 inch, 16 ft boards, were obtained in rough green condition from three sawmills in Alberta. Sixty boards per species were selected on the basis of minimal checking and knots. Two end-matched samples, 2.4m long were cut in length from each board. Sixty samples of each species were then planed, equally on all four sides, in green condition to the dimensions 40 mm x 140 mm. The remaining 60 rough samples from each species were kiln dried using the following schedule, typical of those used in Alberta:

Step	Dry Bulb(°C) (set point)	Wet Bulb(°C) (set point)	Time
1	88	71	12 hours-temperature ramp from 23° C
2	88	71	34 hours

Moisture contents measured with an electrical resistance moisture meter were around 20% for pine, 25% for fir and 30% for spruce. These moisture contents were higher than they should be for kiln-dried wood, possibly because this lumber was fresh off the saw. SPF lumber commonly undergoes some air drying prior to kiln drying. Nevertheless, the moisture contents were similar to those targeted by Treeline Wood Products, the only company commercially treating with borates in Canada at the time (Maskalyk 1995). The samples were planed, equally on all four sides, to the dimensions 38 mm x 140 mm. Forty samples of each species were cut into two 1.2m end-matched samples. The samples were separated into four groups, each group containing 20 green and 20 dry samples per species, ready for treating. The basic treatment process was used

Each of the four groups was treated as in Table 4. The solution strength of the baseline treatment (treatment 3) was increased from 4% to 8% at the request of US Borax. The lumber was sampled immediately after treatment and after 1,2 and 4 weeks storage.

Table 4
Preservatives, Additives and Processes used for Western SPF

	Treating Solution			
Treatment	**%BAE**	**%DDAC**	**%CCA**	**Steam**
1	4.0			Yes
2	3.9	0.46		No
3	8.2			No
4			2.5	No

* - steam for 2.8 hours in kiln
- maximum core temperature of wood = 83°C

Douglas Fir

Douglas fir boards (48 x 123 x 2670 mm) were obtained in rough green condition from a sawmill on the inner south coast of B.C. Samples were taken to check for antisapstain formulation. F2 (a DDAC and borate antisapstain formulation) was detected in small amounts on the surface, so the lumber was planed equally on all four sides, to 38 mm x 114 mm to remove the chemical. The boards were then split into two groups, A and B. Group A was partially air dried through stickering and storage in a dry shed at 25° C for one week. Group B was kept green by storage outside under tarpaulin. Twenty boards from each group were then selected on the basis of maximum heartwood content. Four end-matched samples, 0.85 m in length were cut from each board, as well as two 50 mm moisture samples. Moisture content samples were weighed, oven dried for 24 hours at 105 °C, and reweighed. Group A and Group B had average moisture contents of 20.3% and 32.6% respectively. The samples were then separated into four end-matched groups, each group containing 20 green and 20 dry samples ready for treating.

Table 5
Preservatives, Additives and Processes used for Douglas Fir

Treatment #	% BAE	% DDAC	Steam
1	11.9		No
2	12.1	0.56	No
3	12.0		Yes
4	12.1	0.56	Yes

The pre-steaming process consisted of exposure to live steam for 4.0 hours in a kiln. The maximum dry bulb temperature was 100° C, reached after 1.75 hrs, and the maximum wet bulb temperature was 94° C. The maximum temperature at the centre of the wood was 95°C reached after 4 hours. The lumber bundle was stickered with 6.5 mm strips and pre-shaped to fit the pressure retort. The time taken between the completion of steaming and the start of the vacuum in the retort was 7 minutes.

The lumber was sampled immediately after treatment and after 1,2,and 4 weeks storage.

Eastern SPF and White Pine

White pine (48 x 140 x 4900 mm), balsam fir (37 x 140 x 4900 mm), and black spruce (48 x 89 x 4900 mm) were obtained (25 pieces) in rough green and kiln dried condition from sawmills in Ontario and Quebec. Jack pine (48 x 89 x 2450 mm) was obtained in rough green condition. The pines and spruce were planed to a thickness of 37 mm. Half of the jack pine was then air-dried. White pine, balsam fir and black spruce were then cut into four end-matched samples 1.0 m long as well as two 50 mm moisture samples. Jack pine was cut into two end-matched samples 1.0 m long as well as a central 50 mm moisture sample. Moisture content samples were weighed, oven dried for 24 hours at 105° C, and reweighed. The final moisture content of the dry black spruce was found to be high, so it was further air-dried. The MC for white pine, balsam fir, jack pine and black spruce were 14%, 21%, 19% and 17% respectively for dried material and 85% 92%, 29% and 26% for green material. The samples were then separated into four end matched groups, (with the jack pine having end matching between groups 1;2, and 3;4) each group containing 20 green and 20 dry samples ready for treating. The green samples were stored in a cool room (3-6° C), and the dry samples were tarped prior to treating.

Table 6
Preservatives, Additives and Processes used for Eastern SPF and White Pine

Treatment #	% BAE	% DDAC	Steam
1	9.0		No
2	9.0	0.45	No
3	9.0		Yes
4	9.0	0.47	Yes

The presteaming process consisted of loading the retort with the lumber, filling the retort with sufficient water to cover the steam coils, then using 345 kPa steam to heat the coils. This produced steam in the retort in approximately 30 minutes. The maximum temperature at the centre of the wood was 100° C reached a further 40 minutes and for 20 minutes. The steam was then released, this took 15 minutes for a total time of 105 minutes, and then the vacuum of the treatment began.

The lumber was sampled immediately after treatment and after 2,4 and 6 weeks.

Results and Discussion

Western Hemlock Study 1

Pre-steaming with a 30 minute vacuum increased solution uptake in green western hemlock by 93% (Table 7). The apparent increase in heartwood penetration immediately after treatment (Table 7) was not statistically significant using a t test.

After seven days diffusion, the presteamed samples, treatment 1.2, had mean heartwood penetrations 134% higher than the non-steamed samples, treatment 1.1, (Table 7). The difference was statistically significant using the more powerful paired t-test on end-matched material. Of the steamed samples 64% had 80% cross-sectional penetration after seven days. There were no significant differences between mean penetrations obtained after seven days among the three processes involving pre-steaming.

Over seven days of diffusion, the non-steamed hemlock showed a 7 mm increase in mean heartwood penetration while the pre-steamed hemlock showed a 26 mm increase. This could be caused by the elevated temperature or a partial vacuum in the centre of the samples, created by cooling. The second seems more likely since the dodai were put outside to cool after only one day. Observation of cross-cut samples showed that the untreated zones continued to soak up treating solution after the end of the pressure process. The results from studies 2A & 2B suggest that this process may be facilitated by the surfactant effect of the DDAC in the solution.

Reducing the time under vacuum to zero, to minimise cooling effects, had no statistically significant effect on penetration. It appears, therefore, that a vacuum period may not be necessary to take advantage of pre-steaming. Alternatively the cooling effect of the vacuum may reduce the temperature differential with the treating solution offsetting the beneficial effects of removing water or air from the wood. Increasing the vacuum time to 60 minutes did not provide any improvement in preservative penetration.

Western Hemlock Study 2

The addition of 0.05% DDAC gave a small increase in DOT solution uptake over the controls (Table 8) and 0.50% DDAC increased uptake substantially. The addition of 0.50% SDDS reduced the solution uptake. Differences among solution uptakes were all significantly different from one treatment to another ($p < 0.05$). Penetration data immediately after treatment (Table 8) showed a similar pattern to the uptake data but none of the additives gave a statistically significant increase in penetration.

After 10 days diffusion, the material treated with DOT alone had shown no further increase in preservative penetration via diffusion. Wood treated with DOT and 0.05% or 0.5% DDAC did show further increases in preservative penetration, although the increased penetration was only statistically significant for 0.5% DDAC. These findings were somewhat unexpected since storage normally improves diffusion for DOT alone. Furthermore, while DDAC might be expected to improve mass flow during pressure treatment it would not be expected to affect subsequent diffusion.

Experiment 2B did not fully confirm the results of experiment 2A perhaps because the material was inherently more treatable. Uptakes in experiment were 43% higher and did not correlate as well with the penetration data (Table 9). Such differences in the treatability of western hemlock between sources also occurs with CCA treatment and it is difficult to evaluate penetration enhancing processes in more treatable material (Morris 1995). The apparent increased uptakes with 0.1% and 0.2% DDAC were not statistically significant. Unexpectedly, the addition of 0.5% DDAC also had no effect on uptake in this second experiment. There was also no statistically significant effect of adding 0.1%, 0.2% or 0.5% DDAC on initial penetration nor on the penetration obtained in the first seven days. The reason for the lack of increase in penetration, in three of the four treatments, in the first seven days is unknown. However, as with experiment 1, after 14 days storage there was a statistically significant difference between the penetrations in all the treatments with DDAC and the penetration achieved in the controls.

Observation of the cross-cut sections, prior to oven drying, confirmed the effect of DDAC on penetration during storage and suggested an action on capillary movement (wetting) rather than on diffusion.

Western SPF

In terms of solution uptake, there was not a great deal of variation among the three borate treatments or between these three and the CCA treatment (Tables 10, 11, 12). Unlike the results obtained with western hemlock, neither the pre-steaming nor the addition of DDAC improved initial solution uptakes in alpine fir and lodgepole pine. There was some indication of a higher solution uptake in spruce with the DDAC additive and this was confirmed by chemical analysis (Table 13).

In terms of penetration immediately after treatment, the 8.0% BAE samples showed the highest mean penetration results overall, with the dry spruce, pine, and fir having average penetrations greater than 10 mm (Tables 10, 11 and 12). Dry pine had virtually through treatment at 17 mm. The penetration with the 8% solution appeared to drop after one week of diffusion. No explanation for this phenomenon appears obvious. Neither pre-steaming nor DDAC in the solution appeared to have provided any benefit. Since the solution uptakes were similar for the 4% and 8% solutions it is possible that the apparent deeper penetration with the 8% solution was due either to diffusion prior to drying of the samples or to the sensitivity of the curcumin reagent. If a preservative gradient had been created by stripping or diffusion, this reagent would show up the higher retention given by the 8% BAE more effectively than those given by 4% BAE. For the borate treatments, the green samples generally showed lower initial penetration than the dry samples. This was probably due to water-filled cells preventing inflow of treating solution.

For the CCA treatment, there was no significant difference between the mean penetrations for the green and dry samples (Tables 10, 11 and 12). This treatment is a useful reference since it confirms that the test material has a pattern of treatability typical of SPF. Without incising, the order of treatability with CCA is normally pine>fir>spruce (Morris 1991a,b).

The dry pine and fir showed no significant increase in penetration with storage. This was expected since there should be no diffusion in dry wood. However, contrary to expectations, the dried spruce samples showed a statistically significant 120% increase for 4%BAE-pre-steamed and a 133% increase, for 4%BAE-0.5%DDAC over 4 weeks storage. This must have been due to the higher moisture content of the spruce after drying (30% mc).

As expected, the green samples showed a significant increase in penetration after 4 weeks diffusion. With the 8% solution, fir and spruce had 88% and 33% increases in average penetration respectively. The green pine was well treated to begin with and showed no subsequent increase in penetration. Overall, after 4 weeks diffusion, all the samples had an average penetration of 10 mm or greater, with the exception of green spruce. From the ANOVA the effects of different species, moisture conditions and borate treatments were all statistically significant.

The higher retentions in the white spruce, non-steamed and treated with 4% BAE plus DDAC compared to the pre-steamed 4% BAE treatment (Table 13) confirmed the apparent difference in uptakes (Table 12). This suggests that, at least for white spruce, there was some benefit from the addition of DDAC.

Douglas Fir

As expected, with the conventional pressure treatment the air dried material picked up more treating solution than the green material (Table 14). This was presumably taken up by the sapwood since it did not result in any difference in initial heartwood penetration. The addition of DDAC gave a 53% uptake improvement in the air dried and a 64% improvement in the green material. Pre-steaming also improved the uptakes by 18% and 26% respectively. The combination of pre-steaming and DDAC gave improvements of 38% and 120%. Interestingly, the combination treatment resulted in similar uptakes in both air dried and green material. This could be useful for lumber with a wide range of moisture contents. The variation in uptakes was very high as shown by the large standard deviations.

The data on penetration immediately after treatment showed a somewhat similar pattern to the uptake and retention data. Immediately after the conventional pressure treatment, both the air dried and green material showed very limited average penetrations at 3.0 mm or less (Table 14). The addition of DDAC more than doubled the initial penetration but presteaming had less of an effect. It increased the penetration in air-dried material by 33% and in green material by 78%. In air-dried material, pre-steaming plus DDAC did not appear to be as effective as either DDAC or pre-steaming alone. There is no apparent reason for this phenomenon. In green material the combination appeared to give no better initial penetration than DDAC alone. This did not fit with the retention data and is also unexplained. The very limited effect of presteaming on treatment of partially air dried lumber found here was consistent with the results of Lebow and Morrell (1993) although these authors air-dried their lumber to 12% m.c. It appears that a moisture content at or above fibre saturation is required to benefit from pre-steaming.

All treatments, but one, seemed to show similar rates of increasing penetration with time. The exception was the combined pre-steaming plus DDAC treatment on green material. This showed a sharp jump in penetration after 4 weeks. Examination of the raw data showed that five samples had jumped from between 3 and 6 mm to full penetration. This was due to diffusion from the opposite surface of the lumber, the sapwood face. The better diffusion from sapwood into heartwood than from the heartwood face was a common phenomenon noted during the penetration measurements.

The analysis data for Douglas fir (Table 15) showed a similar pattern to the uptake data. The one anomaly in these data is the retention of 1.4% BAE at 0 weeks in air dried material treated with a DDAC additive. One sample in this set had a retention of 8.2 % BAE. If this value is eliminated from the calculation the mean retention was 1.0% BAE which is in line with the results at 1,2 and 4 weeks. There was no consistent pattern of decrease in assay retention over time thus there was little or no diffusion out of the analysis zone. All four analyses can therefore be averaged for discussion purposes. With the conventional pressure treatment, air dried material had a mean retention of 0.43 % BAE, slightly higher than the retention in green material, 0.36 % BAE (Table 15). The addition of DDAC more than doubled the retention in both air dried (1.00 % BAE) and green (0.81 % BAE) material. Presteaming had very little effect on air dried m.c. material (0.55 % BAE) but more than doubled the retention in green material to 0.85% BAE. The combination of DDAC and pre-steaming was similar to DDAC alone for air dried (0.97 % BAE) material but gave a 4.5 times increase in retention in green material (1.63 % BAE).

Eastern SPF and White Pine

White pine, either green or dried, showed the highest uptakes. Balsam fir and jack pine had very similar uptakes in the dry condition but reacted quite differently when wet. Balsam fir, and black spruce, showed higher uptakes in the green condition rather than dry condition. With jack pine, the uptake was lower in the green condition

After four weeks storage the wet boards generally had a deeper penetration than the dried boards. Nevertheless, the amount of diffusion we found in air-dried lumber was somewhat unexpected. Diffusion is normally held to occur at a reasonable rate only above fibre saturation. The moisture contents are given in Tables 16 - 19.

Somewhat surprisingly, we did not see any improvement in uptake or penetration resulting from pre-steaming or DDAC addition. It is difficult to draw any conclusions about differences in response to presteaming among species since in-retort steaming was used on eastern species and in-kiln steaming on western species. The lack of effect on uptake with DDAC is consistent with the results for western SPF but the lack of an effect on penetration during storage is not.

Compliance with AWPA Standards

The borate treatment standard, AWPA C31-95 (AWPA 1995c), references only southern pine and hem-fir. Hem-fir has a requirement for 80% at or over 10mm penetration and a retention of 2.7 kg/m^3 oxide (1.25% BAE). Since penetration and retention requirements for hem-fir, Douglas fir and the individual species in SPF are similar in other AWPA standards, the treatment quality obtained with western SPF, Douglas fir and eastern SPF will be compared to the requirements for hem-fir.

Green western hemlock that had been borate treated with no presteaming met the AWPA penetration requirement after two weeks diffusion. With presteaming and 30 or 60 minutes vacuum, the standard was met after one week of diffusion.

The hemlock used for experiment 2A was much more refractory and all the treatments would have required longer than 10 days diffusion to meet the AWPA specification. In contrast, the hemlock used for experiment 2B was very treatable. With no additive it took two weeks diffusion but with 0.1 to 0.5% DDAC this material met the AWPA penetration requirement immediately after treatment. No retention data were generated for the studies on western hemlock.

Dried lodgepole pine and alpine fir met the AWPA penetration requirement two weeks after treatment with either an 8% solution or a 4% solution with DDAC (Tables 10 and 11). Green lodgepole pine and alpine fir met this requirement four weeks after treatment with the 8% solution. White spruce failed to meet the AWPA penetration requirement after 4 weeks diffusion, whether it was green or dry and whichever treating process was used. Based on the rate of penetration of borate into the dried white spruce (Table 12), compliance with the AWPA penetration requirement might be expected after six weeks diffusion.

All the borate treatments of western SPF (Table 13), with the exception of the spruce pre-steamed and treated with 4% BAE, passed the retention requirement of AWPA C31-95 (AWPA 1995c).

The alpine fir, lodgepole pine and white spruce, green or dry, treated with CCA failed to meet the penetration or retention requirements for the AWPA C2-95 standard (AWPA 1995b), 80% at or over 10mm and 6.4 kg/m^3 (Tables 10 to 13). Dried alpine fir did come close on the retention.

Only the combined pre-steaming plus DDAC treatment of high m.c Douglas fir would meet the AWPA retention requirement (Table 15) and only after more than 4 weeks diffusion would it make the penetration requirement (Table 14).

With all the eastern species, the AWPA penetration specification was met with one or more treatment processes and diffusion time. White pine, green or dry, met the requirement immediately after treatment or within one week of storage (Table 16). The other three species generally met the standard in a shorter time when treated green. Balsam fir and jack pine took two or four weeks (Tables 17 and 18). Black spruce took four or six weeks (Table 19).

White pine and jack pine exceeded the AWPA retention requirements with all treatment processes whether green or air/kiln dried (Table 20). Balsam fir passed on retention when treated green but only after presteaming when kiln dried. Black spruce failed on retention with all treatments but came very close with green lumber presteamed or with a DDAC additive. A small increase in solution strength would be adequate to ensure this species passed the AWPA retention requirement.

Conclusions

The addition of didecyldimethyl ammonium chloride to solutions of disodium octaborate can increase the penetration of borate into some species during the pressure process and in some species during subsequent storage.

Pre-steaming is an effective means of improving uptake of borates into green lumber during pressure treatment and enhances penetration during subsequent storage.

A range of wood species and treatment options can be used to meet borate treatment standards in export markets.

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Table 7
Effects of Presteaming on Preservative Solution Uptake/Penetration in Green Western Hemlock

Treatment #	% BAE	% DDAC	Steam	Vacuum (min)	Uptake per sample (kg)	Penetration (mm)		
						0 week	1 week	2 weeks
					mean (SD)	mean (SD)	mean (SD)	mean (SD)
1.1	1.8	0.10	No	30	2.8 (1.2)	11 (11)	18 (13)	20 (14)*
1.2	1.9	0.10	Yes	30	5.4 (2.7)	16 (14)	42 (16)*	40 (18)*
1.3	1.9	0.10	Yes	0	3.8 (1.5)	14 (13)	33 (23)	36 (21)
1.4	1.8	0.10	Yes	60	3.9 (1.3)	15 (12)	37 (20)*	32 (19)*

SD = Standard deviation
* = 80% > 10mm

Table 8
Effect of Additives on Borate Solution (4.0% BAE) Uptake and Penetration in Green Western Hemlock - Experiment 2A

Treatment #	% BAE	Additive	Steam	Uptake per sample (kg)	Penetration (mm)	
					0 days	10 days
				mean (SD)	mean (SD)	mean (SD)
2A1	4.0	None	No	0.28 (0.15)	7 (5)	7 (3)
2A2	4.0	0.05% DDAC	No	0.33 (0.18)	8 (7)	14 (10)
2A3	4.0	0.50% DDAC	No	0.38 (0.18)	10 (7)	12 (6)
2A4	4.0	0.50% SDDS	No	0.19 (0.10)	5 (3)	6 (2)

Table 9
Effect of Additives on Borate Solution Uptake and Penetration in Green Western Hemlock - Experiment 2B

Treatment #	% BAE	% DDAC	Steam	Uptake per sample (kg)	Penetration (mm)		
					0 week	1 week	2 weeks
				mean (SD)	mean (SD)	mean (SD)	mean (SD)
2B1	1.8	None	No	0.43 (0.24)	23 (20)	21 (19)	30 (21)*
2B2	1.8	0.10%	No	0.51 (0.23)	20 (17)*	25 (20)*	46 (14)*
2B3	1.8	0.20%	No	0.47 (0.20)	24 (19)*	20 (17)*	44 (16)*
2B4	1.8	0.50%	No	0.42 (0.17)	29 (20)*	24 (16)*	43 (15)*

* = 80% > 10mm

Table 10
Effect of Process on Alpine Fir Solution Uptake and Penetration -

% BAE	% DDAC	Steam	Wood Condition	Uptake per sample (kg)	Penetration (mm)			
					0 week	1 week	2 weeks	4 weeks
				mean (SD)	mean (SD)	mean (SD)	mean (SD)	mean (SD)
4%	-	Yes	KD	0.91 (0.79)	10 (8)	9 (8)	11(7)	12 (7)
			Green	0.97 (0.89)	12 (8)	13 (7)	9 (8)	10 (8)
4%	0.50%	No	KD	0.74 (0.28)	11(7)	12 (7)	14 (6)*	12 (7)
			Green	0.85 (0.49)	6 (7)	5 (6)	12 (7)	9 (7)
8%	-	No	KD	0.83 (0.34)	15 (5)	9 (7)	16 (6)*	15 (6)
			Green	0.65 (0.31)	8 (6)	6 (6)	12 (6)	15 (6)*
2.5% CCA			KD	1.39 (1.15)	8(8)		-	-
			Green	0.74 (0.76)	9 (8)			

* = 80% > 10mm

Table 11
Effect of Process on Lodgepole Pine Solution Uptake and Penetration

% BAE	% DDAC	Steam	Wood Condition	Uptake per sample (kg)	Penetration (mm)			
					0 week	1 week	2 weeks	4 weeks
				mean (SD)	mean (SD)	mean (SD)	mean (SD)	mean (SD)
4%	-	Yes	KD	1.18 (0.57)	12 (7)	10 (7)	13 (7)	15 (5)
			Green	0.70 (0.40	7 (4)	5 (6)	11 (7)	13 (6)
4%	0.50%	No	KD	1.27 (0.75)	11 (7)	13 (8)	15 (5)	14 (7)*
			Green	0.59 (0.27)	7 (6)	8 (6)	10 (6)	12 (7)
8%	-	No	KD	1.42 (0.61)	17 (4)	15 (6)	17 (4)*	18 (3)*
			Green	0.78 (0.49)	13 (7)	12 (7)	13 (7)	15 (6)*
2.5% CCA			KD	1.26 (0.45)	11 (7)		-	-
			Green	0.81 (0.37)	10 (7)			

* = 80% > 10mm

Table 12

Effect of Process on White Spruce Solution Uptake and Penetration

% BAE	% DDAC	Steam	Wood Condition	Uptake per sample (kg)	Penetration (mm)			
					0 week	1 week	2 weeks	4 weeks
				mean (SD)	mean (SD)	mean (SD)	mean (SD)	mean (SD)
4%	-	Yes	KD	1.20 (0.54)	5 (5)	5 (3)	10 (6)	13 (5)
			Green	0.68 (0.29)	4 (4)	4 (3)	7 (5)	7 (6)
4%	0.50%	No	KD	1.66 (0.64)	6 (6)	7 (4)	11 (6)	14 (5)
			Green	0.99 (0.42)	4 (3)	3 (3)	6 (5)	8 (6)
8%	-	No	KD	1.44 (0.72)	10 (6)	8 (6)	9 (6)	13 (5)*
			Green	0.62 (0.24)	6 (5)	6 (5)	7 (5)	8 (5)
2.5% CCA			KD	1.24 (0.34)	3 (2)	-	-	-
			Green	0.76 (0.27)	4 (2)			

* = 80% > 10mm

Table 13
Borate Retention in a 16 mm Assay Zone for Western SPF

% BAE	% DDAC	Steam	Wood Condition	Retention (% BAE)		
				Fir	Pine	Spruce
4%	-	Yes	KD	1.8	1.5	0.9
			Green	1.6	1.2	0.7
4%	0.50%	No	KD	1.7	4.0	2.6
			Green	3.5	2.0	1.8
8%	-	No	KD	2.8	4.0	3.2
			Green	1.4	3.6	1.4
				Retention kg/m3 oxide		
2.5% CCA			KD	6.3	5.9	2.4
			Green	4.4	5:3	1.7

Table 14
Effect of Process on Solution Uptake and Penetration into Douglas Fir

% BAE	% DDAC	Steam	Wood Condition	% Soln. Update	Penetration (mm)			
					0 week	1 week	2 weeks	4 weeks
				mean (SD)	mean (SD)	mean (SD)	mean (SD)	mean (SD)
11.9	-	No	AD	0.19 (0.12)	3(4)	2 (1)	4 (3)	5(3)
			Green	0.13 (0.10)	3 (2)	4 (4)	4 (4)	6 (2)
12.1	0.50%	No	AD	0.29 (0.20)	6 (6)	5 (5)	7 (6)	8 (5)
			Green	0.21 (0.13)	6 (6)	4 (4)	6 (4)	8 (5)
12.0	-	Yes	AD	0.22 (0.14)	4 (5)	3 (1)	4 (4)	4 (2)
			Green	0.17 (0.16)	5 (5)	5 (5)	7 (5)	7 (4)
12.1	0.50%	Yes	AD	0.22 (0.16)	3 (2)	6 (4)	6 (4)	6 (4)
			Green	0.28 (0.16)	6 (7)	9 (7)	8 (6)	13 (6)*

* = 80% > 10mm
AD = Partially air dried

Table 15

Effect of Process on Retention of Borate in Douglas Fir

% BAE	% DDAC	Steam	Wood Condition	% BAE			
				0 week	1 week	2 weeks	4 weeks
				mean (SD)	mean (SD)	mean (SD)	mean (SD)
11.9	-	No	AD	0.28 (0.14)	0.59 (0.95)	0.42 (0.16)	0.43 (0.29)
			Green	0.31 (0.16)	0.39 (0.28)	0.39 (0.19)	0.37 (0.19)
12.1	0.50%	No	AD	1.40 (1.80)	0.99 (0.77)	0.78 (0.59)	0.81 (0.54)
			Green	0.88 (1.05)	0.74 (0.83)	0.76 (0.80)	0.85 (0.72)
12.0	-	Yes	AD	0.52 (0.34)	0.54 (0.32)	0.58 (0.42)	0.55 (0.37)
			Green	0.66 (0.34)	1.01 (1.04)	0.86 (0.62)	0.87 (0.77)
12.1	0.50%	Yes	AD	0.98 (0.29)	1.05 (0.78)	0.99 (0.41)	0.86 (0.37)
			Green	1.59 (1.72)	1.65 (1.53)	1.60 (1.25)	1.67 (1.65)

AD = Partially air dried

Table 16

Effect of Process on White Pine Solution Uptake and Penetration

% BAE	% DDAC	Steam	Wood Condition	Uptake per sample (kg)	Penetration (mm)			
				mean (SD)	0 week	1 week	2 weeks	4 weeks
					mean (SD)	mean (SD)	mean (SD)	mean (SD)
9.0	-	No	KD	2.26 (0.44)	17 (3)*	-	18 (1)*	18 (2)*
			Green	1.09 (0.28)	18 (2)*	-	16 (4)*	18 (0)*
9.0	0.45%	No	KD	2.25 (0.50)	14 (5)*	18 (2)*	17 (2)*	18 (2)*
			Green	1.22 (0.37)	14 (6)	17 (2)*	17 (3)*	17 (4)*
9.0	-	Yes	KD	2.35 (0.63)	15 (4)	-	16 (4)*	18 (0)*
			Green	1.33 (0.26)	17 (4)*	-	18 (0)*	18 (0)*
9.0	0.47%	Yes	KD	2.26 (0.65)	16 (4)*	16 (4)*	15 (4)*	17 (3)*
			Green	1.19 (0.26)	13 (5)	17 (3)*	16 (3)*	18 (0)*

* = 80% >10mm

Table 17
Effect of Process on Balsam Fir Solution Uptake and Penetration

% BAE	% DDAC	Steam	Wood Condition	Uptake per sample (kg)	Penetration (mm)			
				mean (SD)	0 week	2 weeks	4 weeks	6 weeks
					mean (SD)	mean (SD)	mean (SD)	mean (SD)
9.0	-	No	KD	0.59 (0.37)	8 (6)	11 (6)	15 (5)*	16 (3)*
			Green	0.65 (0.27)	11 (6)	12 (7)	15 (5)*	17 (2)*
9.0	0.45%	No	KD	0.51 (0.29)	5 (5)	10 (6)	15 (5)	-
			Green	0.64 (0.25)	10 (7)	13 (6)	14 (5)	-
9.0	-	Yes	KD	0.55 (0.20)	5 (5)	10 (6)	14 (5)	13 (5)
			Green	0.77 (0.30)	13 (6)	12 (8)	17 (2)*	18 (0)*
9.0	0.47%	Yes	KD	0.71 (0.32)	9 (6)	10 (6)	15 (5)	-
			Green	0.86 (0.30)	11 (6)	14 (5)*	17 (3)*	-

* = 80% >10mm

Table 18
Effect of Process on Jack Pine Solution Uptake and Penetration

% BAE	% DDAC	Steam	Wood Condition	Uptake per sample (kg)	Penetration (mm)			
				mean (SD)	0 week	2 weeks	4 weeks	6 weeks
					mean (SD)	mean (SD)	mean (SD)	mean (SD)
9.0	-	No	AD	0.55 (0.25)	11 (5)	15 (5)*	16 (4)*	17 (4)*
			Green	0.39 (0.18)	11 (6)	14 (6)	16 (4)*	18 (2)*
9.0	0.45%	No	AD	0.48 (0.32)	8 (5)	13 (5)	15 (4)*	16 (3)*
			Green	0.32 (0.14)	11 (6)	14 (5)*	16 (4)*	18 (2)*
9.0	-	Yes	AD	0.51 (0.19)	9 (5)	10 (5)	13 (5)	16 (4)*
			Green	0.44 (0.20)	8 (5)	13 (5)	16 (4)*	18 (0)*
9.0	0.47%	Yes	AD	0.63 (0.36)	11 (6)	11 (6)	15 (5)	15 (4)
			Green	0.44 (0.18)	12 (6)	13 (5)	18 (4)*	17 (4)*

AD = Air dried
* = 80% > 10mm

Table 19
Effect of Process on Black Spruce Solution Uptake and Penetration

% BAE	% DDAC	Steam	Wood Condition	Uptake per sample (kg) mean (SD)	Penetration (mm) 0 week mean (SD)	2 weeks mean (SD)	4 weeks mean (SD)	6 weeks mean (SD)
9.0	-	No	KD	0.23 (0.09)	6 (4)	10 (5)	11 (5)	12 (4)
			Green	0.31 (0.09)	8 (5)	13 (5)	15 (3)*	17 (2)*
9.0	0.45%	No	KD	0.23 (0.10)	3 (2)	8 (5)	10 (6)	12 (6)
			Green	0.30 (0.10)	8 (5)	12 (5)	13 (5)	15 (5)*
9.0	-	Yes	KD	0.22 (0.07)	5 (3)	9 (5)	10 (4)	11 (4)
			Green	0.30 (0.07)	7 (3)	11 (4)	14 (3)*	17 (2)*
9.0	0.47%	Yes	KD	0.24 (0.06)	5 (4)	7 (4)	10 (5)	11 (6)
			Green	0.34 (0.10)	10 (6)	13 (4)	15 (1)*	15 (2)*

* = 80% > 10mm

Table 20
Borate Retention in a 16mm assay zone for Eastern SPF

% BAE	% DDAC	Steam	Wood Condition	Retention % BAE Fir	Pine	Spruce	White Pine
9.0	-	No	KD/AD	1.20	3.25	0.91	6.26
			Green	1.93	2.78	1.08	3.01
9.0	0.45	No	KD/AD	0.99	2.35	0.50	5.46
			Green	2.00	1.35	1.24	2.51
9.0	-	Yes	KD/AD	1.94	2.00	0.69	6.38
			Green	2.63	1.57	1.10	2.84
9.0	0.47	Yes	KD/AD	1.51	2.79	0.73	6.06
			Green	2.58	1.34	1.24	2.87