Boron Diffusion in Surface-Treated Framing Lumber

Patricia K. Lebow
Stan T. Lebow
Steven A. Halverson

Abstract

The extent of boron penetration in framing lumber treated by spray applications during construction is not well quantified. This study evaluated the effect of formulation and concentration on diffusion of boron in lumber specimens that were equilibrated in conditions that produced wood moisture contents of 18 to 21 percent. One set of specimens was pressure treated with water before equilibration. Borate solutions were prepared from powdered disodium octaborate tetrahydrate (DOT) or from two commercial glycol-borate formulations and applied with a garden-type sprayer. The DOT solution was applied at a 15 percent concentration, while the glycol-borate formulations were applied at 15 and 23 percent concentrations. Boron penetration was evaluated after 6, 13, and 26 weeks and boron retention after 26 weeks of diffusion. Boron penetration was observed for all treatments and progressed for the duration of the study. There was no significant penetration difference between the powdered DOT and glycol-borate solutions when they were applied at the same (15%) DOT concentration. However, after 6 weeks, the glycol-borate solutions applied at the 23 percent DOT concentration produced significantly greater depth of penetration than the solutions applied at the 15 percent concentration. The exception was the 15 percent DOT solution applied to the specimens that had been wetted and then dried down to equilibrium conditions. These specimens had the greatest penetration, possibly as a result of their higher equilibrium moisture content. Retention analysis revealed that the glycol-borate solutions applied at the 23 percent DOT concentration yielded significantly greater boron retentions in the outer assay zone. This effect was less apparent for the inner assay zones. Although boron retentions in the outer assay zone were below those standardized for pressure-treated wood, in some cases they exceeded reported concentrations needed for protection against termites and decay fungi.

Borate preservatives are used in a wide range of applications to provide protection against fungal and insect attack. One such application is the treatment of framing lumber used in interior construction. Pressure treatment of framing lumber with borates has become accepted practice, and research has demonstrated that these treatments result in deep penetration of boron into the wood (Morrell and Lebow 1991; Morris et al. 1996, 1997; Baker et al. 2001; Lebow et al. 2005). Borate formulations may also be spray applied to framing lumber during the construction process. Some degree of boron penetration (diffusion) into the framing lumber is expected from these treatments, but the extent of penetration is poorly quantified. Much of the past research on boron diffusion following nonpressure treatments has been conducted with green lumber and typically involved an immersion period followed by a controlled diffusion period (Smith and Williams 1969, Fowlie et al. 1988, Barnes et al. 1993, Puettmann and Schmidt 1997, Wang et al. 2007). The conditions for boron diffusion are likely to be less favorable when borate solutions are sprayed onto framing lumber. It is typically recommended that framing lumber be dried to below 19 percent moisture content (Bergman 2010) to minimize concerns with shrinkage and other moisture-related problems. Although measured moisture contents often exceed 19 percent (Garrahan et al. 1991), the moisture content of framing lumber is still likely to be substantially lower than that of green lumber treated by traditional immersion/diffusion processes. The concentration of boron applied to the wood surface with a spray application may also be lower than that applied by an immersion treatment. In some cases, additives such as glycol are used to thicken the borate solutions and

The authors are, respectively, Mathematical Statistician, Research Forest Products Technologist, and Physical Science Technician, USDA Forest Serv., Forest Products Lab., Madison, Wisconsin (plebow@fs.fed.us [corresponding author], slebow@fs.fed.us, shalverson@fs.fed.us). This paper was received for publication in September 2012. Article no. 12-00098.

Forest Prod. J. 63(7/8):275–282.
doi:10.13073/FPJ-D-12-00098

potentially allow higher surface loadings, but the benefit of these additives is also poorly quantified.

A recent evaluation of the ability of surface-applied borates to penetrate framing lumber found that diffusion can occur in wood maintained at 18 to 20 percent moisture content (Lebow et al. 2010), suggesting that diffusion may be possible in some framing applications. The finding of diffusion occurring at 18 to 20 percent moisture content conflicts with the assumption that diffusion will cease at moisture contents below the fiber saturation point (Becker 1976). However, Schoeman et al. (1998) reported up to 4 and 6 mm of boron penetration in southern pine specimens dipped in a 5 percent disodium octaborate tetrahydrate (DOT) solution and maintained in conditions that produced approximately 20 and 25 percent moisture content, respectively. Based on specimens exposed in other conditions, they concluded that some diffusion could occur at wood moisture contents as low as 15 percent. Morrell and Freitag (1995) also observed borate diffusion in wood with 20 percent moisture content, although in that study additional moisture was provided because the borate solutions were added to shallow wells machined into the wood. In a study of the use of coatings to minimize boron depletion from treated wood exposed outdoors, researchers concluded that boron leaching and thus diffusion occurred at moisture contents of 18 to 20 percent (Peylo and Willeitner 1995). In contrast, a study of diffusion of boric acid from adhesive found that although diffusion did occur in specimens conditioned at 100 percent relative humidity (RH) and 25°C, it was minimal at 88 percent RH and 25°C (Lesar et al. 2011). Moisture content was not reported in that study, but these conditions might have been expected to produce equilibrium moisture contents of approximately 19 and 25 percent, respectively. Researchers in New Zealand also reported limited boron penetration when a glycol-borate solution was brushed onto the exterior surface of multiple stud framing units but noted that penetration in studs and nail-laminated lintels could be improved with a combination of brushing and internal injection applications (Page and Singh 2011, Simpson et al. 2012). Wood moisture content was not reported in those studies.

The moisture content groups evaluated in Lebow et al. (2010) were achieved by pressure treating the wood with water and then gradually drying to the target moisture content. Although this approach may simulate a situation where framing lumber is installed at elevated moisture contents and equilibrates in place, it less closely simulates the adsorption that occurs when dry framing lumber is exposed to high humidity, such as in a crawl space. Wood typically equilibrates to a slightly lower moisture content during adsorption than desorption, and it is possible that at low moisture contents, even slight moisture content differences could have an effect on boron diffusion.

For in-place applications, borates are generally available as powdered solids, such as DOT, that are then dissolved in water or as liquids formulated with glycol to aid borate solubility. Lebow et al. (2010) did not find any significant difference in penetration between two glycol-borate formulations and a solution of DOT in water. This latter finding conflicts with previous research (Vinden et al. 1990, Puettmann and Williams 1992, Wang et al. 2007) and the commonly held assumption that the thickened borates allow for greater subsequent boron diffusion. Two aspects of the Lebow et al. (2010) methodology may have contributed to lack of observed glycol effect on boron penetration. First, the DOT concentration in all treatments was limited to 15 percent to ensure DOT solubility. In contrast, thickened glycol-borates are often applied commercially at a 23 percent DOT concentration. Second, the formulations in Lebow et al. (2010) were applied by briefly dipping the specimens in each liquid. This dipping technique was used to reduce variability in application of the formulations but may have resulted in greater solution absorption than typically occurs in spray applications. This greater solution absorption may have helped to obscure differences between the formulations.

The objective of this follow-up study was to further evaluate boron penetration from surface-applied DOT and glycol-borate formulations applied to framing lumber during construction. In this follow-up study, the target moisture content in all but one set of samples was achieved by adsorption rather than desorption, and the DOT concentration of the thickened glycol-borates was increased to the strongest concentration currently used commercially. The borate solutions were also applied by spraying rather than by brief immersion to more closely simulate commercial practice.

Materials and Methods

Specimen preparation

Specimens were prepared from flat-sawn southern pine lumber and selected to be free of heartwood, mold, and sapstain and with growth ring widths ranging from 4 to 9 mm. Six 356-mm-long specimens (to allow matched specimens for six treatment combinations) were cut from each of 10 parent boards. These parent boards had been stored indoors and had moisture contents in the range of 10 to 12 percent. Their densities at that moisture content ranged from 499 to 593 kg/m^3, with an average density of 539 kg/m^3. The specimens were end coated with a neoprene rubber sealant, and five of the six specimens from each parent board were allowed to equilibrate in a room maintained at 27°C, 90 percent RH (conditions that produce between 18% and 21% wood moisture content). These specimens were intended to represent framing lumber that had been adequately dried before construction but was subsequently exposed to humid conditions within the structure. The sixth specimen cut from each parent board was pressure treated with water to a moisture content of approximately 60 to 80 percent, allowed to air-dry to approximately 30 percent moisture content, and then placed in the 27°C, 90 percent RH conditioning room with the other specimens. These wetted specimens were included to allow direct comparison with the method used in an earlier study (Lebow et al. 2010) that attempted to simulate a scenario where framing lumber had not been adequately dried prior to construction.

Preservative solution and specimen preparation combinations

Two commercial thickened glycol-borate formulations (GB1 and GB2) and powdered DOT were evaluated. Both thickened glycol-borate formulations are supplied as concentrates containing 40 percent DOT, with the remainder of the formulation composed of one or more forms of ethylene glycol. The glycol-borate formulations were evaluated with DOT concentrations of 15 and 23 percent, while the DOT/water solution was prepared as 15 percent DOT. In the previous study (Lebow et al. 2010), only the 15 percent concentration was evaluated, but labeling on the glycol-borate formulations allows use at a 23 percent DOT concentration. The formulations were mixed with deionized water to obtain the desired treatment concentration. The six treatment groups evaluated were as follows:

DOT-15 percent: DOT powder mixed to obtain a concentration of 15 percent DOT

DOT-HiLo: DOT powder mixed to obtain a concentration of 15 percent DOT (these specimens were pressure treated with water to higher moisture contents and then equilibrated with the other specimens)

GB1-15 percent: Glycol-borate 1 diluted to obtain a concentration of 15 percent DOT

GB1-23 percent: Glycol-borate 1 diluted to obtain a concentration of 23 percent DOT

GB2-15 percent: Glycol-borate 2 diluted to obtain a concentration 15 percent DOT

GB2-23 percent: Glycol-borate 2 diluted to obtain a concentration 23 percent DOT

Method of application

The specimens were weighed and then placed on edge (on a narrow face) on a wire mesh. The exposed surfaces were sprayed until they were uniformly wetted and excess solution was dripping off the specimens (approximately 5 s). A handheld compressed air sprayer (Model 456, Solo, Newport News, Virginia) was used but was adapted to allow pressurization with an air compressor and regulator to maintain a constant 138-kPa pressure. Specimens were reweighed 1 minute after spraying to estimate the amount of solution applied.

Diffusion conditions

Following treatment, the specimens were returned to the room maintained at 27°C, 90 percent RH, and removed only for cutting of penetration sections.

Penetration determination

After 6, 13, and 26 weeks of diffusion, a 25-mm-thick cross section was cut from each specimen and air-dried. The air-dried 25-mm-thick cross sections were again cut to reveal a fresh cross section, brushed to remove wood dust particles, and then sprayed with curcumin–salicylic acid boron indicator solutions prepared in accordance with standards of the American Wood Protection Association (AWPA 2011a). This curcumin–salicylic acid indicator produces reddish color at boron concentrations in the wood above approximately 0.6 to 0.8 percent (as B_2O_3; Morrell and Freitag 1995). Borate penetration was measured in two ways. The average depth of penetration on each face was estimated visually using a measurement template, and an overall weighted average depth of penetration was calculated. The cross sections were also photographed and the digital images analyzed using ImageJ software (Version 1.32j, US National Institutes of Health, Bethesda, Maryland; Rasband 2004). Each specimen's cross-sectional area and boron-penetrated area were manually outlined on the digital image, allowing calculation of the percentage of the cross section penetrated with preservative.

Retention analysis

At the conclusion of the test (after 26 wk of diffusion), an additional cross section was cut for use in determining boron retention. These cross sections were further cut to obtain assay zones corresponding to 0- to 6-mm and 7- to 12-mm depths from the wide faces of the specimens. The corresponding assay zones from the faces of the cross section were combined to obtain one sample per assay zone for each specimen. The remaining 14-mm-wide center section constituted the third assay zone. The samples were then milled, digested, and analyzed for boron content by inductively coupled plasma emission spectrometry following AWPA Method A21-08 (AWPA 2011b).

Data analysis

The penetration measurements were analyzed as randomized block designs with nested repeated measurements over the diffusion period using the mixed procedure in SAS (Version 9.2, SAS Institute Inc., Cary, North Carolina). Unstructured covariance matrices were assumed for both penetration depth and cross-section percent based on likelihood ratio tests and other model criteria, thus allowing for some heterogeneity and unequal correlations between repeat measurements. Within each diffusion period, initial overall tests for any differences were significant (<0.05). These were followed by the pairwise means comparisons within each diffusion period (Table 1). The change in extent of penetration over time was also of interest in this study. Because the statistical analysis did not detect interaction between treatment groups and diffusion period, the penetration measurements for all six treatment groups were combined for an overall test of changes in diffusion rates (Table 2).

The boron assay concentrations were analyzed as a split-block design (also known as a strip plot) with factors for treatment and zone using the glimmix procedure in SAS version 9.2. Variability appeared to increase with increasing concentrations and models that allowed for this heterogeneity were investigated. In particular, the model based on logarithmic concentrations appeared to fit the data the best (i.e., concentrations appeared lognormally distributed). With this model, comparisons of treatment medians within each zone were performed (this model compares means on the transformed scale and then transforms back to the original scale to give comparisons of medians on the original scale). Within each assay zone, initial overall tests for any differences were significant (<0.05). These were followed by the pairwise medians comparisons within each zone (using the simulation method for multiple comparison adjustments).

Results and Discussion

Boron penetration increased during the diffusion period for all treatment groups (Table 1; Fig 1). Statistical analysis confirmed that both depth of penetration and percent cross section penetrated increased significantly between 6 and 13 weeks and again between 13 and 26 weeks (Table 2). As shown in Table 2, the rate of diffusion (millimeters per week or percentage of cross section per week) did not statistically decrease during the 13- to 26-week period, indicating that diffusion would be expected to continue under these wood moisture content conditions. There was no consistent or obvious difference in radial versus tangential

Table 1.—Summary of penetration measurements and moisture content for each diffusion period.[a]

Treatment solution	Weeks of diffusion	Penetration depth (mm)		% cross section penetrated		Moisture content (%)
		Mean (SD)	Mean compare	Mean (SD)	Mean compare	
DOT-15%	6	4.6 (0.6)	C	33 (2.5)	C	18.6
DOT-HiLo	6	5.9 (0.6)	A	39 (7.1)	A	21.7
GB1-15%	6	4.7 (0.5)	C	34 (5.2)	BC	18.4
GB1-23%	6	5.3 (0.4)	B	38 (5.5)	AB	18.8
GB2-15%	6	4.7 (0.5)	C	33 (3.1)	C	18.3
GB2-23%	6	5.3 (0.6)	B	37 (3.7)	ABC	18.5
DOT-15%	13	6.0 (1.0)	D	41 (3.6)	D	18.9
DOT-HiLo	13	8.0 (0.8)	A	52 (6.9)	A	21.4
GB1-15%	13	6.2 (0.6)	CD	41 (4.7)	D	18.9
GB1-23%	13	6.8 (0.6)	BC	47 (5.0)	B	19.2
GB2-15%	13	6.4 (0.5)	BCD	42 (2.9)	CD	18.8
GB2-23%	13	6.9 (0.7)	B	45 (3.6)	BC	18.9
DOT-15%	26	9.4 (0.9)	C	58 (5.5)	BC	18.7
DOT-HiLo	26	11.2 (0.8)	A	68 (11.3)	A	20.9
GB1-15%	26	9.7 (1.4)	BC	59 (9.0)	BC	18.7
GB1-23%	26	10.4 (1.1)	AB	65 (5.6)	AB	18.6
GB2-15%	26	9.3 (1.2)	C	57 (9.6)	C	18.6
GB2-23%	26	10.1 (0.9)	BC	61 (4.8)	BC	18.7

[a] Means within a common diffusion period that do not share a letter in the ''mean compare'' column are significantly different at the 0.05 significance level ($n = 10$).

Table 2.—Statistical tests to determine if the extent of boron diffusion into the specimens increased over time.

Comparison	Penetration depth			% cross section		
	Rate estimate (mm/wk)	Standard error	P value (prob > $\|t\|$, df = 54)	Rate estimate (%/wk)	Standard error	P value (prob > $\|t\|$, df = 54)
Diffusion rate						
6–13 wk	0.2305	0.0138	<0.0001	1.3185	0.0760	<0.0001
13–26 wk	0.2556	0.0093	<0.0001	1.2601	0.0620	<0.0001
Difference between the two rates	0.0251	0.0191	0.1947	−0.0584	0.1090	0.5942

penetration, although on average penetration was slightly greater on the wide than on the narrow faces.

Possible diffusion penetration differences as a function of formulation and concentration warrant closer examination. One of the objectives of this study was to evaluate the effect of the glycol in formulations GB1 and GB2 on diffusion during storage. This effect can be evaluated by comparing the penetration of GB1 and GB2 at 15 percent DOT to that of the nonglycol 15 percent DOT at equivalent moisture content. As shown in Table 1, boron penetration in specimens treated with 15 percent GB1 or 15 percent GB2 was not significantly greater than in those treated with 15 percent DOT at any time period. This suggests that with equivalent solution concentrations, the glycol provided little benefit in increasing penetration.

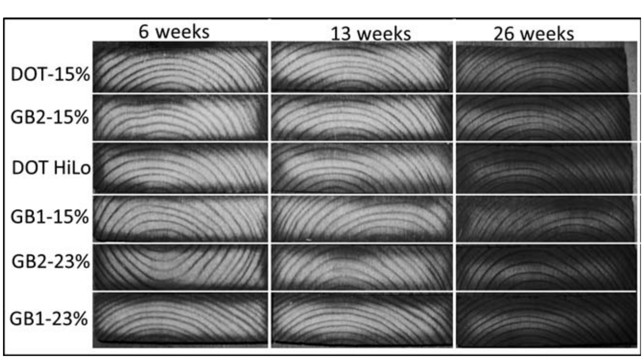

Figure 1.—Examples of boron diffusion in end-matched specimens 6, 13, or 26 weeks after spray application with solutions containing 15 or 23 percent DOT. Darker color indicates the presence of boron.

Another objective of this study was to determine if increasing the DOT concentration from 15 to 23 percent, the concentration often used in commercial glycol-borate applications, would increase subsequent diffusion penetration. According to Fick's first law of diffusion, increased surface concentrations should result in increased diffusion under steady-state conditions (Ra et al. 2001). As shown in Table 1, the higher solution concentration resulted in significantly greater penetration in some but not all cases. For example, after 6 weeks of diffusion, the depth of penetration (mm) was greater for the 23 percent solutions than for any of the 15 percent solutions except the DOT-HiLo–treated specimens. However, after 6 weeks, the percentage of cross section penetrated by specimens treated with GB2-23 percent was not significantly greater than those of specimens treated with the 15 percent solutions. Similar mixed results were observed for the 13- and 26-week diffusion periods. After 26 weeks, specimens treated with GB1-23 percent had significantly greater depth of penetration (mm) than those treated with 15 percent concentrations of GB2 or DOT, but there was no significant difference between GB1-23 percent and GB1-15 percent. Diffusion penetration from the GB1 and GB2 formulations was similar. No significant difference in either depth of penetration or percent cross section penetrated was observed when GB1 and GB2 were compared at equivalent DOT concentrations and diffusion periods. Although the findings on the effect of solution concentration are not clear-cut, they do indicate that the primary benefit of the GB formulations is that they allow use of higher solution concentrations, which in turn deposit a greater concentration of boron on the wood surface to drive the diffusion process.

In general, the greatest penetration occurred with the DOT-HiLo specimens (specimens that were dried down from a higher moisture content), and this difference was often statistically significant. This increased diffusion is likely a result of the slightly higher moisture content that these specimens maintained throughout the diffusion period (Table 1). The higher moisture content in these specimens is likely a result of sorption hysteresis; the amount of water absorbed from a dry condition to equilibrium with any relative humidity is less than the amount retained in the process of drying to equilibrium from a wetter condition. Slightly greater penetration of both DOT and GB formulations was also observed in the earlier study in which all specimens were brought to equilibrium from higher moisture contents (Lebow et al. 2010).

The assay of boron retention revealed that the 23 percent DOT glycol-borate formulations did deliver significantly greater concentrations to the wood surface than the 15 percent DOT formulations (Fig. 2). Although this effect was most obvious in the outer assay zone, the GB1-23 percent formulation also produced significantly higher boron concentrations in the 7- to 12-mm assay zone than did the DOT-15 percent formulation or the 15 percent GB1 or GB2 formulations. There was no significant difference in boron retention between the 23 percent GB1 and GB2 formulations in any assay zone or at either concentration. The GB1-23 percent formulation did appear to yield slightly greater boron retentions than the GB2-23 percent formulation, but this difference was not statistically significant.

There was also little significant difference in boron concentration in the specimens treated with the three 15 percent formulations, although one of the glycol-thickened 15 percent formulations (GB1) did yield significantly greater boron in the outer assay zone than the nonthickened 15 percent DOT formulation. This finding could indicate that the more viscous glycol formulation allowed more solution to remain on the wood surface during spray applications. However, specimens sprayed with the glycol-thickened 15 percent DOT formulations did not appear to have greater weight gains than those sprayed with the nonglycol 15 percent DOT solution. The average weight gain of specimens sprayed with 15 percent GB1 and GB2 was 10.3 and 10.2 g, respectively, while the average weight gain of specimens sprayed with nonglycol 15 percent DOT was 10.5 g. The DOT-HiLo specimens had an average weight gain of 11.3 g, while average weight gains of specimens sprayed with the GB1 and GB2-23 percent DOT solutions were 10.9 and 11.5 g, respectively. With the possible exception of the DOT-HiLo specimens, the treatment group weight gains do not appear to correspond with the trends seen in either penetration or retention.

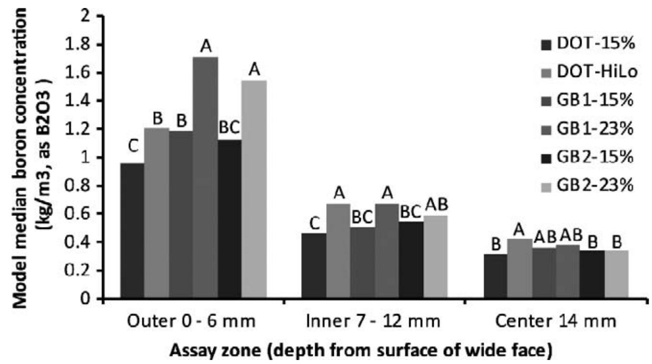

Figure 2.—Pairwise comparison of median boron concentration (expressed as kilograms per cubic meter B_2O_3) in each assay zone. Because the data have a lognormal distribution, statistical comparisons were performed on medians instead of means. Medians within a common assay zone and having the same letter are not significantly different at the 0.05 significance level.

As noted for boron penetration, the additional moisture in the DOT-HiLo specimens appeared to benefit diffusion. These specimens had significantly greater boron concentrations than specimens treated with the nonglycol-thickened 15 percent DOT solution in every assay zone. They also had greater boron concentrations than the 15 percent glycol-borate solutions in the 7- to 12-mm assay zone. In general, the boron assay results further indicate that surface concentration and wood moisture content are the keys to boron diffusion and that the primary benefit of the glycol formulations is that they allow use of more concentrated treatment solutions.

The results of this study support the earlier finding (Lebow et al. 2010) that boron diffusion can occur in wood with wood moisture contents in the range of 18 to 20 percent. The results further indicate that diffusion can proceed at these relatively low moisture contents when the wood is initially dry but then exposed to wetting or humid conditions during and after construction. It is likely that concept of fiber saturation point as an abrupt transition for boron diffusion is overly simplistic. As noted by Siau (1995), both free and bound water may be present over a range of moisture contents below the fiber saturation point. More recently, researchers using magnetic resonance imaging to determine the distribution of liquid water in sugar maple reported the coexistence of liquid and bound water at moisture contents below the fiber saturation point (Hernandez and Caceres 2010). Mass movement of bound water through the cell structure has also been discussed as a mechanism of moisture movement below the fiber saturation point (Choong 1963). Although most wooden members in most structures have less than 20 percent moisture content, moisture contents of 20 percent or greater have been reported in some framing members (Glass and TenWolde 2007). Temperature and humidity conditions similar to those evaluated in this study can occur in the vented crawl spaces of air-conditioned homes during warm, humid weather.

A further consideration with the surface-applied borate treatments is their ability to deliver a sufficient concentration of boron to prevent biological attack. There have been numerous reports on the concentration of boron needed to prevent colonization by decay fungi, as summarized in an article by Freitag and Morrell (2005). Depending on the fungus evaluated and the methodology used, threshold concentrations have been reported to vary from as low as 0.13 kg/m^3 (as B_2O_3) to as high as 2.6 kg/m^3 B_2O_3. In their article, which reported on a method intended to simulate wood used aboveground, Frietag and Morrell concluded that the threshold retention was in the range of 0.22 to 0.24 kg/m^3 (as B_2O_3). If so, even the center portion of the specimens evaluated in this study would meet the efficacy threshold (Fig. 2). Subsequently, Lesar et al. (2009) evaluated the sensitivity of six decay fungi to borates and reported that retentions between 0.2 and 0.8 kg/m^3 (as B_2O_3) are effective in agar-block tests while noting that higher retentions might be needed for soil-block tests. Other studies have reported higher threshold concentrations, and an earlier review reported the threshold as approximately 1.1 kg/m^3 B_2O_3 (Drysdale 1994). Only the outer assay zone of the specimens in this study would exceed this more conservative assumption of fungal toxicity threshold. However, spray-applied treatment solutions, such as those used in this study, are typically more concentrated than those needed for pressure treatment, and Kartal et al. (2004) reported that solution concentrations as low as 0.5 percent DOT protected wood against attack by both decay fungi and Formosan subterranean termites.

Borates are less effective in preventing growth of mold fungi than decay fungi, although their efficacy can be enhanced with the use of co-biocides (Fogel and Lloyd 2002, Clausen and Yang 2004, Micales-Glaeser et al. 2004). Toxic thresholds for mold and sapstain fungi have been reported to range from 0.06 to 1.1 kg/m^3 (as B_2O_3; Fogel and Lloyd 2002), but because molds colonize primarily the wood surface, retentions expressed on the basis of wood volume may be less relevant for mold fungi than for decay fungi. Application of a 5 percent DOT solution to wood surfaces was found to be ineffective in preventing mold growth (Clausen and Yang 2004), while applications of 8.5 or 15 percent DOT solutions was reported to inhibit or partially inhibit mold growth, depending on the fungal and wood species (Micales-Glaeser et al. 2004). Based on these findings, the 15 to 23 percent DOT concentrations applied to wood surfaces during spray treatment of framing lumber might also be expected to provide partial protection against mold growth.

The minimum protective threshold for termite protection with borates also has not been precisely established. Previous researchers have reported effective borate (as B_2O_3) concentrations ranging from below 0.7 to over 7.0 kg/m^3 (Drysdale 1994, Peters and Fitzgerald 2006). Much of this variability arises from differences in test methods, wood species, and termite species. Laboratory tests generally indicate efficacy at retentions of around 1.4 kg/m^3, while some field tests indicate that higher retentions are needed to ensure protection (Peters and Fitzgerald 2006). A recent study in which treated specimens were weathered (leached) down to a range of boron concentrations before exposure to termites concluded that the threshold of effectiveness was about 1.12 kg/m^3 (Lake and McIntyre 2007). In this study, the concentrations in the outer assay zone were generally above this threshold, but those in the inner and center assay zones were not (Fig. 2). Current pressure treatment standards for framing lumber specify boron retention of 2.7 kg/m^3 (as B_2O_3) for most applications and a higher retention (4.5 kg/m^3) for locations with Formosan subterranean termites (AWPA 2011c). The assay zone for these pressure treatment retentions is 0 to 15 mm from the wood surface. Building codes require pressure treatment for sill plates but typically do not require preservative treatment (pressure or nonpressure) for other framing members. Clearly, none of the surface-applied treatments evaluated in this study achieved the AWPA-specified pressure treatment boron retentions. There is also some indication that formulations with glycol may be effective at lower concentrations than those without glycol. When evaluated by oral toxicity, Tokoro and Su (1993) found that a glycol-borate formulation was toxic at a lower boron concentration than DOT or boric acid formulations. However, Grace and Yamamoto (1992) concluded that although ethylene glycol does exhibit a low level of toxicity toward termites, the DOT component is the primary contributor to the efficacy of the glycol-borate formulations.

The role of preservative penetration and retention in providing protection of framing members is less clear than for exterior members. Penetration is necessary in exterior members because drying checks and saw cuts break the outer layer of treatment and expose untreated wood to decay and termite attack. In framing lumber, breaks in the treated shell are also likely to occur when the framing is cut to install electrical, plumbing, and other utilities. However, if sufficient moisture is present to support fungal growth and if the area of moisture extends to the wood surface, boron from the surface may diffuse into the previously unprotected area. While the nearly ubiquitous presence of airborne fungal spores ensures contact with exposed wood surfaces, it is less likely that foraging termites will encounter small breaks in the treated shell within a much larger surface treated with high concentrations of borates. Even if fabrication during construction exposes some untreated inner surfaces, in many cases the termites would still be required to traverse over surfaces coated with high boron concentrations to reach the vulnerable wood. Although the level of deterrence provided by a borate-treated surface is not well understood, one study has reported that a borate application to concrete substantially decreased the length and viability of termite mud tubes across the treated surface (Smith and Lloyd 2004). Subsequent research indicated that although one type of glycol-borate surface treatment did deter termites from crossing treated wood to attack untreated wood, termites were able to construct mud tubes across sill plates pressure treated with borates (Wu et al. 2007).

Conclusions

Boron penetration by diffusion was observed for all solutions evaluated in this study, even at moisture contents well below the fiber saturation point. Diffusion continued between the 13- and 26-week samplings, indicating that this diffusion was not solely attributable to water uptake from the spray application. This finding indicates that spray-applied borates have potential for diffusion into framing lumber under some conditions. There was no significant difference in penetration between the powdered DOT and glycol-borate solutions when they were applied at the same DOT solution concentration (15%). However, in some cases, the glycol-borate solutions applied at the 23 percent DOT concentration produced significantly greater penetration than the solutions applied at the 15 percent concentration. Thus, the glycol did not appear to aid diffusion but did provide benefit by allowing the use of more concentrated treatment solutions. The results also indicate that even slight differences in moisture content may cause significant differences in the extent of penetration for wood below the fiber saturation point and that this effect may be greater than that of solution concentration. The assay results revealed that the glycol-borate solutions applied at the 23 percent DOT concentration yielded significantly greater boron retentions in the outer assay zone. Although these retentions are below those specified for pressure treatment, they did exceed many of the published values of retentions needed to prevent attack by subterranean termites. Retentions in the inner assay zones appeared less likely to provide protection against termites, but the role of penetration in providing protection of framing members from termite attack is less clear than for exterior members. The retentions resulting from the 15 percent solution concentrations were marginal in comparison to reported termite threshold retentions. Both the 15 and the 23 percent DOT solutions yielded retentions in the outer assay zone greater than most published values of threshold retentions needed to prevent fungal decay. Inner retentions were more marginal, but greater inward diffusion of boron might be expected at moisture contents needed to sustain growth by decay fungi.

Acknowledgment

The authors acknowledge Ensystex, II Incorporated (Fayetteville, North Carolina), for providing funding for this research.

Literature Cited

American Wood Protection Association (AWPA). 2011a. Standard methods for determining penetration of preservatives and fire retardants. Standard A3-08. *In:* Book of Standards. AWPA, Birmingham, Alabama. pp. 196–201.

American Wood Protection Association (AWPA). 2011b. Standard method for the analysis of wood and wood treating solutions by inductively coupled plasma emission spectrometry. Standard A21-08. *In:* Book of Standards. AWPA, Birmingham, Alabama. pp. 248–251.

American Wood Protection Association (AWPA). 2011c. Use category system, commodity specification a: Sawn products. *In:* Book of Standards. AWPA, Birmingham, Alabama. pp. 20–37.

Baker, C., C. Wilson, S. M. McFarling, and P. I. Morris. 2001. Pressure treatment of Canadian SPF with heated borate solutions. *Proc. Can. Wood Preserv. Assoc.* 21:69–78.

Barnes, H. M., J. R. W. Landers, and L. H. Williams. 1993. Thermal treatment of southern pine timbers with borates. *Forest Prod. J.* 43(3):31–34.

Becker, G. 1976. Treatment of wood by diffusion of salts. *J. Inst. Wood Sci.* 7(4):30–36.

Bergman, R. 2010. Drying and control of moisture content and dimensional changes. *In:* Wood Handbook—Wood as an Engineering Material. General Technical Report FPL-GTR-190. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. pp. 13.1–13.19.

Choong, E. T. 1963. Movement of moisture through a softwood in the hygroscopic range. *Forest Prod J.* 13(11):489–498.

Clausen, C. A. and V. W. Yang. 2004. Curbing indoor mold growth with mold inhibitors. *In:* Proceedings of the Woodframe Housing Durability and Disaster Issues Conference, October 4–6, 2004, Las Vegas, Nevada; Forest Products Society, Madison, Wisconsin. pp. 303–306.

Drysdale, J. A. 1994. Boron treatments for the preservation of wood—A review of efficacy data for fungi and termites. Document No. IRG/WP 94-30037. Presented at the Twenty-Fifth Annual Meeting of the International Research Group on Wood Preservation, May 29–June 3, 1994, Bali, Indonesia; International Research Group on Wood Preservation, Stockholm. 21 pp.

Fogel, J. L. and J. D. Lloyd. 2002. Mold performance of some construction projects with and without borates. *Forest Prod. J.* 52(2):38–43.

Fowlie, D. A., P. J. Walcheski, and A. F. Preston. 1988. Borate diffusion treatments of Douglas-fir lumber. *Proc. Am. Wood Preserv. Assoc.* 84:156–172.

Freitag, C. M. and J. J. Morrell. 2005. Development of threshold values for boron and fluoride in non-soil contact applications. *Forest Prod. J.* 55(4): 97–101.

Garrahan, P., J. Meil, and D. M. Onysko. 1991. Moisture in framing lumber—Field measurement, acceptability and use surveys. Canada Mortgage and Housing Corporation, Project Implementation Division, Ottawa.

Glass, S. V. and A. TenWolde. 2007. Review of in-service moisture and temperature conditions in wood-frame buildings. General Technical Report FPL-GTR-174. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 53 pp.

Grace, J. K. and R. T. Yamamoto. 1992. Termiticidal effects of a glycol borate wood surface treatment. *Forest Prod. J.* 42(11/12):46–48.

Hernandez, R. E. and C. B. Caceres. 2010. Magnetic resonance microimaging of liquid water distribution in sugar maple wood below fiber saturation point. *Wood Fiber Sci.* 42(3):259–272.

Kartal, S. N., T. Yoshimura, and Y. Imamura. 2004. Decay and termite resistance of boron-treated and chemically modified wood by in situ co-polymerization of allyl glycidyl ether (AGE) with methyl methacrylate (MMA). *Int. Biodeterior. Biodegrad.* 53(2):111–117.

Lake, M. A. and C. R. McIntyre. 2007. Formosan termite response to weathered borate-treated wood. *In:* Wood Protection 2006. H. M. Barnes (Ed.). Forest Products Society, Madison Wisconsin. pp. 295–298.

Lebow, S. T., C. A. Hatfield, and W. Abbott. 2005. Treatability of SPF framing lumber with CCA and borate preservatives. *Wood Fiber Sci.* 37(4):605–614.

Lebow, S. T., P. K. Lebow, and S. A. Halverson. 2010. Penetration of boron from topically applied borate solutions. *Forest Prod. J.* 60(1):13–22.

Lesar, B., P. Kralj, and M. Humar. 2009. Montan wax improves performance of boron-based wood preservatives. *Int. Biodeterior. Biodegrad.* 63(3):306–310.

Lesar, B., A. Ugovsek, M. Kariz, M. Sernek, and M. Humar. 2011. Influence of boron compounds in adhesives on the bonding quality and fungicidal properties of wood. *Wood Res.* 56(3):285–296.

Micales-Glaeser, J. A., J. D. Lloyd, and T. L. Woods. 2004. Efficacy of didecyl dimethyl ammonium chloride (DDAC), disodium octaborate tetrahydrate (DOT) and chlorothalonil (CTL) against common mold fungi. Document No. IRG/WP 04-30338. Presented at the Thirty-Fifth Annual Meeting of the International Research Group on Wood Preservation, June 6–10, 2004, Ljubljana, Slovenia; International Research Group on Wood Preservation, Stockholm. 15 pp.

Morrell, J. J. and C. M. Freitag. 1995. Effect of wood moisture content on diffusion of boron-based biocides through Douglas-fir and western hemlock lumber. *Forest Prod. J.* 45(3):51–55.

Morrell, J. J. and S. T. Lebow. 1991. Borate treatment of seasoned western hemlock and Douglas-fir lumber. *Forest Prod. J.* 41(1):27–29.

Morris, P. I., A. Byrne, J. F. G. Mackay, and S. M. McFarling. 1997. The effect of steaming prior to pressure treatment on the penetration of borates into western hemlock. *Forest Prod. J.* 47(3):62–65.

Morris, P. I., A. Byrne, and D. R. Minchin. 1996. Achieving ''shell'' or ''complete'' penetration of western hemlock and Pacific silver fir with borates by pressure/diffusion treatments. *Forest Prod. J.* 46(3):51–55.

Page, D. and T. Singh. 2011. Remedial treatment of difficult to access framing timber- comparison of two treatment methods. Report prepared for the Department of Building and Housing, Wellington New Zealand. New Zealand Forest Research Institute Limited, Wellington. 18 pp.

Peters, B. C. and C. J. Fitzgerald. 2006. Borate protection of softwood from *Coptotermes acinaciformis* (Isoptera: Rhinotermitidae) damage: Variation in protection thresholds explained. *J. Econ. Entomol.* 99(5):1749–1756.

Peylo, A. and H. Willeitner. 1995. Influence of hydrophobic agents on the leachability of boron. IRG/WP/95-30064. International Research Group on Wood Preservation, Stockholm. 10 pp.

Puettmann, M. E. and E. L. Schmidt. 1997. Boron diffusion treatment of aspen lumber stored under various relative humidities. *Forest Prod. J*. 47(10):47–50.

Puettmann, M. E. and L. H. Williams. 1992. Treatment of log-home logs with thickened boron. *Forest Prod. J*. 42(11/12):30–32.

Ra, J. B., H. M. Barnes, and T. E. Conners. 2001. Determination of boron diffusion coefficients in wood. *Wood Fiber Sci*. 33(1):90–103.

Rasband, W. S. 2004. ImageJ. US National Institutes of Health, Bethesda, Maryland. http://rsb.info.nih.gov/ij.

Schoeman, M. W., J. D. Lloyd, and M. J. Manning. 1998. Movement of borates in a range of timber species at various moisture contents. IRG WP 98-30181. International Research Group on Wood Preservation, Stockholm. 8 pp.

Siau, J. F. 1995. Wood: Influence of moisture on physical properties. Department of Wood Science and Forest Products, Virginia Polytechnic Institute and State University, Blacksburg. 227 pp.

Simpson, I., D. Page, and T. Singh. 2012. Spread and retention of a preservative on difficult to access lintel members using a remedial treatment method. Report prepared for the Department of Building and Housing, Wellington New Zealand. New Zealand Forest Research Institute Limited, Wellington. 22 pp.

Smith, D. N. and A. I. Williams. 1969. Wood preservation by the boron diffusion process: The effect of moisture content on diffusion time. *J. Inst. Wood Sci*. 22(4):3–10.

Smith, W. R. and J. D. Lloyd. 2004. Prevention of termite tubing over non-wood construction materials using glycol borate. Document No. IRG/WP 04-30358. Presented at the Thirty-Fifth Annual Meeting of the International Research Group on Wood Preservation, June 6–10, 2004, Ljubljana, Slovenia; International Research Group on Wood Preservation, Stockholm. 14 pp.

Tokoro, M. and N. Su 1993. Oral toxicity of TIM-BOR, Bora-Care, boric acid and ethylene glycol against the formosan subterranean termite and eastern subterranean termite. IRG/WP 93-10045. IRG Secretariat, International Research Group on Wood Preservation, Stockholm.

Vinden, P., J. Drysdale, and M. Spence. 1990. Thickened boron treatment. Document No. IRG/WP 90-3632. Presented at the Twenty-First Annual Meeting of the International Research Group on Wood Preservation, May 13–18, 1990, Rotorua, New Zealand; International Research Group on Wood Preservation, Stockholm. 8 pp.

Wang, J., P. I. Morris, S. McFarling, and T. Byrne. 2007. Developments in borate treatment of Canadian species for decay and termite resistance. Document No. IRG/WP 07-30443. Presented at the Joint IRG–IUFRO Regional Research Symposium, October 29–November 2, 2007, Taipei, Japan; International Research Group on Wood Preservation, Stockholm. 12 pp.

Wu, Q., W. R. Smith, J. D. Lloyd, P. Merrick, J. Curole, M. Voitier, T. F. Shupe, and D. Ring. 2007. Tower test for evaluating resistance of common building materials to Formosan subterranean termites. *Proc. Am. Wood Prot. Assoc*. 103:48–50. (Abstract.)