Penetration of Boron from Topically Applied Borate Solutions

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Abstract

Borate penetration relies on diffusion when borate and glycol-borate preservatives are applied to the surface of wood. This study evaluated the extent of borate penetration in framing lumber as a function of preservative formulation, wood moisture content, and diffusion time after treatment. In Phase I of the study, end-matched specimens were conditioned to target average moisture contents of 15, 25, or 35 percent, briefly immersed in borate formulations, and then placed into wooden frames to minimize air exchange during diffusion. Penetration in these specimens was generally less than 5 mm (or 35% of the cross section) regardless of treatment solution, target moisture content at time of treatment, or diffusion period (2, 4, or 8 wk). Assay of boron concentrations after 8 weeks of diffusion also indicated that the boron was concentrated in the outer 5 mm of the wood. Diffusion appeared to have been limited by the relatively rapid drying of the specimens, even with the restricted air movement within the wooden frames. In Phase II of the study, specimens were conditioned to a target average moisture content of 20 percent prior to dip immersion and then placed in a room that maintained an equilibrium moisture content of 19 to 21 percent. Penetration in these specimens was assessed after 6, 13, and 26 weeks of diffusion. After 6 weeks of diffusion, average boron penetration exceeded 5 mm, and after 26 weeks of diffusion, penetration exceeded 11 mm, or over 70 percent of the cross section. Little difference in diffusion was observed between the types of borate formulations evaluated in either phase of this study. The results of this study indicate that rapid drying conditions may limit penetration of boron from spray applications; however, in situations where high humidity is maintained in a structure, substantial diffusion is possible.

With the exception of sill plates, lumber used in the interior of structures in the United States is typically not treated with preservatives. However, consumers are increasingly interested in framing lumber with protection against fungal and insect attack, especially in areas with high termite hazard. Borate-based preservatives are most commonly used for these interior applications because the borates are odorless, have relatively low toxicity, and are effective against termites and decay fungi (Manning 2008). The primary disadvantage of borates—their poor resistance to leaching—is also less of a concern in indoor applications. Pressure treatment of framing lumber with borates has become an accepted practice (Manning 2008), although use is largely limited to sill plates and other items in contact with construction foundations as specified in building codes. Although widely used in Hawaii, use in whole-structure construction packages has been slow to gain building industry acceptance in mainland North America.

Substantial research has been conducted on pressure treatment of lumber with borates, indicating that penetration equal to or exceeding other types of preservatives is possible (Lebow and Morrell 1989; Morrell and Lebow 1991; Morris et al. 1996, 1997; Baker et al. 2001; Lebow et al. 2005). An additional advantage of borates is that because they do not react with wood, they may continue to diffuse more deeply into wood after pressure treatment. This ability of borates to diffuse into the wood is the basis of non–pressure immersion treatments. Research has showed that extended immersion of green lumber in concentrated borate solutions, followed by a diffusion period, can produce satisfactory penetration in many wood species (Smith and Williams 1969, Fowlie et

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Table 1.—Study parameters.

Treatment solutions[a]	Target moisture content (%)	Diffusion condition	Weeks of diffusion for penetration	Weeks of diffusion for assay	Assay zones (mm from narrow faces)
Phase I					
EB, CB, DOT, CTL/EB, CTL/CB	15, 25, 35	Wooden frame	2, 4, 8	8	0–5, 6–10, 11–15
Phase II					
EB, CB, DOT	20	27°C (80 °F), 90% RH	6, 13, 26	No assay	No assay

[a] EB = experimental glycol-borate, CB = commercial glycol-borate, DOT = disodium octaborate tetrahydrate, CTL = chlorothalonil, CTL/CB = chlorothalonil/experimental glycol-borate.

al. 1988, Barnes et al. 1993, Puettmann and Schmidt 1997, Wang et al. 2007), and this method of application was commercialized in New Zealand (Hedley and Page 2006, Wang et al. 2007). Glycol-borate solutions were developed to increase the volume of solution retained on the wood and to overcome difficulties with hydrophobic wood surfaces in some species (Vinden et al. 1990, Puettmann and Williams 1992, Wang et al. 2007).

An alternative approach to protection of framing lumber is topical preservative application to the framing lumber as part of the construction process. Typically these solutions are applied with handheld or backpack sprayers after framing is completed and prior to installation of insulation or mechanical systems. This approach is potentially less expensive than pressure or immersion treatments and does not require drying after treatment or preordering treated material. However, the degree of preservative penetration with these surface applications is poorly quantified, and the diffusion conditions differ from those present in either pressure or immersion treatments. Conventional diffusion treatments depend on the available moisture in the unseasoned wood, followed by a diffusion period to ensure that sufficient time and moisture are available for diffusion. In contrast, framing lumber has conventionally been targeted for moisture contents below 19 percent (Simpson 1999) to minimize concerns with shrinkage and other moisture-related problems. Actual moisture contents in framing lumber during construction are likely to vary substantially, and a study of framing lumber in Canada reported that the majority of members were above the 19 percent moisture content specified in the building code (Garrahan et al. 1991). Still, the moisture content of framing lumber is likely to be substantially lower than that of the green lumber traditionally treated by immersion/diffusion processes. Although borate pressure treatments are effectively applied to dry lumber, the pressure treatment process introduces sufficient moisture to allow subsequent diffusion to occur. Framing lumber treated during construction also may not experience conditions equivalent to the diffusion period provided for immersion treatments, although the moisture conditions could be similar if the lumber is enclosed soon after the spray application. Previous studies demonstrate that moisture content plays a key role in borate diffusion and especially in the range from 30 to 80 percent moisture content (Smith and Williams 1969, Fowlie et al. 1988, Morrell et al. 1990). Becker (1976) postulated that diffusion will cease at moisture contents below the fiber saturation point, but previous reports have indicated slight diffusion at lower moisture contents (Page et al. 1987, Barnes et al. 1993, Morrell and Freitag 1995, Freitag and Morrell 2002), possibly as a result of water provided with the borate application.

It is apparent that several factors may influence the penetration of boron when applied topically to framing during construction. The objective of our research was to determine the extent of borate penetration in framing lumber from the Southern Pine species group as a function of preservative formulation, wood moisture content, and diffusion time after treatment.

Materials and Methods

This study was conducted in two phases. In each phase, end-matched specimens were conditioned to an average target moisture content, briefly immersed in a borate formulation, and then stored for diffusion to occur (Table 1). The two phases differed in wood moisture content at time of treatment and wood moisture content during diffusion.

Specimen preparation

Specimens were prepared from 2 by 4 nominal (51 by 102 mm) lumber from the Southern Pine species group and selected to be free of heartwood, mold, and sap stain. The lumber was purchased in 8-foot (2.44-m) lengths that will be referred to as *parent studs* in this article. The studs were initially allowed to equilibrate indoors until the moisture content of all pieces was below 15 percent. In Phase I of the study, which evaluated the effect of moisture content at time of treatment on penetration, five 14-inch (356-mm)-long defect-free specimens were cut from each of 30, 8-foot (2.44-m)-long parent studs. This experimental design resulted in a random assignment of each of the five dip solution combinations to each parent stud at one target moisture content. We subsequently determined that evaluation of long-term diffusion under controlled high-humidity conditions could provide useful information. In Phase II of the study, three 14-inch (356-mm) specimens were cut from an additional 10 parent studs and randomly assigned to one of three preservative solutions (two preservative solution combinations were not evaluated in this portion of the study). In all cases, specimens were end-sealed with two coats of a neoprene-rubber sealant. During the cutting process, excess sections from each parent board were retained to allow determination of the parent stud's ovendry specific gravity.

Preservative solution combinations

Two types of glycol-borate formulations and powdered disodium octaborate tetrahydrate (DOT) were evaluated. Disodium octaborate tetrahydrate was selected as the form of borate because it has greater water solubility than alternatives such as borax or boric acid. One of the glycol-borates evaluated is a commercially available product

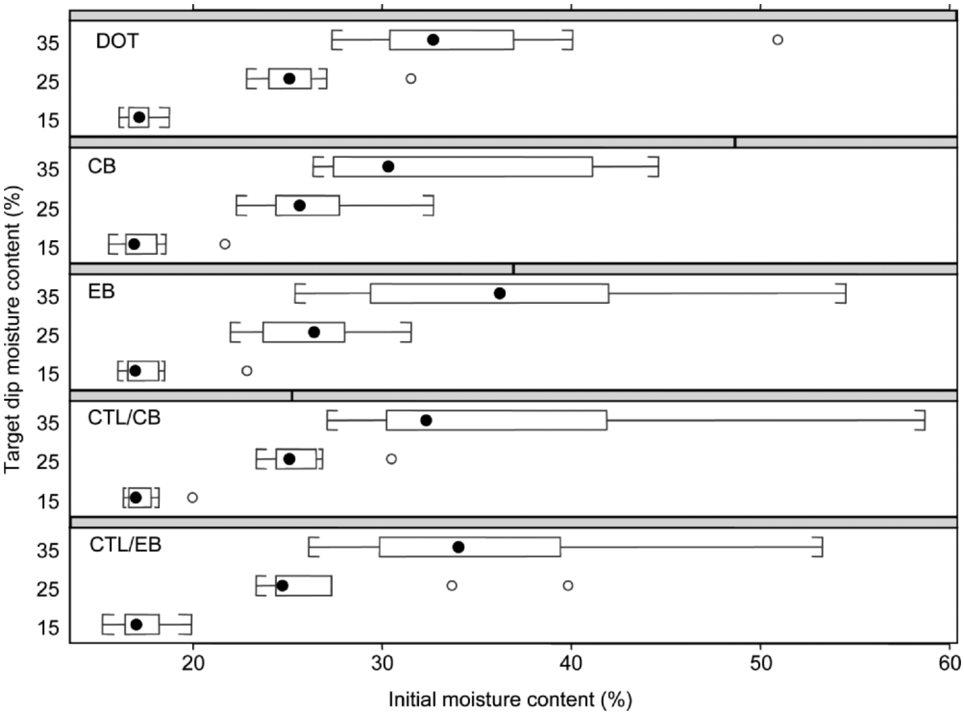

Figure 1.—Distribution of moisture content values within each target moisture content group and treatment type. The black dot represents the median, the box displays the interquartile range, and the whiskers represent either 1.5 times the interquartile range or the maximum/minimum values. Circles show points that are greater than 1.5 times the interquartile range. DOT = disodium octaborate tetrahydrate, CB = commercial glycol-borate, EB = experimental glycol-borate, CTL/CB = chlorothalonil/commercial glycol-borate, CTL/EB = chlorothalonil/experimental glycol-borate.

(commercial glycol-borate [CB]), whereas the other is an experimental formulation (experimental glycol-borate [EB]). Both 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. For all treatments, the borate formulations or powder were diluted with deionized water to obtain a treatment solution concentration containing 15 percent DOT. This concentration was limited by the useful working concentration of powdered DOT in water and is lower than that typically used for glycol-borate formulations. Notably, commercial preventative and remedial termite treatments with glycol-borate solutions use a 23 percent DOT solution.

Borates have limited effectiveness against mold fungi, and in some cases moldicides may be applied to framing lumber independently of borate treatments (Burley 2008). In Phase I of this study, we also assessed the effect of a pretreatment with a moldicide on boron penetration from a subsequent glycol-borate treatment. The moldicide evaluated was a 1 percent concentration of a water dispersible chlorothalonil (CTL) formulation. The CTL treatment was evaluated in combination with both glycol-borate treatments but not with the DOT borate treatment. The five treatment solution combinations for Phase I were as follows:

- Experimental glycol-borate (EB)
- Commercial glycol-borate (CB)
- DOT
- 1 percent CTL treatment followed by treatment with the EB borate (CTL/EB)
- 1 percent CTL treatment followed by treatment with the CB borate (CTL/CB)

Obtaining target moisture contents

Target moisture contents were obtained by pressure treating specimens with water and then allowing them to dry in a room maintained at 2°C (36°F) and 82 percent relative humidity (RH). These drying conditions were selected to slow drying and minimize any moisture gradient that might develop during drying. A subset of the specimens was weighed daily to allow calculation of average moisture content. The extent of moisture gradient that developed was not determined, since the moisture content was calculated based on the weight of the entire specimen. Similar moisture gradients might be expected in framing lumber that is not adequately dried prior to construction.

For Phase I of the study, the specimens were pressure treated with water in two batches. Each batch was composed of specimens cut from 15 of the 30 replicate parent studs. When the average moisture content of all 75 specimens in the batch approached the target moisture content (either 35%, 25%, or 15%), all five specimens cut from five preselected parent studs were transferred to the laboratory and allowed to return to ambient temperature prior to treatment with the test preservatives. This approach was used to prevent selecting specimens based on their drying rate, but it did result in a wide distribution of moisture contents within the 35 percent and 25 percent target moisture content groups (Fig. 1). This process was repeated for specimens cut from the remaining 15 parent studs. In the second phase of the study (long-term diffusion at high humidity), specimens cut from all 10 parent studs were treated in one batch and conditioned to a target of 20 percent moisture content before preservative treatment.

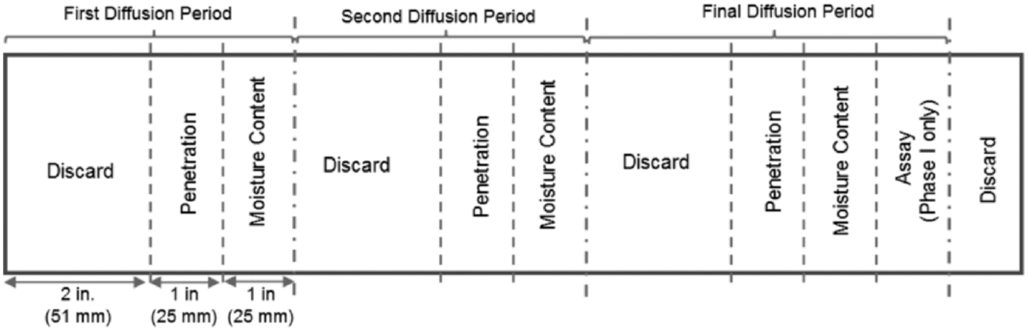

Figure 2.—Pattern used for cutting penetration, moisture content, and assay samples from specimens (top view). Diffusion periods were 2, 4, and 8 weeks for Phase I and 6, 13, and 26 weeks for Phase II.

Application of preservative solutions

The volume of preservative solution applied by spray applications can be variable. To minimize variability and ensure uniform coverage, the treatment solutions in this study were applied with 30-second immersions in the test solutions. Each specimen was weighed immediately before immersion, immersed for 30 seconds in the appropriate treatment solution, allowed to drip for 60 seconds, and then reweighed. The specimens were then placed into diffusion storage.

For the two-stage immersions, the specimens were first immersed for 30 seconds in the 1 percent chlorothalonil dispersion, allowed to air dry for 1 hour, reweighed, and then immersed in the borate solution.

Diffusion storage

One of the challenges in this study was choosing appropriate diffusion storage conditions. In commercial practice, the drying conditions experienced by framing lumber after borate application treatment will vary depending on construction methods, geographic location, and time of year. In Phase I of this study, we attempted to create moderate drying conditions by placing groups of 10 treated specimens within 24 by 32-inch (607 by 813-mm) wooden frames constructed from untreated 2 by 4-inch nominal (51 by 102-mm) studs and oriented strandboard sheathing. The wooden frames were stored in ambient laboratory conditions, and penetration was measured 2, 4, and 8 weeks after treatment. A subset of five replicates from each treatment group was assayed for boron retention at the 8-week sampling point. As the study progressed, we determined that the specimens dried relatively rapidly. The intent of the wooden frames was to minimize air circulation and slow drying, but because the sheathing and studs used in the frames were dry (approximately 8% moisture content), the moisture-storage capacity of the frames themselves may have hastened drying.

In Phase II, the study was expanded to include additional treated specimens (Table 1) that were placed into a conditioning room maintained at 90 percent RH and 27°C (80°F), to simulate more humid construction conditions. Penetration in these specimens was determined after 6, 13, and 26 weeks of diffusion.

The sampling pattern was the same for both Phase I and Phase II specimens. At each designated diffusion time, a 2-inch (51-mm) length was cut from one end of each specimen and discarded (Fig. 2). An adjacent 1-inch (25-mm) section was then removed and allowed to air dry for penetration measurement, and the next adjacent 1.0-inch (25-mm) section was removed, weighed, and oven-dried to determine moisture content. If an assay section was required (a subset of Phase I specimens) an additional 1.0-inch (25-mm) section was removed after 8 weeks of diffusion.

Penetration measurements

The air-dried, 1-inch (25-mm) sections cut after each diffusion period were cut again to reveal a fresh cross section, brushed with a soft brush to remove wood dust

Table 2.—Average penetration (depth or percentage of cross section) for each dip treatment, moisture content, and diffusion period.[a]

	Dip type					
	CTL/EB			CTL/CB		
MC group (%)	Wk 2	Wk 4	Wk 8	Wk 2	Wk 4	Wk 8
	Depth of penetration (mm)					
15	3.05 (0.42)	3.28 (0.40)	3.54 (0.38)	3.09 (0.19)	3.34 (0.28)	3.51 (0.40)
25	3.96 (1.53)	4.70 (2.38)	4.31 (2.01)	3.45 (0.60)	4.11 (0.59)	4.01 (0.43)
35	4.15 (0.99)	4.70 (1.31)	4.23 (0.48)	3.80 (0.62)	4.31 (0.53)	4.06 (0.23)
	Percentage of cross section penetrated					
15	24.83 (3.70)	24.61 (3.48)	28.33 (6.41)	26.29 (2.62)	25.29 (5.58)	28.13 (6.81)
25	31.82 (13.11)	35.28 (14.65)	32.58 (11.27)	28.01 (3.94)	31.57 (5.40)	30.23 (6.32)
35	33.51 (14.66)	35.06 (8.15)	34.22 (5.69)	27.10 (5.01)	28.89 (4.47)	28.90 (4.94)

[a] Values in parentheses represent 1 standard deviation. MC = moisture content, CTL/EB = chlorothalonil/experimental glycol-borate, CTL/CB = chlorothalonil/commercial glycol-borate, EB = experimental glycol-borate, CB = commercial glycol-borate, DOT = disodium octaborate tetrahydrate.

Table 3.—Least squares mean penetration (depth or percentage of cross section) for each type of dip treatment.[a]

Dip type	Depth of penetration (mm)	Mean separations[b]	Cross-section penetration (%)	Mean separations
CTL/EB	3.99 (0.19)	A	31.14 (1.75)	AB
CTL/CB	3.75 (0.19)	A	28.30 (1.75)	A
EB	4.13 (0.19)	A	32.12 (1.75)	B
CB	4.09 (0.19)	A	32.05 (1.75)	B
DOT	3.96 (0.19)	A	29.99 (1.75)	AB

[a] Values in parentheses represent least squares standard error for the mean. CTL/EB = chlorothalonil/experimental glycol-borate, CTL/CB = chlorothalonil/commercial glycol-borate, EB = experimental glycol-borate, CB = commercial glycol-borate, DOT = disodium octaborate tetrahydrate.

[b] Mean separations, based on simulations with significance level 0.05. Means connected with the same letter are not significantly different at the 0.05 significance level.

particles, and then sprayed with curcumin–salicylic acid boron indicator solutions prepared in accordance with American Wood Protection Association (AWPA) standards (AWPA 2008). Borate penetration was measured in two ways. The average depth of penetration on each face was estimated visually using a measurement template, and 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.

Assay sampling (Phase I)

Five of the 10 replicate specimens from each moisture content/preservative solution treatment group were assayed to determine boron retention. The assay cross sections removed after 8 weeks of diffusion were cut to obtain assay zones corresponding to 0- to 5-mm, 6- to 10-mm, and 11- to 15-mm depths from the narrow faces of the specimens. The corresponding assay zones from the two ends of the cross section were combined to obtain one sample per assay zone for each specimen. The samples were then milled, digested, and analyzed for boron content using inductively coupled plasma emission spectrometry. Boron assay retentions were not determined for the Phase II specimens.

Data analysis and interpretation

The penetration data from Phase I of the study were analyzed to determine whether the treatment type, treatment moisture content, or diffusion period significantly affected boron penetration. The study was designed as a replicated, split-plot Latin-square experimental design with repeated measurements, with moisture content levels assigned to boards (whole plot), treatments assigned to specimens within boards, and diffusion time within specimens. Latin squares were used to remove variation caused by boards and wooden frame assignment. The data were analyzed using a mixed-model approach with SAS (SAS Institute Inc., Cary, North Carolina) and Spotfire S+ software (TIBCO, Palo Alto, California). In each case, up to five sources of variation were present—batch, batch × dip moisture content (dipmct), batch × dipmct × parent, batch × dipmct × wooden frame, and batch × dipmct × parent × wooden frame as well as possible correlations between repeated measurements. The penetration data from Phase II of the study were analyzed as a repeated measure experiment (with blocking).

Results

Phase I, effect of moisture content at time of treatment

Average penetration of cross sections was generally less than 5 mm deep and 35 percent of the cross section, regardless of the treatment solution, target moisture content at time of treatment, or diffusion period (Table 2). Statistical analysis indicates that the percentage of cross section penetrated with the CTL/CB treatment was statistically less than that for the EB or CB treatments (Table 3). This may indicate that the initial CTL pretreatment reduced uptake or hindered subsequent diffusion with the CB formulation. Simultaneous dip application of CTL mixed with borate

Table 2.—Extended.

Dip type								
EB			CB			DOT		
Wk 2	Wk 4	Wk 8	Wk 2	Wk 4	Wk 8	Wk 2	Wk 4	Wk 8
Depth of penetration (mm)								
3.29 (0.31)	3.70 (0.29)	3.55 (0.42)	3.37 (0.27)	3.70 (0.14)	3.54 (0.33)	3.23 (0.47)	3.46 (0.16)	3.54 (0.48)
3.80 (0.64)	4.32 (0.75)	4.04 (0.61)	3.73 (0.57)	4.30 (0.76)	4.22 (0.82)	3.87 (0.88)	4.23 (0.85)	4.15 (0.70)
4.87 (1.19)	5.01 (0.97)	4.45 (0.52)	4.29 (0.74)	5.05 (1.20)	4.65 (1.29)	4.06 (0.87)	4.86 (1.10)	4.30 (0.54)
Percentage of cross section penetrated								
27.90 (3.87)	27.96 (5.31)	29.27 (6.58)	26.97 (2.17)	27.03 (4.08)	27.72 (3.80)	25.78 (4.78)	25.23 (4.85)	27.34 (5.43)
30.72 (9.61)	33.58 (8.50)	31.67 (5.15)	30.64 (6.58)	33.67 (7.07)	35.41 (8.47)	29.43 (8.41)	32.65 (8.83)	30.88 (7.54)
38.26 (11.41)	34.76 (6.32)	34.21 (6.04)	36.07 (9.90)	35.40 (8.90)	35.86 (8.04)	33.58 (9.81)	33.32 (6.99)	32.45 (6.49)

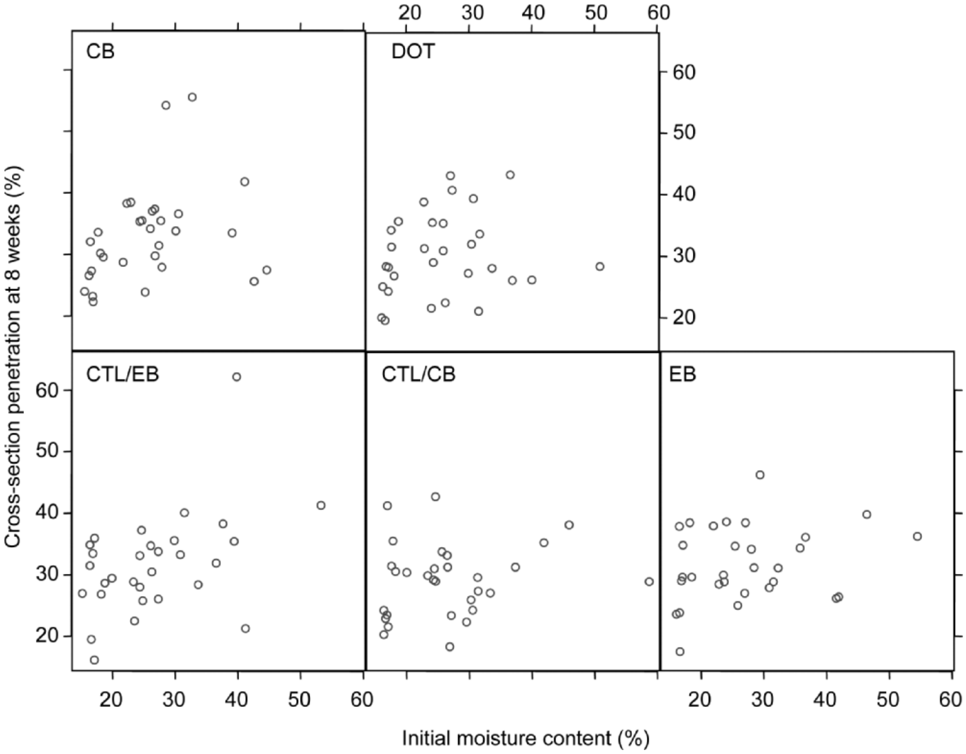

Figure 3.—Relationship between specimen moisture content at time of treatment and percentage of the cross section penetrated after 8 weeks of diffusion. CB = commercial glycol-borate, DOT = disodium octaborate tetrahydrate, CTL/EB = chlorothalonil/experimental glycol-borate, CTL/CB = chlorothalonil/commercial glycol-borate, EB = experimental glycol-borate.

products was not tested. Average depths of penetration were not significantly different based on type of dip treatment. The effect of diffusion period was marginally significant ($P = 0.0900$) for the percentage of cross section penetrated, and highly significant ($P < 0.0001$) for depth of penetration. Cross-section penetration based on the initial moisture content factor and the diffusion period factor (weeks) resulted in a significant interaction, apparently caused by a significant difference between 2 and 4 weeks at the 25 percent initial moisture content group. Least squares (LS) mean comparisons of penetration for each moisture content and diffusion period were conducted and revealed that the only significant difference ($P < 0.05$) resulting from initial moisture content was in depth of penetration for the 35 percent (LS mean = 4.79 mm) and 15 percent (LS mean = 3.50 mm) groups after 4 weeks of diffusion. Initial moisture content did not significantly affect percent cross-section penetration for any diffusion period. The experimental design allowed closer comparison within each moisture content group, and in some cases the diffusion period did have a small, inconsistent but significant effect on the penetration depth and percentage of cross section penetrated.

The lack of a strong relationship between penetration and initial moisture content or diffusion period is somewhat surprising. This lack of relationship appears to be a result of relatively rapid drying of specimens, as well as the wide range of moisture contents within each target moisture content group (Fig. 1). Regardless of moisture content at time of treatment, all specimens had dried to within a range of 10 to 18 percent (average close to 14%) moisture content within 2 weeks of storage in the wooden frames. Thus, there may have been insufficient moisture for significant further diffusion to occur after 4 or 8 weeks of storage. This rapid drying may not be characteristic of some conditions, such as application of insulation and/or vapor barriers immediately after the framing is sprayed. The effect of initial target moisture content on penetration may have also been obscured by variability in individual specimen moisture content within the 35 and 25 percent moisture content groups (Fig. 1). To further examine the effect of treatment moisture content on penetration, we plotted initial moisture content compared with the percentage of cross section penetrated for individual specimens across all three target moisture content groups at 8 weeks. As shown in Figure 3, there was little relationship between treatment moisture content and penetration for individual specimens, further indicating that rapid drying minimized the effect of initial moisture content.

Assay retention

Assay retention of Phase I specimens after 8 weeks of diffusion showed that nearly all of the boron remained in the outer 5 mm (Fig. 4). This finding is in agreement with the penetration measurements made on these specimens. Specimens targeted for treatment at 25 percent moisture content appeared to have slightly greater boron concentrations in the outer 5 mm than did specimens targeted for treatment at 15 or 35 percent moisture content, but this effect may be an anomaly. Treatment solution appeared to have little consistent effect on boron concentration, although the CTL/CB dip combination appeared to yield lower boron concentrations in the outer 5 mm. The minimum protective threshold for termite protection with borates has not been

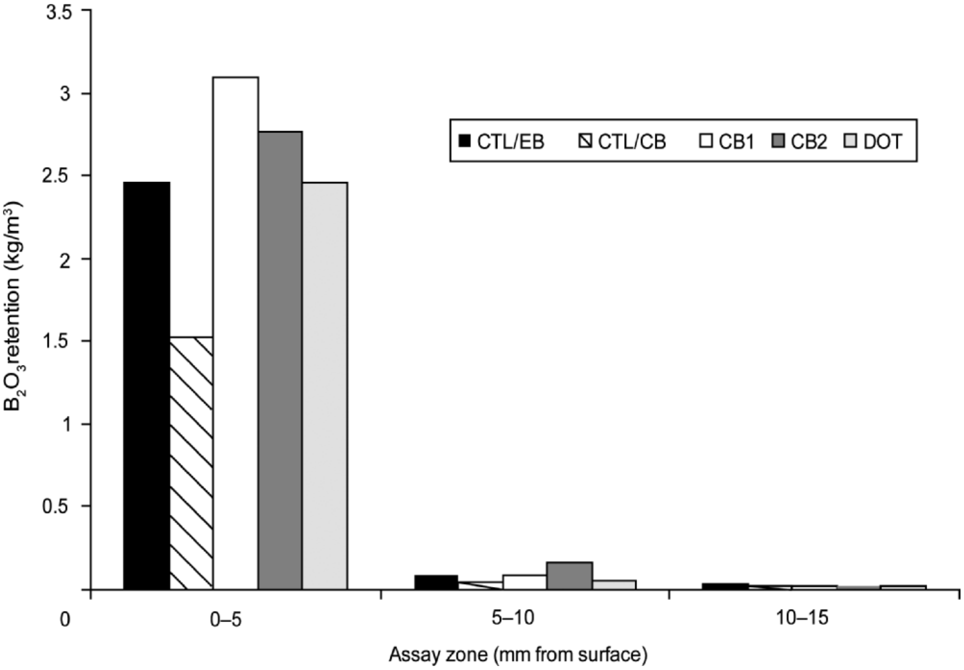

Figure 4.—Boron retention, as B_2O_3, for each assay zone. Values for the three target moisture contents were averaged. CTL/EB = chlorothalonil/experimental glycol-borate, CTL/CB = chlorothalonil/commercial glycol-borate, CB = commercial glycol-borate, DOT = disodium octaborate tetrahydrate.

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 of retentions of around 1.4 kg/m^3, whereas some field tests indicate that higher retentions are needed to ensure protection (Peters and Fitzgerald 2006). With the exception of the CTL/CB treatment combination, borate retentions in this study were generally over 2 kg/m^3 in the outer assay zone (Fig. 4). It is important to note that borate retentions, or at least those near the wood surface, are dependent on the concentration of the treatment solution. In this study, the solution concentrations (15%) were limited by the useful working concentration of powdered DOT in water. The glycol-borate solutions used commercially are typically applied at a concentration 50 percent greater than that used in this study and would be expected to yield much greater borate concentrations on the wood surface.

Phase II, long-term diffusion at high humidity

Diffusion of boron in the specimens stored at high humidity (90 percent RH) and at 27°C (80°F) was greater than that observed for the specimens stored in wooden frames at lower humidity (Phase I; Table 4). This finding is intriguing given that the average moisture content of the specimens at the time of treatment was only 22%, and that the moisture content of the outer portion of the specimens may have initially been lower if a moisture gradient developed during drying. As the diffusion period progressed, average moisture contents stabilized in the range of 18.7 to 20.5 percent (Table 4). Diffusion, as measured by either depth of penetration or the percentage of cross section penetrated, increased between 6 and 13 weeks and between 13 and 26 weeks (Fig. 5), even though the specimens' moisture contents had equilibrated by 13 weeks. Statistical analysis also indicated that both depth of penetration and percentage of cross section penetrated were significantly greater at 26 weeks than at 13 weeks, and that penetration at 13 weeks was greater than at 6 weeks (with $P < 0.01$). This indicates that the diffusion was not solely attributable to moisture supplied during dipping and that diffusion proceeds steadily in wood that has equilibrated to 20 percent moisture content.

The finding of boron diffusion at 20 percent moisture content conflicts with the assumption that transport is dependent on the presence of free water within the cell lumens (Becker, 1976) and that diffusion of salts essentially stops when the wood moisture content falls below the fiber

Table 4.—Average depth of penetration, percentage of cross-section penetration, and diffusion moisture content.[a]

Weeks of diffusion	Depth of penetration (mm)			Cross section penetrated (%)			MC after diffusion period (%)		
	EB	CB	DOT	EB	CB	DOT	EB	CB	DOT
6	5.75 (0.76)	5.63 (0.34)	5.68 (0.46)	47.07 (4.95)	44.70 (2.63)	43.15 (2.93)	19.03 (0.29)	18.82 (0.35)	18.65 (0.26)
13	7.47 (0.80)	7.67 (0.86)	7.88 (0.52)	52.74 (4.37)	54.60 (4.13)	52.01 (4.22)	20.46 (0.53)	19.91 (0.71)	20.36 (0.21)
26	11.70 (1.26)	11.61 (1.12)	11.38 (1.13)	74.76 (4.75)	71.58 (3.86)	74.30 (6.14)	20.28 (0.58)	19.89 (0.34)	20.05 (0.40)

[a] Values in parentheses represent 1 standard deviation. MC = moisture content, EB = experimental glycol-borate, CB = commercial glycol-borate, DOT = disodium octaborate tetrahydrate.

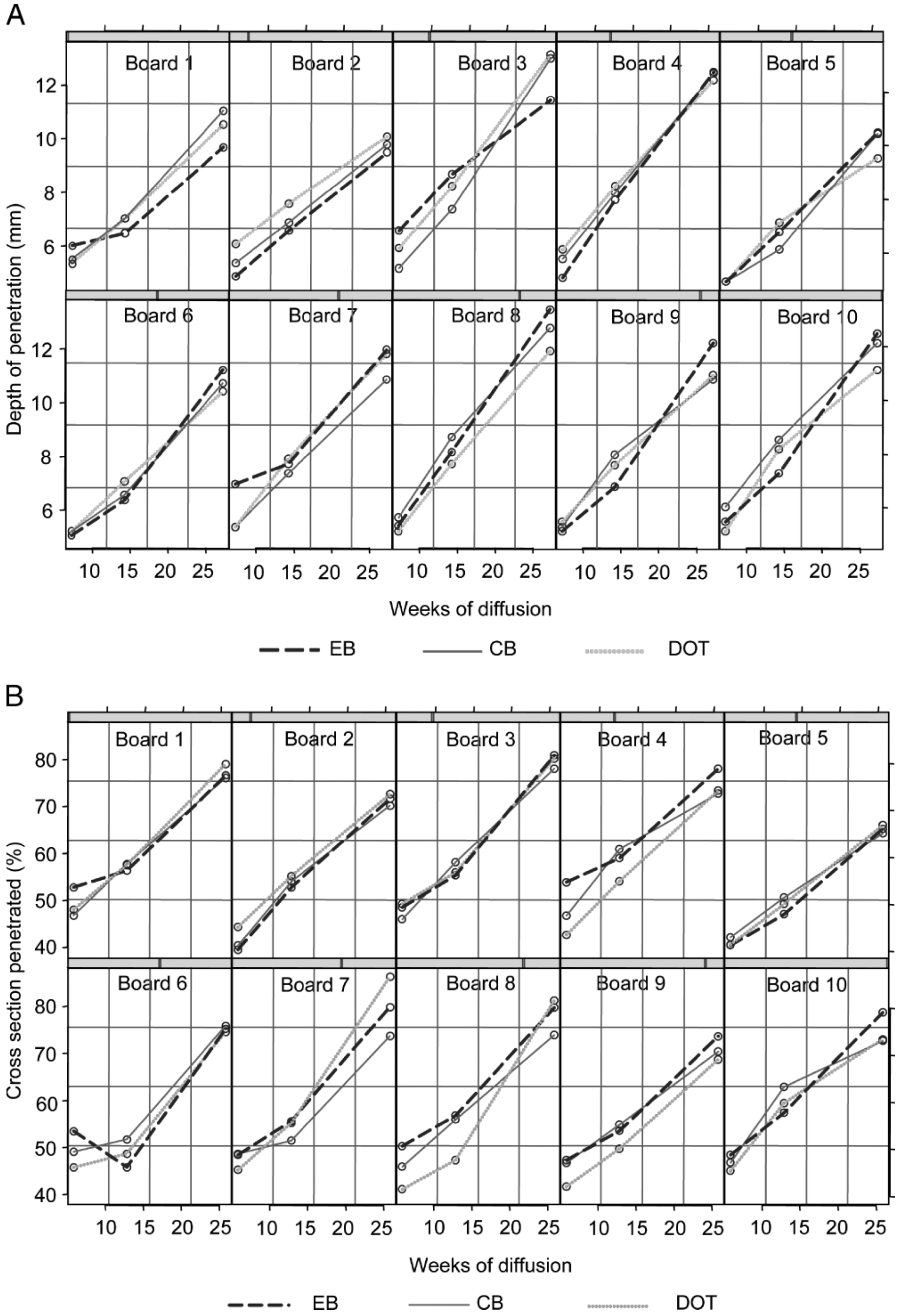

Figure 5.—Depth of penetration (A) and percentage of cross section penetrated (B) vs. weeks of diffusion for specimens cut from each parent board. EB = experimental glycol-borate, CB = commercial glycol-borate, DOT = disodium octaborate tetrahydrate.

saturation point. This study did not attempt to discern the mechanism of boron movement at 20 percent moisture content, but the finding suggests that some portion of water within the wood structure remains in the liquid phase. As noted by Siau (1995), the term *fiber saturation point* is misleading, because both free and bound water are present over a range of moisture contents below this point. 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). 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. Schoeman et al. (1998) reported 6 mm of boron penetration in southern pine specimens dipped in a 5 percent DOT solution and maintained in conditions that produced approximately 25 percent moisture content. Based on specimens exposed in other conditions, they concluded that some diffusion could occur at wood moisture contents as low as 15 percent. In a study of the use of coatings to minimize boron depletion from treated wood exposed outdoors, researchers concluded that boron diffusion, and thus depletion, occurred at moisture contents below 20 percent (Peylo and Willeitner 1995).

No significant difference in extent of penetration was observed among the three types of borate solutions. The characteristics of the parent board from which the specimens were cut did influence borate diffusion, demonstrating the importance of end-matching specimens when making these types of comparisons (Fig. 5).

Discussion

The results of the Phase I and Phase II studies highlight the importance of moisture content in potential boron diffusion for topically applied treatments of framing lumber. Based on this study, it appears that the equilibrium moisture conditions within the structure may have a larger influence on boron diffusion than the moisture content of the wood at the time of treatment. Although boron penetration is likely to be minimal under the conditions used in Phase I of this study (relatively low borate concentrations and rapid drying conditions), the results of Phase II demonstrate that substantial boron diffusion can occur in a higher humidity environment. Glycol-borate applications for structural protection more typically use higher borate concentrations (23% DOT), which potentially drive the borate penetration. In addition, the higher borate concentration is accompanied by higher glycol levels. Glycol has been reported to assist borate penetration in wood at moisture contents near the fiber saturation point (Edlund et al. 1983), although this effect can be variable (Freitag and Morrell 2002). A recent review of moisture contents for in-service wood-frame buildings indicates that most members in most structures have moisture contents below 20 percent (Glass and TenWolde 2007). However, studies have reported moisture contents in excess of 20 percent and even 30 percent in some members at certain times of the year. One example is the vented crawlspaces of air-conditioned homes in warm, humid climates, where the temperature of the floor members can be below the outdoor dew point temperature (Glass and TenWolde 2007). It is unclear how often these high-moisture situations might occur, and they certainly would not represent desirable conditions. Less information is available on the moisture content of building components during and in the first few months after construction, although a study conducted in Canada found that the moisture content of framing lumber was often over 19 percent immediately prior to the installation of insulation, vapor retarders, and drywall (Garrahan et al. 1991). Framing members installed at moisture contents above 19 percent may be slow to dry under conditions of high humidity.

The importance of borate penetration in providing protection of framing members is less clear for termites than for fungi, because there have been few reports of termite damage in structures topically treated with borates, despite their application under a wide range of conditions. 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. Although borate treatments are considered to be nonrepellent, there is evidence that foraging subterranean termites will eventually begin to avoid areas where borate-treated wood is present (Campora and Grace 2007).

Conclusions

Average penetration of boron in specimens placed into simulated wall units following treatment was generally less than 5 mm regardless of treatment solution, target moisture content at time of treatment, or diffusion period. Assay of boron concentrations also indicated that the boron was concentrated in the outer 5 mm of the wood. Diffusion appears to have been limited by the relatively rapid drying of the specimens, which occurred in the low-humidity environment, even with the restricted airflow within the wooden frames. Little difference in diffusion was observed between the types of dip treatments evaluated in this study, although pretreatment with a moldicide did appear to slightly hinder penetration of one of the glycol-borate solutions. Boron penetration was noticeably greater for treated specimens maintained under higher humidity conditions (equilibrium moisture content = 20%). Such high-humidity conditions may be typical of some applications because conditioned air is not provided during construction. After 6 weeks of diffusion, average boron penetration exceeded 5 mm, and after 26 weeks of diffusion, penetration exceeded 11 mm or over 70 percent of the cross section. The extent of boron diffusion in wood conditioned to 20 percent moisture content indicates that diffusion can occur in wood below the fiber saturation point.

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