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Borate and Copper Naphthenate Dual Treatment of Bridge Timbers-Borate movement over time

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ABSTRACT

Preservative treated wooden bridge ties in the South Eastern USA have a service life of about 15 to 20 years, which falls well below the average service life of 40 years of railroad cross ties (sleepers). It has been shown that cross tie life is significantly extended using borate dual treatment and this is now commercialized in bridge timbers using borate inserts. In previous research, it was demonstrated that distribution of disodium octaborate tetrahydrate (DOT) within the wooden bridge ties was dramatically accelerated during Boulton treatment.

The objective of this study was to determine how much diffusion of borate inside the bridge tie after initial treatment occurred over time. Green hardwood bridge ties were ported, borate treated, and then Boulton seasoned and treated with copper naphthenate at a commercial tie treatment plant in Pennsylvania, U.S.A. Retention and location of borate within the wood was tested at 3, 14 and 40 weeks after the treatment. It appeared that borate continued to diffuse inside of the tie and would likely treat and protect a significant volume of the heartwood over time and thus increase bridge tie life in a similar way to crossties.

Keywords: borate**,** bridge timbers, copper naphthenate, DOT, dual treatment, sleepers, ties

1. INTRODUCTION

The versatility and durability as well as cost effectiveness of preservative-treated wood have made it an important engineering material in railroad bridge construction for over 100 years (Uppal and Rizkalla 1992). The service life of bridge ties is a keen interest for railroads because railroad bridges often serve as a bottle neck for the regional railroad systems and thus bridge down-time during bridge tie replacement critically affects overall railroad network logistics. The cost to install a bridge tie is at least ten times that of a standard crosstie even without the cost difference between 30×30×300 cm (10 in.×10 in.×10 ft) or larger bridge tie versus a regular 18×23×258 cm (7 in.×9 in.×8.5 ft) crosstie. The replacement of bridge ties is often less automated and more labor intensive and pose additional safety issues being tens of meters above water or roadways. In addition, because of the bottlenecks and traffic disruption associated with a bridge project, every single bridge tie and guard timber is replaced regardless of their condition, which incurs additional unnecessary costs to a project (Brient 2015). For these reasons, the railroad industry is interested in superior performances.

Traditionally, bridge ties have been treated with creosote and more recently and increasingly with copper naphthenate. Traditional pressure treatment provides protection on the outer 2.5-5 cm (1-2 in.) shells, leaving most of the heartwood unprotected. Increasing creosote retention to increase service life is not feasible because additional preservative per unit volume raises environmental issues such as creosote bleeding/dripping onto roadways, wetlands and waterways.

Due to the broad spectrum of efficacy against all wood destroying organisms, low mammalian toxicity, low cost, and low environmental impact, borates have been used as wood preservatives since the 1940s (Lloyd 1997). Borates are water soluble and mobile in wood above 15% moisture content (Schoeman *et al*. 1997) and this diffusion characteristic enables borate to be used as wood preservatives for specific end uses (Smith and Williams 1967, Freeman 2009). There have been efforts to increase the service life of railroad ties by dual treating them with borate and oil borne preservatives such as creosote or copper naphthenate (Arthur 1967, RTA 2010, Kim *et al*. 2011). Borates in dual treated ties have been shown to penetrate and protect the otherwise untreated interior against wood-destroying organisms and protect wood around spikes from corrosion induced decay (Amburgey *et al*. 2003, Amburgey and Sanders 2009, RTA 2010). Dual-treatment is especially effective on ties containing a large portion of heartwood and hard-to-treat wood species such as white oak and hickory (Kim *et al*. 2011, Zeta Tech 2011). In addition, borate treatment on green or partially seasoned ties protects wood from incipient decay during storage and seasoning (Schoeman *et al.* 1997), which can otherwise lose strength from decay (Wilcox 1978, Taylor *et al*. 2013).

Currently, dual treatments with DOT and other borates have been widely commercialized in the USA for crossties. However, the benefits of dual treatment would be even more beneficial for the larger and more expensive hardwood bridge ties and timbers. Due to their size, they are more difficult to treat and leave more untreated volume than regular crossties, which make them more vulnerable to decay and a reduced service life. Hardwood bridge ties and timbers are treated from ‘green’ wood of high moisture content and so need to be Boulton conditioned. This makes the current dual treatment methods impractical because it is difficult to achieve adequate preservative retentions and penetrations of either preservative systems (the borate or the oil-borne treatment) by diffusion or pressure treatment (Taylor *et al*. 2013). Therefore, many research efforts have been focused on remedial or supplemental treatment for wood and wood products including bridge timbers and ties (Barnes *et al*. 2011, Wacker and Crawford 2003, Morrell *et al*. 1996, DeGroot *et al*. 2000, Ritter 1990, Lloyd *et al*. 1999). Insertion of diffusible wood preservatives such as borate through injection ports in wood has been well practiced as a remedial treatment of wood (Edlund *et al*. 1983, Dietz and Schmidt 1988, Dirol 1988, McCarthy *et al*. 1993, Dickinson 1990, DeGroot and Felton 1998, Grace and Yamamoto 1994).

To effectively deliver borate inside bridge ties and timbers, Lloyd *et al*. (2014) inserted high concentration DOT liquid through a series of holes (ports) in the hardwood bridge ties and subsequently Boulton treated with copper naphthenate. The result gave good DOT retention and penetration during the Boulton seasoning and preservative treatment. The objective of the current study is to determine the effect of time and species on on-going diffusion of DOT in the bridge ties treated in this way.

2. EXPERIMENTAL METHODS

Four timber species were selected for the test: sweetgum (*Liquidambar styraciflua*); white oak (*Quercus alba*); red oak (Quercus rubra); and hickory (*Carya spp*.). The size of each tie was 25 ×25×300 cm (10 in.×10 in.×10 ft). Drilling patterns for the delivery of DOT were as follows:

Drilling pattern 1 (3 week old gum, white oak and hickory): Two 5.1 cm diameter × 15.2 cm deep (2 in. diameter × 6 in. deep) holes about 61 cm (2 ft) apart from each other and 90 cm (3 ft) away from the end (Fig. 1A). Holes were filled with 45% DOT solution and capped with specially designed caps/plugs.

Drilling pattern 2 (14 week old red oak, white oak): Two 5.1 cm diameter × 15.2 cm deep (2 in. diameter × 6 in. deep) holes about 122 cm (4 ft) apart from each other and 90 cm (3 ft) away from the end (Fig. 1B). Holes were filled with 45% DOT solution and capped.

Drilling pattern 3 (40 week old red oak, white oak, 14 and 40 week old gum and hickory): One 5.1 cm diameter × 15.2 cm deep (2 in. diameter × 6 in. deep) hole at the center of a tie. The hole was filled with 45% DOT solution to 12.7 cm (5 in.) depth and capped.

For all three drilling patterns, 334 g of 45% DOT solution was applied per hole. The bridge ties with borate treated holes were Boulton conditioned and then pressure treated at 88 °C (190 °F) in copper naphthenate (obtained commercially as QNAP from Nisus Corporation) solution diluted with No. 2 fuel oil to 0.8% Cu, meeting AWPA Standard HSA-14. Total charge time was 18 hrs. Ties and the holes were inspected after the treatment.

All the ties were placed in the outside in East Tennessee (Nisus Corporation located Rockford, TN) for various time periods. The average temperature ranges from 19 (67) to 31 (88) °C (°F) in July and -2.8 (27) to 7.8 (46) °C (°F) in January and mean annual temperature is 15°C (59 °F). The annual rainfall was 1223 mm (48.18 in). Rockford is located in Decay Hazard Zone 4 and the decay hazard (Sheffer) index in Knoxville, TN, located 24 km (15 miles) north of Rockford, TN was 67.6 (Carll 2009).

After three weeks, ties with drilling pattern 1 were cut cross-wise to a 120-150 cm (4-5 ft) section containing two holes, and then in a longitudinal direction using a Wood Mizer band saw (through the hole) to reveal a pair of fresh surface. Other ties (drilling pattern 2 and 3) were exposed for 14 and 40 weeks and then rip-sawn in half in longitudinal direction. The diffusion of borate from the holes was examined by applying curcumin/salicylic acid on the freshly cut surfaces (Smith and Williams 1969, AWPA A78-12). One of the longitudinally cut tie pieces was further cut into series of cross sections to reveal fresh cross sectional surfaces using a Wood-Mizer band saw. For the ties with drilling pattern 1, the tie piece was cut in 1.3, 6.4 or 15.2 cm thick (0.5, 2.5, or 6 in.) sections (Fig. 1 A). For the ties with drilling pattern 2 and 3, the tie piece was cut in 1.3 or 6.4 cm thick (0.5 or 2.5 in.) sections (Fig. 1 B and C). Between each cut, the saw was cleaned by cutting fresh wood that does not contain DOT.

For each cross-sectional specimen, one freshly cross cut surface was curcumin/salicylic acid tested to check borate presence. (AWPA A78-12). The curcumin/salicylic acid indicator solution can change the yellow color of curcumin solution into red to magenta when the retention of DOT in wood is greater than 0.8 kg/m^3. Each cross-sectional specimen after curcumin/salicylic acid test was photographed and the borate penetrated area was manually outlined using Image J digital image analysis software to calculate the percentage of cross-sectional area affected by borate (Version 1.32j, US National Institute of Health, Bethesda, Maryland-; Rasband 2004). The 1.3 cm

(0.5 in.) sections were further knife-milled for DOT extraction and subsequent quantification using inductively coupled plasma optical emission spectrometry (ICP-OES) following AWPA A21-16.

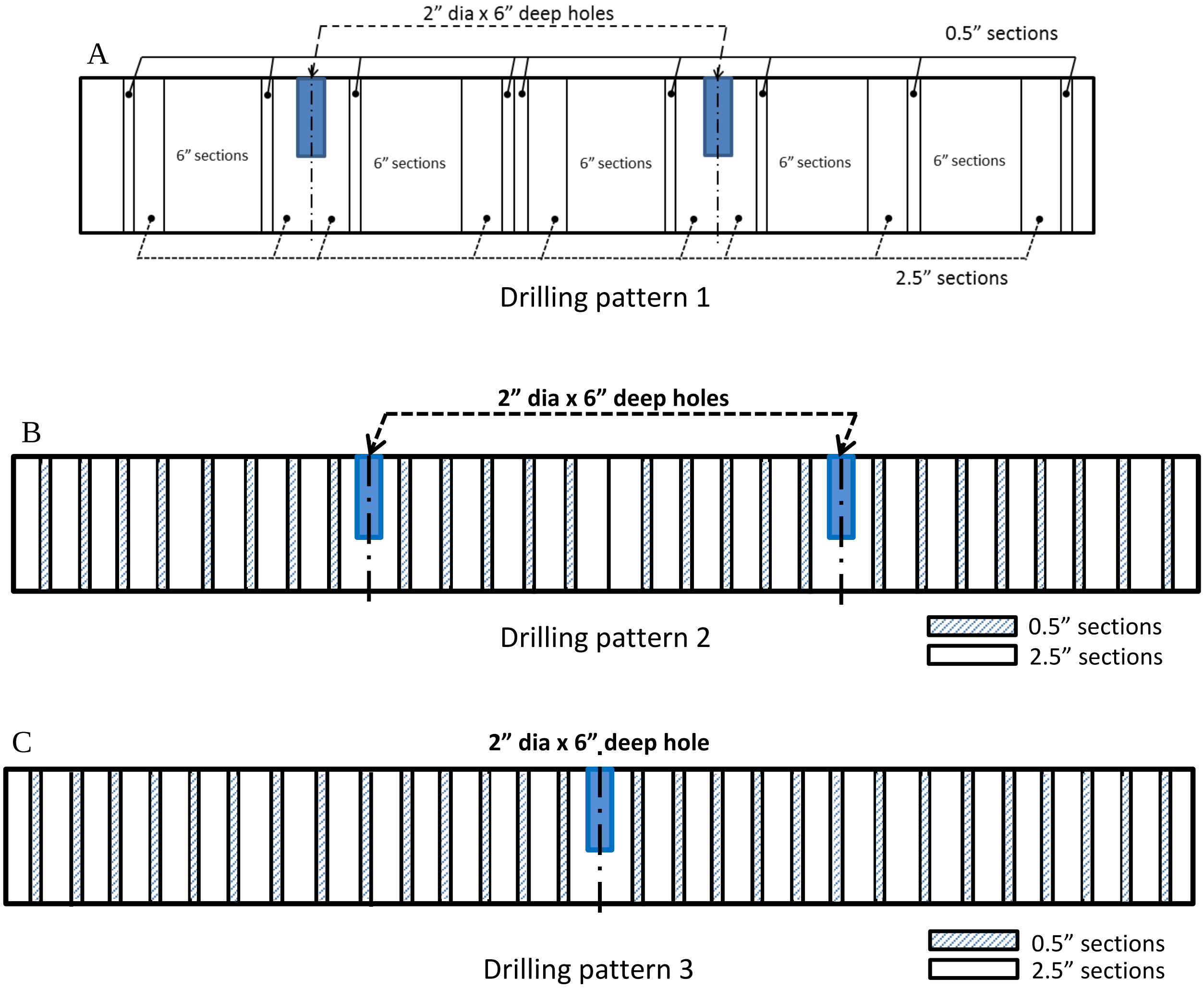


Figure 1: Diagram of treated bridge ties showing various drilling patterns and cross-cut sections used for curcumin/salicylic acid and chemical analysis by extraction and ICP-OES.

3. RESULTS AND DISCUSSION

The freshly cut longitudinal surfaces of the bridge ties after Boulton conditioning and copper naphthenate treatment are shown in Fig. 2. Most of the holes were dry and empty with slight signs of DOT residue, suggesting most of liquid DOT in the holes had diffused into the tie (Fig. 2 A and B). For some bridge ties, undispersed liquid DOT residue was observed inside of the holes (Fig. 2 C).

Figure 2: Freshly cut surfaces of bridge ties after 14 (A) and 40 (B) weeks of the treatment. Some residual liquid borate was found inside of the hole (C) while no liquid borate was found in the all 40-week-old ties (B).

The freshly cut longitudinal surfaces were cleaned and dried for several days before spraying with curcumin/salicylic acid indicator. Figures 3 to 5 showed the curcumin/salicylic acid tested surfaces of the 3-, 14- and 40-week-old ties. The 3-week-old ties shown in the Fig 3 are half length parts of the whole ties containing the holes. All the ties clearly showed longitudinal as well as transverse movement of borate. For some ties, the longitudinal movement of borate appeared to cover the entire tie length. Movement of the borate in heartwood of white oak and hickory appeared as good as or better than gum heartwood. It also appeared that checks and cracks especially, the centre ‘heart checks’ or pith in the tie, serve as a pathway to transport borate away from the hole in a tie especially in the longitudinal direction. For the 40-week-old gum tie (Fig. 5), where there was no visible checks connected to the hole, the borate movement was limited compared to other ties. The elevated temperature and steam generated during the Boulton cycle and following preservative treatment would also enhance the diffusion of borate.

Figure 3: Presence of DOT (red) in freshly cut bridge ties tested 3 weeks after Boulton conditioning and treatment in copper naphthenate.

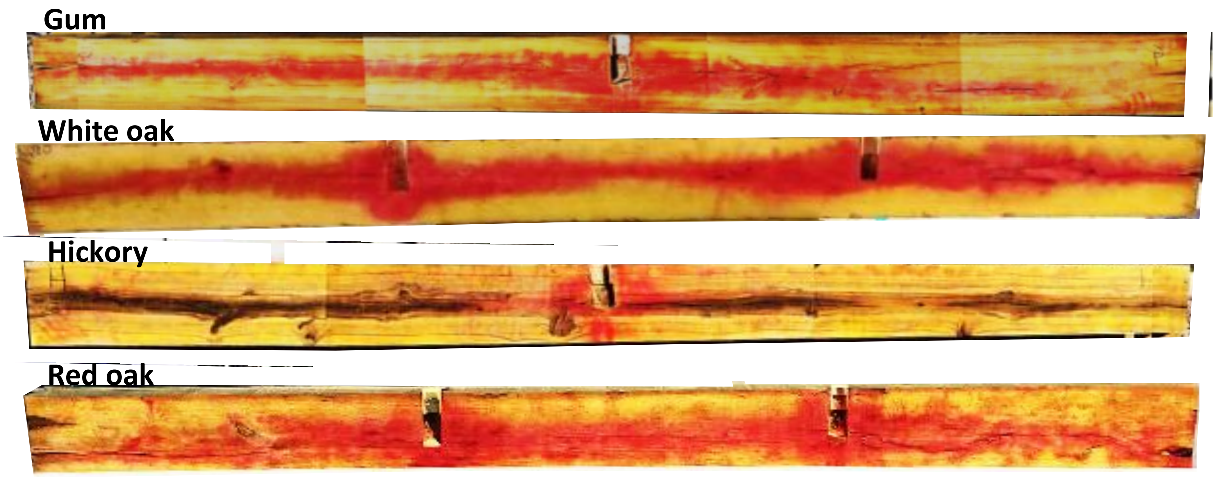
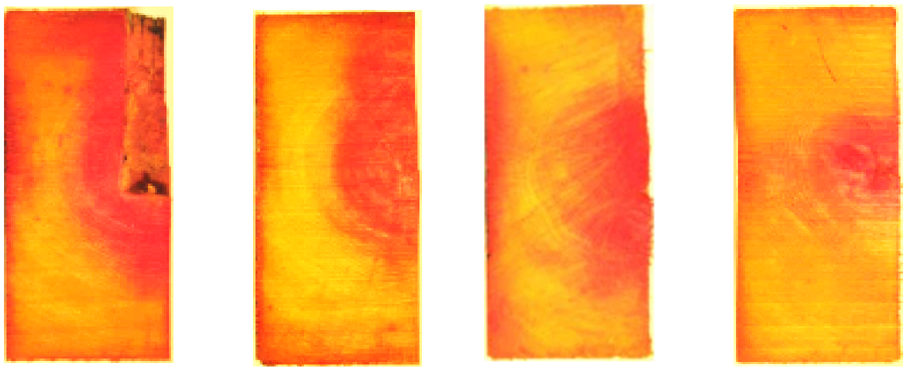


Figure 4: Presence of DOT (red) in freshly cut bridge ties tested 14 weeks after Boulton conditioning and treatment in copper naphthenate (some pictures are composites from 90-120 cm tie sections).

Figure 5: Presence of DOT (red) in freshly cut bridge ties tested 40 weeks after Boulton conditioning and treatment in copper naphthenate.

In addition to the longitudinal surface, curcumin/salicylic acid test was also performed on freshly cut cross-sectional surfaces. Fig. 6 shows curcumin/salicylic acid test on a series of cross-sectional surfaces of the 14-week-old white oak tie, sampled varying distances from the center of the injection port. Clearly, borate diffused in the transverse direction as well as longitudinal direction. The movement of borate appears much greater in the longitudinal direction than in the transverse direction.



0 cm | 6cm | 31cm | 46cm

Figure 6: Cross-sectional surfaces of 14-week-old white oak ties tested with curcumin/salicylic acid. Numbers are distance from the center of the hole.

The longitudinal as well as transverse movement of borate in some species was much greater than others. Species dependency of borate movement from injection port was also reported (DeGroot and Felton 1998). In addition, Williams (1991) also suggested that there is an inverse relationship between the density of wood and the rate of diffusion. The differences in borate movement in this study could be due to the difference in density and/or the internal structure such as heart checks which serves as a pathway for borate movement. The transportation of borate through the checks appeared greater than that of borate through diffusion alone.

From the curcumin/salicylic acid test, it appeared that longer storage time does not always result in better diffusion of borate, as the initial movement during Boulton drying is so good. For example, longitudinal movement of borate in the 14-week-old hickory tie did not appear to be better than the 3-week-old hickory tie. Similarly, movement of borate in the 40-week-old gum tie appeared less than the 14-week-old gum tie. In fact, no visible defects were found at the freshly cut longitudinal surface of the 40-week-old gum tie while the 14-week-old gum tie had visible heart checks and clearly showed the presence of borate. This clearly suggested that heart checks served as a channel for the borate movement in longitudinal direction and the majority of movement occurred during the Boulton conditioning and treatment.

The movement of borate in the transverse direction was also observed (Fig. 6). Again, it appeared that small checks and cracks play an important role in the movement of borate in the transverse direction. As expected, the area treated with borate on the freshly cut cross-sectional surface appeared to be decreased as the distance from the hole increased.

Figures 7 to 9 show the DOT assay retention of the tie sections by ICP-OES method (AWPA A21-16). As expected, the DOT retention was highest at the sections containing the hole and decreased as the distance from the hole increased. The DOT retention of the sections containing the hole appeared to decrease with time, suggesting the DOT may have diffused into the wood. However, it was difficult to determine any species effect on borate diffusion from the chemical analysis. For the 40-week-old ties, DOT retention of the red oak and hickory around the hole was relatively low. Some of the DOT may be lost during Boulton and pressure treatment or while preparing samples as shown in Fig. 2C. Although the scope of work here is very large, unfortunately, there are still relatively few replicates.

In Fig. 8, the white oak tie, which had two holes, had a higher DOT retention over time than red oak, and higher than other species which had only one hole.

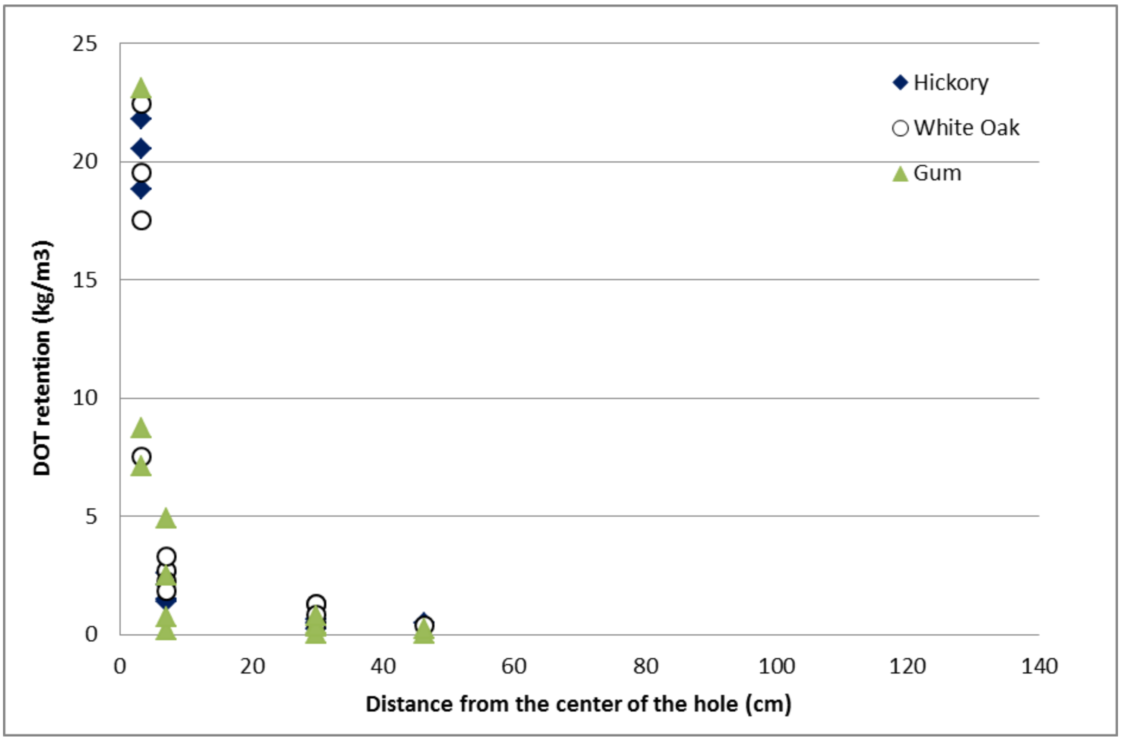


Figure 7: DOT assay retention of bridge tie pieces 3 weeks after the treatment.

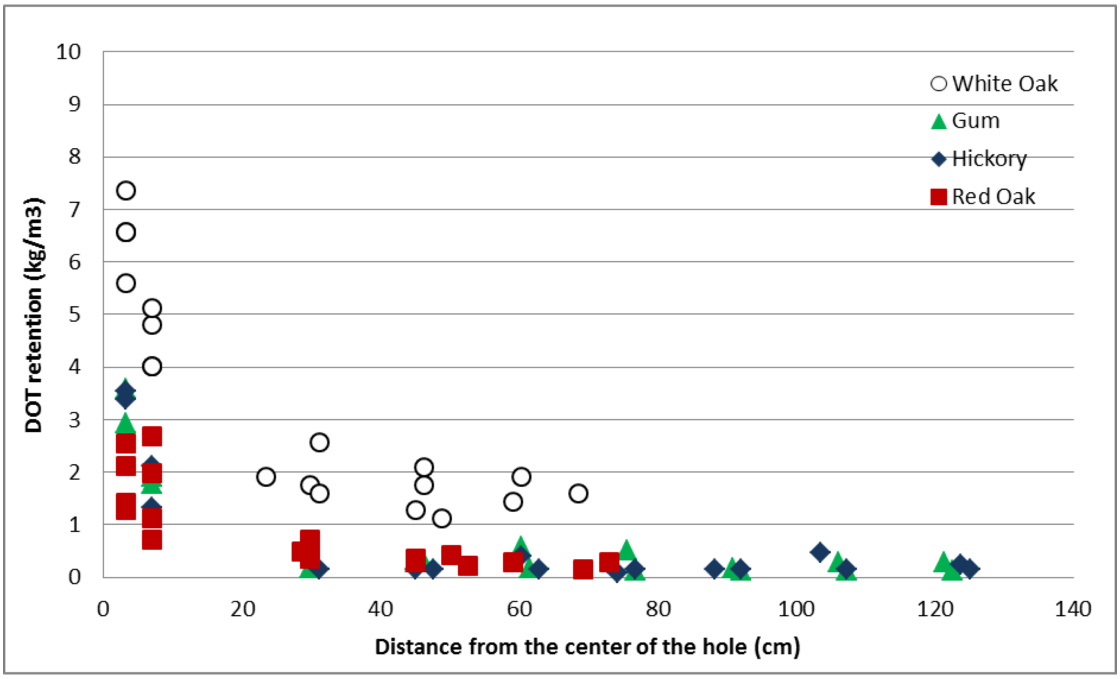


Figure 8: DOT assay retention of bridge tie pieces 14 weeks after the treatment.

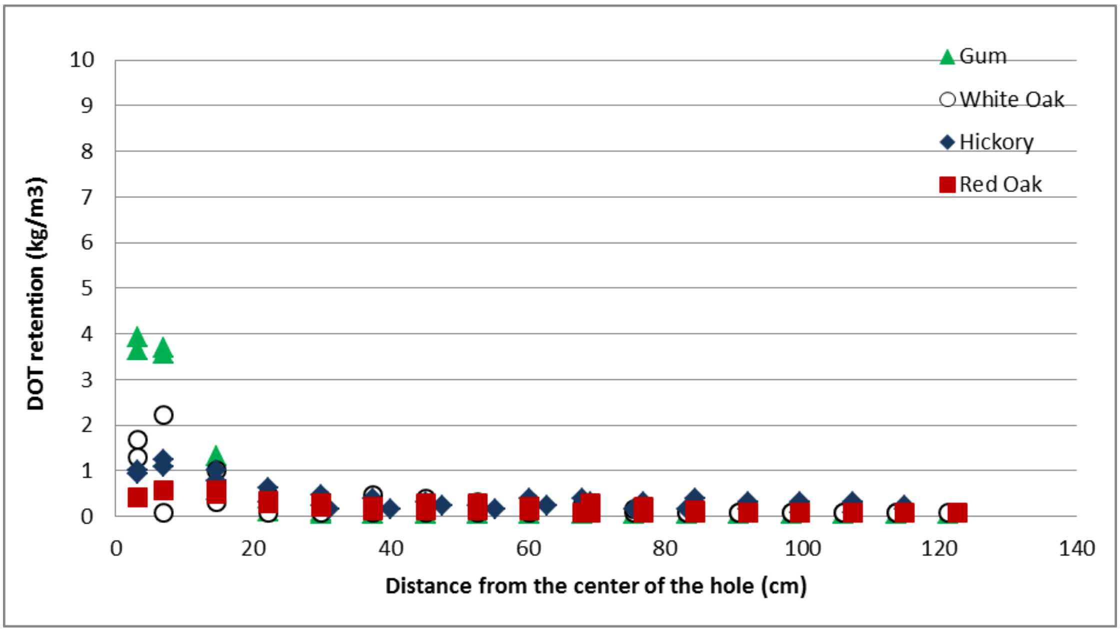


Figure 9: DOT assay retention of bridge tie pieces 40 weeks after the treatment.

From the DOT retention data at a given storage time, an exponential function was used to fit the retention vs distance from the hole of all species using the Eq. 1. The best fit exponent curve functions were obtained by least squares approximation. The DOT retention *C* was expressed as a function of distance *x* and parameters u_0,u_1, and y_0 (Eq. 1).

$$C(x) = y_0 + \exp\ (u_0 + u_1 x) \qquad \text{(Eq. 1)}$$

The r^2 value of the curves ranged from 0.6 to 0.97. Figure 10 shows fitting curves for the average DOT retention over time for all species. For the 3-week-old ties, the DOT retention decreased significantly up to 10 cm from the center of the hole. The DOT retention of the 14 wks old ties with two holes were higher than those ties with one hole. For the ties with two holes, the DOT retention of the 14- week-old had a lower DOT retention up to 10 cm from the hole than that of 3-wks old ties but the DOT retention of the 14-wks old ties were higher after 10 cm than the 3-week-old ties suggesting movement of the DOT with time. A similar trend was also observed for the ties with one hole; DOT retention of the 40-wks old ties had lower retention up to 10 cm from the hole than that of 14-wks old ties but DOT retention of the 14-wks old ties were higher after 10 cm than the 14-wks old ties.

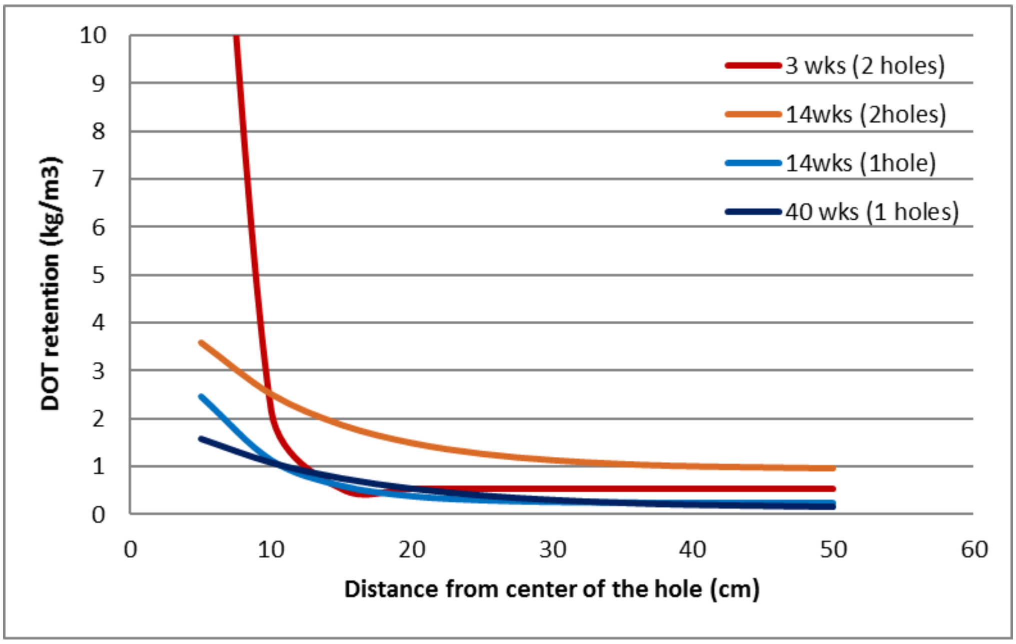


Figure 10: Fitted curves from Eq 1 and DOT assay retention data.

Fig. 11 shows the 14-week-old white oak tie after the curcumin/salicylic acid test on the longitudinal surface and corresponding DOT retention obtained from selected cross-sections along the length. Table 1 shows the curcumin/salicylic acid test results on selected cross-sectional surfaces, DOT retention and percentage of the cross-sectional area penetrated with borate. The borate retention and percentage of cross-sectional area were in good agreement.

Fig 12 shows the 40-week-old white oak tie after curcumin/salicylic acid test on longitudinal surface and corresponding DOT retention obtained from selected cross-sections along the length. The curcumin/salicylic acid test on both longitudinal- and cross-sectional surfaces showed that the right half (E, F, G, and H) of the tie had more borate (red) than the left half (A, B, C, and D). The DOT retention data exactly matches with the curcumin test data indicating higher DOT retention in the right half of the tie. Table 2 shows the curcumin/salicylic acid test results on selected cross-sectional surfaces, DOT retention and the percentage of the cross-sectional area penetrated with borate.

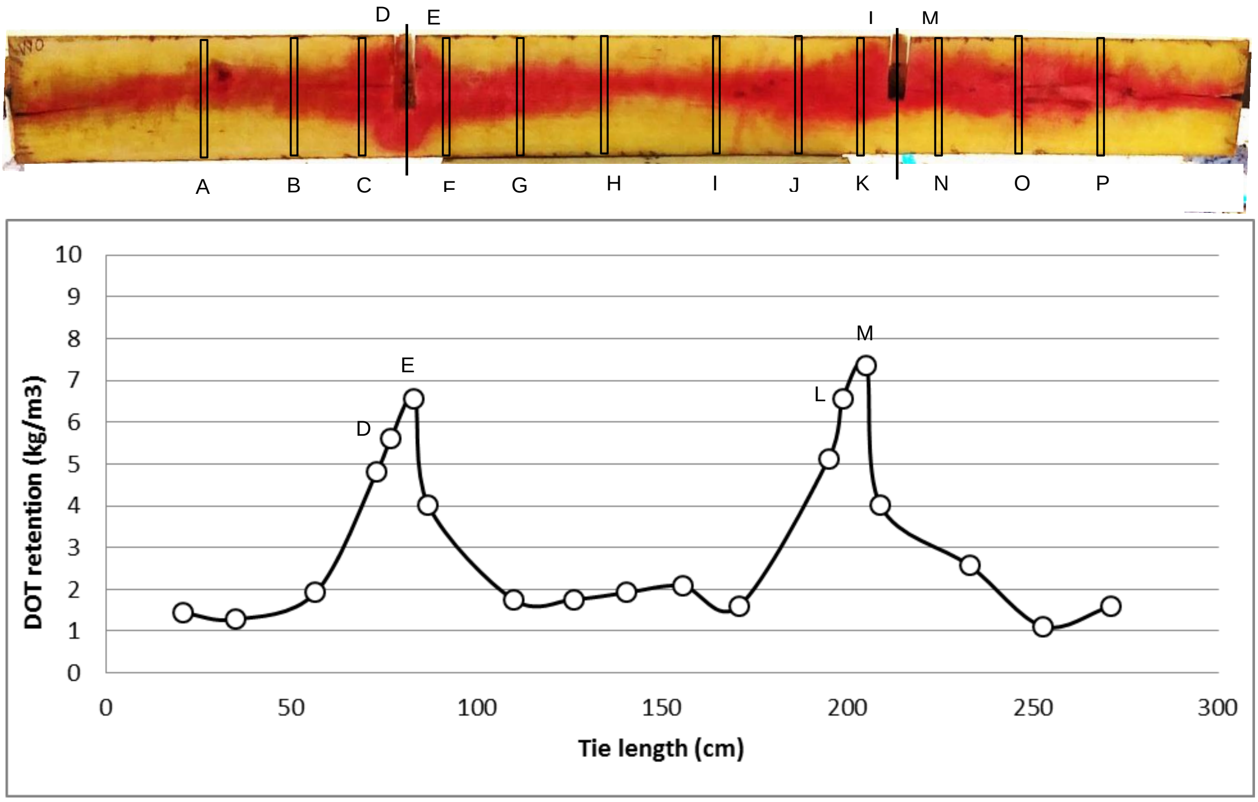
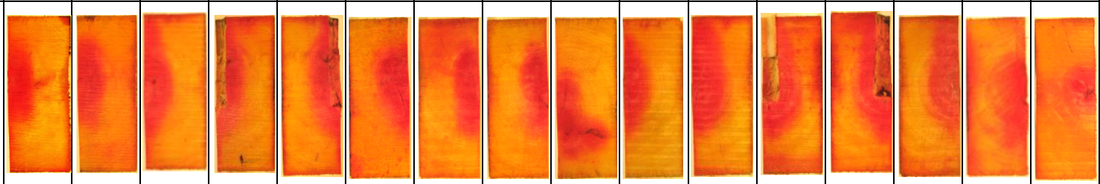
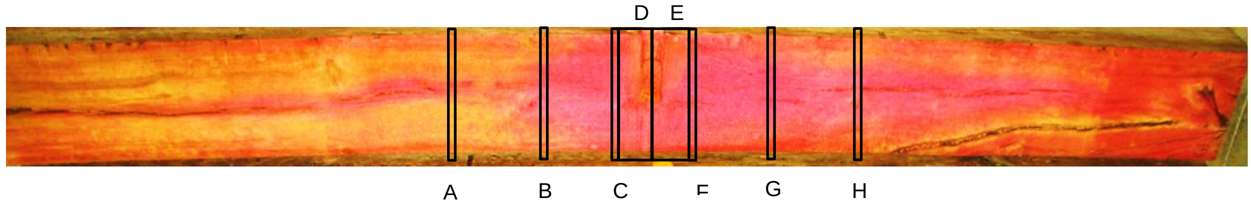


Figure 11: Curcumin/salicylic acid test on the longitudinal surface of the 14-week old white oak tie sample and corresponding assay retentions from sections.

Table 1: Curcumin/salicylic acid test on cross-sectional surfaces of the 14-week old white oak tie samples. DOT retention and percentage of the cross-sectional area penetrated with borate are presented.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Distance [cm]	45	31	6	0	0	6	31	45	45	31	6	0	0	6	31	45
																
DOT Retention [kg/m^3]	1.3	1.9	4.8	5.6	6.6	4.0	1.8	1.8	2.1	1.6	5.1	6.6	7.4	4.0	2.6	1.1
%area[%]	21	22	28	30	32	28	17	25	33	22	34	39	41	30	24	13



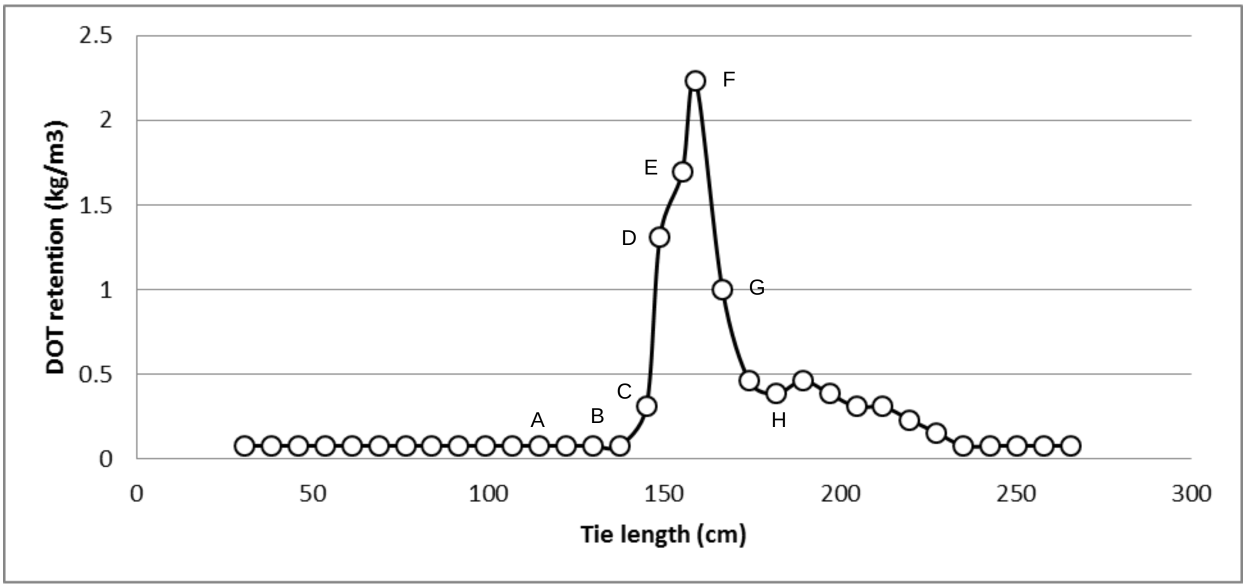


Figure 12: Curcumin/salicylic acid results on the longitudinal surface of the 40 week old white oak tie sample and corresponding assay retentions from sections.

Table 2: Curcumin/salicylic acid results on the cross-sectional surface of the 40-week-old white oak tie sample. DOT retention and the percentage of the cross sectional area penetrated with borate are presented.

	A	B	C	D	E	F	G	H
Distance [cm]	45	31	6	0	0	6	31	45
								
DOT Retention [kg/m^3]	0.08	0.08	0.31	1.31	1.69	2.23	0.38	0.38
%area[%]	0	0.5	28	39	41	35	14	14

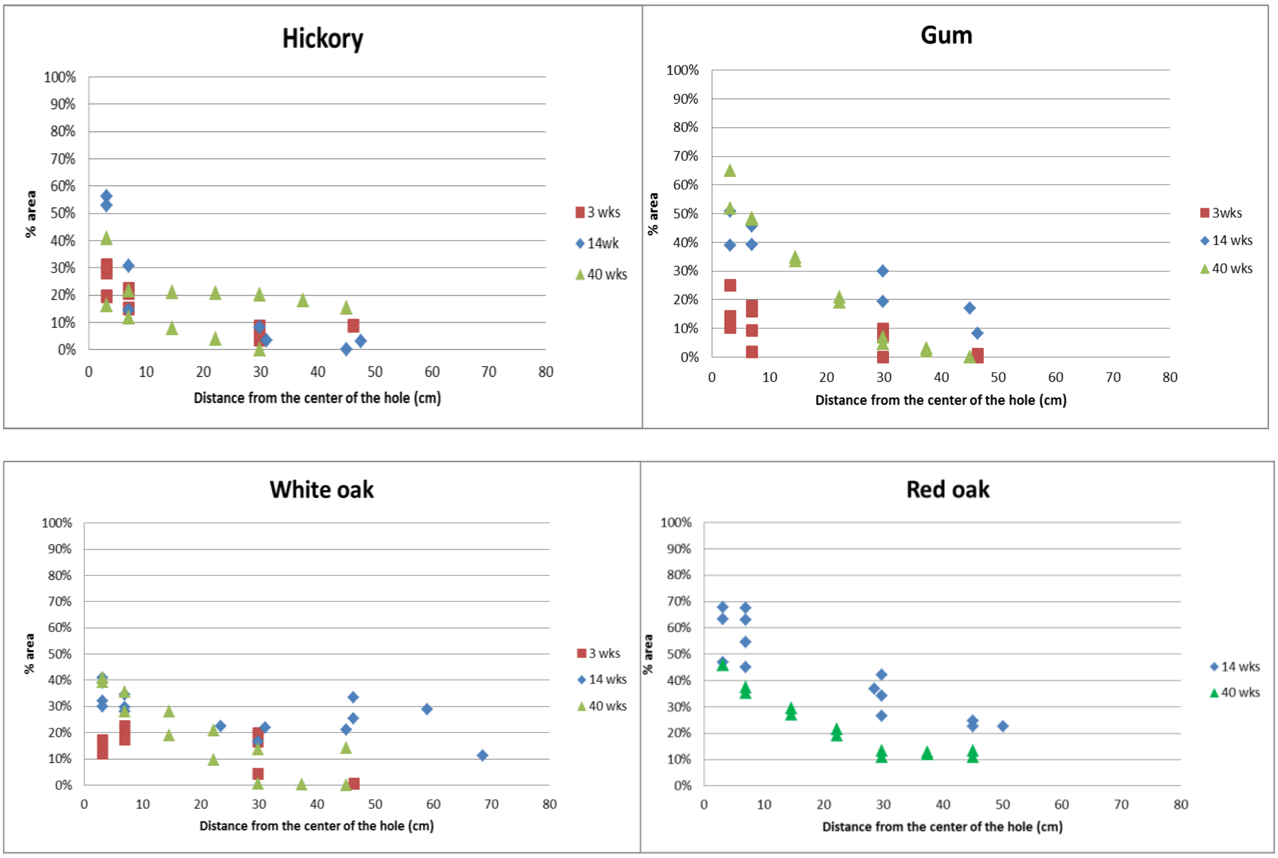


Figure 13: Percentage of the cross-sectional area treated with borate at different distances from the hole.

Fig. 13 shows the percentages of the cross sectional area penetrated with borate after curcumin/salicylic acid test. In general, the percentage area decreased with increasing distance from the center of the hole. For gum, it appeared that near the center of the hole, the percent area tended to increase with time. This could suggest that near the hole, where borate concentration is high, borate was more readily diffused into wood with time and thus increased the percent area. This would agree with Fick’s law and shows that diffusion is concentration driven.

Fig. 14 shows the relationship between the percentage of the cross sectional area penetrated with borate after curcumin/salicylic acid test and DOT retention. The high DOT retention but low percent area of the 3-week-old ties was because little DOT had diffused into the wood and a large portion of DOT remained concentrated close to the holes. As the exposure time increased, the DOT retention around a hole tended to decrease but the percent area was increased suggesting DOT is diffusing into the wood with time affecting more volume of wood as expected. In other words, at a given retention, the percent area increased with time, due to diffusion.

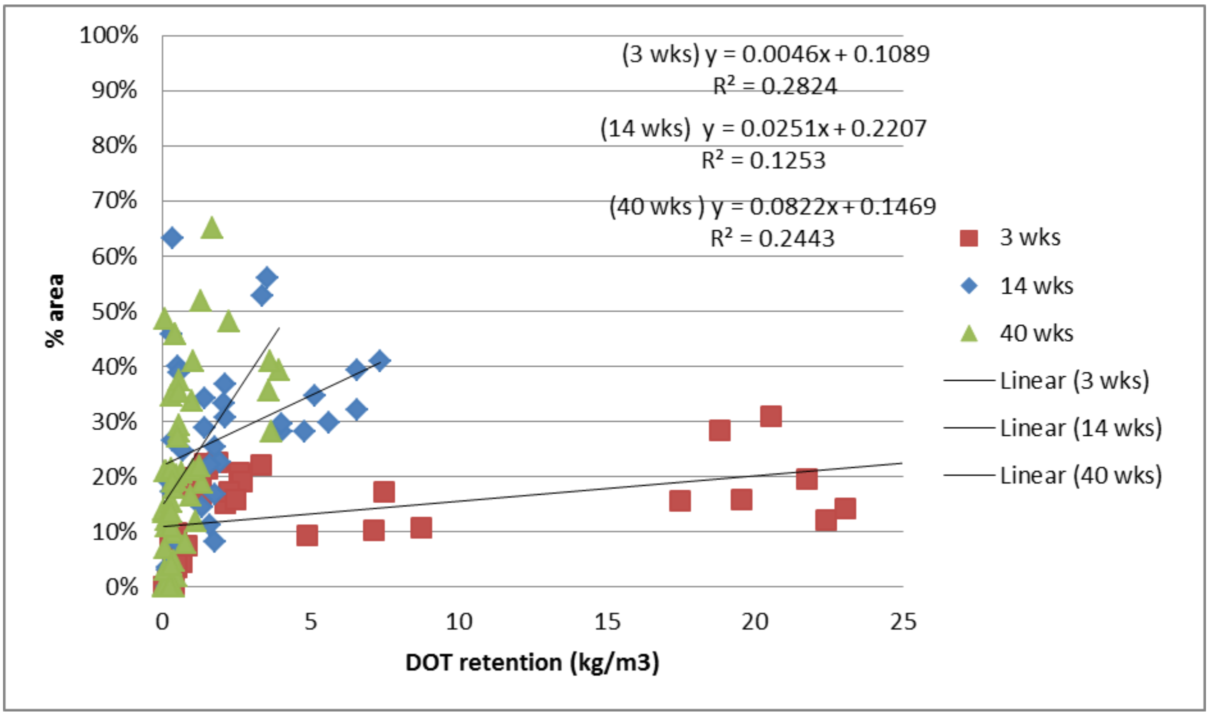


Figure 14: Percentage of the cross sectional area penetrated with borate at different distances from the hole.

Table 3: Percentage to the maximum retention of whole bridge ties estimated from the fit curve.

Species	Percentage to the maximum retention (%)		
	3 weeks	14 weeks	40 weeks
Gum	>100	57	51
Hickory	>100*	52	45
White Oak	>100*	>100*	31
Red Oak	N/A	41*	23
Average	>100	63	38

*: bridge ties with two holes.
Numbers in the parentheses are percentage of maximum achievable retention based on the amount of applied DOT.

Table 3 is a summary of the percentage of estimated overall retentions from the fitted equations of all ties tested to the maximum achievable DOT retention. The maximum achievable DOT retention was 0.76 kg/m^3 for the ties with one hole and 1.52 kg/m^3 for the ties with two holes, provided that all DOT solution applied had diffused into wood. *N.B.* the toxic threshold is 0.76 kg/m^3 (Lloyd 1997). At 3 weeks, the average retention of all species was over 100% of maximum retention due to the overestimation of DOT retention by the fit curve near the injection ports. It appeared that the retention tended to decrease with time. It was difficult to directly compare the retention of the ties with two ports to one. The data suggested that over the period of 37 weeks of outdoor exposure, not much if any of the DOT was lost but about half the borate is unaccounted for. The leaching of borate in dual treated ties depends on initial borate retention, geographical location, and species (Lloyd 1995). In one study, about 40-60% of borate in the dual treated tie leached out after one year (Lloyd 2004). The borate leaching in the ties treated with ports appears much less than conventionally dual treated ties probably because the concentration gradient is reversed from high surface to low center, to high center and low surface retention.

Table 4: Average percentage borate-treated area (cross sectional area that changed to red after curcumin salicylic acid test divided by total cross sectional area of the section) of the sections cut from the center of the hole. Numbers in the parentheses are the average of DOT retention (kg/m^3) of the same sections that contain the hole.

Species	Average percent area [%]and DOT assay retention [kg/m^3] at the port		
	3 weeks	14 weeks	40 weeks
Gum	15.2 (19.1)*	44.9 (3.26)	58.3 (3.78)
Hickory	27.3 (22.5)*	54.4 (3.45)	28.6 (0.98)
White Oak	15.1 (16.7)*	35.0 (6.52)*	40.0 (1.50)
Red Oak	N/A	57.1 (1.83)*	45.9 (0.42)
Average	19.2 (19.4)	44.8 (3.77)	43.1 (1.67)

*: bridge ties with two holes.

Table 4 shows the average percent of the cross-sectional area that changed to red color after curcumin salicylic acid test on the sections taken at the center of the hole. Numbers in parentheses are the average of DOT retention of the sections that contain the hole. For all species tested except red oak, the average percentage area measured at 14 weeks was increased compared to that of the 3-week-old ties. However, the average percent area of hickory and red oak measured at 40 weeks was decreased compared to that of the 14-week-old ties. The average retention of the samples decreased over time. Again, there are not enough replicates.

The volume in the ties penetrated by borate was estimated based on the percent area data. These values were calculated by considering the percentage area from curcumin/salicylic acid test on a cross sectional sample and the dimension of that section. The main assumption is that for a given cross sectional sample, the percent area measured at the surface is the same through the thickness. For the sections that are not curcumin/salicylic acid tested but positioned between the tested samples, percent area was estimated by interpolating between tested samples. The treated volume is smaller than the volume that actually would provide protection against fungi and insect because the color change by curcumin/salicylic acid test occurs above 0.8 kg/m^3 of DOT, which is at or above the toxic threshold of decay fungi, which is at 0.76 kg/m^3 for white rot fungi and 0.59 kg/m^3 for brown rot fungi according to EN113 (Lloyd 1997).

Table 5: Potential volume penetrated by borate as shown by curcumin/salicylic acid results.

Time	Average percent of the estimated volume penetrated by borate (%)	
	1 port	2 ports
3 wks	N/A	7
14 wks	9	28
40 wks	7	N/A

4. CONCLUSIONS

From the results obtained it can be seen that good DOT distribution can be achieved by treating via ports drilled in bridge ties and large timbers immediately after the Boulton treatment. It appeared that the Boulton treatment in copper naphthenate dramatically enhanced DOT distribution from these ports. Distribution of borate inside the tie appeared to be extensive in the longitudinal direction and also occurred in the radial and tangential directions the latter probably via traditional diffusion, the former probably by mass flow of the borate carried in the escaping steam. It is inferred that the penetration of DOT was largely driven by transportation of liquid DOT through the checks inside of wood and diffusion which was enhanced by the elevated temperature and steam generation during the Boulton cycle (steam is generated due to the combination of elevated temperature and vacuum used in Boulton conditioning).

Cross-sectional curcumin/salicylic acid results confirm that diffusion of DOT occurs in longitudinal and transverse directions over time. The DOT retention within the wood at various distances from treatment ports also confirmed the curcumin qualitative results. It is anticipated that DOT in the tie will diffuse further and re-distribute within the timber in service although this is slow and initial borate distribution appears critical. The DOT loss is smaller compared to ties treated with conventional pressure treatment or dip diffusion method (e.g. compared to that shown by Smith and Williams, 1969). This is because surface borate concentration in this tie is low to zero at the time the bridge ties would go into service and all of the concentration to drive diffusion (or leaching) is within the centre of the tie. However, about 50% is unaccounted for explain.

The results suggest that hardwood ties can be successfully treated with dual treatment technology using DOT in ports and copper naphthenate Boulton treatment. It can be seen that the DOT in the heartwood of these large dimensional timbers diffuse into wood with time. Combining results from this study with those of tie life extension demonstrated by Amburgey and Sanders (2009) it can be concluded that the longevity of bridge ties in service will be dramatically improved, (possibly doubled), and it is hoped that this will allow the continued and effective use of sustainable hardwood bridge ties. *N.B.* similar results have now also been confirmed with Boulton treatment in creosote but are not reported here.

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