HIGH AIR VELOCITY AND RELATIVE HUMIDITY REDUCE DEVELOPMENT OF KILN BROWN STAIN IN *PINUS RADIATA*

B. KREBER, A.N. HASLETT, and M. G. C. NORRIS

New Zealand Forest Research Institute,
Private Bag 3020, Rotorua, New Zealand

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ABSTRACT

Kiln drying of *Pinus radiata* D. Don sapwood causes the development of a brown subsurface coloration, commonly called kiln brown stain. Planing exposes the stain and this can spoil one of the appealing features of *P. radiata*—its light colour.

Kiln schedule modifications—for example, drying with low kiln temperatures—reduced the frequency and intensity of kiln brown stain but increased drying times. An attempt was made to shorten drying times and produce an acceptable colour in the dried lumber by using high air velocities as well as high relative kiln humidities in conjunction with medium kiln temperatures. Depth (below the wood surface) and thickness of kiln brown stain were also determined in the dried *P. radiata*.

Using stepped kiln schedules with either high air velocities or high relative humidity reduced development of kiln brown stain compared to accelerated conventional temperature 90°/60°C drying, but considerably longer drying times were needed. Furthermore, stain formed about 0.5 mm underneath the surface with a thickness of up to 2 mm. The best method for countering the effect of kiln brown stain would be to plane 2 mm off the surface of kiln-dried lumber during remanufacturing.

Keywords: kiln brown stain; drying time; air velocity; relative humidity; *Pinus radiata*.

INTRODUCTION

A chocolate-brown discoloration, hereafter referred to as kiln brown stain, is regularly observed after *P. radiata* sapwood is dried at temperatures over 80°C. Kiln brown stain is not restricted to specific clones of *P. radiata* and is also common after drying *P. radiata* in Australia and Chile (Kreber, McDonald, Haslett unpubl. data). Brown discolorations have been reported also in North American pines (Millet 1952; Stutz 1959; Cech 1966; Schmidt *et al.* 1995) and other softwood species (Miller *et al.* 1983; Avramidis *et al.* 1993; Kreber & Byrne 1994). Although kiln brown stain develops underneath the wood surface, skim-dressing exposes the stain during subsequent remanufacturing. This disfigures the natural light colour of *P. radiata*, and has caused substantial loss in revenues for New Zealand's high-value lumber exporters (Laytner 1994; McLean 1995).

In investigations of the chemistry of kiln brown stain, potential stain precursors were isolated from *P. radiata* (McDonald *et al.* 1997). Detailed chemical analysis showed that kiln brown stain develops because of a thermo-chemical reaction involving low molecular weight sugar- and nitrogen-containing compounds (McDonald *et al.* in prep.). Further parallel research provided strong evidence that translocation and accumulation of such compounds occurred during kiln drying which resulted in a concentration gradient from the inside to the outside of the board and corresponded with the formation of stain (Kreber *et al.* 1998).

Kreber & Haslett (1997a) showed that kiln brown stain formation was temperature-dependent and cumulative, with its severity increasing as wood moisture content decreased. The authors further showed that low-temperature drying at 45°/35°C and 50°/39°C yielded kiln brown stain levels which perhaps were industrially acceptable, but which resulted in long drying times.

In kiln drying of lumber, three process-control variables are available to reduce drying time: increase of kiln schedule temperatures and/or air velocity, and decrease of kiln relative humidity (Price 1981; Haslett 1998; Herzberg *et al.* 1985). However, high kiln temperatures and low relative humidity are known to promote kiln brown stain formation (Kreber & Haslett 1997a). High air velocities reduce drying time of *P. radiata* lumber (Haslett 1998) but their effect on kiln brown stain development in *P. radiata* has not been investigated previously.

In trials on the effect of kiln relative humidity on kiln brown stain formation, Kreber & Haslett (1997a) found that fewer kiln brown stain precursors were translocated to the wood surface in drying with high than with low relative humidity. Therefore, further trials were undertaken to evaluate the use of mild, stepped, kiln schedules in conjunction with high relative kiln humidities as an alternative means for control of kiln brown stain.

It was decided to investigate the feasibility of removing kiln brown stain by planing, as an alternative to use of kiln schedule modifications, since other procedures have proved unsatisfactory (Kreber & Haslett 1997b; Kreber & McDonald 1997; Kreber *et al.* 1999). Therefore, detailed measurements were also made of the deposition of kiln brown stain at different kiln schedule temperatures to determine the depths of wood fibre that had to be removed in planing in order to yield clear *P. radiata*.

The objectives of the current investigation were to assess the effect of high air velocity and relative kiln humidity on kiln brown stain development. More specific objectives of the study were to determine the influence of high air velocity on drying time and the effect of relative humidity on depth and thickness of kiln brown stain.

MATERIAL AND METHODS

Use of High Air Velocity

Freshly sawn, random width (< 200-mm) *P. radiata* sapwood lengths (40 mm thick) were selected from the green chain at a local mill. A 100-mm section was cut from both ends of the boards and discarded. Each length was then cross-cut alternately into 20-mm-long cross-sections and six 580-mm-long, end-matched samples. The cross-sections were immediately weighed and oven dried (103°C, 48 hours) to determine the initial wood

moisture content for each sample. The 580-mm-long samples were labelled by board number and position within the length, and end-coated twice with aluminium epoxy paint before being individually weighed green. The sets of sample boards with the same letter (e.g., 1A–20A) were dipped in a commercial anti-sapstain formulation to control microbial discolorations, placed in plastic bags, and stored outside under cover until they were needed.

Prior to drying, the initial moisture content of each 20-mm cross-section and the green weight of each sample were used to calculate the sample board oven-dry weight and target weight at 60% and 10% moisture content. Samples were dried in a laboratory drying tunnel which simulated a commercial-width kiln stack. One set of sample boards (n = 20 in two layers) was assembled in the drying tunnel, along with an another 20 wet blanks, 10 positioned on the bottom and 10 on top of the stack with the two layers of sample boards between them (Fig. 1). Boards from the sample layers were weighed every 12 hours during drying to determine a drying curve.

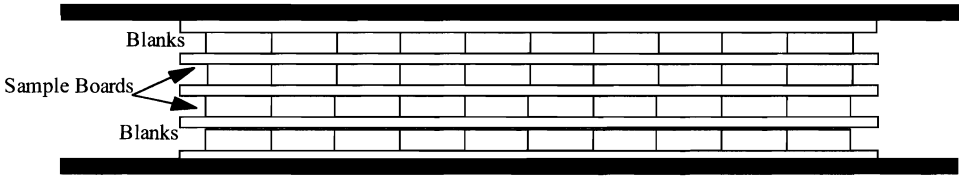

FIG. 1–Kiln stack configuration used for drying of random-width *Pinus radiata* sapwood boards.

TABLE 1–Kiln schedules used in drying of random-width *Pinus radiata*.

Kiln schedule	Air velocity (m/s)	Air flow reversal (hours)	Equalisation/steaming
45°/35°C (LT)	8	12	75°/75°C (6 h)
70°/60°C (CT)	8	12	75°/75°C (6 h)
80°/77.5°C, green to 60% m.c. 65°/56°C, 60% m.c. to dry (Step)	8	12	100°/100°C (4 h)
90°/60°C (ACT)	4.5	12	100°/100°C (4 h)

Four experimental runs were performed using low temperature (LT), conventional temperature (CT), and stepped temperature conditions (Step), and an accelerated conventional temperature (ACT) schedule (Table 1). With the exception of ACT, the schedules were chosen because they had reduced intensity of kiln brown stain in previous trials (Kreber & Haslett 1997a). An air velocity of 8 m/s was used for the kiln schedules evaluated, except for the accelerated conventional temperature (ACT) 90°/60°C control schedule which had an airflow of 4.5 m/s (Table 1). Air velocity was measured prior to drying using an airflow meter on the outlet side of the stack in both forward and reverse directions. Fan direction was reversed every 12 hours of drying for each of the evaluated kiln schedules. At the end of drying, the charge was equalised or steam conditioned and left to cool over night before the sample boards were reweighed.

After kiln drying, one 90-mm-long section was trimmed from each end of the sample, along with two 20-mm-long cross-sections. The 20-mm-thick sections were again used to determine mean final wood moisture content of each sample board and drying time to 12% moisture content for each kiln charge. The remaining portion of each sample board was cut down to provide a 360 × 100 × 40-mm board which was then skim-dressed (to remove 0.5 mm) on the outer face and assessed for intensity of kiln brown stain. For each of the boards, a subjective stain intensity rating was given ranging from 0 (no stain) to 3 (severe stain), as described previously by Kreber & Haslett (1997a). For each schedule, an overall kiln brown stain intensity rating (n = 20) was then calculated.

Effect of Relative Humidity

Three separate runs were performed in a small laboratory kiln to examine the effect of high humidity. Another 20 green-off-saw *P. radiata* sapwood boards (100 × 40 mm) were cross-cut into six sets of end-matched samples as described above. One set of samples (n = 20) was stacked in the kiln, along with 10 wet blanks positioned at the side of the incoming air flow. In the first run, kiln drying was performed at 80°/77.5°C (relative humidity 90%) and an air velocity of 4.5 m/s. Sample boards were periodically removed and weighed to determine the target wood moisture content of 60% for the schedule change point, after which they were kilned at 50°/39°C (relative humidity 52%). Drying was curtailed when samples reached the final 12% target moisture content. A second set of samples was similarly dried at 80°/77.5°C until 60% wood moisture content before the kiln schedule temperature was changed to 80°/65.5°C (relative humidity 52%). The two kiln schedules were chosen because in a previous study (Kreber & Haslett 1997a) high relative humidity in the kiln significantly reduced kiln brown stain formation, possibly due to a lower drying rate causing more diffuse translocation and deposition of kiln brown stain precursors near the wood surface. A third set of samples was dried to serve as a control using a straight-through, ACT 90°/60°C kiln schedule at 4.5 m/s air velocity.

After kiln drying, 110 mm were cut from both ends of each sample board and discarded. One 20-mm-long cross-section was then sawn from one end of the board to determine final wood moisture content. The remaining 360-mm-long sample was divided into a grid with six 60 × 100-mm areas, and two thickness measurement points per area were marked on the board's edge. Initial thickness measurements were taken to the nearest 0.01 mm at thickness measurement points on each of the sawn dried boards (before planing). Samples were then planed, and a second measurement was taken at measurement points as soon as kiln brown stain was exposed and a third one after it was completely removed. Thickness measurements were used to determine location (depth below the surface) and thickness of kiln brown stain by calculating the average for each individual grid area and then using these six averages to calculate an average for each sample board. The intensity of kiln brown stain was also assessed in the six grid areas during planing as soon as the stain became exposed. Intensity of stain was rated using a visual grading system from 0 (non-stained) to 6 (severe stain). That grading system was preferred over the three-point system described above because it allowed better discrimination between the slight differences in kiln brown stain levels. An average stain intensity value was then calculated for each sample board.

A one-way analysis of variance was used to determine statistically significant differences in the means of stain intensity, depth, and thickness between kiln schedules (treatments). A

pair-wise multiple comparison procedure (Tukey test) was then applied to decide significant differences in the stain intensity and thickness means between treatments. Statistical difference was determined at the 5% significance level.

RESULTS AND DISCUSSION

Use of High Air Velocity

In spite of air velocity at 8 m/s, the LT, CT, and stepped kiln schedules still had lengthy drying times to 12% moisture content compared to the 90°/60°C kiln schedule. The drying rate was not substantially accelerated and thus drying time was not reduced to commercially acceptable levels (Table 2). In addition, the kiln schedules tested yielded no significant gain in stain reduction. Compared to control samples dried at the 90°/60°C kiln schedule (with 28% relative humidity), intensity of brown stain was reduced by 50% in drying with a stepped (80°/77.5°C; 65°/56°C) high humidity kiln schedule (Table 2). After ACT kiln drying, the control samples showed an average stain rating of 2.95 signifying a severe level of stain, while a light/moderate level of stain with a rating of 1.45 was observed with the stepped kiln schedule. In the latter kiln schedule, the coloration (brown stain intensity) in 12 out of 20 sample boards was rated as light which is likely to be commercially acceptable. This seemed to support the results of a previous study by Kreber & Haslett (1997a) which indicated that fewer kiln brown stain precursors accumulate near the wood surface during drying at high relative humidity. However, a general darkening, not to be confused with kiln brown stain, was observed throughout the sample thickness after drying with the stepped kiln schedule. It is likely that the stepped schedule, with a high kiln humidity and high temperature during the first one-third of the drying, induced conditions similar to those prevailing during final steam-conditioning which is known to darken the wood surface of *P. radiata* (Wastney *et al.* 1997).

TABLE 2–Effect of kiln schedule on overall kiln brown stain rating observed after drying, and total drying time of *Pinus radiata* (n = 20).

Kiln schedule	Initial m.c. (%)	Final m.c. (%)	Stain rating	Drying time (h)
45°/35°C (LT)	167	13	2.5	232
70°/60°C (CT)	169	10	2.8	125
80°/77.5°C, green to 60% m.c. 65°/56°C, to dry (Step)	170	14	1.45	261
96°/60°C (ACT)	167	10	2.95	50

Surprisingly, kiln drying at 45°/35°C and 70°/60°C at high air velocity did not alleviate kiln brown stain intensity. However, by using a low air velocity (4.5 m/s) Kreber & Haslett (1997a) showed a significant reduction in the development of kiln brown stain when drying at 45°/35°C. To summarise, none of the kiln schedules evaluated in the study reported here reduced kiln brown stain and they required a much longer drying time.

Effect of High Relative Humidity

Using air velocity of 4.5 m/s, the two stepped kiln schedules with high relative humidity generally reduced kiln brown stain intensity by half compared to control samples dried using

the standard 90°/60°C ACT kiln schedule (with 28% relative humidity) (Table 3). ACT drying of the control samples yielded an average stain rating of 5.15 (on a rating from 0 to 6), signifying a severe intensity of stain. In contrast, average stain ratings for the two medium-temperature, stepped, kiln schedules were 2.76 and 2.34 respectively, which signified a light/moderate level of stain formation. Statistical analysis showed a highly significant difference between the ACT control and the two stepped kiln schedules ($p < 0.001$), but there was no significant difference between the two 80°C kiln schedules.

TABLE 3–Effect of kiln schedules on overall* intensity, depth, and thickness of kiln brown stain in dry *Pinus radiata*.

Kiln schedule	Stain rating	Depth of stain (mm)	Stain thickness (mm)
ACT 90°/60°C	5.15 (0.66)†	0.55 (0.34)	1.94 (0.51)
80°/77.5°C – 52°/39°C	2.76 (1.29)	0.54 (0.26	1.54 (0.65)
80°/77.5°C – 80°/65.5°C	2.34 (1.13)	0.53 (0.27)	1.58 (0.75)

* = overall average from total number of sample boards.
† = standard deviation in parentheses.

Kiln schedule temperature has been identified as a significant factor in promoting kiln brown stain (Kreber & Haslett 1997a). In particular, temperatures of 60°C and above dramatically increased *in vitro* kiln brown stain intensity (McDonald *et al.* 1997). Given that the current trial assessed schedules with 80°–90°C dry bulb temperature, it is likely that the lower severity of kiln brown stain was due to the slower drying caused by the use of high relative humidity. It is likely that more kiln brown stain precursors are translocated to near the wood surface during the faster drying (low humidity) of *P. radiata* and these then undergo a thermo-chemical reaction. Thus, the current study provided evidence that kiln relative humidity also affects brown stain formation, along with temperature and wood moisture content (Kreber & Haslett 1997a).

Although the intensity of kiln brown stain was influenced by kiln schedule, the difference in depth of stain between the three schedules was not statistically significant. For all three schedules the kiln brown stain was located approximately 0.5 mm underneath the wood surface, meaning that the stain became exposed after skim-dressing approximately 0.5 mm (Table 3).

Stain thickness was greatest in the samples dried with a standard 90°/60°C kiln schedule, with an average thickness of 1.94 mm. Drying of samples at 80°C kiln temperature reduced stain thickness by approximately 20%, yielding 1.58 and 1.54 mm respectively (Table 3). One-way analysis of variance showed that the difference in average stain thickness between standard 90°/60°C drying and the two, stepped, kiln schedules was statistically significant ($p = 0.02$). However, there was no significant difference in stain thickness between the two stepped kiln schedules.

Some practical implications arose from the current investigation. As observed in previous studies (Kreber & Haslett 1997a), kiln schedule modifications were unable to completely eliminate kiln brown stain during drying of *P. radiata*. However, it is possible to reduce the occurrence and intensity of kiln brown stain by drying at low kiln temperature or with mild (not above a dry bulk of 80°C) kiln schedule temperatures at high relative humidity.

Unfortunately, the long drying times associated with these schedules would make them commercially unacceptable. In New Zealand, current turnaround time for drying of random-width *P. radiata* sapwood is 50–60 hours (Ministry of Forestry 1997) With the use of longer kiln schedules, New Zealand *P. radiata* exporters would be unlikely to be able to compete in global markets for clear, high-value, appearance-grade timber.

At present the only effective method for eliminating kiln brown stain in dried *P. radiata* sapwood is by planing off the stain. The current study showed that in order to remove the kiln brown stain that occurs during kiln drying at 90°/60°C, lumber should be over-cut by at least 4–5 mm. Although this approach means that valuable wood fibre is lost, a recent cost-benefit analysis showed that planing is the preferred option over kiln schedule modification and compression-rolling for controlling kiln brown stain in New Zealand *P. radiata* sapwood, unless log prices are well above current market prices (Kreber, McDonald, Haslett unpubl. data).

CONCLUSIONS

Although reducing drying temperature to less than 60°C may limit the intensity of kiln brown stain to within commercially acceptable levels, the lengthy drying times are likely to preclude the commercial use of low-temperature kiln schedules. Furthermore, even when high air velocities are used in association with such schedules, the reduction in drying time is still likely to be insufficient to see low-temperature/high air velocity schedules being used as a means of controlling stain intensity.

For similar reasons of lengthy drying times, schedules with high relative humidity offer some improvement in stain intensity but are also unlikely to be adopted by industry. It appears that the most likely method of controlling kiln brown stain will be the removal of stain by planing after kiln drying.

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