United States
Department of
Agriculture

**Forest Service**

Forest
Products
Laboratory

Research
Note
FPL–RN–266

# Effect of Air Velocity on the Drying Rate of Single Eastern White Pine Boards

**William T. Simpson**

# Abstract

The qualitative effect of air velocity on drying rate of lumber has long been known. This report provides quantification of the effects of air velocity on drying rate of individual eastern white pine boards. An empirical equation correlating moisture content with time during drying was used to aid in the analysis. The drying rate increased with air velocity for moisture contents above approximately 40% to 50%. The drying rate gradually decreased and tended to level off with air velocities above 3.05 to 3.56 m/s (600 to 700 ft/min) and moisture contents below approximately 80% to 90%. The results provide guidelines for selecting experimental air velocities in full-scale kiln tests.

Keywords: drying, kiln schedules, eastern white pine

September 1997

---

Simpson, William T. 1997. Effect of air velocity on drying rate of single eastern white pine boards. Res. Note FPL–RN–266. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 5 p.

A limited number of free copies of this publication are available to the public from the Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53705–2398. Laboratory publications are sent to hundreds of libraries in the United States and elsewhere.

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

# Effect of Air Velocity on Drying Rate of Single Eastern White Pine Boards

**William T. Simpson,** Research Forest Products Technologist
Forest Products Laboratory, Madison, Wisconsin

## Introduction

The relative importance of evaporation of water from the surface and internal movement of water to the surface changes throughout lumber drying. This change affects the relationship between air velocity and drying efficiency. Rapid surface evaporation dominates early in the drying process (constant drying rate period) and air velocity needs to be high at this time. Later, the internal movement of water (falling drying rate period) gradually assumes dominance and air velocity does not need to be as high. Thus, at any stage of drying, there is an optimum air velocity. Slowing the drying process below these optimum values wastes kiln capacity, increases heat loss from the kiln, and risks lumber stain. Accelerating the drying process by using higher than optimum values wastes electrical energy for operating fans and imposes unnecessary wear on the fan–motor–shaft system. Because of fan characteristics, modest reductions in air velocity cause great reductions in electrical power (Simpson 1991). For example, a 25% reduction in air velocity results in >50% reduction in power (Fig. 1).

Knowledge of air velocity effects on drying rate is useful for determining optimum air velocity. In fact, if the optimum air velocity were known for each step in a kiln schedule, air velocity specifications could be added to dry- and wet-bulb temperatures for each step.

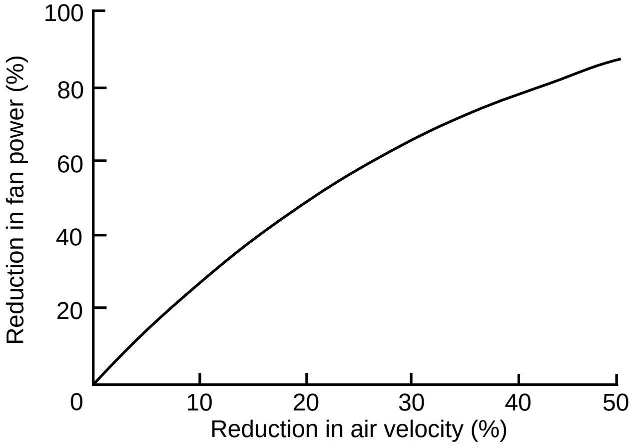

**Figure 1—Relationship between reduction in air velocity and reduction in electrical power to run fans.**

This report describes the effect of air velocity on the drying rate of eastern white pine at temperatures and relative humidities representative of early and mid-stage kiln drying. The results are from tests on single boards and offer insights and guidelines for full-width stacks of lumber in a dry kiln.

## Background

Several studies have increased our understanding of the effect of air velocity on drying rate. Torgeson (1940) reported the effect of air velocity and average moisture content on the drying rate of mixed sugar maple sapwood and heartwood at 54ºC (130ºF) and 76% relative humidity (RH), using a 1.22-m- (4-ft-) wide lumber stack. The results, which are summarized in Figure 2, offer guidelines on optimum air velocity. The temperature and relative humidity conditions were close to the conditions of the recommended kiln schedule for sugar maple at approximately 35% moisture content (MC). The optimum air velocity seemed to be in the 2.03- to 2.54-m/s (400- to 500-ft/min) range (Fig. 2), although the slope of the curve was small at these conditions and a judgment would be required on the value of increasing air velocity for a small increase in drying rate.

Salamon and McIntyre (1969) studied the effect of air velocity on the drying rate of 0.91-m- (3-ft-) wide stacks of western hemlock, western white spruce, and Douglas-fir. The authors compared the relative drying rates for several moisture content intervals. High air velocities in the range of moisture content from green to 24% had the greatest effect on drying rate; the increase varied by species. Air velocity had little or no effect in the range of 20% to 15% MC. These results offer guidelines for these species in the range of green to 15% MC and 2.03 to 4.57 m/s (400 to 900 ft/min) air velocity.

Steinhagen (1974) did not find any effect of air velocity on the drying rate of nominal 25-mm- (1-in.-) thick yellow poplar below 40% MC when drying according to a kiln schedule. Each kiln charge consisted of four layers of specimens. For each layer, three 51-mm- (2-in.-) wide specimens were placed side by side, so that the layer was 153 mm (6 in.) wide. Only the specimens in the center of the second and third layers (the two innermost specimens of each stack) were used for measurements. Steinhagen concluded that a drying rate of 1.27 m/s (250 ft/min) was sufficient below 40% MC.

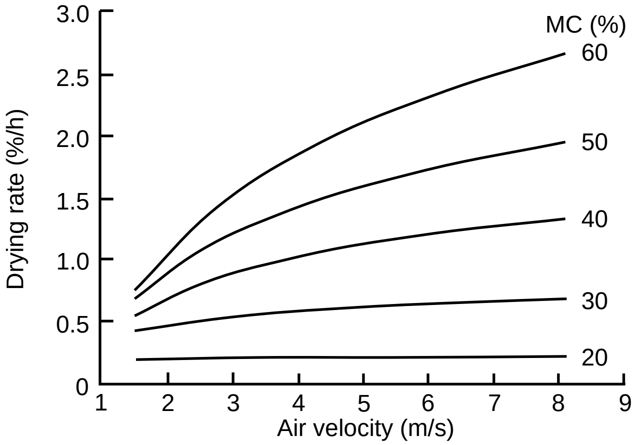

**Figure 2—Effect of air velocity and moisture content on drying rate of sugar maple mixed sapwood and heartwood, dried in a 1.22-m- (4-ft-) wide stack at 54°C (130ºF) and 76% RH (Torgeson 1940).**

Above 40% MC, a change in air velocity from 1.78 m/s (350 ft/min) to 2.54 m/s (500 ft/min) was required to cause a significant change in drying rate.

Hart and others (1986) used a drying simulation to estimate the effects of air velocity on drying time of full-width kiln stacks of Southern Pine. Their results showed that drying time progressively decreased as air velocity increased from 1.27 to 2.54 to 3.81 m/s (250 to 500 to 750 ft/min) at conventional drying temperatures.

Milota and Tschernitz (1990) determined the drying rates of single Southern Pine boards with variation in dry-bulb temperature, wet-bulb temperature, air velocity, and board thickness. They also developed a mathematical expression for correlating drying rate to these variables. In another study, Milota and Tschernitz (1994) developed a drying simulation to apply this correlation to full-width lumber stacks and found that the simulation results compared favorably with experimental results.

# Experimental

Flat-sawn eastern white pine (*Pinus strobus*) boards, obtained from northern Wisconsin, were processed into surfaced specimens 102 by 305 by 29 mm (4 by 12 by 1.125 in.). Previous research had shown that short boards with good end-coats can produce the same drying rate data as can full-length lumber (Simpson and others 1994). Specimens were wrapped in two layers of plastic bags and stored in a freezer until ready for use. Before each test run, the edges and ends of each specimen were painted with two coats of aluminum paste and exterior varnish mixed at a ratio of 18 g of paste to 100 g of varnish.

Specimens were dried in a wind tunnel attached to a generator unit for temperature and relative humidity control and equipped with a blower. The speed of the blower could be adjusted for variable air velocity. A perforated plate was installed just upstream from the specimens to help create uniform air flow.

There were two experimental drying conditions: (1) 49ºC (120ºF), 60% RH, and (2) 54ºC (130ºF), 40% RH. These conditions are similar to the initial steps in the eastern white pine anti-brown-stain kiln schedule (Simpson 1991). Three air velocity rates were used for each condition: 1.52, 3.30, and 5.08 m/s (300, 650, and 1,000 ft/min). Two replicate runs of six specimens each were conducted for each air velocity and each condition, for a total of 72 specimens. Specimens were weighed periodically during drying: at short intervals early in drying when the drying rate was high, and then at increasing intervals as drying progressed and drying rate decreased.

# Analytical Methods

The moisture content–time data from each of the 72 specimens were fit to an empirical equation by nonlinear regression. The empirical equation is based on the generalized logistic equation (DeWitt 1943)

$$y = \frac{K}{1 + b\ \exp(F(t))} \tag{1}$$

where $K$ and $b$ are coefficients and $F(t)$ is some function of time $t$.

DeWitt's analysis showed that the logistic equation is capable of faithfully representing a large variety of physical and chemical rate data. Wilke (1944) applied a specific form of the logistic equation to drying data and found that it represented the data well (Marshall 1950, Tschernitz 1996). The form used by Wilke can be written as

$$E = \frac{1}{1 + a\ \exp[b \ln t + c(\ln t)^3]} \tag{2}$$

where

$E = (m - m_e)/(m_i - m_e)$,

$m$ = moisture content at any time $t$ (h),

$m_e$ = equilibrium moisture content (%),

$m_i$ = initial moisture content (%),

$a,b,c$ = coefficients determined by nonlinear regression, and

$t$ = time (h).

Examination of Equation (2) suggests that adding a squared term for ln $t$ could make the equation more powerful in its curve-fitting ability. This form is

$$E = \frac{1}{1 + a\ \exp[b \ln t + c(\ln t)^2 + d(\ln t)^3]} \tag{3}$$

where an additional regression coefficient is added. The four regression coefficients have no known physical significance in drying. The values of $m_e$, taken from published equilibrium moisture content data (Simpson 1991), are 9.7% at 49ºC (120ºF), 60% RH, and 6.4% at 54ºC (130ºF), 40% RH.

## Results and Discussion

Two moisture content–time curves are shown in Figure 3. Both the experimental data points and the Equation (3) regression curve are shown. Figure 3a shows the best fit of all 72 specimens, with an average deviation between experimental and calculated points of 0.10% MC. Figure 3b shows the worst fit, with an average deviation of 1.78% MC. The overall average deviation of all the specimens was 0.61% MC, which shows that Equation (3) can provide a good representation of the drying data.

The Equation (3) regression coefficients *a* ,*b* ,*c*, and *d* were determined for each specimen, and their average values and standard deviations are listed in Table 1. The relationship of the coefficients to air velocity is shown in Figure 4. Results of regression fits of the coefficients to air velocity are shown to allow interpolation between experimental air velocities. The consistency of the relationships between the coefficients and air velocity further shows that Equation (3) can be useful in correlating drying data. If the coefficients showed no consistent variation with air velocity, the value of Equation (3) would be severely limited.

The effect of air velocity and moisture content on drying rate is shown in Figure 5. The curves were calculated using the correlation between the regression coefficients and air velocity. All calculated curves were started from 140% MC, the average initial moisture content of the 72 specimens. Figure 5a shows the effect at 49ºC (120ºF) and 60% RH from green to 60% MC, which is similar to the first few steps in the eastern white pine kiln schedule. Figure 5b shows the effect at 54ºC (130ºF) and 40% RH from 60% to 30% MC, which is similar to the middle steps in the kiln schedule. The results agree with previous qualitative results: air velocity has a pronounced effect on drying rate early in the drying process, when moisture content and drying rates are high.

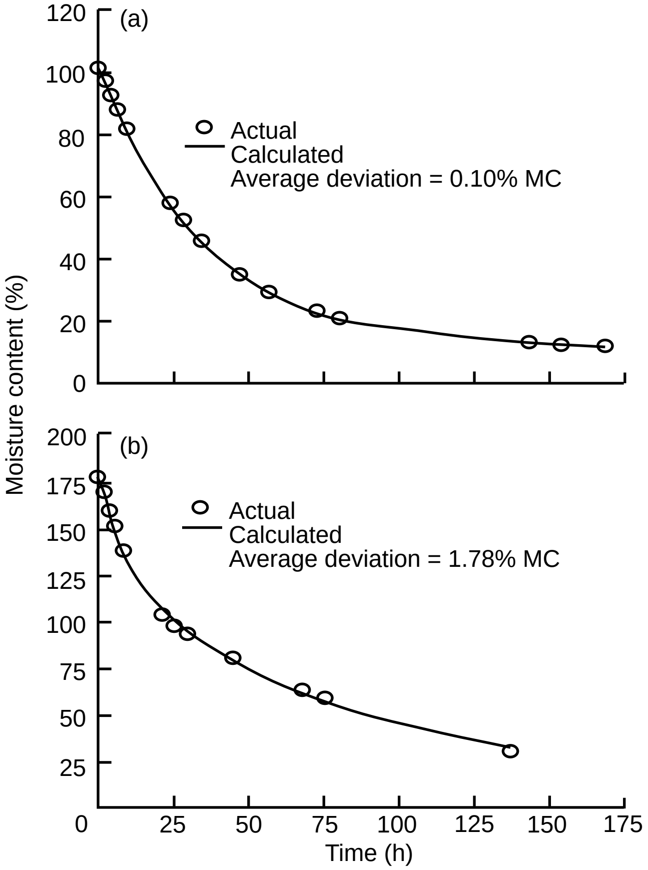

**Figure 3—Moisture content–time drying curves fitting nominal 25-mm eastern white pine drying data to Equation (3): (a) best fit (49°C, 1.52 m/s), (b) worst fit (54°C, 1.52 m/s).**

The rise in drying rate with air velocity is gradual (Fig. 5a), with the greatest increases at low air velocities. At moisture contents below approximately 60%, air velocity has little effect on drying rate (Fig. 5b).

**Table 1—Average regression coefficients of Equation (3) for describing moisture content–time drying data for nominal 25-mm eastern white pine[a]**

| Drying temperature and time | *a* | *b* | *c* | *d* |
|---|---|---|---|---|
| 49°C (120°F) | | | | |
| 1.52 m/s (300 ft/min) | 0.00477 (0.00375) | 3.13 (0.661) | −0.859 (0.262) | 0.118 (0.0383) |
| 330 m/s (650 ft/min) | 0.0132 (0.00824) | 2.37 (0.701) | −0.639 (0.331) | 0.104 (0.0461) |
| 5.08 m/s (1,000 ft/min) | 0.0295 (0.0116) | 1.58 (0.428) | −0.321 (0.190) | 0.0592 (0.0326) |
| 54°C (130°F) | | | | |
| 1.52 m/s (300 ft/min) | 0.0165 (0.0106) | 2.16 (0.798) | −0.527 (0.343) | 0.0869 (0.0491) |
| 3.30 m/s (650 ft/min) | 0.0392 (0.0125) | 1.45 (0.465) | −0.246 (0.239) | 0.0525 (0.0283) |
| 5.08 m/s (1,000 ft/min) | 0.0587 (0.0149) | 1.22 (0.367) | −0.131 (0.178) | 0.0337 (0.0181) |

[a] Standard deviations are shown in parentheses.

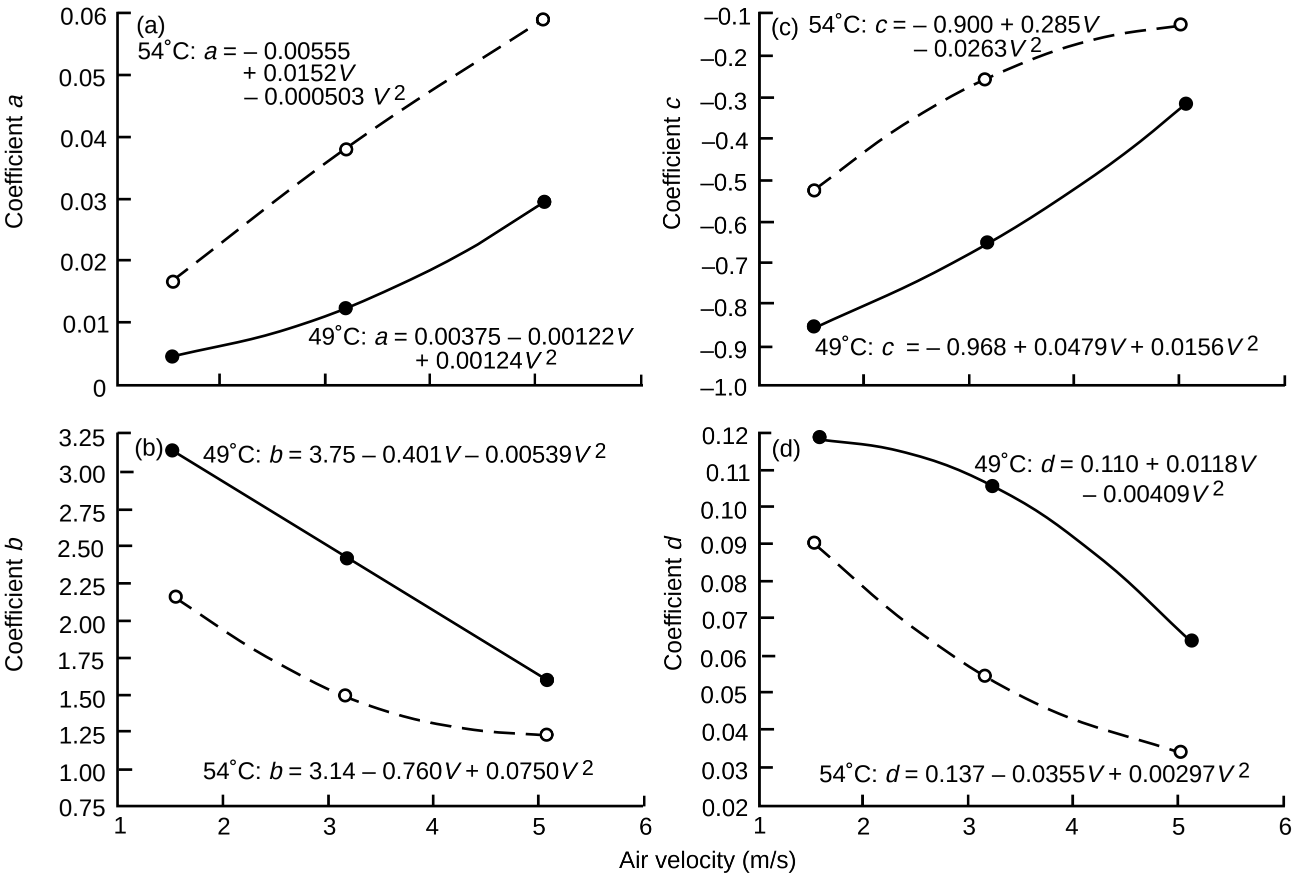

**Figure 4—Relationships between four regression coefficients of Equation (3) and air velocity *V*.**

Figure 6 shows the effect of air velocity on drying time. The time to dry from green to 60% MC at 49ºC (120ºF) varied from about 35 h at an air velocity of 1.52 m/s (300 ft/min) to about 20 h at 5.08 m/s (1,000 ft/min). The rate of decrease in drying time with increase in air velocity diminished at higher air velocities, but some reduction in drying time still occurred up to 5.08 m/s (1,000 ft/min). The time to dry from 60% to 30% MC at 54ºC (130ºF) showed less variation—from about 24 h at 1.52 m/s (300 ft/min) to 20 h at 5.08 m/s (1,000 ft/min). Above approximately 4.06 m/s (800 ft/min), little decrease in drying time occurred with increased air velocity.

Although the data collected in this study are somewhat limited and do not allow complete optimization of air velocity in kiln drying eastern white pine lumber, they do offer useful information. This study was conducted on individual boards. Another factor should be considered when drying full-width stacks of lumber. In a full-width stack in a dry kiln, drying conditions vary across the width of the stack. Water evaporated from the first board on the entering-air side of the stack increases the relative humidity and reduces the temperature of the air passing over it. As a result, the drying rate decreases progressively downstream, and each board downstream has a slightly higher moisture content than the adjacent board upstream. Therefore, although we may be able to reduce air velocity without decreasing the drying rate of upstream boards, the higher moisture content boards downstream may still require a higher air velocity to maintain the drying rate. Although this factor limits the ability of using the data from this study to optimize air velocity in a kiln, our results nevertheless offer guidelines for selecting air velocities for experimental kiln tests.

## Conclusions

From this exploratory study on the effect of air velocity on the drying rate of nominal 25-mm eastern white pine lumber, we conclude the following:

- Equation (3) is a useful empirical equation for correlating moisture content with time during drying.
- The basic drying rate of individual boards varies with air velocity at temperatures and relative humidities similar to the first few steps in the kiln schedule. Drying rate increased with air velocity for moisture contents above approximately 40% to 50%. The rate of increase in drying rate with air velocity gradually decreased and tended to level off with air velocities above approximately 600 to 700 ft/min and moisture contents below approximately 80% to 90%.

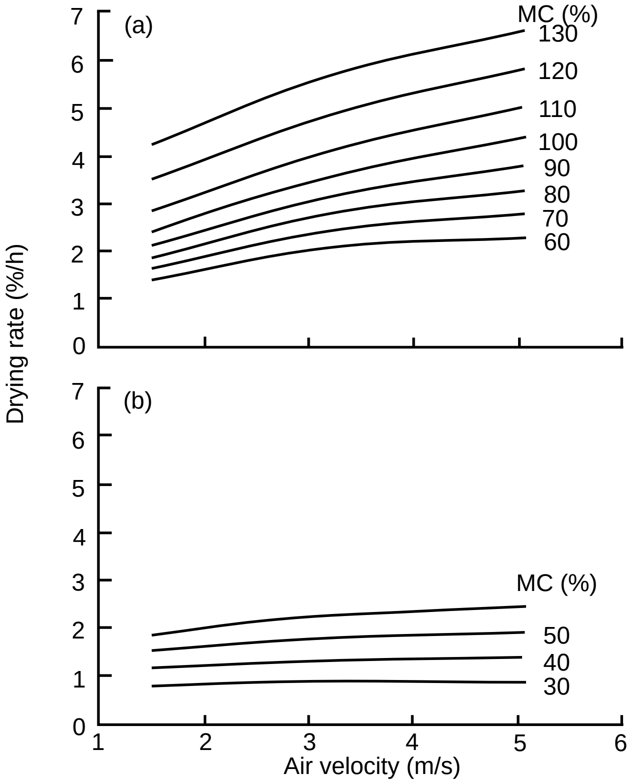

**Figure 5—Effect of air velocity and moisture content on drying rate of individual nominal 25-mm eastern white pine boards dried at (a) 49°C (120°F), 60% RH, and (b) 54°C (130ºF,) 40% RH (6.4% equilibrium moisture content).**

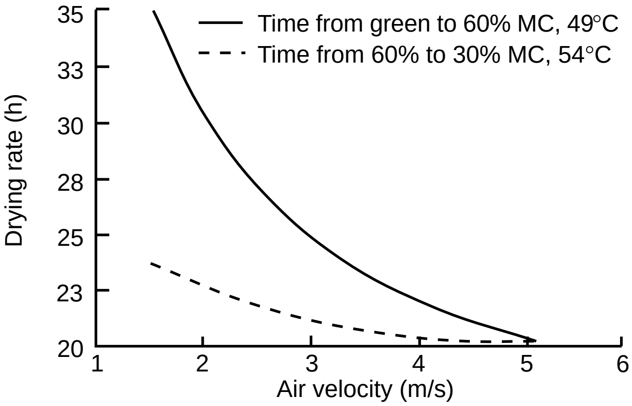

**Figure 6—Effect of air velocity on drying time of nominal 25-mm eastern white pine from green to 60% MC and from 60% to 30% MC.**

- The results of this study provide guidelines for selecting experimental air velocities in test runs to optimize air velocity for full kiln loads of nominal 25-mm eastern white pine lumber.

## References

**DeWitt, C.C.** 1943. Correlation of rate data. Industrial and Engineering Chemistry. 35(6): 695–700.

**Hart, C.A.; Denig, J.; Hanover, S.** 1990. Variables affecting drying rate and quality. In: Proceedings, Drying softwood and hardwood lumber for quality and profit conference; 1986; Charlotte, NC. Madison, WI: Forest Products Research Society.

**Marshall, W.R.** 1950. Principles of drying solids. Unpublished manuscript. Madison, WI: University of Wisconsin. 395 p.

**Milota, M.R.; Tschernitz, J.L.** 1990. Correlation of loblolly pine drying rates at high temperature. Wood and Fiber Science. 22(3): 298–313.

**Milota, M.R.; Tschernitz, J.L.** 1994. Simulation of drying in a batch lumber kiln from single-board tests. Drying Technology. 12(8): 2027–2055.

**Salamon, M.; McIntyre, S.** 1969. Manipulation of air velocity permits drying time savings. Canadian Forest Industries. 89(9): 49–53, 55–57.

**Simpson, William T., ed.** 1991. Dry kiln operator's manual. Agric. Handb. 188. Washington, DC: U.S. Department of Agriculture. 274 p.

**Simpson, W.T.; Tschernitz, J.L.; Sarfo, J.S**. 1994. Short, clear specimens for estimating drying time of sugar maple lumber. Wood and Fiber Science. 26(2): 171–177.

**Steinhagen, H.P.** 1974. Effect of kiln air velocity, at various moisture content levels, on drying rate of 4/4 yellow-poplar sapwood. Forest Products Journal. 24(4): 45–47.

**Torgeson, O.W.** 1940. The drying rate of sugar maple as affected by relative humidity and air velocity. Res. Rep. FPL 1274. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

**Tschernitz, J.L.** 1996. Personal communication.

**Wilke, C.R.** 1944. The falling rate period in through circulation drying. Madison, WI: University of Wisconsin. Ph.D. dissertation.