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Effect of Drying Methods on Warp and Grade of 2 by 4's From Small-Diameter Ponderosa Pine

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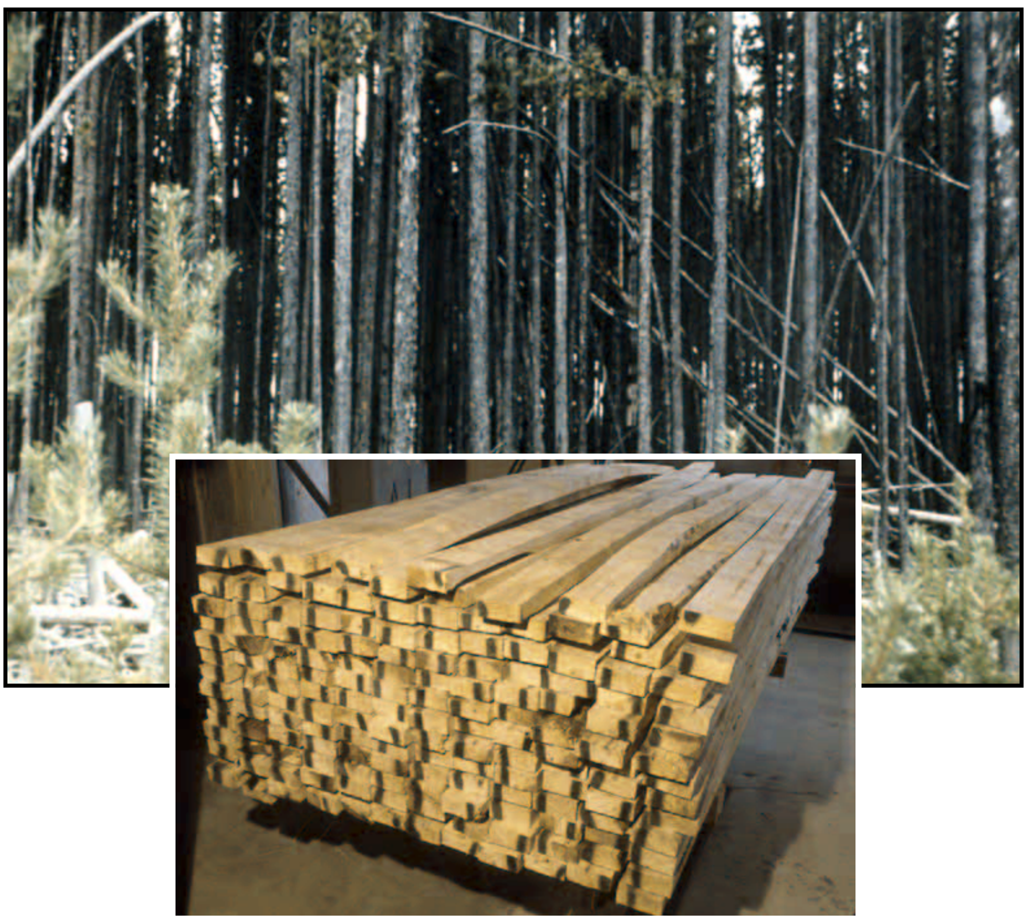

Abstract

Two studies were performed to characterize and control warp in nominal 2- by 4-in. (standard 38- by 89-mm) dimension lumber sawn from small-diameter ponderosa pine trees. One study was conducted at a commercial sawmill with trees harvested in central Arizona. The other study was conducted at the USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, in small experimental kilns with lumber from trees harvested in central Idaho. The three main variables in the studies were top loading, presteaming, and a high-temperature kiln schedule. A limited study of hot press drying was also included. The high-temperature kiln schedule in the experimental kilns reduced drying time to about half that of the conventional temperature schedule. Press drying time was slightly more than 3 h. Crook and bow caused most of the warp and the grade loss from warp. There was no evidence that presteaming affected warp or grade loss from warp. Top loading had a modest effect in reducing warp and grade loss from warp. High-temperature drying did not affect measured warp compared with the conventional temperature schedule. Grade loss from warp was less in high-temperature than in conventional temperature dried lumber. This might be explained by differences in moisture content change during storage. Press drying did not reduce warp or grade loss from warp.

Keywords: kiln drying, warp, ponderosa pine, small-diameter timber

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Contents

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Introduction

Many forests in the western United States contain stands of softwood timber, such as ponderosa pine and Douglas-fir, that are so dense with small-diameter trees that forest health is in jeopardy and the risk is high for catastrophic forest fires that could destroy old growth, large-diameter trees. Larson and Mirth (1998) estimate that thinning for restoration could produce 1 billion ft^3 (billion = 10^9) (see Table 1 for conversion factors to metric units) of wood fiber from trees in the 5- to 16-in. diameter range. Removal of these small trees for forest restoration and/or timber products is expensive, and therefore, interest in value-added manufacture of timber products made from small-diameter material is high. It is difficult for the value of timber products to pay for harvest because the ratio of the number of stems removed to volume of finished wood product is very high.

Table 1—Conversion of inch–pound to metric units

To convert from	To	Multiply by
in.[a]	m	2.540×10^{-2}
ft	m	3.058×10^{-1}
ft^3	m^3	2.832×10^{-2}
lb	N	4.448
lb/ft^2	Pa	4.788×10^{1}
lb/in^2	Pa	6.894×10^{3}
ft/min	m/s	5.080×10^{-3}
°F	°C	$T_C = (T_F - 32)/1.8$

[a]Nominal 2- by 4-in. dimension lumber is standard 38- by 89-mm dimension lumber.

Compounding this removal issue is an additional problem that can lower the value of lumber sawn from small-diameter softwood trees. The warp that occurs during kiln drying of this lumber can be so high and pervasive that it can cause significant grade, utility, and value loss. Warp can also occur during additional moisture loss, which often occurs when processed lumber is subjected to low relative humidity environments, such as in the arid western United States.

Another factor involved in the potential warp and grade recovery problem in lumber from small-diameter trees is the nature of growth conditions. Small-diameter trees grown in open conditions may have been relatively fast growing when young, resulting in a large proportion of warp-prone juvenile wood. Trees that have grown in densely stocked conditions are suppressed, resulting in slow growth, narrow growth rings, and a relatively small amount of juvenile wood volume per stem. Lumber from suppressed trees may be less prone to warp and may yield higher grade lumber (Shelly and Simpson 1999, Gorman and Green 1999).

The problem of excessive warp in lumber from small-diameter softwood trees and logs has been recognized for many years, yet effective solutions still have not been developed. As the harvest of large-diameter trees continues to decline and as the concerns about forest health, fire danger, and restoration increase, the interest in technology to reduce warp increases. The objective of the two studies reported here was to examine the effectiveness of combinations of several warp-reducing techniques on nominal 2- by 4-in. dimension lumber (2 by 4's) from small-diameter ponderosa pine trees. One study was done in cooperation with a commercial sawmill using their commercial-sized dry kilns, and the other study was done at the USDA Forest Service, Forest Products Laboratory (FPL), using small experimental dry kilns.

Background

A number of approaches have been applied to reduce warp in lumber during drying. Examples are sawing pattern modifications, pretreatments, special stickers, kiln schedule modifications, composite configurations, and mechanical restraint by top loading with dead weights or springs and press drying between heated platens. Species studied include ponderosa pine, Douglas-fir, the southern pines, radiata pine, red pine, and the western hemlock–true fir commercial mix.

Arganbright and others (1978) studied the effects of top loading with dead weight (200 lb/ft^2) and drying method (air drying, conventional kiln schedule (180°F), and high-temperature kiln schedule (240°F)) on warp in 2 by 4's from what they termed small-diameter ponderosa pine (<24-in. diameter). They found that it warped severely during drying, with downgrade ranging from 34% to 51%. The major cause of the grade loss was crook. The top loading seemed to be effective in lumber dried by the conventional kiln schedule (especially on twist) but not in that dried by high temperature. However, the high-temperature dried lumber was over-dried, which increases warp (Bassett 1973). They made no attempt to adjust warp measurements for final moisture content, which ranged from 8.7% (high-temperature drying) to 16.2% (air drying) for their 12 kiln runs, so it is difficult to arrive at conclusions from their results.

Mackay and Rumball (1972) compared the effectiveness of presteaming (4 h at 175°F or 210°F) and dead-weight top loading (110 or 210 lb/ft^2) on radiata pine 2 by 4's sawn from 10- to 12-in.-diameter logs and dried at high temperature (240°F). The idea was to plasticize the wood with the presteaming before any drying, hold the shape firmly in place with the top load during drying, and then allow the lumber to cool before removing the top load. Their best results were at the high levels of top loading and presteaming temperature. Around 95% met grade warp requirements. They had neither conventional temperature (180°F or less) nor top-load conditions for comparison.

Gough (1974) investigated the effect of kiln schedule (190°F or 250°F) and top load (115 or 230 lb/ft^2) on warp in studs sawn from 8- to 9-in.-diameter thinnings of slash pine. The combination of the highest drying temperature and the highest top load resulted in the greatest grade recovery.

Blake and Voorhies (1980) determined grade recovery in 2 by 4's sawn from 10-in.-diameter ponderosa pine trees. They top loaded at 112 lb/ft^2, and tested four drying methods—a combination of air drying and kiln drying; a conventional temperature schedule (160°F to190°F); an elevated temperature schedule (180°F to 220°F); and a quasi-high-temperature schedule that started at 230°F but then reduced to 195°F after 12 h. In drying to a final moisture content of 10%, STUD grade recovery ranged from 36% to 45%, with the highest recovery being in the group dried by the conventional temperature schedule. There was no statistical difference in STUD grade recovery between the four experimental schedules, but the conventional temperature schedule had the best average recovery (45%) and the combination of air and kiln drying had the worst recovery (27%). Crook was the major cause of grade loss.

Smith and Siau (1979) studied the effect of kiln schedule (conventional (maximum 180°F) and high temperature (240°F)) and top load (200 lb/ft^2) on plantation-grown red pine 2 by 4's sawn from trees 8 to 12 in. in diameter. The top load resulted in reduction in twist, bow, and crook ranging from 40% to 70%, with the greatest reduction from the high temperature schedule.

Dedrick and Ziegler's (1984) research on warp control included the use of a continuously rising temperature (CRT) kiln schedule (140°F ramped to 220°F over 40 h, and then held at 220°F for 20 h) and variable top restraint pressure. They used a patented leaf spring device capable of 250 lb/ft^2 pressure on the top unit of a lumber stack before drying. The pressure was reduced to some unstated lesser pressure when the lumber was dried to 9% moisture content. The lumber was 2- by 4-in. dimension sawn from small logs of the western hemlock–true fir commercial mix. Grade loss was reduced by about one-third compared with top units without the restraint. The grade loss in the restrained top units was about the same as grade loss in bottom units, which benefited from the cumulative weight of the upper units.

Koch (1971) developed a process for straightening and drying southern pine 2 by 4's sawn from veneer cores or small diameter (6- to 8-in.) logs. Kiln drying was at 240°F. The restraining device was a clamping system that provided almost total restraint against crook, bow, and twist. Lateral aluminum strips were inserted running the length of each board to prevent crook, and spring-loaded bolts were run vertically up the lumber stack through stickers clamped to boards to prevent bow and twist. Compared to 2 by 4's dried unrestrained at temperatures up to 180°F, the restrained 2 by 4's dried at high temperature had substantially less warp and higher grade yield. Crook was reduced by about half, bow by about one-quarter, and twist by about two-thirds. Grade yield in No.1, No.2, and STUD (SPIB 1968) was 91% for the high-temperature dried and restrained 2 by 4's and 59% for the conventional temperature dried and unrestrained 2 by 4's.

Koch (1974) also investigated the effectiveness of a serrated sticker design in conjunction with a top load and high-temperature drying (240°F) on warp suppression in 2 by 4's sawn from southern pine veneer cores. The serrated stickers were pressed into the 2 by 4's with clamping forces of 50 to 200 lb per sticker pair per 2 by 4. The 2 by 4's dried between the serrated stickers had crook, bow, and twist averaging only 54%, 70%, and 46%, respectively, of 2 by 4's dried between smooth stickers.

Wengert and Baltes (1974) developed a "pinned" sticker to reduce crook during drying and applied it in drying 2 by 4 southern pine studs sawn from veneer cores and dried at 230°F. The pinned sticker was a conventional sticker modified with metal pins inserted vertically to provide side restraints if a board attempted to crook more than the 0.125-in. spacing between board edges and the pin. Crook was reduced 29% compared with 2 by 4's dried between conventional stickers.

Shelly and Simpson (1999) compared the warp that developed in drying 1-in.-thick lumber sawn from small-diameter suppressed Douglas-fir. Logs averaged about 7 in. in diameter and were from trees ranging from 70 to 90 years old, with growth rates of about 20 years per inch of radius. Drying variables were the eight combinations of two kiln schedules (a conventional temperature steam-heated kiln schedule and a lower temperature schedule typical of a dehumidifier kiln schedule); presteamed or not presteamed; and top loaded (200 lb/ft^2) or not top loaded. The only drying factor that was effective in reducing warp was application of the top load in reducing twist. However, the top-load restraint did not reduce the magnitude of twist to below the limits for high-grade select lumber. Bow and crook were well within grade limits in all eight drying schemes.

Milota (1992) did not find any effect of kiln schedule on the amount of warp that developed in 2- by 6-in. lumber sawn from both large (16- to 27-in. diameter) and small (average diameter of 10 in.) material. The four kiln schedules tested ranged in temperature from 160°F to 190°F. Milota (2000) also tested the effect of kiln schedule on warp in 2 by 4's of the commercial western hemlock–true fir mix of species. He found that drying at high temperature (240–250°F) resulted in less bow and crook than lumber dried at conventional temperature (180°F), although the reduction was not significant.

Maeglin and Boone (1983) studied the effect of sawing pattern and kiln schedule on the grade recovery of studs sawn from 8- to 12-in.-diameter ponderosa pine trees. Kiln schedules were conventional (maximum temperature 180°F) and high temperature (240°F), with no top loading. In addition to a conventional sawing pattern (centered cant and split taper), they included the saw–dry–rip (SDR) pattern, which is accomplished by producing flitches from live sawing, drying the flitches, and ripping to 2 by 4 in. after drying. STUD grade yields varied from 60% to 73% — the lowest values for conventional sawing–conventional temperature drying and the highest values (by only a slight margin) for conventional sawing–high temperature drying. They concluded that with the additional modifications of heavy top load and serrated stickers, SDR might be effective in improving the economics of processing young ponderosa pine into lumber.

Maeglin and Boone (1986) also applied SDR to plantation-grown southern pine (6- to 12-in.-diameter trees) in the production of 2 by 4 studs, using only high temperature (240°F) drying. They found an 11% to 16% increase in the yield of STUD grade 2 by 4's produced by SDR compared with the yield from conventional sawing.

Erickson and others (1989) investigated predrilling and vertical stacking to improve drying results in aspen 2 by 4's. Two rows of 0.375-in.-diameter holes on 6-in. centers were drilled through the thickness of each green 2 by 4 for the purpose of decreasing drying time and improving the uniformity of final moisture content. The lumber was stacked on edge and top loaded in an effort to reduce crook. Unfortunately during drying, vertical rods placed to maintain the boards on edge in the stack interfered with the top load, resulting in only partial restraint and inconclusive results.

Compton and others (1977) developed a process they termed edge-glue-and-rip (EGAR) and applied it to lumber sawn from 6- to 13-in.-diameter shortleaf pine logs. In the EGAR process, logs were live sawn, the flitches were lightly edged for more efficient use of kiln space, and the logs were then kiln dried with a schedule of 205°F maximum temperature. After kiln drying, the flitches were fully edged to eliminate all wane and the edged boards were glued into panels. After the glue cured, lumber of any width could be sawn from the panels. For 2 by 4 lumber, bow was reduced by 57% and crook by 44%. Twist was not reduced.

Another approach to warp reduction is the restraint from platens in hot press drying, which has been shown to reduce warp in plantation-grown loblolly pine 2 by 4's (Simpson and others 1988, 1992). Platen pressures of 25 lb/in^2 were found to be effective and represent a high level of top-load restraint — about 3,600 lb/ft^2 in a press compared with the 100 to 200 lb/ft^2 using dead weight top loads in kilns. In most cases, warp in press drying was less than one-half of the warp in kiln drying. Another advantage of press drying is short drying cycles — about 90 to 120 min for nominal 2-in.-thick loblolly pine at platen temperatures ranging from 350°F to 410°F.

The warp problem in lumber from small-diameter trees goes beyond just during kiln drying. Storage after kiln drying can also be an important factor. Typically softwood dimension lumber is dried to about 15% moisture content, sometimes to 12% in dryer parts of the United States. But sometimes lumber will continue to dry as it equilibrates to prevailing weather conditions after it has been removed from the kiln and unstacked, especially in the arid western United States. Markstrom and others (1984) showed this effect for ponderosa pine studs sawn from 9- to 14-in.-diameter ponderosa pine trees. The studs were kiln dried to between 15% and 19% moisture content and then stored in conditions that reduced moisture content to 9% and then 6%. They noted a marked reduction in the percentage of boards that met STUD grade (and an increase in culls) as moisture content was reduced from between 15% and 19% immediately after kiln drying to 9% and then to 6% moisture content.

Experimental

Two drying studies were conducted. One study was done in cooperation with a commercial sawmill (Fremont Lumber Company, Lakeview, Oregon, owned by The Collins Companies). This study utilized 80- to 100-year-old suppressed-growth trees that were 6 to 16 in. in diameter harvested from the Flagstaff, Arizona, area. The other study was done at the Forest Products Laboratory with 30- to 35-year-old open-grown trees with about a 9-in. diameter from a planted stand in Idaho. The lumber was sawed in a Boise–Cascade mill (Boise, Idaho) and shipped to Madison, Wisconsin, for drying.

Drying Variables

This study concentrated on presteaming, top loading, and kiln schedule as the principal variables. A limited investigation of press drying was also planned.

Arizona: Four experimental groups were planned:

No presteaming/top load	NPS-TL
No presteaming/no top load	NPS-NTL
Presteaming/top load	PS-TL
Presteaming/no top load	PS-NTL

The kiln schedule was the conventional temperature schedule used by Fremont Sawmill for ponderosa pine dimension lumber (Table 2). Target final moisture content was 15%. All four experimental groups were dried in the kiln at the same time. The two groups that were not to be presteamed were kept outside the kiln during presteaming and then pushed into the kiln. Each of the four groups was the top unit on a lumber stack. Because of production practicalities and the need for some of the material for other lumber classes and sizes as part of a broader yield study conducted by the USDA Forest Service, Pacific Northwest Research Station, it was not possible to maintain the same number of boards (2 by 4's) in each group. The numbers are as follows:

NPS-TL	203
NPS-NTL	195
PS-TL	117
PS-NTL	105

The plan was to presteam at 175°F for 4 h. However, in practice, the kiln was not able to accomplish that performance. The actual presteaming was a gradual rise in steaming temperature from 120°F to 130°F during a 10 h period before going into the kiln schedule shown in Table 2. Top loading was with concrete slabs that produced 75 lb/ft^2 of pressure.

Idaho: The following nine experimental groups were planned:

Conventional temperature schedule/ presteaming/top load	CT-PS-TL
Conventional temperature schedule/ presteaming/no top load	CT-PS-NTL
Conventional temperature schedule/ no presteaming/top load	CT-NPS-TL
Conventional temperature schedule no presteaming/no top load	CT-NPS-NTL
High-temperature schedule/ presteaming/top load	HT-PS-TL
High-temperature schedule/ presteaming/no top load	HT-PS-NTL
High-temperature schedule/ no presteaming/top load	HT-NPS-TL
High-temperature schedule/ no presteaming/no top load	HT-NPS-NTL
Press drying	PD

The kiln schedules are shown in Table 2. Air velocity was approximately 550 ft/min for the conventional temperature schedule and 1,000 ft/min for the high-temperature schedule. Final target moisture content was 15% as estimated with a conductive moisture meter with electrode pins driven into the edge of boards to a depth of 0.75 in. and as corrected for temperature and species. Each kiln charge consisted of 13 courses of 12 boards each, for a total of 156 boards per group. Moisture content during kiln drying was estimated by metering the edge boards of seven courses on one side of the charge (in two locations along the length of each edge board) and the edge boards of the remaining six courses on

Table 2—Kiln schedules for drying ponderosa pine 2 by 4's

Time (h)	Dry-bulb temperature °F (°C)	Wet-bulb temperature °F (°C)
Arizona		
0–12	140 (60)	130 (54)
12–24	145 (63)	130 (54)
24–36	155 (68)	130 (54)
36–48	165 (74)	130 (54)
48–60	180 (82)	130 (54)
Eqlz. to 17%	180 (82)	162 (72)
Cond. 8 h	180 (82)	172 (78)
Idaho		
Conventional temperature schedule		
0–24	160 (71)	140 (60)
24–36	165 (74)	140 (60)
36–end (15% MC)	170 (77)	140 (60)
End + 5	170 (77)	163 (73)
High-temperature schedule		
0–12	230 (110)	205 (96)
12–24	230 (110)	200 (93)
24–end (15% MC)	230 (110)	195 (91)
End + 5	180 (82)	173 (78)

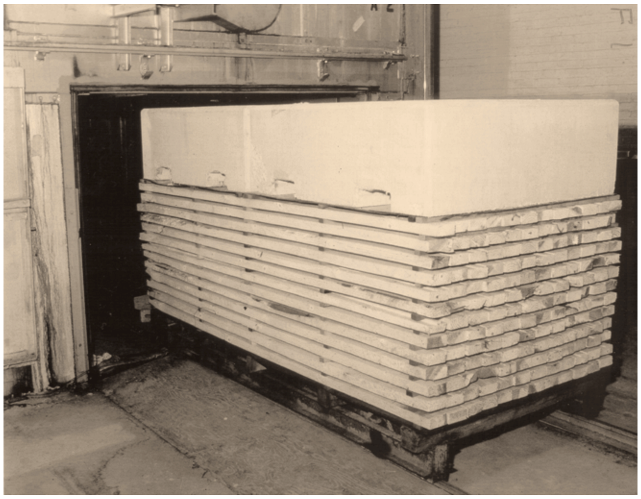

Figure 1—Ponderosa pine 2 by 4's from Idaho with 200-lb/ft^2 top load awaiting kiln drying in Forest Products Laboratory experimental dry kiln.

Figure 2—Measuring warp in ponderosa pine 2 by 4's from Arizona.

the other side of the charge. Presteaming was at 190°F to 200°F and held for 4 h after warm-up. Top loading was 200 lb/ft^2 applied with 16-in.-thick concrete slabs (Fig. 1). Press drying was with a platen temperature of 375°F and pressure of 25 lb/in^2 (3,600 lb/ft^2). For press drying, it was necessary to first develop a drying rate curve so that the press time required to reach the target moisture content of 15% could be estimated. This was done by press drying six press loads of six boards each, periodically opening the press to weigh the boards, and including a final weight after 6 h, which was taken as the ovendry weight for moisture content calculations. Thus, a moisture content versus time curve was established for determining the average time required to reach 15%.

Experimental Material

Arizona: The logs were shipped from Flagstaff, Arizona, to Lakeview, Oregon, for sawing and drying because it was not possible to find a cooperating mill closer to the harvest site. The main study involving this material was a grade and yield study, but as one part of the study, some material was allocated to observe warp and look at ways to reduce it. Because of this, it was not possible to produce the exact quantities and sizes of lumber we would have liked. Besides the unequal numbers of boards in each of the four groups, there was also a mixture of lengths (most were 16 ft long, but some were 8, 10, 12, and 14 ft long), which complicated warp comparisons.

Idaho: The lumber was 8-ft-long 2 by 4's sawn from small-diameter planted ponderosa pine trees in Idaho. After sawing, the individual packages of lumber were wrapped in plastic and shipped to Madison, Wisconsin. This was done in the winter, and all drying was completed before the warm weather of spring reduced moisture content or caused appreciable mold. Green moisture content for each group was estimated by weighing and ovendrying two extra boards for each group. Enough lumber was prepared to supply 156 boards for each of the nine experimental groups, plus some extras. Unfortunately, one of the kilns failed during a test run, so that run was replaced by the lumber intended for press drying. Consequently, only 36 boards from the extras were available for evaluating the effect of press drying on warp.

Experimental Measurements

Arizona: The lumber was planed to 1.5 by 3.5 in. after drying. Then crook, bow, and twist were measured with a wedge gauge divided into 1/32-in. increments (Fig. 2). Moisture content was measured with a conductance meter in two positions, about 18 to 24 in. from each end. Because not all boards were the same length, it was necessary to adjust warp measurements to a common length, which was chosen to be 16 ft. To adjust crook and bow (assuming they scribe the arc of a circle), the adjustment formula is

$$w_2 = w_1(a_2/a_1)^2$$

where w_2 is crook or bow at the adjusted length (16 ft for this study); w_1, crook or bow at the measured length (8, 10, 12, or 14 ft); a_2, adjustment length (16 ft for this study); a_1, actual board length (8, 10, 12, or 14 ft).

To adjust twist,

$$t_2 = t_1(a_2/a_1)$$

where t is twist and all other symbols are the same as for crook and bow. Twist adjustment for width is also necessary in the general case, but since all boards here were 2 by 4's, no width adjustment was necessary. The derivation of the above formulas is given in Simpson and Shelly (2000).

Idaho: When the lumber arrived in Madison, it was graded green and rough by a quality supervisor for the Western Wood Products Association using grading rules for Structural Light Framing (WWPA 1998). The boards were then randomly assigned to the nine experimental groups so that all five grades (Select Structural, #1, #2, #3, and Economy) were equally represented in all nine groups.

After drying, the 2 by 4's were measured for crook, bow, and twist with the wedge gauge. Moisture content was measured with a conductance meter in two positions, about 18 to 24 in. from each end. The boards were next planed to 1.5 by 3.5 in. and then stored in conditions of approximately 10% to 12% equilibrium moisture content for several months. The lumber was then regraded according WWPA Structural Light Framing rules, both as observed (including any warp) and ignoring warp.

Results and Discussion

Drying Times and Moisture Contents

Arizona: Drying times and final moisture contents are shown in Table 3 and average approximately 120 h and 13%, respectively.

Table 3—Drying times and initial and final moisture contents for the nine experimental groups of ponderosa pine 2 by 4's

Drying schedule[a]	Drying time (h)	Green moisture content (%)	Final moisture content (%)
Arizona			
NPS-TL	118	—	12.2 (14.8)[b]
NPS-NTL	118	—	14.1 (25.7)
PS-TL	140[c]	—	12.9 (17.8)
PS-NTL	140[c]	—	13.0 (15.4)
Idaho			
CT- PS- TL	91	138	15.4 (25.5)
CT- PS-NTL	73	155	13.3 (35.9)
CT-NPS- TL	87	151	15.3 (19.0)
CT-NPS-NTL	62	158	16.5 (21.4)
HT- PS- TL	45	168	16.1 (36.3)
HT- PS-NTL	39	154	15.2 (23.8)
HT-NPS- TL	36	181	12.8 (29.6)
HT-NPS-NTL	47	167	9.8 (23.9)
PD	3.2	165	17.0 (46.0)

[a]NPS, no presteaming; PS, presteaming; NTL, no top load; TL, top load; CT, conventional temperature schedule; HT, high-temperature schedule; PD, press dried.
[b]Coefficient of variation in parentheses.
[c]Includes 15 h of kiln malfunction.

Idaho: Drying times and green and final moisture contents are listed in Table 3. The high-temperature schedule reduced drying time by about half compared with the conventional temperature schedule (from approximately 80 to 40 h). Press drying time was slightly more than 3 h. Average green moisture content was 160%, and final moisture contents varied from 9.8% for one of the high-temperature runs to 17.0% for press drying.

Arizona and Idaho: As discussed in the literature review, final moisture content affects the amount of warp. Warp comparisons between boards that were dried to different final moisture contents may not be entirely accurate. Therefore, an attempt was made to adjust warp measurements for each board from the estimated final moisture content of the board to a common moisture content basis by developing a relationship between warp and final moisture content for each of the experimental groups. An example is shown for crook in Figure 3. The plots were typically highly scattered and non-normally distributed, which precludes any statistical conclusions based on linear regression. However, plots for all 12 combinations of the four Arizona groups and three forms of warp and all 27 combinations of the nine Idaho experimental groups and three forms of warp show an increase in warp as final moisture content decreases. Table 4 gives the linear regression coefficients used to adjust crook, bow, and twist measurements from actual final moisture contents to 15% moisture content so that all comparisons were on an equal basis. Because of the high degree of scatter of the plotted points and the consequent uncertainty of the warp adjustment, warp analysis was conducted on both actual and adjusted final moisture contents.

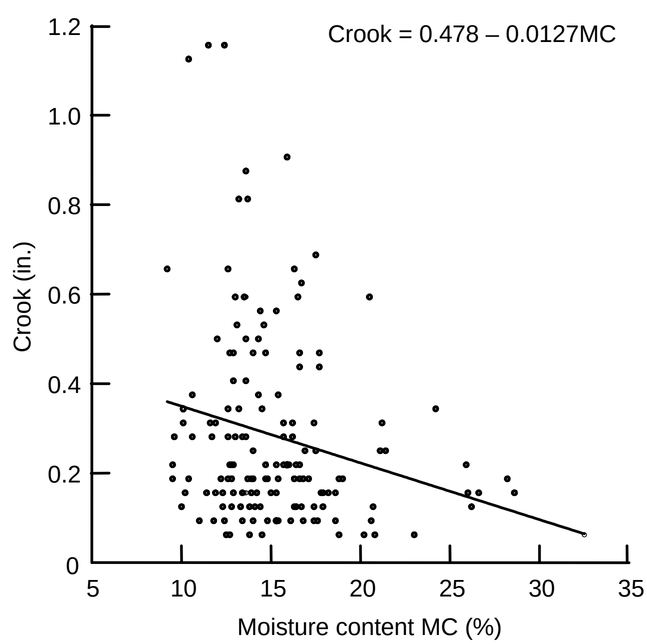

Figure 3—Relationship between crook in ponderosa pine 2 by 4's and final moisture content.

Table 4—Linear regression coefficients of warp versus final moisture content for ponderosa pine 2 by 4’s (Warp (in.) = *a* + *b* × final moisture content)

	Crook			Bow			Twist		
Drying schedule[a]	*a*	–*b*	R^2	*a*	–*b*	R^2	*a*	–*b*	R^2
Arizona									
NPS–TL	1.127	0.0428	0.025	3.105	0.148	0.076	0.515	0.0213	0.048
NPS–NTL	1.338	0.0501	0.080	2.340	0.0720	0.066	0.572	0.0222	0.122
PS–TL	1.177	0.0485	0.058	3.392	0.163	0.099	0.511	0.0188	0.032
PS–NTL	1.245	0.0472	0.034	3.078	0.136	0.074	0.509	0.0106	0.003
Idaho									
CT–PS–TL	0.478	0.0127	0.052	0.811	0.0230	0.068	0.321	0.0113	00.114
CT–PS–NTL	0.779	0.0283	0.135	1.411	0.0568	0.263	0.476	0.0183	0.156
CT–NPS– TL	0 .998	0.0445	0.173	1.156	0.0365	0.050	0.287	0.0083	0.030
CT–NPS–NTL	0.704	0.0225	0.104	0.845	0.0211	0.045	0.350	0.0099	0.049
HT–PS–TL	0.355	0.0044	0.020	0.522	0.0057	0.015	0.187	0.0033	0.029
HT–PS–NTL	0.553	0.0164	0.058	0.966	0.0262	0.070	0.328	0.0068	0.017
HT–NPS–TL	0.363	0.0070	0.019	0.618	0.0132	0.025	0.161	0.0041	0.022
HT–NPS–NTL	0.559	0.0163	0.014	0.553	0.0025	0.003	450	0. 0204	0.061
PD	0.594	0.0178	0.254	0.936	0.0244	0.218	0.265	0.0038	0.036

[a]NPS, no presteaming; PS, presteaming; NTL, no top load; TL, top load; CT, conventional temperature schedule; HT, high-temperature schedule; PD, press dried.

Warp Immediately After Drying

Preliminary statistical analysis of the warp data showed that it was not normally distributed. Therefore, a nonparametric analysis, Kruskal–Wallis one way analysis of variance on ranks (Glanz 1992), was used. This analysis considers median values instead of mean values. When the results of the analysis of variance showed a significant treatment effect, the Student–Newman–Keuls method (Glanz 1992) for individual group comparisons was used.

Arizona: Table 5 shows the median values of crook, bow, and twist for the four experimental groups. Results at actual final moisture contents and those adjusted to 15% final moisture content are shown. Warp values are shown for 16-ft lengths and also for 8-ft lengths for comparison with the Idaho results. It is difficult to see trends or draw conclusions from the data in Table 5. None of the differences in unadjusted medians for a given type of warp were significantly different in the top load/no top load comparisons or the presteam/no presteam comparisons. In fact, in some cases, the median warp was greater in top-loaded or presteamed boards than in no top load or no presteam. This could be explained by differences in final moisture content. In all comparisons, adjusted crook, bow, and twist medians were less for top loading than for no top loading. However, in the direct comparisons of the effect of top loading (when presteaming or no presteaming is held constant in the comparison), only the NPS-TL versus NPS-NTL comparison for bow shows a significant difference. The summary of this result is somewhat weak evidence that top loading does reduce warp by a modest amount. A factor in this comparison is the low level of top loading. Plans were to top load at 150 lb/ft^2, but only 75 lb/ft^2 were available. If top loading could have been at the 150- to 200-lb/ft^2 level, it might have been more effective.

Idaho: The median values of crook, bow, and twist for the Idaho study are also shown in Table 5, for both unadjusted and adjusted final moisture contents. The results of the individual comparisons using the Student–Newman–Kreuls method is shown in Table 6, noting statistically significant differences. (The Arizona results were not included in Table 6 because so few of the comparisons were significantly different. In the interest of space efficiency, the few that were are noted in Table 5). Press drying was not included in the analysis of variance because of the limited number of specimens. In general, top loading was effective in reducing all forms of warp, as indicated by the significant differences in Table 6. The comparisons in Table 6 are the direct comparisons for the effect of top loading, that is when the other two variables, presteaming and kiln schedule, are the same. There are four of these comparisons for each combination of warp type and the three main variables. The comparisons not shown in Table 6 were not significantly different. The one exception to the effectiveness of top loading was that bow in CT–NPS–TL was greater than in CT–NPS–NTL. This significant difference was noted in the bow values not adjusted to 15% moisture content. In the bow comparison for values that were adjusted to 15% moisture content, the difference was not statistically significant even though the median value of bow was greater in the top-loaded group (Table 5). There is no apparent explanation for this unexpected observation. If this one suspected anomaly is ignored, the

Table 5—Median values of warp in drying ponderosa pine 2 by 4's

Drying schedule[a]	Final moisture content (MC) (%)	Warp unadjusted for final MC (in.)			Warp adjusted to 15% final MC (in.)		
		Crook	Bow	Twist	Crook	Bow	Twist
Arizona							
				16-ft-long basis			
NPS-TL	12.2	0.438	1.041	0.234	0.311	0.615[b]	0.173[c]
NPS-NTL	14.1	0.406	1.156	0.219	00.412	1.103b[b,d]	0.199
PS-TL	12.9	0.400	1.000	0.188	0.336	0.656[d]	0.156
PS-NTL	13.0	0.440	1.086	0.250	0.377	0.931	0.226[c]
				8-ft-long basis			
NPS-TL	12.2	0.111	0.260	0.117	0.078	0.154[b]	0.087[c]
NPS-NTL	14.1	0.101	0.289	0.111	0.103	0.276[b,d]	0.100
PS-TL	12.9	0.100	0.250	0 .094	0.084	0.164[d]	0.039
PS-NTL	13.0	0.110	0.272	0.125	0.094	0.233	0.113[c]
Idaho[e]							
				8-ft-long basis			
CT- PS- TL	15.4	0.188	0.344	0.094	0.218	0.356	0.127
CT- PS-NTL	13.3	0.250	0.484	0.156	0.266	0.489	0.169
CT-NPS- TL	15.3	0.219	0.469	0.125	0.266	0.524	0.138
CT-NPS-NTL	16.5	0.266	0.375	0.156	0.305	0.441	0.168
HT- PS- TL	16.1	0.250	0.406	0.125	0.242	0.384	0.119
HT- PS-NTL	15.2	0.219	0.469	0.156	0.248	0.499	0.174
HT-NPS- TL	12.8	0.219	0.344	0.094	0.190	0.303	0.077
HT-NPS-NTL	9.8	0.297	0.438	0.188	0.235	0.424	0.100
PD	17.0	0.172	0.406	0.125	0.278	0.422	0.146

[a]NPS, no presteaming; PS, presteaming; NTL, no top load; TL, top load; CT, conventional temperature schedule; HT, high-temperature schedule; PD, press dried.
[b,c,d] Values with letters in common are significantly different.
[e]Significant differences detailed in Table 6.

percentage reductions in the median values of warp due to top loading are

Warp form	Unadjusted for final MC (%)	Adjusted to 15% final MC (%)
Crook	13.7	13.1
Bow	21.3	26.3
Twist	32.3	25.4

Even though it seems reasonable to conclude that top loading causes a statistically significant reduction in all forms of warp, the question remains whether or not the reduction also reduces grade loss. This question is addressed in the next section.

Despite press drying not being included in the statistical analysis, the median warp values in Table 5 suggest that it has no large effect in suppressing warp. This is interesting because it represents an extreme level of top loading.

The results of presteaming and kiln schedule comparisons (head-to-head comparisons when the other two main variables are held constant) show little consistency of any effect in terms of statistical differences. In several comparisons in Table 6, the results were contrary to what was expected. Therefore, it seems likely that there is no evidence of any reduced warp soon after drying with either presteaming or high-temperature drying when applied to ponderosa pine.

Grade After Drying

Ponderosa pine dimension lumber can be graded by three systems in the WWPA (1998) grading rules—Light Framing, Structural Light Framing, and STUD. There is a commonality in the grade warp limits (Table 7) between these three systems. For the purpose of this analysis, warp is generalized into four levels: A, B, C, and D (Table 7). For example, the crook limit (8-ft-length basis) for Construction (Light Framing), Select Structural/#1 (Structural Light Framing), and STUD (STUD) is 0.25 in., and this limit will be considered level A for this analysis.

Table 6—Statistically significant differences in crook, bow, and twist between experimental groups of Idaho ponderosa pine 2 by 4's. Analysis was the Kruskal–Wallis one way analysis of variance on ranks, with the Student–Newman–Keuls method for pairwise comparisons (Glanz 1992)

Crook	Bow	Twist
	Unadjusted for final moisture content	
Top loading		
CT-PS-**TL**<CT-PS-**NTL**[a]	CT-PS-**TL**<CT-PS-**NTL**	HT-NPS-**TL**<HT-NPS-**NTL**
HT-NPS-**TL**<HT-NPS-**NTL**	HT-PS-**TL**<HT-PS-**NTL**	HT-PS-**TL**<HT-PS-**NTL**
CT-NPS-**TL**<CT-NPS-**NTL**	CT-NPS-**NTL**<CT-NPS-**TL**	CT-PS-**TL**<CT-PS-**NTL**
	HT-NPS-**TL**<HT-NPS-**NTL**	CT-NPS-**TL**<CT-NPS-**NTL**
Presteaming		
HT-**PS**-NTL<HT-**NPS**-NTL	CT-**NPS**-NTL<CT-**PS**-NTL	HT-**PS**-NTL<HT-**NPS**-NTL
	CT-**PS**-TL<CT-**NPS**-TL	CT-**PS**-TL<CT-**NPS**-TL
		HT-**NPS**-TL<HT-**PS**-TL
Kiln schedule		
CT-NPS-NTL<**HT**-NPS-NTL	**HT**-NPS-TL<**CT**-NPS-TL	**CT**-NPS-NTL<**HT**-NPS-NTL
HT-PS-NTL<**CT**-PS-NTL	**CT**-NPS-NTL<**HT**-NPS-NTL	**HT**-NPS-TL<**CT**-NPS-TL
	Adjusted to 15% final moisture content	
Top loading		
CT-NPS-**TL**<CT-NPS-**NTL**	HT-PS-**TL<**HT-PS-**NTL**	HT-PS-**TL**<HT-PS-**NTL**
	CT-PS-**TL**<CT-PS-**NTL**	CT-NPS-**TL**<CT-NPS-**NTL**
	HT-NPS-**TL**<HT-NPS-**NTL**	CT-PS-**TL**<CT-PS-**NTL**
		HT-NPS-**TL**<HT-NPS-**NTL**
Presteaming		
CT-**PS**-NTL<CT-**NPS**-NTL	CT-**PS**-TL<CT-**NPS**-TL	HT-**NPS**-TL<HT-**PS**-NTL
	HT-**NPS**-TL<HT-**PS**-TL	HT-**NPS**-TL<HT-**PS**-TL
Kiln schedule		
HT-NPS-NTL<**CT**-NPS-NTL	**HT**-NPS-TL<**CT**-NPS-TL	**CT**-PS-NTL<**HT**-PS-NTL
		HT-NPS-NTL<**CT**-NPS-NTL
		HT-NPS-TL<**CT**-NPS-TL
		HT-PS-TL<**CT**-PS-TL

[a]The less than sign indicates that the CT-PS-NTL group was significantly greater than the CT-PS-TL group.

Table 7—Warp limits for ponderosa pine dimension lumber under three Western Wood Products Association grading systems (WWPA 1998)

	Crook (in.) for different board lengths					Bow (in.) for different board lengths					Twist (in.) for different board lengths					
Grade	8 ft	10 ft	12 ft	14 ft	16 ft	8 ft	10 ft	12 ft	14 ft	16 ft	8 ft	10 ft	12 ft	14 ft	16 ft	Level
								Light Framing								
Construction	0.250	0.375	0.500	0.625	0.750	0.500	1.375	1.500	2.000	2.500	0.375	0.438	0.565	0.625	0.750	A
Standard	0.375	0.500	0.688	0.875	1.000	0.750	1.500	2.000	2.500	3.125	0.500	0.625	0.750	0.875	1.000	B
Utility	0.500	0.750	1.000	1.250	1.500	1.000	2.750	3.000	4.000	5.000	0.750	0.875	1.125	1.250	1.500	C
Economy	No limit															D
								Structural Light Framing								
Select structural	0.250	0.375	0.500	0.625	0.750	0.500	1.375	1.500	2.000	2.500	0.375	0.438	0.563	0.625	0.750	A
No 1	0.250	0.375	0.500	0.625	0.750	0.500	1.375	1.500	2.000	2.500	0.375	0.438	0.563	0.625	0.750	A
No 2	0.375	0.500	0.688	0.875	1.000	0.750	1.500	2.000	2.500	3.125	0.500	0.625	0.750	0.875	1.000	B
No 3	0.500	0.750	1.000	1.250	1.500	1.000	2.750	3.000	4.000	5.000	0.750	0.875	1.125	1.250	1.500	C
Economy	No limit															D
								STUD								
Stud	0.250					0.500					0.375					A
Economy	No limit															D

Table 8—Cumulative percentage of ponderosa pine 2 by 4's that met grade warp limits before planing (WWPA 1998)

	Percentage of boards meeting grade warp limits															
	Crook				Bow				Twist				Any			
Drying schedule[a]	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Arizona (16 ft)	Unadjusted for final moisture content															
NPS-TL	71.9	81.3	92.6	100	87.2	93.1	99.5	100	97.5	99.6	100	100	65.5	75.8	92.1	100
NPS-NTL	71.7	81.6	91.5	100	86.4	93.7	99.5	100	97.9	98.9	99.4	100	64.9	76.9	90.5	100
PS-TL	77.8	85.5	92.3	100	86.3	91.4	97.4	100	96.6	98.3	100	100	67.5	78.6	89.7	100
PS-NTL	72.6	82.0	89.5	100	88.7	94.4	99.1	100	85.8	97.1	98.0	100	60.4	79.3	87.8	100
	Adjusted to 15% moisture content															
NPS-TL	76.8	85.2	94.6	100	93.1	95.1	99.5	100	98.0	99.5	100	100	72.4	80.8	94.1	100
NPS-NTL	74.3	83.2	91.6	100	89.0	93.2	99.5	100	97.9	98.9	100	100	68.1	78.0	91.1	100
PS-TL	82.1	87.2	94.9	100	92.3	94.0	99.1	100	95.7	99.1	100	100	76.1	84.6	94.9	100
PS-NTL	75.5	83.0	94.3	100	93.4	98.1	99.0	100	86.8	96.2	98.1	100	67.0	79.3	91.6	100
Idaho (8 ft)	Unadjusted for final moisture content															
CT-PS-TL	64.1	78.2	86.5	100	73.1	83.4	91.1	100	93.6	98.7	100	100	45.5	66.7[b]	80.2	100
CT-PS-NTL	51.9	64.8	74.3	100	53.2	70.5	80.8	100	79.5	88.5	96.2	100	29.5	44.9[b]	62.8	100
CT-NPS-TL	59.0	76.3	84.6	100	52.6	72.5	83.4	100	90.4	97.5	100	100	29.5	56.4	73.7	100
CT-NPS-NTL	50.0	69.9	80.8	100	60.3	80.2	93.0	100	92.3	95.5	99.3	100	31.4	60.2	74.3	100
HT-PS-TL	53.2	76.3	89.1	100	71.8	88.5	95.6	100	96.8	98.7	100	100	38.5	66.7[b]	85.3	100
HT-PS-NTL	57.0	73.8	84.1	100	54.5	72.4	88.4	100	80.1	91.6	987	100	26.3	48.7[b]	73.7	100
HT-NPS-TL	64.7	76.2	87.1	100	69.2	85.2	92.3	100	98.7	99.3	100	100	43.6	65.4[b]	80.8	100
HT-NPS- NTL	43.6	60.3	75.0	100	59.0	75.0	91.0	100	80.1	91.0	97.4	100	21.8	39.7[b]	67.3	100
PD	63.9	69.5	80.6	100	63.9	75.0	80.6	100	88.9	97.2	100	100	47.2	55.5[b]	69.4	100
	Adjusted to 15% moisture content															
CT-PS-TL	59.0	75.7	86.0	100	69.9	84.0	91.7	100	93.6	98.7	100	100	41.0	66.0[b]	80.1	100
CT-PS-NTL	48.1	65.4	76.3	100	51.3	75.7	86.6	100	84.6	91.0	97.4	100	25.0	48.7[b]	67.9	100
CT-NPS-TL	47.4	71.1	85.2	100	48.1	70.5	82.0	100	89.1	97.4	100	100	18.6	51.9	71.1	100
CT-NPS-NTL	37.8	61.5	78.8	100	59.6	80.8	91.7	100	87.7	96.1	99.3	100	25.0	52.6	71.8	100
HT-PS-TL	52.6	71.8	86.5	100	67.9	86.5	94.8	100	96.8	98.7	100	100	35.3	62.2[b]	82.7	100
HT-PS-NTL	50.6	71.8	85.9	100	50.6	74.3	87.1	100	78.8	89.1	98.7	100	21.8	46.8[b]	73.7	100
HT-NPS-TL	64.7	77.5	87.1	100	72.4	83.9	93.5	100	98.7	99.3	100	100	46.2	64.1[b]	81.4	100
HT-NPS-NTL	55.1	67.9	81.4	100	59.0	74.4	90.4	100	90.4	95.5	99.3	100	27.6	48.8[b]	74.4	100
PD	38.9	66.7	86.1	100	52.8	66.7	83.4	100	88.9	97.2	100	100	22.2	47.2[b]	72.2	100

[a]NPS, no presteaming; PS, presteaming; NTL, no top load; TL, top load; CT, conventional temperature schedule; HT, high-temperature schedule; PD, press dried.

[b]Percentage meeting grade warp limits of at least level B is significantly higher (99.9% confidence level) in top-loaded boards than in those not top loaded (chi square analysis of contingency tables (Glanz 1992)).

Arizona: Table 8 shows the percentage of boards that meet grade warp limits according to crook, bow, and twist separately as well as the percentage that meet grade limits based on any form of warp as the limiting factor. The percentages are cumulative so that 100% meet level D limits. For example, for the group NPS-TL, unadjusted for final moisture content, 81.3% would meet level B if only crook is considered, 93.1% if only bow is considered, and 99.6% if only twist is considered. The percentages of most practical concern are those for meeting grade based on any form of warp being the limiting factor, and 75.8% would meet level B on this basis. The percentages meeting level B based on any form of warp were analyzed statistically for significant differences, and there is no evidence that top loading increased the percentage of boards meeting level B. Table 8 shows that crook and bow caused more grade loss that twist. This is also shown in Table 9, where the percentage of boards put into the lowest grade is listed by crook, bow, or twist. Crook caused the most grade loss, with about one-quarter of boards placed in the lowest grade because of crook. Only a few percent were placed in the lowest grade because of twist.

Table 9—Cause of warp downgrade in ponderosa pine 2 by 4's

Drying schedule[a]	Percentage of boards placed in lowest grade from			Growth
	Crook	Bow	Twist	
Arizona (after planing)				
NPS-TL	25.6	9.9	1.0[b]	Suppressed
NPS-NTL	27.2	9.4	1.6	Suppressed
PS-TL	21.4	9.4	2.6	Suppressed
PS-NTL	25.5	8.5	10.4	Suppressed
Idaho (before planing)				
CT-PS-TL	54.1	45.9	8.2	Planted
CT-PS-NTL	58.2	52.7	16.4	Planted
CT-NPS-TL	46.4	56.4	9.1	Planted
CT-NPS-NTL	65.4	38.3	6.5	Planted
HT-PS-TL	70.8	35.4	4.2	Planted
HT-PS-NTL	48.7	47.0	16.5	Planted
HT-NPS-TL	56.8	47.7	2.3	Planted
HT-NPS-NTL	60.7	41.0	13.9	Planted
PD	52.6	57.9	10.5	Planted

[a]NPS, no presteaming; PS, presteaming; NTL, no top load; TL, top load; CT, conventional temperature schedule; HT, high-temperature schedule; PD, press dried.
[b]Rows total more that 100% because in some boards, more than one form of warp placed the board in the lowest grade.

Idaho: The effect of the drying variables on lumber grade was analyzed in two ways: (1) by comparing the measured warp values with WWPA grade limits before planing; and (2) by having the lumber actually graded after planing. Each approach has strengths and weaknesses. By measuring warp before planing as in method 1, the effects of planing on altering the amount of warp present and possibly masking the effects of the drying variables are avoided. However, the weakness is that lumber is typically graded after planing, not before, so the usual sequence of processing and evaluation steps is not followed. Also, in method 1, "grade" assignment is by warp limits only and does not include other effects. Method 2 has the advantage of adhering to the industrial sequence of processing and evaluation steps but has the disadvantage of the planing possibly clouding the effects of the drying variables on warp. Also, because of limitations in research capabilities, it was not possible to have the lumber all planed and graded until about 3 months after the drying and initial warp measurements were taken. The effects of this storage time, when moisture contents and changes in warp might occur, could also cloud the effects of the drying variables on warp.

Method 1 (Idaho)—WWPA Grade Limits Before Planing

Table 8 shows the percentage of boards meeting grade warp limits according to crook, bow, and twist separately as well as the percentage that lost grade for exceeding grade limit for any form of warp. The percentages are cumulative so that 100% meet level D limits. For example, for the group CT-PS-TL, unadjusted for final moisture content, 64.1% would meet level A if only crook is considered, 73.1% if only bow is considered, and 93.6% if only twist is considered. But only 45.5% would meet level A if any one of the three forms of warp exceeded the limit.

The most useful observations in Table 8 are from the level B and C columns. Level B and C correspond to grades #2 and #3 in the Structural Light Framing grading system. The green grade results showed that 58.7% of the boards were #2 and 21.4% were #3 (with 0.3%, 13.7%, and 5.9%, respectively, in Select Structural, #1, and Economy). Thus, there is little practical reason to be concerned if boards do not meet level A warp limits in the Structural Light Framing (or Light Framing) systems because factors other than warp lower most boards below the grade that corresponds to this warp limit. (However, STUD grade must meet level A. Therefore, the level A columns are of interest for that system.) One observation from Table 8 is that crook and bow are far more likely to cause grade loss than twist. The amount that met grade limits, as judged by twist alone, was usually above 90%, while the amounts for crook or bow were considerably lower. This is also shown in Table 9, where the percentage of boards put into the lowest grade is listed by crook, bow, or twist. Only about 10% of boards are placed in their lowest grade because of twist.

Another observation is that top loading is effective in increasing the percentage that met warp grade limits considering any form of warp (with the exception of the previously mentioned anomaly caused by the bow comparisons CT-NPS-TL versus CT-NPS-NTL). For example, in the CT–PS comparisons (uncorrected for final moisture content), 66.7% of the top-loaded boards met at least level B and only 44.9% of the boards not top loaded met at least level B. The comparable percentages for the HT-PS and HT-NPS comparisons were 66.7% versus 48.7% and 65.4% versus 39.7%, respectively. This observation also applies to warp as corrected to 15% moisture content. All of these differences were statistically significant. There is no apparent pattern or effect of either presteaming or high-temperature drying on the values in Table 8.

Tables 8 and 9 also show that in general, lumber from the Arizona trees had less downgrade from warp than lumber from the Idaho trees. This is consistent with the premise that lumber from suppressed, slow-grown small-diameter trees will have higher grade yields than lumber from open, fast-grown small-diameter trees.

Method 2 (Idaho)—WWPA Grade After Planing

The cumulative grade distribution in the Structural Light Framing system after planing is shown in Table 10, and the statistical significance is shown in Table 11. High-temperature dried boards showed a significantly higher grade recovery than those dried at conventional temperature. There is evidence that top loading resulted in higher grade. But the results of presteaming were contrary to what would be expected—no presteaming resulted in higher grades than did presteaming.

Another way to analyze the results after planing is to consider the total amount of grade loss, that is, the difference between the actual after-planing grade and the grade if no warp were present, in each of the groups. Compared with analyzing just the grade results after planing, the total amount of grade loss counts the result when a board lost more than one grade level. Table 12 shows the total grade loss due to warp for each group, and Table 13 shows the statistical significance of the observed differences. There is no clear effect of top loading on the total amount of grade loss.

In three of the four possible direct comparisons between groups for the effect of presteaming, presteaming caused more grade loss than no presteaming. There is also a consistent and statistically significant effect of kiln schedule. High-temperature drying caused less grade loss than the conventional schedule. A explanation for this result is not clear, but considering that high-temperature drying or presteaming did not significantly reduce warp measurements immediately after drying, any effect must have occurred during the 3 months between drying and the grading after planing. Differences in final moisture content after drying but before the 3-month storage may help explain these two observations. The average final moisture content of the groups dried by the conventional temperature schedule was 15.1% (average total grade loss of 130), and for the high-temperature dried boards, 13.5% (average total grade loss of 66). Similarly, the average final moisture content for the groups that were presteamed was 15.0% (average total grade loss of 111) and 13.5% (average total grade loss of 85) for those that were not presteamed. While it was unfortunate that no constant equilibrium moisture content storage was available between the time the groups were finished drying and the time they were graded, the prevailing weather conditions in the Madison area during the summer led to approximately 10% to 12% equilibrium moisture content. Therefore, after kiln drying, all of the groups lost moisture content down to this range. The groups that were dried by conventional temperature lost more moisture during storage than those dried at high temperature, and the groups that were presteamed

Table 10—Cumulative percentage of Idaho ponderosa pine 2 by 4's meeting Structural Light Framing grade warp limits after planing (WWPA 1998)

	Percentage meeting grade warp limits				
Drying schedule[a]	Select structural	No. 1	No. 2	No. 3	Economy
CT-PS-TL	0	0.6	27.5	53.1	100
CT-PS-NTL	0	0	8.3	50.6	100
CT-NPS-TL	0	0	32.7	80.8	100
CT-NPS-NTL	0	0	14.7	54.4	100
HT-PS-TL	0	1.3	37.8	72.4	100
HT-PS-NTL	0	0 .6	39.1	80.1	100
HT-NPS-TL	0	0.6	53.8	80.7	100
HT-NPS-NTL	0	1.3	44.2	82.7	100
PD	0	2.8	30.6	63.9	100

[a]CT, conventional temperature schedule; HT, high-temperature schedule; PS, presteaming; NPS, no presteaming; TL, top load; NTL, no top load; PD, press dried.

Table 11—Statistical significance of grade in Idaho ponderosa pine 2 by 4's after planing. Kruskal–Wallis one way analysis of variance on ranks, with Student–Newman–Keuls method for pairwise comparisons (Glanz 1992)[a]

Top loading	Presteaming	Kiln schedule
CT-PS-**NTL**<CT-PS-**TL**[b]	CT-**PS**-NTL<CT-**NPS**-NTL	**CT**-PS-NTL<**HT**-PS-NTL
CT-NPS-**NTL**<CT-NPS-**TL**	CT-**PS**-TL<CT-**NPS**-TL	**CT**-NPS-NTL<**HT**-NPS-NTL
HT-PS-**TL**<HT-PS-**NTL**	HT-**PS**-TL<HT-**NPS**-TL	**CT**-PS-TL<**HT**-PS-TL
HT-NPS-**NTL**<HT-NPS-**TL**	HT-**PS**-NTL<HT-**NPS**-NTL	**CT**-NPS-TL<**HT**-NPS-TL

[a]CT, conventional temperature schedule; HT, high-temperature schedule; PS, presteaming; NPS, no presteaming; TL, top load; NTL, no top load.
[b]The less than sign indicates that the CT-PS-TL group was significantly greater than the CT-PS-NTL group.

Table 12—Total and median grade loss in Idaho ponderosa pine 2 by 4's after planing

Drying schedule[a]	Total[b]	Median
CT-PS-TL	143	1
CT-PS-NTL	148	1
CT-NPS-TL	89	0
CT-NPS-NTL	140	1
HT-PS-TL	81	0
HT-PS-NTL	72	0
HT-NPS-TL	65	0
HT-NPS-NTL	46	0
PD	82[c]	0

[a]CT, conventional temperature schedule; HT, high-temperature schedule; PS, presteaming; NPS, no presteaming; TL, top load; NTL, no top load; PD, press dried.
[b]Total number for grades lost in the 156 boards per group; that is, if a board lost two grade levels because of warp, then two went into calculation of the total.
[c]Prorated to 156 boards.

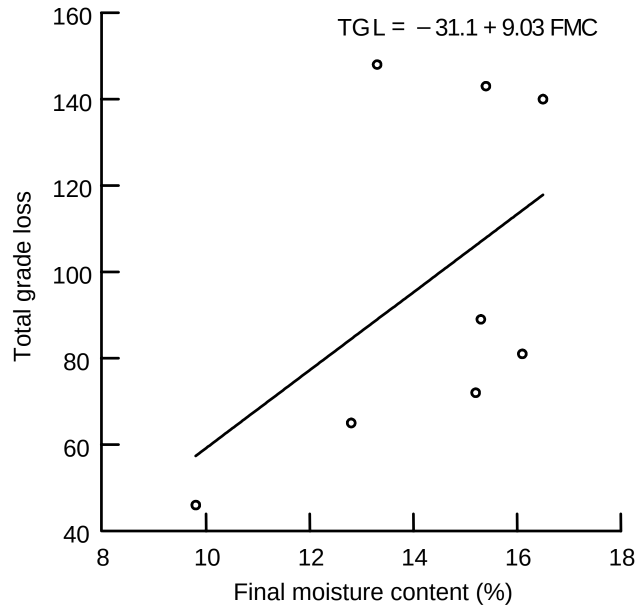

Figure 4—Relationship between total grade loss (TGL) in Idaho ponderosa pine 2 by 4's and final moisture content (FMC) after drying.

lost more moisture during storage than those that were not presteamed. This greater moisture loss may have led to more warp during storage, which was reflected in the amount of grade loss. This effect is illustrated in Figure 4 where total grade loss is plotted with group final moisture content, showing an increase in total grade loss as final moisture content increases.

Effect of Course Number on Warp

Arizona: The boards in this part of the study were all in the top units of larger kiln truck loads, and these units ranged from 11 to 17 courses of lumber. The effect of course number on warp was analyzed by linear regression, and the results are shown in Table 14 in terms of the regression coefficients. Of the 12 possible combinations of experimental groups and warp form, 10 resulted in negative slopes of the warp versus course number regression, indicating that warp decreased as course number increased from 1 at the top of the stack to 11 to 17 at the bottom of the stack. However, the effect of course number was statistically significant in only one of the 12 possible combinations.

Idaho These results are based on small experimental-sized kiln loads of lumber, so the results of top loading only apply to the top unit in a commercial kiln. This study had only 13 courses of lumber, where a commercial kiln load would have many more and the effect of many courses would be a heavy top load on the lower courses. Assuming green and final moisture content averages of 160% and 14% and a specific gravity of 0.38 (Forest Products Laboratory 1999), each course of 12 boards applies a top load of about 9 lb/ft^2 when green and about 4 lb/ft^2 when dry at 14% moisture content.

Table 13—Statistical significance of total grade loss in Idaho ponderosa pine 2 by 4's after planing. Kruskal–Wallis one way analysis of variance on ranks, with Student–Newman–Keuls method for pair-wise comparisons (Glanz 1992)[a]

Top loading	Presteaming	Kiln schedule
CT-NPS-**TL**<CT-NPS-**NTL**[b]	CT-**NPS**-TL<CT-**PS**-TL	**HT**-PS-NTL<**CT**-PS-NTL
HT-NPS-**NT**L<HT-NPS-**TL**	HT-**NPS**-TL<HT-**PS**-TL	**HT**-NPS-NTL<**CT**-NPS-NTL
	HT-**NPS**-NTL<HT-**PS**-NTL	**HT**-PS-TL<**CT**-PS-TL
		HT-NPS-TL<**CT**-NPS-TL

[a]CT, conventional temperature schedule; HT, high-temperature schedule; PS, presteaming; NPS, no presteaming; TL, top load; NTL, no top load.
[b]The less than sign indicates that the CT-NPS-NTL group was significantly greater than the CT-NPS-TL group.

Table 14—Linear regression coefficients of ponderosa pine 2 by 4 warp versus course number (Warp (in.) = *a* + *b* × course number)

	Crook		Bow		Twist	
Drying schedule[a]	*a*	–*b*	*a*	–*b*	*a*	–*b*
Arizona						
NPS-TL	0.720	0.0129	1.351	0.00658	0.289	0.00376
NPS-NTL	0.646	0.00181	1.140	–0.0209	0.259	0.000164
PS-TL	0.574	0.00499[b]	1.585	0.0452	0.233	–0.00502
PS-NTL	0.712	0.0129	1.635	0.0522	0.534	0.0265
Idaho						
CT-PS-TL	0.309	0.00405	0.478	0.00310	0.213	0.00942[b]
CT-PS-NTL	0.600	0.0284[b]	1.020	0.0525[b]	0.385	0.0219[b]
CT-NPS-TL	0.325	0.00129	0.602	0.00070	0.160	0.00006
CT-NPS-NTL	0.381	0.00694	0.738	0.0344[b]	0.230	0.00617
HT-PS-TL	0.357	0.0104[b]	0.400	–0.00424	0.152	0.00256
HT-PS-NTL	0.334	0.00426	0.710	0.0204[b]	0.331	0 .0153[b]
HT-NPS-TL	0.300	0.00365	0.440	–0.00119	0.152	0.00622[b]
HT-NPS-NTL	0.488	0.0127	0.645	0.0165[b]	0.310	0.00874

[a]NPS, no presteaming; PS, presteaming; NTL, no top load; TL, top load; CT, conventional temperature schedule; HT, high-temperature schedule.
[b]Effect of course number on warp is statistically significant by Kruskall–Wallis one way analysis of variance on ranks, with Student–Newman–Keuls pairwise comparisons.

Thus, the 200-lb/ft^2 top load was equivalent to about 22 courses of green lumber and about 50 courses of dry lumber. Press drying was equivalent to about 400 courses of green ponderosa pine lumber and about 900 courses of dry lumber.

The effect of weight of the courses on warp as measured soon after drying is summarized in Table 14. A linear regression was conducted of the effect of course number on crook, bow, and twist for each of the eight experimental kiln groups. The statistical analysis of the effect of course number on warp resulted in 11 of the 24 possible comparisons being significant, and 8 of those 11 were for groups not top loaded. In the regression analysis, 22 of the 24 possible comparisons had negative slopes to the warp versus course number curves (Fig. 5), which also demonstrates the effectiveness of upper courses on suppressing warp in lower courses.

Effect of Pith on Warp

The presence of pith in boards signifies the presence of juvenile wood, which is known to aggravate warp.

Arizona: The percentage of boards containing pith in each of the four experimental groups ranged from 19% to 21%. The results of the analysis to examine the effect of the presence of pith on warp is shown in Table 15, and in general, these results support the expectation that boards containing pith show more of all forms of warp than those that do not contain pith.

Idaho: The percentage of boards containing pith ranged from 75% to 85%, which was much higher than the Arizona pine. The results of the analysis are shown in Table 15. Although the median values of crook were generally greater in boards containing pith, none of the differences were statistically significant. The results shown in Table 15 for bow indicate weak evidence that boards containing pith may bow less than boards that do not. They also show that boards with pith twist more during drying than boards without.

Summary and Conclusions

Results were reported on two studies that attempted to characterize and control warp in 2 by 4's cut from small-diameter ponderosa pine trees. The warp that occurs during drying this type of lumber has long been recognized, but no effective measures have been developed for controlling it. One of the studies was conducted at a commercial sawmill with trees harvested in the central Arizona area. The other study was conducted at the USDA Forest Service, Forest Products Laboratory, using an experimental-sized dry kiln and lumber from trees harvested in central Idaho. Based on results from past studies reported in the literature, several potential warp-reducing strategies were chosen for study. The three main variables were top loading, presteaming, and a high-temperature kiln schedule. A limited study of hot press drying was also included.

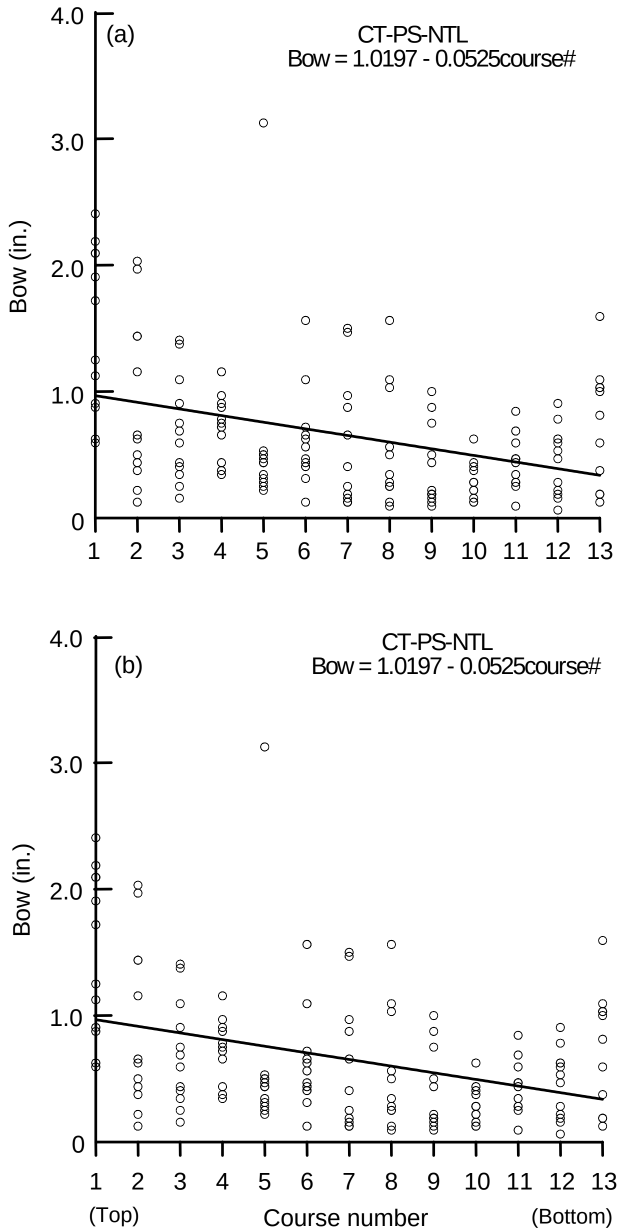

Figure 5—Relationship between bow and course number: a, typical weak relationship; b, typical strong relationship (CT-PS-NTL, conventional temperature schedule/presteaming/no top load).

Warp (crook, bow, and twist) was evaluated in several ways in the two studies. It was measured directly, and its effect was also evaluated in terms of reduction in lumber grade from exceeding grade warp limits. Warp results were varied, and it is difficult to draw many conclusions. Nevertheless, there were a number of observations backed by evidence ranging from weak to strong.

Drying time can be greatly reduced by the use of high drying temperatures. The high-temperature kiln schedule (240°F) reduced kiln residence time to about half the time of the conventional temperature (max 180°F) schedule—from approximately 80 to 40 h. Hot press drying at 375°F reduced drying time to slightly more than 3 h.

Crook and bow caused most of the grade loss, with very little grade loss attributed to twist.

The major result of the study was that top loading at 200 lb/ft^2 did reduce crook, bow, and twist, as well as grade loss from warp. However, the effect was not large. Warp reduction was probably limited to the 10% to 25% range, and at best, grade recovery increased from about 50% to 67%. Furthermore, the effect was not consistent. Very little increase in grade recovery from top loading was apparent in the Arizona material (at least partially due to lower (75 lb/ft^2) load level), and only the 50% to 67% increase occurred in the Idaho material.

Grade recovery from the Arizona material was generally higher than from the Idaho material, regardless of the warp-reducing attempts. This may be due to the fact that a much lower percentage of the Arizona boards contained pith.

Neither presteaming nor the high-temperature kiln schedule had any effect on warp as measured soon after drying. However, grade loss in the Idaho material after planing and 3-months storage was significantly less in the high-temperature dried lumber than in the conventional temperature dried lumber. Differences in final moisture may account for this observation.

Grade loss from warp was less in lumber from suppressed, slow-grown trees than in lumber from fast, open-grown trees.

Press drying (3,600 lb/ft^2) did not appear to be effective in reducing measured warp or grade loss from warp. However, experimental difficulties prevented a full investigation of press drying, so the lack of evidence for effective warp suppression should not be considered conclusive.

In general, warp decreased from the upper to lower lumber courses.

The analysis of the effect of the presence of pith in boards on warp was, in general, what we would expect—boards containing pith warp more than boards that do not contain pith, presumably because of the likelihood of boards with pith containing more juvenile wood. However, one exception was that some of the Idaho experimental groups showed more bow when pith was not present. Whether this was a real effect or an experimental anomaly is not known.

The overall observation of the studies is that none of the warp-reducing strategies appeared to be a major improvement over no specific attempt to control warp. The small improvement from top loading may not be sufficient by itself to make lumber production from small-diameter ponderosa pine trees economical but could make a useful contribution to that end.

Table 15—Effect of presence of pith on median values of warp[a] in ponderosa pine 2 by 4's

Drying schedule[b]	Warp (in.) Crook Pith	Crook No pith	Bow Pith	Bow No pith	Twist Pith	Twist No pith	Percentage with pith
Arizona							
NPS-TL	0.656[c]	0.383[c]	1.750[c]	0.887[c]	0.313[c]	0.214[c]	19.2
NPS-NTL	0.688[c]	0.344[c]	1.406	1.063	0.336[c]	0.214[c]	19.9
PS-TL	0.375	0.400	1.360[c]	0.885[c]	0.325[c]	0.151[c]	21.4
PS-NTL	0.750[c]	0.417[c]	1.444[c]	0.880[c]	0.521[c]	0.200[c]	19.8
Idaho							
CT-PS-TL	0.188	0.188	0.281[c]	0.594[c]	0.125[c]	0.0625[c]	80.1
CT-PS-NTL	0.250	0.250	0.468	0.625	0.156	0.125	75.6
CT-NPS-TL	0.219	0.234	0.438	0.656	0.125	0.0625[c]	79.5
CT-NPS-NTL	0.250	0.281	0.375	0.438	0.188	0.0938[c]	78.8
HT-PS-TL	0.250	0.219	0.375[c]	0.406	0.125[c]	0.0625[c]	85.3
HT-PS-NTL	0.234	0.219	0.438[c]	0.672[c]	0.203[c]	0.0937[c]	75.6
HT-NPS-NTL	0.219	0.203	0.348	0.359	0.0938[c]	0.0313[c]	82.1
HT-NPS-NTL	0.313	0.281	0.406	0.500	0.250[c]	0.125[c]	76.3

[a]Warp not adjusted for final moisture content. Statistical significance is the same for medians adjusted to 15% final moisture content.
[b]NPS, no presteaming; PS, presteaming; NTL, no top load; TL, top load; CT, conventional temperature schedule; HT, high-temperature schedule.
[c]Difference in median between pith not present and pith present statistically significant by Mann–Whitney rank sum *t*-test (Glanz 1992).

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