United States
Department of
Agriculture

Forest Service

Forest
Products
Laboratory

Research
Note
FPL–RN–0310

Operation and Cost of a Small Dehumidification Dry Kiln

Richard D. Bergman

Abstract

Obtaining small quantities of custom kiln-dried lumber can be an expensive process for an individual woodworker. Building and operating a small kiln capable of drying custom cuts of lumber (such as slabs, bowl blanks) gives woodworkers another option. Our approach was to build and operate a small dehumidification dry kiln. The four charges of lumber ranged from 600 to 700 board feet (bf), and a woodworker with no dry-kiln experience operated the kiln. The first charge of mixed air-dried 4/4 hardwoods and softwoods was kiln-dried from 18.4% to 7.3% moisture content (MC) in 15 days with no casehardening. The second charge of 5/4 black cherry lumber was kiln-dried from 47.5% to 6.8% MC in 27 days with no casehardening, and the third charge of 4/4 northern red oak lumber was kiln-dried from 82.9% to 6.1% MC in 45 days and to 5.2% MC in 50 days with severe casehardening relieved by conditioning. A fourth charge of 300 bf 4/4 northern red oak, 200 bf of 4/4 shagbark hickory, and 100 bf of mixed 4/4 box elder and 4/4 black cherry was kiln-dried from 69.7% to 8.5% MC in 29 days with casehardening only in the northern red oak, and that was relieved by conditioning. We found that greater control of the dehumidifier operation earlier in the kiln schedule to maintain the safe drying rate would decrease the severity of casehardening when drying green northern red oak. New building materials, which are most of the initial cost, could be replaced by reused lumber. Drying small amounts of lumber using a dehumidification kiln is a suitable option for woodworkers even with limited knowledge of kilns.

Keywords: dehumidification, dry kiln, small, MATC, drying, operation, DH, cost

October 2008

Bergman, Richard D. 2008. Operation and Cost of a Small Dehumidification Dry Kiln. Research Note FPL-RN-0310. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 20 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 53726–2398. This publication is also available online at www.fpl.fs.fed.us. 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.

Acknowledgments

I thank Patrick Molzhan, Program Director, Wood Technics Department, Madison Area Technical College; Terry Mace, Forest Utilization and Marketing Specialist, Wisconsin Department of Natural Resources; Scott Bowe, Associate Professor and Wood Products Specialist, University of Wisconsin-Madison; and Jim Gilbertson and Tedd Mianowski (retired), Technicians, U.S. Forest Service, Forest Products Laboratory.

Conversion Table

To convert from	To	Multiply by
feet per minute (ft/min)	meters per seconds	0.00508
horsepower (hp)	kilowatts (kW)	0.746
pounds (lb)	kilograms (kg)	0.454
pints (pt)	liters (L)	0.473
feet (ft)	meters (m)	0.305
feet squared (ft^2)	meters squared (m^2)	0.0929
feet cubed (ft^3)	meters cubed (m^3)	0.0283
gallons (gal)	liters (L)	3.78
miles (m)	kilometers (km)	1.61
tons (t)	tonne ($\times 10^3$ kg)	0.907
board feet (bf)	meters cubed (m^3)	0.00236
british thermal units (Btu)	megajoules (MJ)	0.001055

Contents

Operation and Cost of a Small Dehumidification Dry Kiln

Richard D. Bergman, Research Chemical Engineer
Forest Products Laboratory, Madison, Wisconsin

Introduction

In the past, custom woodworkers would simply visit a local sawmill or lumber retail store to buy lumber, especially kiln-dried material, for their projects. This material might not be exactly what they needed and cost twice the wholesale price (personal communication on September 8, 2006, with Terry Mace, Forest Products Utilization and Management Specialist, Wisconsin Department of Natural Resources, Division of Forestry, Madison, Wisconsin). Using a custom lumber-drying facility to dry green lumber sawn for use by the woodworker could be expensive. Some woodworkers simply stock up on green lumber and air dry their own material. Individual woodworkers would like other options to help lower the cost of kiln-dried cuts of lumber.

Kiln-drying lumber is an expensive process; therefore, kiln-dried lumber is sold at a significantly higher price than green lumber. Prices from Hardwood Review Weekly (August 11, 2006) for both green and kiln-dried (gross tally) 4/4 #2 common red oak in the North Central Region are 505 and 750 dollars per thousand board feet, respectively. For 5/4 Select & Better black cherry, these prices are 2,520 and 3,400 U.S. dollars per thousand board feet, respectively. The major reason for the difference in price is the cost of energy required to kiln-dry green lumber to a lower moisture content (MC) prior to final manufacturing. Typical MC range for kiln-dried lumber is 6% to 8% for interior use in the United States to maintain dimensional stability (FPL 1999). Most kiln-drying of lumber is done by conventional steam kilns, which can be energy-intensive operations. For a conventional steam dry kiln, the approximate amount of energy to kiln-dry a thousand board feet of Douglas-fir, Southern Pine, and northern red oak green lumber is 1.2, 3.0, and 6.5 million Btu, respectively (Comstock 1975).

Large commercial dry-kiln facilities produce most of the available kiln-dried lumber at a significantly lower cost per unit than other methods. A typical large dry-kiln operation uses steam coils as the indirect heating source fueled either by burning woody biomass, fossil fuels, or both. The size and type of dry kilns needed for these operations has limited the ability for small operators to enter the commodity market or produce kiln-dried lumber for their own use at a competitive price. However, some small dehumidification (DH) dry kilns under 3 horsepower have been commercially available since 1976. One company, Nyle Corporation (Bangor, Maine), has already sold 5,000 DH units intended for 2,000 to 5,000 board feet. More than 7,000 DH units under 10 horsepower are in use along with many large ones (personal communication on October 10, 2006, with E.M. Wengert, Professor Emeritus in Wood Processing, Department of Forest Products, Virginia Tech University). One problem is that most commercially dried lumber is in standard thicknesses and lengths that may not meet an individual woodworker's needs. In the United States, woodworkers have expressed interest in producing their own kiln-dried lumber from less expensive green lumber to maintain greater control throughout the manufacturing process. Sometimes specialty lumber is required, but buying the material commercially or using a custom kiln-drying operation can be cost-prohibitive.

Technology has advanced not only in understanding the process of wood drying on small scales (less than a thousand board feet) but also in commercially available products used to build these small dry kilns capable of producing high-quality lumber. Types of dry kilns capable of commercial operation include solar, vacuum (radio-frequency, heated platens, or super-heated steam), microwave, and dehumidification. All these systems have their advantages and disadvantages. For example, solar dry kilns perform better in areas with higher solar radiation, whereas radio-frequency vacuum kilns have high initial capital costs and require a highly trained operator.

Research on drying small quantities of lumber began decades ago at the Forest Products Laboratory (FPL) with a significant focus on solar kilns (Peck 1961; Simpson and Tschernitz 1984; Simpson and Tschernitz 1988; Tschernitz and Simpson 1985). For the remote locations designed for solar drying, DH kilns were not as applicable as solar kilns because inexpensive and stable grid-quality electricity was not available. Recent research also showed the potential for solar drying on a small scale in southern climates (Bond 2006). However, in northern climates such as the northern United States, DH kilns have the advantage of running multiple charges during the year, whereas solar kilns are often limited to one charge during the winter because of limited solar radiation. Also, unless a solar kiln has photovoltaic power to the fans, both systems still require electricity. Other research included combining solar and dehumidification capabilities into one kiln, which increased energy efficiency by 30% (Chen and Helmer 1987).

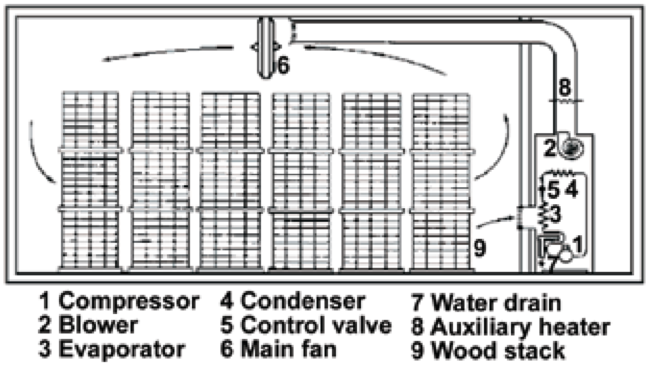

Figure 1—Typical dehumidification kiln (FPL 1999 p. 12–10).

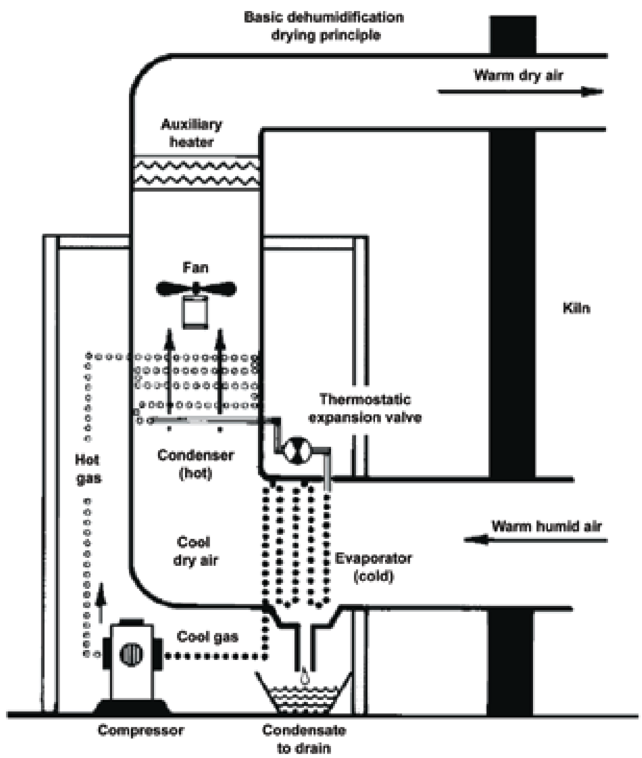

Figure 2—Typical dehumidification cycle (FPL 1999 p. 12–10).

Dehumidification dry kilns are not as significantly affected by outside environments as are solar kilns because air exchange is not needed to remove moisture-laden air. Instead of using steam coils and vents for moisture removal from the lumber and the dry kiln as is done in commercial dry kilns, the dehumidifier uses electricity to cool the air enough to condense the moisture released by the lumber. This condensation action keeps the heat of evaporation in the kiln. This heat is usually lost in kilns using vents for wet-bulb control. The fans circulate air through the lumber stack and as the warm, moist air leaving the stack contacts the cooling coils of the dehumidifier, the moisture is condensed (Fig. 1). For commercial operations, waste heat from the fans and

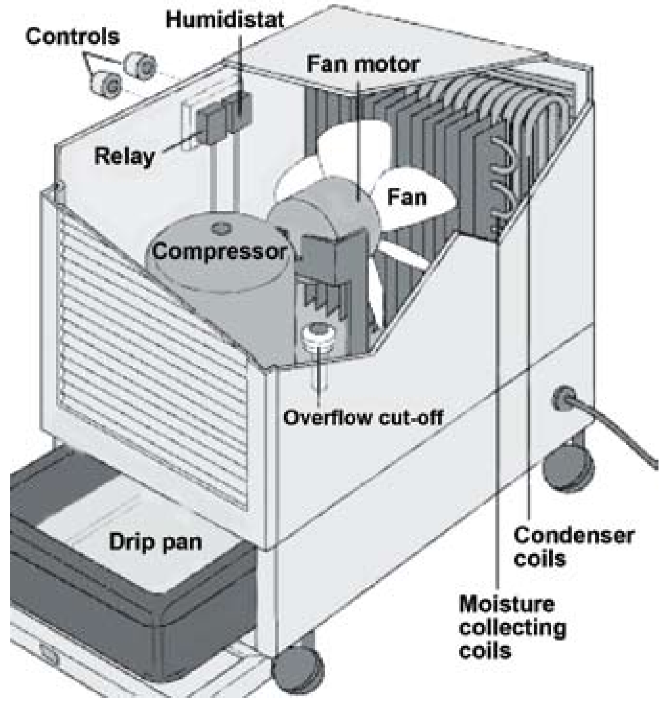

Figure 3—Residential dehumidifier.

dehumidifier keeps the drying chamber at the required temperature once the kiln reaches operating temperature (Fig. 2).

For smaller DH kilns, a commercial stand-alone dehumidifier is placed in the kiln (drying chamber). This dehumidifier works likes an air conditioner except the dehumidifier has both its hot and cold coils in one unit. A fan draws the warm moist air into the unit and the moisture condenses on the cold coils that are similar to an air conditioner's evaporator coils. The condensation drips through a hose to a drain or into a removable bucket (Fig. 3). The second set of coils warms the cool dry air, and the warm, dry (reconditioned) air is pumped into the kiln to absorb more moisture from the lumber. Some residential dehumidifiers have digital controls for setting the relative humidity, whereas other dehumidifiers can be controlled by a humidistat that allows dehumidifiers to cycle on and off to maintain a wider range of relative humidity (RH) than is possible by standard controls. The amount of condensate can be used to track the drying rate to adjust the RH setting for an optimal drying rate. Optimal drying rate is dependent on the species, initial moisture content, wood temperature, air speed, and lumber thickness.

This project was a collaboration between the Wisconsin Department of Natural Resources and Madison Area Technical College (MATC) to construct a 600-bf dehumidification dry kiln based on plans from an article (AW 2002) for drying small quantities of lumber. The main objective was testing the versatility and functionality of drying several domestic wood species at different moisture contents using a woodworker with no previous dry-kiln operational experience.

Figure 4—Front view of the dehumidification dry kiln (empty) with main doors on the side.

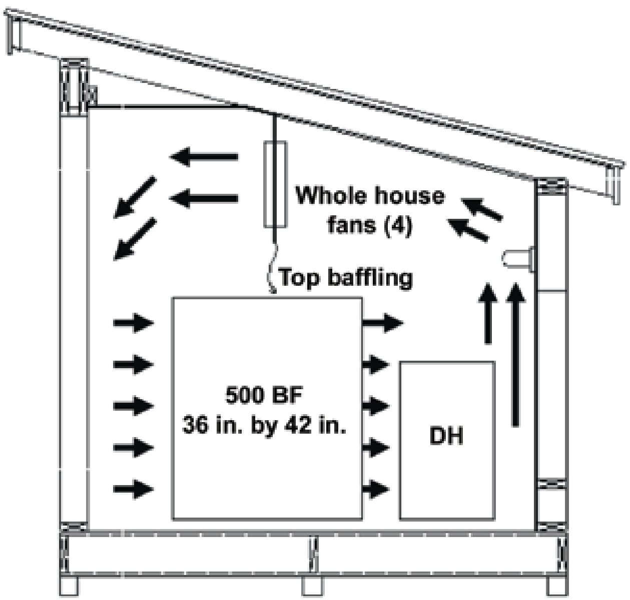

Figure 5—Side view of dry kiln indicating air direction and location of major components. DH is dehumidification.

Methodology

Material

The Madison Area Technical College (MATC) Wood Technics Department (WTD) bought the material listed in Appendix A using a grant through the Wisconsin Department of Natural Resources. Personnel from MATC WTD built the 600-bf dehumidification dry kiln based on 2-in. by 6-in. residential housing practices. See Bowe and others (2007) for greater construction detail on building this kiln (Fig. 4).

All the kiln components were commercially available. A Maytag 30-pint residential model dehumidifier (Whirlpool Corporation, Benton Harbor, Michigan) using standard 115-volt power was installed for dehumidification; maximum dehumidifier power consumption was 0.851 kilowatts (kW). Suggested dehumidifier compressor sizing was 1 horsepower per 1,000 board feet of mixed hardwoods (Wengert and others 1988). This dehumidifier could be digitally set from a maximum of 90% to a low of 35% relative humidity (RH), and the setting was used to change the drying rate. Also, the installed circulating fans operated only in one direction as only one typical-size pack of lumber was loaded in the kiln (Fig. 5). Commercial dry kilns reverse fan direction to even the drying rate for the large number of packs. Supplemental heat was from an electric baseboard heater capable of generating roughly 800 (75%) or 1,150 (100%) watts depending on its setting. This heater was used later in the drying cycle if needed or could be used when the kiln operated outside during cold weather to maintain kiln temperatures above 65°F. Most dehumidifiers perform poorly under 65°F and the risk of freezing the coils also increases. Top baffling was constructed from 1/2-in. CDX sheathing (C-D Exposure 1 plywood) and could be raised while loading and unloading the kiln. This baffling forced the circulating air through the pack, and the lumber was stacked to prevent side air flow past the pack. The circulating fans were also installed into the 2-in. by 4-in. framework as shown in Figure 6. Air flow readings of 25 and 200 ft/min were measured at bottom and top of charge, respectively, using an Alnor Velometer hand-held aerometer (Alnor Products, Shoreview, Minnesota). Two more fans were installed after Run 2 to both increase fan speed to roughly 400 ft/min and evenly distribute the air flow. Both sets of fans can be operated independently. Metal components not made of stainless steel were used to save money and were evaluated on their corrosion resistance after the four runs were complete.

Experimental Procedure

After construction was completed, the dry kiln was loaded with a local supply of air-dried 4/4 hardwood and softwood species including red pine, bur (white) oak, black cherry, and shagbark hickory. All kiln operations were run by MATC personnel with oversight by FPL personnel. All four dry-kiln runs were done inside a temperature- and humidity-controlled building, although the kiln can be used outside. Run 1 was conducted to verify proper operation of the new DH kiln using air-dried lumber. Air-dried lumber has a minimal chance of casehardening during kiln-drying compared with green lumber (Denig and others 2000).

After Run #1 was complete and the dry-kiln operation verified, the dry kiln was unloaded and reloaded with 5/4 green black cherry (*Prunus serotina*) lumber sawn from a local portable chainsaw mill operation. The black cherry lumber was transported in a truck in two trips for a total kiln capacity of 640 bf for Run 2. After kiln-drying the black cherry, the kiln was unloaded. Prior to reloading, two fans were added to the fan deck to increase air flow and uniformity and then the kiln was reloaded with 4/4 green northern red oak (*Quercus rubra*) lumber sawn from a local sawmill. The

Figure 6—Dehumidification dry kiln loaded with air-dried mixed hardwood and softwood.

Figure 7—Dehumidification dry kiln loaded with green mixed hardwood (four fans are shown, because two were added).

northern red oak lumber was transported in two trucks for a total of 600 bf for Run 3. The dry kiln was unloaded and reloaded with 300 bf of 4/4 northern red oak, 200 bf of 4/4 shagbark hickory (*Carya ovata*), and 100 bf of mixed 4/4 black cherry and box elder (*Acer negundo*) lumber sawn from a local sawmill. This lumber was sawn from logs end-coated and stored for 5 weeks prior to sawing. The lumber was transported in two trucks for a total of 600 bf for Run 4 (Fig. 7).

Both kiln samples and condensate collected from the dehumidifier were used to monitor the MC change throughout the drying process. Three to four kiln samples were used per run and placed both at the corners roughly 1 ft from the edges and at the center of the pack. For all runs, the moisture loss from the kiln samples was monitored with the expectation that measurements would be taken daily. Along with using kiln samples to monitor lumber MC, the condensate was collected from the dehumidification process. A bucket collected the condensate, and the condensate volume was measured and recorded including the day and time of collection for estimating moisture loss.

Ways to reduce the initial drying rate and casehardening for northern red oak were evaluated after finding severe casehardening in Run 3. The controls did not allow for a higher relative humidity setting; therefore, a simple lamp timer was installed on the dehumidifier to shorten the dehumidifier operating time. The dehumidifier also has its own fan that was set on high for black cherry and low for northern red oak. Lowering the fan speed on the dehumidifier, however, does lower its efficiency.

Average daily moisture loss (DML) was calculated using Equation (1) and sample board weights for each run.

$$\mathrm{DML} = \left(\frac{\mathrm{MC_{DBO}} - \mathrm{MC_{DBF}}}{d} \right) \times 100 \qquad (1)$$

DML	is	average daily moisture loss (%),
$\mathrm{MC_{DBO}}$		initial moisture content of the lumber on a dry basis (%),
$\mathrm{MC_{DBF}}$		final moisture content of the lumber on a dry basis (%), and
d		total number of days between measuring moisture content.

Kiln samples are used for higher value wood products such as hardwood lumber to prevent drying defects but still maintain the maximum safe drying rate to produce the highest volume possible. Daily weighing of kiln samples is highly recommended. Figure 8 shows an example of a kiln sample used; detailed instruction on procedures for cutting and using sample boards are in Appendix B. Core and shell MC were also taken for one run to calculate the difference and determine if equalization of the lumber was needed. Equalization is the process of reducing the moisture between the core and shell of the lumber because variations in final MC can cause later processing problems. Figure 9 illustrates the proper method of cutting sections for measuring the shell and core MC.

Prong tests were also performed at the completion of the charge to check for drying stresses. Drying stresses are discussed in chapter 1 of the *Dry Kiln Operator's Manual* (Simpson 1991). These test sections were cut along the width of the board and the interior wood was removed (Fig. 10a). When the sections of the board have stress, the two outer prongs close in because any drying stress is released by the saw cut (Fig. 10b). Only the two-prong test was done in this study, although a larger number of prongs may be used. Figure 11 highlights the extent of casehardening possible from drying. More details are available in chapter 6 of the *Dry Kiln Operator's Manual* (Simpson 1991).

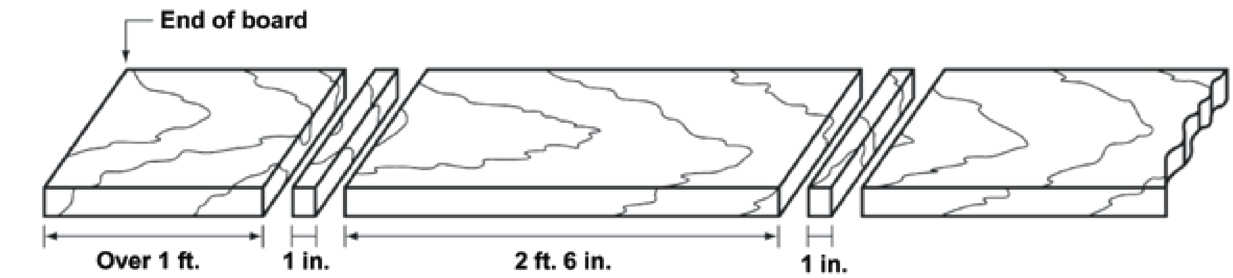

Figure 8—Proper method of cutting kiln samples from a full board.

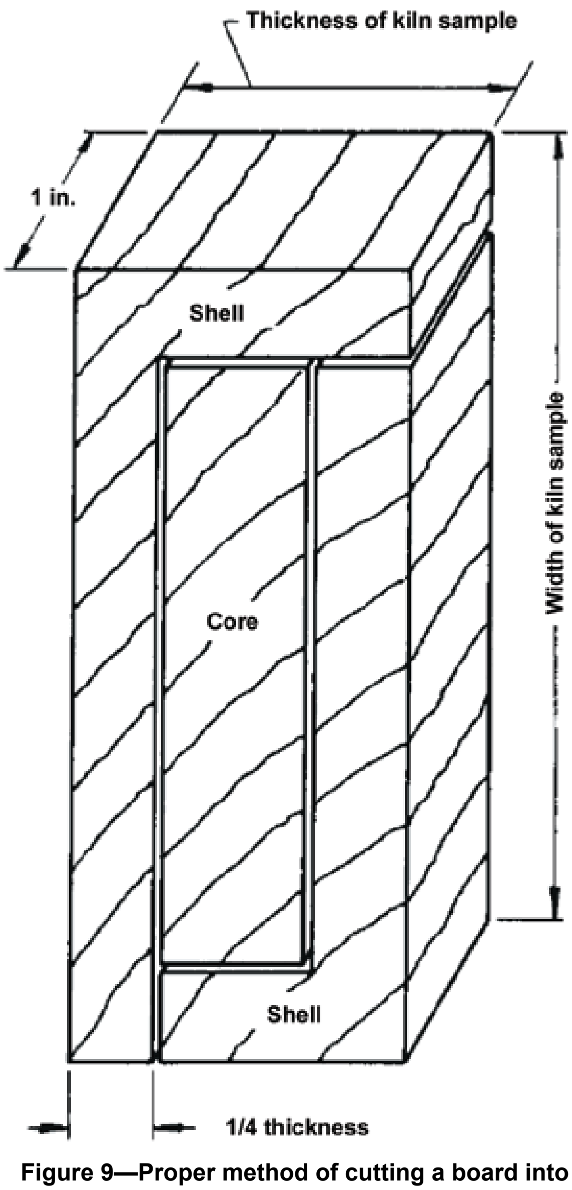

Figure 9—Proper method of cutting a board into sections for shell and core moisture content (MC) (Simpson 1991, p. 125)

For relieving casehardening found after drying, an electric steam kettle was used initially but it required refilling every half hour; therefore, a Lasko Model 1129 High Efficiency Circulating Humidifier (Lasko Products, Inc., West Chester,

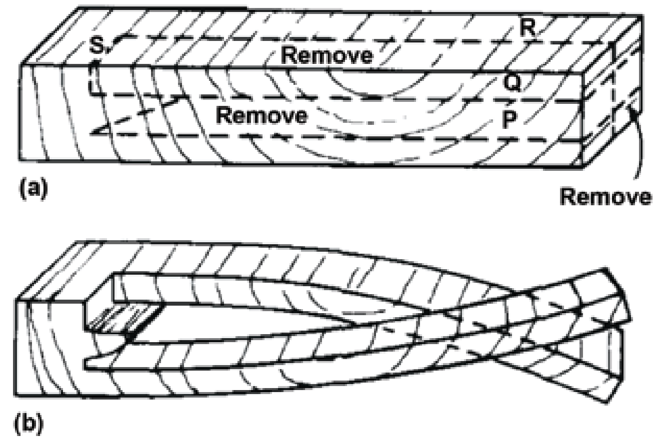

Figure 10—Proper cutting for two-prong test (Simpson 1991, p. 126).

Pennsylvania) capable of emitting 9 gallons per day of water vapor was used. The amount of use depended on the severity of casehardening (Fuller and Hart 1994; Simpson 1991).

Results

Kiln Data

Run 1

The drying schedule shown in Appendix C (Table 1) was based on tracking condensate output from the dehumidifier. Changes in MC of the four kiln samples are shown in Appendix C (Table 2). Initial and final average MC_{DB} of 18.4% and 7.3% were calculated for the charge of air-dried material using kiln samples, respectively. The run was completed in 15 days with no casehardening present during prong test; thus, no conditioning was required. An average daily moisture loss (DML) of 0.74% was calculated.

Run 2

The drying schedule shown in Appendix C (Table 3) was based on tracking condensate output from the dehumidifier. Changes in MC of the three kiln samples are shown in Appendix C (Table 4). Initial and final average MC_{DB} of 47.5% and 6.8% were calculated for the charge of 5/4 black cherry using the kiln samples, respectively. The run was complete in 27 days with no conditioning required because the prong tests showed no casehardening. Core and shell final MC_{DB}

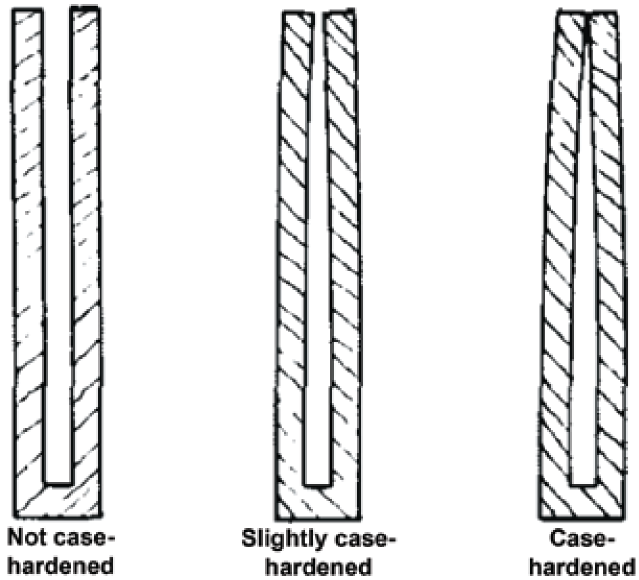

Figure 11—Different levels of casehardening found after drying for the two-prong test (Simpson 1991, p. 126).

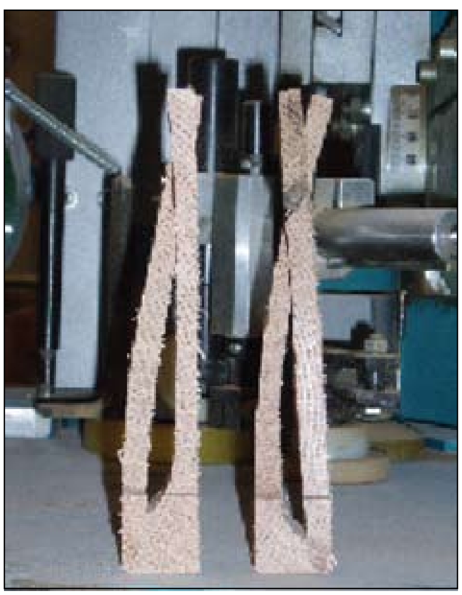

Figure 12— Kiln-dried northern red oak lumber 36 h after conditioning.

were 8.6% and 6.8%, respectively, indicating lumber was properly equalized (<2% difference).

A total of 248 pints of condensate were recorded during the run with an expected condensate collection of 635 pints based on an estimated oven-dried mass of 1,627 lb. The oven-dried mass for the black cherry charge was calculated using a green density of 45 lb/ft^3 and an initial calculated percentage of MC_{DB} of 47.5% for 640 actual bf of lumber (FPL 1995). A maximum safe drying rate of 0.0071 pints per hour per board foot using a dehumidifier setting of 85% was listed in AW (2002). This corresponded to a daily moisture loss of 7.0% for 4/4 black cherry lumber. This value of 7.0% is higher than the maximum daily moisture loss of 5.8% found in other literature (Denig and others 2000). In this study, the highest estimated daily moisture loss (DML) observed was 3.3%, although it may have been higher because this loss was averaged over 3 days of the highest drying period. The overall DML for the entire run was 1.5%.

Figure 13—Conditioning completed: before (left) after (right).

Run 3

The drying schedule shown in Appendix C (Table 5) was based on tracking condensate output from the dehumidifier. Moisture loss for the four kiln samples are shown in Appendix C (Table 6). Because a kiln operator was unavailable, the dehumidifier and fans were not started until 6 days after loading the charge. The main kiln door was open to allow some air-drying in the temperature- and humidity-controlled building. The 4/4 northern red oak lumber was kiln-dried from 82.9% to 6.1% MC_{DB} in 39 days and to 5.2% MC_{DB} in 44 days with prong tests showing severe casehardening after the 44-day period. Measured air flow readings from end to end in the center of load were 400 lb/ft and from top to bottom were 350 to 450 lb/ft after the two fans were installed. Adding these two fans increased air flow by a factor of two, and flow was more evenly distributed.

The kiln-dried northern red oak lumber required conditioning to remove the drying stress (Figs. 12 and 13). An electric steam kettle was used initially, but then the Lasko Humidifier was used instead to finish for a total conditioning time of 24 h between the two methods. Core and shell final MC_{DB} were 5.5% and 4.4%, respectively, indicating the lumber was properly equalized (<2% difference). A

Table 1—Estimated electrical consumption and cost for the small dry kiln

Run No.	Run time (days)	Electrical use (kW-h)	Electrical cost[a] ($)	Charge (actual bf)	Cost ($/$10^3$ bf)	Consumption (kW-h/10^3 bf)
2	27	920	46.00	640	72	1,440
3	44	1,734	86.72	600	145	2,890
4	29	1,152	57.61	600	96	1,920

[a] Average electrical power at MATC (2005) is $0.05 per kilowatt-hour, although residential cost is closer to $0.10 per kilowatt-hour.

significantly larger deviation of final to initial MC existed for this run compared with the previous two runs. This indicates the necessity of using intermediate kiln samples to monitor MC for future runs of northern red oak.

Highest DML was 4.6% compared with the maximum daily moisture loss of 1.0% to 3.8% found in the literature (Denig and others 2000) and falls outside the range of values reported by Denig and others. The DML may have been higher because this loss was averaged over the first 5 days of kiln operation (kiln samples were not measured daily). A basic specific gravity of 0.56 and green density of 63.6 lb/ft^3 was calculated using ASTM D2395-02, and specific gravity (SG) compares well with the literature values of 0.56 and 63 for northern red oak, respectively (FPL 1999).

Run 4

The drying schedule shown in Appendix C (Table 7) was based on tracking condensate output from the dehumidifier. Moisture loss for the four kiln samples was shown in Appendix C (Table 8). The mixed 4/4 hardwoods were kiln-dried from 69.7% MC_{DB} to 8.5% MC_{DB} in 29 days, with prong tests showing slight casehardening initially (Fig. 14, left) and severe casehardening 1 month later for the northern red oak only (Fig. 14, right). Drying stresses occurring after 2 days indicated a moisture content gradient that required equalizing, although the three kiln samples used to measure MC gradient between the core and shell showed less than 2% difference. No conditioning was done until one month later.

Highest daily moisture loss was 5%, which is higher than the 1% to 3.8% found in the literature (Denig and others 2000) and may have been even higher because the value of 5.0% was averaged over the first 4 days of operation (kiln samples were not measured daily).

Economic Analyses

Electrical Consumption

Electrical consumption and costs were estimated for Runs 2, 3, and 4 (Table 1). Run 2 had two fans operating at 100% for the entire run, a dehumidifier at 100% for the first 20 days only, and 1 day each for the electrical heater at 75% and 100% power. Run 3 had four fans operating 100% for entire run and dehumidifier operating at 100% for first 2 days and 50% for next 22 days only (no electric heat). Run 4 had four fans operating at 100% for the entire run and a dehumidifier operating at 50% for the first 18 days only (no electric heat).

Initial Cost

Cost for building materials was roughly $2,700 (Appendix A), and the estimated time to build, insulate, paint, and wire the unit was 60 h (personal communication on September 3, 2006, with Patrick Molzahn, Cabinet Making and Millwork Program Director, Madison Area Technical College, Madison, Wisconsin). Assuming labor costs for an experienced builder, an hourly labor rate of $35.00 was set; therefore, total cost for the installed and operational dry kiln was $4,800, including the $2,100 for labor. Most of the cost of the kiln was for structural material. The dehumidifier, fans, heater, and controls accounted for only about 20% of the cost. A capable woodworker could reduce costs greatly by purchasing used (reused) materials or using cheaper materials for construction.

Operational Cost

A detailed analysis of the entire costs for Run 3 included the purchase of 600 bf of 4/4 green #2 common red oak for $322.83 (including tax) directly from a local sawmill located 50 miles from MATC. Two standard trucks were used to transport the lumber, costing $0.50 per mile for total transportation costs of $100.00. Electrical costs were $86.72, with additional wood-handling costs of $200.00 assuming 10 h of labor. Additional wood handling is associated mostly with loading and unloading kiln and monitoring the kiln. These costs were listed as operational costs because this work was completed by the woodworker who would use the kiln-dried material. A general labor cost of $20.00 per h was assigned for additional wood handling functions.

A typical woodworker would buy small quantities of lumber, usually less than 100 board feet. The retail price on February 14, 2007, for rough 4/4 #2 common red oak lumber was $1,430 per thousand board feet. In 2006, wholesale price for rough 4/4 #2 common red oak lumber was $750 per thousand board feet on a kiln-dried gross tally (Hardwood Review Weekly: August 11, 2006). Therefore, buying only a small quantity increases the price to $2.00 per board feet for planed, dried #2 common red oak lumber (personal communication on May 15, 2007, with Terry Mace, Forest Products Utilization and Management Specialist, Wisconsin

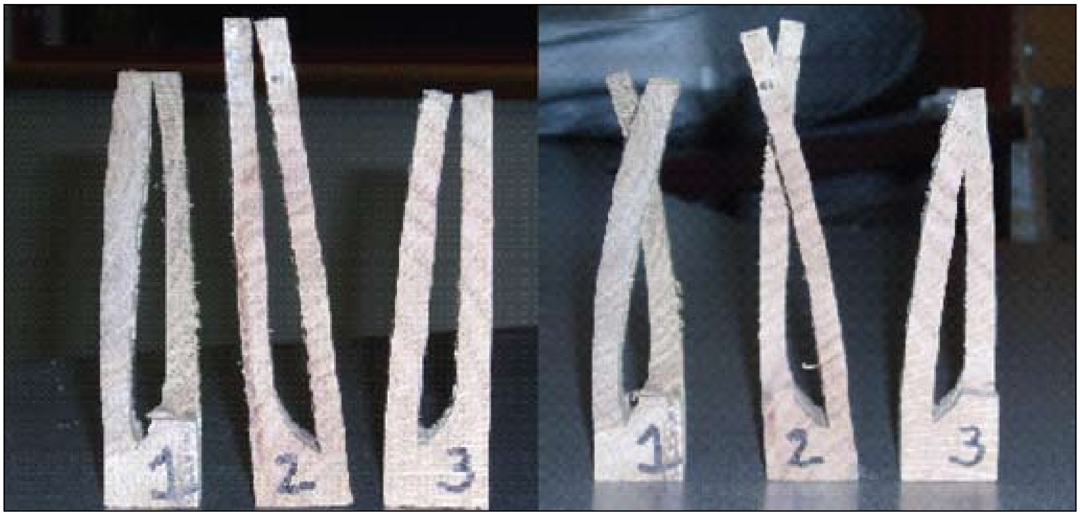

Figure 14—Prong tests for red oak with no conditioning (initial, left; one month later, right).

Table 2—Cost comparison for the MATC and Post dry kiln

	Cost ($/10^3 bf)					
Kiln type	Electricity	Capital costs	Maintenance	Labor	Transportation	Total
MATC 600	106–159	220	50[a]	330	165	871–924
Post 2500	50	100	50	200	0[b]	400

[a] Maintenance costs for 600-bf kiln assumed to be the same as 2,500-bf kiln.
[b] Lumber was delivered to the facility for drying.

Department of Natural Resources, Division of Forestry, Madison Wisconsin). Based on the initial installed costs of $4,800 and operating costs for Run 3 of $740 including lumber, with an expected revenue of $858, the payback period would be 4.4 years, assuming 10 runs per year for a total of 44 runs of 600 board feet of 4/4 #2 common red oak lumber. However, using 4/4 #1 common red oak would reduce the number of runs to 17 with operating costs of $876 including lumber, with revenue of $1,158, for a payback period of 1.7 years. No equipment failure or other changes are considered during this payback period. Increasing kiln operational efficiency was not taken into account for this analysis. Also, as noted, using higher valued lumber would give a quicker payback.

System Comparison Cost

Values for a 2,500-bf dehumidification kiln were compared with the MATC dry kiln (Post 2002). The Post 2500-bf dry kiln is over four times larger than the MATC dry kiln and uses kiln carts to move lumber in and out of the kiln. Using a kiln cart reduces the transient time between the end of one cycle and the start of another but increases the amount of space required. Transient times are more critical for larger operations. Also, track kilns such as the Post 2500 are one of the two typical options for larger conventional kilns. For the Post 2500, a compressor typical for larger DH kilns is used instead of a dehumidifier for the MATC 600. This result showed that the larger Post DH dry kiln would cost roughly 50% less than the MATC dry kiln (Table 2). No forklift is included in this comparison, but air-drying the material is included in the electrical consumption for the Post 2500. Air-drying the material prior to kiln-drying would decrease kiln operation time and the amount of electricity used.

Discussion

Several items were noted during the runs:

- A simple timing feature was installed on dehumidifier during Day 2 of Run 3 to slow the drying rate to prevent drying stresses. Drying stresses had occurred, although the highest setting for relative humidity on the dehumidifier was 90%, and this setting was higher than or equal to the maximum value any species required for initial drying based on data from AW (2002). After installation, the dehumidifier cycled on and off at 6-h increments to prevent exceeding maximum daily moisture loss. However, the drying rate was still exceeded for both Runs 3 and the northern red oak in Run 4.
- Kiln samples were significantly more accurate in calculating moisture loss than measuring volume of condensate collected from the dehumidifier. This was because the dry kiln was not vapor-tight even though a vapor barrier was installed in the walls during construction. We determined this because no condensate was collected at later drying stages although the weight of the

Figure 15—Corrosion effect of kiln-drying northern red oak on metal fasteners.

kiln samples was still decreasing. The main cause was that the door seals were not holding; therefore, the seals need to be either redesigned or manufactured from a different material.

- Calculated electrical consumption on a kW-h per thousand board foot basis was higher than expected because of long drying times. Typical commercial dry kilns consumed roughly 500 to 750 kW-h per thousand board foot (Denig and others 2000).
  - Run 2 (black cherry) was roughly two to three this value at 1,440 kW-h
  - Run 3 (red oak) was roughly four to six times this value at 3,180 kW-h
  - Run 4 (mostly red oak) was roughly three to four times this value at 2,120 kW-h
- Actual run times were very conservative because (1) the dehumidifier was assumed to be running full-time, although the unit was not usually operating prior to lowering the RH setting; and (2) the dry kiln operated 5 days longer than required for Run 3. Therefore, the lumber was over-dried. Even though the timer cycled the dehumidifier on and off, that slowed the drying rate for Run 3 (6 h on/6 h off) and the fans ran longer. Run 4 gave a more accurate value for electrical usage than Run 3 because of better control of dehumidifier and because the lumber for Run 3 was over-dried.
- The primary drying defect was casehardening. Relieving casehardening is vital to producing high-quality lumber for wood products. A new method of conditioning for Run 4 used a continuous water input into the electric steam kettle, which was effective but time consuming.

Recommendations

- Original AW (2002) settings for northern red oak were too aggressive. Greater control of the dehumidifier operation earlier in the kiln schedule would lower the amount of casehardening occurring for northern red oak. One way to reduce the initial drying rate and resulting casehardening for northern red oak is installing additional pins on the timer to shorten the dehumidifier operating time for northern red oak to 3 h on and 6 h off. Other ways are to install a humidistat to control the dehumidifier to allow wider ranges of RH control and decrease the dehumidifier fan speed to low speed for slower drying species such as northern red oak. Another option is turning off the dehumidifier and fans at night during the early stages of drying to slow the drying rate and allow RH to increase, thus conditioning the lumber.
- Building and operating small dehumidification dry kilns give woodworkers greater control and flexibility of the drying process and the entire manufacturing process.
- Daily monitoring of the dry kiln is a must, especially in the earlier stages of drying.
- Increasing the size of the dehumidification dry kiln by over four times decreases the overall cost per board foot by roughly 50%. Also, custom drying typically cost $300 per 1,000 board feet (personal communication, E.M. Wengert, Professor Emeritus in Wood Processing, Department of Forest Products, Virginia Tech University, October 10, 2006). Therefore, preferred uses for this kiln are drying small quantities of a select species and working with custom material.
- Corroding metal brackets and hinges for the kiln doors mostly occurred from kiln-drying northern red oak (Fig. 15). Less expensive metal was chosen over stainless steel to determine its effectiveness against corrosion. More runs are required to determine the level of corrosion occurring for the current metal. No corrosion was found inside the kiln.

References

AW (American Woodworker). 2002. Dry your own wood. American Woodworker Magazine. 94: 42–55.

American Society for Testing and Materials (ASTM). 2002. Standard D 2395-02 - Standard test methods for specific gravity of wood and wood-based materials. ASTM International, West Conshohocken, PA. http://www.astm.org.

Bond, B. 2006. Design and operation of a solar-heated dry kiln. Publication Number 420-030. Blacksburg, VA: Department of Wood Science and Forest Products, Virginia Tech, Virginia Cooperative Extension.

Bowe, Scott; Molzahn, Patrick; Bond, Brian; Bergman, Richard; Mace, Terry; Hubbard, Steve. 2007. Dehumidification drying for small woodworking firms and hobbyists; building your own lumber dry kiln with local building materials. PUB-FR-396 2007. Madison, WI: UW Extension–Wisconsin Department of Natural Resources. 14 p.

Chen, Peter Y.S.; Helmer, Wayne A. 1987. Designs and tests of a solar-dehumidifier kiln with heat storage and heat recovery systems. Forest Products Journal. 37(5):26–30.

Comstock, G.L. 1975. Energy requirements or drying of wood products. In: Wood residue as an energy source. Proceedings No. P-75-13. Madison, WI: Forest Products Research Society: 8–12.

Denig, J.; Wengert, E.M.; Simpson, W.T. 2000. Drying hardwood lumber. Gen. Tech. Rep. FPL–GTR–118. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 138 p. http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr118.pdf.

FPL. 1995. Hardwoods of North America. General Technical Report FPL–GTR–83. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 136 p. http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr83.pdf.

FPL. 1999. Wood handbook—wood as an engineering material. General Technical Report FPL–GTR–113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 463 p. http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr113/fplgtr113.pdf.

Fuller, James; Hart, C.A. 1994. In: Proceedings, 4th IUFRO International Wood Drying Conference, Rotorua, New Zealand. Factors that influence the prong test. p. 313–320. www.fpl.fs.fed.us/documnts/pdf1994/fulle94b.pdf.

Hardwood Review Weekly. 2006. Hardwood Review Weekly 22(49):6. Charlotte, North Carolina: Hardwood Publishing.

Peck, Edward C. 1961. Drying 4/4 red oak by solar heat. Forest Products Journal. 12(2):103–107.

Post, Irwin. 2002. Drying: how to improve the quality of your lumber while reducing your workload. Independent Sawmill & Woodlot Management. June/July 2002. 8 p.

Simpson, W.T. 1991. Dry kiln operator's manual. Agriculture Handbook AH–188. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 274 p. http://www.fpl.fs.fed.us/documnts/usda/ah188/ah188.htm.

Simpson, W.T.; Tschernitz, John L. 1984. Solar dry kiln for tropical latitudes. Forest Products Journal. 34(5):25–34.

Simpson, W.T.; Tschernitz, John L. 1988. Performance of solar/wood energy kiln in tropical latitudes. Forest Products Journal. 39(1):23–30.

Tschernitz, John L.; Simpson, William T. 1985. FPL design for lumber dry kiln using solar/wood energy in tropical latitudes. General Technical Report FPL–GTR–44. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 17 p.

Wengert, E.M.; Grimm, P.; Lamb, F.; Muench, J. 1988. Opportunities for dehumidification drying of hardwood lumber in Virginia. Sandston, VA: Department of Forest Products, Virginia Tech University. 34 p.

Appendix A—Bill of Materials

Item	Material	Quantity	Cost/unit ($)	Total cost ($)
Deck				
Runners	4-in. by 4-in. by12-ft TTD	2	11.16	22.32
Floor	½-in. by 4-in. by 8-ft. TTD plywood	3	32.84	98.52
Floor	¾-in by 4-ft by 8-ft CDX	3	28.68	86.04
Rim joists	2-in. by 8-in. by 12-ft	2	11.77	23.54
Center blocking	2-in. by 8-in. by 8-ft	1	7.96	7.96
Rim joists	2-in. by 8-in. by 8-ft	2	7.96	15.92
Joists	2-in. by 8-in. by 8-ft	7	7.96	55.72
Insulation	2-in. by 4-in. by 8-ft rigid foam	8	19.89	159.12
Insulation	1-in. by 4-in. by 8-ft rigid foam	3	9.45	28.35
Walls				
Studs	2- by 6- by 92-5/8-in.	30	5.92	177.6
Plates	2- by 6- by 92-5/8-in.	6	5.92	35.52
Plates	2- by 6- by 12-in.	5	8.81	44.05
Header	9-1/2-in. LVL (LF)	20	3.09	61.8
Insulation	R-19 Fiberglass Batt (150 SF)	3	14.99	44.97
Interior sheathing	½-in. by 4-in. by 8-ft CDX	8	21.01	168.08
Siding	½-in. by 4-in. by 8-ft T-111	10	37.53	375.3
Sill sealer	50-ft roll	1	3.6	3.6
Corners	1-in. by 4-in. by 8-ft SPF	8	3.36	26.88
"Z" flashing	1-1/4-in. by 10 ft	5	2.26	11.3
Water table	2-in. by 4-in. by 10-ft	4	3.73	14.92
Vapor barrier	Roll	1	12.99	12.99
Doors				
Frames	2-in. by 4-in. by 8-ft SPF	9	2.98	26.82
Face molding	1-in. by 4-in. by 8-ft SPF	10	3.36	33.6
Insulation	Rigid foam	4	14.65	58.6
Casing	1-in. by 4-in. by 8-ft SPF	8	3.36	26.88
Roof				
Rafters	2-in. by 6-in. by 10-ft	7	7.93	55.51
Sub-fascia	2-in. by 6-in. by 12-ft	2	8.81	17.62
Fascia	1-in. by 8-in. by 10-ft SPF	2	6.65	13.3
Fascia	1-in. by 8-in. by 12-ft SPF	2	7.98	15.96
Soffit	¼-in. by 4- by 8-in.	1	14.5	14.5
Interior sheathing	½- by 4-in. by 8-in. CDX	4	21.01	84.04
Exterior sheathing	½- by 4- by 8-ft CDX	2	21.01	42.02
Insulation	R-19 fiberglass Batt (100SF)	2	14.99	29.98
Felt	15# asphalt felt	1	13.94	13.94
Shingles	Fiberglass	4	11.99	47.96
Drip edge	"D" style 10-ft lengths	5	2.78	13.9
Hardware				
Slide bolts for doors		12	5.47	65.64
Handles for doors		8	6.24	49.92
Weather-stripping	70 lF (10-ft/Package)	7	2.56	17.92
Whole house fans		4	37.99	151.96
Dehumidifier	30-pint residential model	1	229.00	229.00
Drain hose		1	5.74	5.74
Electric baseboard		1	49.98	49.98
Remote hygrometer/thermometer	Radio Shack (Corporation, Fort Worth, Texas) Model 63-1030	1	54.68	54.68
Miscellaneous				
Exterior stain	Gallons	2	20.96	41.92
Paint for interior	Gallons	2	15.98	31.96
Anchor seal end coating	Quarts	2	18.00	36.00
Total cost of building materials				$2,703.85

Appendix B—Procedure for Cutting and Using Kiln Samples

1. Select a few boards from the pack of lumber that represent the slowest drying material. This would be the widest, thickest, and highest moisture content boards. Also choose those boards that contain the most heartwood or are quartersawn.

2. Cut a 24–30-in. sample that is free of knots and at least 12 in. from the end of the board. Then cut two 1-in. sections from the sample board as shown in (Figure 8). Make sure to number the sections and sample board.

3. Immediately weigh the 1-in. sections (accuracy of about 0.1 g required) and record the weight. Measure rapidly after cutting because it is important that the sections do not lose weight before weighing. Place in air-tight bag if not able to weigh within a minute or two.

4. End coat the sample board with either a wax emulsion, rubber-based sealing compound, or two coats of aluminum paint. Now, weigh the sample board and record weight on sample (accuracy of 0.1 g).

5. Place sample board in the lumber stack in a location where it will dry at the same rate as the rest of the lumber in the dryer.

6. Place the 1-inch sections in an oven 215–218°F (102–103°C) and dry—usually 48 h in an oven with good circulation. Reweigh and obtain the oven-dry weight.

7. Calculate the moisture content (MC) of each section and average the MC of two sections to obtain the MC for the sample board.

$$\%\text{MC} = \left(\frac{\text{wet weight}}{\text{oven dry weight}} - 1 \right) \times 100$$

8. Estimate ovendry weight of sample board using average MC above and weight from step 4. and record so these data can be used for future moisture content calculations to monitor the drying rate.

$$\text{Estimated OD weight} = \frac{\text{wet weight, step 4}}{(100 + \%\text{MC})} \times 100$$

9. To determine the moisture content at any time, reweigh the sample board and calculate.

$$\text{Current } \%\text{MC} = \left(\frac{\text{current weight}}{\text{Estimated OD weight}} - 1 \right) \times 100$$

Appendix C—Drying Schedules

Table 1—Experimental drying schedule for the mixed air-dried wood species (Run #1)

Date	Days	Average MC_{DB} (%)	Kiln temperature (°F)	Relative humidity (%)	Equilibrium moisture content (%)	Dehumidifier setting
3/21/2005	0	18.4	—	—	—	90%
3/22/2005	1	[a]	73.9	74	14.0	70%
3/24/2005	3	16.5	81.6	64	11.5	60%
3/28/2005	7	13.1	86.0	44	8.1	40%
3/29/2005	8	[a]	93.0	38	7.1	35%
3/30/2005	9	[a]	95.0	35	6.6	No change
3/31/2005	10	10.7	93.4	33	6.3	Heater 1200W
4/1/2005	11	[a]	128	23	4.2	Heater off
4/4/2005	14	7.7	96.1	20	4.2	[b]
4/5/2005	15	7.3	93.5	18	3.9	End of run

[a] Kiln samples were not weighed on these particular days.
[b] Dehumidifier not running (relative humidity less than 35%).

Table 2—Experimental kiln sample record for the mixed air-dried wood species (Run #1)

KILN SAMPLE RECORD

MATERIAL THICKNESS OR SIZE ____________ "4/4" SPECIES ___Mixed air dried lumber______
KILN NO. ___MATC DH________ DATE RUN STARTED __3/21/2005 1200________ ENDED ___4/5/2005 0800________

SAMPLE NO.	MOISTURE SECTION	A	B	Avg	Species	KILN SAMPLE Green Wt.	KILN SAMPLE Calc OD Wt	DATE: / HOUR: / Total days:	3/21/2005 1200	3/24/2005 745 3	3/28/2005 7:30 7	3/31/2005 7:30 10	4/4/2005 7:00 14	4/5/2005 8:00 15	Remarks
1	GR WT	603.2	1084					WT	683	669.2	648.2	634	617.8	617.8	
	OD WT	510	914			683	577.5	MC	18.3%	15.9%	12.2%	9.79%	6.98%	6.98%	
	MC	18.3%	18.6%		Pine			Loss/day		0.80	0.91	0.82	0.70	0.00	
2	GR WT							WT	707.1	693.9	673.2	658.5	642.1	641.3	
	OD WT					707.1	597.8	MC	18.3%	16.1%	12.6%	10.1%	7.40%	7.27%	
	MC				Pine			Loss/day		0.74	0.87	0.82	0.69	0.13	
3	GR WT							WT	1078.5	1064.4	1036.1	1014.9	986.7		
	OD WT					1078.5	909.4	MC	18.6%	17.0%	13.9%	11.6%	8.5%		
	MC				Wht Oak			Loss/day		0.52	0.78	0.77	0.78		
4	GR WT							WT	1094.5	1078.3	1048.1	1025.5	995.8	993.4	
	OD WT					1094.5	922.9	MC	18.6%	16.8%	13.6%	11.1%	7.90%	7.64%	
	MC				Wht Oak			Loss/day		0.59	0.82	0.82	0.80	0.26	
	GR WT							WT							
	OD WT							MC							
	MC							Loss/day							
	GR WT							WT							
	OD WT							MC							
	MC							Loss/day							
	GR WT							WT							
	OD WT							MC							
	MC							Loss/day							
	GR WT							WT							
	OD WT							MC							
	MC							Loss/day							
								AVG MC OF ALL SAMPLES:	18.4%	16.5%	13.1%	10.7%	7.7%	7.3%	
								AVG MC OF ___2___ WETTEST SAMPLES:	18.6%	16.9%	13.8%	11.4%	8.2%	7.6%	
								AVG MC LOSS PER DAY FOR ___2___ WETTEST SAMPLES:		1.7%	3.2%	2.4%	3.2%	0.6%	
								MC OF WETTEST SAMPLE:	18.6%	17.0%	13.9%	11.6%	8.5%	7.6%	
								MC OF DRIEST SAMPLE:	18.3%	15.9%	12.2%	9.8%	7.0%	7.0%	

Table 3—Experimental drying schedule for the green 5/4 black cherry (Run #2)

Date	Days	Average MC_{DB} (%)	Kiln temperature (°F)	Relative humidity (%)	Equilibrium moisture content (%)	Dehumidifier setting
9/8/2005	0	47.5	—	—	—	Off
9/9/2005	1	45.5	75.9	92	21.6%	85%
9/12/2005	4	[a]	84.4	93	22.0%	85%
9/13/2005	5	37.9	97.5	93	21.5%	85%
9/14/2005	6	[a]	100	90	19.5%	80%
9/15/2005	7	[a]	98.4	87	18.0%	80%
9/16/2005	8	31.0	90.3	86	17.8%	80%
9/19/2005	11	23.3	101.7	72	12.7%	70%/65%
9/20/2005	12	[a]	103.1	66	11.4%	50%
9/22/2005	14	[a]	105.6	56	9.5%	40%
9/23/2005	15	14.8	106.2	49	8.4%	35%
9/27/2005	19	10.4	95.2	35	6.6%	[b]
9/29/2005	21	[a]	92.5	32	6.2%	[b]
9/30/2005	22	9.1	91	29	5.8%	[b]
10/3/2005	25	8.3	96.8	31	6.0%	Heater 1200W
10/4/2005	26	[a]	131.7	20	3.7%	Heater 900W
10/5/2005	27	6.9	123.1	20	3.9%	End of run

[a] Kiln samples were not weighed on this particular day.
[b] Dehumidifier not running (relative humidity less than 35%).

Table 4—Experimental kiln sample record for the green 4/4 and 5/4 black cherry (Run #2)

KILN SAMPLE RECORD

MATERIAL THICKNESS OR SIZE ________ 5/4 Stock SPECIES ________ Black Cherry

KILN NO. ______ MATC DH DATE RUN STARTED ______ 9/8/2005 1000 ENDED ______ 10/5/2005 0630

SAMPLE NO.	MOISTURE SECTION				KILN SAMPLE		DATE:	9/8/2005	9/9/2005	9/13/2005	9/16/2005	9/19/2005	9/23/2005	9/27/2005	9/30/2005	10/3/2005	10/5/2005	Remarks
		A	B	Avg	Green Wt.	Calc. OD Wt.	HOUR:	1000	1500	630	1400	630	630	630	630	630	630	
							Total days:		1	5	8	11	15	19	22	25	27	
1	GR WT	235.4	215.8		935.9	613.1	WT	935.9	921.8	877.1	844	792.6	726.7	689.7	677.3	670.8	659.6	
	OD WT	154.54	141.05				MC	52.66%	50.36%	43.07%	37.67%	29.28%	18.54%	12.50%	10.48%	9.42%	7.59%	
	MC	52.3%	53.0%	52.66%			Loss/day		1.90%	2.00%	1.63%	3.13%	2.69%	1.51%	0.67%	0.35%	0.91%	
2	GR WT	162.3	152.8		882.6	578.1	WT	882.6	870.4	822.5	762.8	710.4	659.3	635.2	629	625	617.1	
	OD WT	104.97	101.39				MC	52.66%	50.55%	42.27%	31.94%	22.88%	14.04%	9.87%	8.80%	8.10%	6.74%	
	MC	54.6%	50.7%	52.66%			Loss/day		1.75%	2.28%	3.11%	3.38%	2.21%	1.04%	0.36%	0.23%	0.68%	
3	GR WT	148.1	132.8		1129.9	822.8	WT	1129.9	1116.8	1055.4	1015.7	968.2	918.9	894.9	888.1	883.2	871.8	
	OD WT	104.81	99.59				MC	37.33%	35.73%	28.27%	23.45%	17.67%	11.68%	8.76%	7.94%	7.34%	5.96%	
	MC	41.3%	33.3%	37.33%			Loss/day		1.32%	2.05%	1.45%	2.15%	1.50%	0.73%	0.28%	0.20%	0.69%	
	GR WT						WT											
	OD WT						MC											
	MC						Loss/day											
	GR WT						WT											
	OD WT						MC											
	MC						Loss/day											
	GR WT						WT											
	OD WT						MC											
	MC						Loss/day											
	GR WT						WT											
	OD WT						MC											
	MC						Loss/day											
							AVG MC OF ALL SAMPLES:	47.5%	45.5%	37.9%	31.0%	23.3%	14.8%	10.4%	9.1%	8.3%	6.8%	
							AVG MC OF __2__ WETTEST SAMPLES:	52.7%	50.5%	42.7%	34.8%	26.1%	16.3%	11.2%	9.6%	8.8%	7.2%	
							AVG MC LOSS PER DAY FOR __2__ WETTEST SAMPLES:		1.82%	2.14%	2.37%	3.26%	2.45%	1.28%	0.52%	0.29%	0.80%	
							MC OF WETTEST SAMPLE:	52.66%	50.55%	43.07%	37.67%	29.28%	18.54%	12.50%	10.48%	9.42%	7.59%	
							MC OF DRIEST SAMPLE:	37.33%	35.73%	28.27%	23.45%	17.67%	11.68%	8.76%	7.94%	7.34%	5.96%	

Table 5—Experimental drying schedule for the green 4/4 northern red oak (Run #3)

Date	Days	Average MC_{DB} (%)	Kiln temperature (°F)	Relative humidity (%)	Equilibrium moisture content (%)	Dehumidifier setting
10/25/2005	0	82.9	60.0	50	9.4	90%
10/31/2005	6	[a]	62.6	96	24.9	85%
11/1/2005	7	[a]	79.3	97	25.4	85%
11/1/2005	7	[a]	89.4	93	21.8	85%
11/2/2005	8	[a]	86.5	96	24.2	85%
11/3/2005	9	[a]	93.2	93	21.7	85%
11/4/2005	10	64.5	94.8	90	19.7	80%
11/7/2005	13	[a]	91.0	89	19.3	75%
11/8/2005	14	[a]	95.2	85	17.2	70%
11/9/2005	15	47.2	97.5	83	16.3	65%
11/10/2005	16	[a]	103	73	13.0	60%
11/11/2005	17	[a]	104	68	11.8	45%
11/14/2005	20	29.5	99.3	55	10.0	35%
11/15/2005	21	[a]	110	48	8.2	35%
11/16/2005	22	23.7	111	39	6.9	35%
11/17/2005	23	[a]	109	35	6.4	35%
11/18/2005	24	[a]	111	31	5.8	35%
11/21/2005	27	[a]	102	26	5.1	35%
11/22/2005	28	14.7	102	24	4.8	35%
11/28/2005	34	9.8	106	19	3.9	35%
11/29/2005	35	[a]	108	17	3.6	35%
11/30/2005	36	8.8	106	16	3.4	35%
12/1/2005	37	[a]	106	16	3.4	35%
12/2/2005	38	[a]	105	16	3.4	35%
12/5/2005	41	7.1	106	15	3.2	[b]
12/6/2005	42	[a]	104	15	3.2	[b]
12/7/2005	43	[a]	104	15	3.2	[b]
12/8/2005	44	[a]	104	15	3.2	[b]
12/9/2005	45	6.1	104	15	3.2	[b]
12/13/2005	49	[a]	107	14	3.0	[b]
12/14/2005	50	5.2	107	14	3.0	End of run

[a] Kiln samples not weighed on these days.
[b] Dehumidifier not running (relative humidity less than 35%).

Table 6—Experimental kiln sample record for the green 4/4 northern red oak (Run #3)

KILN SAMPLE RECORD

MATERIAL THICKNESS OR SIZE ______________ 4/4 Stock

SPECIES ________ #2 Common Red Oak

KILN NO. _______ MATC DH

DATE RUN STARTED __________ 10/25/2005 1100

ENDED _______ 12/14/2005 0630

SAMPLE NO.	MOISTURE SECTION				KILN SAMPLE		DATE:	10/25/05	10/31/05	11/04/05	11/09/05	11/14/05	11/16/05	11/22/05	11/28/05	11/30/05	12/05/05	12/09/05	12/14/05	Remarks
		A	B	Avg	Green Wt.	Calc OD Wt	HOUR:	1100	630	700	630	630	630	630	630	930	630	630	630	
							Hours b/t checks			97	119	120	48	144	144	51	117	96	120	
1	GR WT	129.9	128.7				WT	1185.5	1185.5	1074.1	962.2	845	805.2	742	707.7	700.9	689.2	683	677.5	Dehumifier turned on 10/31/05 0630
	OD WT	70.08	69.75		1185.5	641.0	MC	84.94%	84.94%	67.56%	50.10%	31.82%	25.61%	15.75%	10.40%	9.34%	7.52%	6.55%	5.69%	
	MC	85.36%	84.52%	84.94%			Loss/day			4.31%	3.51%	3.66%	3.10%	1.64%	0.89%	0.50%	0.37%	0.24%	0.17%	
2	GR WT	127.2	121.0				WT	1182.1	1182.1	1055.7	941.9	829.4	792.3	736.8	708	701.6	690.8	684.5	679.1	No condensate formed until 11/1/05 0630
	OD WT	69.1	66.07		1182.1	643.8	MC	83.61%	83.61%	63.98%	46.30%	28.83%	23.06%	14.44%	9.97%	8.98%	7.30%	6.32%	5.48%	
	MC	84.08%	83.14%	83.61%			Loss/day			4.87%	3.56%	3.49%	2.88%	1.44%	0.75%	0.47%	0.34%	0.24%	0.17%	
3	GR WT	156.0	156.3				WT	1125.8	1125.8	1012.3	908.2	799.9	765.2	711.7	681.6	675.6	664.8	659	653.3	Added timer 11/2/05 0630
	OD WT	87.01	86.37		1125.8	625.0	MC	80.13%	80.13%	61.97%	45.31%	27.98%	22.43%	13.87%	9.06%	8.10%	6.37%	5.44%	4.53%	
	MC	79.29%	80.97%	80.13%			Loss/day			4.51%	3.35%	3.47%	2.78%	1.43%	0.80%	0.45%	0.35%	0.23%	0.18%	
	GR WT						WT													
	OD WT						MC													
	MC						Loss/day									44				
	GR WT						WT									39				
	OD WT						MC													
	MC						Loss/day													
	GR WT						WT													
	OD WT						MC													
	MC						Loss/day													
	GR WT						WT													
	OD WT						MC													
	MC						Loss/day													
	GR WT						WT													
	OD WT						MC													
	MC						Loss/day													
							AVG MC OF ALL SAMPLES:	82.9%	82.9%	64.5%	47.2%	29.5%	23.7%	14.7%	9.81%	8.80%	7.06%	6.10%	5.23%	
							AVG MC OF ___2___ WETTEST SAMPLES:	84.27%	84.27%	65.77%	48.20%	30.32%	24.34%	15.10%	10.19%	9.16%	7.41%	6.43%	5.59%	
							AVG MC LOSS PER DAY FOR ___2___ WETTEST SAMPLES:			4.59%	3.53%	3.58%	2.99%	1.54%	0.82%	0.48%	0.36%	0.24%	0.17%	
							MC OF WETTEST SAMPLE:	84.94%	84.94%	67.56%	50.10%	31.82%	25.61%	15.75%	10.40%	9.34%	7.52%	6.55%	5.69%	
							MC OF DRIEST SAMPLE:	80.13%	80.13%	61.97%	45.31%	27.98%	22.43%	13.87%	9.06%	8.10%	6.37%	5.44%	4.53%	

Table 7—Experimental drying schedule for the green 4/4 mixed hardwoods (Run #4)

Date	Days	Average MC_{DB} (%)	Kiln temperature (°F)	Relative humidity (%)	Equilibrium moisture content (%)	Dehumidifier setting
8/3/2006	0	69.7	81.1	89	19.6	90%
8/4/2006	1	[a]	92.3	94	22.4	85%
8/7/2006	4	50.8	96.1	88	18.6	85%
8/9/2006	6	43.1	96.8	81	15.5	85%
8/14/2006	11	29.7	97.9	64	11.1	60%
8/15/2006	12	[a]	103.1	56	9.5	55%
8/16/2006	13	24.7	104.4	49	8.4	50%
8/18/2006	15	20.4	105.8	37	6.7	35%
8/21/2006	18	[a]	108.3	27	5.2	[b]
8/22/2006	19	[a]	110	26	5.0	[b]
8/23/2006	20	[a]	113.2	24	4.7	[b]
8/28/2006	25	[a]	115	18	3.6	[b]
8/29/2006	26	[a]	104	23	4.6	[b]
8/30/2006	27	[a]	96.4	26	5.2	[b]
9/1/2006	29	9.1	80.4	38	7.3	End of run

[a] Kiln samples not weighed.
[b] Dehumidifier not running (relative humidity less than 35%).

Table 8—Experimental kiln sample record for the green mixed hardwoods (Run #4)

KILN SAMPLE RECORD

MATERIAL THICKNESS OR SIZE ______________ 4/4 Stock   SPECIES ________ #2 Common Red Oak

KILN NO. _______MATC DH   DATE RUN STARTED __________ 8/3/2006   ENDED ___09/01/2006________

SAMPLE NO.	MOISTURE SECTION	A	B	Avg	KILN SAMPLE Green Wt.	Calc OD Wt	DATE:	08/03/06	08/07/06	08/09/06	08/14/06	08/16/06	08/18/06	08/28/06	08/29/06	09/01/06	Remarks
							HOUR:	1100	700	700	700	700	700	700	7:00	15:00	
							Total Hrs:		92	48	120	48	48	240	17	72	
1	GR WT	112.7	108.4		1144.3	714.8	WT	1144.3	1011.3	967.4	893.8	864.5	840.5	777.9	775.3	776.2	
	OD WT	69.8	68.3				MC	60.09%	41.48%	35.34%	25.04%	20.94%	17.59%	8.83%	8.46%	8.59%	
	MC	61.46%	58.71%	60.09%			Loss/day		4.85%	3.07%	2.06%	2.05%	1.68%	0.88%	0.51%	-0.04%	
2	GR WT	89.6	112.6		1129.1	638.6	WT	1129.1	1013.9	940.4	846.7	811.4	781.7	701.3	697.7	696.6	
	OD WT	50.5	63.9				MC	76.82%	58.78%	47.27%	32.59%	27.07%	22.42%	9.82%	9.26%	9.09%	
	MC	77.43%	76.21%	76.82%			Loss/day		4.71%	5.76%	2.93%	2.76%	2.33%	1.26%	0.80%	0.06%	
3	GR WT	96.9	96.2		1014.3	588.8	WT	1014.3	895.3	863.7	774.6	742.3	714	639.2	636.3	635.2	
	OD WT	56.7	55.4				MC	72.27%	52.06%	46.69%	31.56%	26.08%	21.27%	8.56%	8.07%	7.88%	
	MC	70.90%	73.65%	72.27%			Loss/day		5.27%	2.68%	3.03%	2.74%	2.40%	1.27%	0.70%	0.06%	
	GR WT						WT										
	OD WT						MC										
	MC						Loss/day										
	GR WT						WT										
	OD WT						MC										
	MC						Loss/day										
	GR WT						WT										
	OD WT						MC										
	MC						Loss/day										
	GR WT						WT										
	OD WT						MC										
	MC						Loss/day										
	GR WT						WT										
	OD WT						MC										
	MC						Loss/day										
							AVG MC OF ALL SAMPLES:	69.7%	50.8%	43.1%	29.7%	24.7%	20.4%	9.1%	8.6%	8.5%	
							AVG MC OF ______2________ WETTEST SAMPLES:	74.55%	55.42%	46.98%	32.08%	26.57%	21.84%	9.33%	8.86%	8.84%	
							AVG MC LOSS PER DAY FOR _______2_______ WETTEST SAMPLES:		4.99%	4.22%	2.98%	2.75%	2.36%	1.26%	0.75%	0.06%	
							MC OF WETTEST SAMPLE:	76.82%	58.78%	47.27%	32.59%	27.07%	22.42%	9.82%	9.26%	9.09%	
							MC OF DRIEST SAMPLE:	60.09%	41.48%	35.34%	25.04%	20.94%	17.59%	8.56%	8.07%	7.88%	