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THE EFFECT OF AIR VELOCITY ON REACHING DRY KILN SATURATION TEMPERATURES FOR OAK

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In today's marketplace, no one need be reminded of the high cost of hardwood lumber, particularly sought-after species such as oak, ash, walnut, and cherry. Because of these high lumber costs, every effort is made to minimize yield losses from the sawmill through the finished product. One of the areas of manufacture where yield losses are heavy is drying.

Probably the most difficult native furniture species to kiln dry without degrade is oak. It is characterized as a refractory drying species and is prone to checks, honeycomb, and collapse when not handled with care. Probably more has been written and researched about drying and handling this wood than any other native U.S. species. In spite of the problems in handling and drying this wood, its popularity in furniture, trim, molding, and flooring continues. Its production continues at a level of about 3.5 billion board feet a year and leads all other hardwood species in volume use.

The other three species, ash, cherry, and walnut are relatively easy to dry and pose no special problems except in drying thicker stock. With oak the situation is different.

Kiln operators using recommended kiln schedules have been dismayed and frustrated to find kiln charges of oak, 4/4 and thicker, ruined by deep checking and/or honeycomb.

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Training in lumber drying procedures has stressed proper air drying, stacking, and kiln-drying techniques emphasizing the need for cautious use of kiln schedules and alternative drying procedures. One area of concern has been largely ignored: the design and use of proper kiln-drying equipment.

It has long been known and preached that uniform and adequate air circulation through the lumber stacks is the key to proper kiln drying. The most careful stacking procedures and precise adjustment of kiln schedules are of minor importance if the proper conditions of heat and humidity are not uniformly and adequately carried across the lumber load by brisk air movement.

The two major types of conventional steam-heated dry kilns in use today each have advantages and disadvantages in their ability to dry lumber with minimum degrade. While other methods of drying are important, conventional steam-heated kilns are of greater use and so are emphasized here. Because oak is the most refractory drying species in popular use today, remarks will be made with this wood in mind.

Kiln Types

Package-Loaded Kiln

The package-loaded kiln is characterized by a large square or rectangular building, usually aluminum prefab, loaded and unloaded by forklift trucks in an operation requiring approximately one-half dayFans and heating coils aregenerally overhead and air is delivered through several rows of packages (fig. 1). Package-loaded kilns range in size from 30 to 100 MBF holding capacities. There may be one or two dry bulbs; if only one,it is located above the fan floor; if two, they are located one each in the plenum spaces. One wet bulb is located in the rear plenum space, usually at shoulder level. Fixed steel posts are usually placed across the rear of the kiln to delineate loading depth limits, thereby preventing plenum space encroachment. Loading limit in front at the loading door is sometimes delineated by paint marks on the floor.When loaded properly, plenum spaces at rear and front are equal. The plenum spaces are wide enough so that static pressure buildup in these areas is sufficient to deliver uniform air velocities up and down, as well as across the lumber load. When properly loaded with lumber from side to side and with all ceiling and end baffles in place, air velocities through the lumber sticker spaces should be fairly uniform. Distance of air travel before reheating may be 20-30 feet. Air velocities in older units may be about 200 fpm, in some newer units 300-400 fpm. More recently kiln companies have increased fanpower to deliver higher air velocities. Very serious differences in air velocities readily occur, however, when any of the above loading and baffling requirements are not met.

The popularity of the forklift-loaded package kiln is due largely to the fact that it is much more economical to buy and install. Most drying facilities already have a forklift truck on the yard for handling lumber and therefore can use the same equipment to load and unload the dry kiln.

Track Kiln

The track-type lumber dry kiln-- similar in construction to the package kiln--is characterized by tracks on which the bunks of lumber are rolled in and out of the structure. The track kiln may have doors at each end to facilitate loading and unloading or may have doors only at one end. Unloading and loading requires 1 to 2 hours. Track kilns can be single-, double-, or even triple-track (fig. 2). Lumber is usually taken from a stacker and loaded by forklift onto the waiting kiln trucks and rolled into the kiln as soon as the previous charge has been dried.

The fan system is usually above the load, as with the package kiln, and the dry bulbs are usually located on each wall in the plenum space with one wet bulb located adjacent to one of the dry bulbs. If it is a long kiln, there may be double-end controls requiring two sets of dry bulbs, to give better temperature control throughout the chamber. Some track kilns may be 100 feet long or more and hold up to 100,000 board feet of lumber per charge.

Baffling is usually fixed: a ceiling baffle from the ceiling and a floor baffle which may consist of a concrete walkway or hinged steel panel lifted up from the floor against the load (fig. 2). End baffles are also used, generally swinging out from the wall near the ends of the dry kiln to prevent short circuiting of air around the ends of the bunks of lumber. Because lumber loads of a specific height and width are placed on kiln trucks when lumber is rolled into the kiln, the correct plenum space is maintained and correct baffling is also usually assured. If the lumber is properly stacked on kiln trucks and the kiln filled, the air velocities are usually very uniform.

Another important feature of the multi-track-type kiln (double- or triple-track) is the inclusion of reheat or booster coils between tracks (fig. 2). The temperature of the reheat coils is usually under control. Maximum air travel before reheating is the width of one track, 8 feet or less.

The track-type kiln, on the other hand, requires steel track, kiln trucks, and additional space for the transfer car system. As a result, it costs considerably more than the popular package-loaded kiln.

Considerations

Air Circulation

The purpose of air circulation is to distribute the proper dry bulb and wet bulb temperature uniformly through the stickered lumber. Good air circulation carries the heat to the wood, evaporating the water from its surface and carrying it away. Good air circulation provides a means of mixing and conditioning the air to the desired dry-bulb and wet-bulb conditions before it enters the load; it provides effective heat transfer from the heating coils. Without uniform air circulation, it would be difficult, if not impossible, to dry the lumber uniformly in a conventional dry kiln.

The package-loaded lumber dry kiln, by nature of its design, encourages variable loading. It is difficult for this type of kiln to be loaded exactly the same way each time. Rows of lumber are not always correctly positioned against the walls, neither are spaces between rows always the same, and, if the kiln is not completely filled, it is difficult to baffle properly. This variation in loading has a direct effect on uniformity and speed of air travel through the lumber.

Because the track-type kiln, by nature of its design, is difficult to load improperly, plenum spaces are maintained, baffles are in correct position, and consequently air velocities tend to be uniform load after load.

Kiln Function

When first introduced, the package-loaded dry kiln was intended to dry air-dried stock, primarily hardwoods. Traditionally all hardwood lumber was well air dried before kiln dried. Recognizing the fact that moisture leaves wood more slowly when the wood is below fiber saturation point (about 30% moisture content), the package-loaded kiln seemed a logical way to dry lumber more cheaply. When wood is below the fiber saturation point, the moisture in it is moving primarily by diffusion and high air velocities are not as important to the uniform drying of lumber. Probably the only function of high air velocities below fiber saturation point is to continue to keep the heat transfer rate high between the heating system and the wood, For many years the package-loaded kiln did an acceptable job when loaded properly and baffled correctly with air-dried stock. Invariably, with time, the package kiln was used more and more for drying partly air-dried or green lumber, particularly when management became pushed for production. Presently, too many package-loaded dry kilns are being used in this way--incorrectly.

The track-type kiln, on the other hand, was designed to dry either green or air-dried stock by virtue of its uniform air velocity and short air travel before reheating.

Potential for Degrade

Both types of kilns use similar heating, venting, humidification, and controlling equipment. The basic differences are two: (1) method of loading, and (2) length of air travel without reheat.

The method of loading the package kiln can vary from load to load. This variation in loading results in variations in air velocity at various locations in the kiln load.

The track kiln, with its fixed ceiling and floor baffle system, and its necessary standard loading systems, usually results in the load being uniformly and correctly positioned in the kiln. Air velocities are therefore usually very uniform.

The second difference in the two kiln types mentioned is length of air travel without reheat. As the proper conditions of heat and humidity (dry bulb and wet bulb temps) enter the load, evaporation of water from the wood surfaces begins and the dry-bulb temperature begins to drop. Over a distance of air travel in wet lumber, the dry-bulb temperature will drop until it reaches the same temperature as the wet bulb. This can easily happen during the initial stages of drying of green oak when the dry-bulb and wet-bulb temperature differences are small. When this occurs, the air becomes saturated and can hold no more water vapor as it moves across the remaining portion of the course of lumber.

If saturation is reached in a short distance of air travel, the lumber beyond that point will dry much more slowly or not at all. When fans reverse, the same thing begins in the other direction. In long air travel, therefore, a "wet zone" will be maintained throughout a center part of the load. This situation applies particularly to green or partly air-dried lumber when schedules call for small wet-bulb depressions. Changes made in the schedule will be based upon sample board moisture contents during this critical initial drying period. However, because sample boards are usually placed only on the entering or leaving air side of the charge, nothing is known about moisture contents in the interior of the charge where saturation may be occurring. What is done during the early stages of oak drying is responsible for severe checking and later development of honeycomb.[1/] [2/]

Equation and Examples

A mathematical equation was developed to show the effect of air speed and sticker thickness on temperature drop across a load of red oak lumber at a given rate of drying. Material balance equations can be written over a 12-inch-wide section of stock for a time base of 1 minute.

Water loss rate is calculated as:

$$W = \left(\frac{\Delta M}{100 \times 24 \times 60}\right)\left(\frac{12\ t\ L}{144}\right)\left(\rho_{SG}\right)\left(62.4\right) \ \text{lb } H_2O/\text{min} \qquad (1)$$

where

ΔM = moisture loss per day, %,

t = board thickness, in,

L = length of air flow path, ft.,

ρ_{SG} = specific gravity wood.

Air flow rate is calculated as:

$$A = \frac{12d\ \nu}{144} \times 0.081 \ \text{lb air/min} \qquad (2)$$

where

d = sticker spacing, in,

ν = air velocity, ft/min.

[1/] McMillen, J.M. 1963. Stresses in wood during drying. FPL Report 1652. USDA, Forest Service, Forest Products Laboratory, Madison, Wis.

[2/] Bois, P.J. 1977. The four stages of drying in thick oak. FPRS News Digest J-1.3.

Water loss per pound of air can then be calculated:

$$\Delta H = W/A \text{ lb. } H_2O/\text{lb air}$$

$$= 0.00535\ \Delta M(\rho_{SG})\frac{t\ L}{d\ \nu} \qquad (3)$$

Wet-bulb temperature function, as published,[3] is:

$$\Delta H_s = H_s - H = \frac{0.26}{1026}(t_D - t_W) \text{ lb } H_2O/\text{lb air} \qquad (4)$$

where

subscript s = saturated absolute humidity at t_D,

t_D = entering dry-bulb temperature, °F,

t_W = wet-bulb temperature, °F.

If $\Delta H_s = \Delta H$, equation (3) can be combined with equation (4) to yield:

$$\frac{t\ L}{d\ \nu} = \frac{0.04737(t_D - t_W)}{\Delta M(\rho_{SG})} \qquad (5)$$

Realizing that:

$$H_i = \frac{0.62\ p_i}{760 - p_i} \qquad (6)$$

and

$$RH = \frac{p_i}{p_s} \times 100 \qquad (7)$$

where

p_i - partial pressure H_2O, mm Hg,

p_s = vapor pressure H_2O, mm Hg,

RH - relative humidity.

[3] Zimmerman, O.T., and Lavine, I. 1964. Psychrometry tables and charts, 2nd ed. Ind. Res. Service, Inc., Dover, N.H., p. 4.

The tables were generated by a simple computer program using equations (5), (6), and (7), along with a suitable vapor pressure function for water (not shown).

Tables l-4 illustrate how far air travels before reaching saturation at each step of the green schedule for 4/4-8/4. The calculations were not carried out beyond Step 5 where wood moisture contents are below 30% and where rate of moisture removal from wood slows upThe results are startling and very likely explain why package-loaded kilns with long air travel and poor air circulation are responsible for poor lumber quality.

A few examples from the table will illustrate the problem. In a kiln of 6/4 oak with 200 fpm air velocity and 3/4-inch stickers, during Step 1 of the schedule, the air on the entering side of the load travels about 9-l/2 feet before reaching saturation. At fan reversal, the same thing happens from the other direction. In a package kiln with 24 feet of air travel, the central 4+ feet of lumber dries little or not at all. When kiln schedules are advanced, based on the moisture content of kiln samples located near the edges, drying progresses somewhat further as the wet-bulb depression increases, but still a zone in the center is not drying. As the kiln temperatures are raised and the wet-bulb is dropped, kiln conditions increase in severity and the potential for degrading the oak increases in the central portion of the charge.

In another example using a track kiln and the same set of initial conditions (6/4 oak, 200 fpm and 3/4-inch stickers), if the load is 8 feet wide or less (typical), the air does not reach saturation before leaving the load; and with fan reversal, uniform drying conditions can be maintained throughout the width of the lumber charge. This assumes in multi-track kilns that the reheat coils and proper venting are bringing the dry-bulb temperature back up to set point before the air re-enters any additional loads. Both higher air velocities and thicker stickers permit longer air travel before saturation is reached (Tables l-4).

When Step 5 is reached, long air travels are possible without fear of reaching saturation. This step of schedule coincides with a moisture content of 30% and would be the advisable starting place for a load of oak in a package kiln.

Remember, this moisture content, or below, is the starting moisture content recommended for kilns of this type when they were introduced!

To ensure defect-free dried lumber, use these tables with air speed and sticker thickness in your oak kiln(s) to determine if saturation is being reached before the air gets through your package(s) of lumber.

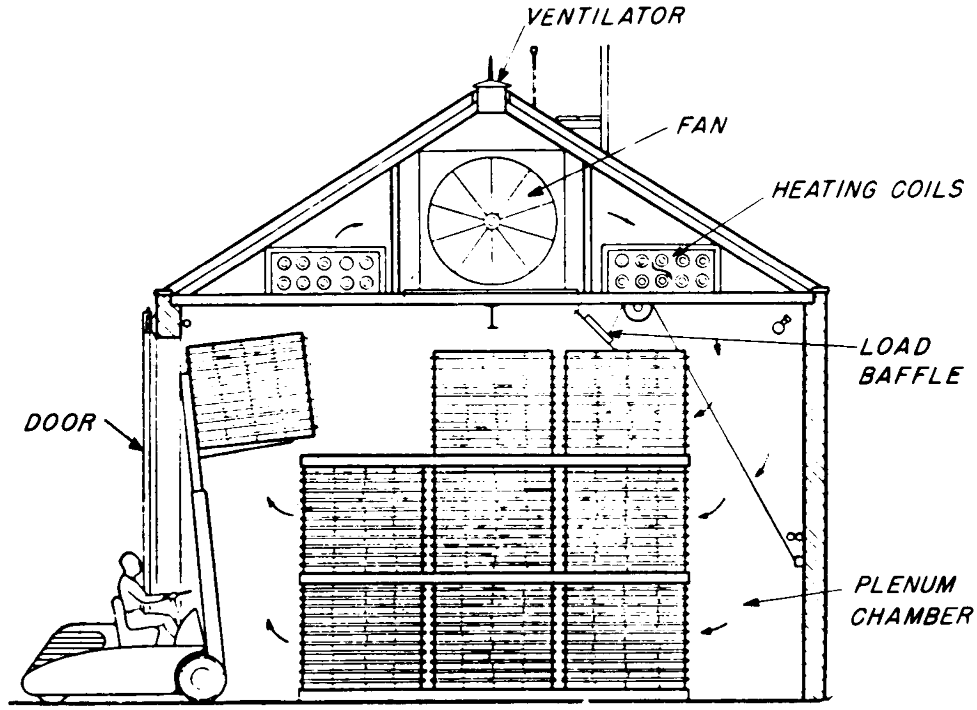

Figure 1.--Package-loaded, trackless compartment kiln of long-shaft, internal fan type. More recent models are usually of the direct connected internal fan type. Ventilators are mounted between fans.

(ZM 105 910)

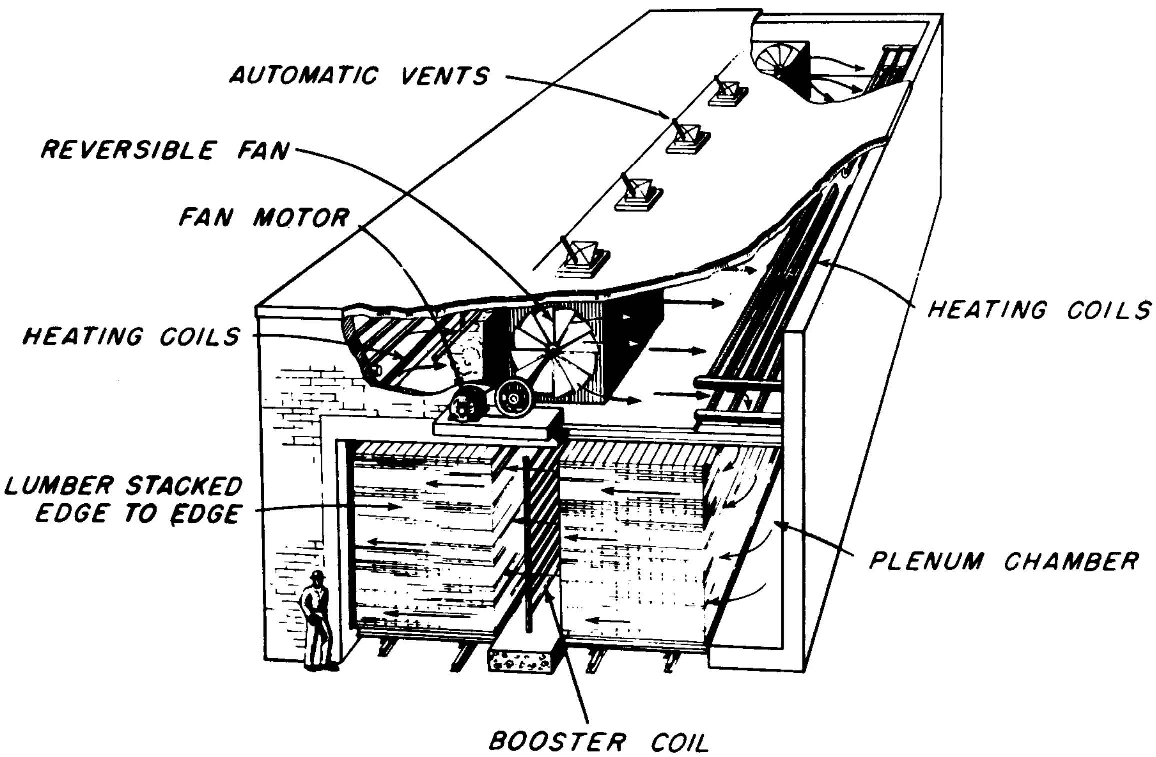

Figure 2.--Track kiln with long-shaft external motor. Booster or reheat coil is located between the two tracks.

(ZM 105 908)

Table 1.--Calculated air travel distance to saturation in drying 4/4 red oak by FPL kiln schedules T3-D1[1]

Air Velocity[2]	Sticker Thickness	Step 1 (110° F Dry Bulb, 106° F Wet Bulb)	Step 2 (110° F Dry Bulb), 105° F Wet Bulb)	Step 3 (110° F Dry Bulb, 102° F Wet Bulb)	Step 4 (110° F Dry Bulb, 96" F Wet Bulb)	Step 5 (120° F Dry Bulb, 90° F Wet Bulb)
fpm	In.	ft.				
100	1/2	4.2	5.3	8.5	14.8	30.7
	3/4	6.3	7.9	12.7	22.2	46.0
	1	8.5	10.6	16.9	29.6	61.3
200	1/2	8.5	10.6	16.9	29.6	61.3
	3/4	12.7	15.9	25.4	44.4	92.0
	1	16.9	21.1	33.8	59.2	122.7
300	1/2	12.7	15.9	25.4	44.4	92.0
	3/4	19.0	23.8	38.1	66.6	138.0
	1	25.4	31.7	50.8	88.8	184.0
400	1/2	16.9	21.1	33.8	59.2	122.7
	3/4	25.4	31.7	50.8	88.8	184.0
	1	33.8	42.3	67.7	118.4	245.3
500	1/2	21.1	26.4	42.3	74.0	153.3
	3/4	31.7	39.7	63.4	111.0	230.0
	1	42.3	52.9	84.6	148.0	306.6
600	1/2	25.4	31.7	50.8	88.8	184.0
	3/4	38.1	47.6	76.1	133.2	276.0
	1	50.8	63.4	101.5	177.6	368.0
700	1/2	29.6	37.0	59.2	103.6	214.6
	3/4	44.4	55.5	88.8	155.4	322.0
	1	59.2	74.0	118.4	207.2	429.3
800	1/2	33.8	42.3	67.7	118.4	245.3
	3/4	50.8	63.7	101.5	177.6	368.0
	1	67.7	84.6	135.3	236.8	490.6
900	1/2	38.1	47.6	76.1	133.2	276.0
	3/4	57.1	71.4	114.2	199.8	414.0
	1	76.1	95.2	152.3	266.5	551.9
1000	1/2	42.3	52.9	84.6	148.0	306.6
	3/4	63.4	79.3	126.9	222.0	460.0
	1	84.6	105.7	169.2	296.1	613.3

[1] For purposes of this calculation, drying rate was a constant 4%/day, a reasonable amount down to about the fiber saturation point (about 30% m.c.).

[2] Measured on leaving air side through sticker spaces.

Table 2.--Calculated air travel distance to saturation in drying 5/4 red oak by FPL kiln schedules T3-D1[1/]

Air Velocity[2/]	Sticker Thickness	Step 1 (110° F Dry Bulb, 106° F Wet Bulb)	Step 2 (110° F Dry Bulb, 105° F Wet Bulb)	Step 3 (110° F Dry Bulb, 102° F Wet Bulb)	Step 4 (110° F Dry Bulb, 96° F Wet Bulb)	Step 5 (120° F Dry Bulb, 90° F Wet Bulb)
fpm	In.	ft.				
100	1/2	3.4	4.2	6.8	11.8	24.5
	3/4	5.1	6.3	10.2	17.8	36.8
	1	6.8	8.5	13.5	23.7	49.1
200	1/2	6.8	8.5	13.5	23.7	49.1
	3/4	10.2	12.7	20.3	35.5	73.6
	1	13.5	16.9	27.1	47.4	98.1
300	1/2	10.2	12.7	20.3	35.5	73.6
	3/4	15.2	19.0	30.5	53.3	110.4
	1	20.3	25.4	40.6	71.1	147.2
400	1/2	13.5	16.9	27.1	47.4	98.1
	3/4	20.3	25.4	40.6	71.1	147.2
	1	27.1	33.8	54.1	94.7	196.2
500	1/2	16.9	21.1	33.8	59.2	122.7
	3/4	25.4	31.7	50.8	88.8	184.0
	1	33.8	42.3	67.7	118.4	245.3
600	1/2	20.3	25.4	40.6	71.1	147.2
	3/4	30.5	38.1	60.9	106.6	220.8
	1	40.6	50.8	81.2	142.1	294.4
700	1/2	23.7	29.6	47.4	82.9	171.7
	3/4	35.5	44.4	71.1	124.3	257.6
	1	47.4	59.2	94.7	165.8	343.4
800	1/2	27.1	33.8	54.1	94.7	196.2
	3/4	40.6	50.8	81.2	142.1	294.4
	1	54.1	67.7	108.3	189.5	392.5
900	1/2	30.5	38.1	60.9	106.6	220.8
	3/4	45.7	57.1	91.4	159.9	331.2
	1	60.9	76.1	121.8	213.2	441.6
1000	1/2	33.8	42.3	67.7	118.4	245.3
	3/4	50.8	63.4	101.5	177.6	368.0
	1	67.7	84.6	135.3	236.8	490.6

[1/]For purposes of this calculation, drying rate was a constant 4%/day, a reasonable amount down to about the fiber saturation point (about 30% m.c.).

[2/]Measured on leaving air side through sticker spaces.

Table 3--Calculated air travel distance to saturation in drying 6/4 red oak by FPL kiln schedules T3-D1[1/]

Air Velocity[2/]	Sticker Thickness	Step 1 (110° F Dry Bulb, 107° F. Wet Bulb)	Step 2 (110° F Dry Bulb, 106° F Wet Bulb)	Step 3 (110° F Dry Bulb, 104° F Wet Bulb)	Step 4 (110° F Dry Bulb, 100° F Wet Bulb)	Step 5 (120° F Dry Bulb, 95° F Wet Bulb)
fpm	In.			ft.		
100	1/2	2.8	3.8	5.6	9.4	23.5
	3/4	4.2	5.6	8.5	14.1	35.2
	1	5.6	7.5	11.3	18.8	47.0
200	1/2	5.6	7.5	11.3	18.8	47.0
	3/4	8.5	11.3	16.9	28.2	70.5
	1	11.3	15.0	22.6	37.6	94.0
300	1/2	8.5	11.3	16.9	28.2	70.5
	3/4	12.7	16.9	25.4	42.3	105.7
	1	16.9	22.6	33.8	56.4	141.0
400	1/2	11.3	15.0	22.6	37.6	94.0
	3/4	16.9	22.6	33.8	56.4	141.0
	1	22.6	30.1	45.1	75.2	188.0
500	1/2	14.1	18.8	28.2	47.0	117.5
	3/4	21.1	28.2	42.3	70.5	176.2
	1	28.2	37.6	56.4	94.0	235.0
600	1/2	16.9	22.6	33.8	56.4	141.0
	3/4	25.4	33.8	50.8	84.6	211.5
	1	33.8	45.1	67.7	112.8	282.0
700	1/2	19.7	26.3	39.5	65.8	164.5
	3/4	29.6	39.5	59.2	98.7	246.7
	1	39.5	52.6	78.9	131.6	329.0
800	1/2	22.6	30.1	45.1	75.2	188.0
	3/4	33.8	45.1	67.7	112.8	282.0
	1	45.1	60.2	90.2	150.4	376.0
900	1/2	25.4	33.8	50.8	84.6	211.5
	3/4	38.1	50.8	76.1	126.9	317.2
	1	50.8	67.7	101.5	169.2	422.9
1000	1/2	28.2	37.6	56.4	94.0	235.0
	3/4	42.3	56.4	84.6	141.0	352.5
	1	56.4	75.2	112.8	188.0	469.9

1/ For purposes of this calculation, drying rate was a constant 3%/day, a reasonable amount down to about the fiber saturation point (about 30% moisture content).

2/ Measured on leaving air side through sticker spaces.

Table 4.--Calculated air travel distance to saturation in drying 8/4 red oak by FPL kiln schedules T3-D1[1/]

Air Velocity[2/]	Sticker Thickness	Step 1 (110° F Dry Bulb, 107° F Wet Bulb)	Step 2 (110° F Dry Bulb, 106° F Wet Bulb)	Step 3 (110° F Dry Bulb, 104° F Wet Bulb)	Step 4 (110° F Dry Bulb, 100° F Wet Bulb)	Step 5 (120° F Dry Bulb, 95° F Wet Bulb)
fpm	In.			ft.		
100	1/2	3.2	4.2	6.4	10.6	26.4
	3/4	4.8	6.4	9.6	15.8	39.6
	1	6.4	8.4	12.6	21.2	52.8
200	1/2	6.4	8.4	12.6	21.2	52.8
	3/4	9.6	12.6	19.0	31.8	79.4
	1	12.6	17.0	25.4	42.2	105.8
300	1/2	9.6	12.6	19.0	31.8	79.4
	3/4	14.2	19.0	28.6	47.6	119.0
	1	19.0	25.4	38.0	63.4	158.6
400	1/2	12.6	17.0	25.4	42.2	105.8
	3/4	19.0	25.4	38.0	63.4	158.6
	1	25.4	33.8	50.8	84.6	211.4
500	1/2	15.8	21.2	31.8	52.8	132.2
	3/4	23.8	31.8	47.6	79.4	198.2
	1	31.8	42.2	63.4	105.8	264.4
600	1/2	19.0	25.4	38.0	63.4	158.6
	3/4	28.6	38.0	57.0	95.2	238.0
	1	38.0	50.8	76.2	126.8	317.2
700	1/2	22.2	29.6	44.4	74.0	185.0
	3/4	33.4	44.4	66.6	111.0	277.6
	1	44.4	59.2	88.8	148.0	370.0
800	1/2	25.4	33.8	50.8	84.6	211.4
	3/4	38.0	50.8	76.2	126.8	317.2
	1	50.8	67.6	101.6	169.2	423.0
900	1/2	28.6	38.0	57.0	95.2	238.0
	3/4	42.8	57.0	85.6	142.8	356.8
	1	57.0	76.2	114.2	190.4	475.8
1000	1/2	31.8	42.2	63.4	105.8	264.4
	3/4	47.6	63.4	95.2	158.6	396.6
	1	63.4	84.6	126.8	211.4	528.6

[1/] For purposes of this calculation, drying rate was a constant 2%/day, a reasonable amount down to about the fiber saturation point (about 30% moisture content).

[2/] Measured on leaving air side through sticker spaces.

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