SOME COMMENTS ON AIR-WOOD TEMPERATURE GRADIENTS AND TEMPERATURE DROPS ACROSS THE LOAD AS THEY RELATE TO DRYING RATE

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Simple logic dictates that the rate at which a board loses moisture in a kiln is dependent upon the rate at which thermal energy is transferred from the contacting air to the board interior and that the rate of heat transfer is, in turn, related to the temperature difference between the air and the wood.

Also, the definition of specific heat (Btu/mass, degree) permits the statement that the change in temperature experienced is directly related to the amount of energy change in the mass of material. In the dry kiln the air quantity is expressed as volume so a volumetric specific heat (Btu/ft^3, degree) equates the temperature change with the change in energy content of the volume of air involved. Also, if the rate of air flowing is known the temperature difference is directly related to the rate of energy change (Btu/hour). And, if the relation between the amount of energy change and the amount of water vaporized is known (effective heat of vaporization) the change in air temperature is a measure of the rate of drying (e.g., pounds of water per hour) at the time of observation.

These concepts were recognized qualitatively by Weyerhaeuser Research Division personnel during the 1960s as the concept of CRT processing was being developed and as the temperature drop across the load (as an independent variable) was being reduced to practice to provide predetermined drying rates.

The opportunity to test these concepts more quantitatively was made available to this writer (some years after his direct relation with Weyerhaeuser experimental work had ended) in the form of data from a test which had been designed to gain further information concerning the effects of kiln variables on CRT drying rate.

The data bank consisted of six drying trials using pre-surfaced (3.5" x 1.5" x 8') Douglas fir. Each trial consisted of eight courses of 24 boards each (192 boards) or 56 ft^3 of green volume. The trials were conducted in the Weyerhaeuser Research Division experimental kiln which was then located in Longview. The kiln had performance capabilities not found in most commercial kilns, including providing entering air dry bulb temperatures up to 300°F and achieving and maintaining wet bulb temperatures from ambient to 212°F. In addition, total charge weight was automatically recorded at ten-minute intervals.

As the charge was built, a lath with five type-J arc welded thermocouples was laid across the load in slot two from the bottom. These thermocouples were positioned at mid-slot thickness and opposite boards 1, 6, 12, 18 and 24 from the entering air side. Similar thermocouple placement was made in slot 6. In addition, thermocouples were inserted mid-thickness into boards 6, 12, and 18 in course two and into boards 1, 6, 12, 18 and 24 in both courses six and seven. Thus, the dry bulb temperature across the load could be measured for two slots relating to four of the eight courses and the temperature gradient between air and wood interior could be calculated for thirteen positions. Thermocouple readings were recorded at thirty-minute intervals.

Descriptive data for the six trials are shown in Table 1 in all cases both dry bulb and wet bulb temperatures were programmed to increase at the rate of 4°F per hour so that a constant wet bulb temperature depression was maintained in each case until the wet bulb temperature reached 212°F after which time the wet bulb temperature remained constant and the kiln atmosphere consisted of superheated steam. Air circulation direction was not changed.

RESULTS

The data were in harmony with previous observations that drying rate is increased by increasing "starting" temperature and by increasing wet bulb temperature depression.

Charge Drying Rate

The familiar three-segment drying curve typical of CRT drying schedules in which entering air dry bulb temperatures extend substantially above 212°F were obtained for each of the six trials. Early fast falling-rate drying in the first segment merged into constant rate (A) which was maintained for several hours. During the last few hours of kiln residence the drying rate became accelerated (B). Figure 1.

Air-Wood Temperature Gradient

Figure 2 shows the general relationship between air and wood interior temperatures during drying. In every case the air dry bulb temperature increases from ambient to set point at a much faster rate than the wood temperature. The temperature difference which is high at first gradually decreases until the rate of temperature rise of the wood becomes substantially equal to that of the air. This condition of equal gradient continues until the wood temperature reaches 212°F at which time the wood temperature remains constant or increases slowly while the air temperature continues to rise at set point rate. The air-wood temperature gradient increases as a result.

The time at which the temperature gradient becomes constant (A) corresponds with the time at which the charge drying rate becomes constant (A). Also the time at which the gradient increases (B) corresponds with the time at which the charge drying rate begins to increase (B).

The air-wood temperature gradient is the intensity factor of energy transfer. The charge drying rate is highly sensitive to changes in gradient. It is significant that every board in the charge, regardless of position or moisture content responds in the same manner.

The individual gradients vary with green moisture content. There are insufficient data in these trials to establish a statistically valid relationship. It would represent a valuable contribution to the understanding of kiln drying mechanism to inter-relate the gradient (driving force) with moisture content and kiln variables. Previous studies have shown that CRT drying rate is affected by starting temperature, CRT rate and wet bulb temperature depression so it may be assumed that air-wood temperature gradients for individual boards are sensitive to these variables among others.

Temperature Drop Across the Load

Since the temperature drop across the load is proportional to the drying rate (above) it would be expected that the temperature drop-time curves would correspond, shape- and time-wise, with the drying rate curve for the charge.

The data permit calculations showing the limitations and potential of using the temperature drop across the load to make valuable calculations.

Only under unrealistic conditions will the temperature drop across all of the slots in a charge of lumber have the same value. It would be required that the moisture contents of the boards defining each slot be the same or that every board in the charge have the same moisture content. Also slot volumes and air velocities must be the same.

Calculations

Two values which may be used with reasonable confidence and have been reported by this writer are 0.0165 Btu/ft^3, degree for the volumetric specific heat of air in the normal dry kiln temperature and humidity range; and 1200 Btu per pound as the effective heat of vaporization of water during drying. Substitution of these values into the specific heat equation yields

$$(0.0165)(\text{Volume of air/hour})(T_L)/1200 = \text{Pounds } H_2O\text{/hour}$$

The rate of air flow is given by

(60 min/hr)(Air velocity in ft/min)(total slot area ft^2)

Slot area=(number of slots)(slot length ft)(slot thickness ft)

Substitution yields

$$(0.000825)(\text{slot length})(\text{slot thickness})(\Delta T_L)=\text{lb/hour}$$

In these trials:

Number of slots = 8

Slot thickness = 3/4" = 3/48 feet

Slot length = 7.5 feet (subtract 6" to account for sticker width)

The air velocity was maintained at 500 feet per minute for all except Trial 468 which was maintained at 600 feet per minute.

Substituting at 500 fpm $(1.547)(\Delta T_L)$ = Rate of drying (lb water/hour)

at 600 fpm $(1.856)(\Delta T_L)$ = Rate of drying

Also, the product of rate and time (use average T_L) yields the quantity of water vaporized during the time period.

The drying rates during the constant rate period were calculated using the rate equations and the average of the T_L values for the two slots and the values compared with the rate measured as the slope of the charge drying curve for each trial. The values are tabulated in Table 2. The mean difference (observed value basis) of -.3% appears to be an acceptable confirmation of the validity of the calculations.

Also the number of degree hours required to vaporize the total amount of water as measured by the kiln scale was calculated and compared with the observed degree hours (average of the two slots). Again the calculations appear valid with an average deviation (observed value basis) of 0.9%. See Table 3 and Figure 3.

It must be re-emphasized that a temperature drop across the charge value is of no value unless the air velocity is known and remains constant.

It is to be noted that the temperature drop across the load calculations are independent of quantity of lumber, lumber dimension or moisture content. Only the quantity of air and its change in temperature are involved.

There is no evidence of any "break" in the temperature drop across the load at any moisture content in the kiln drying range down to 6% or less when CRT processing is used. Therefore, the temperature drop across the load per se has no potential as an indicator of when to shut down the kiln. If experience indicates that a certain weight of water is consistently removed from a charge of lumber to yield a satisfactory kiln dry moisture content the elapsed degree-hours product will indicate when that quantity of water has been vaporized.

The analogy with the speedometer and odometer of an automobile is apropos. The speedometer as calibrated measures the rate of travel at the moment of observation and the odometer indicates distance traveled but is incapable of recognizing landmarks to tell when a predetermined destination has been reached unless the distance to be covered is known precisely.

The temperature drop across the load measurement has potential in schedule control and schedule modification. Since the measurement indicates drying rate, adjustment of kiln conditions to yield different temperature drops will serve to adjust drying rate quantitatively to best preserve product quality.

Although the discussion has been based on CRT drying, there is no reason to believe that the basic conclusions do not apply equally well to any type of drying situation. The driving force determining the rate of energy transfer from air to wood will always be a function of the temperature gradient between contacting air and wood interior at any time and the rate of drying at any time will be reflected by the temperature drop across the charge.

Table 1. Descriptive data for six trials

Trial	463	464	465	466	467	468
Initial DB Temp	164°F	130°F	156°F	158°F	158°F	155°F
Final DB Temp	258°F	292°F	252°F	258°F	247°F	266°F
Initial WB Temp	112°F	115°F	96°F	128°F	93°F	130°F
Final WB Temp	190°F	212°F (25 hr)	192°F	212°F (22 hr)	185°F	212°F
WB Depression	52°F	15°F	60°F	30°F	63°F	25°F
Air Velocity (FPM)	500	500	500	500	500	600
Drying Time (Hr)	24	40	24	25	23	28
Green MC Lb. (%)	(40.2%) 636 lb	(41.4%) 642 lb	(40.0%) 621 lb	(28.3%) 477 lb	(48.4%) 743 lb	(53.4% 831 lb
KD MC Lb. (%)	(9.0%) 143	(6.3%) 97	(10.5%) 163	(7.7%) 122	(11.5%) 177	(7.6%) 118
H_2O Lost Lb.	493	545	458	325	566	713
OD Weight (Calc)	1584 lb	1549 lb	1551 lb	1578 lb	1536 lb	1556 l

Table 2. Comparison of calculated and observed temperature drops across the load for constant rate segments

Trial	Observed T_L (^oF)	Observed Rate (lb/hr)	Calculated Rate (lb/hr)	Difference (%)
463	9.1	13.9	14.1	+1.4
464	7.7	10.6	11.9	+12.3
465	10.9	16.9	16.9	0.0
466	6.2	10.9	9.6	-11.9
467	10.5	16.6	16.2	-2.4
468	11.8	22.6	21.9	-3.1
				(-).63)

Table 3. Comparison of calculated and observed degree-hours of temperature drop across the load for each charge

Trial	Water lost (pounds)	Drying time (hours)	Degree - Hours Observed	Degree - Hours Calculated	Difference (%)
463	493	24	293	317	+8.2
464	545	40	376	353	-6.4
465	458	24	312	296	-5.1
466	325	25	199	210	+5.5
467	566	23	377	366	-2.9
468	713	28	363	384	(+0.90)

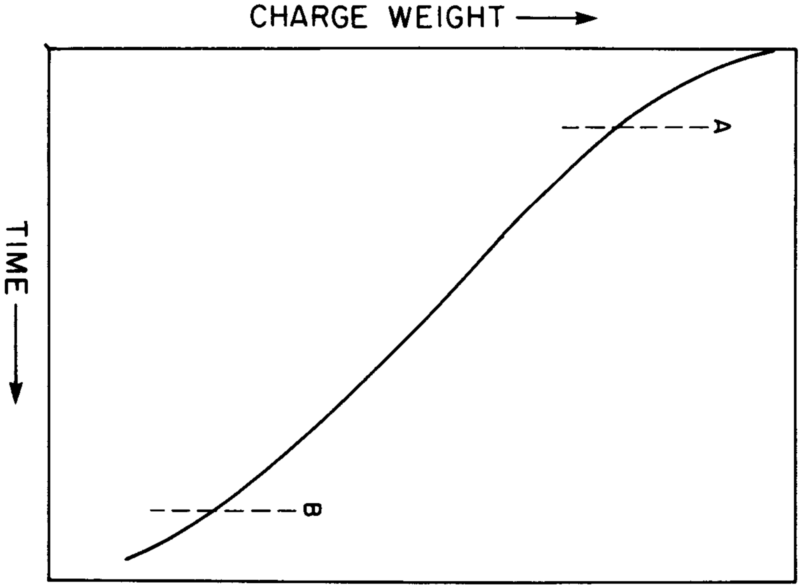

Figure 1. Plot of falling and constant rates of drying

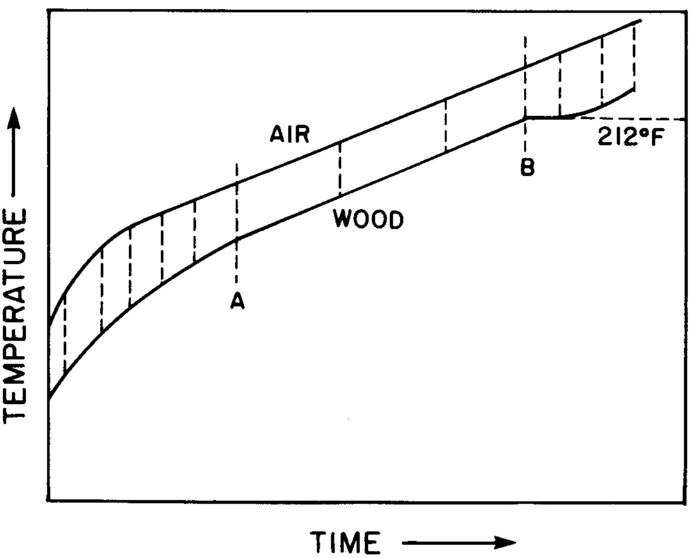

Figure 2. Relationship between air and wood temperatures during drying

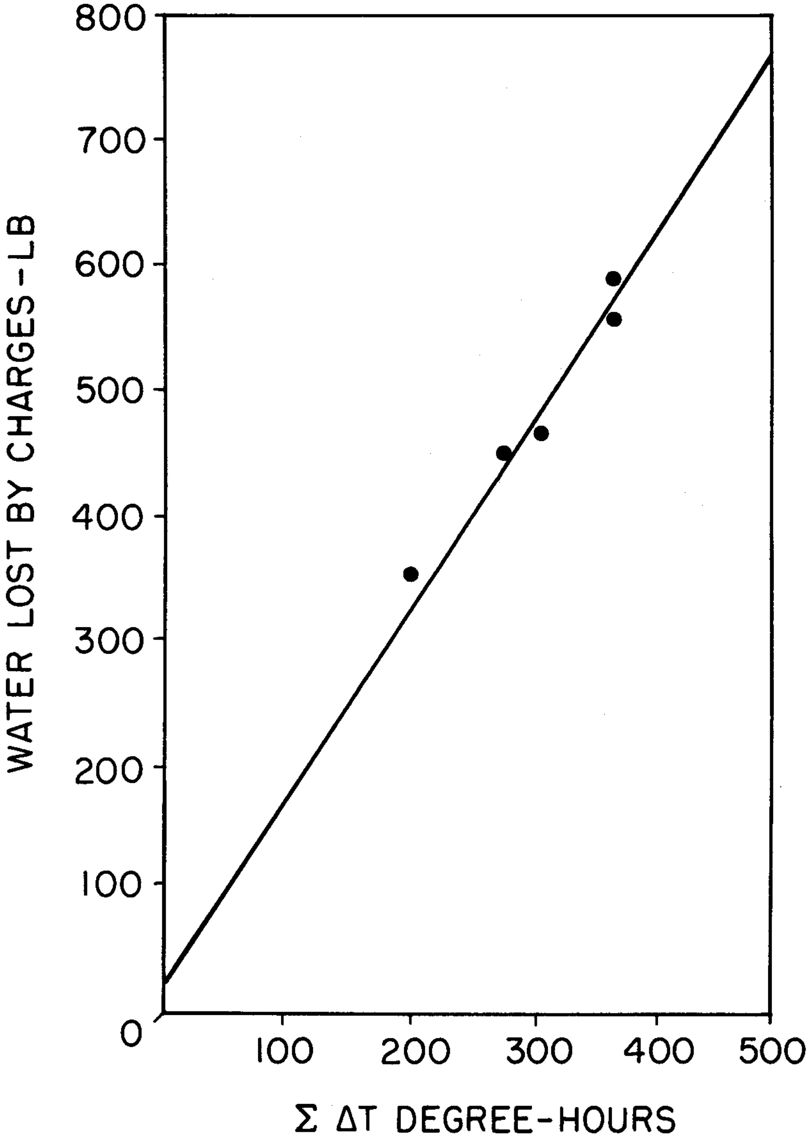

Figure 3. Water lost per charge plotted over T-hours