EQUILIBRIUM MOISTURE CONTENT OF WOOD AT HIGH TEMPERATURES

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ABSTRACT

In answer to increased interest in using high-temperature (above 212 F) drying of wood, a method is described to extrapolate low-temperature equilibrium moisture content (EMC) data to high temperatures. The results are compared with data in the literature, and EMC data from 212 F to 300 F are presented in a form useful for kiln control as well as for other uses.

Keywords: Equilibrium moisture content, relative humidity, dryer control, high-temperature drying.

INTRODUCTION

Relationships of equilibrium moisture content (EMC), relative humidity (RH), and temperature of wood at temperatures up to 210 F have been well established (Forest Products Laboratory (FPL) 1974). They have served the forest products industry well for estimates of EMC's of wood products in use and as critical process-control guidelines in dryer control. For the last 10 to 15 years interest and use of high-temperature (above 212 F) drying have been steadily increasing. High-temperature drying offers increased processing efficiency, and it is likely that the application of this high-temperature drying will be further encouraged.

Optimum process control in high-temperature drying depends on a knowledge of EMC-RH-temperature relationships at these high temperatures. Unfortunately, in the high-temperature drying range few data are available on EMC's. Similarly, although psychrometric relationships are available from a number of sources, none have been presented in a form easily useful for kiln control at high temperatures. Psychrometric information is necessary for evaluating energy use and for energy recovery potentials from dry kilns and veneer dryers.

This paper describes a method of extrapolating low-temperature EMC data to higher temperatures, compares these results with data in the literature, and presents EMC data from 212 F to 300 F comprehensively and in a form most useful for kiln control.

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LITERATURE REVIEW

The EMC-RH-temperature data presented in the Dry Kiln Operator's Manual (Rasmussen 1961) and the Wood Handbook (U.S. FPL 1974) to 210 F are based largely on Sitka spruce (*Picea sitchensis*) during what has been termed "oscillating desorption" from the initial green condition (Stamm and Loughborough 1935; Seborg and Stamm 1931). Although thorough documentation is not available, the authors understand that the data of several other species are also represented. Despite these imperfections, the data have served their practical purpose well for many years.

Most of the EMC data in the literature at temperatures above 212 F are with pure steam at atmospheric pressure. Keylwerth (1949) experimentally determined the EMC of spruce and beech in saturated steam at several temperatures between 217 F and 248 F; for comparison, he also extrapolated low-temperature data. The experimental EMC's were somewhat lower (1% to 3% MC) than extrapolated values, but he attributed this to faulty experimental apparatus. Grumach (1951) determined EMC's of mountain ash (*Eucalyptus regnans*) and hoop pine (*Araucaria cunninghamii*) in saturated steam at temperatures up to 310 F. Kollman and Malmquist (1952) presented data on high-temperature EMC's of pine up to 266 F.

Of the several references in the literature that present extrapolated values for EMC's above 212 F, it is not always clear how the extrapolation was accomplished. One common technique, presented by Stamm and Loughborough (1935) and used by Kauman (1956) to extrapolate low-temperature data, involves plotting lines of constant EMC (isosteres) on a coordinate system of the logarithm of water vapor pressure versus the reciprocal of absolute temperature and extending them to higher temperatures. Sturany (1952) has extrapolated low-temperature EMC data (Stamm and Loughborough 1935; Rasmussen 1961; U.S. FPL 1974) to 266 F. Ladell (1957) has extrapolated low-temperature EMC data of Stamm and Loughborough (1935) and Keylwerth (1949) and presented a table of EMC's as a function of dry-bulb temperatures from 212 F to 260 F, wet-bulb temperatures from 160 F to 212 F, and RH.

Lutz (1974), Hann (1965), Strickler (1968), and Engelhardt (1979) have experimentally determined EMC values in saturated steam at temperatures above 212 F. Lutz's data were on red oak at temperatures from 220 F to 250 F, and were determined on veneer steamed in various types of dryers. Hann's data were on yellow-poplar (*Liriodendron tulipifera*) at 250 F; Strickler's data on grand fir (*Abies grandis*) for temperatures between 212 F and 338 F. Engelhardt determined EMC values of beech between 230 F and 338 F, and attempted to make corrections for thermal degradation.

ESTIMATES OF HIGH-TEMPERATURE EMC'S

Wet-bulb and relative humidity

Rosen and Simpson (1980) have discussed the difference between the adiabatic saturation temperature, or thermodynamic wet-bulb temperature, and the true wet-bulb temperature. When unsaturated air is brought in contact with water, the air is humidified and cooled. If the system is operated so that no heat is gained or lost to the surroundings, the process is adiabatic. Thus, if the water remains

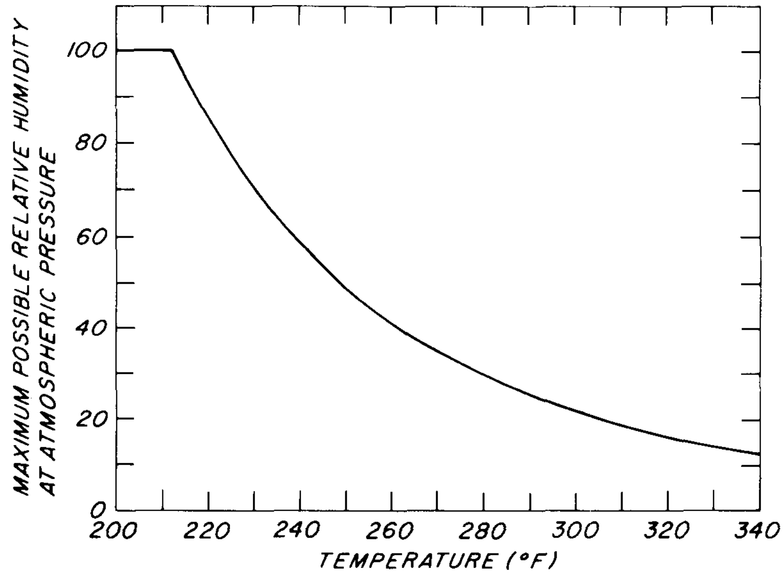

FIG. 1. Maximum possible relative humidities at temperatures above 212 F and at atmospheric pressure.

at constant temperature, the latent heat of evaporation must equal the sensible heat released by the air in cooling. If the temperature reached by the air when it becomes saturated is the same as the water, this temperature is called adiabatic saturation temperature, or the thermodynamic wet-bulb temperature.

When unsaturated air is passed over a wetted thermometer bulb, so that water evaporates from the wetted surface and causes the thermometer bulb to cool, an equilibrium temperature (called the true wet-bulb temperature) is reached. At this point the rate of heat transfer from the wetted surface is equal to the rate at which the wetted surface loses heat in the form of latent heat of evaporation. The thermodynamic wet-bulb and true wet-bulb temperatures are not necessarily equal. Rosen and Simpson (1980) have shown that in the range of 215 F to 300 F these temperatures are negligibly different. Thus, the RH's based on the difference between the dry-bulb temperature and the thermodynamic wet-bulb temperature do not differ significantly from RH's based on the difference between the dry-bulb temperature and the true wet-bulb temperature. The maximum difference is 0.54% RH; on the average, the difference is ±0.25% RH.

Relative humidity can be calculated from the adiabatic saturation temperature by the following procedure (Hawkins 1978). By writing energy and mass balances for the process of adiabatic saturation:

$$Y = Y_s - \frac{(0.24 + 0.44Y_s)(T_{db} - T_s)}{1094 + 0.44T_{db} - T_s} \tag{1}$$

where

Y = specific humidity (lb water/lb dry air)

Y_s = specific humidity for saturation at T_s (lb water/lb dry air)

T_{db} = dry-bulb temperature (F)
T_s = adiabatic saturation temperature (F)

and

$$Y_s = \frac{p_s}{1.61(p_t - p_s)} \qquad (2)$$

where

p_s = vapor pressure at T_s (in. Hg)
p_t = total pressure (in. Hg).

To calculate relative vapor pressure at T_{db} and T_s, it is necessary to calculate partial pressure p at T_{db} and T_s:

$$p = \frac{1.61\,Yp_t}{1 + 1.61\,Y} \qquad (3)$$

and relative vapor pressure h is:

$$h = \frac{p}{p^*} \qquad (4)$$

where

p^* = saturated vapor pressure at T_{db} (in. Hg).

RH is then defined as:

$$\text{RH} = h \times 100. \qquad (5)$$

At atmospheric pressure (at which most kiln-drying is done), it is not possible to obtain wet-bulb temperatures above 212 F. Thus, at dry-bulb temperatures above 212 F, the maximum possible RH is less than 100%. These maximum possible RH's are shown in Fig. 1 and vary from just under 100% at a dry-bulb temperature of 213 F to about 12% at 340 F.

Relative humidity and equilibrium moisture content

After the RH-wet- and dry-bulb relationship is established, the EMC-RH relationship can be calculated from sorption models that relate EMC and RH. Simpson (1971, 1973) has shown that many of these models can be fitted to EMC-RH data by nonlinear regression techniques. One convenient model, the Hailwood and Horrobin model (1946), can predict the sorption data tabulated in the Dry Kiln Operator's Manual (Rasmussen 1961) and the Wood Handbook (U.S. FPL 1974) within 1% MC. The model is:

$$M = \left[\frac{K_1K_2h}{1 + K_1K_2h} + \frac{K_2h}{1 - K_2h}\right]\frac{1800}{W} \qquad (6)$$

where

M = MC (%)
h = relative vapor pressure
K_1, K_2, W = coefficients of the model.

Simpson (1971) has determined the values of the coefficients for sorption data between 30 F and 210 F to be:

TABLE 1. *Equilibrium moisture content of wood[1] from 215 F to 245 F.*

Wet-bulb depression (F)	Dry-bulb temperature (F) 215 Twb (F)	215 RH (%)	215 EMC (%)	220 Twb (F)	220 RH (%)	220 EMC (%)	225 Twb (F)	225 RH (%)	225 EMC (%)	230 Twb (F)	230 RH (%)	230 EMC (%)	235 Twb (F)	235 RH (%)	235 EMC (%)	240 Twb (F)	240 RH (%)	240 EMC (%)	245 Twb (F)	245 RH (%)	245 EMC (%)
4	211	92.1	14.4																		
5	210	90.3	13.5																		
6	209	88.5	12.7																		
7	208	86.7	12.0																		
8	207	85.0	11.4																		
9	206	83.3	10.8	211	84.0	10.8															
10	205	81.6	10.3	210	82.3	10.3															
11	204	79.9	9.8	209	80.6	9.8															
12	203	78.3	9.4	208	79.0	9.4															
13	202	76.7	9.0	207	77.4	9.0															
14	201	75.1	8.7	206	75.9	8.6	211	76.2	8.5												
15	200	73.5	8.3	205	74.3	8.3	210	74.7	8.2												
16	199	72.0	8.0	204	72.8	8.0	209	73.2	7.9												
17	198	70.5	7.8	203	71.3	7.7	208	71.8	7.6												
18	197	69.0	7.5	202	69.9	7.4	207	70.3	7.3												
19	196	67.6	7.3	201	68.4	7.2	206	68.9	7.1	211	69.3	7.0									
20	195	66.1	7.0	200	67.0	7.0	205	67.5	6.9	210	67.9	6.7									
22	193	63.3	6.6	198	64.2	6.6	203	64.7	6.4	208	65.2	6.3									
24	191	60.7	6.2	196	61.5	6.2	201	62.1	6.1	206	62.6	6.0	211	63.1	5.9						
26	189	58.1	5.9	194	59.0	5.8	199	59.5	5.7	204	60.1	5.7	209	60.6	5.6						
28	187	55.5	5.6	192	56.4	5.5	197	57.1	5.4	202	57.6	5.4	207	58.2	5.3						
30	185	53.1	5.3	190	54.0	5.3	195	54.7	5.2	200	55.3	5.1	205	55.9	5.0	210	56.5	4.9			
35	180	47.3	4.7	185	48.3	4.6	190	49.0	4.6	195	49.7	4.5	200	50.3	4.4	205	51.0	4.4	210	51.8	4.3
40	175	42.1	4.2	180	43.1	4.2	185	43.8	4.1	190	44.5	4.0	195	45.2	4.0	200	45.9	3.9	205	46.7	3.8
45	170	37.3	3.8	175	38.3	3.7	180	39.0	3.7	185	39.8	3.6	190	40.5	3.5	195	41.2	3.5	200	42.0	3.4
50	165	32.9	3.4	170	33.9	3.4	175	34.7	3.3	180	35.4	3.3	185	36.2	3.2	190	36.9	3.1	195	37.7	3.1
55	160	28.9	3.0	165	29.9	3.0	170	30.7	3.0	175	31.4	2.9	180	32.2	2.9	185	33.1	2.8	190	33.8	2.8
60	155	25.3	2.7	160	26.2	2.7	165	27.0	2.7	170	27.8	2.6	175	28.6	2.6	180	29.3	2.6	185	30.2	2.6
70	145	19.0	2.2	150	19.9	2.2	155	20.7	2.2	160	21.5	2.1	165	22.2	2.1	170	23.0	2.1	175	23.8	2.1
80	135	13.8	1.7	140	14.7	1.7	145	15.5	1.7	150	16.2	1.7	155	17.0	1.7	160	17.7	1.7	165	18.4	1.7
90	125	9.6	1.3	130	10.4	1.3	135	11.2	1.3	140	11.9	1.3	145	12.6	1.3	150	13.3	1.3	155	14.0	1.3
100	115	6.2	.9	120	7.0	.9	125	7.7	1.0	130	8.4	1.0	135	9.1	1.0	140	9.7	1.0	145	10.4	1.0
110	105	3.5	.5	110	4.1	.6	115	4.9	.6	120	5.5	.7	125	6.2	.7	130	6.8	.7	135	7.4	.8
120	95	1.3	.2	100	1.9	.3	105	3.0	.4	110	3.2	.4	115	3.8	.5	120	4.4	.5	125	5.0	.5
130	85	—	—	90	—	—	95	.8	.1	100	1.4	.2	105	1.9	.2	110	2.5	.3	115	2.7	.3
140	75	—	—	80	—	—	85	—	—	90	—	—	95	—	—	100	.9	.1	105	1.4	.2

[1] Column abbreviations are: *Twb*, wet-bulb temperature, *RH*, relative humidity, and *EMC*, equilibrium moisture content.

TABLE 2. *Equilibrium moisture content of wood*[1] *from 250 F to 300 F.*

Wet-bulb depression (F)	Dry-bulb temperature (F) 250 Twb (F)	250 RH (%)	250 EMC (%)	255 Twb (F)	255 RH (%)	255 EMC (%)	260 Twb (F)	260 RH (%)	260 EMC (%)	270 Twb (F)	270 RH (%)	270 EMC (%)	280 Twb (F)	280 RH (%)	280 EMC (%)	290 Twb (F)	290 RH (%)	290 EMC (%)	300 Twb (F)	300 RH (%)	300 EMC (%)
40	210	47.3	3.7																		
45	205	42.7	3.3	210	43.4	3.3															
50	200	38.4	3.0	205	39.1	2.9	210	39.9	2.9												
55	195	34.5	2.7	200	35.2	2.7	205	36.0	2.6												
60	190	30.9	2.5	195	31.6	2.4	200	32.4	2.3	210	33.7	2.2									
70	180	24.5	2.0	185	25.2	2.0	190	26.0	1.9	200	27.3	1.8	210	28.6	1.6						
80	170	19.1	1.6	175	19.8	1.6	180	20.6	1.6	190	21.9	1.5	200	23.2	1.3	210	24.5	1.2			
90	160	14.7	1.3	165	15.4	1.3	170	16.0	1.2	180	17.3	1.2	190	18.6	1.1	200	19.8	1.0	210	21.0	0.8
100	150	11.0	1.0	155	11.6	1.0	160	12.3	1.0	170	13.5	.9	180	14.7	.9	190	15.9	.8	200	17.0	.6
110	140	8.0	.8	145	8.6	.8	150	9.2	.8	160	10.3	.7	170	11.4	.7	180	12.5	.6	190	13.6	.5
120	130	5.5	.5	135	6.1	.6	140	6.6	.6	150	7.6	.5	160	8.7	.5	170	9.7	.5	180	10.7	.4
130	120	3.5	.4	125	4.0	.4	130	4.5	.4	140	5.5	.4	150	6.4	.4	160	7.3	.4	170	8.3	.3
140	110	1.9	.2	115	2.4	.2	120	2.8	.3	130	3.7	.3	140	4.6	.3	150	5.4	.3	160	6.2	.2
150	100	—	—	105	1.0	.1	110	1.4	.1	120	2.3	.2	130	3.1	.2	140	3.8	.2	150	4.6	.2
160	90	—	—	95	—	—	100	—	—	110	1.1	.1	120	1.8	.1	130	2.5	.1	140	3.1	.1
170	80	—	—	85	—	—	90	—	—	100	—	—	110	—	—	120	1.5	.1	130	2.1	.1

[1] Column abbreviations are: *Twb*, wet-bulb temperature; *RH*, relative humidity; and *EMC*, equilibrium moisture content.

TABLE 3. *Comparison of data in the literature for high-temperature equilibrium moisture content in pure steam.*

		Experimental equilibrium moisture content (%)								Extrapolated equilibrium moisture content (%)					Moisture content (%)	
		Keylwerth 1949														
Temperature (F)	Relative humidity (%)	Spruce	Beech	Grumach 1951	Kollman and Malmquist 1952	Hann 1965	Strickler 1968	Lutz 1974	Engelhardt 1979	Keylwerth 1949	Sturany 1952	Kauman 1956	Ladell 1957	Simpson and Rosen (This paper)	Maximum discrepancy[1]	Maximum discrepancy[2]
215	93.9	—	—	17.0	17.4	—	—	—	—	16.0	15.4	15.2	15.5	15.4	2.0	1.6
217	90.5	10.5	11.7	—	—	—	—	—	—	—	—	13.3	—	12.1	2.8	1.6
220	85.6	—	—	11.5	12.8	—	—	11.3	—	11.5	10.7	11.4	11.3	11.3	2.1	1.5
221	83.8	8.8	10.4	—	—	—	—	—	—	—	—	10.0	—	10.9	2.1	2.1
225	77.6	—	—	8.9	10.1	—	—	—	—	9.0	8.3	8.7	8.7	8.8	1.8	1.3
230	70.5	6.3	6.6	7.3	8.3	—	—	6.9	7.0	7.5	6.8	7.2	6.9	7.2	2.0	1.1
235	64.1	—	—	6.3	6.7	—	—	—	—	6.3	5.7	5.9	5.8	6.1	1.0	.6
239	59.5	4.3	—	—	—	—	—	—	—	—	—	5.1	—	5.3	1.0	1.0
240	58.3	—	—	5.6	5.7	—	—	5.4	—	5.4	4.9	5.0	5.0	5.2	.8	.5
245	53.2	—	—	5.0	—	—	—	—	—	4.8	4.2	4.4	4.2	4.4	.8	.6
248	50.3	—	3.6	—	—	—	—	—	—	—	—	4.0	4.2	4.1	.5	.5
250	48.5	—	—	4.6	—	3.5	—	3.8	—	4.3	3.7	3.9	3.8	3.9	1.1	.7
255	44.2	—	—	4.2	—	—	—	—	—	3.8	3.3	3.6	3.4	3.4	.9	.8
260	40.4	—	—	3.9	—	—	—	—	—	3.4	3.1	3.2	3.1	3.0	.9	.9
266	36.1	—	—	—	—	—	3.5	—	3.0	—	—	2.6	—	2.5	1.0	1.0
270	33.6	—	—	3.3	—	—	—	—	—	—	—	2.5	—	2.2	1.1	1.1
280	27.9	—	—	2.8	—	—	—	—	—	—	—	2.1	—	1.7	1.1	1.1
290	23.2	—	—	2.4	—	—	—	—	—	—	—	1.7	—	1.2	1.2	1.2
300	19.1	—	—	2.1	—	—	—	—	—	—	—	1.4	—	.8	1.3	1.3
302	18.4	—	—	—	—	—	1.4	—	1.8	—	—	—	—	.7	1.1	1.1

[1] Between all referenced data.
[2] Between data of this paper and all referenced data.

$$K_1 = 3.730 + 0.03642T_{db} - 0.0001547T_{db}^2 \quad (7)$$

$$K_2 = 0.6740 + 0.001053T_{db} - 0.000001714T_{db}^2 \quad (8)$$

$$W = 216.9 + 0.01961T_{db} + 0.005720T_{db}^2 \quad (9)$$

Extrapolation of low-temperature equilibrium moisture content

The relationship between wet- and dry-bulb temperature and RH was determined using Eqs. 1–5. The values of K_1, K_2, and W were determined by using equations to extrapolate between 210 F and 300 F. Then the value of these coefficients and the appropriate values of h determined from Eqs. 1–4 were used in Eq. 6 to extrapolate EMC data of 30 F to 210 F to higher temperatures. The results of these calculations are shown in Table 1 for dry-bulb temperatures from 215 F to 245 F; and in Table 2, from 250 F to 300 F.

COMPARISON WITH EQUILIBRIUM MOISTURE CONTENTS IN THE LITERATURE

As discussed, some high-temperature EMC data in the literature are experimental and some are extrapolated. Almost all of the experimental data at high temperatures and at atmospheric pressure were determined in saturated steam, i.e., the wet-bulb temperature was 212 F. A summary of the data in the literature, both experimental and extrapolated, is shown in Table 3, as are extrapolated values calculated in this paper. The maximum discrepancy between reported values at a common temperature is 2.8% MC; most discrepancies are 2% or less. The maximum discrepancy between the values determined by the extrapolation of this paper and all referenced data is 2.1% MC, with all others 1.6% or less. Because of different species, different experimental techniques, and different extrapolation techniques and bases for extrapolation, exact agreement cannot be expected. Whether or not these discrepancies are large enough to be of practical concern is uncertain.

Little comparative data are available to comprehensively establish the species dependency of the sorption isotherm. In the absence of these data, the high-temperature EMC data in the literature, as well as those developed in this paper, apparently can serve as a useful guideline in process control and other uses of EMC data.

SUMMARY

A technique is described in this paper for extrapolating the low-temperature (below 212 F) relationship between wet- and dry-bulb temperature, RH, and the EMC of wood to temperatures between 215 F and 300 F. Although comprehensive experimental EMC data at these temperatures are not available, the extrapolated values agree closely enough to data available in the literature so that they can be considered useful estimates.

REFERENCES

ENGELHARDT, F. 1979. Investigations on the sorption of water vapor by beech at temperatures ranging from 110° to 170° C. Holz Roh- Werskt. 37(3):99–112.

GRUMACH, M. 1951. The equilibrium moisture content of wood in superheated steam. CSIRO, Div. For. Prod., Proj. S 17 Prog. Rep. 5.

HANN, R. A. 1965. An investigation of the drying of wood at temperatures above 100 degrees centigrade. Ph.D. thesis. N.C. State University. Raleigh, NC.

HAILWOOD, A. J., AND S. HORROBIN. 1946. Absorption of water by polymers: Analysis in terms of a simple model. Trans. Faraday Soc. 42B:84–102.

HAWKINS, G. A. 1978. Thermal properties of substances and thermodynamics. *In* Mark's standard handbook for mechanical engineers. 8th ed. McGraw-Hill, NY. Pp. 4–31.

KAUMAN, W. G. 1956. Equilibrium moisture content relations and drying control in superheated steam drying. For. Prod. J. 6(9):328–332.

KEYLWERTH, R. 1949. Fundamentals of high-temperature drying of wood. Holz Zentralbl. 75(76):953–954.

KOLLMAN, F., AND L. MALMQUIST. 1952. Research on seasoning sawn pine timber at high temperatures. Medd. Sven. Traforskn. Inst. Avd. 23.

LADELL, J. L. 1957. High temperature kiln drying of eastern Canadian softwoods. West. For. Prod. Lab. Tech. Note 2. Vancouver, B.C., Can.

LUTZ, J. F. 1974. Drying veneer to a controlled final moisture content by hot pressing and steaming. USDA For. Serv. Res. Pap. FPL 227. For. Prod. Lab., Madison, WI.

RASMUSSEN, E. F. 1961. Dry kiln operator's manual. U.S. Dep. Agric., Agric. Handb. 188. Washington, D.C. P. 11.

ROSEN, H. N., AND W. T. SIMPSON. 1980. Evaluating humidity at dry-bulb temperatures above the normal boiling point of water. Wood Fiber. 13(1):97–101.

SEBORG, C. O., AND A. J. STAMM. 1931. Ind. Eng. Chem. 23:1271–1275.

SIMPSON, W. T. 1971. Equilibrium moisture content prediction for wood. For. Prod. J. 21(5):48–49.

———. 1973. Predicting equilibrium moisture content of wood by mathematical models. Wood Fiber. 5(1):41–49.

STAMM, A. J., AND W. K. LOUGHBOROUGH. 1935. Thermodynamics of the swelling of wood. J. Phys. Chem. 39:121–132.

STRICKLER, M. D. 1968. High temperature moisture relations of grand fir. For. Prod. J. 18(4):69–75.

STURANY, H. 1952. The Schilde air-free steam dryer for wood. Holz Roh- Werkst. 10:358–362.

U.S. FOREST PRODUCTS LABORATORY. 1974. Wood handbook. U.S. Dep. Agric., Agric. Handb. 72, rev., For. Prod. Lab., Madison, WI. Pp. 3–8.