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Investigation of Historic Equilibrium Moisture Content Data from the Forest Products Laboratory

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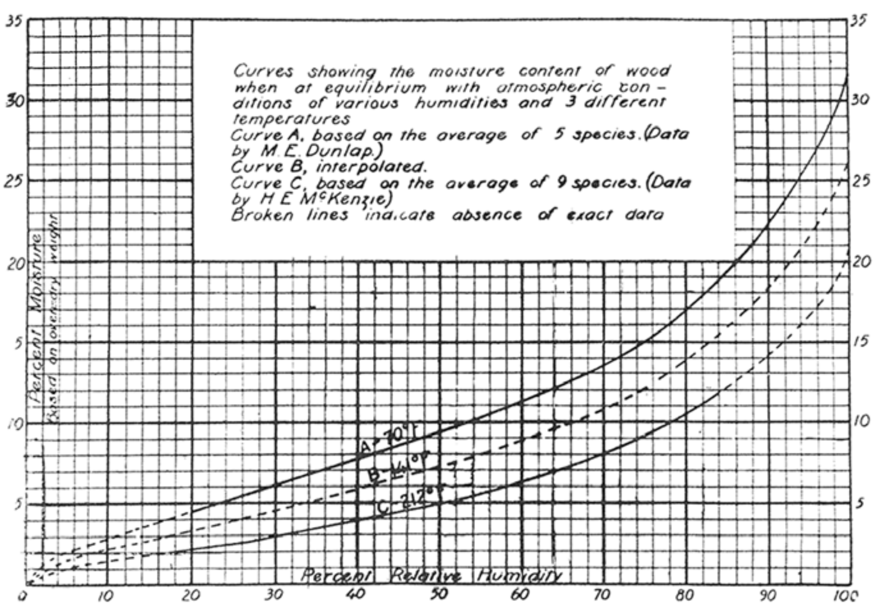

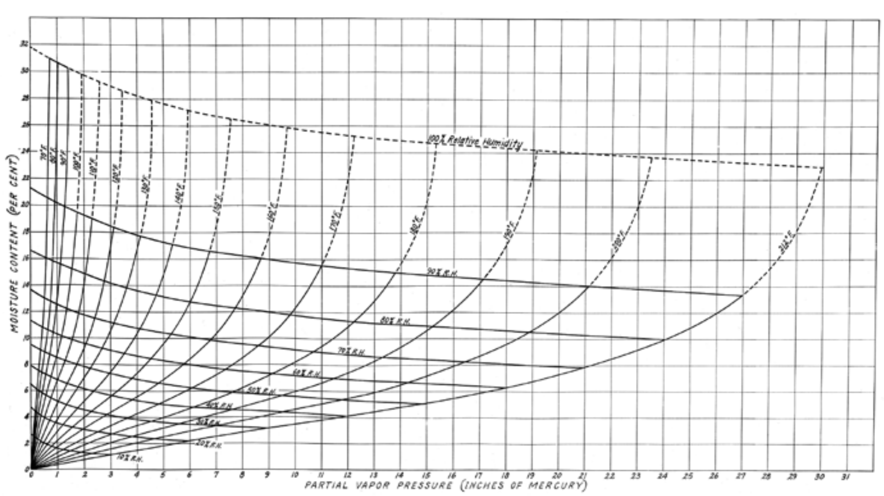

Abstract

The Forest Products Laboratory (FPL) has provided equilibrium moisture content (EMC) values of wood for given temperature and relative humidity (RH) conditions in various forms over the course of its history, primarily for practical purposes related to drying lumber and controlling moisture content. The FPL EMC data have been widely cited and reprinted, not only in literature of a practical nature such as the *Wood Handbook*, but also in textbooks and journal articles as a basis for scientific discourse on the thermodynamics of water vapor sorption in wood and evaluation of physical models. Using the data for such scientific purposes presupposes that the methods by which the data were acquired are well documented and accepted. This report questions previous assumptions about the historic EMC data and attempts to uncover and evaluate the original data sources. It also addresses a number of related topics, including how the presentation of data has evolved in the literature and whether the data are practically applicable to all wood species. We find that the data are unreliable for scientific purposes, such as thermodynamic analysis and testing of physical models, for three reasons: lack of proper documentation of methodology; the unsolvable problem of knowing which values are determined from direct observations and which are interpolated; and the absence of definitive measurement error analysis. However, we affirm that the data are indeed useful for practical applications, such as lumber drying, conditioning of wood specimens prior to testing physical or mechanical properties, and modeling of moisture content of wood members in buildings. We show that a number of mathematical models provide adequate fits to the data for practical use.

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The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Keywords: Equilibrium moisture content, hygroscopicity, sorption, Wood Handbook, kiln drying, air drying, seasoning, conditioning, mathematical model

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1. Introduction

The Forest Products Laboratory (FPL) has provided equilibrium moisture content (EMC) values of wood for given temperature and relative humidity (RH) conditions in various forms over the course of its history, having published data as early as 1919 (Koehler 1919; FPL 1919a,b,c). These data have primarily served practical, technological purposes related to drying lumber and controlling moisture content. The importance of the FPL EMC data can be appreciated by considering how widely they have been reprinted in literature of a practical nature: the data appear in the *Wood Handbook* (FPL 1935, 1940, 1955, 1974, 1987, 1999b, 2010); in publications relating to the use of wood in aircraft construction (FPL 1919c, 1928, 1941a, 1942, 1943, 1944, 1946, 1951; U.S. Army Air Forces 1944; Voorhies and Loughborough 1943); in wood drying manuals such as the *Dry Kiln Operator's Manual* (Rasmussen 1961; Simpson 1991), *Air Drying of Lumber* (FPL 1999a), and *Drying Hardwood Lumber* (Denig et al. 2000); and in international standards, particularly the *Standard Guide for Moisture Conditioning of Wood and Wood-Based Materials* (ASTM 2010). The Forest Products Laboratory and other organizations in North America have long considered the FPL EMC data set to be the first place to go for such data.

In addition to their frequent appearance in documents of a practical nature, the FPL EMC data have been cited in scientific journals and textbooks as a basis for scientific discourse on the thermodynamics of water vapor sorption in wood (Stamm and Loughborough 1935; Stamm 1964; Kollman and Côté 1968; Skaar 1988; Siau 1995; Keey et al. 2000). In addition, several journal articles (Simpson 1971, 1973, 1980) have evaluated the ability of mathematical models, some of which were derived from physical principles, to fit the FPL data. Using the data for such scientific purposes presupposes that the data are of sufficient quality and that the methods by which the data were acquired are well documented and accepted. Is this actually the case?

Although the FPL EMC data have been cited extensively, their origins are obscure. Several FPL publications have in fact urged caution regarding general use of the data. Simpson (1973), for example, cautioned that the data do not represent either adsorption or desorption in the usual sense. He identified the species used in the original measurements as Sitka spruce and referred the reader to Stamm and Loughborough (1935) for experimental details. Simpson and Rosen (1981) made similar comments on the source of the data and stated, "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." More recently, Denig et al. (2000) commented, "These standard EMC data, which were collected more than 50 years ago, are primarily based on the drying of small shavings of Sitka spruce in a dryer with a small oscillation in RH. In spite of the potential shortcomings of the data, they serve very well for drying hardwood lumber."

We are primarily interested in answering the question of whether the methods by which the FPL EMC data were obtained are sufficiently well documented to allow the data to be used for scientific purposes such as thermodynamic analysis and evaluation and validation of physical models. The fact that data serve well for practical purposes does not necessarily imply that the methods by which they were acquired are documented and accepted for such scientific purposes. In this review, we question previous assumptions about the historic EMC data and attempt to uncover and evaluate the original data sources. In the process, we raise a number of related questions about the data: how and why has the presentation of data evolved in the literature? Are the data practically applicable to all wood species? What have FPL publications said in the past regarding sorption hysteresis? Is the level of precision given by FPL publications on mathematical modeling of EMC appropriate?

2. Sources of Data

2.1 H.E. McKenzie

H.E. McKenzie (n.d.) conducted two series of water vapor sorption experiments at the Yale Forest School and filed an FPL progress report reviewing the literature and presenting his results. The date of his experiments and report, though uncertain, are definitely prior to 1917 because the report was cited by Tiemann (1917).[1] Both series of experiments were conducted near 212 °F (100 °C).

The first series of experiments included spruce, longleaf pine, red oak, and white oak. The documentation of experimental details is poor. Apparently only one specimen was measured for each species, with dimensions 50 mm by 50 mm by 13 mm (the orientation with respect to grain direction was not stated). Specimens were exposed to five different relative humidity levels: 25%, 33%, 50%, 66%, and 100% RH. Humidity values less than 100% were attained using vacuum. The initial condition of the specimens (green or dry) and the order of measurements are not stated. Further, it is unclear whether specimens were oven-dried before or after they were conditioned at various RH levels. However, the EMC data are presented in order of decreasing RH (desorption). Finally, it is questionable whether equilibrium values were actually attained, as mass readings were taken just a few hours after the relative humidity was changed; no data are shown to indicate whether specimen mass became stable over this short time.

McKenzie did not regard the measurements at 100% RH as equilibrium values: "It was determined by later investigations, however, that a true equilibrium between a saturated vapor and a moisture-holding substance is impossible." These later investigations involved monitoring specimen mass with time at 100% RH: "…the absorption process appears to be unending though its velocity continuously diminishes."

The second series of experiments included spruce, southern yellow pine (identified as longleaf pine in the report text but as loblolly pine in the data table), tulip, hickory, blue gum, and white ash. The author does not describe specimen dimensions, the number of specimens, the initial condition, or the order of measurements. A slightly different range of RH levels was used: 17%, 33%, 50%, 66%, and 84% RH for spruce and pine; 17%, 33%, 50%, and 66% RH for tulip; and 33%, 50%, 66%, and 82% RH for hickory, blue gum, and white ash.

[1]Tiemann (1924) dated McKenzie's work as ca. 1908. However, the report had to have been written in 1910 or later because 1) McKenzie states in the introduction, "A careful search for work done along these lines by other investigators has been made through 'Science Abstracts', covering a period of fifteen years (1896 to 1910)," and 2) the Forest Products Laboratory did not exist prior to 1910. The FPL library catalog gives an estimated date of ca. 1912–1915. McKenzie may have been done the experiments at Yale prior to joining FPL.

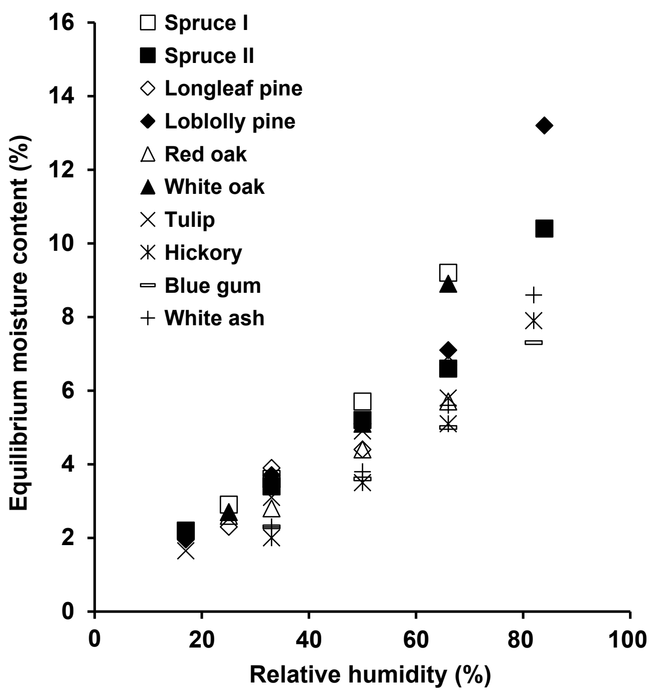

Figure 1. EMC data from McKenzie (n.d.).

Figure 1 plots the values from both of McKenzie's data tables. Given that the methodology was largely undocumented and probably did not include replicate measurements, this data set is of questionable reliability.

2.2 M.E. Dunlap

2.2.1 Methodology

Matthew E. Dunlap (1919) conducted a series of sorption experiments at room temperature with seven wood species "taken from laboratory stock": white oak, black walnut, Sitka spruce, yellow birch, ash, mahogany (African), and longleaf pine (2.4% and 25.0% resin content). Specimens were soaked for several hours, and shavings 13 mm by 140 mm were cut with a hand plane. These shavings were strung to copper wires (Fig. 2) so that specimens could be weighed *in situ* inside a sealed chamber (Fig. 3). The chamber also included a dew point hygrometer, dry-bulb thermometer, and fan. Temperature and humidity inside the chamber were not actively controlled. Temperatures were between 75 °F (24 °C) and 86 °F (30 °C), with an average near 80 °F (27 °C). Two matched specimens of a given species were placed in the chamber at a time, one at a slightly lower MC than the other. The relative humidity was thus regulated by the hygroscopicity of the specimens, whose moisture contents (MCs) tended to approach an intermediate value. EMC was defined as the average MC of the two specimens after 24 h. Dry-bulb and dew point temperatures were also recorded after 24 h (from which RH was determined). For the next step, one specimen was dried by a few percent MC, and then both specimens were placed in the chamber to

Figure 2. Specimens used in sorption experiments by Dunlap (1919).

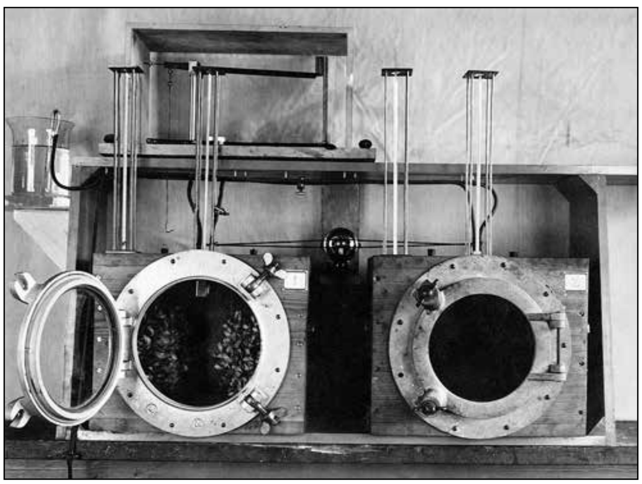

Figure 3. Apparatus used in sorption experiments by Dunlap (1919).

equilibrate at a slightly lower EMC than the previous step. Because of the drying and resorption of one of the specimens, we refer to this method as “quasi-desorption.” This process was repeated to give EMC values over a range from 100% RH down to about 20% RH. After all the measurements were completed, the specimens were dried to constant weight at 212 °F (100 °C).

2.2.2 Findings, Caution, Call for Further Work, and Speculation

Dunlap’s results are shown in Figure 4 together with the average of all species from 20% to 100% RH in 5% RH increments, as reported by Dunlap.

Dunlap advised that his data were not to be used at high temperatures: “The results of this work should be applied only to conditions at approximately 65 to 85 °F. They do not apply directly to kiln operations where higher temperatures are used. We have not obtained any information on the moisture content of wood at the same humidities but higher

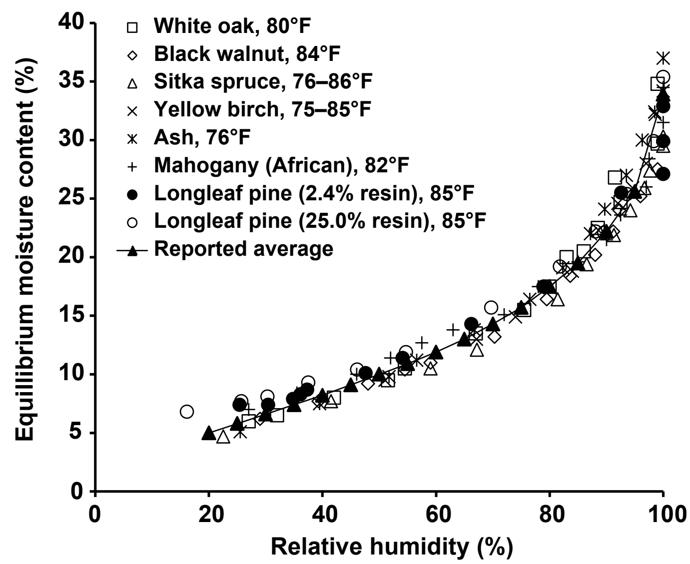

Figure 4. EMC data from Dunlap (1919).

temperatures, but it has been observed in dry kiln operation that lower values for the moisture content at a given humidity are obtained when higher temperatures are used.” Dunlap wisely recommended further work in this area: “It would be extremely valuable in kiln drying operations to have similar data obtained at temperatures of say 120 °F, 140 °F, 160 °F, and 180 °F.”

Regarding differences between species, Dunlap exhibited less caution: “It is interesting to note that there is comparatively little variation in the values obtained for the individual species tested and in a general way it is thought that the average curves would apply practically to any wood.” Although Dunlap is correct that the species he studied showed little variation, it does not follow logically that little variation in EMC exists among all wood species. However, this unjustified speculation is balanced by a statement that “…work carried out at room temperatures on additional species would be of value.”

2.2.3 Critique

Comparing Dunlap’s progress report with McKenzie’s, we observe that Dunlap’s methodology is far more clearly documented, that Dunlap recorded measurements at a greater number of RH levels, and that Dunlap’s data show much smaller between-species variation. Although the improvements are considerable, we find several methodological problems in Dunlap’s experiments:

- RH values are reported to a precision of 0.1% RH, but there is no estimate of error in RH (which would be based on error in dry-bulb and dew point temperatures).
- No data are presented to justify that 24 h was sufficient for equilibration. Nothing is reported regarding the

magnitude of the difference in MC between the two specimens that were averaged to determine EMC after 24 h. However, the thin wood shavings used in the experiments would be expected to equilibrate much more rapidly than wood blocks, and the average of the two specimens (one losing moisture and the other gaining moisture) would not be expected to change considerably over time.

- A number of measurements are reported at 100% RH; however, the report does not explain how this condition was achieved. McKenzie (n.d.) had previously rejected measurements at 100% RH because equilibrium could not be established. As might be expected, the variability in Dunlap's data is considerably higher for values at 100% RH than for values at lower RH; this is shown by the following analysis. For all values reported at 100% RH, the standard deviation is 2.9 percentage points (denoted % MC). By contrast, a three-parameter parabolic fit (Eq. (1)) to all the data yields a root-mean-square error (RMSE) of 1.5% MC. When data points with RH ≥ 98% are excluded from the fit, the RMSE drops to 1.0% MC. The form of the fitting equation is

$$m = \frac{h}{Ah^2 + Bh + C} \qquad (1)$$

where m is equilibrium moisture content (decimal) and h is relative humidity (decimal).

2.3 C.A. Menzel

Carl A. Menzel (1921) investigated moisture content and shrinkage of red oak at 80 °F (27 °C). Introductory remarks state that although no extensive tests were possible (data were acquired as time and apparatus permitted), information was obtained that would be valuable in planning a thorough investigation of the hygroscopic and shrinkage properties of wood. Prior to beginning this study, Menzel had noticed that wood of various species placed in different conditioning rooms in the "Propeller Laboratory" displayed great differences between species and within species in regard to rate of change in moisture content as well as equilibrium moisture content. This research had an obvious practical application in aircraft design and construction, which is explored further in Section 3.

2.3.1 Methodology

Specimens were taken from 1-m-long sticks of air-dried red oak, both plain and quarter sawn, with a wide range in specific gravity. These were cut to 25 mm in length along the grain and planed to 50 mm in width and 22 mm in thickness. Initial moisture content was about 10%. A total of 46 specimens were used for EMC measurements.

Specimens were conditioned in rooms maintained at 80 °F (27 °C) and at RH levels of approximately 30%, 60%, and 90%. A 100% RH condition was attained by placing blocks in a large closed stone jar containing water (though this is not relevant to the EMC data; dimensions were measured to determine shrinkage values). Relative humidity in the conditioning rooms was determined from dry- and wet-bulb thermometers read to within 0.5 °F (0.3 °C). Specimens were weighed to 0.001 g with an analytical balance. Specimens were divided into two groups of 23 each and subjected to different conditioning sequences:

1. 30%–60%–90%–60%–30%–oven dried–30%–60%–90%–100%–soaked in water–oven dried–30%–60%–90%–oven dried
2. 30%–60%–90%–60%–oven dried–30%–60%

The amount of time at each humidity condition varied from 16 to 50 days. Successive weighing showed small fluctuations over time that may have been caused by humidity fluctuations. The author apparently assumed that the specimens had reached equilibrium.

2.3.2 Findings, Interpretation, and Speculation

Figure 5 shows Menzel's EMC data as a function of oven-dry specific gravity (equivalent to oven-dry density expressed in g cm^{-3}) for the second group of 23 specimens. Clearly EMC is not correlated with specimen density. Technical Note 89 (FPL 1920) provides a summary table of Menzel's EMC and density data for nine representative specimens.

A fair degree of scatter is evident in the data. Menzel pointed out that the variability is higher at the low and high RH levels than at intermediate RH levels. Standard deviations are 0.6%, 0.3%, and 0.7% MC at relative humidities of 38%, 61%, and 88% RH, respectively. Menzel referred to other (apparently unpublished) experiments he had done that showed the opposite for hard maple—lower variability at the humidity extremes.[2] He also states, "In general other species show small variations in moisture content at low humidities, growing greater with increase of relative humidity." He ascribes variability in hygroscopicity between different species and within the same species to "different proportions of various hygroscopic substances in the wood, each one of which has a distinct moisture humidity curve." Although he did not specifically name cellulose, hemicelluloses, and lignin, Menzel clearly suggested that variation in EMC stems from variation in wood chemistry. This is the first instance of this argument in FPL literature, to the best of our knowledge. Later research showed that these classes of wood polymers do, in fact, differ in hygroscopicity, hemicelluloses being the most hygroscopic and lignin the least hygroscopic (Christensen and Kelsey 1958).

Menzel found that the oven-dry mass decreased upon successive dryings: specimens lost an average of 1.35% of their

[2]Tiemann (1920) includes a figure showing EMC data for maple and birch at 80 °F (27 °C), which he attributes to Menzel, in addition to the data for red oak.

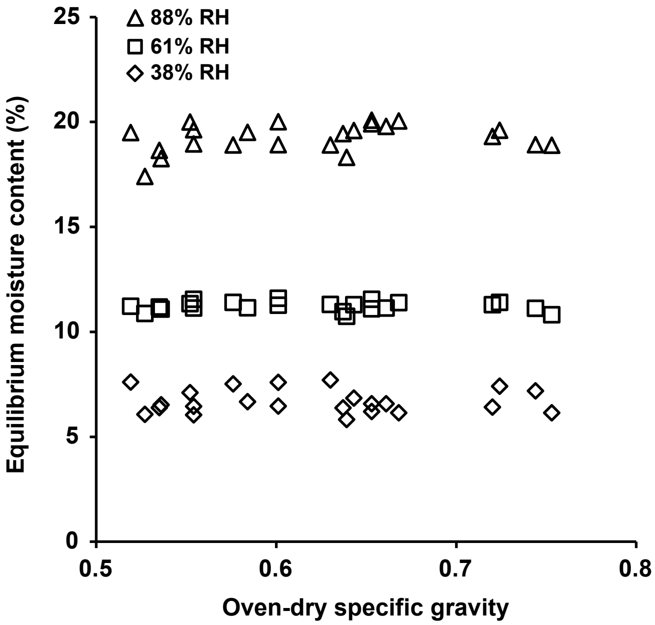

Figure 5. EMC versus oven-dry specific gravity for 23 red oak specimens (Menzel 1921).

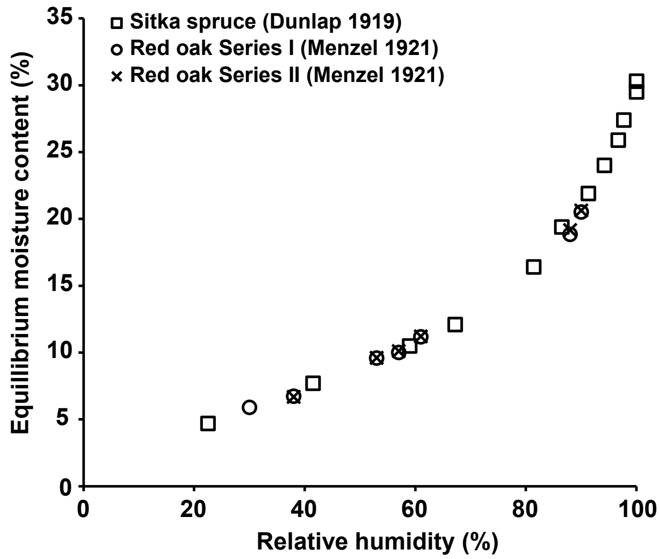

Figure 6. Comparison of EMC data at approximately 80 °F (27 °C) for Sitka spruce shavings (Dunlap 1919) and red oak blocks (Menzel 1921).

mass between the first and second dryings but only 0.08% between the second and third dryings. Menzel ascribed this to a loss of volatile matter. He noted that the first oven drying was done following conditioning at 30% RH, the second following soaking in water, and the third following conditioning at 90% RH. He suggested that volatile matter is lost more readily when wood is oven dried from a high moisture content than from a low moisture content because some volatile constituents are dissolved and carried away when water is driven off.

Menzel also found that the EMC curve for "reabsorption" after oven drying was about 2% MC lower on average than the curve prior to oven drying, based on the same first oven-dry mass. He did not offer any suggestion as to why this occurs. Menzel fit the EMC data with parabolic functions, which he extrapolated to 100% RH as a theoretical fiber saturation point (FSP). He obtained a value of 23.6% MC for red oak that had not been oven dried, and 21.4% for red oak after the first oven drying.

Tiemann (1922) reviewed Menzel's work, praising the accuracy and extent of his measurements but disagreeing with some interpretations. Tiemann argued that the mass loss between the first and second oven dryings was a result of extraction rather than vaporization; specimens had been soaked in water at 80 °F (27 °C), and soluble materials had likely leached out. Tiemann also cited unpublished data on yellow birch blocks that showed little difference in oven-dry mass after drying from a low moisture content as compared to drying from a high moisture content. Tiemann suggested that EMCs on "reabsorption" after oven drying may be lower than those before oven drying because of loss of volatile oils in the oven or reduction in hygroscopicity. The concept of sorption hysteresis was not mentioned. Tiemann noted that Menzel's data for red oak prior to oven drying corresponded very closely with Dunlap's data for Sitka spruce. This close correspondence can be seen in Figure 6.

2.3.3 Critique

In general, Menzel's measurements are well documented. He describes the number of specimens, their source, and the conditions to which they were exposed. Specimen mass was measured with high precision. However, the number of RH levels was limited (30%, 60%, 90%), RH conditions fluctuated considerably, and RH measurements lacked precision. The stated uncertainty in dry- and wet-bulb temperature measurements, ±0.5 °F (±0.3 °C), implies an RH uncertainty of approximately ±4% RH.

2.4 W.K. Loughborough

2.4.1 EMC Data: Published yet Concealed

The practical need for EMC data over a broader temperature range, as recommended by Dunlap (1919), may have been the motivation for new FPL measurements. These data first appear in several publications in the 1930s. From what follows below, it is clear that W. Karl Loughborough was responsible for the measurements and completed them prior to 1931. However, there is no FPL report that clearly documents the actual measurements, to the best of our knowledge.

The data were first published in an FPL technical bulletin entitled *Wood-Liquid Relations* (Hawley 1931).[3] This bulletin presents the data in a figure showing EMC values for Sitka spruce from 70 °F (21 °C) to 212 °F (100 °C), reprinted here as Figure 7. Although Hawley (1931) notes, "The data represented in these curves are the work of W.K. Loughborough," there is no reference to published work, and the text is silent regarding the measurement methodology. The text does state, "The solid lines in the curves … are based on experimental data; the dotted parts of the lines are calculated." However, the calculation method for the dotted parts of the curves is not described.

The same figure appears in journal articles by Loughborough and Rietz (1932) and by Stamm and Loughborough (1935).

2.4.2 Methodology

Although the emphasis of the article by Stamm and Loughborough (1935) is thermodynamic analysis, they do provide a brief description of the experiments.

Specimens were 3-mm-thick strips of green flat-sawn Sitka spruce. Specimen oven-dry mass was between 100 g and 125 g (presumably determined after EMC measurements were completed). The number of specimens measured at a given temperature and humidity condition ranged from 25 to 40. Specimens were suspended from lead stoppers located in the roof of a chamber and were weighed *in situ*.

The apparatus consisted of four chambers, each with a volume of about 0.45 m^3. An electric blower moved the air within the chambers at a velocity of about 0.5 m s^{-1}. Dry-bulb temperature and humidity (as wet-bulb temperature) were controlled with thermostats. Conditions were read frequently through glass windows. It was noted that both dry- and wet-bulb temperatures oscillated, with average amplitudes of 0.25 °F (0.14 °C) and 0.5 °F (0.3 °C), respectively. The dry- and wet-bulb temperatures would sometimes be out of phase, such that the wet-bulb depression was sometimes 0.75 °F (0.4 °C) greater or less than desired. This resulted in relative humidity oscillations in the range from 1.5% to 3% at higher temperatures and from 4% to 8% at lower temperatures. EMC measurements were made in steps of successively lower RH. The method is thus called "oscillating vapor pressure desorption." Unfortunately, the period of oscillation and the time required to reach equilibrium were not mentioned. Nothing was said regarding the criterion for defining equilibrium (e.g., change in mass less than some threshold over a certain time period).

Stamm and Loughborough (1935) claimed that this method practically eliminated sorption hysteresis: "The hysteresis phenomenon encountered in desorption and adsorption measurements made on very small specimens under the most carefully controlled vapor pressure conditions was largely eliminated in these measurements. The specimens used were sufficiently large to permit the setting up of moisture gradients across the sections during the process of drying. This combined with the oscillations in vapor pressure permit alternate desorption and adsorption to take place, thus tending to establish an intermediate moisture content equilibrium."

To illustrate their point, Stamm and Loughborough (1935) compared their data taken under oscillating vapor pressure desorption conditions with data acquired under "carefully controlled conditions [that] tend to promote the maximum hysteresis effect." Figure 8 shows this comparison. The desorption and adsorption boundary curves were obtained using small cross sections of Sitka spruce weighed *in situ* under tight thermostat control (25 °C ± 0.02 °C; 77 °F ± 0.04 °F) and stable RH, regulated by saturated salt solutions (Seborg and Stamm 1931). Stamm and Loughborough (1935) claimed, "All the available drying data obtained under industrial control conditions on other softwood species also gave curves which fell within this hysteresis loop." However, no published data on other softwood species were cited. The data were presumably unpublished measurements from FPL.

2.4.3 Critique

Measurement of moisture content at 100% RH and extrapolation of measured values to 100% RH are both problematic. Regarding measurement, it is practically impossible to achieve equilibrium at 100% RH. This was noted earlier by McKenzie (n.d.). Advancing his line of thought, we argue that 100% RH does not correspond to a unique equilibrium moisture content because 100% RH by definition means that water in wood has the same vapor pressure as bulk liquid water. A range of moisture contents exist that can satisfy this definition, from some lower bound at which liquid water is first present up to maximum saturation.

Hawley (1931) argued that FSP cannot be accurately determined by extrapolation of the sorption isotherm to 100% RH because of capillary condensation:

> "The points where the temperature curves of Figure [7] intersect the 100 per cent relative-humidity curve

[3]Loughborough was clearly involved in the preparation of this technical bulletin authored by Hawley (1931), which includes the following note: "The difficult problem presented by the movement of moisture in wood, which has been unsolved for years, required the best thought of specialists and many points of view, and successful and efficient work demanded close coordination of the efforts of several investigators. The moisture committee of the Forest Products Laboratory was formed to obtain such coordination within the laboratory. The personnel of the committee has included: E. Bateman, F.L. Browne, M.E. Dunlap, L.F. Hawley (chairman), A. Koehler, W.K. Loughborough, A.J. Stamm, R. Thelen, H.D. Tiemann, and F. Tuttle. The wide and varied experience of the members has supplied a comprehensive foundation for the investigative and analytical work of the moisture committee and has therefore contributed largely to this initial report. The sub-committee on publication, Messrs. Bateman, Loughborough (chairman), and Tiemann, has been of special assistance in the study of the literature and in the preparation of the report itself. The author is pleased to acknowledge his indebtedness to his associates."

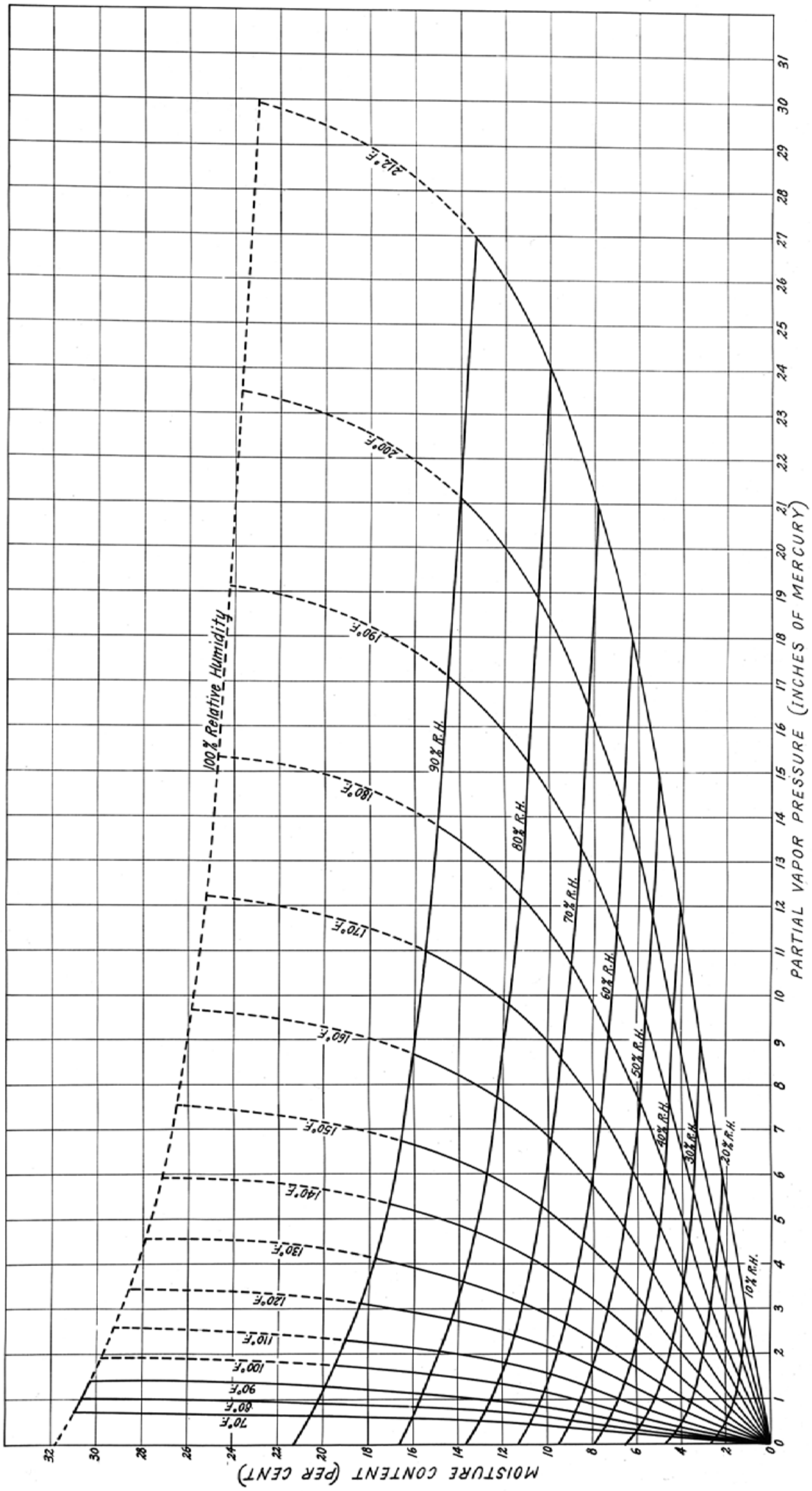

Figure 7. EMC curves based on Loughborough's data (Hawley 1931). The original figure caption reads, "The moisture-content values of Sitka spruce at equilibrium with various temperatures, partial vapor pressures, and relative humidities."

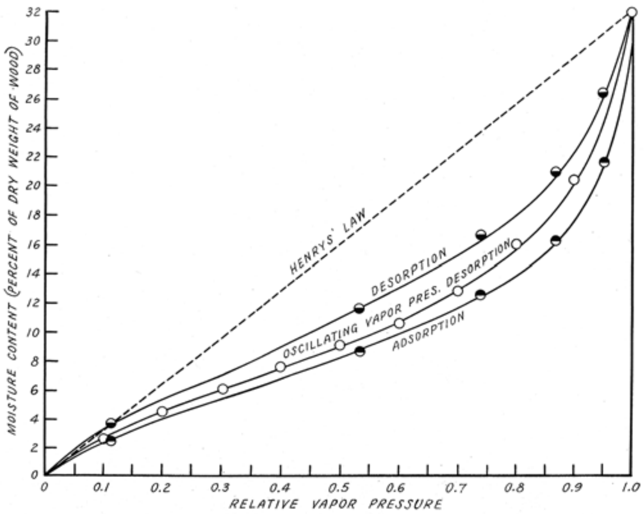

Figure 8. Illustration of sorption isotherms measured under different conditions (Stamm and Loughborough 1935). The original figure caption reads, "Moisture content–relative vapor pressure relationship for Sitka spruce under normal desorption and adsorption conditions and under oscillating vapor pressure desorption conditions at 25°C."

> indicate the fiber-saturation points at the respective temperatures. Most of these points were not actually determined—as indicated by the dotted portions, most of the temperature curves were extrapolated (by calculation) above the 90 per cent relative humidity intersections. The fiber-saturation point can not be accurately and directly determined by the method of Figure [7] because of the small capillaries (the cell cavities) existing in the wood. In a saturated atmosphere these cavities will condense moisture and consequently will give an apparent fiber-saturation point much higher than the actual value that is due to the water absorbed by the cell wall."

Despite these considerations, EMC measurements are shown in Figure 7 as solid curves (implying they were measured values) at 100% RH for temperatures of 70 °F (21 °C), 80 °F (27 °C), and 90 °F (32 °C). Figure 8 also includes a data point at 100% RH (equivalent to a relative vapor pressure of 1.0) and 25 °C (77 °F). Stamm and Loughborough (1935) never explained how equilibrium at 100% RH was achieved. As noted above, the calculation method for extrapolating the dotted parts of the curves in Figure 7 was not described. Moreover, Stamm and Loughborough (1935) referred to the extrapolated values at 100% RH for various temperatures as the fiber saturation point.

Stamm (1971) later commented on the determination of fiber saturation points by extrapolating sorption isotherms. In addition to the fact that different points are reached by extrapolating adsorption and desorption curves, Stamm noted that strictly speaking, extrapolation to 100% is incorrect because of capillary condensation. However, he argued that extrapolation from data points at roughly 97% or 98% RH is justifiable on the following grounds. The largest possible void in the cell wall was considered to be about 200 nm, and by the Kelvin equation, capillary condensation would occur at 99.5% RH. The difference between extrapolating to 99.5% RH versus 100% RH is practically negligible provided the curve does not change drastically between 97% or 98% RH and 99.5% or 100% RH. Stamm claimed that this is the case for wood on the basis of pressure plate measurements.

From our perspective, the most serious problem with Loughborough's data is that the actual data points are concealed. With the exception of Figure 8, the EMC data do not appear as discrete points in graphical or tabular form (though EMC tables appear in later FPL literature; see Section 3.4 below). The following questions cannot be answered from the information provided by Stamm and Loughborough (1935) or by any other documentation to the best of our knowledge:

- How many data points were measured at a given temperature? Were EMCs determined at increments of 10% RH at each temperature, as suggested by Figure 8 (relative vapor pressure increments of 0.1)?
- Were measurements taken at all the temperatures shown in Figure 7, or were some of the curves drawn by interpolation?
- What is the variability across replicate specimens under a given condition?

Menzel (1921) had previously found considerable variability in EMC of red oak specimens (see Fig. 5); standard deviation varied with RH level and was in the range 0.3–0.7% MC. In some cases, the estimated error in EMC determination may be less than the variability across specimens. For Loughborough's data, the measurement error can be estimated as approximately ±0.1% MC based on the reported weighing accuracy (0.05 g) and the specimen size (~100 g oven-dry mass). However, we do find evidence elsewhere that Loughborough considered measurement error to be larger than variability.

An "Office Memorandum" written by Loughborough (1930) discusses errors in moisture content measurement by standard laboratory oven-drying procedures. A large number of yellow birch specimens had been conditioned, used in mechanical tests, and oven dried to determine moisture content. The resulting mean was 10.4% MC with a standard deviation of 0.65% MC. The methodology was clearly different from that used in the study on Sitka spruce; however, the assumptions involved in the analysis are revealing. Notably, it was assumed that EMC does not vary across specimens: "Because all the material had approximately the same history and because each stick was left in the same conditioning room long enough to bring it to an approximate equilibrium moisture content with the temperature and humidity of

Table 1—Summary of FPL EMC data sources

	H.E. McKenzie	M.E. Dunlap	C.A. Menzel	W.K. Loughborough
Wood species	Spruce, longleaf pine, red oak, white oak, loblolly pine, tulip, hickory, blue gum, white ash	White oak, black walnut, Sitka spruce, yellow birch, ash, mahogany (African), longleaf pine	Red oak	Sitka spruce
Type of specimens	Blocks, 50 mm by 50 mm by 13 mm	Groups of shavings, 13 mm by 140 mm	Blocks, 50 mm by 25 mm by 22 mm	Strips of flat-sawn lumber, 3 mm thick
Number of specimens	Not stated	2 per species	46	25–40 at a given condition
Temperature	~100 °C (~212 °F)	24–30 °C (75–86 °F)	27 °C (80 °F)	21–100 °C (70–212 °F)
Sorption direction	Not stated	Quasi-desorption (see description in Section 2.2)	Adsorption and desorption	Oscillating vapor pressure desorption
Concerns	Poor documentation; questionable whether equilibrium was reached; measurement error unknown	Method of determining values at 100% RH not described; measurement error unknown	Imperfect RH control; measurement error unknown	Actual data points not documented; variability across specimens unknown; measurement error unknown

the conditioning room, it may reasonably be assumed that the material was practically uniform in moisture content, i.e. that every stick had approximately the same moisture content." Contrary to Menzel's (1921) suggestion that variation in wood chemistry could explain variation in EMC, Loughborough assumed that there is a single "true moisture content" for all specimens. Consequently, he attributed any deviation from the mean to measurement error.

A further drawback to the documentation provided by Stamm and Loughborough (1935) is that the estimated error in RH was not reported. Dry- and wet-bulb thermometers were most likely calibrated regularly as part of standard laboratory procedure, using a thermometer standardized by the U.S. Bureau of Standards, as indicated in documentation by Loughborough (1922) prior to the work on Sitka spruce. However, the inherent measurement error in dry- and wet-bulb temperatures was likely not better than ±0.2 °F (±0.1 °C). Assuming this value, error in RH at room temperature is larger than ±1% RH (with higher error at lower temperatures but lower error at higher temperatures).

Finally, the thermodynamic analysis of Stamm and Loughborough (1935) is based on the assumption that the oscillating vapor pressure desorption method eliminates sorption hysteresis. Although they showed that the desorption curve under these conditions fell between the normal desorption and adsorption curves (Fig. 8), they did not measure any oscillating vapor pressure *adsorption* curves. To the best of our knowledge, no one has yet measured such a curve or shown that the method actually eliminates sorption hysteresis.

In summary, the Loughborough data set provides practical EMC values for Sitka spruce over a broad range of temperatures, but documentation of the data and methodology are incomplete: actual data points are not presented, the method of determining values at 100% RH is not described, EMC variability across specimens is undocumented, and measurement errors in EMC and RH are unknown.

2.5 Summary of Data Sources

Table 1 summarizes key information about each of the data sources described above. The first two sources collected EMC data on multiple species with limited number of specimens, whereas the last two sources focused on one species each with a large number of replicates. The first three studies were done at a single temperature (either ~212 °F (100 °C) or room temperature), whereas the last study covered a wide range of temperatures. From a scientific perspective, all the studies can be criticized for various problems in methodology and documentation. However, it must be kept in mind that the primary purpose of collecting EMC data at the Forest Products Laboratory during this era was to provide practical information related to drying lumber and controlling moisture content using the available resources. This theme is revisited in the next section.

3. Metamorphosis

This section traces the evolution of the ways in which data have been presented in FPL literature.

3.1 Table of EMC Values at Room Temperature

Technical Note F-13 (FPL 1919b), though anonymous, provides a data table that is clearly based on the work of Dunlap (1919). This table is reprinted here as Table 2. It lists EMC values "at ordinary temperatures" and RH levels between 20% and 95% (5% increments) for seven different woods as well as their average. This table is identical to table II in Dunlap (1919) except that it omits values at 100% RH, noting, "At 100 per cent humidity wood takes on moisture until saturated." The statement regarding species nearly

Table 2—EMC table reprinted from Technical Note F-13 (FPL 1919b)

MOISTURE CONTENT OF WOOD AT VARIOUS ATMOSPHERIC HUMIDITIES
(In percentage of oven-dry weight of wood)

Relative humidity of atmosphere (per cent)	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
Moisture content of:																
White oak	4.5	5.3	6.2	7.0	7.8	8.7	9.5	10.4	11.3	12.6	14.0	15.8	17.5	20.0	23.0	26.5
Black walnut	4.8	5.4	6.2	7.0	7.8	8.6	9.4	10.3	11.2	12.3	13.5	14.9	16.7	18.7	21.3	24.4
Sitka spruce	4.2	5.1	6.0	6.7	7.4	8.1	8.8	9.7	10.5	11.7	12.9	14.3	16.2	18.3	21.0	24.3
Yellow birch	4.2	5.0	5.7	6.5	7.4	8.3	9.2	10.2	11.3	12.4	13.7	15.2	17.0	19.4	22.3	26.0
Ash	4.3	5.1	6.0	6.7	7.7	8.7	9.7	10.7	11.9	13.2	14.6	16.5	18.0	20.5	23.8	28.0
"African mahogany"	5.6	6.5	7.5	8.4	9.3	10.3	11.2	12.2	13.2	14.2	15.3	16.5	18.0	19.7	22.2	25.2
Southern yellow pine, 2.4% resin	5.7	6.4	7.3	8.2	9.0	9.9	10.8	11.8	12.7	14.1	15.5	17.0	18.5	20.2	22.5	26.0
Southern yellow pine, 25% resin	6.7	7.3	8.0	8.8	9.6	10.4	11.2	12.0	12.9	14.0	15.2	16.5	18.3	20.4	22.9	26.5
Average	5.0	5.8	6.6	7.4	8.2	9.1	10.0	10.9	11.9	13.0	14.3	15.7	17.5	19.5	22.2	25.6

duplicates Dunlap's: "It will be noted that only slight differences are shown between the moisture-retaining qualities of the several woods tested, and the average values given, should, therefore, be roughly applicable for all woods." The text briefly mentions other measurements: "Further tests on larger pieces of wood indicate that a variation of about 1 per cent or less may be expected in the same species. These results accurately check the data given in the table between 20 and 70 per cent humidity. Above 70 percent values on larger blocks appear to be somewhat lower than given in the table." This may be a reference to the work of Menzel (1921) on red oak blocks. However, as shown in Figure 6, Dunlap's and Menzel's measurements are in fairly good agreement, even though Dunlap's measurements were taken in quasi-desorption from a wet initial condition, whereas Menzel's measurements at 90% RH were taken in adsorption from a previous condition of 60% RH.

3.2 Table and Figure: EMC Values at Three Temperatures

Technical Note D-5 (FPL 1919a) provides EMC data at three temperatures, as reprinted here in Table 3. The values in this table agree with the curves in Figure 9a, taken from Koehler (1919). The legend makes it clear that the 70 °F (21 °C) curve is based on data from Dunlap, the 212 °F (100 °C) curve is based on data from McKenzie, and the 141 °F (60.5 °C) curve is interpolated. (141 °F is midway between 70 °F and 212 °F. Presumably this value was rounded to 140 °F in Table 3.) Furthermore, the dashed parts of the curves indicate absence of data. This figure appears in nearly identical form in Koehler (1924) and Koehler and Thelen (1926).

Later bulletins from FPL include the same figure with slight modification, as shown in Figure 9b. This can be found in the *Kiln Drying Handbook* (Thelen 1923, 1929), *The Air Seasoning of Wood* (Mathewson 1930), *Moisture Content of Wood in Dwellings* (Peck 1932), the original edition of the *Wood Handbook* (FPL 1935), and numerous publications on wood aircraft (FPL 1928, 1941a, 1942, 1943, 1946). The legend has been removed, and there is no mention of the names Dunlap and McKenzie; furthermore, with the exception of the 1923 *Kiln Drying Handbook*, there is no mention that the 141 °F (60.5 °C) curve is interpolated or that the dashed parts indicate absence of data. This figure, without the legend (as in Fig. 9b), was reprinted in the *Dry Kiln Operator's Manual* (Rasmussen 1961, Simpson 1991), as well as other texts (Siau 1995).

It can be seen in Figure 10a that the 70 °F (21 °C) values differ from Dunlap's reported averages (which were

Table 3—EMC table reprinted from Technical Note D-5 (FPL 1919a)

Relative humidity of air	Moisture content of air-dry wood		
	At 70° F.	At 140° F.	At 212° F.
Percent	*Percent*	*Percent*	*Percent*
20	4.5	3.3	2.2
30	6.0	4.5	2.9
40	7.7	5.9	3.9
50	9.3	7.1	4.9
60	11.2	8.8	6.2
70	13.5	10.7	8.0
80	17.0	14.0	10.5
90	22.2	18.2	14.0
100	32.0	26.2	21.0

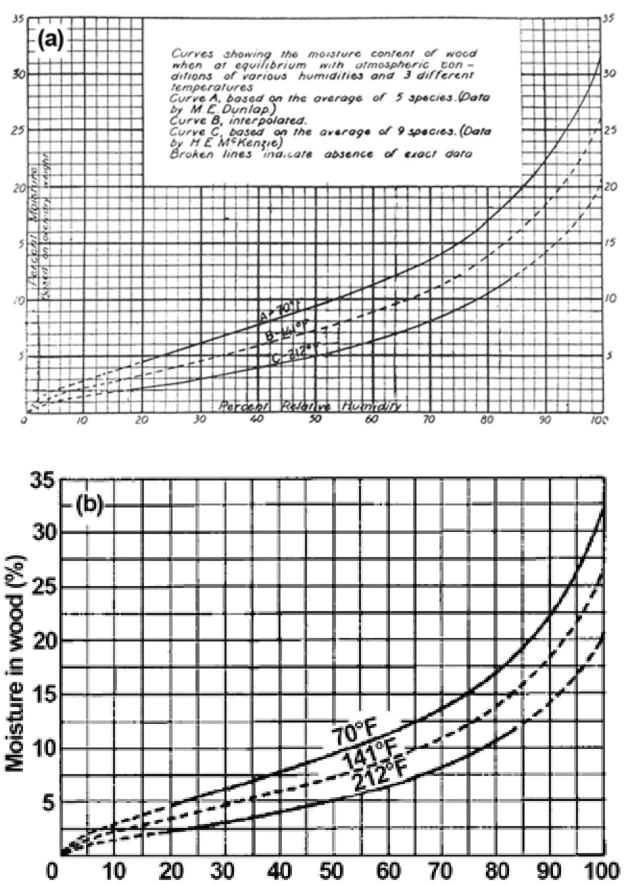

Figure 9. EMC–RH curves from (a) Koehler (1919) and (b) Simpson (1991).

reported as being taken at 75–86 °F (24–30 °C)); the 70 °F (21 °C) values in Table 3 and Figure 9a are generally lower than those of Dunlap except at 90% RH. Dunlap (1919) acquired measurements on seven species (see Section 2.2); however, the legend in Figure 9a indicates that the curve is based on the average of five species. Five out of the seven species that Dunlap studied also appear in a composite curve in *Wood in Aircraft Construction* (FPL 1919c) as shown in Figure 11. "African mahogany" may have been excluded because it was imported, and longleaf pine was likely excluded because it was not commonly used in aircraft construction. The composite curve in Figure 11 agrees well with the values in Table 3 (FPL 1919a). The averaging of five species rather than seven likely explains the discrepancy in Figure 10a.

Another instance of selecting five species can be found in Tiemann (1924), who notes that Dunlap's EMC data for spruce and black walnut are "closely alike"; that white oak, yellow birch, and ash are "closely alike"; and that mahogany is "slightly higher" below 85% RH. Tiemann plots two curves based on Dunlap's data with the noted similarities above: curve A for the average of white oak, yellow birch, and ash; and curve B for the average of spruce and black walnut. Oddly, Tiemann does not mention Dunlap's data for longleaf pine but does mention data for shortleaf pine from Zeller (1920), even though Zeller had acquired data for both shortleaf and longleaf pine.

The 212 °F (100 °C) values in Table 3 and Figure 9a do not represent the true average of McKenzie's data. There is no indication that certain species were excluded; Figure 9a (Koehler 1919) states that the 212 °F (100 °C) curve is based on the average of nine species from McKenzie's data. Figure 10b, however, shows that a curve fit to all the data points is considerably lower in EMC at high RH. The curve fit can be modified to agree with the values in Table 3 by excluding the data for hickory, blue gum, and white ash at values above 33% RH (shown as the "modified fit" in Figure 10b). Again it is not clear why these data should have been excluded. There were no suggestions in McKenzie's report that certain species ought to be excluded.

The issue of interpolation demands further attention. Koehler and Thelen (1926) appear to be the first authors to provide a qualifying statement regarding interpolation of

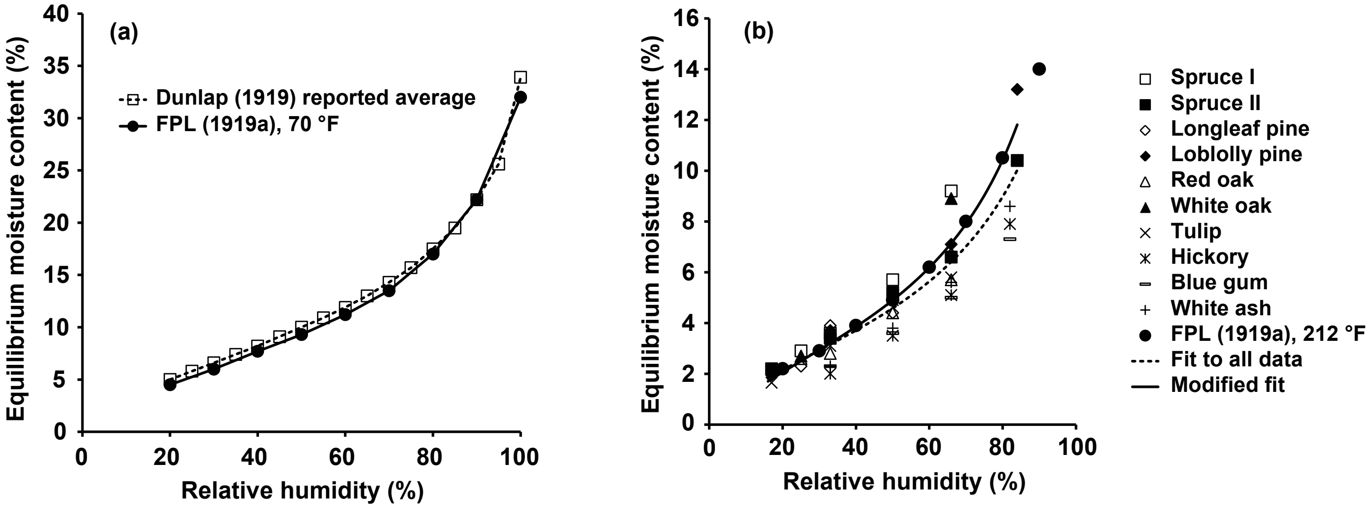

Figure 10. Comparison of EMC values tabulated in Technical Note D-5 (FPL 1919a) with (a) average values reported by Dunlap (1919) and (b) values reported by McKenzie (n.d.). The "modified fit" in (b) excludes hickory, blue gum, and white ash data above 33% RH.

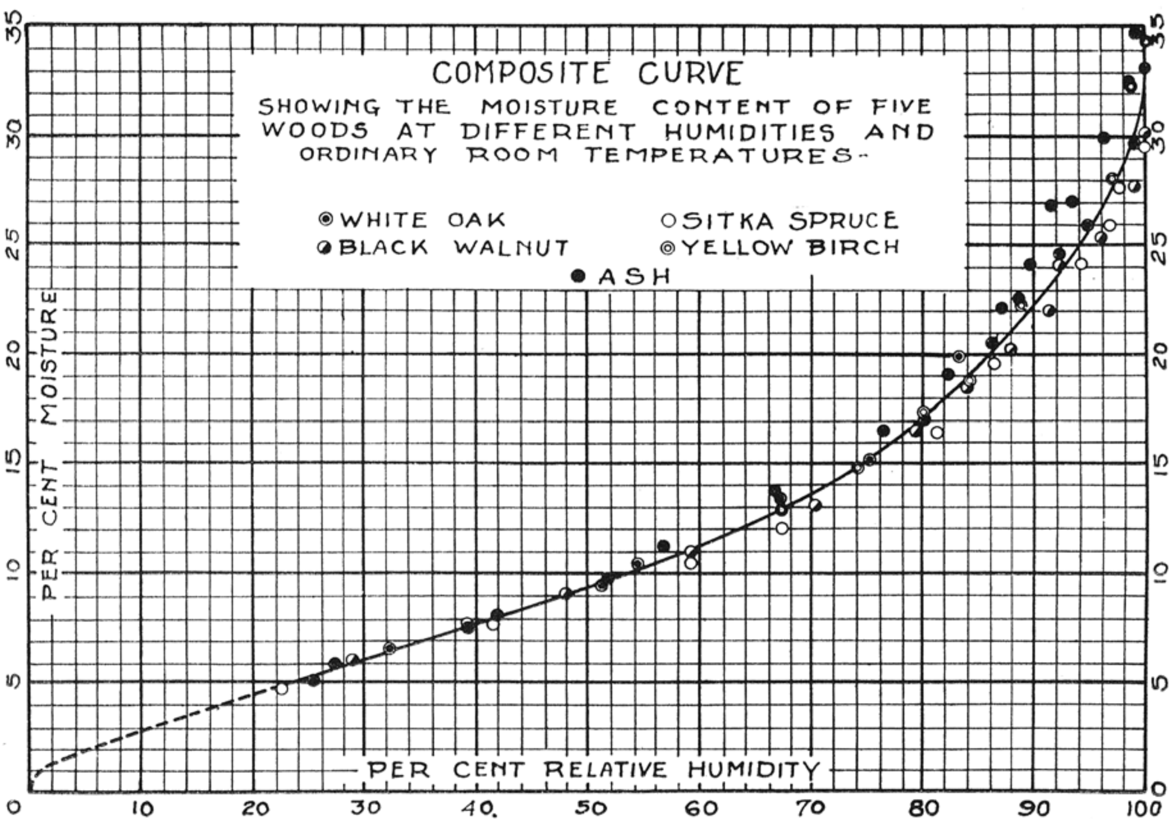

Figure 11. EMC data from *Wood in Aircraft Construction* (FPL 1919c).

EMC values at different temperatures: "The curve at 141°F. is interpolated halfway between the other two curves. Recent observations show that this curve should be somewhat lower, although its exact location has not been determined. With this fact in mind, curves for other temperatures may be interpolated fairly accurately." The mention of "recent observations" may be a reference to the (then unpublished) measurements of Loughborough (Section 2.4). Two observations lend support to this hypothesis. First, a revision (FPL 1941b) of Koehler's (1919) article did not include Figure 9a, but replaced it with the figure based on the work of Loughborough (see Fig. 7). Second, the same figure swap

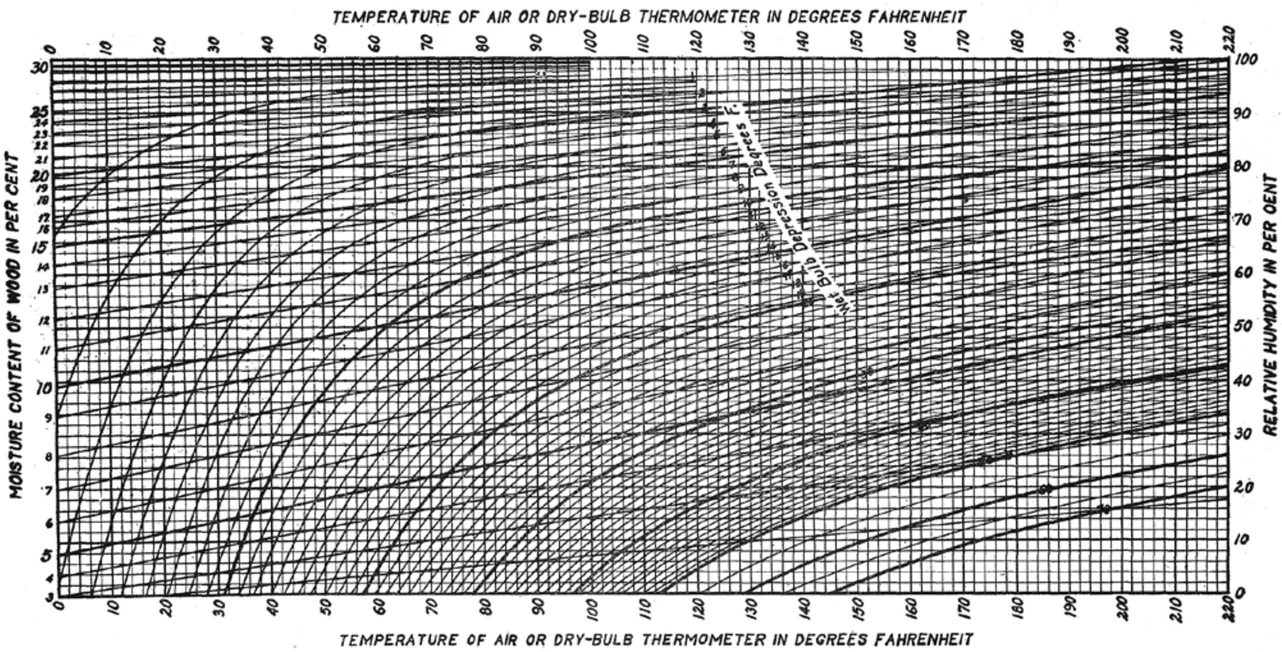

Figure 12. EMC–humidity–temperature chart (U.S. Department of Commerce 1928a).

can be found by comparing *Wood-Liquid Relations* (Hawley 1931) with a marked-up draft manuscript entitled *Wood-Fluids Relations*[4] [sic]. The latter includes Figure 9a, but the curve labeled 141 °F (60.5 °C) is crossed out with red pencil. The published version (Hawley 1931) uses the figure based on the work of Loughborough (see Fig. 7).

In summary, the ways in which Dunlap's and McKenzie's data were presented in the literature over time display an evolution characterized by selective averaging, gradual loss of citation of the data sources, and loss of explicit distinction between curves based on measurement and those based on extrapolation or interpolation.

3.3 Preliminary Figure and Table with Broad Temperature Range

Prior to completion of Loughborough's data set, EMC values appeared in preliminary form, as reprinted in Figure 12, taken from *Seasoning, Handling, and Care of Lumber* [Distributor's edition] (U.S. Department of Commerce 1928a). This figure appears in the context of a discussion of controlling moisture content of lumber in heated storage. Regarding this chart, the report says, "…its chief value is that it is the only one thus far known which gives adequate information regarding the equilibrium moisture content of wood at various stages of air temperature and humidity." The figure caption in the same report reads, "First publication, by courtesy of Forest Products Laboratory, of a chart still under revision and correction, but showing tentatively the equilibrium moisture content of wood over a wide range of air temperatures and humidities. The vertical lines show dry-bulb air temperatures according to top and bottom scales; the horizontal lines show relative percentages of air humidity according to right-hand scale; the curved lines show depressions of wet bulb below dry bulb according to the scale on the face of the chart; and the lines slanting upward from the left side of the chart are lines of moisture content in wood, read on the left-hand scale."

The "Fabricators' edition" of the same report (U.S. Department of Commerce 1928b) includes further detail on the preparation of Figure 12. It first discusses the earlier chart (see Figure 9a), which has EMC curves at 70 °F (21 °C) and 212 °F (100 °C) and notes that the 141°F (60.5 °C) curve was produced by interpolation. It then states, "The chart here shown … has been developed from the original chart, partly by interpolation and partly by additional measurement tests at other temperatures. It has been withheld from publication pending refinement and revision by further measurement tests but is doubtless already amply reliable for the purpose for which it has been used here, and its release to this use by the laboratory is deserving of special recognition." Unlike the previous chart, however, Figure 12 does not use dashed curves to indicate portions that have been interpolated. Certainly portions were also extrapolated; nowhere in the data sources do we find measurements down to 0 °F (–18 °C).

[4]See Bateman et al. (n.d.). On page one of the document, a footnote states the following: "This article is a contribution of the Liquid-Wood Relationship Committee of the Forest Products Laboratory. The committee consists of L.F. Hawley (Chairman), Bateman, Brown, Dunlap, Koehler, Loughborough, Stamm, Tiemann. All members of the committee contributed more or less to the paper but the work of assembling and codifying the information and the preparation was done by a sub-committee whose names appear as authors."

Table 4—Variation of EMC with dry-bulb temperature and wet-bulb depression (reprinted from U.S. Department of Commerce 1928a)

Wet-bulb depression, °F.	Temperature in °F.										
	50	55	60	65	70	75	80	85	90	95	100
4	15.7	16.2	17.0	17.3	17.6	17.9	18.1	18.1	18.2	18.2	18.3
5	13.9	14.5	15.0	15.3	15.6	15.9	16.2	16.4	16.6	16.8	17.0
6	12.5	13.0	13.5	13.9	14.2	14.5	14.8	15.0	15.1	15.3	15.5
7	11.3	11.9	12.4	12.8	13.1	13.4	13.7	13.9	14.1	14.3	14.4
8	10.2	10.8	11.4	11.8	12.2	12.5	12.8	13.1	13.3	13.5	13.7
9	9.2	9.9	10.4	10.9	11.3	11.7	12.0	12.2	12.4	12.6	12.7
10	8.3	9.0	9.6	10.1	10.6	10.9	11.2	11.5	11.8	12.0	12.2
11	7.3	8.1	8.7	9.3	9.9	10.3	10.6	10.8	11.0	11.2	11.3
12	6.4	7.3	8.1	8.6	9.1	9.6	10.0	10.2	10.4	10.6	10.8
13	5.5	6.4	7.2	7.8	8.4	8.8	9.2	9.6	9.9	10.1	10.2
14	4.6	5.7	6.6	7.3	7.9	8.3	8.7	9.1	9.4	9.7	9.9
15	------	5.0	5.8	6.6	7.3	7.8	8.2	8.5	8.8	9.1	9.3
16	------	------	5.2	6.0	6.7	7.2	7.7	8.0	8.3	8.6	8.8
17	------	------	------	5.4	6.1	6.7	7.2	7.5	7.8	8.1	8.3
18	------	------	------	4.8	5.6	6.2	6.7	7.1	7.4	7.7	7.9
19	------	------	------	------	5.0	5.6	6.2	6.6	7.0	7.3	7.5
20	------	------	------	------	------	5.2	5.7	6.2	6.6	6.9	7.1
21	------	------	------	------	------	------	5.3	5.8	6.2	6.5	6.7
22	------	------	------	------	------	------	------	5.3	5.8	6.1	6.3
23	------	------	------	------	------	------	------	------	5.4	5.7	6.0
24	------	------	------	------	------	------	------	------	5.1	5.4	5.7
25	------	------	------	------	------	------	------	------	------	5.1	5.5

As the chart is difficult to read accurately, the report also includes a table of EMCs over a range of dry-bulb temperature and wet-bulb depression (the difference between dry- and wet-bulb temperatures), reprinted here in Table 4. The corresponding RH range calculated from these values varies from 16% to 74% at 50 °F (10 °C), from 24% to 82% at 75 °F (24 °C), and from 30% to 86% at 100 °F (38 °C).

Graphs of the same form as Figure 12 have subsequently been published, presumably based on the completed data set, and no longer considered to be under revision and correction (Voorhies and Loughborough 1943; Smith 1947, 1963; Denig et al. 2000).

3.4 EMC and RH Figures and Tables from 30 °F to 210 °F and Beyond

The original presentation of Loughborough's data was in the form of Figure 7, with a temperature range of 70 °F (21 °C) to 212 °F (100 °C). As stated above, the original discrete data points were never presented in graphic or tabular form. The original figure (Fig. 7) was printed in several works in the 1930s to early 1950s (Hawley 1931; Loughborough and Rietz 1932; Stamm and Loughborough 1935; FPL 1941b, 1942, 1944, 1951).

Several variations on Figures 7 and 12 have also appeared in the literature. We include a sample of these here. Figure 13 shows relative humidity versus dry-bulb temperature with curves of constant EMC and of constant vapor pressure. Figures of this type have been widely published (Peck 1932; FPL 1935, 1940, 1944, 1951, 1955; U.S. Army Air Forces 1944; Denig et al. 2000). Figure 14 shows relative humidity versus vapor pressure with curves of constant EMC and of constant temperature (Loughborough 1942). Both of these figures are essentially transformations of Figure 7 with different axes and a constricted temperature range. Finally, Figure 15 is a plot of wet-bulb temperature versus dry-bulb temperature with curves of constant EMC (Rietz 1931; Smith 1947, 1963).

During the 1940s, a table appeared giving EMC and RH as a function of dry-bulb temperature and wet-bulb depression, presumably based on Loughborough's measurements. This table (see Table 5) has been widely reprinted in FPL publications (FPL 1944, 1946, 1951, 1952, 1955, 1999a; Johnson and Rasmussen 1946; Smith 1947, 1963; Rasmussen 1961; Simpson 1991; Denig et al. 2000).

Several important differences between the values in Figure 7 and Table 5 are evident:

- The original figure displays curves for temperatures every 10 °F from 70 °F to 200 °F plus 212 °F. In contrast, the table begins at 30 °F, increases in 5 °F steps to 130 °F, and then increases in 10 °F steps to 210 °F.
- The original figure displays solid curves (indicating that they are not extrapolated) up to 100% RH at temperatures of 70 °F, 80 °F, and 90 °F. At all other temperatures, the curves are dashed above 90% RH, indicating that they are extrapolated. The table lists EMC values at wet-bulb depression as low as 2 °F, which corresponds to relative humidity values of 78% RH at 30 °F dry-bulb, 90% RH at 70 °F dry-bulb, and 96% RH at 210 °F dry-bulb.

The temperature range of the original data set is unclear. We entertain two hypotheses. The first is that the original temperature range extended down to 30 °F (–1 °C), but temperatures below 70 °F (21 °C) were excluded from Figure 7 because the curves at such temperatures would be difficult to distinguish. This explanation is consistent with the fact that a preliminary table (U.S. Department of Commerce 1928a), reprinted in Table 4, gave EMC values down to 50 °F (10 °C). An alternative hypothesis is that 70 °F (21 °C) is the lower limit of the original temperature range and that additional measurements were taken after 1935 to ex-

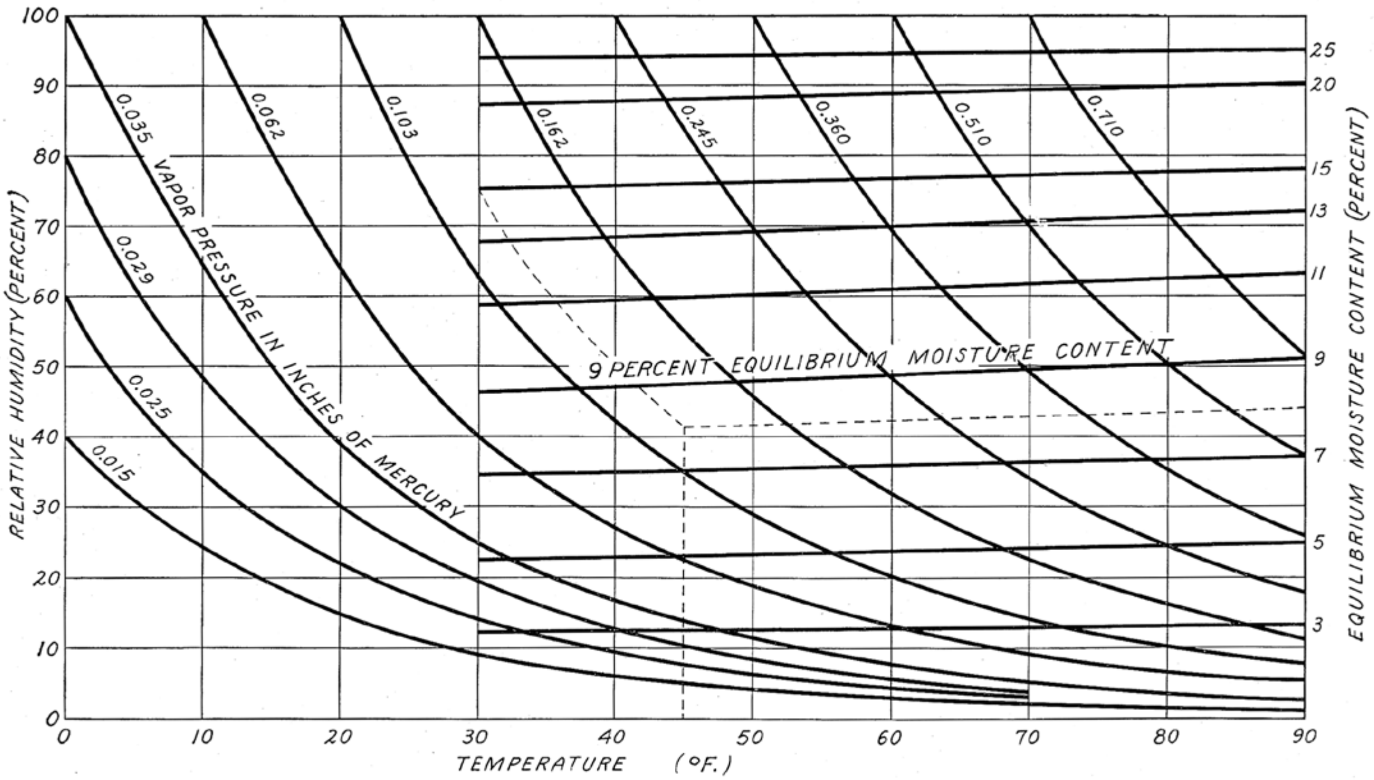

Figure 13. Relative humidity versus dry-bulb temperature, with curves of constant vapor pressure and of constant EMC (FPL 1955).

tend the temperature range down to 30 °F (–1 °C). Under this hypothesis, the EMC values at temperatures below 70 °F (21 °C) given in 1928 would have been extrapolated. It is not possible to determine which hypothesis is correct because documentation is lacking.

It has previously been implied (Simpson 1971, 1973, 1980) that Table 5 represents actual measured data points. Although it is possible that the table contains the actual data points, we find no solid support that these were actually measured values; the evidence is inconclusive. On one hand, the form of the table listing dry-bulb temperature and wet-bulb depression corresponds with the method in which the data were collected: dry- and wet-bulb temperatures were controlled with thermostats (Section 2.4.2). On the other hand, the table does not appear in publications until over a decade after publication of graphs. As discussed above, the Forest Products Laboratory commonly published smoothed curves and tables for practical application, using interpolation and extrapolation from a limited set of measurements, rather than publishing the actual measurements. Given this atmosphere, it seems unlikely that a total of 826 values were actually measured (Table 5) when a smaller number of measurements would have provided a sufficient basis for interpolation.

A rare instance in which discrete data points were published is shown in Figure 8 (Stamm and Loughborough 1935). On the basis of this figure, we propose that the original data were measured at increments of 10% RH. This is consistent with the fact that Figure 7 shows 90% RH as the upper limit for the solid curves (measured values) at temperatures of 100 °F (38 °C) and higher.

We further suggest that Table 5 was generated by interpolation and extrapolation, based on the measured data. This argument is consistent with the fact that the form of Table 5 predates the EMC data, which is evident from a comparison of two different versions of an FPL Technical Note, both bearing the number 156: the *Table of Relative Humidity and Equilibrium Moisture Content for Dry- and Wet-Bulb Hygrometer* (FPL 1952) is a revision of the *Humidity Table for Wet and Dry Bulb Hygrometer* (FPL 1921). The latter is reprinted in Table 6; it gives only RH values as a function of dry-bulb temperature and wet-bulb depression. The layout is similar to Table 5, but with slight differences in temperature range and increment. This RH table was reprinted widely in FPL literature during the late 1910s to early 1940s, with only slight changes in temperature range and increment (Koehler 1919, 1924; Koehler and Thelen 1926; Thelen 1923, 1929; Mathewson 1930; FPL 1941b, 1942). Given the practical use of this table for kiln operation, we suggest that it would have been consistent with FPL trends noted previously to supplement the tabulated RH values with calculated EMC values.

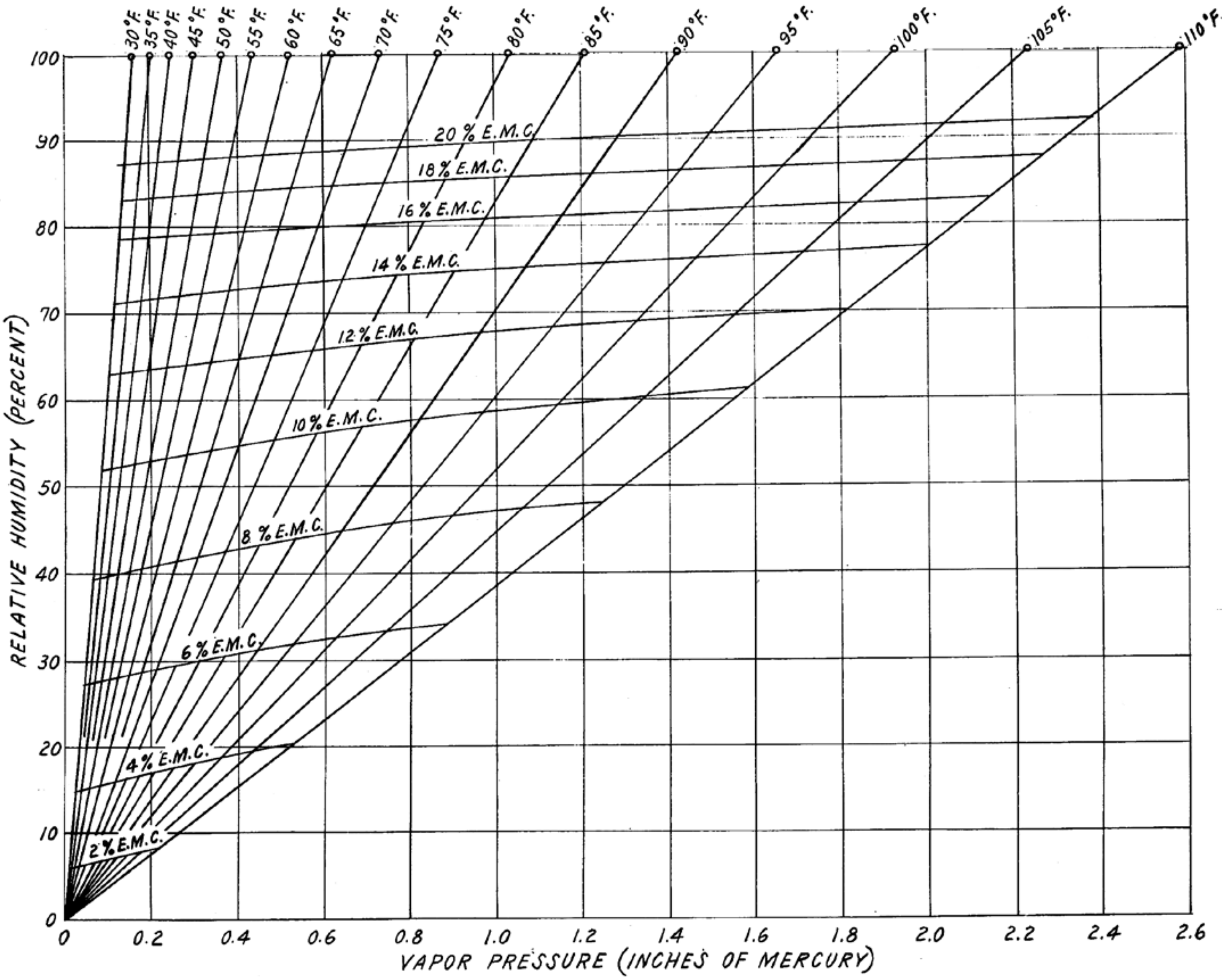

Figure 14. Relative humidity versus vapor pressure, with lines of constant dry-bulb temperature and curves of constant EMC (Loughborough 1942).

Additional evidence consistent with the argument that the values in Table 5 were calculated rather than measured can be found by tracing the source of the RH tables. Of all the FPL publications that print an RH table, Koehler (1924) appears to be the only one to cite his source, which is the humidity diagram of Tiemann (1912). This diagram is reprinted in Figure 16. RH is the *y*-axis (0–100%), and dry-bulb temperature is the *x*-axis (–30 to 220 °F). Convex curves are plotted for constant values of wet-bulb depression (with corrections for barometric pressure), and concave curves are plotted for constant water vapor pressure, with labels indicating water vapor density (absolute humidity) at the temperature of saturation. Tiemann indicates that the relationship between RH, dry-bulb temperature, and wet-bulb temperature is based on Ferrel's formula (see Marvin 1900), but has been extended to higher temperatures. Saturation vapor pressures are based on the U.S. Weather Bureau's Psychrometric Tables (Marvin 1900) and the Smithsonian Meteorological Tables (Smithsonian Institution 1907). Tiemann states that although Ferrel's formula is strictly applicable only below 140 °F (60 °C) (the parameters were deduced from experiments conducted only at temperatures below this), he had reason to extend it to higher temperatures: "Experiments made by the author indicate, however, that the equation holds with reasonable exactness for temperature up to the boiling point, and the curves have therefore been extended to 220 °[F]." The humidity diagram is reprinted in several publications, with slight modification in some cases (Tiemann 1917, FPL 1919c, Koehler and Thelen 1926, U.S. Army Air Forces 1944, Smith 1963).

The similarity between Figures 12 and 16 is striking. Figure 16 was developed as a tool for use in lumber drying. The figure allows conversion of psychrometric

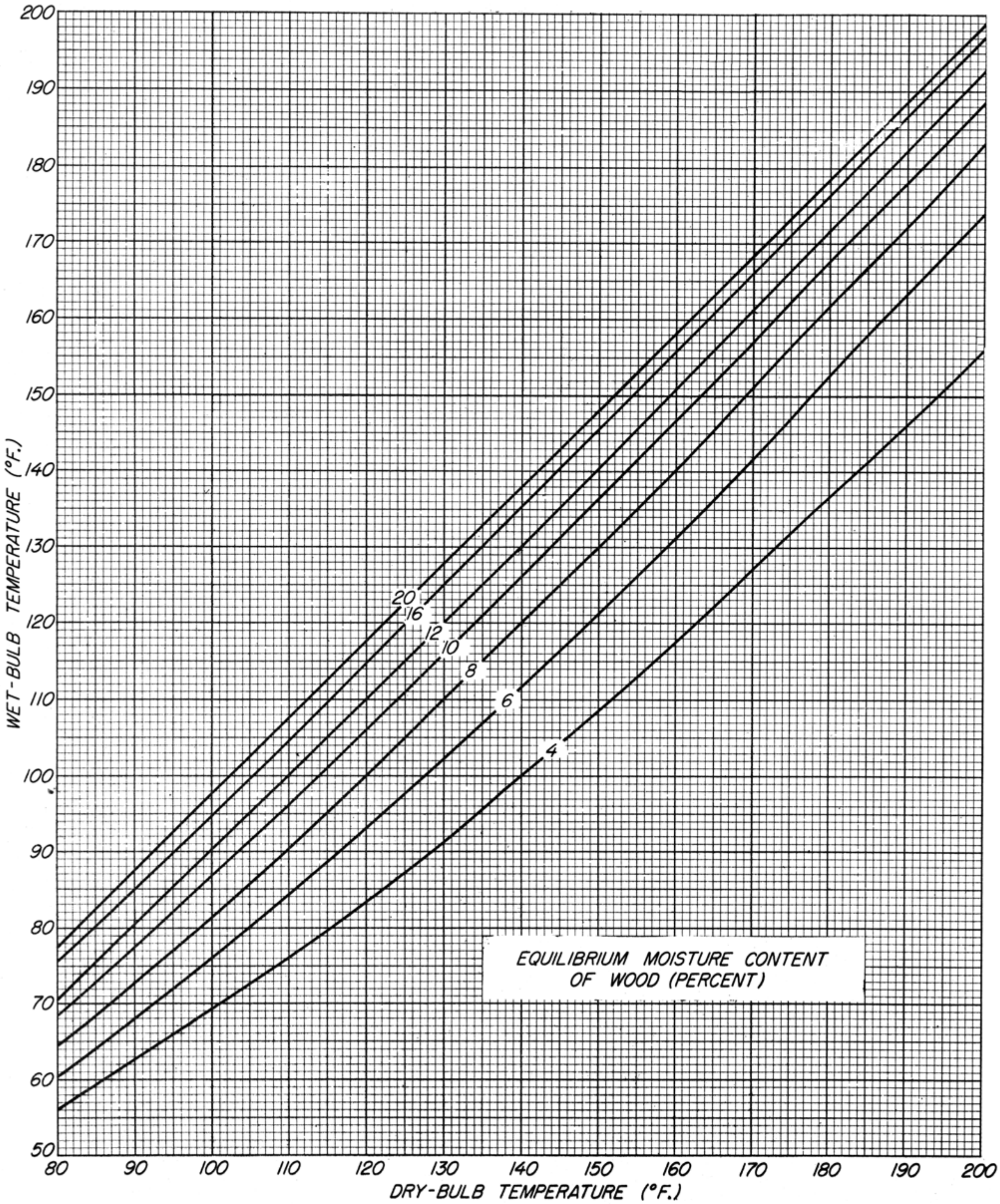

Figure 15. EMC as a function of wet- and dry-bulb temperatures (Rietz 1931; Smith 1947, 1963).

parameters that were commonly measured (wet- and dry-bulb temperatures) to other useful parameters (RH, dew-point temperature, and water vapor density). Figure 12 adopts the same form as Figure 16 but inserts wood EMC curves while removing the water vapor density curves. Later versions of both Figures 12 and 16 are given by Smith (1963). This simple graphical transformation was likely paralleled in tabular form, as suggested above. It would be consistent with previous trends at FPL, once a full EMC data set was available, to take an existing RH table (Table 6) and supplement it with interpolated/extrapolated EMC values (Table 5).

During the 1970s a further transformation occurred in EMC tables: wet-bulb depression disappeared from the table and was replaced by relative humidity. Table 7 shows the table as printed in the 1974 edition of the *Wood Handbook* (FPL 1974). It should be noted that the temperature values range from 30 °F to 210 °F in increments of 10 °F and that the relative humidity values go from 5% to 95% in increments of 5% RH plus 98% RH.

It is not clear how the values in the Table 7 were derived. These values may have been estimated by interpolation/extrapolation using the previously tabulated values, or they may have been calculated from an equation whose parameters were based on least-squares fitting to the previously tabulated values.

Simpson (1971, 1973) used the EMC values tabulated in the 1955 *Wood Handbook* (FPL 1955) to determine parameters for a thermodynamic model developed by Hailwood and Horrobin (1946). The model partitions bound water into "a solid solution of water in the polymer" and "hydrates between water and definite units of the polymer molecule." An arbitrary number of hydrates can be added; equations with parameters fit to the FPL EMC values have been published with one hydrate (Simpson 1971) and two hydrates (Simpson 1973). We refer to the latter as the two-hydrate HH equation:

$$M = \frac{1{,}800}{M_p}\left[\frac{Kh}{1 - Kh} + \frac{K_1Kh + 2K_1K_2K^2h^2}{1 + K_1Kh + K_1K_2K^2h^2}\right] \quad (2)$$

where M is equilibrium moisture content (percentage), h is relative humidity (decimal), and the parameters M_p, K, K_1, and K_2 have a particular physical significance in the model derivation of Hailwood and Horrobin (1946). To account for the temperature dependence of the EMC values, Simpson (1973) made each parameter a second-order polynomial in temperature T (in °F) as follows:

$$\begin{aligned} M_p &= 330 + 0.452T + 0.00415T^2 \\ K &= 0.791 + 0.000463T - 0.000000844T^2 \\ K_1 &= 6.17 + 0.000313T - 0.0000926T^2 \\ K_2 &= 1.65 + 0.0202T - 0.0000934T^2 \end{aligned} \quad (3)$$

By comparing the values tabulated in the 1974 *Wood Handbook* with those generated from the equations given by Simpson (1971, 1973), we find differences of up to 2.7% MC for the one-hydrate equation and up to 0.5% MC for the two-hydrate equation. These differences make it clear that the 1974 *Wood Handbook* tabulated values were not generated directly from either of Simpson's HH equations.

In the 1987 *Wood Handbook* (FPL 1987), a two-hydrate HH equation appears.[5] The parameters in this equation are very similar (but not identical) to those in Equation (3). The temperature coefficients of the K_1 and K_2 parameters given in the 1987 *Wood Handbook* (Eq. (4)) differ from those published by Simpson (1973) (Eq. (3)).

$$\begin{aligned} K_1 &= 6.34 + 0.000775T - 0.0000935T^2 \\ K_2 &= 1.09 + 0.0284T - 0.0000904T^2 \end{aligned} \quad (4)$$

The reason for this difference is unknown. However, it just happens that the EMC values generated using these parameters are in excellent agreement with the tabulated EMC values in the 1974 and 1987 editions of the *Wood Handbook*, the maximum difference being less than 0.1% MC (for temperatures from 30 °F to 210 °F). In order to determine which set of K_1 and K_2 parameters is correct, we compared EMC values predicted by both sets of parameters with values in the 1955 *Wood Handbook*. We find that the parameters in Equation (3) (Simpson 1973) fit the data better than those in Equation (4) (FPL 1987): the RMSE and the maximum absolute error are lower when the parameters in Equation (3) are used. The differences, though, are small; on average the calculated EMC values differ by less than 0.2% MC. It is unclear why the K_1 and K_2 parameters were changed.

An additional transformation in the 1987 *Wood Handbook* is that the tabulated EMC values extend to 270 °F (132 °C) (see Table 8). This extrapolation may have been based on the work of Simpson and Rosen (1981), which showed that the one-hydrate HH equation using the parameters of Simpson (1971) when extrapolated to 300 °F (149 °C) compared reasonably well with measured EMC values at these higher temperatures from the broader literature. However, the tabulated values in the 1987 *Wood Handbook* for temperatures from 220 °F (104 °C) to 270 °F (132 °C) appear to be generated from the two-hydrate HH equation (with K_1 and K_2 parameters from Eq. (4)) rather than the one-hydrate HH equation. According to our analysis, the values in Table 8 and those calculated from the two-hydrate HH equation differ by not more than 0.2% MC; in contrast, the one-hydrate HH equation gives values that differ by up to 1.6% MC from those in the table. The EMC values predicted by the two equations diverge with increasing temperature. For example, EMC values at 30% RH at 220 °F (104 °C) are 3.0% and 2.9% for the one-hydrate and two-hydrate HH

[5]The notation in the 1987 Wood Handbook is incorrect: relative humidity should have been given as a decimal ($0 \le h \le 1$) rather than as a percentage. This was corrected in the 1999 Wood Handbook.

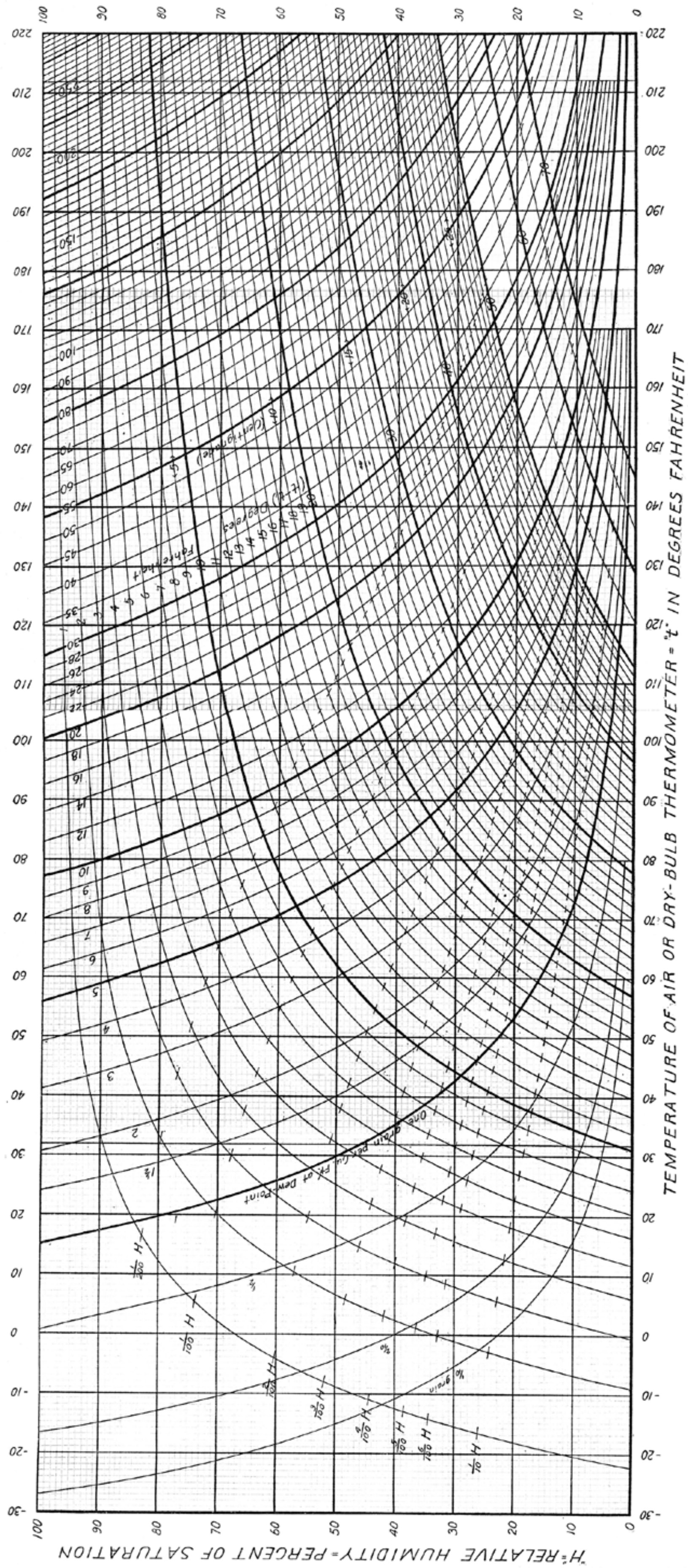

Figure 16. Humidity diagram from Tiemann (1912).

Table 5—Variation of relative humidity and EMC with dry-bulb temperature and wet-bulb depression (reprinted from FPL 1952)

Relative Humidity [1] and Equilibrium Moisture Content [2] Table for Use With Dry-Bulb Temperatures and Wet-Bulb Depressions

Temperature dry bulb (° F.)	Wet bulb—depression (° F.)																																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	32	34	36	38	40	45	50
30	89	78	67	57	46	36	27	17	6																												
		15.9	*12.9*	*10.8*	*9.0*	*7.4*	*5.7*	*3.9*	*1.6*																												
35	90	81	72	63	54	45	37	28	19	11	3																										
		16.8	*13.9*	*11.9*	*10.3*	*8.8*	*7.4*	*6.0*	*4.5*	*2.9*	*0.8*																										
40	92	83	75	68	60	52	45	37	29	22	15	8																									
		17.6	*14.8*	*12.9*	*11.2*	*9.9*	*8.6*	*7.4*	*6.2*	*5.0*	*3.5*	*1.9*																									
45	93	85	78	72	64	58	51	44	37	31	25	19	12	6																							
		18.3	*15.6*	*13.7*	*12.0*	*10.7*	*9.5*	*8.5*	*7.5*	*6.5*	*5.3*	*4.2*	*2.9*	*1.5*																							
50	93	86	80	74	68	62	56	50	44	38	32	27	21	16	10	5																					
		19.0	*16.3*	*14.4*	*12.7*	*11.5*	*10.3*	*9.4*	*8.5*	*7.6*	*6.7*	*5.7*	*4.8*	*3.9*	*2.8*	*1.5*																					
55	94	88	82	76	70	65	60	54	49	44	39	34	28	24	19	14	9	5																			
		19.5	*16.9*	*15.1*	*13.4*	*12.2*	*11.0*	*10.1*	*9.3*	*8.4*	*7.6*	*6.8*	*6.0*	*5.3*	*4.5*	*3.6*	*2.5*	*1.3*																			
60	94	89	83	78	73	68	63	58	53	48	43	39	34	30	26	21	17	13	9	5	1																
		19.9	*17.4*	*15.6*	*13.9*	*12.7*	*11.6*	*10.7*	*9.9*	*9.1*	*8.3*	*7.6*	*6.9*	*6.3*	*5.6*	*4.9*	*4.1*	*3.2*	*2.3*	*1.3*	*0.2*																
65	95	90	84	80	75	70	66	61	56	52	48	44	39	36	32	27	24	20	16	13	8	6	2														
		20.3	*17.8*	*16.1*	*14.4*	*13.3*	*12.1*	*11.2*	*10.4*	*9.7*	*8.9*	*8.3*	*7.7*	*7.1*	*6.5*	*5.8*	*5.2*	*4.5*	*3.8*	*3.0*	*2.3*	*1.4*	*0.4*														
70	95	90	86	81	77	72	68	64	59	55	51	48	44	40	36	33	29	25	22	19	15	12	9	6	3												
		20.6	*18.2*	*16.5*	*14.9*	*13.7*	*12.5*	*11.6*	*10.9*	*10.1*	*9.4*	*8.8*	*8.3*	*7.7*	*7.2*	*6.6*	*6.0*	*5.5*	*4.9*	*4.3*	*3.7*	*2.9*	*2.3*	*1.5*	*0.7*												
75	95	91	86	82	78	74	70	66	62	58	54	51	47	44	41	37	34	31	28	24	21	18	15	12	10	7	4	1									
		20.9	*18.5*	*16.8*	*15.2*	*14.0*	*12.9*	*12.0*	*11.2*	*10.5*	*9.8*	*9.3*	*8.7*	*8.2*	*7.7*	*7.2*	*6.7*	*6.2*	*5.6*	*5.1*	*4.7*	*4.1*	*3.5*	*2.9*	*2.3*	*1.7*	*0.9*	*0.2*									
80	96	91	87	83	79	75	72	68	64	61	57	54	50	47	44	41	38	35	32	29	26	23	20	18	15	12	10	7	5	3							
		21.0	*18.7*	*17.0*	*15.5*	*14.3*	*13.2*	*12.3*	*11.5*	*10.9*	*10.1*	*9.7*	*9.1*	*8.6*	*8.1*	*7.7*	*7.2*	*6.8*	*6.3*	*5.8*	*5.4*	*5.0*	*4.5*	*4.0*	*3.5*	*3.0*	*2.4*	*1.8*	*1.1*	*0.3*							
85	96	92	88	84	80	76	73	70	66	63	59	56	53	50	47	44	41	38	36	33	30	28	25	23	20	18	15	13	11	9	4						
		21.2	*18.8*	*17.2*	*15.7*	*14.5*	*13.5*	*12.5*	*11.8*	*11.2*	*10.5*	*10.0*	*9.5*	*9.0*	*8.5*	*8.1*	*7.6*	*7.2*	*6.7*	*6.3*	*6.0*	*5.6*	*5.2*	*4.8*	*4.3*	*3.9*	*3.4*	*3.0*	*2.4*	*1.7*	*0.9*						
90	96	92	89	85	81	78	74	71	68	65	61	58	55	52	49	47	44	41	39	36	34	31	29	26	24	22	19	17	15	13	9	5	1				
		21.3	*18.9*	*17.3*	*15.9*	*14.7*	*13.7*	*12.8*	*12.0*	*11.4*	*10.7*	*10.2*	*9.7*	*9.3*	*8.8*	*8.4*	*8.0*	*7.6*	*7.2*	*6.8*	*6.5*	*6.1*	*5.7*	*5.3*	*4.9*	*4.6*	*4.2*	*3.8*	*3.3*	*2.8*	*2.1*	*1.3*	*0.4*				
95	96	92	89	85	82	79	75	72	69	66	63	60	57	55	52	49	46	44	42	39	37	34	32	30	28	26	23	22	20	17	14	10	6	2			
		21.3	*19.0*	*17.4*	*16.1*	*14.9*	*13.9*	*12.9*	*12.2*	*11.6*	*11.0*	*10.5*	*10.0*	*9.5*	*9.1*	*8.7*	*8.2*	*7.9*	*7.5*	*7.1*	*6.8*	*6.4*	*6.1*	*5.7*	*5.3*	*5.1*	*4.8*	*4.4*	*4.0*	*3.6*	*3.0*	*2.3*	*1.5*	*0.6*			
100	96	93	89	86	83	80	77	73	70	68	65	62	59	56	54	51	49	46	44	41	39	37	35	33	30	28	26	24	22	21	17	13	10	7	4		
		21.3	*19.0*	*17.5*	*16.1*	*15.0*	*13.9*	*13.1*	*12.4*	*11.8*	*11.2*	*10.6*	*10.1*	*9.6*	*9.2*	*8.9*	*8.5*	*8.1*	*7.8*	*7.4*	*7.0*	*6.7*	*6.4*	*6.1*	*5.7*	*5.4*	*5.2*	*4.9*	*4.6*	*4.2*	*3.6*	*3.1*	*2.4*	*1.6*	*0.7*		
105	96	93	90	87	83	80	77	74	71	69	66	63	60	58	55	53	50	48	46	44	42	40	37	35	34	31	29	28	26	24	20	17	14	11	8		
		21.4	*19.0*	*17.5*	*16.2*	*15.1*	*14.0*	*13.2*	*12.6*	*11.9*	*11.3*	*10.8*	*10.3*	*9.8*	*9.4*	*9.0*	*8.7*	*8.3*	*7.9*	*7.6*	*7.3*	*6.9*	*6.7*	*6.4*	*6.1*	*5.7*	*5.4*	*5.2*	*4.8*	*4.6*	*4.2*	*3.6*	*3.1*	*2.4*	*1.8*		
110	97	93	90	87	84	81	78	75	73	70	67	65	62	60	57	55	52	50	48	46	44	42	40	38	36	34	32	30	28	26	23	20	17	14	11	4	
		21.4	*19.0*	*17.5*	*16.2*	*15.1*	*14.1*	*13.3*	*12.6*	*12.0*	*11.4*	*10.8*	*10.4*	*9.9*	*9.5*	*9.2*	*8.8*	*8.4*	*8.1*	*7.7*	*7.5*	*7.2*	*6.8*	*6.6*	*6.3*	*6.0*	*5.7*	*5.4*	*5.2*	*4.8*	*4.5*	*4.0*	*3.5*	*3.0*	*2.5*	*1.1*	
115	97	93	90	88	85	82	79	76	74	71	68	66	63	61	58	56	54	52	50	48	45	43	41	40	38	36	34	32	31	29	26	23	20	17	14	8	2
		21.4	*19.0*	*17.5*	*16.2*	*15.1*	*14.1*	*13.4*	*12.7*	*12.1*	*11.5*	*10.9*	*10.4*	*10.0*	*9.6*	*9.3*	*8.9*	*8.6*	*8.2*	*7.8*	*7.6*	*7.3*	*7.0*	*6.7*	*6.5*	*6.2*	*5.9*	*5.6*	*5.4*	*5.2*	*4.7*	*4.3*	*3.9*	*3.4*	*2.9*	*1.7*	*0.4*
120	97	94	91	88	85	82	80	77	74	72	69	67	65	62	60	58	55	53	51	49	47	45	43	41	40	38	36	34	33	31	28	25	22	19	17	10	5
		21.3	*19.0*	*17.4*	*16.2*	*15.1*	*14.1*	*13.4*	*12.7*	*12.1*	*11.5*	*11.0*	*10.5*	*10.0*	*9.7*	*9.4*	*9.0*	*8.7*	*8.3*	*7.9*	*7.7*	*7.4*	*7.2*	*6.8*	*6.6*	*6.3*	*6.1*	*5.8*	*5.6*	*5.4*	*5.0*	*4.6*	*4.2*	*3.7*	*3.3*	*2.3*	*1.1*
125	97	94	91	88	86	83	80	77	75	73	70	68	65	63	61	59	57	55	53	51	48	47	45	43	41	39	38	36	35	33	30	27	24	22	19	13	8
		21.2	*18.9*	*17.3*	*16.1*	*15.0*	*14.0*	*13.4*	*12.7*	*12.1*	*11.5*	*11.0*	*10.5*	*10.0*	*9.7*	*9.4*	*9.0*	*8.7*	*8.3*	*8.0*	*7.7*	*7.5*	*7.2*	*7.0*	*6.7*	*6.5*	*6.2*	*6.0*	*5.8*	*5.5*	*5.2*	*4.8*	*4.4*	*4.0*	*3.6*	*2.7*	*1.6*
130	97	94	91	89	86	83	81	78	76	73	71	69	67	64	62	60	58	56	54	52	50	48	47	45	43	41	40	38	37	35	32	29	26	24	21	15	10
		21.0	*18.8*	*17.2*	*16.0*	*14.9*	*14.0*	*13.4*	*12.7*	*12.1*	*11.5*	*11.0*	*10.5*	*10.0*	*9.7*	*9.4*	*9.0*	*8.7*	*8.3*	*8.0*	*7.8*	*7.6*	*7.3*	*7.0*	*6.8*	*6.6*	*6.4*	*6.1*	*5.9*	*5.6*	*5.3*	*4.9*	*4.6*	*4.2*	*3.8*	*3.0*	*2.0*
140	97	95	92	89	87	84	82	79	77	75	73	70	68	66	64	62	60	58	56	54	53	51	49	47	46	44	43	41	40	38	35	32	30	27	25	19	14
		20.7	*18.6*	*16.9*	*15.8*	*14.8*	*13.8*	*13.2*	*12.5*	*11.9*	*11.4*	*10.9*	*10.4*	*10.0*	*9.6*	*9.4*	*9.0*	*8.7*	*8.4*	*8.0*	*7.8*	*7.6*	*7.3*	*7.1*	*6.9*	*6.6*	*6.4*	*6.2*	*6.0*	*5.8*	*5.4*	*5.1*	*4.8*	*4.4*	*4.1*	*3.4*	*2.6*
150	98	95	92	90	87	85	82	80	78	76	74	72	70	68	66	64	62	60	58	57	55	53	51	49	48	46	45	43	42	41	38	36	33	30	28	23	18
		20.2	*18.4*	*16.6*	*15.4*	*14.5*	*13.7*	*13.0*	*12.4*	*11.8*	*11.2*	*10.8*	*10.3*	*9.9*	*9.5*	*9.2*	*8.9*	*8.6*	*8.3*	*8.0*	*7.8*	*7.5*	*7.3*	*7.1*	*6.9*	*6.7*	*6.4*	*6.2*	*6.0*	*5.8*	*5.4*	*5.2*	*4.9*	*4.5*	*4.2*	*3.6*	*2.5*
160	98	95	93	90	88	86	83	81	79	77	75	73	71	69	67	65	64	62	60	58	57	55	53	52	50	49	47	46	44	43	41	38	35	33	31	25	21
		19.8	*18.1*	*16.2*	*15.2*	*14.2*	*13.4*	*12.7*	*12.1*	*11.5*	*11.0*	*10.6*	*10.1*	*9.7*	*9.4*	*9.1*	*8.8*	*8.5*	*8.2*	*7.9*	*7.7*	*7.4*	*7.2*	*7.0*	*6.8*	*6.7*	*6.4*	*6.2*	*6.0*	*5.8*	*5.5*	*5.2*	*4.9*	*4.6*	*4.3*	*3.7*	*3.2*
170	98	95	93	91	89	86	84	82	80	78	76	74	72	70	69	67	65	63	62	60	59	57	55	53	52	51	49	48	47	45	43	40	38	35	33	28	24
		19.4	*17.7*	*15.8*	*14.8*	*13.9*	*13.2*	*12.4*	*11.8*	*11.3*	*10.8*	*10.4*	*9.9*	*9.6*	*9.2*	*9.0*	*8.6*	*8.4*	*8.0*	*7.8*	*7.6*	*7.3*	*7.2*	*6.9*	*6.7*	*6.6*	*6.4*	*6.2*	*6.0*	*5.7*	*5.5*	*5.2*	*4.9*	*4.6*	*4.4*	*3.7*	*3.2*
180	98	96	94	91	89	87	85	83	81	79	77	75	73	72	70	68	67	65	63	62	60	58	57	55	54	52	51	50	48	47	45	42	40	38	35	30	26
		18.9	*17.3*	*15.5*	*14.5*	*13.7*	*12.9*	*12.2*	*11.6*	*11.1*	*10.6*	*10.1*	*9.7*	*9.4*	*9.0*	*8.8*	*8.4*	*8.1*	*7.8*	*7.6*	*7.4*	*7.2*	*7.0*	*6.8*	*6.5*	*6.4*	*6.2*	*6.0*	*5.8*	*5.7*	*5.4*	*5.2*	*4.8*	*4.6*	*4.4*	*3.8*	*3.3*
190	98	96	94	92	90	88	85	84	82	80	78	76	75	73	71	69	68	66	65	63	62	60	58	57	56	54	53	51	50	49	46	44	42	39	37	32	28
		18.5	*16.9*	*15.2*	*14.2*	*13.4*	*12.7*	*12.0*	*11.4*	*10.9*	*10.5*	*10.0*	*9.6*	*9.2*	*8.9*	*8.6*	*8.2*	*7.9*	*7.7*	*7.4*	*7.2*	*7.0*	*6.8*	*6.6*	*6.4*	*6.2*	*6.0*	*5.9*	*5.7*	*5.5*	*5.3*	*5.0*	*4.8*	*4.5*	*4.4*	*3.8*	*3.3*
200	98	96	94	92	90	88	86	84	82	80	79	77	75	74	72	70	69	67	66	64	63	61	60	58	57	55	54	53	52	51	48	46	43	41	39	34	30
		18.1	*16.4*	*14.9*	*14.0*	*13.2*	*12.4*	*11.8*	*11.2*	*10.8*	*10.3*	*9.8*	*9.4*	*9.1*	*8.8*	*8.4*	*8.1*	*7.7*	*7.5*	*7.2*	*7.0*	*6.8*	*6.6*	*6.4*	*6.2*	*6.0*	*5.9*	*5.7*	*5.6*	*5.4*	*5.2*	*4.9*	*4.7*	*4.5*	*4.3*	*3.8*	*3.3*
210	98	96	94	92	90	88	86	85	83	81	79	78	76	75	73	71	70	68	67	65	64	63	61	60	59	57	56	54	53	52	50	47	45	43	41	36	32
		17.7	*16.0*	*14.6*	*13.8*	*13.0*	*12.2*	*11.7*	*11.1*	*10.6*	*10.0*	*9.7*	*9.2*	*9.0*	*8.7*	*8.3*	*8.0*	*7.6*	*7.4*	*7.1*	*6.9*	*6.8*	*6.5*	*6.3*	*6.1*	*5.9*	*5.8*	*5.5*	*5.4*	*5.3*	*5.1*	*4.8*	*4.6*	*4.4*	*4.2*	*3.7*	*3.2*

[1] Relative hu midity values in roman type.
[2] Equilibrium moisture content values in italic type.

Table 6—Variation of relative humidity with dry-bulb temperature and wet-bulb depression (reprinted from FPL 1921)

Relative humidity table for use with wet- and dry-bulb thermometers.

Temperature of dry bulb	Difference between wet-bulb and dry-bulb thermometers, in degrees Fahrenheit																																																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
60	94	89	83	78	73	68	63	58	53	48	43	39	34	30	26	21	17	13	9	5	1																													
70	95	90	86	81	77	72	68	64	59	55	51	48	44	40	36	33	29	25	22	19	15	12	9	6	3																									
80	96	91	87	83	79	75	72	68	64	61	57	54	50	47	44	41	38	35	32	29	26	23	20	18	15	12	10	7	5	3																				
90	96	92	89	85	81	78	74	71	68	65	61	58	55	52	49	47	44	41	39	36	34	31	29	26	24	22	19	17	15	13	11	9	7	5	3	1														
100	96	93	89	86	83	80	77	73	70	68	65	62	59	56	54	51	49	46	44	41	39	37	35	33	30	28	26	24	22	21	19	17	15	13	12	10	8	7	5	4	2	1								
102	96	93	90	86	83	80	77	74	71	68	65	62	60	57	55	52	49	47	45	42	40	38	36	34	32	30	28	26	24	22	20	18	16	15	13	11	10	8	7	5	4	2	1							
104	97	93	90	87	83	80	77	74	71	69	66	63	60	58	55	53	50	48	46	43	41	39	37	35	33	31	29	27	25	23	21	20	18	16	14	13	11	10	8	7	5	4	2	1						
106	97	93	90	87	84	81	78	75	72	69	66	64	61	58	56	53	51	49	46	44	42	40	38	36	34	32	30	28	26	24	23	21	19	17	16	14	13	11	10	8	7	5	4	3	1					
108	97	93	90	87	84	81	78	75	72	70	67	64	62	59	57	54	52	49	47	45	43	41	39	37	35	33	31	29	27	25	24	22	20	19	17	16	14	12	11	10	8	7	5	4	3	2				
110	97	93	90	87	84	81	78	75	73	70	67	65	62	60	57	55	52	50	48	46	44	42	40	38	36	34	32	30	28	26	25	23	21	20	18	17	15	14	12	11	10	8	7	6	4	3	2	1		
112	97	94	90	87	84	81	79	76	73	70	68	65	63	60	58	55	53	51	49	47	44	42	40	38	36	35	33	31	29	27	26	24	23	21	19	18	16	15	14	12	11	9	8	7	6	4	3	2	1	
114	97	94	91	88	85	82	79	76	74	71	68	66	63	61	58	56	54	52	49	47	45	43	41	39	37	35	34	32	30	28	27	25	24	22	20	19	18	16	15	13	12	11	9	8	7	6	5	3	2	1
116	97	94	91	88	85	82	79	76	74	71	69	66	64	61	59	57	54	52	50	48	46	44	42	40	38	36	34	33	31	29	28	26	25	23	22	20	19	17	16	14	13	12	11	9	8	7	6	5	4	2
118	97	94	91	88	85	82	79	77	74	72	69	67	64	62	59	57	55	53	51	49	47	45	43	41	39	37	35	34	32	30	29	27	25	24	23	21	20	18	17	16	14	13	12	11	9	8	7	6	5	4
120	97	94	91	88	85	82	80	77	74	72	69	67	65	62	60	58	55	53	51	49	47	45	43	41	40	38	36	34	33	31	29	28	26	25	23	22	21	19	18	17	15	14	13	12	10	9	8	7	6	5
122	97	94	91	88	85	83	80	77	75	72	70	67	65	63	60	58	56	54	52	50	48	46	44	42	40	39	37	35	34	32	30	29	27	26	24	23	22	20	19	18	16	15	14	13	11	10	9	8	7	6
124	97	94	91	88	85	83	80	78	75	73	70	68	65	63	61	59	57	54	52	50	48	47	45	43	41	39	38	36	34	33	31	30	28	27	25	24	22	21	20	18	17	16	15	14	12	11	10	9	8	7
126	97	94	91	88	86	83	80	78	75	73	70	68	66	64	61	59	57	55	53	51	49	47	45	44	42	40	38	37	35	33	32	30	29	27	26	25	23	22	21	19	18	17	16	15	13	12	11	10	9	8
128	97	94	91	89	86	83	81	78	76	73	71	68	66	64	62	60	58	56	54	52	50	48	46	44	42	41	39	37	36	34	33	31	30	28	27	25	24	23	22	20	19	18	17	16	14	13	12	11	10	9
130	97	94	91	89	86	83	81	78	76	73	71	69	67	64	62	60	58	56	54	52	50	48	47	45	43	41	40	38	37	35	33	32	30	29	28	26	25	24	22	21	20	19	18	16	15	14	13	12	11	10
132	97	94	92	89	86	84	81	79	76	74	71	69	67	65	63	61	58	56	55	53	51	49	47	45	44	42	40	39	37	36	34	33	31	30	28	27	26	24	23	22	21	20	18	17	16	15	14	13	12	11
134	97	94	92	89	86	84	81	79	76	74	72	69	67	65	63	61	59	57	55	53	51	49	48	46	44	43	41	39	38	36	35	33	32	30	29	28	26	25	24	23	21	20	19	18	17	16	15	14	13	12
136	97	94	92	89	86	84	81	79	77	74	72	70	68	65	63	61	59	57	55	54	52	50	48	46	45	43	41	40	38	37	35	34	33	31	30	28	27	26	25	23	22	21	20	19	18	17	16	15	14	13
138	97	94	92	89	87	84	82	79	77	75	72	70	68	66	64	62	60	58	56	54	52	50	49	47	45	44	42	40	39	37	36	35	33	32	30	29	28	27	25	24	23	22	21	20	19	17	16	15	14	14
140	97	95	92	89	87	84	82	79	77	75	73	70	68	66	64	62	60	58	56	54	53	51	49	47	46	44	43	41	40	38	37	35	34	32	31	30	29	27	26	25	24	23	21	20	19	18	17	16	15	14
142	97	95	92	89	87	84	82	80	77	75	73	70	68	66	64	62	60	58	57	55	53	51	49	48	46	44	43	42	40	39	37	36	34	33	32	30	29	28	27	26	24	23	22	21	20	19	18	17	16	15
144	97	95	92	89	87	84	82	80	78	75	73	71	69	67	65	63	61	59	57	55	53	52	50	48	47	45	44	42	41	39	38	36	35	34	32	31	30	29	27	26	25	24	23	22	21	20	19	18	17	16
146	97	95	92	90	87	85	82	80	78	75	73	71	69	67	65	63	61	59	57	56	54	52	50	49	47	45	44	43	41	40	38	37	36	35	33	32	30	29	28	27	26	25	24	22	21	20	19	18	17	17
148	97	95	92	90	87	85	82	80	78	76	73	71	69	67	65	63	61	60	58	56	54	53	51	49	48	46	45	43	42	40	39	38	36	35	34	32	31	30	29	28	26	25	24	23	22	21	20	19	18	17
150	98	95	92	90	87	85	82	80	78	76	74	72	70	68	66	64	62	60	58	57	55	53	51	49	48	46	45	43	42	41	39	38	37	36	34	33	31	30	29	28	27	26	25	24	23	22	21	20	19	18
152	98	95	93	90	88	85	83	81	79	76	74	72	70	68	66	64	62	60	59	57	55	53	52	50	48	47	46	44	42	41	40	39	37	36	35	33	32	31	30	29	28	26	25	24	23	22	21	20	19	19
154	98	95	93	90	88	85	83	81	79	77	74	72	70	68	66	65	63	61	59	57	56	54	52	50	49	47	46	44	43	42	40	39	38	37	35	34	33	32	30	29	28	27	26	25	24	23	22	21	20	19
156	98	95	93	90	88	85	83	81	79	77	74	72	71	69	67	65	63	61	59	58	56	54	53	51	49	48	46	45	43	42	41	40	38	37	36	34	33	32	31	30	29	28	27	25	24	23	23	22	21	20
158	98	95	93	90	88	86	83	81	79	77	75	73	71	69	67	65	63	61	60	58	56	55	53	51	50	48	47	45	44	43	41	40	39	38	36	35	34	33	31	30	29	28	27	26	25	24	23	22	21	20
160	98	95	93	90	88	86	83	81	79	77	75	73	71	69	67	65	64	62	60	58	57	55	53	52	50	49	47	46	44	43	42	41	39	38	37	35	34	33	32	31	30	29	28	27	25	24	24	23	22	21
162	98	95	93	90	88	86	84	82	80	77	75	73	71	69	68	66	64	62	60	59	57	55	54	52	51	49	47	46	45	44	42	41	40	39	37	36	35	34	32	31	30	29	28	27	26	25	24	23	22	22
164	98	95	93	91	88	86	84	82	80	78	75	73	72	70	68	66	64	62	61	59	58	56	54	52	51	49	48	47	45	44	43	41	40	39	38	36	35	34	33	32	31	30	29	28	26	25	25	24	23	22
166	98	95	93	91	88	86	84	82	80	78	76	74	72	70	68	66	65	63	61	59	58	56	54	53	51	50	48	47	45	44	43	42	41	39	38	37	36	35	33	32	31	30	29	28	27	26	25	24	23	23
168	98	95	93	91	88	86	84	82	80	78	76	74	72	70	68	67	65	63	61	60	58	56	55	53	52	50	49	47	46	45	43	42	41	40	39	37	36	35	34	33	32	31	30	29	28	27	26	25	24	23
170	98	95	93	91	89	86	84	82	80	78	76	74	72	70	69	67	65	63	62	60	59	57	55	53	52	51	49	48	47	45	44	43	41	40	39	38	37	35	34	33	32	31	30	29	28	27	26	25	24	24
172	98	95	93	91	89	86	84	82	81	78	76	74	73	71	69	67	66	64	62	60	59	57	55	54	53	51	50	48	47	46	45	43	42	41	39	38	37	36	35	34	33	32	31	30	28	27	26	26	25	24
174	98	95	93	91	89	87	84	83	81	78	76	75	73	71	69	67	66	64	62	61	59	57	56	54	53	51	50	49	47	46	45	43	42	41	40	39	37	36	35	34	33	32	31	30	29	28	27	26	25	24
176	98	96	94	91	89	87	85	83	81	79	77	75	73	71	70	68	66	64	63	61	60	58	56	55	53	52	50	49	48	46	45	44	43	42	40	39	38	37	36	35	34	33	32	31	29	28	27	27	26	25
178	98	96	94	91	89	87	85	83	81	79	77	75	73	72	70	68	66	64	63	61	60	58	56	55	54	52	51	49	48	47	46	44	43	42	41	39	38	37	36	35	34	33	32	31	30	29	28	27	26	25
180	98	96	94	91	89	87	85	83	81	79	77	75	73	72	70	68	67	65	63	62	60	58	57	55	54	52	51	50	48	47	46	45	43	42	41	40	39	38	36	35	35	34	33	31	30	29	28	27	27	26
182	98	96	94	91	89	87	85	83	81	79	77	75	74	72	70	68	67	65	63	62	60	59	57	56	54	53	51	50	49	48	46	45	44	43	42	40	39	38	37	36	35	34	33	32	31	30	29	28	27	26
184	98	96	94	92	89	87	85	83	82	79	77	76	74	72	70	69	67	65	64	62	61	59	57	56	55	53	52	50	49	48	47	45	44	43	42	41	39	38	37	36	35	34	33	32	31	30	29	28	27	27
186	98	96	94	92	90	87	85	83	82	80	78	76	74	72	71	69	67	65	64	62	61	59	58	56	55	53	52	51	49	48	47	45	44	43	42	41	40	39	38	37	36	35	34	33	32	30	30	29	28	27
188	98	96	94	92	90	87	85	84	82	80	78	76	74	73	71	69	68	66	64	63	62	59	58	57	55	54	52	51	50	49	47	46	45	44	43	41	40	39	38	37	36	35	34	33	32	31	30	29	28	27
190	98	96	94	92	90	88	85	84	82	80	78	76	75	73	71	69	68	66	65	63	62	60	58	57	56	54	53	51	50	49	48	46	45	44	43	42	41	39	38	37	36	35	34	33	32	31	30	30	29	28
200	98	96	94	92	90	88	86	84	82	80	79	77	75	74	72	70	69	67	66	64	63	61	60	58	57	55	54	53	52	51	49	48	47	46	45	43	42	41	40	39	38	37	36	35	34	33	32	32	31	30
210	98	96	94	92	90	88	86	85	83	81	79	78	76	75	73	71	70	68	67	65	64	63	61	60	59	57	56	54	53	52	51	50	48	47	46	45	44	43	42	41	40	39	38	37	36	35	34	33	32	32
220	98[a]	96[a]	94[a]	92[a]	91[a]	89[a]	87[a]	85[b]	83	82	80	78	77	75	74	72	71	69	68	66	65	64	62	61	60	58	57	56	54	53	52	51	50	48	47	46	45	44	43	42	41	41	39	39	38	37	36	35	34	33

[a]Possible only at pressures higher than normal atmosphere.

[b]Superheated steam, at normal atmospheric pressure, no air present. At lower humidities air is mixed with the water vapor.

Table 7—EMC table reprinted from the 1974 *Wood Handbook* (FPL 1974)

Temperature dry-bulb, °F.	Relative humidity, percent																			
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	98
30	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.4	13.5	14.9	16.5	18.5	21.0	24.3	26.9
40	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.3	13.5	14.9	16.5	18.5	21.0	24.3	26.9
50	1.4	2.6	3.6	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.3	11.2	12.3	13.4	14.8	16.4	18.4	20.9	24.3	26.9
60	1.3	2.5	3.6	4.6	5.4	6.2	7.0	7.8	8.6	9.4	10.2	11.1	12.1	13.3	14.6	16.2	18.2	20.7	24.1	26.8
70	1.3	2.5	3.5	4.5	5.4	6.2	6.9	7.7	8.5	9.2	10.1	11.0	12.0	13.1	14.4	16.0	17.9	20.5	23.9	26.6
80	1.3	2.4	3.5	4.4	5.3	6.1	6.8	7.6	8.3	9.1	9.9	10.8	11.7	12.9	14.2	15.7	17.7	20.2	23.6	26.3
90	1.2	2.3	3.4	4.3	5.1	5.9	6.7	7.4	8.1	8.9	9.7	10.5	11.5	12.6	13.9	15.4	17.3	19.8	23.3	26.0
100	1.2	2.3	3.3	4.2	5.0	5.8	6.5	7.2	7.9	8.7	9.5	10.3	11.2	12.3	13.6	15.1	17.0	19.5	22.9	25.6
110	1.1	2.2	3.2	4.0	4.9	5.6	6.3	7.0	7.7	8.4	9.2	10.0	11.0	12.0	13.2	14.7	16.6	19.1	22.4	25.2
120	1.1	2.1	3.0	3.9	4.7	5.4	6.1	6.8	7.5	8.2	8.9	9.7	10.6	11.7	12.9	14.4	16.2	18.6	22.0	24.7
130	1.0	2.0	2.9	3.7	4.5	5.2	5.9	6.6	7.2	7.9	8.7	9.4	10.3	11.3	12.5	14.0	15.8	18.2	21.5	24.2
140	.9	1.9	2.8	3.6	4.3	5.0	5.7	6.3	7.0	7.7	8.4	9.1	10.0	11.0	12.1	13.6	15.3	17.7	21.0	23.7
150	.9	1.8	2.6	3.4	4.1	4.8	5.5	6.1	6.7	7.4	8.1	8.8	9.7	10.6	11.8	13.1	14.9	17.2	20.4	23.1
160	.8	1.6	2.4	3.2	3.9	4.6	5.2	5.8	6.4	7.1	7.8	8.5	9.3	10.3	11.4	12.7	14.4	16.7	19.9	22.5
170	.7	1.5	2.3	3.0	3.7	4.3	4.9	5.6	6.2	6.8	7.4	8.2	9.0	9.9	11.0	12.3	14.0	16.2	19.3	21.9
180	.7	1.4	2.1	2.8	3.5	4.1	4.7	5.3	5.9	6.5	7.1	7.8	8.6	9.5	10.5	11.8	13.5	15.7	18.7	21.3
190	.6	1.3	1.9	2.6	3.2	3.8	4.4	5.0	5.5	6.1	6.8	7.5	8.2	9.1	10.1	11.4	13.0	15.1	18.1	20.7
200	.5	1.1	1.7	2.4	3.0	3.5	4.1	4.6	5.2	5.8	6.4	7.1	7.8	8.7	9.7	10.9	12.5	14.6	17.5	20.0
210	.5	1.0	1.6	2.1	2.7	3.2	3.8	4.3	4.9	5.4	6.0	6.7	7.4	8.3	9.2	10.4	12.0	14.0	16.9	19.3

equations, respectively; at 270 °F (132 °C), the values are 2.0% and 0.4%, respectively.

We also note that the 1974 and 1987 editions of the *Wood Handbook* extrapolate EMC values to 98% RH (see also ASTM 2010). The 1999 *Wood Handbook* (FPL 1999b) restricts EMC values to 95% RH (see Table 9). Although the RH range of the original data is not entirely clear, the earliest publications indicate that at most temperatures, data were measured at RH levels no higher than 90% (see Section 2.4).

3.5 Summary of Metamorphosis

The presentation of EMC data in FPL literature evolved as new measurements became available and as practical needs changed. We have highlighted three patterns in this metamorphosis: (1) reduction of data by selective averaging; (2) reuse of figures accompanied by loss of citation of data sources; and (3) recycling of data into new tables and figures, with loss of distinction between values based on measured data and those based on extrapolation or interpolation.

4. Are the Data Valid for Scientific Purposes?

Although this investigative report of the genesis and metamorphosis of the FPL EMC data set is not intended to be a review of the subject of wood–water relationships, it is clear, even from this limited perspective, that the interaction of water with biologically produced materials, such as wood, is a very complex and difficult area of study. What is required to advance the knowledge of wood–water relationships are more creative experiments that expand the response space, that is, tracking moisture content and dimensional changes (and perhaps other pertinent wood properties) as the wood samples are moved about in various temperature and relative humidity state space points. Corresponding mathematical models are needed that not only duplicate the measured phenomena reasonably well but also provide explanatory power.

To this end, the FPL-generated EMC data set will be of limited value with respect to uncovering a deeper understanding of wood–water relationships. Moreover, because of 1) the lack of proper documentation of methodology and procedures, 2) the unsolvable problem of knowing which values are determined from direct observations and which are interpolated, and 3) the absence of definitive measurement error analysis, the FPL data set lacks the certification demanded of the scientific method; i.e., that truth is conditioned by the fundamental idea that sufficient information must be supplied with the results in order for others to duplicate them. In this sense, the FPL data set is strictly unreliable with regard to testing any hypothesis concerning wood–water relationships. That does not take away the value of the data as being a first approximation for average values in the temperature, moisture content, relative humidity, pathway description state space. The data set, unfortunately, must be regarded as unreliable when it comes to being used in scientific studies.

5. Practical Applicability of the Data

EMC data are used for a range of practical applications, some of which include lumber drying, conditioning of wood specimens to desired moisture content prior to testing physical or mechanical properties, and modeling of moisture content of wood members in buildings. The degree of error in EMC values that can be tolerated may differ depending on the application. Variability in EMC values may arise from several sources such as wood chemistry, temperature, and specimen history—including sorption hysteresis as well as irreversible effects such as exposure to high temperature, chemical treatment, or radiation. In the case of lumber drying, the moisture content history of the material is known; it is taken from a high initial MC to a lower MC. In other cases, the moisture content history may not be known, and sorption hysteresis cannot be accounted for.

It is important here to distinguish experimental error in EMC determination from inherent variability in EMC across specimens of a given type of material. This distinction was previously discussed in Section 2.4.3. Apart from a detailed analysis of experimental error, it is not possible to say anything meaningful about inherent variability. Measurement error for gravimetric moisture content determination depends on the balance weighing accuracy and specimen size; on this basis an estimated error of approximately ±0.1% MC is easily achievable. However, additional sources of error in determining EMC may include the criterion used for defining equilibrium, fluctuations in specimen mass near equilibrium resulting from temperature or RH fluctuations, and the method used to determine specimen dry mass. Sources of error for the oven drying method include non-zero RH in the oven and possible evaporation of volatile wood constituents other than water. These sources of error are discussed in detail by Skaar (1988). Error in RH determination may vary widely depending on the means used to control RH, such as saturated salt solutions or mechanically controlled environmental chambers, and the accuracy of the sensor used to measure humidity (as dew point temperature, wet-bulb temperature, or relative humidity).

In this section, we review claims in the FPL literature regarding the applicability of the FPL EMC data set to different wood species, review perspectives on sorption hysteresis in the FPL literature, examine the ability of the data set to represent the best fit to literature data for one species group, and compare the data set with literature values for various species.

5.1 Claims Regarding Wood Species in FPL Literature

Speculation that all wood species have the same EMC–RH relationship started with Dunlap (1919), as mentioned

Table 8—EMC table reprinted from the 1987 *Wood Handbook* (FPL 1987)

Temperature (dry-bulb)	Relative humidity																			
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	98
°F	Percent																			
30	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.4	13.5	14.9	16.5	18.5	21.0	24.3	26.9
40	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.3	13.5	14.9	16.5	18.5	21.0	24.3	26.9
50	1.4	2.6	3.6	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.3	11.2	12.3	13.4	14.8	16.4	18.4	20.9	24.3	26.9
60	1.3	2.5	3.6	4.6	5.4	6.2	7.0	7.8	8.6	9.4	10.2	11.1	12.1	13.3	14.6	16.2	18.2	20.7	24.1	26.8
70	1.3	2.5	3.5	4.5	5.4	6.2	6.9	7.7	8.5	9.2	10.1	11.0	12.0	13.1	14.4	16.0	17.9	20.5	23.9	26.6
80	1.3	2.4	3.5	4.4	5.3	6.1	6.8	7.6	8.3	9.1	9.9	10.8	11.7	12.9	14.2	15.7	17.7	20.2	23.6	26.3
90	1.2	2.3	3.4	4.3	5.1	5.9	6.7	7.4	8.1	8.9	9.7	10.5	11.5	12.6	13.9	15.4	17.3	19.8	23.3	26.0
100	1.2	2.3	3.3	4.2	5.0	5.8	6.5	7.2	7.9	8.7	9.5	10.3	11.2	12.3	13.6	15.1	17.0	19.5	22.9	25.6
110	1.1	2.2	3.2	4.0	4.9	5.6	6.3	7.0	7.7	8.4	9.2	10.0	11.0	12.0	13.2	14.7	16.6	19.1	22.4	25.2
120	1.1	2.1	3.0	3.9	4.7	5.4	6.1	6.8	7.5	8.2	8.9	9.7	10.6	11.7	12.9	14.4	16.2	18.6	22.0	24.7
130	1.0	2.0	2.9	3.7	4.5	5.2	5.9	6.6	7.2	7.9	8.7	9.4	10.3	11.3	12.5	14.0	15.8	18.2	21.5	24.2
140	.9	1.9	2.8	3.6	4.3	5.0	5.7	6.3	7.0	7.7	8.4	9.1	10.0	11.0	12.1	13.6	15.3	17.7	21.0	23.7
150	.9	1.8	2.6	3.4	4.1	4.8	5.5	6.1	6.7	7.4	8.1	8.8	9.7	10.6	11.8	13.1	14.9	17.2	20.4	23.1
160	.8	1.6	2.4	3.2	3.9	4.6	5.2	5.8	6.4	7.1	7.8	8.5	9.3	10.3	11.4	12.7	14.4	16.7	19.9	22.5
170	.7	1.5	2.3	3.0	3.7	4.3	4.9	5.6	6.2	6.8	7.4	8.2	9.0	9.9	11.0	12.3	14.0	16.2	19.3	21.9
180	.7	1.4	2.1	2.8	3.5	4.1	4.7	5.3	5.9	6.5	7.1	7.8	8.6	9.5	10.5	11.8	13.5	15.7	18.7	21.3
190	.6	1.3	1.9	2.6	3.2	3.8	4.4	5.0	5.5	6.1	6.8	7.5	8.2	9.1	10.1	11.4	13.0	15.1	18.1	20.7
200	.5	1.1	1.7	2.4	3.0	3.5	4.1	4.6	5.2	5.8	6.4	7.1	7.8	8.7	9.7	10.9	12.5	14.6	17.5	20.0
210	.5	1.0	1.6	2.1	2.7	3.2	3.8	4.3	4.9	5.4	6.0	6.7	7.4	8.3	9.2	10.4	12.0	14.0	16.9	19.3
220	.4	.9	1.4	1.9	2.4	2.9	3.4	3.9	4.5	5.0	5.6	6.3	7.0	7.8	8.8	9.9	*	*	*	*
230	.3	.8	1.2	1.6	2.1	2.6	3.1	3.6	4.2	4.7	5.3	6.0	6.7	*	*	*	*	*	*	*
240	.3	.6	.9	1.3	1.7	2.1	2.6	3.1	3.5	4.1	4.6	*	*	*	*	*	*	*	*	*
250	.2	.4	.7	1.0	1.3	1.7	2.1	2.5	2.9	*	*	*	*	*	*	*	*	*	*	*
260	.2	.3	.5	.7	.9	1.1	1.4	*	*	*	*	*	*	*	*	*	*	*	*	*
270	.1	.1	.2	.3	.4	.4	*	*	*	*	*	*	*	*	*	*	*	*	*	*

[1] Asterisks indicate conditions not possible at atmospheric pressure.

Table 9—EMC table reprinted from the 1999 *Wood Handbook* (FPL 1999b)

Temperature (°C	(°F))	Moisture content (%) at various relative humidity values 5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
−1.1	(30)	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.4	13.5	14.9	16.5	18.5	21.0	24.3
4.4	(40)	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.3	13.5	14.9	16.5	18.5	21.0	24.3
10.0	(50)	1.4	2.6	3.6	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.3	11.2	12.3	13.4	14.8	16.4	18.4	20.9	24.3
15.6	(60)	1.3	2.5	3.6	4.6	5.4	6.2	7.0	7.8	8.6	9.4	10.2	11.1	12.1	13.3	14.6	16.2	18.2	20.7	24.1
21.1	(70)	1.3	2.5	3.5	4.5	5.4	6.2	6.9	7.7	8.5	9.2	10.1	11.0	12.0	13.1	14.4	16.0	17.9	20.5	23.9
26.7	(80)	1.3	2.4	3.5	4.4	5.3	6.1	6.8	7.6	8.3	9.1	9.9	10.8	11.7	12.9	14.2	15.7	17.7	20.2	23.6
32.2	(90)	1.2	2.3	3.4	4.3	5.1	5.9	6.7	7.4	8.1	8.9	9.7	10.5	11.5	12.6	13.9	15.4	17.3	19.8	23.3
37.8	(100)	1.2	2.3	3.3	4.2	5.0	5.8	6.5	7.2	7.9	8.7	9.5	10.3	11.2	12.3	13.6	15.1	17.0	19.5	22.9
43.3	(110)	1.1	2.2	3.2	4.0	4.9	5.6	6.3	7.0	7.7	8.4	9.2	10.0	11.0	12.0	13.2	14.7	16.6	19.1	22.4
48.9	(120)	1.1	2.1	3.0	3.9	4.7	5.4	6.1	6.8	7.5	8.2	8.9	9.7	10.6	11.7	12.9	14.4	16.2	18.6	22.0
54.4	(130)	1.0	2.0	2.9	3.7	4.5	5.2	5.9	6.6	7.2	7.9	8.7	9.4	10.3	11.3	12.5	14.0	15.8	18.2	21.5
60.0	(140)	0.9	1.9	2.8	3.6	4.3	5.0	5.7	6.3	7.0	7.7	8.4	9.1	10.0	11.0	12.1	13.6	15.3	17.7	21.0
65.6	(150)	0.9	1.8	2.6	3.4	4.1	4.8	5.5	6.1	6.7	7.4	8.1	8.8	9.7	10.6	11.8	13.1	14.9	17.2	20.4
71.1	(160)	0.8	1.6	2.4	3.2	3.9	4.6	5.2	5.8	6.4	7.1	7.8	8.5	9.3	10.3	11.4	12.7	14.4	16.7	19.9
76.7	(170)	0.7	1.5	2.3	3.0	3.7	4.3	4.9	5.6	6.2	6.8	7.4	8.2	9.0	9.9	11.0	12.3	14.0	16.2	19.3
82.2	(180)	0.7	1.4	2.1	2.8	3.5	4.1	4.7	5.3	5.9	6.5	7.1	7.8	8.6	9.5	10.5	11.8	13.5	15.7	18.7
87.8	(190)	0.6	1.3	1.9	2.6	3.2	3.8	4.4	5.0	5.5	6.1	6.8	7.5	8.2	9.1	10.1	11.4	13.0	15.1	18.1
93.3	(200)	0.5	1.1	1.7	2.4	3.0	3.5	4.1	4.6	5.2	5.8	6.4	7.1	7.8	8.7	9.7	10.9	12.5	14.6	17.5
98.9	(210)	0.5	1.0	1.6	2.1	2.7	3.2	3.8	4.3	4.9	5.4	6.0	6.7	7.4	8.3	9.2	10.4	12.0	14.0	16.9
104.4	(220)	0.4	0.9	1.4	1.9	2.4	2.9	3.4	3.9	4.5	5.0	5.6	6.3	7.0	7.8	8.8	9.9			
110.0	(230)	0.3	0.8	1.2	1.6	2.1	2.6	3.1	3.6	4.2	4.7	5.3	6.0	6.7						
115.6	(240)	0.3	0.6	0.9	1.3	1.7	2.1	2.6	3.1	3.5	4.1	4.6								
121.1	(250)	0.2	0.4	0.7	1.0	1.3	1.7	2.1	2.5	2.9										
126.7	(260)	0.2	0.3	0.5	0.7	0.9	1.1	1.4												
132.2	(270)	0.1	0.1	0.2	0.3	0.4	0.4													

previously (Section 2.2.2): "It is interesting to note that there is comparatively little variation in the values obtained for the individual species tested and in a general way it is thought that the average curves would apply practically to any wood."

Publications in the 1920s generally included figures similar to Figure 9a and echoed Dunlap's speculation. Koehler (1924), for example, appealed to wood chemistry for an explanation: "It is interesting to note that this relation is approximately the same for all woods. This might be expected when one considers that the substance of which wood is made is practically the same for all species." On the other hand, might it not be expected that differences in wood chemistry among species could lead to variation in hygroscopicity? Later investigations would make this apparent, as discussed below.

The tendency to speculate regarding species continued throughout FPL history. We note a few further examples.

- Koehler and Thelen (1926): "Although these curves are based on only a very limited number of species of wood, the tests showed that the different species were remarkably similar their moisture-humidity relations. It is believed that these curves are reasonably accurate for almost all woods."
- Loughborough and Rietz (1932): "Other species might show some slight variations, but the general shape of the curves would be the same for all species. For practical engineering purposes these values can be considered about the same for all species of wood."
- FPL (1941b): "These curves were constructed from data obtained on Sitka spruce, but are in general applicable to all species."
- *Wood Handbook* (FPL 1955): "Although different species exhibit some differences in their reactions to relative humidity, for practical purposes [Table 5] applies to the wood of any species." Later editions of the *Wood Handbook* essentially made the same claim.

Nowhere in the FPL literature do we find a suitable definition of general or practical applicability. Non-quantitative, blanket statements regarding accuracy of the data for any species, in conjunction with tabulated EMC values at a high level of precision (to 0.1% MC in Table 5), could be misleading. We discuss this matter further in following sections.

5.2 Perspectives on Sorption Hysteresis in FPL Literature

Koehler and Thelen (1926) present the concept of hysteresis for the first time in FPL literature (to the best of our knowledge) in regard to Figure 9a:

> "The upper curve in the figure shows the moisture content which wood will attain when subjected to different humidities at ordinary room temperature (70°F.). At a humidity of 68 per cent, for instance, wood, if wet, will dry out to approximately 13 per cent; or if it is very dry, it will absorb moisture to about 13 per cent of its weight. In fact, the dry wood will not attain quite so high a moisture content as 13 per cent, and the green wood will not become quite so dry. The curve represents the average moisture content of wet wood losing moisture and dry wood gaining moisture at certain humidities."

Hawley (1931) briefly comments, "like pure cellulosic fibers, wood has a hysteresis effect, with a difference in the equilibrium values when absorbing and when giving off moisture," citing literature from outside FPL.

The most complete discussion of hysteresis in FPL literature is given by Stamm and Loughborough (1935), as discussed in Section 2.4.2. Figure 8 compares data for the normal adsorption and desorption curves and the intermediate "oscillating vapor pressure-desorption curve." Stamm and Loughborough (1935) also state, "All the available drying data obtained under industrial control conditions on other softwood species also gave curves which fell within this hysteresis loop."

Subsequent FPL literature tended to remain silent regarding hysteresis with a few exceptions (e.g., Simpson 1973, Simpson and Rosen 1981). For example, the *Wood Handbook* did not discuss sorption hysteresis in its 1935, 1940, 1955, 1974, and 1987 editions; hysteresis was first mentioned in the 1999 edition. From a practical perspective, hysteresis is not terribly important in wood drying; hence no need to mention it. The 1999 *Wood Handbook* (FPL 1999b) takes a more general view of the practical utility of data obtained under conditions of oscillating vapor pressure desorption, saying the data represent "a suitable and practical compromise for use when the direction of sorption is not always known." In the next section, we investigate this claim using literature data for the southern yellow pine (SYP) species group.

5.3 Comparison with Literature Data for Southern Yellow Pine

Here we attempt to quantify the notion of practical applicability based on statistical analysis of literature EMC data. We selected data for species within the SYP group because numerous measurements have been published over many years. Figure 17 plots data from a variety of sources: Dunlap (1919), Nearn (1955), Higgins (1957), Choong (1969), Lee and Biblis (1976), Richards et al. (1992), Cao and Kamdem (2004), and Zelinka and Glass (2010). All of the measurements were taken between temperatures of 70 °F (21 °C) and 90 °F (32 °C). The pooled data set includes adsorption and desorption measurements. In addition to sorption hysteresis, variability in EMC values could be expected because the publications from which the data were selected span a broad range in time and geographic location. An analysis of experimental error in each of the data sources is beyond the scope of this report. Figure 17 shows three-parameter parabolic fits for desorption alone (63 data points), for adsorption alone (62 data points), and for all data points together ("global fit"). The fitting equations are of the same form as Equation (1). Additionally, the curve of Simpson (1973) representing the FPL data at 80 °F (27 °C) is shown in Figure 17; this curve does in fact fit the measured data very well. The curve for the four-parameter equation from Simpson (1973) is somewhat lower than the best fit curve for the 3-parameter equation at low RH levels, while the two curves are nearly identical above 40% RH.

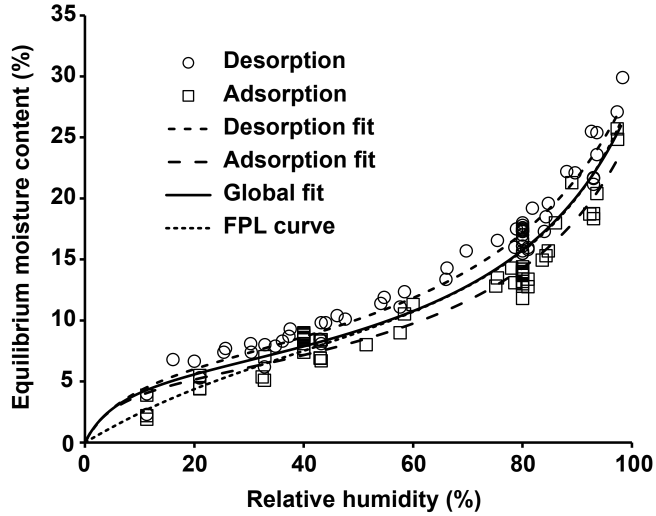

Figure 17. EMC data from the literature for the southern yellow pine species group near room temperature with curve fits (see text). FPL curve is from Simpson (1973).

Table 10 gives statistics related to the three-parameter fits shown in Figure 17. The fit to all data points has a root-mean-square error of 1.7% MC. This error decreases to approximately 1% MC when the adsorption data and desorption data are fit separately. The RMSE for the FPL curve and all the data points (not shown in the table) is 1.8% MC, only slightly higher than that for the three-parameter best fit.

This comparison highlights several important points. First, it lends support to the previously mentioned claim that the data represent "a suitable and practical compromise for use when the direction of sorption is not always known" (FPL 1999). The FPL curve falls nearly in the middle of all the SYP data points. Second, it illustrates the obvious point

Table 10—Statistics related to fitting literature EMC data for southern yellow pine

		Error (% MC)		
Data set	Measurements	Root-mean-square error	Mean absolute error	Maximum absolute error
All data	125	1.7	1.4	4.0
Desorption	63	1.1	0.9	2.4
Adsorption	62	1.2	1.0	3.4

that sorption hysteresis has a substantial effect. Third, it shows that in addition to sorption hysteresis, there are other sources of variability within a species group. For this reason, the FPL data do a good job predicting the average EMC of the group but do not reliably predict the EMC value of every specimen. Finally, use of the FPL EMC values at the reported level of precision (to 0.1% MC in Table 5) would be misguided. Although this level of precision is useful for showing trends in EMC with RH and temperature, the assumption that this level of precision is meaningful not only neglects the effect of sorption hysteresis but also far exceeds the precision required for most practical purposes.

5.4 Comparison with Literature Data for Different Wood Species

Research conducted outside FPL in the 1950s to 1970s looked at differences in EMC between wood species near room temperature (Nearn 1955; Higgins 1957; Spalt 1958; Hedlin 1967; Wangaard and Granados 1967; Choong and Manwiller 1976). These studies indicate that EMC differences between species generally are minor at low and moderate levels of relative humidity but become considerable at high RH levels. Species with high extractive content generally show lower EMC at high RH levels than species with low extractive content.

As a simple illustrative comparison of the FPL curve to literature EMC data of different species, we selected data from one source—Spalt (1958)—because it includes 16 different species. Spalt measured 6 or 7 data points each for adsorption and desorption (12–14 data points for each species) at 32 °C (90 °F). He reported curve fit parameters (using a three-parameter parabolic equation, similar form to that given above in Eq. (1)) for the adsorption and desorption data for each species. Figure 18 shows the 32 curves (adsorption and desorption curves for each of 16 species) together with the FPL curve at the same temperature. Qualitatively, the FPL curve appears to be a suitable average. Table 11 lists the differences between Spalt's adsorption and desorption curves and the FPL curve for each species, at RH levels of 65%, 80%, and 95%. In general, differences increase with increasing relative humidity. At 65% RH, the values from FPL and from Spalt differ by as much as 3.2% MC; at 80%, by 3.4% MC; and at 95% RH, by 5.9% MC. Table 11 also shows that the RMSE for the FPL curve

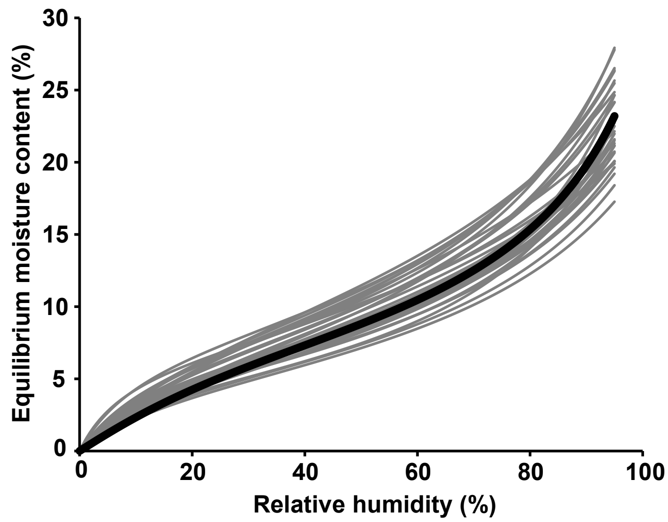

Figure 18. EMC adsorption and desorption curves for 16 species from Spalt (1958), shown in gray, and FPL data shown as heavy black curve (Simpson 1973).

and all 16 species increases with increasing RH in adsorption, desorption, and the average of the two.

In conclusion, the FPL EMC data provide a suitable average for many species for practical purposes, but past FPL literature has overemphasized the similarities and minimized the differences in EMC values between species. Research showing between-species differences in EMC at high RH levels has not been acknowledged in the *Wood Handbook*; we recommend that future editions of the *Wood Handbook* address this issue. We also stress that the precision with which EMC values have been given in past FPL literature such as Table 5 (to 0.1% MC) far exceeds the precision required for most practical purposes.

6. Mathematical Formulations for Practical Use

Given the magnitude of the variability in EMC values resulting from sorption hysteresis and from differences in wood chemistry, we question the need for an equation as complicated and precise as Equation (2). For practical purposes, might a simpler empirical equation with fewer parameters be sufficient?

Table 11—Comparison of FPL EMC data with literature values for various species

	Difference in EMC (% MC) between values of Spalt (1958) and FPL								
	Adsorption			Desorption			Average of adsorption and desorption		
Species	65% RH	80% RH	95% RH	65% RH	80% RH	95% RH	65% RH	80% RH	95% RH
Picea glauca	–0.1	–0.2	–1.6	2.9	3.4	3.2	1.4	1.6	0.8
Pinus monticola	–0.7	–0.9	–2.5	1.6	1.8	1.0	0.5	0.5	–0.8
Pinus ponderosa	–0.6	–0.7	–2.1	1.6	1.8	0.9	0.5	0.5	–0.6
Tsuga heterophylla	0.4	0.4	–0.5	2.9	3.3	2.3	1.6	1.8	0.9
Pseudotsuga menziesii	–0.2	–0.1	–0.7	2.7	3.3	3.1	1.3	1.6	1.2
Thuja plicata	–1.1	–1.7	–4.0	1.3	0.9	–1.9	0.1	–0.4	–2.9
Sequoia sempervirens	–1.1	–1.6	–3.6	1.3	0.6	–2.5	0.1	–0.5	–3.0
Pinus caribaea	–1.1	–1.3	–2.0	1.7	2.0	1.4	0.3	0.4	–0.3
Tilia americana	–1.5	–1.3	–0.3	1.5	2.2	2.5	0.0	0.5	1.1
Ceiba pentandra	–0.3	0.2	1.5	2.1	3.0	4.7	0.9	1.6	3.1
Jacaranda copaia	–0.4	–0.5	–1.2	2.5	3.4	4.6	1.0	1.5	1.7
Dicorynia paraensis	–0.2	–0.4	–1.7	2.7	3.4	3.3	1.2	1.5	0.8
Swietenia sp.	–0.6	–1.1	–3.1	2.2	1.8	–1.1	0.8	0.4	–2.1
Tectona grandis	–1.8	–2.5	–4.8	0.5	–0.1	–3.2	–0.6	–1.3	–4.0
Calophyllum brasiliense	–0.2	–0.8	–3.1	3.2	3.4	1.7	1.5	1.3	–0.7
Licaria cayennensis	–2.2	–3.1	–5.9	0.9	0.2	–3.3	–0.6	–1.4	–4.6
RMSE, all species	1.0	1.3	2.9	2.1	2.5	2.8	0.9	1.2	2.2

As discussed above (Section 3.4), the two-hydrate HH equation was fit to the FPL EMC values by Simpson (1973). When temperature dependence is included, the model effectively changes from one with four fitting parameters to one with 12 fitting parameters, and hereafter we refer to this model as the HH12 model. While the HH12 model fits the data well, it is cumbersome to use and nearly impossible to invert.

If the HH12 model parameters indeed had physical significance relevant to the wood–water system, then giving preference to this model might be justified. The connection between model parameters and physical reality, however, is weak. One thermodynamic property that is often incorporated into models for vapor sorption is the differential heat of adsorption. Simpson (1980) showed that many different sorption models (including the one-hydrate and two-hydrate HH models) predict values for the differential heat of adsorption that drastically differ from experimental values. Furthermore, two other models that have been applied to wood—the Dent (1977) isotherm and the Guggeheim-Anderson-deBoer (GAB) isotherm (Anderson 1946)—are mathematically equivalent to the one-hydrate HH model; they can all be reduced to the form $h/m = Ah^2 + Bh + C$, where h is relative humidity and m is EMC, the same generic parabolic model used previously (Eq. (1)). However, these three isotherms were derived from different starting points and ascribe different physical meanings to the parameters. Although the Dent, GAB, and HH isotherms provide excellent fits to wood EMC data, the physical pictures associated with these models cannot all be true, and therefore these models should not be used for purposes other than curve fitting. Because the HH12 model does not give additional physical insight, it is worthwhile examining whether a simpler equation is adequate for curve fitting.

Avramidis (1989) previously used a subset of the FPL EMC data to evaluate four sorption models that express moisture content as a function of both relative humidity and temperature. These models had two to four fitting parameters. Curve fitting was limited to EMC values at 70, 95, 110, 125, and 160 °F (21, 35, 43, 52, and 71 °C) from the 1955 *Wood Handbook* (FPL 1955). Avramidis found that the model of Zuritz et al. (1979) gave the best fit to EMC data in this temperature range based on RMSE. This model is actually a modification of the equation of Henderson (1952) with 4 parameters. We refer to the model as the 4-parameter Henderson (or H4) model hereafter to highlight the similarity.

Here we performed a curve-fitting analysis using a wider range of models over the complete range of temperatures given in Table 5. We considered models that have from two to six fitting parameters, as well as the HH12 model for reference. Lewicki (2009) recently reviewed 31 sorption models that have been applied to solid food substances and grouped them into those that were theoretically derived, those that were empirical, and those that were hybrids (or semi-empirical). From this list of 31, we chose six models to compare to the HH12 Equation (Table 12). We gave preference to simple, empirical models that are invertible, although we did include a theoretically derived model (GAB); however, we emphasize that in these cases, the model parameters should not be interpreted as having physical meaning.

Table 12—Equations used for fitting FPL EMC data and related statistics[a]

Abbreviation[b]	References	Equation[c]	R^2	RMSE
B2	Bradley 1936	$m = A\ln\left[BT\ln(h)\right]$	0.934	0.0125
H2	Henderson 1952	$m = \left[\dfrac{\ln(1-h)}{AT}\right]^B$	0.952	0.0178
CM3	Oswin 1946; Chen and Morey 1989	$m = (A + BT)\left(\dfrac{h}{1-h}\right)^C$	0.979	0.0066
CP3	Chung and Pfost 1967; Pfost et al. 1976	$m = A + B\ln\left[(C - T)\ln(h)\right]$	0.977	0.0070
H4[d]	Henderson 1952; Zuritz et al. 1979	$m = \left[AT(1 - T/T_c)^B \ln(1-h)\right]^{CT^D}$	0.9998	0.0034
GAB6	Anderson 1946; Lewicki 2009	$m = \dfrac{ABCh\exp\left[(D+E+F)/T\right]}{\left[1 - Ch\exp(F/T)\right]\left[1 + \left[B\exp(E/T) - 1\right]Ch\exp(F/T)\right]}$	0.9996	0.0041
HH12	Hailwood and Horrobin 1946; Simpson 1973	See Equations (2) and (3)	0.9999	0.0013

[a] R^2 is coefficient of determination; RMSE is root-mean-square error in fractional moisture content.

[b] Abbreviations consist of letters referring to names followed by the number of adjustable parameters.

[c] For ease of illustration, the fractional moisture content (m) is written as a function of fractional relative humidity (h) and absolute temperature (T). Each adjustable parameter is given a capital letter starting with "A"; parameters may be positive or negative.

[d] T_c is the critical temperature of water (1164.8 Rankine or 647.1 Kelvin).

We used the complete table of dry-bulb temperature, relative humidity, and EMC values as presented in Table 5 (identical to the 1955 *Wood Handbook*).[6] We used decimal values for relative humidity and moisture content, and we converted Fahrenheit temperature to absolute (Rankine) temperature prior to fitting. The parameters for each model were optimized using the surface-fitting toolbox in Matlab®. For each model, we recorded RMSE and coefficient of determination (R^2) and plotted residuals in 3-dimensional space. Our intention was not to find the model with the best statistics; rather, our goal was to identify whether models simpler than HH12 could fit the data sufficiently well, meaning that they do not exhibit trends in the residuals (i.e., larger errors at extreme temperatures or moisture contents).

As shown in Table 5, the number of RH/EMC values at a given dry-bulb temperature increases with increasing temperature (up to 115 °F, above which the number of values is constant). For the purpose of curve fitting, this effectively gives more weight to values at high temperatures. We therefore compared two fitting methods: 1) the RH/EMC values were not weighted (they were taken directly from Table 5); and 2) the RH/EMC values at each temperature were weighted by the reciprocal of the number of values at that temperature. Across all models, these two methods gave fitting parameters that were largely the same (they differed by less than 10%), and the residuals were visually similar in both cases. We suggest that weighting the data at each temperature is unnecessary not only because it makes little difference but also because it implies we know more about the data than we actually do. We have argued previously (Section 3.4) that the evidence is inconclusive regarding whether the values in the table represent measured data or were generated by interpolation and extrapolation, based on measured data points that are unknown.

The residuals from four of the seven models tested are plotted in Figure 19, and RMSE and R^2 values are listed in Table 12. While the coefficients of determination for all of the models are high, the two- and three-parameter models contain noticeable trends in the residuals. The H4 model gives better statistics than the GAB6 model, even though the latter has more parameters. The H4 model shows minor trends in the residuals: they are consistently negative at lower temperatures and at high temperatures in conjunction with moderate RH levels, and consistently positive at moderate temperatures. The HH12 model gives the best statistics and shows the most random distribution of residuals.

In summary, although the HH12 equation provides an excellent fit to the FPL EMC data, physical meaning should not be assigned to its parameters. Many different equations are able to adequately fit the historic FPL temperature/RH/EMC values with fewer than 12 parameters. The H4 model fits the data well (nearly as well as the HH12 model), shows only minor trends in the residuals, and is easily invertible. For these reasons, the H4 model should work well in practical applications. This model with its parameters is given below.

[6]Table 38 in the 1955 *Wood Handbook* (FPL 1955) contains a typographical error: the RH value given as "50" for a dry-bulb temperature of 40 °F and a wet-bulb depression of 5 °F should actually be "60".

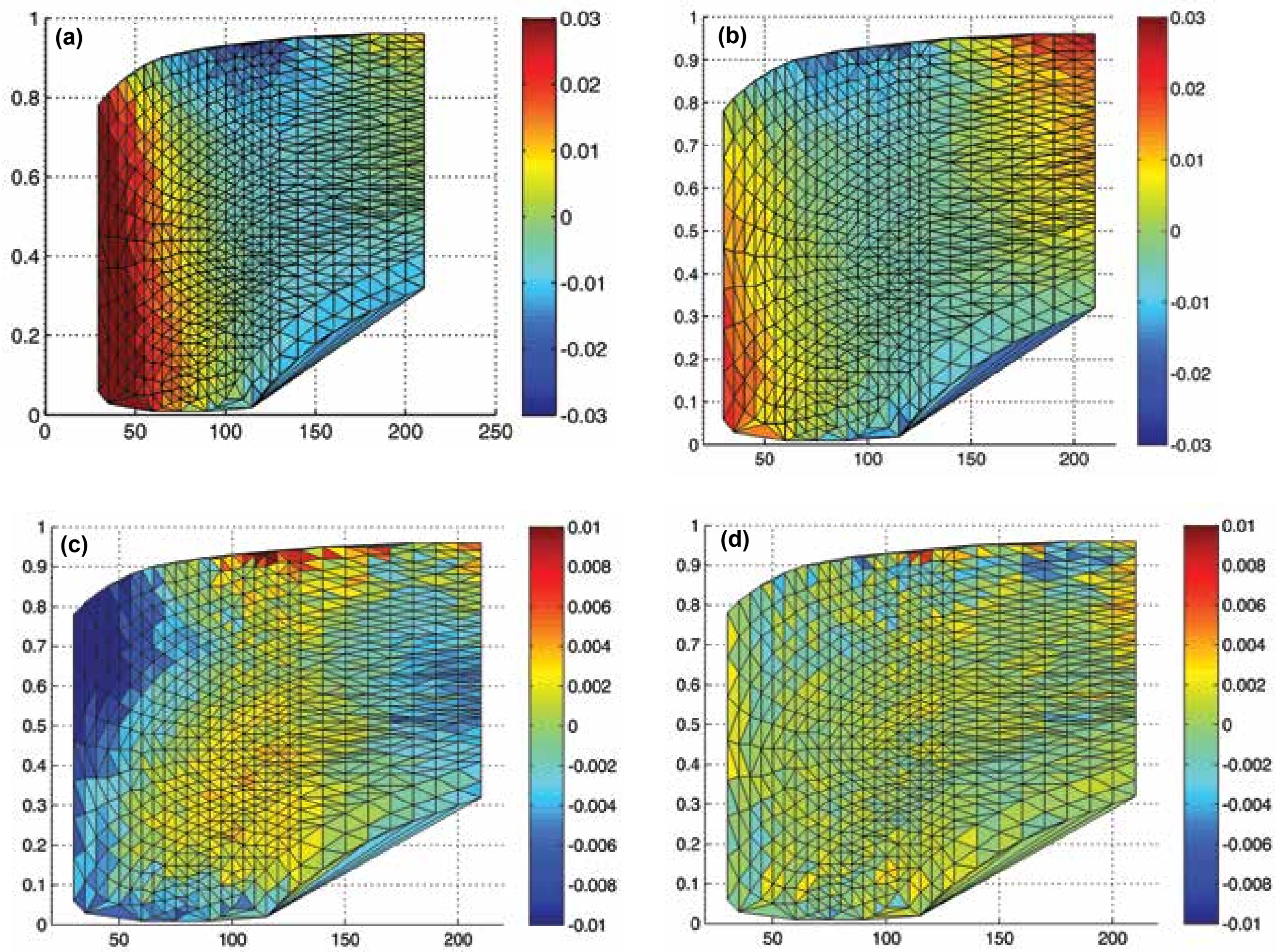

Figure 19. Residuals (in fractional moisture content) as a function of temperature (°F, *x*-axis) and fractional relative humidity (*y*-axis) for four models (see Table 12): B2 (a), CP3 (b), H4 (c), and HH12 (d). Note the difference in scale between (a)-(b) and (c)-(d).

For T in degrees Rankine ([°R] = [°F] + 459.67):

$$m = \left[-0.000340T \left(1 - \frac{T}{1164.8} \right)^{2.43} \ln(1-h) \right]^{0.0448T^{0.430}} \qquad \text{(5a)}$$

For T in kelvins ([K] = [°C] + 273.15):

$$m = \left[-0.000612T \left(1 - \frac{T}{647.1} \right)^{2.43} \ln(1-h) \right]^{0.0577T^{0.430}} \qquad \text{(5b)}$$

where h is relative humidity (decimal) and m is equilibrium moisture content (decimal).

The inverted form of this model is given below. For T in degrees Rankine ([°R] = [°F] + 459.67):

$$h = 1 - \exp\left[\frac{-2940}{T} \left(1 - \frac{T}{1164.8} \right)^{-2.43} m^{22.3T^{-0.430}} \right] \qquad \text{(6a)}$$

For T in kelvins ([K] = [°C] + 273.15)

$$h = 1 - \exp\left[\frac{-1630}{T} \left(1 - \frac{T}{647.1} \right)^{-2.43} m^{17.3T^{-0.430}} \right] \qquad \text{(6b)}$$

On the basis of this analysis, we suggest that future editions of the *Wood Handbook* give the H4 equation in addition to the HH12 equation. We further suggest that future editions of the *Wood Handbook* provide caveats regarding the table of temperature/RH/EMC values. As discussed previously (Section 5), the precision with which EMC values have been given in Tables 7–9 (to 0.1% MC) is potentially misleading: it conceals the variability arising from hysteresis and other sources, and it far exceeds the precision required for most practical purposes.

7. Conclusions

Our primary aim in this report was to investigate whether the methods by which the FPL EMC data were obtained are sufficiently documented to allow the data to be used for scientific purposes such as thermodynamic analysis and evaluation and validation of physical models. In addition we have raised several questions related to practical application of the data.

The FPL-generated EMC data set is unreliable with respect to uncovering a deeper understanding of wood–water relationships for three reasons: lack of proper documentation of methodology; the unsolvable problem of knowing which values are determined from direct observations and which are interpolated; and the absence of definitive measurement error analysis.

Despite these problems, we affirm that the data are useful for practical applications such as lumber drying, conditioning of wood specimens prior to testing physical or mechanical properties, and modeling of moisture content of wood members in buildings. Comparison of the FPL data set with values from the broader literature confirms that the FPL data represent "a suitable and practical compromise for use when the direction of sorption is not always known" (FPL 1999b). However, assuming that the reported level of precision (to 0.1% MC) is meaningful would be misguided. Although this level of precision is useful for showing trends in EMC with RH and temperature, the variability in EMC stemming from sorption hysteresis and differences between species is considerably larger.

Although the HH12 equation provides an excellent fit to the FPL EMC data set, physical meaning should not be assigned to its parameters. Many different equations are able to fit the historic FPL EMC/temperature/RH values adequately for practical purposes.

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