Designation: D4444 – 13

# Standard Test Method for Laboratory Standardization and Calibration of Hand-Held Moisture Meters[1]

This standard is issued under the fixed designation D4444; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

*This standard has been approved for use by agencies of the U.S. Department of Defense.*

## 1. Scope

1.1 This test method applies to the measurement of moisture content (MC) of solid wood products, including those containing additives (that is, chemicals or adhesives) for laboratory standardization and calibration of hand-held moisture meters

1.2 This test method makes no distinction between meter measurement technologies for standardization and calibration requirements. Provision is made for test specimen size to accommodate specific meters. Appendix X1 provides an explanatory discussion and history corresponding to the mandatory sections. Fundamental measurement technologies are described in Appendix X2 when available.

1.2.1 Meters employing differing technologies may not provide equivalent readings under the same conditions. When this test method has been applied, it is assumed that the referenced meter is acceptable unless otherwise specified. Meters shall be calibrated with respect to MC by direct measurement as determined by Test Methods D4442.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1990 Practice for Establishing Allowable Properties for Visually-Graded Dimension Lumber from In-Grade Tests of Full-Size Specimens

D2915 Practice for Sampling and Data-Analysis for Structural Wood and Wood-Based Products

D4442 Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials

D4933 Guide for Moisture Conditioning of Wood and Wood-Based Materials

D5536 Practice for Sampling Forest Trees for Determination of Clear Wood Properties

D7438 Practice for Field Calibration and Application of Hand-Held Moisture Meters

2.2 *Other ASTM Sources:*

ASTM Standards on Precision and Bias for Various Applications, 1992

## 3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *conductance meters*—Conductance meters are those that measure predominantly ionic conductance between points of applied voltage, usually direct current. Direct-current conductance meters are commonly referred to as “resistance” meters. Most commercial conductance meters are high-input impedance (about $10^{12}$ Ω), wide-range ($10^4$ to $10^{12}$ Ω) ohmmeters.

3.1.2 *capacitive-admittance meters*—Capacitive-admittance meters transmit electromagnetic wave energy into the wood to detect the influence of moisture in the wood on these waves as an estimate of MC. Wave energy is most often in the radiofrequency range; hand-held meters commonly are placed directly on the wood surface.

## 4. Significance and Use

4.1 Hand-held meters provide a rapid means of sampling MC of wood-based materials during and after processing to maintain quality assurance and compliance with standards. These measurements are influenced by actual MC, a number of other wood variables, environmental conditions, geometry of the measuring probe circuitry, and design of the meter. The maximum accuracy can only be obtained by an awareness of the effect of each parameter on the meter output and correction of readings as specified by this test method.

4.1.1 This test method employs controlled conditions and straight-grain, clear wood specimens to provide measurements

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[1] This test method is under the jurisdiction of ASTM Committee D07 on Wood and is the direct responsibility of Subcommittee D07.01 on Fundamental Test Methods and Properties.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard’s Document Summary page on the ASTM website.

that are reproducible in a laboratory. The controlled conditions prevent moisture and temperature gradients in the test specimen.

4.1.2 In laboratory calibration, the reference direct moisture measurements (for example, Test Methods D4442) shall be made only in the area of direct measurement of the meter. This minimizes error associated with sampling of differing areas of measurement between this test method and that of the reference (Test Methods D4442).

4.2 Most uses of hand-held moisture meters employ correlative (predictive) relationships between the meter reading and wood areas or volumes that exceed that of the direct meter measurement (for example, larger specimens, pieces of lumber, or lots). These correlative relationships are beyond the scope of this test method. (See Practice D7438.)

## 5. Standardization

5.1 *General*—Standardization provides a measured relationship to a standard reference material that can be used to ensure that a meter is operating properly. Standardization shall be performed to establish the integrity of the meter and electrode. Standardization shall be done before calibration and use. If alternate electrodes can be used with a meter, standardization shall be done for all electrode types and alternate assemblies.

5.2 Standardization shall be based, where feasible, on the direct measurement region of the meter as supplied by the meter manufacturer. If not supplied by the manufacturer, the area of direct measurement shall be determined by test.

5.2.1 If the manufacturer recommends an area, a method, or a standard specimen for standardization that does not reflect the entire direct measurement area of the meter, this shall be noted as the manufacturer recommendation.

5.2.2 The meter circuit and electrode shall be tested with external reference material to verify the precision and bias in the meter response range of anticipated use. The meter shall be evaluated over the range of environmental conditions recommended by the manufacturer. The sensitivity of this standardization procedure to temperature of the meter shall be part of the evaluation.

5.2.2.1 The sensitivity of the standardization reference material to the range of environmental conditions in 5.2.2 shall be evaluated.

5.2.3 *Report*—The report shall indicate (in the meter manual, on the meter or meter scale, or on the supplied reference standard) the meter model, and the electrodes for which the standardization is valid. The sensitivity of the meter, the electrode assembly and the reference material, as evaluated in 5.2.2.1, shall be reported.

5.2.3.1 The manufacturer's recommendation on frequency of standardization shall be included in the report.

## 6. Calibration

6.1 *General*—Calibration of a meter and the electrode shall establish reference data to adjust meter response for species, ambient conditions, and specimen variables, such as size and density. Meter and electrode assemblies shall be standardized in accordance with Section 5 prior to calibration.

6.2 *Calibration:*

6.2.1 *Area of Measurement*—Calibration shall be based, where feasible, on the direct measurement region of the meter as supplied by the meter manufacturer. If not supplied by the manufacturer, the area of direct measurement shall be determined by test. Every effort shall be made to quantify the capability of the meter assembly to estimate moisture content by reducing extraneous sources of error.

6.2.2 *Sampling and Analysis*—This calibration procedure is designed for full-scale calibration of the meter and electrode assembly. If only a limited portion of the scale requires calibration, the number of equilibrium moisture content (EMC) levels can be reduced to as low as two. Calibration should not be extrapolated below the lowest value. Extrapolation above 21 % EMC to the fiber saturation point is permissible, provided that caution be taken in regression extension beyond the moisture data high end point. Calculation of confidence limit envelopes are recommended with use of regression in this fashion. Stratified sampling and analysis of variance, or both, can be applied to quantify sensitivity to wood characteristics. If the test material is other than solid wood, it shall be prepared and tested in a manner consistent with the solid wood calibration procedures.

6.2.2.1 *Wood Characteristics*—Wood characteristics that need to be treated as measurement variables because they may influence meter readings shall be represented in the calibration sampling. Examples of these variables are density and mineral content. These characteristics shall be included, identified, and measured as part of random sampling from a target population or they shall be sampled separately as part of a strategy of stratified sampling.

6.2.3 *Sample Preparation*—The sample size shall be based on the sampling principles of Practice D2915, Section 3.4, based upon subsequent subdivision of the sample into sub-sets for conditioning and testing. Specimen size shall be selected to encompass the direct measurement region of the meter/electrode assembly with minimal excess material. Specimens must be free of visible irregularities such as knots, decay, reaction wood, and resin concentrations. The specimens shall be conditioned at 25 ± 1°C and selected relative humidities to each of five *EMC* levels between 7 and 21 % (see Guide D4933). Alternatively, specimens may be equilibrated (following a desorption path) at each of the five *EMC* conditions.

6.2.3.1 *Species*—Species shall be identified. If the sample represents a species group, the individual species of each specimen shall be identified if anatomically possible.

6.2.3.2 *Sapwood/Heartwood*—Specimens shall be chosen to be entirely sapwood or heartwood, or two separate groups of each, but not mixed in the same specimens. It shall be reported if sapwood/heartwood mixing is unavoidable.

6.2.3.3 *Wood Characteristics*—Specimen selection for wood characteristics shall be considered in setting sample size.

6.2.4 *Testing*—There are two steps in the testing phase of calibration. The first is meter measurements on the wood samples following the procedures of this test method and the applicable criteria provided by the manufacturer. The second step is conducting a direct moisture content determination following Test Methods D4442.

6.2.4.1 *Meter Measurement*—The equilibrated specimens are numbered, weighed, and a meter measurement taken with the electrode aligned on the specimen in accordance with the manufacturers recommendation. The speed of response of the meter will determine the timing of the meter reading; manufacturer's recommendations shall be followed unless this variable is examined as part of the calibration process.

6.2.4.2 *Direct Moisture Test*—The MC of each specimen shall be determined by the appropriate direct method (Test Methods D4442) after the meter measurement. Procedures shall be followed to prevent moisture gain or loss from the specimens between the meter measurement and the direct test.

6.2.5 *Correction Factor Determination*—The corrections applied to moisture meters and the precision and bias of the meters may differ significantly between the technology employed and manufacturing variables. Wood characteristics, species, temperature and chemical additives are specimen variables that may require correction factors. The following procedures shall be followed to determine correction factors for meters.

6.2.5.1 *Correction for Wood Sample Characteristics*—The moisture meter scale readings determined from 6.2.4.1 procedures shall be related to the corresponding MC from 6.2.4.2 for each specimen in the sample by regression or analysis of variance analysis.

*(1)* Species calibrations that are intended to represent an entire species (for example, to correspond to globally-determined design values assigned to structural products) shall be obtained only by conducting species-wide sampling.

*(2)* The species sampling suggested in this test method is not required to be species-wide. Species representation claims based on less-than species-wide sampling shall be correspondingly limited.

6.2.5.2 *Correction for Wood Sample Temperature*—This correction shall be applied after the meter has been standardized in accordance with Section 5 and calibrated in accordance with 6.2.5.1. The options for this correction are to use a standard temperature correction or to conduct a laboratory calibration.

*(1) Determination of Temperature Correction*—The correction shall be based on samples prepared as specified in 6.2.2 except that specimens of known MC (Guide D4933) at 25 ± 1°C (77 ± 1.8°F) shall be placed, with electrodes and temperature probes attached, in a sealed container. The change in indicated MC (meter indication) shall be recorded while changing temperature through the desired range. A final meter reading must be made at 25 ± 1°C (77 ± 1.8°F) to confirm that the MC has not varied from the temperature cycling.

*(2) Standard Temperature Correction*—If a laboratory determination is not made for conductance meters, the following relationship shall be used to correct MC below the fiber saturation point over the temperature range of 0 to 40°C.

$$MC_2 = MC_1 + \left(0.06 MC_1^{0.5}\right)\left(T_2 - 25\right) \quad (1)$$

where:

$MC_1$ = the MC at 25°C.

This information is presented in Appendix X2.

6.2.5.3 *Correction for Chemical Additives*—Meter assemblies applied to wood materials that have been treated with additives and have adhesives interspersed with the fiber, or both, shall be calibrated with those materials following the precepts of this and previous sections on sampling and preparation. Some discretion is appropriate on temperature and moisture levels, depending on the end use of the products.

6.2.6 *Report*—The following wood sample information shall be recorded: MC, size (dimensions in each plane), species and method of species identification, sapwood/heartwood percentage, density or specific gravity, growth rate (rings/25 mm) and ring orientation, and earlywood/latewood percentage. For other materials, the appropriate wood sample information shall be recorded together with adequate data to identify the product and its constituents. The following meter information shall be recorded: manufacturer and model, reference temperature, and electrode type and configuration. The following standardization and calibration information shall be reported: method of analyses and presentation, influence of wood characteristics (variables), influence of temperature and method of correction, and details of electrode placement.

6.2.6.1 If a meter is not accompanied by the calibration data of 6.2.5 or by a discussion of sensitivity of the meter to operating characteristics, it shall be acknowledged that the influence of these operating variables is not known. Measurement of precision and bias for such a meter may have limited merit.

## 7. Presentation of Corrections and Precision and Bias Statements for Moisture Meters

7.1 Meters meeting the requirements of this test method shall have standardization procedures and corrections presented in formats that permit response to the MC, and wood and environmental variables to which the meter may be subjected.

7.1.1 The precision and bias of a meter may differ between the technology and manufacturing variables. If a meter is not accompanied by the calibration data or by a discussion of sensitivity of the meter to operating characteristics, it shall be acknowledged that the influence of these operating variables is not known. Measurement of precision and bias for such a meter may have limited merit.

7.2 Generic statements of precision and bias for hand-held meters are not available at this time.

## 8. Precision and Bias for this Test Method

8.1 Statements for the precision and bias of this test method have not yet been developed.

# APPENDIXES

## (Nonmandatory Information)

## X1. COMMENTARY

## INTRODUCTION

The purpose of this appendix is to supply auxiliary information on the basis for and practice of this test method. It is organized with paragraphs that correspond by section number to those in the mandatory text; text paragraphs needing no explanation are not listed. This concept permits changes at any time in order to keep the standard current and to improve its usefulness.

This is a laboratory test method; thus, "uses," including field calibrations, are not considered in this test method.

**TABLE X1.1**

| Section | Comments |
|---|---|
| 1.1 | Oven-dry measurements had been the basis of calibration in this test method for many years. In 2004, the oven-dry requirement following Test Methods D4442 was replaced by reference directly to Test Methods D4442. This infers that any Test Methods D4442 method is acceptable as the direct reference for a meter. It is anticipated that oven-dry measurement will remain the primary method; however, more flexibility was desired to accommodate newer technologies and specimen needs. |
| 1.2 | The principal concepts of this test method as first incorporated in Test Method D2016 in 1965 and then in subsequent versions of this test method, addressed only meters based on the change of wood conductance or dielectric properties with moisture content. Specific electrode configurations were anticipated, based on early commercial use. Meters were classified as "resistance-type" and "dielectric-type"; no provisions were made for other measurement technologies. Meters are now classified as "conductance" rather than "resistance-type," and "capacitive-admittance" rather than "dielectric-type" to better reflect current understanding of the underlying physics of their function. This test method is formatted to permit technologies other than conductance and capacitive-admittance, as well as combinations of technologies; no distinction is made in requirements. In addition, this method makes provision for specimen sizes to relate to the specific measurement technology of the meter. |
| 4.1.1 | Laboratory use of only the direct area of meter measurement is a change from using an empirical specimen size for all meters of the same generic type. Meter manufacturers need to specify the area of direct measurement of the meter; this may differ by electrode. Specimen sizes used in calibration will differ by meter type and electrode. The resulting calibration will minimize the contribution of wood variable error in the calibration and more uniformly reflect the measurement capability of the meter. Meters "field calibrated" may employ specimens that are different than were used for the direct Test Methods D4442 measurement. While useful, and perhaps essential, for a specific use, this is not a basic calibration of the meter, since the introduction of material (wood, air, support, and so forth) not tested by both techniques does not provide an accurate measure of the meter function. Consequently, field calibration is addressed in Practice D7438. |
| 5.2 | *Standardization*—This is based on the direct area of measurement of the meter unless otherwise specified by the manufacturer to parallel the requirements for calibration. An example is the use of external reference resistors to standardize the insulated pins of a conductance moisture meter. |
| 5.2.1 | This recognizes that some meters and electrode systems, or both, may be difficult to standardize in the manner anticipated in 5.2; consequently, the manufacturer may offer alternatives, noting they are exceptions for physical or mechanical reasons. An example is the use of external reference resistors applied to the tip of uninsulated pins to standardize a conductance moisture meter. |
| 5.2.2 | The standard reference material should be mechanically and physically stable under the environmental conditions of the standardization. It should be non-hydroscopic and provide a minimum of one and preferably two reference points on the measurement scale. The meter should be evaluated over the range of environmental conditions recommended by the manufacturer. The manufacturer should indicate (in the meter manual, on the meter or meter scale, or on the supplied reference standard) the meter model, wood species, and the electrode configuration for which the reference standard is valid. |
| 5.2.3 | The intention is to standardize at the temperature of use, comparing the result with the laboratory and manufacturer data, or both, on temperature sensitivity for corrections or adjustments as needed. |
| 6.2 | Laboratory calibration is intended to provide reference data under controlled conditions which include both the wood and the ambient environmental variables. |

**TABLE X1.1** *Continued*

| Section | Comments |
|---|---|
| 6.2.2 | Sampling design is to ensure that wood variables that influence meter performance are included in order that meter sensitivity is correctly measured in calibration. This will permit this influence to be reported appropriately in Section 7. It may be appropriate for some meter technologies to establish calibration points above the fiber saturation point; however, these should be analyzed separately from the data below the fiber saturation point. |
| 6.2.2.1 | Meter sensitivity to wood variables is evaluated in the laboratory calibration. Examples of these variables are density, growth ring characteristics, and mineral content. If these are not measured and represented adequately in analysis, the bias of the meter will be affected and the effect of these variables cannot be applied as a correction. Wood species, wood characteristics, and the influence of site can be of sufficient importance to justify the focus of a dedicated study. A study plan that identifies the target variables can assist in establishing the appropriate sampling and set the variable boundaries within which the study applies. |
| 6.2.3 | Typically five subsets have been specified for the calibration; however, the complexity of the sampling and analysis may suggest more subsets or a different experimental design. Traditionally a minimum of 75 green, flat-sawn specimens 20-mm thick by 75-mm (minimum) wide by 100-mm along the grain were required for a given species for calibrating conductance meters. For capacitive-admittance meters, 20 or 40 thick by 125 by 125-mm specimens were specified. This sample was then divided into five groups of 15 each for conditioning and testing—one group at each of five EMC levels. Depending on the variability of the MC reading of the meter, wood characteristics being studied and the Test Methods D4442-measured moisture variability, or both, this requirement may be too small or too large. Practice D2915 guides the selection of sample size based on the variability of the sample property with the goal of estimating the true mean reading of the subset within a stated amount and with confidence. Typically 95 % confidence that the mean MC of a subset has been estimated within 5 % would be a reasonable basis. The size of the test specimen for laboratory calibration is determined by the region of test measurement of the meter/electrode assembly. This reduces calibration error due to the Test Methods D4442 test evaluating material not tested by Test Methods D4442 or the reverse where meters examine large specimens. In the tradition of the 20 by 75 by 100-mm specimens, much of the specimen was outside the test area for a conductance meter with small pin spacing and not thick enough for long conductance pin electrodes. For capacitive-admittance meters, the two depths were used to identify if a depth effect existed; yet only the two depths were used for calibration, rather than the depth at which the manufacturer (or laboratory test) determined the limit of sensitivity. Interpolation was permitted between the results at the two depths and extrapolation beyond 40 mm. Some electrode configurations and meter technologies may be difficult to calibrate on the basis of measurement area or volume. In these cases, the manufacturer should identify the basis of calibration. |
| 6.2.3.3 | When examining the effect of a wood characteristic as part of the meter calibration, a sufficient sample size is needed to identify the sensitivity to the characteristic. This may require "side" studies to determine the variability anticipated so that sampling takes place that is appropriate to the anticipated analysis. |
| 6.2.4.2 | Placement will depend upon the type of technology and configuration of the electrode. For example, with conductance meters in solid wood, it is recommended that pins be aligned so that the current flow is parallel to the grain. Traditionally it has been recommended that capacitive-admittance electrodes be supported on low-density polystyrene foam at least 50 mm thick to reduce the chance of signal bias due to penetration into a material below the target specimen. This or an equivalent procedure should be used even where the specimen thickness has been adjusted to encompass the full depth of the signal penetration. |
| 6.2.5 | It is the intent of this test method that meter calibration data shall be provided in a format that permits a user to assess the influence of common wood characteristics and environmental conditions on meter response. This may take the form of correction formulas or hardware or software adjustments. The basis of these adjustments is required in the report of Section 6. |
| 6.2.5.1 | ASTM Committee D07 regards species-wide sampling as meeting the principles that guide the sampling required for Practices D5536 and D1990. |
| 6.2.5.2 | The following procedure has been found to be satisfactory by some users of conductance and capacitive-admittance type meters. The correction for temperature is based on samples prepared as specified in 6.2.3. The specimens are either at a known EMC (Guide D4933) or they are in a green condition. Prior to performing the test each test specimen is weighed so that oven dry MC can be verified at the end of the test in accordance with Test Methods D4442. Any electrodes or thermocouples used to monitor temperature in the test specimen, as well as any sealant used to prevent moisture loss during the application of heat throughout the test, are also weighed. The weights of these materials are then subtracted from the test specimen weight which will be monitored during the test. Electrodes or thermocouples should be placed at different depths in the specimen to ensure that the target test temperature levels are constant for each tested level. Each test specimen is maintained at a constant temperature target level. At each target temperature level, record the meter reading, and weigh the test specimen. Continue this method throughout the desired temperature range. A final meter reading is made at the initial temperature level of the test specimens to confirm that the MC has not varied from the temperature cycling. |
| 6.2.5.3 | Many wood products with additives, including adhesives and wood preservative treatments pose a calibration challenge. Grouping product sizes, types, and additives for general relationships may be useful by working with the meter manufacturer. Additionally, for chemical treatments calibration may not only depend on the chemical used, but also the depth and penetration. |
| 6.2.5 | This correction reflects the wood characteristics of the sample and cannot be extrapolated beyond these variables. This correction is commonly associated with species; however, the type of meter technology determines sensitivity to wood variables. For example, the primary concern with a conductance meter may be species; however, presence of mineral streaks and so forth may be an additional sample characteristic. Capacitive admittance meters often are sensitive to density in a specific sample. Analysis techniques that separate the influence of variables such as density and species should be used; common methods are multiple regressions and analysis of variance. Data presentation should separate the influence of the variables; data collected above fiber saturation should not be combined with that below fiber saturation unless careful analysis can justify combinations. |
| 6.2.6.1 | The MC change can be minimized by using the smallest possible sealed volume containing the specimen and using the shortest possible time to obtain temperature equilibrium. One means of determining the equilibrium time is through the time constant method described in Guide D4933. |

**TABLE X1.1** *Continued*

| Section | Comments |
|---|---|
| 7 | Users of meters expect adjustments and corrections that relate to their intended use. Meters meeting the requirements of this test method are not expected to have the same responses to all the possible combinations of wood use conditions; however, it is the intent of this test method that meters meeting the standard be accompanied with suitable instructions on corrections and adjustments, including discussion of limitations of such procedures. |
| 7.1 | The form and content of meter corrections and the associated precision and bias statements are dependent upon the moisture meter and electrode assembly technology and upon the emphasis placed on basic calibration of the equipment capability and response to operating variables. If the primary goal is correlation with end-use requirements (such as moisture specification limits), meter output may be interpreted differently than if the meter is used to estimate MC over a range of values. These latter aspects are covered in Practice D7438. Corrections presented may take the form of correction formulas or hardware or software adjustments. The basis of these adjustments is required in the report of Section 6. The corrections may differ significantly between the technology employed and manufacturing variables. Examples of conformance to this requirement is for a meter to provide a correction for temperature or for density. There will be a threshold below which the correction is so small for some variables as to not affect the meter function; the standard does not address that threshold. The meter manual should state the threshold applied when the judgement is made to not include a correction factor for a common operating variable. Historically, corrections for temperature for conductance meters have been a standard practice. Corrections for density have not been supplied commonly for capacitive-admittance meters; end-users derive corrections from field calibration studies for particular uses. An extension of this requirement is to emphasize regions of use where a laboratory test-based meter correction may not apply. For example, a meter may have a temperature correction for a standard ambient operating region that does not apply when used in a dry kiln environment. A meter used for general acceptance testing of commodity lumber may require no adjustment for density if acceptance is based on sample density mean values; a correction for density may be critical for a wood product that has been segregated by density or densified by process operation. |
| 7.2 | Conventional use of many meters emphasizes correlative relationships in which the precision and bias of the meter as an instrument, while critical to its function, is only part of the variability observed in the relationship. To fully understand the potential of a meter as a quality instrument, the precision and bias of the meter should be measured. The precision and bias of a meter should be measured at the standard conditions that are required in the calibration process (Section 6) to provide a meaningful link to the calibration. ASTM publication *ASTM Standards on Precision and Bias for Various Applications,* 1992, provides reference standards and examples of measurement and use of these practices. If relevant corrections are not provided for the meter, conducting precision and bias tests on the meter may not be relevant to many end-uses. |

## X2. FUNDAMENTALS OF NONDESTRUCTIVE MOISTURE MEASUREMENT

### INTRODUCTION

This appendix provides background information on the wood physics and the variable interactions that influence the estimation of MC. The information provided is supplemental to the sampling, testing, and analysis requirements of this test method, and while intended to enhance the understanding of moisture measurement, does not supersede those mandatory sections.

### X2.1 Resistance and Resistivity

X2.1.1 *Fundamentals:*

X2.1.1.1 *DC Conductivity*—The electrical resistance of wood is particularly important because of its relationship to MC. Among other variables that affect the DC resistance are temperature, magnitude of applied voltage, grain orientation, and nature of the electrodes. A phenomenon which occurs in all DC conductivity measurements of moist dielectrics is the variation of resistance with time after the initial application of voltage. Most of the theories of DC conductivity are based on the hypothesis that the charge carriers are wholly, or predominately, ions.

X2.1.1.2 *DC Current Flow*—Conductivity is the inverse of specific resistance or resistivity, the resistance of a material having unit cross-sectional area and unit thickness. The measurement of the DC resistivity of a hygroscopic material is, by nature, a dynamic one, requiring the determination of the current flowing in a material of known dimensions under the influence of a fixed voltage. The DC resistivity of a material is defined by:

$$r = \frac{RA}{l} \qquad \text{(X2.1)}$$

where:

$r$ = resistivity (ohm-m),
$R$ = resistance (ohm),
$A$ = area (m$^2$), and
$l$ = length (m).

*(1)* Extreme values of resistivity are $10^{-8}$ ohm-m for good conductors, and $10^{16}$ ohm-m for good insulators. Oven dry wood is considered a good electrical insulator (r~$10^{15}$ ohm-m).

*(2)* However, the presence of moisture greatly decreases the resistivity of wood to a limit of about $10^4$ ohm-m near and above fiber saturation point (FSP).

*(3)* DC current flow in a dielectric can be considered of two types: polarization and free-ion. The polarization current includes electronic, atomic, and dipolar polarizations, all of which occur at low AC frequencies, as well as the slower movement of certain entrapped ions to interfaces where they remain as fixed charges. Since the polarization current includes a transient movement of charges, equilibrium occurs after some finite time, and the contribution toward the total current diminishes with time. Free-ion current, on the other hand, can be considered similar to the normal current flow of electrons, in that Joule (or ohmic) heating occurs from ionic interactions.

*(4)* While electron flow is the movement of negatively-charged carriers through an "electron gas plasma," free ions may be positively or negatively-charged particles, and in the case of moist cellulosic materials, are hydrated. Under the influence of an electric field and, from the inherent thermal energy, ion migration occurs over a path of water molecules. At the same time, hydration and dehydration of the ions proceeds at a random rate, which may provide a large contribution to the mechanism of ionic mobility. The true conductivity of a material exhibiting simple anomalous dispersion is defined by Murphy and Morgan (**1**)[3] as the "infinite-frequency conductivity," which can be obtained by extrapolation of the DC conductivity curve to the point of voltage application.

*(5)* Through ion conductivity studies, Lin (1965) hypothesized that conduction below 20 % MC was dependent on the number of charge carriers, while at higher MC, the ion mobility was considered the controlling factor.

X2.1.1.3 *Electrode Influence*—The type and contact resistance of metallic electrodes can have a large effect of apparent resistance after a short time period of voltage application. Zinc and copper cause large changes, while aluminum is similar to platinum, which has relatively little effect (Hearle 1953).

*(1)* Several investigators have noted that very little change in the apparent ohmic resistance occurs in wood above about 10 volts/mm.

X2.1.2 *Principles of Application of DC Moisture Meters:*

X2.1.2.1 *General Operation*—The pin-type DC moisture meter is normally calibrated for a direct reading of MC from the resistance-MC curve of Douglas Fir. It operates simply as a wide-range ohmmeter from about $10^{14}$ or $10^{11}$ to $10^3$ ohms, as measured between pins usually spaced 25 mm apart. The upper limit on pin-type meters varies, but many meters indicate readings to 70 % MC. Any readings made above FSP are qualitative, except when the temperature correction brings the reading below FSP. Pins installed permanently in wood can provide semi-quantitative values of changing MC above FSP, but point-to-point measurements are usually unreliable.

X2.1.2.2 *Influence of Electrode Variables:*

*(1) Number of Electrode Pins and Pin Spacing*—Most meters are equipped with either 2 or 4-pin (2 parallel pairs) probes for MC measurement of lumber. Special veneer probes are available with 8 pins (4 parallel pairs). The 2-pin probes may have bare or insulated (except the tip) pins. Characteristics of bare 2-pin probes have been reported by Skaar (**2**). A ratio of pin spacing to diameter of 12.5 (for a 10 mm immersion length) is required to provide equivalent resistance and resistivity. For the typical 25 mm spacing, then pin diameter should be about 2 mm to maintain this equivalency. Because a non-uniform electric field is developed around and between the pins, resistivity is higher adjacent to the pins (about 50 % of the total resistance is developed in the region of 25 % of the distance from one pin toward the other. Doubling the pin spacing increases the resistance only about 25 %). Electrodes having different numbers of pins with the same spacing do not give equivalent readings. Since the classic Douglas Fir resistance-MC relationship was based on a 4-pin electrode, the 2-pin electrode reads about twice the resistance of the 4-pin at any MC. Therefore, meter readings for 2-pin electrodes, where calibration has been for 4-pin, are lower (about 0.5 % MC at 10 % MC, 1 % MC at 20 % MC). A relative increase of 5 % at any MC appears sufficient to correct meters calibrated for 4-pin resistivity. Eight-pin (veneer) electrodes read lower in resistance (between 33 % and 50 %) than that of the 4-pin, depending on the relative pin depth and veneer thickness.

*(2) Pin Depth*—The influence of pin depth on readings is largely ignored, but non-insulated pins driven into wood having a uniform MC will give readings that increase with depth because of the greater pin contact area. However, the same effect occurs if the wood has a normal moisture gradient during drying (lower MC on the surface). For this reason, the use of insulated pins provides more accurate and consistent readings.

*(3) Pin Contact*—When pins are implanted to provide long-term readings, several problems may arise. Wood at constant MC gives readings (made intermittently) which decrease with time, apparently because of "fiber relaxation" (the rheological deformation of wood tissue under the mechanical force of the pins), which reduces surface contact. This contact can be restored by lightly tapping the pins. If MC is changing substantially, as in kiln drying, shrinkage of the wood loosens the mechanical fit of the pin, increasing contact resistance. If the MC is high (above about 20 %), pin corrosion may increase this interfacial resistance. The integrity of mechanical contact can be improved by using pre-drilled holes and special pin designs, such as one having screw threads at the tip.

X2.1.2.3 *Wood Variables:*

*(1) Grain Direction*—In accordance with Stamm (1964) (**3**), resistivity perpendicular to the grain is approximately 2 to 3 times that measured parallel to the grain. Since pin-type moisture meters are calibrated for parallel-to-grain resistance, readings made transverse to the grain may be about 1 % to 2 % MC lower than the true values. Radial resistivity is usually lower than tangential because of the influence of the rays.

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[3] The boldface numbers given in parentheses refer to a list of references at the end of the standard.

*(2) Density*—It would be anticipated that as density increases, the DC resistance of wood should decrease since the amount of cell wall material per unit volume is greater. An apparent increase in MC would be caused by this decrease in resistance. Over the span of relative density of commercial species (density nominally 0.3 to 0.8), an error of 0.5 % to 1.0 % MC would be expected, if density were the sole factor influencing DC resistance. For specific wood species, the density variation is too small to cause detectable errors in MC readings.

*(3) Moisture Content*—The quantitative dependence of DC resistance of wood on MC was first established by Stamm (1927) (**4**). Data on ten species of wood indicated a semi-log relationship between resistivity and MC (about 0 % to 10 %; Stamm (1964) (**3**):

$$\log r = 17 - 0.7MC \tag{X2.2}$$

or:

$$\log r = 32 - 1.6MC \tag{X2.3}$$

*(a)* Above about 8 % or 10 % MC to 19 % MC, the data appeared to have a log-log relationship. A sample curve is given in Fig. X2.1 for Douglas Fir (**5**). More complete data was published in the Wood Handbook (1955) (**6**) for the DC resistance of 29 species from 7 % to 25 % MC. The domestic species resistivity data, with additions by James (**7**), was re-graphed in the 1974 and subsequent Wood Handbook editions to illustrate both the general trend and the high variability in the data base (see Fig. X2.2 (**5**)) (Wood Handbook, 1974 and subsequent editions (**6**)).

*(b)* Measurement of DC resistivity above about 20 % MC (depending on the species) can be unreliable because of polarization, which is time-dependent, and the presence of water-soluble extractives. In some wood species above FSP, the resistivity has been shown to clearly increase with decreasing MC when measured between fixed points. However, the relationship of resistivity with MC above FSP is very poor with random sampling, even in the same specimen. Several investigators have noted that very little change in the apparent ohmic resistance occurs in wood above about 10 volts/mm.

*(4) Temperature*—It has been well documented that DC conduction in wood is temperature-related. It follows an Arrhenius behavior (ln r versus $1/T_k$). DC moisture meter readings, which are usually based on the Douglas fir resistivity-MC curve, must be corrected for temperature. The variation of apparent MC with temperature has been published

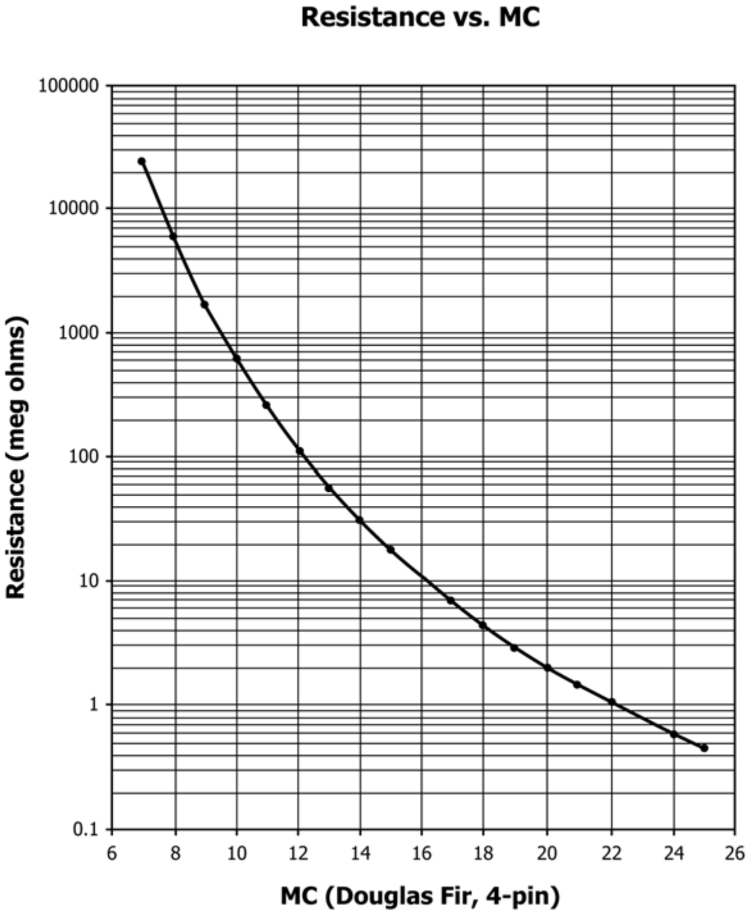
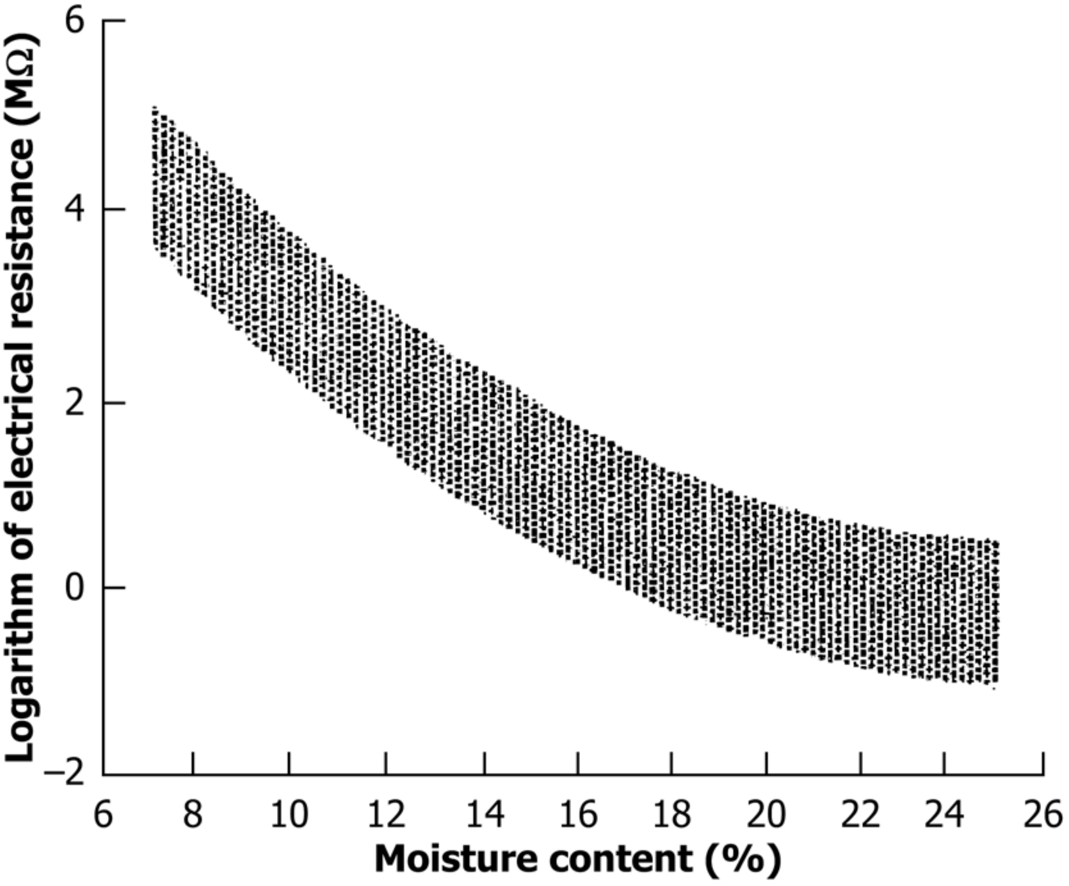


FIG. X2.1 Relation Between Moisture Content and Log of Resistance for Douglas Fir



NOTE 1—90 % of test values are represented by the shaded area.

**FIG. X2.2 Change in Electrical Resistance of Wood with Varying Moisture Content Levels for Many U.S. Species**

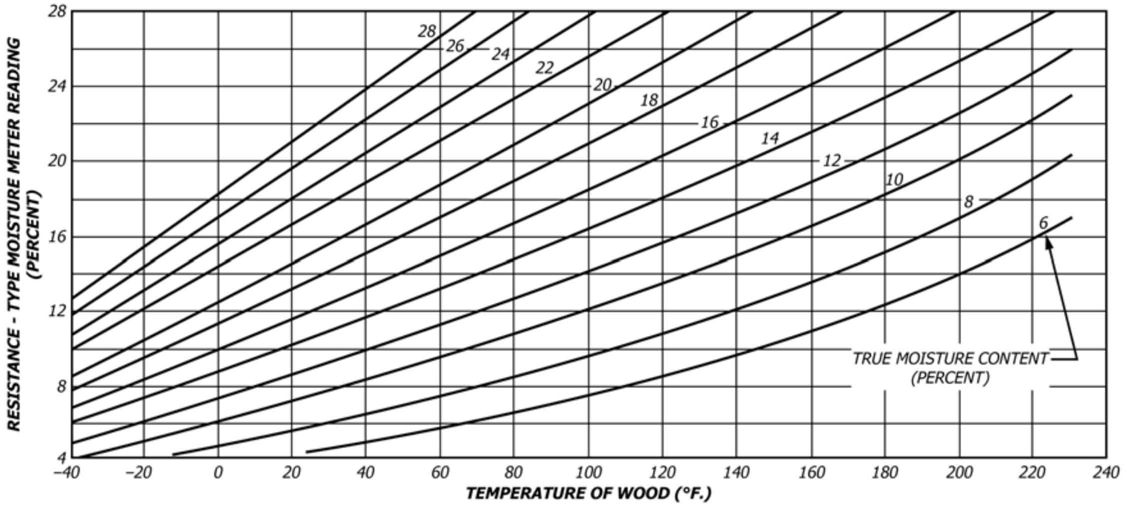
in graphical form by James (**7**) (see Fig. X2.3 (**5**)). Skaar (**2**) has proposed an approximation for this data, based on a reference temperature of 21°C and from 6 % to 28 % MC:

$$\frac{dMC}{dT} = 0.027 + 0.0085MC \quad \text{(X2.4)}$$

*(a)* There are several omissions in this information: (1) no information accompanies the graph by James (**7**) to explain variability, species, significance of the curve-fitting, and so forth, and (2) there is no indication that meter readings above 28 % MC are correctable. Also, Skaar's data (**2**), based on heartwood and sapwood of five species at 12 %, 18 %, and 24 % MC, appear to fit a relationship closer to:

$$\frac{dMC}{dT} = 0.06 + 0.02MC^{0.5} \quad \text{(X2.5)}$$

*(b)* This suggests a reasonably constant slope above about 18 % MC, since the 18 % and 24 % slopes were not significantly different. From the variability in Skaar's data (**2**) (about ±10 % range at 12 % MC, and ±20% range at 18 % and 24 % MC), it appears that the nominal correction curves proposed by James (**7**) may not be generally applicable. Apparently, the mode of DC conductivity is not uniform for many species, particularly at higher MC and probably at higher temperatures.



NOTE 1—Find meter reading on vertical left margin, follow horizontally to vertical line corresponding to the temperature of the wood, interpolate true moisture from family of curves.

*Example*—If meter indicated 18 % on wood at 120°F, true MC would be 14 %.

NOTE 2—This chart is based on a calibration temperature of 70°F. For other calibration temperatures near 70°F, adequate corrections can be obtained by shifting the temperature scale so that the true calibration temperature coincides with 70°F on the percent scale.

*Example*—For meters calibrated at 80°F, at 10°F to each point on the temperature scale (shift the scale 10°F toward the left), and use the chart as before.

**FIG. X2.3 Temperature Corrections for Reading of Resistance-Type Moisture Meters, Based on Combined Data from Several Investigators**

## REFERENCES

**(1)** Murphy, E. J., and Morgan, S. O., "The Dielectric Properties of Insulating Materials," *Bell System Technical Journal,* Vol 16, 1939, pp. 493–512.

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**(3)** Stamm, A. J, *Wood and Cellulose Science,* Ronald Press, New York, NY, 1964.

**(4)** Stamm, A. J., "The Electrical Resistance of Wood as a Measure of Its Moisture Content," *Industrial & Engineering Chemistry,* Vol 19, 1927, pp. 1021–1025.

**(5)** *General Electric Review,* Vol 34, No. 12, December 1931, p. 708.

**(6)** *The Wood Handbook: Wood as an Engineering Material,* USDA Forest Products Laboratory [USDA Agriculture Handbook 72], Madison, WI, 1955, 1974, subsequent revisions.

**(7)** James, W., "Electric Moisture Meters for Wood," *USDA Forest Service Research Note FPL08,* USDA Forest Products Laboratory, Madison, WI, 1963.