Designation: D7438 – 13

Standard Practice for
Field Calibration and Application of Hand-Held Moisture Meters[1]

This standard is issued under the fixed designation D7438; 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.

1. Scope

1.1 This practice applies to the measurement of moisture content of solid wood, including solid wood products containing additives, that is, chemicals or adhesives, by hand-held moisture meters under conditions of end-use.

1.1.1 This practice includes calibration, use, and interpretation of meters for conditions that relate to wood product characteristics, such as nonuniform grain and growth ring orientation, and to end-use process conditions, such as moisture gradients.

1.1.2 Meters employing differing technologies may not provide equivalent readings under the same conditions. When this practice has been applied, it is assumed that the referenced meter is acceptable unless otherwise specified. Meters shall have been calibrated by Test Methods D4444.

1.2 *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]

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-Base Materials

D4444 Test Method for Laboratory Standardization and Calibration of Hand-Held Moisture Meters

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

D6782 Test Methods for Standardization and Calibration of In-Line Dry Lumber 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 have been commonly referred to as "resistance-type" meters. Most commercial conductance meters are high-input impedance (about 10^{12} Ω), wide-range (10^4 to 10^{12} Ω) ohmmeters. Their scales are calibrated to read directly in moisture content (oven-dry mass basis) for a particular calibration species and at a specific reference temperature.

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 moisture content. Wave energy is most often in the radio frequency 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 moisture content of wood-based materials during and after processing to maintain quality assurance and compliance with standards. However, these measurements are inferential; that is, electrical parameters are measured and compared against a calibration to obtain an indirect measure of moisture content. The electrical measurements are influenced by actual moisture content, 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 these test methods. Appendix X1 is a commentary that provides explanation of the mandatory sections and discussion of historical practices. Appendix X2 addresses the influence of process and wood variables.

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[1] This practice 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.

4.1.1 This practice provides for calibration and application of wood products that contain commercial characteristics and that reflect the manufacturing environment.

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, lots). The field calibration section of this practice anticipates the potential need for this type of sampling. These correlative uses are examined in Appendix X3.

5. Standardization

5.1 *General*—Standardization shall be performed to establish the integrity of the meter and electrode under the field conditions of use. The meter circuit shall be tested by applying the reference material in accordance with manufacturer's recommendations, noting the corresponding meter response value, and comparing with the manufacturer's data. Standardization shall be done before calibration. If alternate electrodes are to be used with a meter, standardization shall be done for all electrode types and alternate assemblies.

5.1.1 Initially, standardization should be performed before each period of use. The time interval may be extended if experience shows that the particular meter is stable for a longer time under equivalent use conditions.

5.1.2 Standardization procedures in the field will be affected by the standardization performance of the meter during evaluation under Test Methods D4444. The report of section 5.2.3 of Test Methods D4444 provides this information.

5.2 The standardization shall be carried out with the instrument, including electrodes, at the temperature of the anticipated application. This shall include the range of anticipated conditions; the reference material shall maintain its essential characteristics over this range. The sensitivity of this standardization to temperature of the meter shall be part of the evaluation.

5.2.1 If the environmental conditions change during the usage period beyond those evaluated in the initial standardization, the standardization shall be repeated.

5.2.2 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's recommendation.

5.2.3 Field standardization may be difficult to carry out under some ambient field conditions and with the electrodes to be used. One example is the use in monitoring in-kiln performance. If the measurement conditions are difficult to reproduce or are transient (for example, in a hot dry kiln), then it shall be understood that the validity of the meter readings are dependent upon the laboratory standardization and manufacturer's recommendations.

6. Calibration

6.1 *General*—Under processing conditions, laboratory calibration procedures maybe impractical, particularly because of moisture and temperature gradients, nonstandard temperatures, unverified species within commercial species groups, non straight-grain wood, and common production variables such as mixtures of heartwood and sapwood. Further, these process variables may change or invalidate some of the calibration results obtained under laboratory conditions in Test Methods D4444.

6.2 *Methods*—The principles and procedures of calibration in Test Methods D4444 shall be applied to the degree possible and relevant to develop a meaningful relationship between meter readings and actual moisture content (MC).

6.2.1 All field calibrations shall be referenced to direct MC measurements (Test Methods D4442).

6.2.2 Field calibration shall be carried out with meters that have been laboratory standardized and calibrated for appropriate wood variables, such as species and temperature using Test Methods D4444, and subsequently field standardized.

6.3 *Field Variables*—The calibration may be based on end-use environmental and product and process conditions that are more restricted than those evaluated by Test Methods D4444. In addition, the process conditions may produce interactions that must be considered in the calibration.

6.3.1 Special care must be taken to minimize errors caused by the influence of unintended wood variables, such as density and temperature (uncorrected) on readings. Specimen size for field testing may be selected to represent the appropriate geometry of the target sample. Field meter readings are conditional upon both the prior standardization and calibration process, the influence of wood variables in the field test, and application information supplied by the meter manufacturer.

6.4 *Calibration Steps*—The field calibration shall be conducted on specimens and in conditions that are representative of the process and are carefully documented. See Appendix X2 for discussion of process variables and wood characteristics.

6.4.1 *Sample Selection*—The number of wood specimens used for the calibration shall be selected following the concepts of Practice D2915, considering the variables to be represented and the desired precision of the calibration. For example, if the sample is to represent grain patterns, moisture gradients, etc. found in a lumber grade, these variables shall be considered in setting sampling criteria. (See also Test Methods D4444.)

6.4.2 *Sample Preparation*—While the sample may be intended to include process variables such as moisture gradients, temperature, etc., the measurement and subsequent preservation of these variables prior to and during meter measurement shall be considered part of the sampling process. See Test Methods D4444 for discussion of other relevant issues.

6.4.3 *Testing*—Field calibration shall be based on the relationship of the meter readings to Test Methods D4442 moisture measurement values. Because process conditions may be transient (for example, temperature and moisture gradients, or both), calibration that reflects these variables requires special treatment of specimens (such as subdividing specimens) or additional equipment (such as temperature probes). Care shall be taken to not distort the original specimen condition with these additional steps.

6.4.4 *Determination of Corrections*—To establish a correction that reflects the influence of the measured variables, the principles of Test Methods D4444, section 6.2.4, shall be followed.

6.5 *Report*—Useful application of field test calibration is conditional upon the relevance of the test sample. Consequently, accurate reporting of the wood and process variables (see 6.3 and 6.4) is critical. The report shall follow the practice of Test Methods D4444, section 6.2.5.

6.5.1 Field samples often contain uncertainties with respect to exact species or species mixtures, temperature at the point of electrode measurement, in-exact moisture gradients, and other specimen variables. Where these non-uniformities and uncertainties cannot be measured or corrected, their presence shall be noted in the report and quantified where possible.

APPENDIXES

(Nonmandatory Information)

X1. COMMENTARY

INTRODUCTION

The purpose of this appendix is to supply auxiliary information on the basis for and practice of this practice. 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 practice current and to improve its usefulness.

This is a practice standard; thus, it describes and standardizes, to the degree possible, the calibration and measurement practices that occur outside the environment of the testing laboratory.

TABLE X1.1

Section	Comments
1.1	The principal concepts of this practice, as first incorporated in Practice D2016 in 1965 and then in subsequent editions of this practice, 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 other electrode configurations or 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. The current practice makes no distinction between meter measurement technologies for standardization and calibration requirements. Provision for unique characteristics of measurement technologies is accommodated in Appendix X1 – Appendix X3. The use of “field” to describe calibrations and measurement issues denotes conditions that cannot be controlled as in a laboratory, yet the conditions are very commonly the environment in which the meters are used.
1.1.1	This practice targets use outside of the laboratory where controlled conditions are not usually possible. In addition, most commercial wood products are not “clear” and straight-grain and are heterogenous in other characteristics. Sampling is necessarily tied to commercial product descriptions.
1.1.2	Requiring calibration under Test Methods D4444 ensures prior technical evaluation of a meter, with an associated report describing performance under controlled conditions. Although the intended use may not adhere to these same conditions, the performance in the laboratory establishes the minimum performance criteria for field use as well as reference points on sensitivity to variables such as species, density, temperature, etc.
3.1	This practice is designed to apply to meters using technologies other than the two technologies included in the section. Conductance and capacitive-admittance meters are included because they provide the generic descriptions of principal, current commercial meters. Individual characteristics of commercial meters are not intended to be covered in these generic descriptions. As other meter technologies are developed, more generic descriptions should be added to this section.
4.1.1	Much of the content of this practice was incorporated in previous versions and drafts of Test Methods D4444, and some earlier in Practice D2016. The mixing of test methods and practices in one standard is not desirable; thus, this practice attempts to capture the critical elements of the many and varied commercial applications of hand-held meters while Test Methods D4444 concentrates on the base-line laboratory test methods. Specific issues of meter technology in use are covered in more detail in Appendix X2.
4.2	Correlative methods of data analysis are critical to many meter uses; however, they vary widely and are difficult to characterize as true calibration of a meter. Consequently, Appendix X3 addresses both calibration of a meter and predictive uses as separate topics of standard practice.
5.2.3	The standardization of a meter under severe environmental conditions can be a serious operating issue. If the manufacturer’s recommendations (for example, standard specimens or standard methods for standardization) cannot be followed, the correct operation of the meter is in question.
6.1	The essence of this practice is that many uses of meters demand performance on products and under conditions that are not covered by laboratory calibration (Test Methods D4444). Field calibration is the only recourse. It is emphasized that field-type calibrations often will apply very narrowly to the conditions of that calibration and do not extend to other uses or conditions.
6.2.2	Although the calibrations carried out in the field may be the only ones of commercial interest because they reflect the actual operating conditions, the meter must have the basis of laboratory calibration to ensure satisfactory operation under stable conditions and knowledge of response to variables important in the field.

TABLE X1.1 *Continued*

Section	Comments
6.3	Common wood variables encountered when conducting a calibration on commercial samples include non-uniform grain and growth ring orientation, moisture and density gradients within the measurement zone, mineral streaks, and "wet wood" (bacterially infected pockets). In many cases, the size and shape of the wood specimens is different from that used in laboratory calibration because the goal of the field calibration may be to calibrate the meter assembly for a particular application in which influence of specimen size and shape is an important element. These factors pose a challenge to field calibration because they produce results conditional upon all the incorporated factors; the resultant calibration may not extend to other uses. The results also have a component of sample "error" that may not be clearly identified (see Appendix X3). A common example of a field calibration with a narrow scope is a calibration of a meter used with deep members (for example, 200 mm) dried in a commercial kiln. A gradient is expected and accommodated in the calibration; however, this calibration may not be valid if the depth of the specimens in the next kiln charge is different from the original or if the kiln schedule is changed to accommodate the change in size.
6.5	Because field calibrations can have a very narrow scope, the report must clarify the variables evaluated, the variables not controlled, the "grade" description, etc. These provide boundaries within which the results may apply.

X2. METER USE

X2.1 General

X2.1.1 Measurement of moisture content in end-use applications requires consideration of meter technology, wood characteristics and environmental influences. Sampling and related analysis are additional essential elements. Appendix X2 incorporates historical observations on end-use applications.

X2.1.2 *Meter Technology*—Different meter technologies require differing operating procedures in end-use. Some operating variables, however, have a generally common influence on most meter/electrode assemblies. The following sections include both these generally common influences and those that are technology specific.

X2.2 Common Operating Variables

X2.2.1 Among the more common operating variables that can be addressed in a generic fashion are environmental factor of temperature, the wood variable of species, the sensitivity to chemicals, and the issues of sampling.

X2.2.2 *Temperature Influence and Corrections:*

X2.2.2.1 *Temperature Effect on Meter*—Meter circuits can be temperature sensitive, therefore, frequent zero or span adjustments, or both, may be necessary during use. The manufacturer should indicate the optimum range of temperature for operation of the meter without loss of accuracy due to temperature. It is recommended that whenever possible, the meter be equilibrated with the measurement environment before readings are taken. The intent is that in no case temperature or humidity alter the operating characteristics of a meter (that has been equilibrated and adjusted) to the degree that the accuracy is impaired.

X2.2.2.2 *Temperature Correction*—Temperature corrections are obtainable from manufacturer's data, published data, or using built-in adjustments in the meter. Temperature corrections require special care to obtain the wood (not air) temperature, and may be unreliable to correct some species. A reference temperature of 2°C shall be standard for zero correction. Clearly indicate the reference temperature at some point on the meter. Always make temperature correction before species correction.

X2.2.3 *Species Influence and Corrections:*

X2.2.3.1 *Species Correction*—Only use manufacturer's data developed in accordance with acceptable calibration procedures for the particular meter. The data should be accompanied with documentation on whether the corrections are for either the dial calibration species, a specific species, or for a species market group. Where appropriate correction data are not available, calibrate the meter in accordance with Section 6.

X2.2.3.2 *Other Species Correction Considerations*—There are numerous species-related effects that may result in different meter readings for the same actual moisture content. These include wood property variations related to site or genetics and, for some species, differences in between the heartwood and sapwood portions. Quantifying these effects to a precision sufficient to justify a separate correction, such as for temperature, may be difficult. Similarly, species market groups (such as Hem-Fir and Spruce-Pine-Fir) may contain species that cannot be visually separated at the point of moisture measurement or where such separation is impractical. In field measurements where these influences cannot be practically separated, make some judgment in defining the population that encompass these sources of variation and calibrate the meter in accordance with Section 6.

X2.2.4 *Chemical Additives and Adhesive Influence and Corrections:*

X2.2.4.1 *Chemicals*—Wood products which have been treated with preservatives, fire retardants, or dimensional stabilization agents may give abnormal readings (usually high). Of these chemicals, creosote and pentachlorophenol solutions appear to have insignificant effects.[3] However, salt solutions may cause abnormally high readings that should be considered qualitative or semiquantitative at best. Conductance meters having insulated pins can be used to measure MC of materials that have been surface-treated with chemicals provided that confirmation is made of the accuracy through direct MC determination (for example, Test Methods D4442).

(1) Specific Treatments—CCA-C treatment[4] has been reported to be less conductive than salt treatments, reducing the error of readings of treated southern pine to about 2 % MC in

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[3] James, W. L., "Effects of Wood Preservatives on Electric Moisture Meter Readings," *U.S. Forest Service Research Note*, FPL-0.06, 1965.

[4] Richards, M. J., "Effect of CCA-C Wood Preservative on Moisture Content Readings by Electronic-Type Moisture Meter," *Forest Products Journal*, Vol 40, No. 2, pp. 29–33, 1990.

the range of 12 to 24 % MC. New preservative treatments were introduced in 2004, replacing some traditional treatments; no data on the effect of these treatments on moisture meter readings is available.

X2.2.4.2 *Adhesives*—Adhesives may cause abnormally high readings in reconstituted wood products. Before any particular meter is used in moisture sensing of any particular product containing adhesives, its calibration must be demonstrated on that product. Re-calibration must be carried out following any change in processing conditions. The calibrations must be consistent with these test methods.

X2.2.5 *Sampling:*

X2.2.5.1 *Sampling Plan*—The goals of sampling (for example, estimating mean MC or MC variability, wet spot identification, measurement of within piece gradients, etc.) and the intended use of the information (for example, kiln performance, specification adherence, effect of wood variables, etc.) directly influence a sampling plan. If the moisture and wood characteristics, or both, vary significantly within a piece, more than one location on a piece will need to be sampled. The size of the lot and the number of sampling locations both influence the confidence with which conclusions may be drawn from the resulting data.

(1) Sampling Location—Selection of the location for sampling should consider wood characteristics and possible moisture gradients. For example, in selecting the location on a piece of lumber, take the readings at least 500 mm from the end and in the center of the face. Readings should be taken in areas that are reasonably straight grain and free of characteristics such as knots that affect the moisture level and influence the reading, or both.

X2.2.5.2 *Lot Size*—The number of readings per sample or per lot should be selected for consistency with the desired accuracy. Practice D2915 provides guidance on selection of lot size.

X2.3 Technology-Specific Considerations for End-Use

X2.3.1 The majority of hand-held meters employ either conductance or capacitive-admittance operating technologies. The following sections contain observations on operating characteristics of, and recommendations for, these technologies in end-use.

X2.3.2 *Use of Conductance Meters:*

X2.3.2.1 *Electrode Sensing Region*—Conductance moisture meters respond to the moisture content between the electrodes. They can be used to determine "point" moisture content directly, if insulated pins are used, or average moisture content indirectly. All readings should be taken with the pins aligned so that the current flow is parallel to the grain. Average moisture content can be obtained through the thickness by integrating moisture content versus thickness. Under the following conditions it can also be inferred from a single point measure.

(1) Obtaining an Average MC Reading—Wood of rectangular cross section tends to develop a parabolic gradient during drying (assuming that the maximum moisture content is below fiber saturation point (FSP). From the geometry of a parabola, the point of average MC lies between one fourth and one fifth of the total thickness. Therefore, if the pins are driven to this point, an approximation can be obtained for average MC of the cross section. Using the same principle, a circular cross section has its average MC at one sixth to one seventh of the diameter. The parabolic generalization generally does not pertain if lumber has been dried in conditions that induce steep moisture gradients (such as in drying above 100°C) or if the lumber is known or thought to contain wet pockets or streaks. This can be examined by driving insulated pins to mid-thickness. With thick (deep) members, the difference between one fourth and one fifth of the depth can produce significant differences in MC when a gradient exists; testing is necessary to verify the correct depth.

X2.3.2.2 *Moisture Content Range*—The range of moisture contents that can be detected is from a minimum of 6 or 7 % MC to a maximum of 25 to 27 % MC (nominal value of the fiber saturation point). Meter scales extend above this limit only to permit temperature corrections of moisture contents up to the fiber saturation point and do not imply reliability of readings above the fiber saturation point.

(1) "Hot-Metering"—One use of conductance meters is for "hot metering" of kiln-dried lumber during which readings are taken to determine if the load has reached the desired endpoint MC. However, such readings are subject to considerable error because of "edge-readings," assumptions of wood temperature, unknown moisture gradients, and temperature effects on the meter circuitry. A further use is for moisture measurement of dry lumber that is exposed to below-freezing temperatures. As with hot lumber, considerable errors are possible due to assumptions of wood temperature, unknown moisture gradients, and temperature effects on meter circuitry. Any use of these meters outside of the normal range is contingent upon correlative tests and careful adjustments for the environment effects.

X2.3.2.3 *Moisture Gradients*—Unless the moisture distribution and measuring techniques are well understood, readings can be easily misinterpreted. Three special problems should be considered:

(1) Non-Insulated Electrodes—See X2.3.2.5.

(2) Non-Parabolic Gradients—See X2.3.2.1 *(1)*.

(3) High Surface MC on Sample—High surface MC of the material from condensation, wetting, and high relative humidity can cause excessively high readings that are not representative of the overall moisture content of the wood if non-insulated pins are used. If non-insulated pins are used, a higher surface than core MC can cause a misleading reading at the depth of the pin tips. This can be tested by noting the indication at initial contact and as the pins are driven in.

X2.3.2.4 *Drift*—Direct current conductance meters may show appreciable drift toward lower MC when readings are taken at the upper portion of the MC range. If such drift occurs, take the reading as soon as possible after the pins are driven in and voltage applied. Digital and analog meters may respond differently; contact the meter manufacturer for recommendations.

X2.3.2.5 *Electrodes*—Preferred electrodes for the conductance meter for solid wood measurements are of a two-pin type, insulated except for the tips. If non-insulated pins are used, the wood must be tested for surface moisture content (see

X2.3.2.3 *(3)*). If any other electrode is used, such as four-pin for wood or eight-pin for veneer, the readings must be adjusted as specified by the manufacturer or incorporated into the scale corrections. Different pin configurations should not be used interchangeably on the same meter without the appropriate corrections.

(1) Pin Corrections—Acceptable corrections for solid wood are:[5] reading (two-pin) = 0.29 + 0.91 (reading four-pin), or reading (four-pin) = 1.1 (two-pin) − 0.32. These pin corrections must be made after the temperature correction and before the species correction.

(2) Non-Insulated Pins—Non-insulated pins have been a tradition in industrial use. If "normal" drying gradients exist (driest at the surface; least dry at the center of the piece), this usage may be satisfactory for many applications. To assume such a gradient without verification, however, may result in significant error. (See X2.3.2.1 *(1)* and X2.3.2.3.) Non-insulated pins will bias the reading toward the highest moisture content in contact with the pins.

(3) Extension Electrodes—Extension electrodes maybe necessary for some end-uses. Nails may be used; however, unless they are insulated except at the tips, the precautions for non-insulated pins apply.

(4) Implanted Electrodes—Special precautions are necessary to minimize errors caused by changing electrode contact pressure and electrode-wood contact resistance, particularly when the electrodes are implanted in green wood to monitor drying. It is especially important that d-c voltage not be applied continuously in order to minimize the buildup of contact interfacial resistance from ion migration. Meter systems with low frequency a-c, intermittent d-c, or switched d-c voltages can virtually eliminate irreversible ionic migration.

(5) Surface Moisture on Electrode—Surface films of moisture on the electrode, particularly from condensation (insulated pin holder), may cause large errors. Keep electrodes clean, and store and use under non-condensing conditions.

X2.3.3 *Use of Capacitive-admittance Meters:*

X2.3.3.1 *Electrode Sensing Region*—Moisture content readings will be affected by the electrode configuration and the configuration of the measurement region of the electrode. Laboratory standardization and calibration may be based on a specific reference standard and on a specific electrode configuration. Use of an inappropriate standard reference, a different electrode configuration, or an erroneous assumption of effective measurement region may yield erroneous results and require confirmation of the measurement results by further test, or both.

(1) Measurement Region Undefined—If the measurement region of the meter electrode has not been defined or is uncertain for the wood variable under test, minimize the possibility of reading adjacent material (read-through) by either supporting the specimen ends to create an air gap of at least 25 mm below the sample or placing the sample on a similar thickness of non-hygroscopic, low density foam such as polystyrene or polyurethane. Electrode conformance with the surface may present a special problem with warped specimens, especially if the electrode is rigid. If measurements must be made on warped specimens, one option is to take readings on opposite sides of the specimen and use only the higher value.

(2) Estimation of Measurement Sensing Region—If determination of the measurement region of the meter electrode assembly is desired, a traditional method of testing for sensitivity has been taking readings at two thicknesses: 20 and 40 mm. If a thickness sensitivity is detected, intermediate values between 20 and 40 maybe determined with other thicknesses of wood. Alternatively, a sufficient number of pieces (to minimize read-through) of thin material may be stacked and compressed for readings. For best results, rearrange the pieces for several readings that can then be averaged.

X2.3.3.2 *Moisture Content Range*—The normal range of moisture sensing in capacitive-admittance meters is from 0 % to fiber saturation point. Semi-quantitative readings above fiber saturation point are possible with the capacitive-admittance meter. The scale may be in arbitrary units or direct-indicating for a particular reference species if calibration for the reference species has been carried out according to acceptable calibration procedures. If the species scale is used, the range of density of the calibration species must be given. When correction data are not available, the meter may be calibrated in accordance with the procedures of this practice.

X2.3.3.3 *Moisture Gradients*—Unless the moisture distribution and measuring techniques are well understood, readings can be easily misinterpreted. Measurements with a capacitive-admittance meter must be qualified by the moisture gradient (determined independently with a conductance meter or other means), depth of electric field penetration, thickness of material, surface condition (such as rough or planed), and electrode contact pressure and conformance. In addition, the special problems of condensation on the electrodes (see X2.3.3.4) and moisture on the wood surface should be considered.

(1) High Surface Moisture Content on Specimen—High surface moisture content of the material from condensation, wetting, or high relative humidity can cause excessively high readings.

(2) Low Surface Moisture Content on Specimen—All capacitive-admittance meters have a biased, greater response to moisture nearer the electrode; therefore, for samples that contain moisture gradients, values determined even after species and temperature corrections are qualitative at best, and no limits of accuracy can be implied. However, an increase in accuracy may be obtained if corrected readings taken on both sides of the material are averaged.

X2.3.3.4 *Electrodes*—Electrode configurations will interact with specimen size and test objectives. The depth of field penetration for capacitive-admittance meters should be known, at least qualitatively (see also X2.3.3.1). Contact pressure of the electrode with the specimen may affect the meter response; the manufacturer's recommendations on contact pressure should be followed. The electrode sensing area should be small enough that the field will not extend beyond the specimen edge and large enough to provide reasonable integration. (For

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[5] Cech, M. Y., and Pfaff, F. "Moisture Content Correction Tables for Resistance-Type Moisture Meters," *Canadian Forestry Service, Eastern Forest Products Laboratory, Forestry Technical Report 7*, 1975.

example, if a nominal 2 by 4 is the smallest product size anticipated, the electrode could be sized to integrate over most of the wide face.) A symmetrical configuration is preferred for electrodes in order to minimize the effect of grain direction. Note that the basis of the meter calibration should be known, should be based on the measurement region of the electrode, and readings confined to specimens of this size or larger.

(1) Surface Moisture on Electrode—Surface films of moisture on the meter, particularly from condensation on the electrode, may cause abnormally high readings. Meters should be stored and used under non-condensing conditions.

X3. CONCEPTS OF CALIBRATION AND PREDICTION IN USE OF HAND-HELD MOISTURE METERS

X3.1 Concepts of Calibration

X3.1.1 Calibration of any measurement instrument assesses the bias of the instrument relative to an accepted standard. This bias then can be accommodated in any subsequent use of the data developed by the instrument to adjust as closely as feasible to the accepted standard response. The concept of calibration assumes that the "repeatability" of the instrument has been assessed with a standardization process against an accepted reference.

X3.1.2 *Referencing a Standard Method*—Calibration of hand-held meters are most usually conducted with Test Methods D4442, "Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Base Materials." This standard has several methods for direct measurement of moisture content. The method most often used for reference to hand-held meters is Section 6—Method B—Oven-Drying (Secondary). In this method, the specimen size is "any conveniently sized piece of wood..." (see Test Methods D4442, section 6.2). Consequently, Test Methods D4442 accepts any convenient sized specimen; thus, leaving the choice of the specimen to the user—presumably often the user of Test Methods D4444.

X3.1.3 *Meter Response*—Calibration of the hand-held meters meeting Test Methods D4444 criteria must reflect the operating characteristics of the meter with special attention to the volume of a specimen within which the instrument *actually responds* to moisture and makes a "measurement." This spacial volume of a specimen to which a meter will be sensitive can vary widely between meters of different operating principles (for example, capacitive-admittance versus conductance), meters operating on the same principles but with differing electrode sizes or spacings, meters with similar operating principles but differing parameters (for example, dielectric meters operating at differing frequencies).

X3.1.4 *Calibration versus Prediction*—In the context of much moisture meter use, a distinction should be drawn between *calibration* of a hand-held meter, the determination of the relationship between a meter reading and a Test Methods D4442 measurement—both *within the meter's spacial volume of measurement*—and *prediction*, the inferential process of estimating the moisture content of some volume of wood different from and larger than, or both, that sensed by the meter. While both of these processes are legitimate goals, they are significantly different. Prediction, for example, introduces concepts of sampling which, in turn, can be complicated by many wood variables that may not be within the meter's spacial volume of measurement. The most technically correct precision and bias statement for a hand-held meter should be based on measurements within the meter's spacial volume of measurement. On the other hand, for some applications, the most practical interest may be in the predictive relationship between a meter's limited reading and some larger specimen (for example, a length of lumber).

X3.1.4.1 Calibration tests have an element of prediction, even under the most careful experimental conditions. This element contains the errors of measurement. The distinction made in X3.1.4 is for the more gross predictive situations wherein non meter-measured moisture content (for example, the moisture content of a 20-ft piece of lumber) is estimated by a meter reading (for example, one reading taken 3 ft from the end of the piece).

X3.2 Calibration of Hand-Held Meters

X3.2.1 The goal of calibrating a hand-held meter based on measurement within the area of meter sensitivity is dependent upon knowledge of this area and the ability to sample it for the Test Methods D4442 measurement. An ideal calibration would sample this area accurately; however, often some estimations are needed because the boundaries of the area may be imprecise, being affected by wood variables and the practical issues of collecting the sample. The calibration resulting from this method relates directly the indication of the meter to the MC determined from Test Methods D4442. Often this is an oven dry reading that represents the average of the entire measurement region; however, the sample may be subdivided for gradient or other information.

X3.2.2 *Area of Measurement Sensitivity*—Defining the area of sensitivity of a meter is difficult, affected, as noted above, by wood and sampling variables. The manufacturer may have defined this area; if so, obtaining this information maybe an optimum approach for most users. Note the restrictions placed by the manufacturer upon the stated area: density, moisture content and other physical characteristics of the wood, equilibration of specimens used in the determination, and so forth. If the manufacturer does not supply an area of sensitivity, experiments can be conducted to ascertain this area. These experimental procedures are beyond the scope of this practice; however, Appendix X2 of this practice briefly discusses the effective measurement regions of meter electrodes.

X3.2.3 *Physical Sampling for D4442 Tests*—To compare the moisture content indicated by a moisture meter to that determined by Test Methods D4442 in the measurement area of the meter, delicate sampling is required. The wood specimen will require some form of dissection, carefully preserving the moisture within the dissected pieces. Including material from beyond the measurement region of the meter or, conversely, not including all of the measurement region in the physical sample, will bias the results of the comparison, perhaps in serious and an unknown quantitative degree, or both. Note the influence of insulated electrodes and other electrode geometries on sampling criteria.

X3.2.4 *Analysis*—The calibration of a meter in the region of measurement sensitivity is usually based on comparing the meter output to the Test Methods D4442 oven dry moisture value as an average for the sensitivity region. If the region has been subdivided for study of gradients or other variables, the reconstitution of the sample oven dry values to represent the entire region must reflect the fact that the meter may not be linear in response within the region.

X3.2.4.1 *Precision and Bias*—The measurements obtained in Appendix X3 provide a measure of the inherent measurement capability of a meter and can be used to estimate meter precision and bias. These characteristics provide the basis for the practical value of a meter; however, they often are not the ultimate values desired by many users. Section X3.3 discusses the uses of meters to make moisture content predictions—for which most meters are used.

X3.3 Prediction of Moisture Content Using Hand-Held Meters

X3.3.1 Practical interest in moisture content varies widely. Concerns may be focused small areas like the presence of “wet spots,” the influence of “kiln stickers” on moisture distribution in a piece of lumber, or the effect of rain penetration in a structure. Often, however, the hand meter reading is expected to represent an area of wood much larger than that actually measured. One example is using one reading per specimen in a lot of lumber to assess conformance to a moisture specification. Another example is taking a limited number of measurements on a piece of lumber for correlation with the readings of an in-line moisture meter that has a high frequency of reading (see Test Methods D6782). If a piece of lumber were perfectly uniform in moisture content and all physical variables in the wood were also perfectly uniform, the results of Section X3.2 would apply directly to the larger sample—no major prediction errors would be present. When the reality of the variability of wood characteristics and moisture distributions are considered, it is the wood sampling process, not meter characteristics, that introduces the primary prediction errors. The desire to make moisture predictions well beyond the measurement area requires the use of predictive techniques to quantify the risks associated with this essential process.

X3.3.2 *Defining the Sample*—When the desire is to estimate moisture content for wood beyond the measurement region of the meter, defining the sample to be measured for moisture—the sample intended to represent the targeted moisture content of the larger, untested population—may be one of the more difficult steps in the calibration of a moisture estimating process. This target has technical characteristics that must be appropriately replicated in the sample if the errors in estimation are to be minimized. In many practical applications, the sampling from the target population may also have a time component, thus further complicating the sampling. One example is the sampling of wood recently removed from a dry kiln which has a continuously decreasing but still measurable moisture gradient.

X3.3.2.1 Examples of typical industrial target populations and sampling carried out to estimate moisture content are:

(1) Goal—Predict the moisture content of lumber leaving a kiln while the lumber is still in the kiln.

(a) Target Population—All the lumber in a kiln charge. *Critical elements:* All the lumber is one cross section (for example, 2×4); each kiln cart may have a different length; often a species group—making estimation of actual species extremely difficult; kiln charge dryness affected by imperfect baffling/air flow and heating; lumber is hot and each piece has a moisture gradient.

(b) Sample—Exposed edges of stickered lumber within practical reach of kiln operator. *Critical elements:* Assumption that pieces sampled along the edges of the loads represent the target in physical properties affecting moisture measurement; sufficient sample size selected to include target characteristics.

(c) Comments—A prediction method is required that reflects the complexity of this problem—hot measurements must be related to room temperature; edge measurement and gradients must be related to flat measurement and gradients. Study of the temperature and spacial effects can be carried out on the same specimens; however, the overall goal will have a greater error due to the sampling attempting to represent the entire kiln charge. Note that the temperature correction is the only portion of this study that is directly related to meter performance; virtually all of the other issues are related to sampling adequacy, geometry, and time factors. To address these, a carefully designed study is required.

(2) Goal—Predict the near maximum (specification) moisture content of a unit of lumber.

(a) Target Population—A unit of 220 pieces of lumber selected by a third party to represent the mill production. *Critical elements:* Assumption that the unit selected represents mill production; this is not usually tested and is not a meter issue. The specificity and statistical adequacy of the moisture specification are critical to adequate sampling and interpretation of results. The uniformity of moisture measurement-affecting lumber characteristics throughout the population is important.

(b) Sample—Pieces selected by the third party for test. *Critical elements:* The sample size from the unit and it’s representativeness. The criteria used by the third party to select the sample pieces and locations on the pieces to make moisture measurements.

(c) Comments—A classic estimation study; meter performance is a minor issue, assuming proper standardization and calibration of the meter. The one exception is where the unit was selected in such a way that the meter sensitivity is biased and uncorrected (for example, a density-related grading system). If the specification is focused on a near maximum moisture content, rather than an average, estimation is more difficult. If the variability of moisture within pieces and

between pieces is not known or well estimated and an insufficient number of samples is selected, a simplistic analysis of sample results may have significant error. The assumption of the unit representing mill production is not tested.

(3) Goal—Predict the average moisture content of a piece of lumber.

(a) Target Population—A piece of lumber.
Critical elements: The moisture content may vary significantly within the length and cross section of the piece. The piece may have varying physical characteristics that affect moisture meter measurement.

(b) Sample—One or more locations along the piece.
Critical elements: Location of measurement relative to local wood characteristics such as compression wood, knots, slope of grain, wet spots, etc. Moisture gradients through the cross section. The specification may be critical (that is, when an average is the goal, are wet spots included in the calculation?). Selecting an adequate number of measurement locations depends on good estimates of moisture variability.

(c) Comments—Procedures that specify the number of measurement locations may be arbitrary; that is, not based on measurement or good estimation of within-piece variability. Experience with the moisture history of the piece may be critical (for example, the slowly declining gradient in recently kiln-dried material versus the possibility of post-dry wetting in field exposure). X3.3.2.1 *(3)* is important for field calibration of in-line moisture meters as well as in meeting acceptance specifications.

X3.3.3 *Determining the Sample Size*—Once the physical sample characteristics are defined, the sample size—the number of specimens or measurement locations—is determined. If a mean value is to be estimated, the precision and bias to be associated with the estimate must be chosen. An example is to accept a bias of ±0.5 % MC with 90 % confidence. To make the appropriate estimate, the expected variation of the measurement is needed; if no prior estimates are available, preliminary tests may be necessary. Practice D2915, section 3.4, provides guidance for this calculation. If a near maximum value is to estimated (for example, the upper 5th percentile of the population) so that an estimate may be made about the percent of the population above a specification limit, a non-parametric estimate of the percentile is most often used. To make this estimate, Practice D2915, section 3.4.3, offers methods using a tolerance limit concept.

NOTE X3.1—The Practice D2915 text usually refers to the lower tolerance limit, whereas with moisture measurement it is more common to need the estimate of the upper tolerance limit. The same concepts apply.

X3.3.3.1 Both X3.3.2 and X3.3.3 emphasize identification and selection of samples in order to obtain a credible estimate of moisture content. These concepts apply to both a meter measurement (Test Methods D4444) and a reference measurement (Test Methods D4442). If the variability of one of the two significantly exceeds the other, the sample size will be determined by the more variable of the two.

X3.3.4 *Developing the Predictive Relationship*—Sampling and measuring moisture content following the procedures of X3.3.2 and X3.3.3 can yield either mean or near-maximum values that characterize the population; however, these are single numbers and, aside from providing a ratio of meter to oven-dry, for example, may not provide the insights desired on these two methods relate. To explore this relationship, the individual data collected can be examined using regression and analysis of variance techniques. This requires dispersion in the data; that is, there must be sufficient range in the variables of interest (moisture content, density, etc.) to make an effective analysis. Again, the issue is one of both meter performance and estimation technique. For example, if the goal is to examine the effect of density on the relative performance of a meter versus oven-dry, a regression of the ratio of the two measurements taken at the same locations versus density could be instructive; however, there must be sufficient variability in density over the range of measurement locations to make the comparison meaningful. If the relationships of wood variables are only moderately robust (for example, $R^2 \sim 0.6$) care in selecting the sample is needed to ensure the effect of the variables can be adequately examined. Stratified sampling techniques may be needed. Correct design of the experiment anticipates the analysis to be used.

X3.3.4.1 *Precision and Bias*—The ASTM terms of precision and bias apply directly to the performance of a meter only in the area of its actual measurement. A majority of moisture meter uses go beyond this measurement and apply some concept of predictive function, although not often so stated. In Appendix X3, we have introduced the often-applied concepts of prediction to which a meter is most often linked—the "measurement" of the moisture content of an entire piece of lumber from a few actual measurements is, in actuality, not a "measurement," but a prediction ; the "measurement" (and acceptance) of the moisture content of a unit of lumber from the actual measurement in a few locations on a small sub-sample of pieces. All of these practical uses depend on both the inherent precision and bias of the meter, but, often more importantly, on the nature of the predictive relationship. Standard statistical methods use parameters, such as R, standard error, COV, etc., to demonstrate the effect of variables on predictive relationships; however, it is not correct to confuse the ASTM use of precision and bias of the instrument by incorporating those more broad concepts of sampling and analysis into the measurement capability of the instrument.

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