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Standard Guide for Nuclear Surface Moisture and Density Gauge Calibration[1]

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1. Scope*

1.1 *Procedure A*—This guide describes the process and objective of formulating the mathematical relationship between the density system count of a nuclear surface moisture and density gauge and the corresponding wet density value of the density standard upon which the density system response was observed.

1.2 *Procedure B*—This guide describes the process and objective of ~~calibrating~~comparing the wet density ~~system of~~measured by a nuclear surface moisture and density ~~gauge, or formulating the mathematical relationship between the density system response (the "density count") of a nuclear surface moisture and density~~ gauge and the corresponding density value of the density standard upon which the density system response was observed.

1.3 This guide describes the process and objective of the verification of the measurements of a nuclear surface moisture and density gauge.

1.4 *Procedure A*—This guide describes the process and objective of ~~calibrating the water content system of a nuclear surface moisture and density gauge, or~~ formulating the mathematical relationship between the water content system ~~response (the "water content count")~~ count of a nuclear surface moisture and density gauge and the corresponding water mass per unit volume value of the water content standard upon which the water content system response was observed.

1.5 *Procedure B*—This guide describes the process and objective of ~~verifying the density system of~~ comparing the water mass per unit volume measured by a nuclear surface moisture and density ~~gauge.~~gauge and the corresponding water mass per unit volume of the corresponding water content standard upon which the water content system response was observed.

1.6 This guide describes the process and objective of ~~verifying the water content system of~~ the verification of the measurements of a nuclear surface moisture and density gauge.

1.7 This guide describes two mathematical processes by which the gauge measurement precision may be computed or measured.

1.8 This guide offers guidance for developing and reporting estimates of uncertainties in measurements made with gauges that have undergone calibration ~~or~~and verification.

1.9 All observed and calculated values shall ~~confirm~~conform to the guide for significant digits and rounding established in Practice D6026.

[1] This practice is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.08 on Special and Construction Control Tests.

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***A Summary of Changes section appears at the end of this standard**

1.10 *Units*—The values stated in either SI units or ~~inch pound~~ inch-pound units are to be regarded separately as standard. The values stated in each system ~~may~~are not ~~be~~necessarily exact equivalents; therefore, to ensure conformance with the standard, each system shall be used independently of the ~~other. Combining~~other, and values from the two systems ~~may result in non-conformance with the standard.~~shall not be combined. Within the text of this standard, SI units appear first followed by the inch-pound (or other non-SI) units in brackets.

1.10.1 Reporting of test results in units other than SI shall not be regarded as nonconformance with this guide.

1.11 *This ~~guide~~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 ~~guide~~standard to establish appropriate ~~safety~~ safety, health, and ~~health~~environmental practices and determine the applicability of regulatory limitations prior to use.*

1.12 This guide offers an organized collection of information or a series of options and does not recommend specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.

1.13 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D6026 Practice for Using Significant Digits in Geotechnical Data

D6938 Test Methods for In-Place Density and Water Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)

~~D7013~~D7013/D7013M Guide for Calibration Facility Setup for Nuclear Surface Gauges

D8167/D8167M Test Method for In-Place Bulk Density of Soil and Soil-Aggregate by a Low-Activity Nuclear Method (Shallow Depth)

3. Terminology

3.1 *Definitions*—See Terminology D653 for general definitions. For definitions of common metrology terms used in this standard, refer to the VIM—International Vocabulary of Metrology.[3]

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *~~coverage factor~~density system, ~~—~~calibration, n*—a ~~number larger than one by which a combined standard measurement uncertainty is multiplied to obtain an expanded measurement uncertainty.~~set of processes by which, for each density standard used in the process, a density indication (gauge count or gauge density response) is obtained by the nuclear gauge on the density standard, and a relationship is established between the indications of the gauge and the density of the standard; the uncertainty of the standard and the indication must be established.

~~3.2.2 *definitional uncertainty*[3], *n*—the component of measurement uncertainty resulting from the finite amount of detail in the definition of the measurand. The "measurand" in the case of a nuclear surface moisture density gauge, is typically either in-place density or water mass per unit volume.~~

3.2.2 *density ~~system calibration,~~calibration equation, n*—the ~~method by which the values of the fit parameters in the equation~~

[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.

[3] ~~JCGM 200:2008: International Vocabulary of Metrology—Basic and General Concepts and Associated Terms (VIM). 2008: Joint Document Committee for Guides in Metrology.~~*International vocabulary of metrology—Basic and general concepts and associated terms (VIM)*, 3rd Edition. Joint Committee for Guides in Metrology, 2012. https://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf

mathematical function that relates the density ~~system response (the "density count") of a nuclear gauge and the corresponding density value of the density standard upon which that density system response was observed are computed. In addition, the uncertainty of measurements taken with gauges calibrated by the specific method must be known at representative density values that span the range of densities for which the calibration is valid.~~of the medium under measurement by the gauge (the independent variable) to the density system count response of the gauge (the dependent variable).

3.2.3 *density system verification, n*—a set of ~~operations or processes, or both, by which, for each density standard used in the process, the in-place density value(s) measured by the nuclear gauge on the density standard is related to the corresponding value(s) of the standard or standards. In addition, the uncertainty of measurements taken with gauges that meets the established verification criterion or criteria must be known at representative densities that span the range of densities for which the verification is valid.~~processes by which the acceptability of the associated density calibration equation of a gauge is determined.

~~3.2.5 *detector, n*—a device to detect and measure radiation.~~

~~3.2.6 *expanded measurement uncertainty*[3], *n*—product of a combined standard measurement uncertainty and a coverage factor larger than one.~~

~~3.2.7 *gamma (radiation) source, n*—a sealed source of radioactive material that emits gamma radiation as it decays.~~

~~3.2.8 *in-place density, n*—the total mass (solids plus water) per total volume of soil or soil-aggregates measured in place.~~

~~3.2.9 *measurement uncertainty*[3], *n*—non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand. The "measurand" in the case of a nuclear surface moisture density gauge, is typically either in-place density or water mass per unit volume.~~

~~3.2.10 *neutron (radiation) source, n*—a sealed source of radioactive material that emits neutron radiation as it decays.~~

3.2.4 *nuclear gauge, n*—a device containing one or more radioactive sources used to measure certain properties of soil and soil-aggregates.

3.2.5 *prepared standards, n*—density or water content measurement standards prepared of soil, solid rock, concrete, and engineered materials, that have density or water content values, or both, that are established and known to a specified uncertainty.

3.2.6 ~~*standard measurement uncertainty*~~*soil-equivalent density, n*—~~measurement uncertainty expressed as a standard deviation.~~ the density of an average soil (where an "average soil" is defined herein to have a Z/A value of 0.5) that yields the same gauge density count response as a metallic calibration standard; Z is the average atomic number of a material and A is the average atomic mass number of that same material.

~~3.2.14 *test count, N, n*—the measured output of a detector for a specific type of radiation for a given test.~~

~~3.2.15 *Type A Uncertainty Evaluation*[3], *n*—evaluation of a component of measurement uncertainty by a statistical analysis of measured quantity values obtained under defined measurement conditions.~~

~~3.2.16 *Type B Uncertainty Evaluation*[3], *n*—evaluation of a component of measurement uncertainty by means other than a Type A Evaluation.~~

~~3.2.17 *volumetric water content, n*—the volume of water as a percent of the total volume of soil or rock material.~~

~~3.2.18 *water content, n*—the ratio of the mass of water contained in the pore spaces of soil or soil-aggregate, to the solid mass of particles in that material, expressed as a percentage (*this is sometimes referred to in some scientific fields as gravimetric water content to differentiate it from volumetric water content*).~~

3.2.7 *water content system calibration, n*—~~the method by which the values of the fit parameters in the equation that relates the water content system response (the "water content count") of a nuclear~~ a set of processes by which, for each water content standard

used in the process, a water mass per unit volume indication (gauge count or water mass per unit volume value) is obtained by the nuclear gauge on the water content standard, and a relationship is established between the indication of the gauge and the ~~corresponding~~ water mass per unit volume value of the ~~water content standard upon which that water content system response was observed are computed. In addition,~~ standard; the uncertainty of ~~measurements taken with the gauges calibrated by the specific method must be known at representative water mass per unit volume values that span the range of water mass per unit volume values for which the calibration is valid.~~the standard and the indications must be established.

3.2.8 *water mass per unit volume calibration equation, n*—the mathematical function that relates the water mass per unit volume of the medium under measurement by the gauge (the independent variable) to the water content system count response of the gauge (the dependent variable).

3.2.9 *water content system verification, n*—a set of ~~operations or processes, or both, by which, for each water content standard used in the process, the in-place water mass per unit volume value(s) measured by the nuclear gauge on water content standard is related to the corresponding value(s) of these standards. In addition, the uncertainty of measurements taken with gauges that meets the established verification criterion or criteria must be known at representative~~ processes by which the acceptability of the water mass per unit volume ~~values that span the range of water mass per unit volume values for which the verification is valid.~~calibration equation of a gauge is determined.

~~3.2.21 *water mass per unit volume, n*—the ratio of the mass of water contained in the pore spaces of a soil or soil-aggregate to the total volume occupied by that soil or rock material.~~

4. Summary of Practice

4.1 The ~~objectives~~summary of the practice ~~are~~is as follows:

4.1.1 *Procedure A*—~~The objective of~~ For new gauges and gauges that fail to meet the required density system ~~calibration~~verification ~~is to formulate a mathematical equation, or~~criteria, for each affected index rod position ~~density calibration equation,~~one must perform ~~that~~a **density calibration** in which one relates the gauge density system response (the ~~"density count"~~)gauge counts) to the soil-equivalent density of the ~~standard~~standard(s) on which ~~this response is elicited. The maximum uncertainties of subsequent gauge density readings shall be determined for~~the response is elicited and, in a second step, uses this information to establish a ~~the~~ **calibration process equation.**~~that is used. The standards used for the determination of uncertainty shall be representative of the range of densities for which the gauge will be used.~~

4.1.1.1 The measurement uncertainties of the density standard(s) and the gauge density system counts must be known.

4.1.1.2 The standard(s) used for the determination of uncertainty shall be representative of the range of densities for which the gauge will be used.

4.1.1.3 The mode of density calibration just described is not limited to new gauges or gauges that fail to meet the required density system verification criteria.

4.1.2 *Procedure B*—For gauge index rod positions for which a density calibration equation has been formulated, one has the option of performing a **density calibration** in which one establishes the relation between the soil-equivalent density values of the necessary number of soil-equivalent density standard(s) and the corresponding soil-equivalent density measured by the gauge when used to measure the standards and, in a second step, uses this information to establish the relationship between these two density values.

4.1.2.1 The measurement uncertainties of the density standards and the density measured by the gauge must be known.

4.1.2.2 The standard(s) used for the determination of uncertainty shall be representative of the range of densities for which the gauge will be used.

4.1.3 The objective of density system **verification** is to evaluate the current density calibration equation for the gauge and determine if new calibration constants are required.

4.1.4 *Procedure A*—~~The objective of density system~~ For new gauges and gauges that fail to meet the required water content system verification criteria, one must perform a ~~**verification**~~**water content calibration** ~~is to evaluate the current density calibration equation for the gauge and determine if a new calibration is required. The verification method will be based upon relating, at the~~

~~pertinent density or densities for the specific method, the density value of a known density standard to the density measured by the gauge. The maximum uncertainties of subsequent gauge density readings shall be determined for the verification method used. The standards used for the determination of uncertainty shall be representative of the range of densities for which~~in which one establishes the relation between the water mass per unit volume of the necessary number of water content standard(s) and the corresponding water system gauge counts elicited from the gauge when used to measure these standards and, in a second step, uses this information to establish a ~~**the gauge**~~ **calibration equation.**~~will be used.~~

4.1.4.1 The measurement uncertainties of the water content standard(s) and the gauge counts must be known.

4.1.4.2 The standard(s) used for the determination of uncertainty shall be representative of the range of water mass per unit volume for which the gauge will be used.

4.1.4.3 The mode of water content system calibration just described is not limited to new gauges or gauges that fail to meet the required water content system verification criteria.

4.1.5 *Procedure B*—~~The objective of water content system~~For gauges for which the calibration constants of a water mass per unit volume calibration ~~is to formulate a mathematical equation, or~~ equation have been formulated, one may perform a **water content calibration** ~~**equation,** that relates the gauge water content system response (the "water content count") to~~ in which one establishes the relation between the water mass per unit volume value of the ~~standard on which this response is elicited. The uncertainties of subsequent gauge water mass per unit volume readings shall be known for, at a minimum, a~~ necessary number of water content standard(s) and the corresponding water mass per unit volume ~~level within 32 kg/m~~measured by ~~^{3} [2.0 lbm/ft^3] of the upper extreme of the~~ the gauge when used to measure these standard(s) and, in a second step, uses this information to establish the relationship between these two water mass per unit volume ~~calibration range (typically 300 kg/m~~values.~~^{3} [18.7 lbm/ft^3] or higher).~~

4.1.5.1 The measurement uncertainties of the water content standards and the water mass per unit volume measured by the gauge must be known.

4.1.5.2 The standards used for the determination of uncertainty shall be representative of the range of water mass per unit volume values for which the gauge will be used.

4.1.6 The objective of water content system **verification** is to evaluate the current water content ~~system~~ calibration equation for the gauge and determine if ~~a new calibration is required. This evaluation will be based upon relating, at the pertinent water mass per unit volume values for the specific method, the water mass per unit volume value of a known water mass per unit volume standard to the water mass per unit volume value measured by the gauge. The uncertainties of subsequent gauge water mass per unit volume readings shall be known for, at a minimum, a water mass per unit volume level within 32 kg/m~~new calibration constants are required.~~^{3} [2.0 lbm/ft^3] of the upper extreme of the water mass per unit volume calibration range (typically 300 kg/m^3 [18.7 lbm/ft^3] or higher).~~

~~4.1.5 The density calibration equation relates the in-place density value measured by the gauge on a test site (the "independent variable") with the density test count measured by the gauge on the test site (the "dependent variable") is typically exponential or polynomial in form, with three fit coefficients.~~

4.2 ~~Historically, the most successful methods for calibrating the density system of a gauge is done by taking gauge density readings on three or more density standards, combining the independent and dependent variables into data pairs, and using a least-squares or Newton-Rafson fitting algorithm with these data pairs to compute the fit coefficients. These density standards have unique density values that span the range of densities for which the gauge will be used.~~The density calibration equation relates the wet density value measured by the gauge on a test site (the "independent variable") with the density test count measured by the gauge on the test site (the "dependent variable") and is typically exponential or polynomial in form, with three fit coefficients.

4.2.1 ~~The density system calibration~~ Historically, the most successful methods for computing the density calibration equation for the density system of a gauge is ~~not necessarily limited to the process described in~~done by taking gauge density readings on three or more density standards, combining the independent and dependent ~~4.2. However, for any method that is used in the density system calibration process, one must know the uncertainties of the in-place density readings measured by devices calibrated in this manner over~~ variables into data pairs, and using a least-squares or Newton-Raphson fitting algorithm with these data pairs to compute the fit coefficients. These density standards have unique density values that span the range of ~~density values~~ densities for which the gauge will be used.

4.2.2 ~~For~~ The computation of the density calibration equation is not necessarily limited to the process described in 4.2.1. However,

for any method that is used in the density system ~~verification~~calibration process, one must know the uncertainties of the ~~in-place~~wet density readings measured by devices calibrated in this manner over the range of density values for which the gauge will be used.

4.2.3 The water content calibration equation that relates the ~~in-place~~ water mass per unit volume value measured by the gauge on a test site (the "independent variable") with the water ~~content~~ mass per unit volume test count measured by the gauge on the test site (the "dependent variable") is typically linear in form, with two fit coefficients.

4.3 Historically, the most successful method for ~~calibrating~~computing the water content ~~system~~ calibration equation of a gauge is by taking readings on two water content standards (one of which is a zero water content standard), combining the independent and dependent variables into data pairs, and ~~using a least-squares or fitting algorithm with these data pairs to compute~~ computing the fit coefficients.

4.3.1 The computation of the water content ~~system calibration of a gauge~~ calibration equation is not necessarily limited to the process described in 4.3. However, for any method that is used in the water content system calibration process, one must know the uncertainties of the water mass per unit volume readings measured by devices calibrated in this manner over the range of water mass per unit volume values for which the gauge will be used.

~~4.3.2 For any method that is used in the water content system verification process, one must know the uncertainties of the water mass per unit volume readings measured by devices calibrated in this manner over the range of mass per unit volume values for which the gauge will be used.~~

4.4 See Appendix X1 for a flowchart of the calibration and verification processes.

5. Significance and Use

5.1 Gauge calibration is performed for the following purposes:

5.1.1 ~~To formulate a mathematical equation, or density calibration equation,~~When necessary, to compute the calibration constants of a density calibration equation that relates the gauge density system response (the "density count") to the soil-equivalent density of the standard on which this response is elicited.

5.1.2 ~~To formulate a mathematical equation, or~~ When necessary, to compute the calibration constants of a water content calibration ~~equation,~~equation that relates the gauge water content system response (the "water content count") to the water mass per unit volume value of the standard on which this response is elicited.

5.1.3 To establish the relationship between the density measured by the gauge to the soil-equivalent density of the standard on which this response is elicited.

5.1.4 To establish the relationship between the water mass per unit volume measured by the gauge to the water mass per unit volume of the standard on which this response is elicited.

5.1.5 To ensure that the gauge has an in-place density gauge precision level that is consistent with typical gauge response.

5.1.6 To ensure that the gauge has an in-place water mass per unit volume gauge precision level that is consistent with typical gauge response.

5.2 Gauge verification is performed for the following purposes:

5.2.1 To indicate to the party or agency performing the verification when the mathematical relationship between the in-place density reading indicated by the gauge and the corresponding gauge density test count needs to be adjusted so that the gauge ~~calibration meets the required level of measurement uncertainty.~~measurement errors do not exceed the specified absolute maximum measurement error for the calibration method used.

5.2.2 To indicate to the party or agency performing the verification when the mathematical relationship between the water mass per unit volume indicated by the gauge and the corresponding gauge water content test count needs to be adjusted so that the gauge ~~calibration meets the required level of measurement uncertainty.~~measurement errors do not exceed the specified absolute maximum measurement error for the calibration method used.

5.2.3 Gauge verification and calibration require specialized training and equipment. Gauge calibration and verification ~~should only be~~ are best conducted by those trained in the proper operation of the gauge, the calibration ~~or verification~~ standards, and any tables, charts, graphs, or computer programs required for the proper execution of these operations.

NOTE 1—The quality of the result produced by this standard is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with Practice D3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.

6. Interferences

6.1 Gauge calibration ~~and verification should~~ shall be performed in an area where the gauge being calibrated can be protected from the outside influences of and background radiation from other nuclear gauges.

6.2 Gauge calibration ~~and verification should~~ shall be performed in an area where any walls surrounding or in ~~close~~ proximity to the gauge do not cause reflected radiation that can be detected by the gauge.

6.3 Consult Guide ~~D7013~~D7013/D7013M ~~should be consulted~~ in its entirety to ensure that the calibration area is configured properly and that the interferences described in 6.1 and 6.2 can be avoided.

6.4 The accuracy and duration of gauge calibrations ~~or verifications~~ may be seriously compromised if the gauge has not undergone routine maintenance or proper servicing prior to ~~calibration or verification.~~calibration.

7. Apparatus

7.1 *Nuclear Density/Moisture Gauge*—While exact details of construction of the apparatus may vary, the system shall consist of:

7.1.1 *Gamma Source*—A sealed source of high-energy gamma radiation such as cesium or radium.

7.1.2 *Gamma Detector*—Any type of gamma detector such as a Geiger-Mueller tube(s).

7.1.3 *Fast Neutron Source*—A sealed mixture of a radioactive material such as americium, radium, and a target material such as beryllium, or a neutron emitter such as californium-252.

7.1.4 *Slow Neutron Detector*—Any type of slow neutron detector such as boron trifluoride or helium-3 proportional counter.

7.2 *Gauge Reference Standard*—A block of material used for checking instrument operation, correction of source decay, and to establish conditions for a reproducible reference count rate.

7.3 *Density Reference Standard*—A standard of a known in-place density value (or values) with a known uncertainty (or uncertainties) that can be used in the process of calibrating ~~or~~and verifying the density systems of a nuclear density/moisture gauge.

7.4 *Water Content Reference Standard*—A standard of a known in-place water mass per unit volume value (or values) with a known uncertainty (or uncertainties) that can be used in the process of calibrating ~~or~~and verifying the water content system of a nuclear density/moisture gauge.

7.5 *Probe*—A slender, elongated device, part of the gauge that is inserted into the soil under measurement by the gauge. This device may contain either a radioactive source, a radiation detection device, or both. Probes containing only a radioactive source are commonly referred to as "source rods."

8. Hazards

8.1 These gauges utilize radioactive materials that may be hazardous to the health of the users unless proper precautions are taken. Users of these gauges must become familiar with applicable safety procedures and government regulations.

8.2 Effective user instructions, together with routine safety procedures and knowledge of and compliance with ~~Regulatory Requirements,~~regulatory requirements, are a mandatory part of the operation and storage of these gauges.

9. Density Systems ~~Calibration~~Calibration, Procedure A (Curve Fitting Method)

~~9.1 The density systems of the gauge shall undergo a *calibration* initially after manufacture and subsequently after any repairs or modifications that can affect the gauge geometry or the accuracy of the existing calibration curve.~~

9.1 Each depth at which the nuclear gauge is able to take a density measurement has its own independent density system, and each of these density systems requires a distinct ~~calibration initially after manufacture and subsequently after any repairs or modifications that can affect the gauge geometry or the accuracy of the existing calibration curve.~~and independent calibration. The methods described herein as Procedure A, or the methods described in Procedure B, may be followed.

9.2 The ~~calibration of a given density system consists of the computation~~ density systems of the gauge shall undergo the calibration method described in 4.1.1~~and deployment of the mathematical formula that relates the in-place density value measured by the gauge on a density standard (the "independent variable") with the density test count measured by the gauge on a density standard (the "dependent variable"). The resulting fit parameters of this formula are commonly referred to as the "calibration constants" for the density system.~~, Procedure A, after manufacture and subsequently after any repairs or modifications that can affect the gauge geometry or the accuracy of the existing calibration equation, or at the discretion of the gauge owner or the calibrating agency.

9.2.1 The calibration of a given density system by Procedure A consists of the computation and deployment of the mathematical formula that relates the in-place wet density value measured by the gauge on a density standard (the "independent variable") with the density test count measured by the gauge on a density standard (the "dependent variable"). The resulting fit parameters of this formula are commonly referred to as the "calibration constants" for the density system.

9.2.2 The mathematical formula that is computed as the result of the calibration of a density system should be stored in the memory of the gauge, printed on tables, or shown graphically in such a manner that the test readings acquired with the gauge can be used in the formula to compute the corresponding in-place density value, either by the user or by the instrument itself.

9.2.3 Whereas the process used to compute the calibration constants for a gauge density systems is at the discretion of the party or agency performing the calibration, the selected process for computing the calibration constants should comply with the requirements of 4.2.2.

9.2.4 This density system calibration may be done by the gauge manufacturer, the user, or an independent vendor.

~~9.4 The mathematical formula that is computed as the result of the calibration of a density system should be stored in the memory of the gauge, printed on tables, or shown graphically in such a manner that the test readings acquired with the gauge can be used in the formula to compute the corresponding in-place density value, either by the user or by the instrument itself.~~

~~9.5 The method and test procedure used in collecting the density test count data to be used in the density calibration constant formulation shall be the same as those used for obtaining the field test count data.~~

~~9.6 The density system calibration may be done by the gauge manufacturer, the user, or an independent vendor.~~

~~9.7 Whereas the process used to calibrate the gauge density systems is at the discretion of the party or agency performing the calibration, the calibration process should comply with the requirements of 4.2.1.~~

~~9.8 For a density system that has just completed a density system calibration, the maximum permissible measurement error for in place density measured by the gauge on a density standard used in the calibration typically does not exceed 16 kg/m^3 [1 lbm/ft^3] of the density value assigned to the standard. This assigned density of this standard is based upon the density response of a typical gauge of this type on the standard.~~

~~9.9 For any specific density system calibration process, the uncertainty in density measurements over the range of densities for~~

~~which gauges calibrated in this manner are used shall be known. Uncertainties shall be known for a single maximum uncertainty value applicable to the entire density range of the gauge, or, at a minimum, one value from each of the following three density levels:~~

~~9.9.1 At a density level within 5 % of the lower extreme of the density calibration range (typically 1755 kg/m^3 [109.6 lbm/ft^3]).~~

~~9.9.2 At a density level within 5 % of the mid value of the density calibration range (typically 2145 kg/m^3 [133.9 lbm/ft^3]).~~

~~9.9.3 At a density level within 5 % of the upper extreme of the density calibration range (typically 2612 kg/m^3 [163.1 lbm/ft^3]).~~

~~9.10 Using the procedure described in either 15.1.1 or 15.1.2, ensure a gauge count precision of at least one-half the gauge count precision required for field use, assuming field use measurement of one-minute duration.~~

~~9.11 The density system of the gauge shall undergo a calibration or a verification at periods not to exceed twelve months.~~

10. Density Systems Calibration, Procedure B (Direct Comparison Method)

10.1 Any gauge density system that already has an established calibration equation from the past performance of the calibration method Procedure A may undergo the Procedure B calibration procedure described herein without first repeating the calibration method Procedure A.

10.2 This calibration procedure of a given density system consists of directly observing the relationship between the in-place density value measured by the gauge on a density standard and the soil-equivalent wet density of the density standard.

10.3 Whereas the procedure (A or B) used to calibrate the gauge density system is at the discretion of the party or agency performing the calibration, the selected calibration process shallcomply with the requirements of 4.1.1.1 - 4.1.1.3 or 4.1.2.1 - 4.1.2.2.

10.4 This density system calibration may be done by the gauge manufacturer, the user, or an independent vendor.

11. Density Systems Calibration, Estimated Measurement Uncertainties

11.1 For any specific density system that undergoes either the Procedure A or Procedure B calibration method, the uncertainty in density measurements over the range of densities for which gauges calibrated in this manner are used shall be known. Uncertainties shall be known for a single maximum uncertainty value applicable to the entire density range of the gauge, or one value from each of the following three density levels:

11.1.1 At a density level within 5 % of the lower extreme of the density calibration range (typically 1755 kg/m^3 [109.6 lbm/ft^3]).

11.1.2 At a density level within 5 % of the mid value of the density calibration range (typically 2145 kg/m^3 [133.9 lbm/ft^3]).

11.1.3 At a density level within 5 % of the upper extreme of the density calibration range (typically 2612 kg/m^3 [163.1 lbm/ft^3]).

NOTE 2—In 11.1, *three* density levels are specified as points at which the gauge density measurement uncertainty must be knows for the specific calibration method. Three points are used because, at a minimum, three points define the mathematical form of the calibration equation for the density measurement system. The values of the three ranges were selected to reflect the range of the typical low density, mid density, and high density calibration standards used for the calibration of these gauges.

12. Density Systems Verification

12.1 ~~For gauges that have undergone at least one previous density systems calibration and have not undergone any repairs or modifications that can affect the gauge geometry or the accuracy of the existing calibration curve, one may perform a density systems verification in lieu of a density system calibration. The frequency of density systems calibrations is given in~~The verification of the density system means that it fulfills specified requirements. Those specified requirements are that the measurement errors of the wet density readings obtained by the calibrated gauge under specified conditions do not ~~9.11.~~ exceed a specified density value.

~~10.2 The density system verification may be done by the gauge manufacturer, the user, or an independent vendor.~~

12.2 ~~For any specific density system verification process, the uncertainty in density measurements over the range of densities for which gauges verified in this manner are used shall be known. Uncertainties shall be known for a single maximum uncertainty value applicable to the entire density range of the gauge, or, at a minimum, one value from each of the following three density levels:~~The verification for a density system of the gauge shall be performed at the conclusion of either Procedure A or Procedure B calibrations.

~~10.3.1 At a density level within 5 % of the lower extreme of the density calibration range (typically 1755 kg/m^3 [109.6 lbm/ft^3]).~~

~~10.3.2 At a density level within 5 % of the mid value of the density calibration range (typically 2145 kg/m^3 [133.9 lbm/ft^3]).~~

~~10.3.3 At a density level within 5 % of the upper extreme of the density calibration range (typically 2612 kg/m^3 [163.1 lbm/ft^3]).~~

12.3 ~~For a density system that has just completed a successful density system verification, the maximum permissible measurement error for in place density measured by the gauge on a density standard typically does not exceed 32 kg/m~~The verification process for a calibration performed using Procedure A may be accomplished by next performing the calibration procedure defined in Procedure B for each density system, then computing the absolute measurement error for each comparison ^{3} ~~[2 lbm/ft^3]~~ of the density value ~~assigned to the standard. This assigned density of this standard is based upon the density response of a typical gauge of this type on the standard.~~measured by the gauge and the associated soil-equivalent density of the density standard upon which the measurement was made.

~~NOTE 2—In 9.9 and 10.3, *three* density levels are specified as points at which the gauge density measurement uncertainty must be knows for the specific calibration method. Three points are used because, at a minimum, three points define the mathematical form of the calibration curve for the density measurement system. The values of the three ranges were selected to reflect the range of the typical low density, mid density, and high density calibration standards used for the calibration of these gauges.~~

12.3.1 In the instance where the density system verification process follows 12.3, the maximum permissible absolute measurement error for in place density measured by the gauge on a density standard used in the calibration process typically does not exceed 16 kg/m^3 [1 lbm/ft^3] of the density value assigned to the standard. This assigned density of this standard is based upon the density response of a typical gauge of this type on the standard.

12.4 In the instance where the density system calibration is performed using Procedure A and the verification process is performed using other empirical, historical, or statistical evaluations not directly related to the empirical method described in 12.3, the maximum permissible absolute measurement error for in place density calculated by this method on a density standard typically does not exceed 16 kg/m^3 [1 lbm/ft^3] of the density value assigned to the standard. This assigned density of this standard is based upon the density response of a typical gauge of this type on the standard.

12.5 In the instance where the density system calibration was performed using Procedure B and new calibration constants were **not** computed prior to this calibration, the maximum permissible absolute measurement error for in place density calculated by this method on a density standard typically does not exceed 32 kg/m^3 [2 lbm/ft^3] of the density value assigned to the standard. This assigned density of this standard is based upon the density response of a typical gauge of this type on the standard.

12.6 In instances where there are more than three density calibration standards used in either a Procedure A or Procedure B calibration, the permissible absolute measurement error could exceed the values described in 12.3 through 12.5 due to regression errors and/or regression residuals.

12.7 Failure to meet the specified measurement errors requires that the calibration constants be calculated again, so Calibration Procedure A must be performed.

12.8 The density content system of the gauge shall undergo a calibration and verification at periods not to exceed twelve months.

13. Standards Used for Density Systems Calibration ~~and Verification~~

13.1 The density value(s) of any manufactured metallic, natural stone, or non-soil standard used in the calibration ~~or verification~~

of the density system of the gauge shall be determined in such a manner that the estimated standard deviation of the measurement results used in this determination shall not exceed ~~0.5%~~0.5 % of the measured standard density or densities.

13.2 The density value(s) assigned to a standard that is comprised of materials that have the potential to change over time in density, such as soil, concrete, or solid rock, typically need to be reestablished or verified at periods not exceeding twelve months. If the standard material is shown to maintain its density within the estimated standard deviation described in ~~11.1~~13.1 for the environment in which it is stored and used, then the reestablishment or verification period can be extended accordingly.

13.3 The density response of a nuclear gauge is influenced by both the density of the material and the elemental composition of the material. The contribution of the elemental composition of the material to the density response of the gauge must be taken into consideration when establishing the density value of a density standard.

NOTE 3—Different nuclear density calibration techniques often utilize different nuclear physics principles to determine how the elemental composition of the material influences the density response of the instrument. As a result, there may be a statistically significant bias between the density values read between gauges that are calibrated using different density calibration techniques. Consequently, gauge users who take measurements with gauges calibrated using different density calibration techniques may need to adjust measurement results to compensate for this bias.

~~NOTE 3—Different nuclear density calibration techniques often utilize different nuclear physics principles to determine how the elemental composition of the material influences the density response of the instrument. As a result, there may be a statistically significant bias between the density values read between gauges that are calibrated using different density calibration techniques. Consequently, gauge users who take measurements with gauges calibrated using different density calibration techniques may need to adjust measurement results to compensate for this bias.~~

13.4 If the density standard is a solid block of material, the physical dimensions of the density standard ~~should~~shall be sufficient in size so that the count rate of the gauge used to read the standard will not change if the standard is enlarged in any dimension. Otherwise, follow the block manufacturer's recommendations; lateral abutting plates or other density standards may be positioned so that the count rate will not be affected.

NOTE 4—For density standards that are solid blocks of material, minimum surface dimensions of approximately 610 by 430 mm [24 by 17 in.] have proven satisfactory. For the backscatter method a minimum depth of 230 mm [9 in.] is adequate; while for the direct transmission method the depth shall be at least 50 mm [2 in.] deeper than the deepest rod penetration depth. A larger surface area may be necessary for the backscatter/air-gap method. For blocks with widths or lengths smaller than the sizes specified, follow the block manufacturer's recommendations for proper installation and use.

The most successful standards that have been established for density system calibration and verification have been blocks made of magnesium, aluminum, aluminum/magnesium, granite, and limestone. These blocks have been used in combination with each other, with historical equation information, and with other prepared block(s) to produce accurate and reliable density system adjustments and calibrations.

~~NOTE 4—For density standards that are solid blocks of material, minimum surface dimensions of approximately 610 by 430 mm [24 by 17 in.] have proven satisfactory. For the backscatter method a minimum depth of 230 mm [9 in.] is adequate; while for the direct transmission method the depth should be at least 50 mm [2 in.] deeper than the deepest rod penetration depth. A larger surface area should be considered for the backscatter/air-gap method. For blocks with widths or lengths smaller than the sizes specified, follow the block manufacturer's recommendations for proper installation and use.~~

~~The most successful standards that have been established for density system calibration and verification have been blocks made of magnesium, aluminum, aluminum/magnesium, granite, and limestone. These blocks have been used in combination with each other, with historical curve information, and with other prepared block(s) to produce accurate and reliable density system adjustments and calibrations.~~

14. Water Content System ~~Calibration~~Calibration, Procedure A (Curve Fitting Method)

14.1 The water content system of the gauge shall undergo ~~a calibration~~ the calibration method described in 4.1.4 initially after manufacture and subsequently after any repairs or modifications that can affect the gauge geometry or the accuracy of the existing calibration ~~curve.~~equation.

14.2 ~~The~~This calibration of a water content system consists of the computation of and deployment of the mathematical formula that relates the water mass per unit volume value measured by the gauge on a water content standard (the "independent variable") with the water content test count measured by the gauge on a water content standard (the "dependent variable"). The resulting fit parameters of this formula are commonly referred to as the "calibration constants" for the water content system.

14.3 The mathematical formula that is computed as the result of a calibration of the water content system ~~should~~shall be stored in the memory of the gauge, printed on tables, or shown graphically in such a manner that the test readings acquired with the gauge can be used in the formula to compute the corresponding water mass per unit volume value, either by the user or by the instrument itself.