Soil Water Measurement by Neutron Thermalization

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INTRODUCTION

Nearly 50 yr after its first use, the neutron thermalization method remains the best available method for repeated measurement of soil profile volumetric water content[1] because it is nondestructive, can be field calibrated with high precision, works successfully to depths not easily attained with other methods, and works well in stony soils and cracking clays in which other methods work poorly. Also, the large volume of measurement means that fewer replicates are required than for other methods to produce a given precision, that soil disturbance during tube installation has minimal effect on results (unlike electronic sensor methods), and that field calibration is successful because volumetric soil samples can be obtained from within the volume measured by the probe at each depth (unlike electronic methods used in access tubes that have much smaller measurement volumes). The technology is mature with a wide literature base describing applications and problems.

The neutron thermalization method employs a radioactive source of fast neutrons (mean energy of 5 MeV) and a detector of slow neutrons (~0.025 eV or 300°K). High energy neutrons emitted from the source (~10^9/s) are either slowed through repeated collisions with the nuclei of atoms in the soil (scattering and thermalization), or are absorbed by those nuclei. A small fraction of scattered neutrons will be deflected back to the detector. Of these, an even smaller fraction (~10^3/s) will have been slowed to thermal (room temperature) energy levels and will be detected. Soil density and chemical composition affect the concentration of thermalized neutrons around the detector. The most common atoms in soil (aluminum and silicon) scatter neutrons with little energy loss because they have much greater mass than a neutron. However, if a neutron hits a hydrogen atom its energy is halved, on average, because the mass of the hydrogen nucleus is the same as that of the neutron. On average, 19 collisions with hydrogen are required to thermalize a neutron. Carbon, nitrogen, and oxygen are also relatively efficient as neutron thermalizers (about

120, 140 and 150 collisions, respectively). On the time scales of common interest in water management, changes in soil carbon and nitrogen content are minor and have little affect on the concentration of thermal neutrons. Also, on these time scales, changes in soil hydrogen and oxygen content occur mainly due to changes in soil water content. Thus, the concentration of thermal neutrons is most affected by changes in water content; and volumetric water content can be accurately and precisely related to the count of thermal neutrons through empirical calibration.

Because hydrogen and carbon effectively thermalize neutrons, the organic matter content of soil affects the calibration. Also, organic matter and most clays contain important amounts of hydrogen, some not in the form of water, that may not be driven off by heating to 105°C (the standard temperature for drying soil samples). So, separate calibrations are often required for soil layers that differ in organic matter or clay content from layers above or below. In arid or semi-arid zones, many soils have layers rich in $CaCO_3$ and $CaSO_4$ that require separate calibration.[3] Atoms that absorb neutrons include boron, cadmium, chlorine, iron, fluorine, lithium and potassium. Although these usually comprise a small fraction of soil material, soils or soil horizons that contain large or fluctuating amounts of such elements will require separate calibrations or adjustments in data interpretation. For example, soils high in iron, such as Oxisols or soils rich in magnetite, typically require separate calibration, as may soils high in chloride salts. In some US soils, boron is present in sufficient quantity to affect calibration.

NEUTRON MOISTURE METERS

Neutron moisture meter (NMM) equipment comes in two forms: 1) a profiling meter with a source - detector pair assembled into a cylindrical probe that is lowered into a hole in the soil, and 2) a flat-based meter that is placed on the soil surface with the source and detector fixed at separate locations inside the base of the meter.

The volume measured by the surface meter is roughly hemispherical and extends into the soil for a distance that decreases as soil water content and soil density increase, and which varies from ~0.15 m in wet soil to ~0.3 m in dry soil.[3] The precision is less than can be attained with a profiling meter; and it suffers even more when soil moisture changes greatly with depth near the surface,[4] a common occurrence. Good precision has been reported under fairly stringent conditions including: 1) flattening the surface to fit the meter bottom with no air gaps, 2) marking the measurement site so that the meter can be repeatedly placed in identical position, and 3) using a neutron absorber shield made of cadmium around the meter (except for the bottom) to reduce effects of surrounding vegetation.[5] However, even in the latter study the strong depth dependency of calibration coefficients and the inability to accurately estimate the depth of reading led to great uncertainty as to the accuracy of measurements.

More commonly used in soil and water science is the profiling NMM, which is operated at user-chosen depths in the soil (Fig. 1). A cylindrical access tube is used to line the hole, protecting the probe and ensuring a constant hole diameter. The probe is connected to a counter, data storage and display module by a cable that allows the probe to be lowered into the tube and stopped at intervals to measure the thermal neutron concentration. Common probe diameters are 38 and 51 mm. When not in use, the probe is locked in the instrument shield, which comprises a block of high-density polyethylene, and which is commonly attached to the readout and control unit. In the probe, the source is either directly beneath the detector, or is centered around or on one side of it. The relative position of the source and detector affects the calibration;[6] but for modern meters, source-detector geometry has little effect on the attainable precision.[2, 7, 8] In modern meters the source is a mixture of americium-241 and beryllium with an activity ranging from 0.4 to 1.9 gigabequerels. The nuclear reaction is $(^9Be(\alpha,n)^{12}C)$ in which ^{241}Am emits an alpha particle that is absorbed by a Be atom, which then produces ^{12}C and a fast neutron. The measurement volume is approximately a sphere. For a soil of specified volumetric water content (θ_v, m^3 m^{-3}), about 95% of the measured slow neutrons are from a sphere of radius R (cm).[9]

$$R = 15(\theta_v)^{-1/3} \qquad (1)$$

ACCESS TUBES AND DEPTH CONTROL

Access tubing materials that have been used successfully include stainless steel, mild steel, polyvinylchloride (PVC), polycarbonate, and polyethylene plastics, and aluminum. The hydrogen in plastics affects calibration as does the neutron absorber
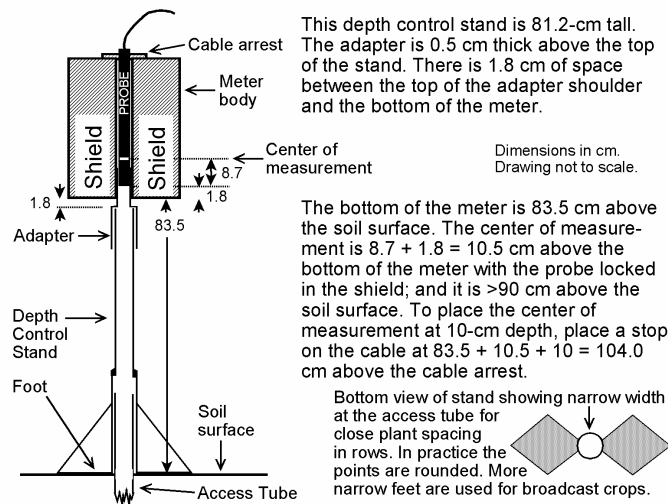

This depth control stand is 81.2-cm tall. The adapter is 0.5 cm thick above the top of the stand. There is 1.8 cm of space between the top of the adapter shoulder and the bottom of the meter.

Dimensions in cm.
Drawing not to scale.

The bottom of the meter is 83.5 cm above the soil surface. The center of measurement is 8.7 + 1.8 = 10.5 cm above the bottom of the meter with the probe locked in the shield; and it is >90 cm above the soil surface. To place the center of measurement at 10-cm depth, place a stop on the cable at 83.5 + 10.5 + 10 = 104.0 cm above the cable arrest.

Bottom view of stand showing narrow width at the access tube for close plant spacing in rows. In practice the points are rounded. More narrow feet are used for broadcast crops.

Fig. 1 Cross-sectional schematic of a profiling neutron moisture meter in place on top of a depth control stand. The probe is locked in the meter shield; and the stand is in place over an access tube that has been inserted into the soil. For the dimensions given here, to measure at 10-cm depth, the probe must be lowered 104 cm through the stand and into the access tube. Dimensions will vary for meters of different manufacture.

chlorine in PVC tubes. Aluminum is nearly transparent to neutrons, while the neutron absorber iron affects calibration in steel tubes. Thus, it is important that a NMM be calibrated in the same tubing as will be used in the field. Although calibration precision decreases slightly if plastic tubes are used[7], precision and accuracy are much more dependent on the tube installation and calibration methods employed than on tube material. Recommendations for installation of access tubes are given in Ref. [10].

It is common practice to place the NMM on top of the access tube near the soil surface before lowering the probe for readings. This practice is not recommended for two reasons. First, when the NMM is placed near the soil surface, the shield in the meter body may influence near-surface counts to a degree that depends strongly on the height of the meter above the soil.[11] Second, in field use, the height of access tubes above the soil is likely to change with tillage, rainfall induced settling, erosion or deposition, or other factors, resulting in an equivalent change in the depth of probe placement. For readings above 0.3-m depth, the depth of the probe will strongly influence the reading and the calibration equation due to loss of neutrons to the atmosphere.[4, 12]

These problems are addressed by using a depth control stand[1]. This device comprises a length of access tube fixed to a 0.2-m length of slightly larger tubing that is in turn supported by a foot resting directly on the soil (Fig. 1). The larger diameter of the lower length of tubing allows it to be slipped over the top of an access tube so that the foot rests on the soil surface. This maintains the reading depth at an exact distance relative to the soil surface. Cable stops are arranged to achieve the desired depth placement of the probe. The stand described is tall enough to be suitable for taking standard counts with the NMM mounted on the stand and the probe locked in the meter shield. Standard counts taken with the meter too close to the soil surface may vary with the moisture content of the soil.[13, 14]

STATISTICS OF NEUTRON EMISSION

Neutron emission is a random process that occurs according to a Poisson probability distribution. An important property of the Poisson distribution is that, for a series of counts over equal time periods, the

standard deviation is equal to the square root of the mean value. One result of this fact is that the coefficient of variation of counts can be reduced by increasing the counting time. The sample mean, m, is computed as

$$m = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad (2)$$

where x_i is the value of a single count and N is the number of counts (all taken with the probe in one position). The sample standard deviation, s, is computed as

$$s = \left[\frac{1}{N-1}\sum_{i=1}^{N}(x_i - m)^2\right]^{1/2} \qquad (3)$$

For a properly operating meter with the probe in a constant environment, the ratio of $s/(m)^{1/2}$, called the Chi ratio, should be close to unity. This ratio is related to the χ^2 statistic by

$$\frac{s}{m^{1/2}} = \left(\frac{\chi^2}{N-1}\right)^{1/2} \qquad (4)$$

Values of χ^2 (Chi-squared) for a given probability level (P) are given in statistical tables for different values of $(N - 1)$. We may write the right-hand-side of Eq. [4] for the upper and lower limits of χ^2 and thus obtain upper and lower values of the Chi ratio for the chosen probability level and number of samples. For example, for a 95% probability level and 32 samples, we find the values of χ^2 as 17.5 for P = 0.975 and 48.1 for P = 0.025; and from Eq. [4] the Chi ratio should be between 0.75 and 1.25 about 95 times in every hundred. Some meters divide the count by a fixed number in order to reduce the displayed count to a reasonably small value. In computing Chi ratios for such meters, the user should first multiply the recorded counts by the factor that the meter used to reduce them.

CALIBRATION

Manufacturers' calibration equations are seldom useful for soil moisture determination (e.g., Ref. [13]). Calibration of NMMs involves correlating measured count ratio values with independently determined

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[1] Evett, S.R. 2000. Construction of a Depth Control Stand for Use with the Neutron Probe [Online]. 7 pp. USDA-ARS-SPA-CPRL, Bushland, TX. Available at http://www.cprl.ars.usda.gov/programs/ (posted 5 July 2000; verified 28 July 2000).

volumetric water contents, θ_v (m^3 m^{-3}). For modern meters and the normal range of values of soil water content, the calibration is linear and of the form

$$\theta_v = b_0 + b_1 C_R \tag{5}$$

where b_0 and b_1 are the calibration coefficients as determined by linear regression, and C_R is the count ratio defined as

$$C_R = x/x_s \tag{6}$$

where x is the count in the measured material and x_s is a standard count taken with the probe within a standard and reproducible material. Count ratio values are used because the source activity and thus counts will decline over time, and because the detector efficiency is somewhat temperature dependent.[15] Recommendations for taking standard counts are given in Ref. [10], as are recommendations for field calibration using the wet site - dry site method of Evett and Steiner.[2] Careful field calibrations done using the wet site - dry site method and the depth control stand should attain root mean squared errors < 0.01 m^3 m^{-3} and r^2 values greater than 0.9, even for depths near the surface (e.g. 10 cm in Table 1).

Table 1 Calibration of water content (θ_v, m^3 m^{-3}) vs. count ratio (C_R) for the Amarillo fine sandy loam using the method in Ref. [2]. A depth control stand was used.

Depth (cm)	Equation	RMSE	r^2	N
10	$\theta_v = 0.014 + 0.2172 C_R$	0.004	0.997	6
30 – 190	$\theta_v = -0.063 + 0.2371 C_R$	0.007	0.988	44
30 – 90	$\theta_v = -0.066 + 0.2421 C_R$	0.008	0.988	24
110 – 190	$\theta_v = -0.057 + 0.2299 C_R$	0.006	0.992	20

RMSE is root mean squared error, N is the number of samples, and r^2 is the coefficient of determination for the regression analysis.

SAFETY AND USE CONSIDERATIONS

Safety concerns relate to radiation safety and to back and knee strains incurred during repeated bending and kneeling to operate meters placed on access tubes. The depth control stand described above allows users to work standing up, and has virtually eliminated physical injuries where it is used. Due to the low levels of radioactivity involved, the principle of reducing exposure to as low as reasonably achievable (ALARA) guides most radiation safety rules. Users may lower

radiation received by increasing distance from the meter, decreasing time spent near the meter, and increasing shielding. The probe should always be locked into the shield except when it is lowered into an access tube. Users should be made aware that the source emits radiation at all times, even when the meter is turned off and batteries removed. Guidelines for ALARA use of the NMM are found in Ref. [16]. The USDA Radiation Safety Staff maintains an Internet site of useful information on radiation safety and hazardous materials transport (http://www.usda.gov/da/shmd/rss1. htm) as does the International Atomic Energy Agency (http://www.iaea.org/worldatom/).

Due to regulation, the method is not usable for automatic measurements. Due to its large measurement volume, the method is inappropriate where detailed vertical definition is required. This can be particularly important near the surface where water content often changes rapidly with depth. In such cases, the NMM can be used for deeper measurements in conjunction with time domain reflectometry (TDR) measurement of the near-surface soil water content.[17] The time and effort required to install access tubes and calibrate for each soil type is nontrivial. There is also a substantial cost for the equipment and for necessary training and licenses to handle and transport radioactive materials.

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