A Depth Control Stand for Improved Accuracy with the Neutron Probe

S. R. Evett,* J. A. Tolk, and T. A. Howell

ABSTRACT

The neutron thermalization method for soil water content measurement is well established as being accurate for deep soil profile measurements. However, the method has been criticized as inaccurate for shallow measurements (<30 cm). It is in this shallow zone that many plants have the largest root density and water uptake and where infiltration and evaporation typically cause the largest changes in water content. We show how neutron probe depth influences soil water readings in the top 30 cm of soil, and we describe a depth control stand that serves to control probe depth relative to the soil surface so that probes may be accurately calibrated and successfully used in the field for measurements at shallow depths. Using the stand, calibrations for the 10-cm depth may be obtained routinely with linear regression r^2 values >0.98 and RMSE values of calibration <0.01 m^3 m^{-3}. The stand is also useful for elevating the gauge high enough above the surface so that standard counts are not influenced by the water content or nature of the surface, thus enhancing accuracy of both the calibration and subsequent water content readings, both of which depend on standard count values. Also, the stand serves to prevent repetitive strain injuries to backs and knees caused by bending and kneeling to place the gauge on top of access tubes, but without additional occupational exposure to radiation.

THE NEUTRON THERMALIZATION METHOD of soil water content measurement was developed more than 50 yr ago and has long been considered an accurate method, once calibrated, for deep measurements of porous media water content in the vadose zone. However, the method has been characterized as inaccurate at depths <30 cm because of the loss of neutrons to the air at these shallow depths and due to calibration equations with values of RMSE >0.01 m^3 m^{-3}. The theory, interferences, calibration methods, and achievable accuracies are well established (Hignett and Evett, 2002). Briefly, the method uses a source of fast neutrons that are slowed to ambient temperature (thermalized) by repeated collisions with the nuclei of soil materials, forming a cloud of slow neutrons around the source. The slow neutrons that pass through a detector tube are then counted electronically. The detector tube and fast neutron source are packaged together in a probe that slides inside an access tube for soil water assessment below the soil surface. Because H is by far the most effective element for slowing neutrons, and because rapid changes in soil H content are almost completely due to changes in soil water content, the count of slow neutrons is proportional to soil water content. For modern probes, the proportionality is linear and can be parameterized for a given porous medium by slope and intercept values obtained through field calibration (Hignett and Evett, 2002). For probe designs common in the 1960s, about 95% of the measured slow neutrons were from a nearly spherical volume of radius R (cm), with the value of R dependent on the medium's volumetric water content (θ_v, m^3 m^{-3}), (IAEA, 1970).

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

Thus, the volume of sensitivity was predicted to have a radius of roughly 20 cm for saturated media, up to 40 cm for air-dry media.

For profile water content measurements, a cylindrical probe is lowered to different depths for measurements in an access tube installed vertically in the porous medium. Despite the relatively large volume measured, the depth interval between readings has been as small as 0.15 m, or even 0.10 m (Carrijo and Cuenca, 1992; Vandervaere et al., 1994). Depth intervals as small as 0.15 m may provide added value in soils with large and rapid changes in water content with depth (McHenry, 1963; Stone, 1990). This is because sensitivity decreases exponentially with distance from the probe. A depth interval of 0.10 m was reported to improve precision of profile water content (Carrijo and Cuenca, 1992), but the improvement may have been due to the increased counting time resulting from the additional readings rather than any new information about the profile (Stone and Weeks, 1994). Depth intervals of >0.2 m are sometimes used where water content changes slowly with depth. When not in use, the probe is locked within a shield case filled with high density polyethylene or similar hydrogenous material. Modern equipment called the neutron moisture meter (NMM) consists of this shield case, with an electronic counter, display, and keyboard attached, and a cable of useful length connecting the counter to the probe (Fig. 1). Marks or clamps on the cable are used as reference points for placement of the probe at fixed depths.

To avoid damage by machinery, access tubes are typically installed in crop rows with only 10 to 15 cm of the tube exposed above the soil surface. It is common practice to place the shield case on top of the access tube before releasing the probe from the shield and lowering it for readings in the soil. Doing so may lead to errors for two reasons. First, when the shield case is placed on top of the access tube, the shield material may influence near-surface counts to a degree that depends strongly on the height of the case above the soil and the depth of the probe (Stone et al., 1993). Second, in field use, the actual height of access tubes above the soil is likely to change with tillage, rainfall-induced compaction, erosion or deposition, or other factors, resulting

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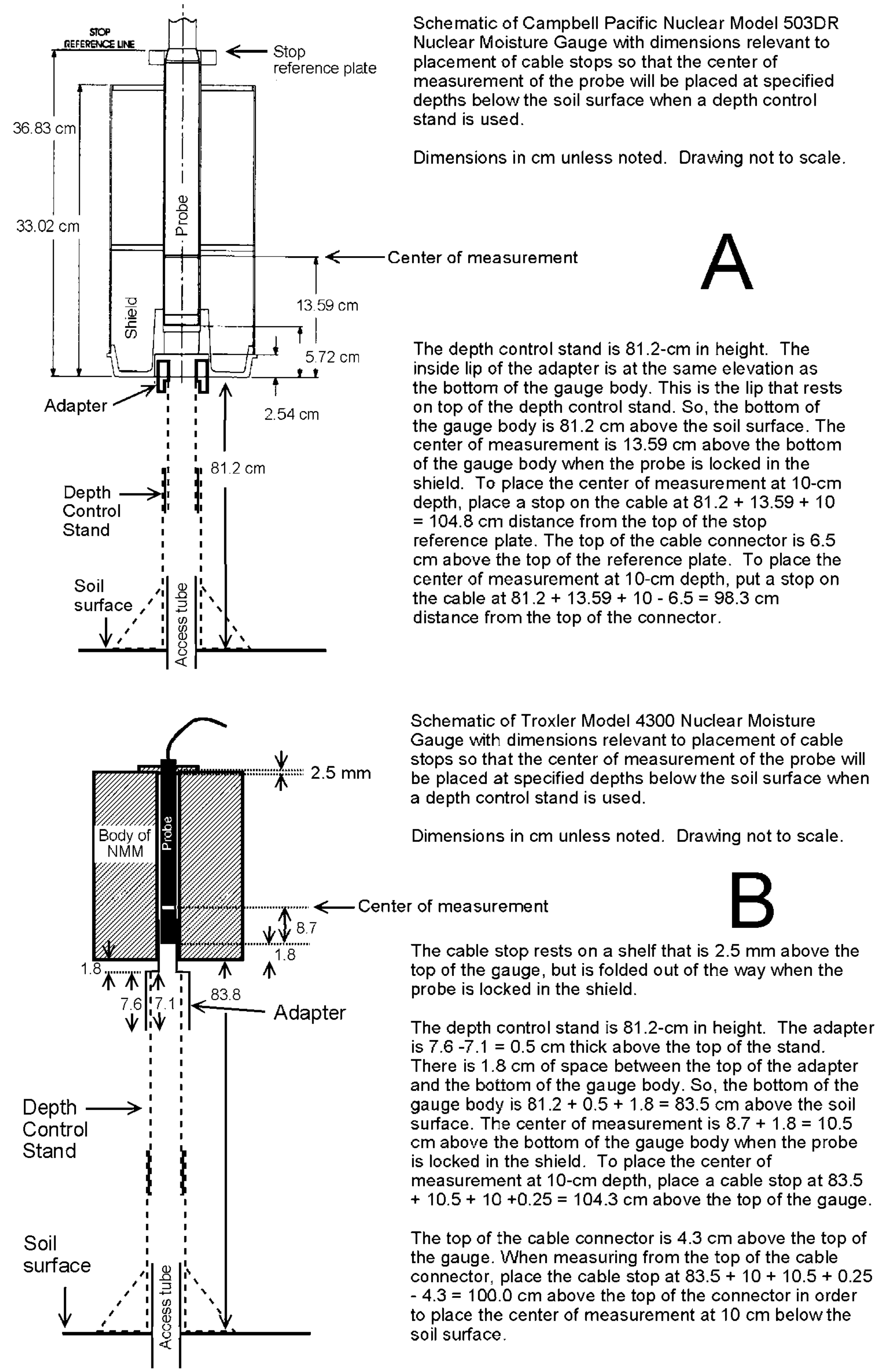
Abbreviations: EMT, electromechanical tubing; NMM, neutron moisture meter.



Schematic of Campbell Pacific Nuclear Model 503DR Nuclear Moisture Gauge with dimensions relevant to placement of cable stops so that the center of measurement of the probe will be placed at specified depths below the soil surface when a depth control stand is used.

Dimensions in cm unless noted. Drawing not to scale.

The depth control stand is 81.2-cm in height. The inside lip of the adapter is at the same elevation as the bottom of the gauge body. This is the lip that rests on top of the depth control stand. So, the bottom of the gauge body is 81.2 cm above the soil surface. The center of measurement is 13.59 cm above the bottom of the gauge body when the probe is locked in the shield. To place the center of measurement at 10-cm depth, place a stop on the cable at 81.2 + 13.59 + 10 = 104.8 cm distance from the top of the stop reference plate. The top of the cable connector is 6.5 cm above the top of the reference plate. To place the center of measurement at 10-cm depth, put a stop on the cable at 81.2 + 13.59 + 10 - 6.5 = 98.3 cm distance from the top of the connector.

Schematic of Troxler Model 4300 Nuclear Moisture Gauge with dimensions relevant to placement of cable stops so that the center of measurement of the probe will be placed at specified depths below the soil surface when a depth control stand is used.

Dimensions in cm unless noted. Drawing not to scale.

The cable stop rests on a shelf that is 2.5 mm above the top of the gauge, but is folded out of the way when the probe is locked in the shield.

The depth control stand is 81.2-cm in height. The adapter is 7.6 -7.1 = 0.5 cm thick above the top of the stand. There is 1.8 cm of space between the top of the adapter and the bottom of the gauge body. So, the bottom of the gauge body is 81.2 + 0.5 + 1.8 = 83.5 cm above the soil surface. The center of measurement is 8.7 + 1.8 = 10.5 cm above the bottom of the gauge body when the probe is locked in the shield. To place the center of measurement at 10-cm depth, place a cable stop at 83.5 + 10.5 + 10 +0.25 = 104.3 cm above the top of the gauge.

The top of the cable connector is 4.3 cm above the top of the gauge. When measuring from the top of the cable connector, place the cable stop at 83.5 + 10 + 10.5 + 0.25 - 4.3 = 100.0 cm above the top of the connector in order to place the center of measurement at 10 cm below the soil surface.

Fig. 1. Drawings showing dimensions relevant for placing cable stops on cables to achieve accurate depth placement of the probe center of measurement for (A) a CPN International Model 503DR neutron moisture meter (NMM) and (B) a Troxler Electronics Laboratories, Inc. Model 4301 NMM (B).

in an equivalent change in the depth of probe placement. For readings at depths of <0.3 m, the depth of the probe will influence the reading and the calibration, even in a uniformly wetted medium, because of loss of neutrons to the atmosphere (Van Bavel et al., 1961). The loss of a substantial fraction of neutrons from the surface soil during near-surface readings (<0.3 m) necessitates a separate calibration for any depths in this zone. Special techniques for surface layer calibration are described by Grant (1975) and Parkes and Siam (1979). It is critical to accurately and precisely control probe depth for calibrations and subsequent soil water content readings at depths <0.3 m.

Because the activity of the fast neutron source decreases with time, the number of slow neutrons detected for a given value of θ_v will decrease with time, rendering a calibration based on neutron counts unstable with time. For this reason calibration equations are of the form

$$\theta_v = a + bC_R \qquad [2]$$

where a and b are the intercept and slope parameters, respectively, and C_R is the count ratio $= C/C_s$, where C_s is a standard count taken with the probe in a reproducible medium and C is the count in the calibration medium or porous medium where water content measurements are needed.

Many users prefer the convenience of using the small plastic shield in the meter body as a standard. This count is stable and unaffected by the soil and nearby bodies if the shield is mounted at least 0.8 m above the soil surface during the count (Fig. 4 in Dickey, 1990; Fig. 1 in Allen and Segura, 1990), and at least 3 m from surrounding objects (including the operator). Failure to separate the instrument sufficiently from the ground will lead to substantial errors in water content determination. In a 10-yr study, such probe shield counts were found to be reliable and highly precise (Stone and Nofziger, 1995; Stone et al., 1995). Although some manufacturers recommend placing the meter on its carrying case for the standard count, this may lead to errors because the height of the case is not large enough to avoid the influence of materials below the case. Although placement of the meter on the tailgate of a vehicle may raise it the necessary height above the soil, the nearness of neutron absorbers and moderators in the body and fuel tank of the vehicle makes it poor practice.

The problems summarized above may be addressed by using a depth control stand. This device comprises a length of tubing, of the same diameter as the access tube, fixed to a 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 NMM shield. We describe the construction and use of such a stand, report results of a study of the NMM probe's sensitivity to nearness to the soil–air interface and the effects of inaccurate depth control on water content readings, and report results of field calibrations achieved using the stand.

MATERIALS AND METHODS

Depth Control Stand

The depth control stand may be constructed of either steel or aluminum; the latter being preferred by NMM operators for its lightness. The stands described here are intended for use with access tubes made of thin-wall galvanized (electroplated) steel electromechanical tubing (EMT), otherwise known as electrical conduit. They will also work with thin-wall PVC tubing. By "thin-wall" we mean ~2.8-mm wall thickness (or Schedule 10 in the United States). Stand diameters may be changed easily to accommodate other access tube sizes. Construction details are given on the Internet (Evett, 2000) for the two most common sizes of access tubes and for both steel and aluminum construction. In the appendix we discuss briefly construction of an aluminum stand to work with 48.3-mm outside diameter access tubing (nominal 1.5-inch diameter in the United States, 2.77-mm wall thickness), which works well with the common 38-mm (1.5-inch) diameter neutron probes.

Details and dimensions relevant to placing cable stops to measure at specified depths using the depth control stand are given in Fig. 1 for both Troxler Electronic Laboratories (Research Triangle Park, NC) and CPN International (Martinez, CA) NMMs.[1] Because cable stops may slide on the cable or the insulation may move up or down the cable, it is advisable to check the positions of cable stops periodically during the measurement season.

Base Plate

It is sometimes inconvenient to find an installed access tube over which to place the stand for purposes of taking a standard count. A base plate for stabilizing the stand may be made from a 35.6-cm (14-inch) square piece of 0.32-cm (1/8 inch) steel plate. The corners of the plate are turned down to allow the plate to be easily leveled by pressing the points so made into the ground. A 20-cm length of steel access tubing is welded to the center of the plate on the side away from the corner points.

Use of the Stand

Access tubes are set to extend 10 to 20 cm above the soil surface. The exact height is not critical—it is sufficient to make sure that there is enough access tube above the surface to prevent the stand from tipping.

The user should step away from the gauge (one or two steps) when taking a shallow reading (say at the 10-cm depth), and when taking a standard count (at least 3 m away), to avoid receiving unnecessary radiation (Arslan et al., 1997) and to avoid influencing the readings. Standard counts may be taken at any location away from possible neutron moderators (e.g., heavy vegetation, buildings, vehicles) by placing the base plate on the ground and putting the stand and NMM on it.

Tests for Soil–Air Interface Sensitivity

The response of the NMM to nearness to the soil–air interface was investigated in 55-cm diameter, 75-cm tall columns of repacked soil (Pullman silty clay loam, fine, mixed, superactive, thermic Torrertic Paleustoll). Soil was packed over a 5-cm layer of fine silica sand covered with polyester felt filter fabric. The sand base was connected to a water source for saturating the column from the bottom. Columns were packed in place on electronic scales (model DS3040-10K, Weigh-Tronix, Inc., Fairmount, MN), each with four load beams connected using a six-wire bridge to a datalogger (model CR7x, Campbell Scientific, Inc., Logan, UT) and calibrated to a precision of 50 g. Columns were packed with air-dry soil in 5-cm lifts, and

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[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-ARS.

each lift was subsampled three times for gravimetric water contents, which were determined by drying at 105°C for 24 h. The final soil mass measured by the scales was corrected to dry mass using the mean gravimetric water content. Bulk density was calculated from the soil dry mass and column volume. Soil porosity was calculated assuming a particle density of 2.65 g cm^{-3}. Likewise, the air-dry volumetric water content was calculated from the column-mean gravimetric water content and bulk density.

Using a depth control stand, the NMM probe (model 503DR, CPN International) was lowered from a position 32-cm above the soil column in 4-cm increments to a position 48 cm below the soil surface in an access tube, with counts taken at each incremental position. Three standard counts were taken with the NMM on the depth control stand, and count ratio values were calculated. For convenience of interpretation, count ratios were converted to water contents, θ_v, using a previously obtained field calibration for the Bt horizon of the Pullman soil. A five-parameter sigmoidal curve was fit to the data from three replications

$$\theta_v = y_0 + a/\{1 + \exp[-(z - z_0)/b]\}^c \qquad [3]$$

where z is the height of the probe center relative to the soil surface and y_0, a, z_0, b, and c are the fitted parameters. The probe center was taken to be the center of the thermalized neutron detector tube. We determined the value of z at which θ_v calculated by Eq. [3] decreased from its maximum value by 5% of the difference of maximum and minimum values of θ_v. Likewise, we determined the value of z at which θ_v increased from its minimum value by 5% of the difference. The difference in these values of z was taken to be the 90% axial distance of sensitivity for the probe.

The soil column was perfused with CO_2 gas from the bottom and then saturated with water from the bottom before repeating the axial sensitivity measurements. Column mass change was used to calculate the increase in volumetric water content over its initial value.

Field Calibration

A field calibration was undertaken in 2002 on the Pullman silty clay loam soil at Bushland, TX (35°11′ N, 102°06′ W, 1170 m elevation above mean sea level). A dry soil site was easy to find, and a nearby site was bermed so that water could be ponded on it to create a wet site. Three 48.3-mm outside diameter, 2.77-mm wall thickness (1.5-inch nominal diameter) electrogalvanized steel tubes were installed, separated by 2 m, in each site. Three standard counts were taken with the NMM placed on the stand and base plate. Counts were taken in the access tubes at the 10-cm depth and at 20-cm depth increments below that depth. At each access tube, six volumetric soil samples centered on the 10-cm depth were taken by inserting the Madera probe vertically into the soil within 15-cm radial distance from the access tube (see Evett, 2001 for Madera probe description). Soil was then excavated by trenching alongside each access tube, and at each tube four volumetric soil samples were taken at each reading depth by inserting the Madera probe horizontally within 15 cm of the tube center at each depth. Because the Madera probe is 16 cm long, compressed or shattered samples could be visually detected and were discarded and replacement samples taken. After the wet site was thoroughly saturated, as evidenced by preliminary NMM readings, it was allowed to drain for 3 d to eliminate rapid changes in water content due to drainage. To further minimize water content changes due to drainage, neutron counts were taken in one tube at a time and volumetric water contents immediately sampled as described above. The excavation was then backfilled before the next wet site access tube was read and sampled.

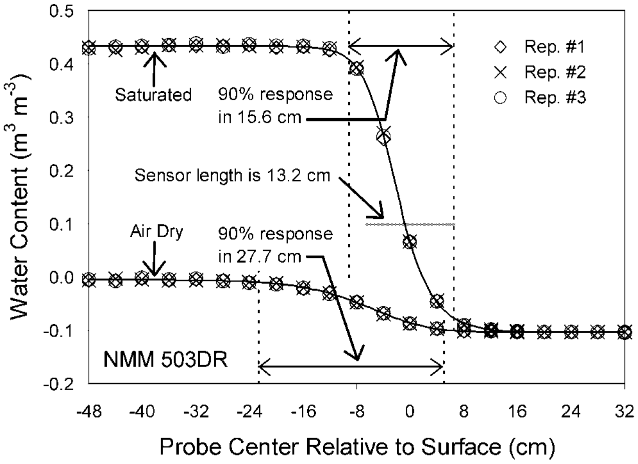

Fig. 2. Response of the neutron moisture meter (NMM) probe to nearness to the soil–air interface in air-dry and saturated soil.

Soil samples were weighed, dried at 105°C for 24 h, and weighed again to determine mass of the water in the 60-cm^3 samples. Volumetric water content was determined by converting the mass of water to its volume in cubic centimeters and dividing by 60. Bulk density was calculated by dividing the sample dry mass in grams by 60. Data were screened for outliers in bulk density and water content. Mean water content for each depth at each tube was calculated from the remaining data. The Pullman soil has a silty clay loam A horizon, a clay-textured Bt horizon, and a Btca horizon containing 50% $CaCO_3$ below the Bt. Corresponding to data from these horizons, linear regressions of the form of Eq. [2] were run on the data for the 10-cm depth separately, the 30- through 110-cm depths combined, and the 130- through 190-cm depths combined.

RESULTS

The column mean air-dry soil water content was 0.056 m^3 m^{-3}, and the saturated water content was 0.433 m^3 m^{-3}. Water contents below 16 cm in the saturated soil were accurately estimated using the field calibration, indicating both that the 27.5-cm radius of the columns was larger than the radius of the volume of soil measured by the NMM in the saturated soil, and that the presence of other access tubes in the columns had little effect on the NMM. Above the 16-cm depth, water content estimates were increasingly inaccurate due to loss of neutrons to the air. In the air-dry soil, water contents were underestimated at depths $>$24 cm by approximately 0.05 m^3 m^{-3}, probably due to the presence of other access tubes in the columns.

In air-dry soil, the NMM probe exhibited a 90% axial sensitivity to the soil–air interface for a range of 27.7 cm, extending from 5 cm above the surface to 22.7 cm below the surface (Fig. 2). In saturated soil, the range of 90% axial sensitivity was 15.6 cm, extending from 6.5 cm above the surface to 9.1 cm below the surface. In air-dry soil the center of sensitivity was 8.9 cm below the soil surface, while in saturated soil it was 1.3 cm below the surface. In both cases, the center of sensitivity was probably biased downwards due to the positioning of the fast neutron source just below the detector tube in

Table 1. Calibrations of water content (θ_v, $m^3\ m^{-3}$) vs. count ratio (C_R) obtained using the depth control stand for a neutron moisture meter (NMM) in this and a past study.†

Depth	NMM serial no.	NMM model	Equation	RMSE	r^2	n
cm						
			Pullman soil, this study			
10	5446	503DR	$\theta_v = 0.014 + 0.2344C_R$	0.003	0.991	5
30–110	5446	503DR	$\theta_v = -0.086 + 0.2635C_R$	0.007	0.987	30
130–230	5446	503DR	$\theta_v = -0.030 + 0.2193C_R$	0.007	0.982	35
10	5447	503DR	$\theta_v = 0.020 + 0.2115C_R$	0.003	0.998	5
30–110	5447	503DR	$\theta_v = -0.082 + 0.2420C_R$	0.007	0.987	30
130–230	5447	503DR	$\theta_v = -0.030 + 0.2023C_R$	0.008	0.981	35
10	6190	503DR	$\theta_v = 0.009 + 0.2278C_R$	0.003	0.998	5
30–110	6190	503DR	$\theta_v = -0.095 + 0.2604C_R$	0.007	0.987	30
130–230	6190	503DR	$\theta_v = -0.034 + 0.2132C_R$	0.008	0.981	35
10	6503	503DR	$\theta_v = 0.021 + 0.2374C_R$	0.007	0.992	5
30–110	6503	503DR	$\theta_v = -0.098 + 0.2813C_R$	0.007	0.986	30
130–230	6503	503DR	$\theta_v = -0.040 + 0.2334C_R$	0.008	0.983	35
			Amarillo soil (Evett and Steiner, 1995)			
10	386	3331	$\theta_v = 0.054 + 0.5270C_R$	0.006	0.992	6
10	385	3331	$\theta_v = 0.028 + 0.5388C_R$	0.004	0.997	6
10	326	4301	$\theta_{v\_} = 0.001 + 0.4943C_R$	0.002	0.999	6
10	6190	503DR	$\theta_{v\_} = 0.001 + 0.2196C_R$	0.002	0.999	6
10	0698	503DR	$\theta_{v\_} = 0.021 + 0.2105C_R$	0.005	0.996	6
10	5447	503DR	$\theta_{v\_} = 0.014 + 0.2172C_R$	0.004	0.997	6
30–90	5447	503DR	$\theta_{v\_} = -0.066 + 0.2421C_R$	0.008	0.988	24
110–190	5447	503DR	$\theta_{v\_} = -0.057 + 0.2299C_R$	0.006	0.992	20

† Model 503DR is from CPN International, Inc., Martinez, CA; Models 3331 and 4301 are from Troxler Electronics Laboratories, Inc., Research Triangle Park, NC.

the probe. The smaller vertical range of sensitivity in saturated soil allowed the center of sensitivity to be closer to the surface.

Equation [1] predicts a radius of 95% sensitivity equal to 39 cm for soil at 0.056 $m^3\ m^{-3}$ water content and a radius of 20 cm for a soil at 0.433 $m^3\ m^{-3}$. Our results appear to be about one-half of those predicted by Eq. [1] if we consider that the extension of sensitivity below the surface was approximately 23 cm in air-dry soil and 9 cm in saturated soil. Using Eq. [3] and the fitted parameters, we calculate that a 2-cm positional error upwards from the 10-cm depth would result in a 0.009 $m^3\ m^{-3}$ error in our air-dry soil and a 0.018 $m^3\ m^{-3}$ error in our saturated soil. Because the center of sensitivity is above the 10-cm depth in both air-dry and saturated soils, the error rate increases for positional errors above that depth. The maximum error rate is 0.005 $m^3\ m^{-3}$ per centimeter of positional error in air-dry soil and 0.052 $m^3\ m^{-3}$ per centimeter in saturated soil.

The field calibration equations found by linear regression for the Pullman soil all exhibited coefficients of determination >0.98 and RMSE values <0.01 $m^3\ m^{-3}$ (Table 1). These statistics are in agreement with those from other field calibrations performed using the depth control stand (Evett, 2001), in particular the calibrations for the 10-cm depth from Evett and Steiner (1995) included in Table 1 for comparison.

DISCUSSION

Probe design for the NMM has changed greatly since its invention. On the basis of early probe designs and theoretical calculations, Olgaard (1965) presented an equation for the effective radius of measurement

$$R = 100/(1.4 + 10\theta_v) \qquad [4]$$

that, for water contents up to 0.3 $m^3\ m^{-3}$, predicted larger values of R than those predicted by Eq. [1], which in turn was based on designs of the late 1960s. For example, for water contents of 0.05 and 0.45 $m^3\ m^{-3}$, we computed R values of 53 and 17 cm, respectively, using Eq. [4] compared with the values of 41 and 20 cm, respectively, computed using Eq. [1]. Because water content is much more likely to change in the vertical direction than horizontally, we may question if the radius of influence is the most appropriate criterion of evaluation for many studies of field soil water content. Our results indicate that, for modern probe designs, the limits of axial sensitivity of the neutron probe may be as small as one-half of the R values computed using Eq. [1]. This result is supported by the observation of Stone (1990) that depth increments as small as 15 cm between readings add precision to the measurement of profile soil water content, and further by the observation of Carrijo and Cuenca (1992) that increments as small as 10 cm likewise improved precision. Recently, the axial sensitivity of the neutron probe in a soil at 0.35 $m^3\ m^{-3}$ water content was found to be 15 cm by an experimental procedure similar to ours (IAEA, 2002). Using this new datum and our measurements, a preliminary equation for the axial distance of influence, A (cm), was determined by nonlinear regression to be

$$A = 9(\theta_v)^{-0.33} \qquad [5]$$

with adjusted r^2 value of 0.76 and RMSE of 3.3 cm. Equation [5] supports the idea that depth increments for NMM readings should be as small as 15 cm in wet soils, to ensure good overlap, or 20 cm with minimal overlap.

The large r^2 values and low RMSE values obtained for the 10-cm depth calibration in this and other studies in which the depth control stand was used indicate that reproducible depth control was obtained and that accurate water content determination can be achieved at shallow depths with the neutron probe. The similarity in RMSE and r^2 values for different NMMs and for NMMs from different manufacturers indicates that most of the noise in the data is in the soil water content values measured by volumetric sampling, not in the NMMs. However, the low RMSE values indicate that the technique of obtaining four volumetric soil samples at each NMM reading depth at each tube is an efficient method of sampling the volume measured by the NMM. Certainly, the existence of four samples per depth and tube allows easy screening for outliers in bulk density and water content. Both the Amarillo (fine-loamy, mixed, superactive, thermic Aridic Paleustalf) and Pullman soils have a Btca horizon rich in $CaCO_3$ that results in calibration equation slopes that are invariably smaller than those for the clay-rich Bt horizon (Table 1) (Evett and Steiner, 1995). The lower slopes indicate that there are more thermal neutrons detected per unit water content in the Btca horizons. Similar results were obtained for carbonate-rich horizons in soils in Uzbekistan (Evett et al., 2002). Both C and O are relatively efficient at neutron thermalization compared with other common soil elements; we suppose that this explains the smaller slope values in these horizons.

The depth control stand has been in use at Bushland since the early 1990s and has allowed us to reach two objectives that are essential for accurate water content readings with the neutron probe. The first objective is to ensure that the probe is at the correct depth for each reading. We take readings at the 10-cm depth and in 20-cm increments below that. Our stands (Fig. 1) slide over the access tubes and keep the NMM a constant height above the soil surface, in our case 81.2 cm (32.4 inches) from NMM base to soil surface. We then set cable stops to give the desired depths of measurement. With this system we always get reading depths referenced to the soil surface, not to the top of the access tube. In normal field use, the user can walk through the field quite readily with gauge in one hand and stand in the other, even in tall corn. Accuracy and precision in both calibration and field readings are achieved.

The second objective is to ensure that standard counts were not influenced by soil water content or other influences. We set the stand on a base plate to take standard counts in the field away from vegetation. Previous to this, we saw that standard counts varied depending on whether the soil was wet after a heavy rain or dry (this with the NMM carrying case placed on the soil surface and the NMM placed on the case for the standard count).

A third objective, not related to accurate water contents but definitely related to accurate crop water use data, is that the use of the probe not interfere with the plants in closely planted rows. The diamond shape of the feet allow the stand to be placed over an access tube in a crop row with minimal plant disturbance. Smaller feet can be affixed easily for use in broadcast seeded crops such as grains.

Other advantages of the stands are that (i) the user can operate the gauge while standing, avoiding the back and knee strains incurred when the gauge is set directly on top of the access tube, (ii) any interference of the gauge shield with the 10-cm depth reading is eliminated, and (iii) in case a user is inattentive, the gauge is more visible to machine operators when on top of the stand than when on top of an access tube.

Users of NMMs at Bushland wear dosimeters that register both γ and fast neutron radiation, and which are read by an independent laboratory quarterly. No additional exposure to radiation was recorded after the use of the stands was instituted. Additional exposure is unlikely due to several factors. First, the probe is rapidly moved from the NMM shield through the stand and into the soil. Second, the operator is standing rather than kneeling next to the NMM to operate it, as is commonly done when the NMM is placed directly on top of an access tube. This reduces exposure when readings are taken near the soil surface. This is particularly true because the operator can easily step away from the NMM while a shallow reading is taken, unlike the case when the operator is kneeling beside the NMM. Arslan et al. (1997) measured γ and neutron radiation 50 cm from a Model 503DR source at the 10-cm depth in the soil and again with the source locked in the NMM shield. With the source at the 10-cm depth, the radiation was equivalent to 60% of the radiation received at 50 cm from the NMM case when the source is locked in the shield. They found that at the 50-cm distance an operator would receive the recommended yearly limit of radiation exposure in 865 h. This is equivalent to 24 wk of full time work (36 h per week at 50 cm from the source), much longer than the typical time that operators spend using the NMM even at an active research station. When reading at the 10-cm depth, the source in a Model 503DR is at the 17.5-cm depth, considerably deeper than for the measurements of Arslan et al. (1997). The 50-cm distance is approximately the distance from the source at the 17.5-cm depth to an operator kneeling to work with the NMM. For an operator who is standing, the distance to the torso is easily twice as great, reducing the exposure by 75%, and the operator may easily increase the total distance by stepping away from the NMM. We conclude that, rather than increase exposure, use of the stand is likely to decrease total exposure.

Depth control stands similar to those described here are available from Soil Measurement Systems (Tucson, AZ; http://www.soilmeasurement.com).

APPENDIX

Construction of a Depth Control Stand

More detailed instructions for building depth control stands for different diameter access tubes and from both steel and aluminum are given at http://www.cprl.ars.usda.gov/programs/. Aluminum strap, plate, and tubing materials for the stand are listed in Table 2. The aluminum strap is cut into two 44.5-cm (17.5-inch) lengths, and each piece is bent in three places (Fig. 3A), using heat to prevent cracking (propane or acetylene torch). The plate is cut to produce two diamond-shaped pieces with distance between the points of about 18.4 and 16.2 cm (7 1/4 and 6 3/8 inch). The points of the diamonds are rounded with a grinder to produce the shapes shown in Fig. 3A.

Table 2. Material list for aluminum stand for the common 38-mm (1.5-inch) diameter neutron probe with 48.3-mm outside diameter access tubing (nominal 1.5-inch diameter in the United States, 2.77-mm wall thickness) electromechanical access tubing.

Number or length of pieces	Material
1	57.0-cm (22.44-inch) length of 4.445-cm (1.750-inch) o.d., 0.147-cm (0.058-inch) wall thickness 6063-T832 drawn aluminum tubing†
1	10.0-cm (3.94-inch) length of 4.763-cm (1.875-inch) o.d., 0.147-cm (0.058-inch) wall thickness 6063-T832 drawn aluminum tubing
1	34.2-cm (13.78-inch) length of 5.080-cm (2.000-inch) o.d., 0.147-cm (0.058-inch) wall thickness 6063-T832 drawn aluminum tubing
91.5 cm	2.54 by 0.32 cm (1 by 1/8 inch) aluminum strap
1	0.32-cm (1/8-inch) aluminum plate, 12.1 by 27.9 cm (4 3/4 by 11 inch)
6	1.27-cm (1/2-inch) #10 wafer-top screws
6	1.27-cm (1/2-inch) #10 flat-head screws
10	#10 lock nuts with nylon inserts
6	1.27-cm (1/2-inch) #8 by 32 machine screws
As needed	Fluxless aluminum brazing rod, metal fluxless II, Nutech

† Telescoping aluminum tubing of the needed diameters may be obtained from Texas Towers, Plano, TX; www.texastowers.com.

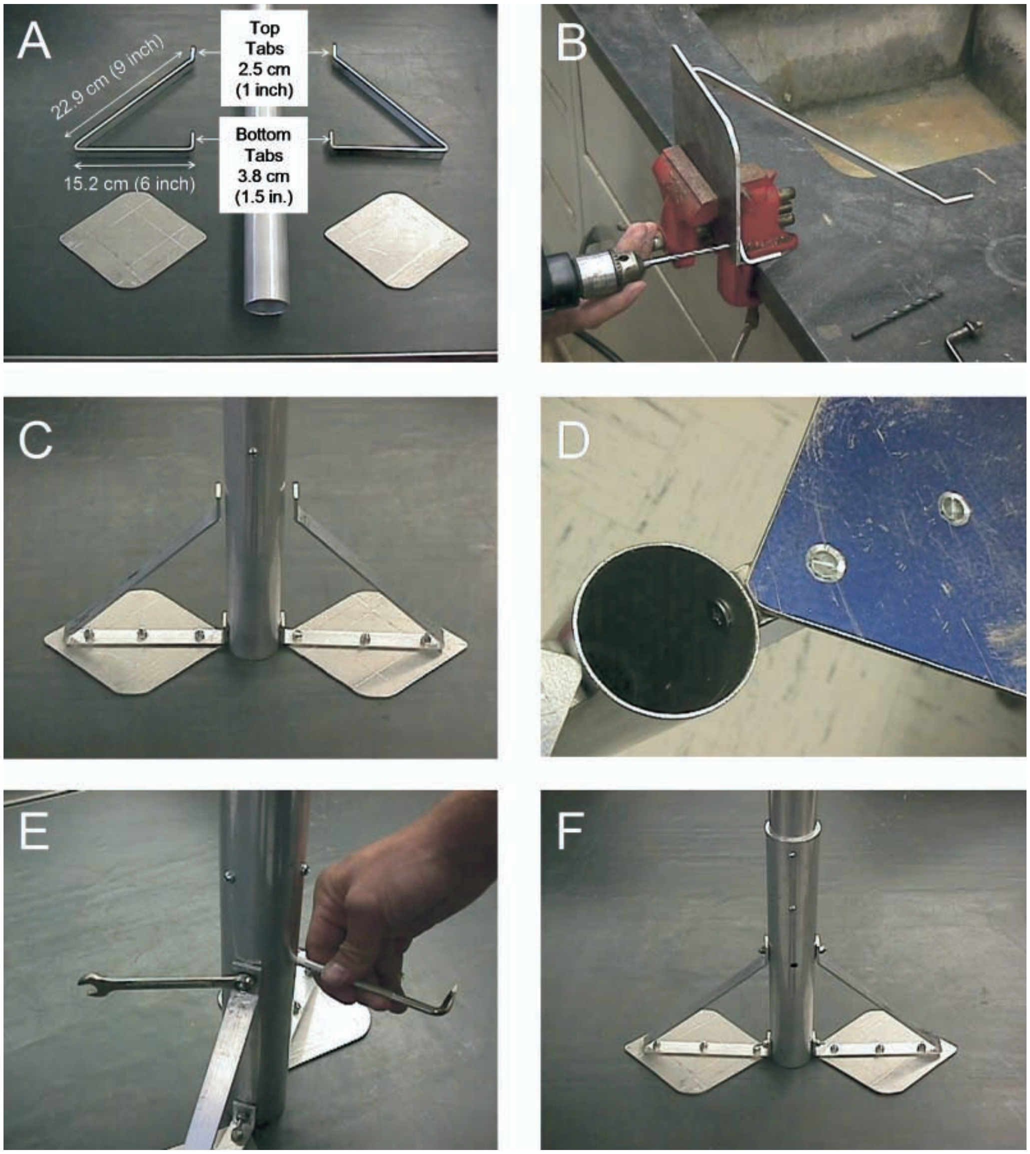

Fig. 3. (A) Bent aluminum strap, with dimensions, and diamond-shaped aluminum plates shown with cut tubing. (B) Drilling through the aluminum plates and strap. After drilling to accept no. 10 flat-head screws, the hole is countersunk. (C) Feet and tubing positioned for marking drill holes on the tubing through the holes already drilled in the tabs of the feet. (D) Detail showing one of the wafer-top screws fastening the bottom tab of one foot to the tubing. The wafer top fits into the oversize (0.8-cm) hole to allow clearance for the access tube to fit inside. (E) Right angle screwdriver inserted through the third hole in the tubing to prevent the wafer-top screw from turning as the lock nut is tightened. (F) Assembled stand (top not shown).

The diamond-shaped plates are fastened, one each, to the bottoms of the bent strap pieces using flat-head screws, orienting the long axis of the diamond coincident with the axis of the strap (Fig. 3B). The bottom sides of the plates are countersunk so that the flat-head screws are flush with the surface. The assembled bent straps and plates are called the feet. Using screws allows the plates to be replaced with smaller plates if the stand is used in a closely planted crop such as wheat.

The 10-cm aluminum tube is inserted inside the 34.2-cm tube so that the ends meet at one end (the top end), and a hole is drilled through the tubes near the top using a 4.5-mm (or #29) bit. With the bit left in place, the 57-cm tube is slipped inside the top end until the assembled length of the tubes is 81.2 cm. With the tubes prevented from slipping, the drill hole is extended into the 57-cm tube. The hole is tapped for a 4.5-mm by 0.5-mm thread (or #8-32) round-top machine screw, and a screw is inserted. Holes are drilled and tapped through all three tubes in five more places, placing screws 2 cm from the top of the 10-cm tube and 2 cm from its bottom, and 4.5-mm (or #8) machine screws are inserted. The machine screws are shortened as necessary so they do not protrude into the inside of the stand. A locking compound is used on the screw threads during final assembly.

The feet are connected to the tubing with screws or by welding. If using screws, the top and bottom tabs of the bent aluminum strap are drilled to accept 5 by 0.8 mm thread (or #10) wafer-top screws (Fig. 3A, two screws through the bottom tab). The feet are placed on opposite sides of the 34.2-cm piece of tubing, and the tubing is marked for drilling (Fig. 3C) with an 0.8-cm (5/16-inch) bit. The bottom tabs of the feet are assembled to the tubing using the wafer-top screws and lock nuts (Fig. 3D) or welding. The next steps are easier with two persons. The assemblage is placed on a table with the tubing perpendicular to the table top and the feet held flat against the table top. The top tab of the bent aluminum strap is pressed against the tubing, and a hole is drilled in the tubing through the hole in the tab, or the tab is welded in place. This process is repeated for the other foot. If using screws, the holes in the tubing are then enlarged using a 0.8-cm (5/16-inch) bit. A third hole is drilled in the tubing at 90° from the position of the last two holes. The top tabs of the feet are fastened to the tubing with wafer-top screws and lock nuts. A right-angle bend screwdriver is passed through the third hole in the tube to hold the head of the screw while tightening the lock nuts (Fig. 3E). All edges are dressed to remove burrs and sharp edges. The stand is primed and painted a bright orange to improve its visibility to machine operators.

An assembled stand is shown in Fig. 3F. If aluminum welding is available (e.g., Nutech aluminum brazing rod, Albuquerque, NM), many of the screw fastenings may be replaced by welds.

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