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### 3.1.3.10 Neutron Thermalization

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#### 3.1.3.10.a Principle

**Neutron Thermalization.** The method uses a radioactive source of fast neutrons (mean energy of 5MeV) and a detector of slow neutrons ( $\sim 0.025\text{eV}$  or 300 K). High energy neutrons emitted from the source at a rate of approximately  $10^{27}\text{ s}^{-1}$  are either slowed through repeated collisions with the nuclei of atoms in the soil (scattering), or are absorbed by those nuclei. A small fraction will be deflected back to the detector. Of these, an even smaller fraction ( $\sim 10^3\text{ s}^{-1}$ ) will have been slowed to thermal (room temperature) energy levels and will be detected. The most common atoms in soil (Al, Si, and O) scatter neutrons with little energy loss because they have much greater mass than a neutron. However, if the neutron hits a hydrogen atom its energy is reduced on average to about half, 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, N, and O are also relatively efficient as neutron thermalizers (about 120, 140 and 150 collisions, respectively). The concentration of thermal neutrons changes mainly with the hydrogen content of the surrounding material. On the time scales of normal interest in water management, changes in H content occur mainly due to changes in soil water content. Therefore, the concentration of thermal neutrons surrounding a source placed in the soil can be precisely related to the soil volumetric water content.

The source and detector are commonly placed together in a cylindrical probe that is lowered into a hole in the soil. In this case, the measurement volume is approximately a sphere with radius of about 0.15 m in a wet clay soil and up to 0.5 m if water content declines to  $0.02\text{ m}^3\text{ m}^{-3}$  (van Bavel et al., 1956). For a soil of specified volumetric water content ( $\theta_v, \text{m}^3\text{ m}^{-3}$ ), about 95% of the measured slow neutrons are from a sphere of radius  $r$  (cm) (Olgaard, 1965).

$$r = 100/(1.4 + 10 \theta_v) \quad [3.1.3-49]$$

(N.B. In the original publication, the factor 10 before  $\theta_v$  was missing. Also, after publication of this chapter, a more accurate relationship came to light. It is  $R = 15(\theta_v)^{-1/3}$  as shown in: IAEA. Neutron moisture gauges. Tech. Rep. Ser. No. 112. International Atomic Energy Agency, Vienna, Austria. 1970.)

**Interferences.** Both soil density and chemical composition affect the concentration of thermalized neutrons by changing the scattering and absorption properties of the soil. Collisions between neutrons and soil materials have three possible outcomes depending on the nature of the atom with which the neutron collides: scattering of the neutron with little energy loss, scattering with large energy loss, and absorption of the neutron by the nucleus of the atom. For a given element, the probability of scattering is described by the scattering cross-section,  $a_s$  (barn, 1 barn =  $10^{-24}\text{ cm}^2$ ).

Because H and C are both effective neutron thermalizers, the organic matter content of soil affects the calibration. Both organic matter and most clays contain important amounts of H that may not be in the form of water and may not be driven off by heating to 105°C (the standard temperature for drying soil samples, Section 3.1.3.1). This H will also affect calibration. Atoms that absorb neutrons include B, Cd, Cl, Fe, F, Li and K. 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 Fe, such as Oxisols or soils rich in magnetite, typically require separate calibration as do soils high in chloride salts. In some US soils, B is present in sufficient quantity to affect calibration. The probability of absorption is described by the absorption cross-section,  $a_a$  (barn). Finally, measurements closer to the surface than 0.3 m are typically affected by the escape of neutrons to the atmosphere (Grant, 1975). Reliable calibration and use in the surface to 0.3-m depth range requires exact and repeatable depth placement of the probe. The combined effect of these processes is complex; so an empirical calibration is needed to convert the thermal neutron concentration to soil volumetric water content.

### 3.1.3.10.b Method

**Equipment.** Neutron moisture meter (NMM) equipment comes in two forms. A profiling meter is most often used for agricultural applications and is designed to measure soil water content and sometimes density to depths of 10 m or greater. A surface meter is used where only shallow measurements are needed (depths to ~0.15 m) and is commonly equipped with a gamma ray source for density testing in engineering applications (for density measurements see the section on gamma ray attenuation). The fast neutron source in modern gauges is  $^{241}\text{Am}$  mixed with Be. The radioactive  $^{241}\text{Am}$  emits an alpha particle that is absorbed by a Be nucleus, which emits a fast neutron ( $^9\text{Be}(\alpha, n)^{12}\text{C}$ ). The source is welded into double encapsulations of stainless steel. Common activities are 0.4 and 1.9 GBq. The detector is a tube filled with  $^3\text{He}$  or boron trifluoride ( $\text{BF}_3$ ) gas. It works by the reverse of the nuclear reaction that creates fast neutrons. The  $^3\text{He}$  or B nucleus absorbs a thermal neutron and emits an alpha particle. A cathode wire in the middle of the detector tube is charged to a large voltage relative to the tube wall; and the voltage differential drives the alpha particle to this wire where it causes an instantaneous voltage change that is detected by the attached circuitry and counted electronically.

*Profiling Moisture Meter.* This device has a readout and control unit connected by cable to a cylindrical probe that is lowered into a bore hole that is usually cased with an access tube. The probe contains the sealed source and detector. The source is either directly beneath the detector, or is centered around the detector. The relative position of the source and detector directly affects the calibration (McCauley and Stone, 1972). But, for modern gauges, source-detector geometry has little effect on the attainable precision (Allen et al., 1993; Dickey et al., 1993; Evett and Steiner, 1995). The probe is lowered into the tube, and stopped at intervals to measure the thermal neutron concentration set up by the source at that depth. Common probe diameters are 38 and 51 mm. When not in use, the probe is locked in the instrument shield, which consists of a block of high density polyethylene, and which itself is commonly attached to the readout and control unit.

*Surface Moisture Meter.* For nonintrusive measurements, the surface NMM is placed on the soil surface. The source and detector are located just above the base of the meter and are commonly separated by several centimeters. The volume measured is roughly hemispherical and extends into the soil for a distance that decreases as the soil water content and density increase, and which varies from ~0.15 m in wet soil to ~0.3 m in dry soil (van Bavel et al., 1956). 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 (van Bavel et al., 1961), a common occurrence. Good precision has been reported under fairly stringent conditions including (i) flattening the surface to fit the gauge bottom with no air gaps, (ii) marking the measurement site so that the gauge can be repeatedly placed in identical position, and (iii) using a Cd neutron absorber shield around the meter (except for the bottom) to reduce effects of surrounding vegetation (Nakayama and Allen, 1990). 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. For example, calibrations developed for the surface to 2-cm and surface to 8-cm depth ranges could not be used to estimate the water content in the 2- to 8-cm depth range.

#### *Suppliers<sup>1</sup>*

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Troxler Electronics Laboratory, Inc.  
3008 Cornwallis Road, Research Triangle Park, NC 27709, USA  
Tel: 919.549.8661, Fax: 919.549.0761  
E-mail: troxsale@troxerlabs.com, Internet: www.troxerlabs.com

Volumetric soil sampling equipment designed for NMM calibration (Madera probe)  
Precision Machine Company, 2933 North 36th street, Lincoln, NE, 68504-2498, USA  
Tel: 402.467.5528, Fax: 402.467.5530

**Site Selection and Representivity.** Design of a NMM installation is a compromise between the number of tubes needed for a sufficiently precise measure of soil water and the cost of installing and reading the network of access tubes. Most installations aim to limit the tube numbers to those that can be read in a day.

Modern instruments can take a reading of adequate precision at a single depth in 30 s. The depth range of each measurement can be assumed to be at least 0.15 m above and below the reading point. Readings are often taken at 0.2-m intervals. Therefore 10 readings, or 5 min are needed to scan a single tube to 2-m depth. If tubes are located close together, then a reading rate of 10 tubes per hour is a reasonable goal for a single instrument and operator. The number of tubes that can be read in a day will decrease as travel time to the site and between tubes increases.

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<sup>1</sup>The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

In reported studies, the depth interval between readings has been as small as 0.15 or even 0.10 m (Carrijo and Cuenca, 1992; Vandervaere et al., 1994a). 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). A depth interval of 0.10 m was reported to improve precision of profile water content (Carrijo and Cuenca, 1992), but the improvement was 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  $>0.3$  m are sometimes used where water content changes slowly with depth. However, this is done at the risk of losing some information because the effective range of the NMM may be only 0.15 m from the center of the probe in wet soil. The desirable maximum depth of reading will depend on the particular aims of a study. But in many studies it should be well below the maximum depth of rooting and below any expected zero flux plane for soil moisture (Wright, 1990).

The number of tubes required to control variance in water content measurement is a complex matter. Variance arises from four sources: (i) random variation in neutron emission from the source (neutron emission follows a Poisson statistical distribution), (ii) counting error, (iii) variation in water content across the site, and (iv) calibration error. Based on randomness of emission, a typical reading of 10 000 counts has a variance of 1%. Modern instruments obtain this many counts in 15 s in most soils and this source of error can be reduced simply by taking longer counts at each point. Counting error is negligible in properly operating meters. Variation in water content across a site is a function of soil properties, topography, climate, uniformity of any irrigation or precipitation, time since the last wetting, and the type and growth stage of any plants. It is not possible to make a decision about the number of access tubes required to achieve an acceptable precision in a particular environment without additional information about the soil and plant environment to be studied. If the work is to be at a site where previous experimental work has been done, then the best source of information about site variability is in reports from that work. If this information is not available, then the sections of this manual on geostatistical methods (Section 1.5) and soil variability (Section 1.2) will provide some basic guidelines about how to assess the soil matrix variability on a new site. References dealing with variance and spatial variability of NMM measurements include Haverkamp et al. (1984), Sinclair and Williams (1979), Vandervaere et al. (1994a, b), and Vauclin et al. (1984).

Spatial variability studies usually find that variance between soil moisture samples increases with separation distances. But, the same studies indicate that there is a nugget effect; that is, the variance between samples does not go to zero at small distances. It is this small-scale ( $<1$  m), non-zero variance that influences the variability of a single measurement. Hawley et al. (1982) studied the relationship between sample volume and variance of water content samples, using eight different sample volumes ranging from 7 to 825 cm<sup>3</sup>, and concluded that variance increased for smaller volumes. The same was true when a 15-cm<sup>3</sup> sampler was compared with a 60-cm<sup>3</sup> sampler for NMM calibration (Allen et al., 1993; Dickey et al., 1993). Most other studies of soil moisture variability used only one sample size or did not report the sample size. The NMM measures, at minimum, a volume of  $\sim 14\,000$  cm<sup>3</sup>. Comparing this with the much smaller sampling volumes of most gravimetric methods, or time domain reflectometry (TDR) and capacitance probes, indicates that more measurements would be needed with these technologies to give a field or plot mean profile water content with precision comparable to that from neutron thermalization. This was recognized as early as the 1960s and was an important factor in the adoption of the NMM for crop water use

measurements based on soil water balance (Calif. Dept. Water Res., 1963). In comparing the variance in water content as measured by the NMM with that by other means, it is useful to keep in mind that measured variation of water content in a field is likely to increase as the volume of soil that is measured decreases. Approximately 24 soil samples (50-mm diameter and 0.3-m long, 589 cm<sup>3</sup>) would be needed to sample the same soil volume as one NMM measurement. Small scale variation of soil moisture is controlled by topography, vegetation, soil properties, sampling depth (Hawley et al., 1982); and, for a particular location, variability changes with time since wetting (Schmitz and Sourell, (2000) and with moisture content (Hawley et al., 1982; Schmitz and Sourell, 2000). Therefore, no simple statement of the desired sample volume can be given, other than to state that fewer large volume samples will be needed to determine the mean value within a given confidence interval than would be needed if smaller volume samples were obtained. Readers are referred to Section 1.4, which discusses sample number determination for given variance and confidence level. For a parallel and useful discussion relevant to irrigation scheduling see Schmitz and Sourell (2000). Variance in soil properties can also affect the precision of the calibration of the NMM (see below).

### **Field Installation.**

*Access Tube Materials and Dimensions.* Aluminum is usually recommended for access tubes as it has minimal effect on neutrons. However, it is relatively expensive, not particularly strong and can quickly corrode in saline or alkaline conditions. Mild steel tubing is cheap, strong, and will last for at least 3 yr in all but very acid soils. It has the disadvantage that it absorbs neutrons and decreases sensitivity of the instrument by about 2%, but with no apparent affect on accuracy. Hence it may have the apparent effect of slightly increasing calibration error. Stainless steel can be used, but it is expensive and also decreases sensitivity. Polyethylene has been used successfully and has the advantage that it is flexible (useful in stony soils). But, flexibility can be a disadvantage with some installation methods (see below). The H and C in polyethylene tubes increase the NMM count by ~20% (cf Al). However, both the density and wall thickness of plastic tubes vary, particularly between batches, which introduces a small additional random error. Calibration must be done using material of the same batch as the main installation. The root mean squared error of regression increased by 0.003 m<sup>3</sup> m<sup>-3</sup> when polyvinylchloride (PVC) rather than Al tubing was used by Allen et al. (1993). Neutron count values were ~50% larger for Al vs. PVC tubing in two studies (Allen et al., 1993; Allen and Segura, 1990) due to neutron capture by the Cl atoms in the PVC. Accurate and precise calibration and water content determination are much more dependent on other factors explained below than on the material used for access tubing.

The access tube should be as small as possible to maximize sensitivity, but have sufficient tolerance to allow the probe to move freely, even if there are small distortions in the tube. Tubes of 44- to 56-mm outside diameter and walls of 1.6-mm thickness are used commonly. Both larger diameter and greater wall thickness may result in decreased meter counts (Allen and Segura, 1990). Larger diameter tubes are used with larger diameter probes. The larger diameter tends to increase the radius of the volume of influence and decrease the vertical resolution of the instrument (Stone, 1990). Access tubes should be about 0.3-m longer than the greatest depth to be measured. This allows 0.15-m extra at the bottom to prevent the deepest reading from being influenced by the soil at the end of the tube (Stone et al., 1993), plus an allowance of 0.1 to 0.15 m of tube to extend above

the surface to make the tube visible in the field and to prevent accession of surface water. Protrusion from the soil should be minimized to prevent rainfall collection and heat conduction from the soil surface. A rubber bung or inverted container should be used to prevent rain and animals from entering the tube. It is also a good idea to clearly mark the tube with a number to aid identification.

*Removable Extensions.* Where tillage is needed, the tube is constructed so that the top section (usually 0.3m) is held in place by a slightly oversize sleeve. Before cultivation the top section of tube is removed and a bung attached to a coloured wire is inserted. After cultivation, the hole is again located by tracing the wire back to the bung. Other methods of locating such buried tubes include measurements from fixed reference points, and the use of a metal detector. Removable tube tops present calibration problems at the join (double thickness of tube), with soil disturbance adjacent to the tube, and with water leaks into the join during soil saturation periods. With care, they can be used successfully.

*Installing Access Tubes.* Neutron moisture meters are relatively immune to installation problems because the soil volume affected by access tube placement is small compared to the volume of measurement. The tube needs to be tight fitting with no cavities around the tube, both because the calibration depends on the cavity size (Allen and Segura, 1990), and to prevent free surface water from leaking down the outside of the tube.

Several methods of installation are commonly used:

1. **Ramming.** A hardened tip is placed on the access tube; and the tube is forced into the soil with an hydraulic system. This method is not recommended except in soft, incompressible materials such as loose sand.
2. **Sample and ream.** A hydraulically driven push tube or hand auger is used to dig a slightly undersized hole. Then the access tube is pushed into the hole and an auger used to clean out the excess soil by extracting it from inside the tube. Hand augering is preferable to machine augering or push tube sampling to minimize soil disturbance around the tube. To keep the access tube centered in the undersized hole, it can be an advantage to put a bevel on the outer edge of the access tube.

If a push tube is used to install access tubes it may cause compaction around the tube, particularly if the bit on the push tube is bevelled on the outside, and if installation is into a moist, compressible soil. Push tubes are best used with incompressible soils such as sands, or when soil is very dry, or saturated (and therefore incompressible). In susceptible soils, the effect of the tube (like any pile or penetrometer) can extend several diameters into the clay affecting much of the measurement volume (Farrell and Greacen, 1965). The direct effect on the NMM may be small, but reduction of air filled pores, and the small increase in strength can have large effects on the plant root environment, reducing root development next to the access tube. This problem is not important where plants are established before installation but can cause the measurement zone to dry later than the field as a whole in an annual crop environment due to restricted root development adjacent to the access tube. The problem can be detected if temporary access tubes are installed and read as soon as the soil starts to dry in spring. Also, small

- reductions in mean pore size may cause the soil adjacent to the tube to have higher water content at equilibrium than does surrounding uncompressed soil.
3. Center tube soil withdrawal. This method provides the best results, minimizing compaction of soil near the tube and voids between the tube wall and soil, but is very difficult and time consuming if done manually. The tube is inserted a short distance into the soil and pushed down in shallow lifts while augering from inside the tube. For this method, the tube should be beveled on the inside so that all soil is pushed toward the center as the tube is pushed down.
  4. The slurry method. A slightly oversized hole (2 mm) is dug using an auger or push tube. The access tube is sealed at the bottom, and a slurry of local soil with 10% cement as a binder is poured down the hole and the access tube quickly inserted so that the slurry rises to fill the gap around it. The slurry should be as dense as possible to minimize shrinkage on drying. If local soil is unsuitable, a mixture of 10% cement, 40% kaolin clay and 50% water (by weight) can be used. The clay in this mixture will affect the calibration, necessitating a field calibration procedure, particularly if the local soil is low in clay content. This method is recommended except where extreme accuracy is required. Note that the shrink-swell clay bentonite should not be used. It will shrink on drying, leading to the possibility of free water traveling down shrinkage cracks immediately adjacent to the access tube.

Note that with most tube installation methods the soil sample extracted from the hole may be used for calibration checks. If there is a risk of water entering the tube from below, the tube should be plugged with a rubber plug, hydraulic cement seal (poured down a tube inserted inside the access tube), or other watertight material. Traffic by vehicles during installation should be controlled to ensure that access tubes are not installed in wheel tracks. Compaction by foot traffic in the immediate vicinity of an access tube should be avoided. This may require the use of a protective platform, such as a pallet during installation.

*Site Maintenance and Protection.* The NMM can repeatedly and nondestructively sample a site; but this advantage can be negated by careless operators. If soil or plants within 1.5 m of the tube are damaged by repeated operator traffic then the value of the site is compromised. Firm operating procedures to avoid crop damage, such as the exact place the operator is to stand while taking readings and the path to be followed by people and vehicles near access tubes, are important factors in good experimental design. In wet conditions, the operator should gain access by using a portable platform or walk board, possibly suspended over the site.

**Control of Probe Depth Placement and Shield Height.** It is common practice to place the NMM on top of the access tube before releasing the probe from the shield and lowering it for readings in the soil. This practice is not recommended for two reasons. First, when the NMM is placed on top of the access tube, 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 (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 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 due to loss of neutrons to the atmosphere (van Bavel et al., 1961; Grant, 1975).

These problems are addressed by using a depth control stand. 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. 3.1.3.10-1). 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. Instructions for fabricating and using a depth control stand are available (Evelt, 2000c). 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 gauge shield (see below). For both Troxler and Campbell Pacific Nuclear International meters, the center of measurement of the probe is marked by an embossed line encircling the probe. See the manufacturer's manual for meter dimensions relevant to setting the depth of the center of measurement, or see the depth control stand instructions (Evelt, 2000c) for dimensions relevant to meters currently in production.

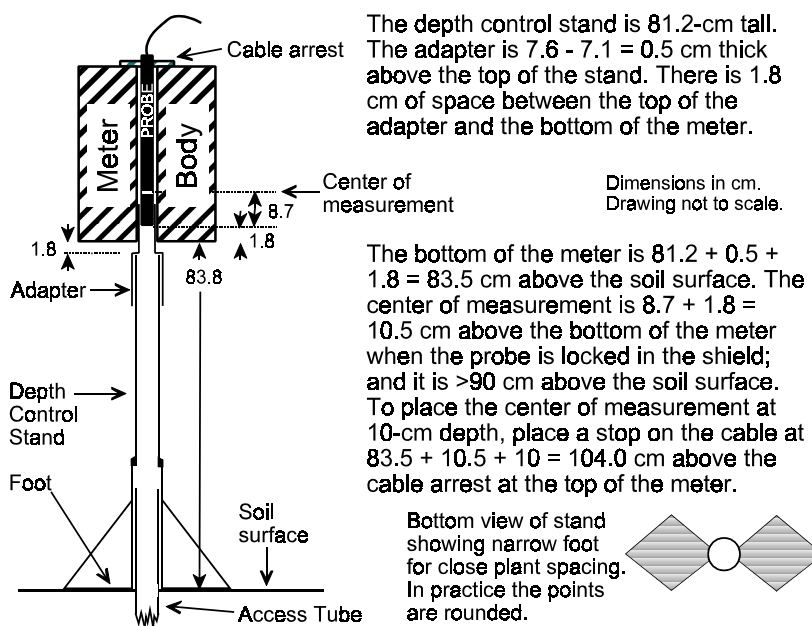


Figure 3.1.3.10-1. Example dimensions relevant to placing cable stops on cables to achieve accurate depth placement of the probe center of measurement when using a depth control stand.



### Neutron Counts.

*Statistics of Neutron Emission.* Neutron emission is a random process that occurs according to a Poisson probability distribution. A relevant 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

$$m = \frac{1}{N} \sum_{i=1}^N x_i \quad [3.1.3-50]$$

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

$$s = \left[ \frac{1}{N-1} \sum_{i=1}^N (x_i - m)^2 \right]^{1/2} \quad [3.1.3-51]$$

For a properly operating gauge 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  $\chi^2$  (Chi-squared) statistic by

$$\frac{s}{m^{1/2}} = \left( \frac{\chi^2}{N-1} \right)^{1/2} \quad [3.1.3-52]$$

Values of  $\chi^2$  for a given probability level are given in statistical tables for different values of  $(N - 1)$ . We may write the right-hand-side of Eq. [3.1.3-52] for the upper and lower limits of  $\chi^2$  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  $\chi^2$  as 17.5 for  $P = 0.975$  and 48.1 for  $P = 0.025$ ; and from Eq. [3.1.3-52] the Chi ratio should be between 0.75 and 1.25 about 95 times in every hundred. Note that some gauges divide the count by a fixed number in order to reduce the displayed count to a reasonably small value. If the above calculations are applied to such reduced counts, the Chi ratios computed will be incorrect. To compute Chi ratios, the user should first multiply the recorded counts by the factor that the gauge used to reduce them.

These facts allow the user to check gauge operation by computing the Chi ratio. In fact, all modern gauges include an internal function for doing so, either through a special “STAT” function, or as a normal part of taking a standard count (see below). The range of the Chi ratio for a particular gauge will depend on the number of samples that that particular gauge uses in computing the standard count and Chi ratio values. An occasional Chi ratio outside of the 0.95 probability range is no large cause for concern, but should be checked by making another test. However, a series of Chi ratio values that average above or below unity signals a problem in the gauge electronics or internal geometry, and indicates inaccurate readings. For this reason, a quality assurance program

for NMM measurements should include daily measurement and recording of the standard count and Chi ratio.

*The Standard Count.* While modern instruments are quite reliable, it is good operating practice to measure the count rate in a standard medium at regular intervals (i.e. daily) to check the machine for faults. Even if the Chi ratio remains near unity, a sudden change in this standard count signals a problem with the gauge that should be corrected before more field readings are taken. Problems that can occur include failure of electronic components, cable and connector failures, and detachment of the detector tube inside the probe (change in geometry of measurement).

The standard count is taken, in the case of surface gauges, with the gauge placed on its “calibration” block or, in the case of profile meters, with the probe locked in the shield or in an access tube surrounded by a large volume of water. The operator should stand at least 3-m away to avoid influencing the count. For profile meters, the ideal standard is a 200-L container (or, at least 0.55-m diameter and 0.8-m height) filled with distilled water and equipped with a central access tube of the same material and size as is used in the field (Hodnett and Bell, 1991). The center of measurement of the probe should be located in the center of the volume of water; and the access tube should extend to the bottom of the container to avoid the influence of nearness of the end of the tube. If the ratio between the field standard count and the 200-L container of water is known then the count ratio (see below) can still be expressed relative to the count in water.

A 0.5-m diameter by 0.5-m high container of plastic pellets embedded in epoxy or fiberglass resin has also been used. This is more appropriate for field use as it does not leak or evaporate. During counting however, it must be located such that the count is not influenced by surroundings. A container or shield such as this is also invaluable for reduction of operator radiation exposure during servicing of the probe.

Many users prefer the convenience of using the small plastic shield in the meter body as a standard. This is less reliable as the count can be affected by the soil and nearby bodies. However, it is acceptable provided the shield is mounted at least 0.8-m above the soil surface during the count (Fig. 4 in Dickey, 1990a, Fig. 1 in Allen and Segura, 1990), and at least 3-m from surrounding objects (including the operator). The depth control stand described above is useful for this purpose. Failure to separate the instrument sufficiently from the ground will lead to substantial errors in water content determination. In a ten-year study, such probe shield counts were found to be reliable and highly precise (Stone and Nofziger, 1995; Stone et al., 1995). The practice of placing the meter on its case for the count is to be avoided 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 Count Ratio.* Calibration equations for surface gauges and profile meters are typically linear functions of a count ratio ( $C_R$ ). The value of  $C_R$  is the ratio of the count,  $x$ , made in the measured material to a standard count,  $x_s$ .

$$C_R = x/x_s \quad [3.1.3-53]$$

It is good practice to express the calibration in terms of the count ratio. Using a calibration based on count ratio rather than in terms of direct counts, allows the same calibration equation to remain valid even as the source strength decays. The half-life of  $^{137}\text{Cs}$  is 30.6 yr and that of  $^{241}\text{Am}$  is 458 yr. To maintain 0.1% accuracy for density measurements ( $^{137}\text{Cs}$ ), the standard count must be re-determined every 2 wk. To do the same for moisture measurements ( $^{241}\text{Am}$ ), the standard count must be re-determined every 8 mo. By use of the standard count and count ratio an accurate calibration may be used for many years. It is recommended that the ratio between the standard count in regular use and the count in water using an access tube of known characteristics be measured from time to time to provide a more universal standard.

**Calibration.** Contrary to Gardner (1986), manufacturers' calibration equations are seldom useful for routine soil moisture determination (e.g., Dickey, 1990a, b). Calibration of NMMs involves correlating measured count ratio values with independently determined volumetric water contents,  $\theta_v$  ( $\text{m}^3 \text{m}^{-3}$ ). For modern gauges and the normal range of values of soil water content, the calibration is linear and of the form

$$\theta_v = b_0 + b_1 C_R \quad [3.1.3-54]$$

where  $b_0$  and  $b_1$  are the calibration coefficients as determined by linear regression, and  $C_R$  is the count ratio defined above. Because of the wide variety of agricultural soils, it is necessary to calibrate for specific soils even though NMMs come with factory calibrations. If possible, it is best to calibrate in the field so soil horizon-specific calibration coefficients may be determined. Otherwise, fairly large errors may result because calibration coefficients vary widely for horizons rich in clay, organic matter,  $\text{CaCO}_3$ ,  $\text{CaSO}_4$ , or close to the surface. Several calibration methods are commonly used. Each has qualities that recommend it for a particular use.

*Method 1: Calibration in a Uniform Soil – Laboratory Method.* Where a soil is uniform to considerable depth a calibration can be carried out in the laboratory. Excavate approximately  $2 \text{ m}^3$  of soil from the field and transport to the laboratory. Air dry it and crush to pass a 5-mm sieve and mix it thoroughly. The soil will be packed into a steel container of at least 1.22 m in both diameter and height (to obtain an equivalent infinite volume, van Bavel et al., 1961), open at top and bottom and divided so that it can be split vertically into two halves to simplify removal of the soil. An access tube of the same composition and size as used in the field is mounted in the center of the container.

Add air-dry soil to the container in quantities of 40 kg, spread evenly, and lightly pack. Take samples for gravimetric water content and density throughout the packing to calculate density and volumetric water content for the whole container. Measure the NMM reading at four depths (the container center point, at 0.1-m above and below it, and at 0.1-m depth) for five times the normal counting period. Split the container into its two halves and remove the soil, crushing any cohering lumps. If the soil has >2% organic matter or clay then it should be repacked using a greater packing pressure (a smaller rammer) to achieve a higher density and the count rate again taken to measure the effect of density and nonwater H. The soil is then removed, crushed and a calculated amount of distilled water is sprayed onto it and the soil thoroughly mixed and left to stand overnight under a cover. After mixing again, the container is repacked, again sampling for density and water content,

and the NMM readings repeated for the higher water content (at high and low density if necessary). This process is repeated until the soil is too wet to work.

The volumetric water content of each packing is estimated from the average density and the gravimetric water content of the soil and plotted against the count ratio of the NMM. A linear regression is then fitted to the data points using the variable (count ratio or water content) with the least error as the independent variable. This is because regression theory requires that the independent variable be known precisely; and both NMM count and water content have error (Morris et al., 1987). If water content is known more precisely, and is used as the independent variable, then the equation can be inverted before use. If the high and low density points are fitted separately, then the effect of density and volumetric nonwater H (which changes with density) can be measured also.

*Method 2: Field Calibration for Uniform Soil or Horizon.* This is the most common calibration method. While a calibration should include as wide a range of soil water contents as possible, a common mistake is to derive this range from different horizons. If this is done, differences in calibration coefficients due to water content differences are often confounded with differences due to soil materials because both soil materials and water content commonly change with depth.

It is best to establish both wet and dry sites in a field for calibration, either at the same time or sequentially. Establishment of wet and dry sites ensures adequate numbers of wet and dry samples for each horizon, and helps ensure that the slope of the calibration equation is determined as accurately as possible (Fig. 3.1.3.10-2). A dry site may be established by growing a crop that normally dries the profile, and/or waiting for a time of year when the soil is normally dry. A wet site may be established by berming an area and ponding water on it until the wetting front has descended below the lowest horizon to be calibrated. If the soil is a heavy clay it may take many days to wet the profile. Typically, three access tubes will be installed at each of the dry and wet sites with at least 1-m spacing between tubes.

Prior to using the NMM, check the depth stops on the cable to ensure accurate depth positioning (Fig. 3.1.3.10-1). Take at least three standard counts, and check counts and Chi ratios for stability. Take 60-s or longer counts at all the depths required for calibration. For the wet site, wait an appropriate time after ponded water is removed in order to allow rapid internal drainage to take place before taking counts. This ensures that soil water content does not change appreciably between the time counts are taken and the time that soil samples are obtained. For the same reason, it is important to obtain the gauge readings and soil samples for the wet site in the same day.

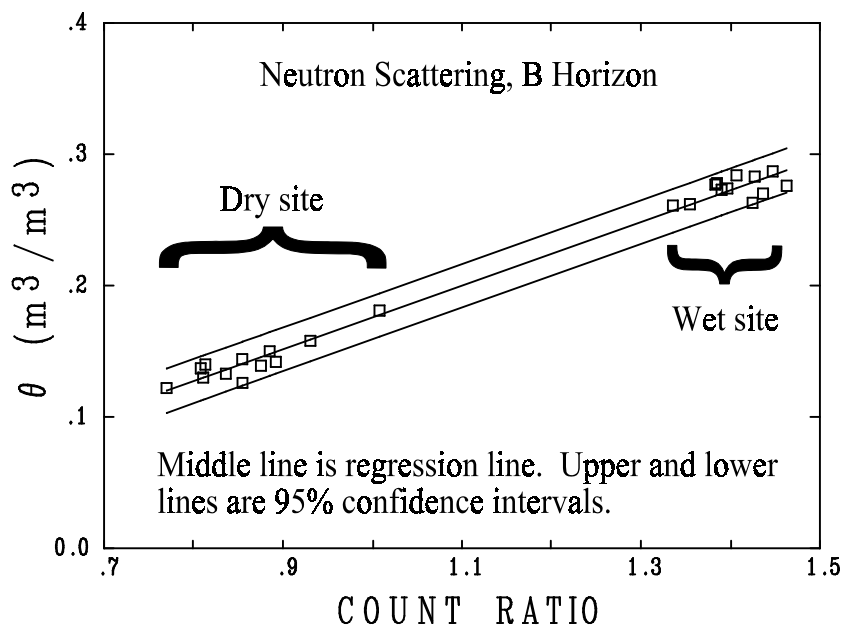


Figure 3.1.3.10-2. Typical differences in water content between wet and dry profiles and calibration line from a wet site - dry site calibration.

Take multiple volumetric soil samples at each depth around each tube. Sample around the wet site tubes immediately after counts are taken. A volumetric soil sampler such as the Madera probe (Evett, 2000a) or thin-walled metal cylinders should be used. To lessen compaction, the sample surface area should be at least 90% of the area of the hole created by the sampler. A minimum of four samples should be taken from within 0.15 m of the tube at the reading depth (that is, sample from the volume of soil measured by the probe). Take care when removing the soil near the tube so as not to disturb the remaining soil before the remaining samples are taken (avoid compaction or soil loosening). Samples may be taken horizontally from the side of a pit dug on one side of the access tube. Alternatively, the soil may be removed to a depth about 0.1 m above the reading depth and the samples taken vertically (Fig. 3.1.3.10-3). To calibrate at depths >0.5 m, it is best to dig a trench not closer than 0.5 m from the tube, then work from the trench to excavate to the sample depth. While taking soil samples, note depth of any soil horizons that might lead to different calibrations. Before regression analysis, calculate the mean and standard deviation of soil water content and bulk density for each measurement depth at each access tube. Examine these data and recompute the means after removing obvious outliers. For example, in Table 3.1.3.10-1, each of the N values is the mean of four samples taken at a particular depth at a particular access tube (six samples for the 10-cm depth). This method is designed to provide a mean soil water content for the volume of soil that is read by the NMM. It can routinely produce root mean squared error values (RMSE) for linear regression of  $<0.01 \text{ m}^3 \text{ m}^{-3}$  (Table 3.1.3.10-1) (Evett, 2000a).



Figure 3.1.3.10-3. Sampling the NMM measurement zone with volumetric cylinders. The black mark near the top of the access tube indicates the original soil surface and is used to measure the depth of soil removal prior to sampling.

A variant of this method was used by Allen et al. (1993) and Dickey et al. (1993) in which samples were taken with a 1.22-m-long tube probe pushed into the ground with a hydraulic ram. Both wet and dry sites were used. The sample was extruded from the tube onto a tray and sectioned into lengths corresponding to the depth intervals measured with the NMM. The process was repeated to create a hole at least 1.5-m deep. The volume of each sample was calculated as the area of the cutting edge of the tube probe multiplied by the length of that section. Access tubes were installed in the holes created by sampling and NMM measurements taken at the centers of the depth ranges sampled. The method achieved the best results of the three methods they compared in three soils (which did not include Method 2 described here), but also gave consistently higher  $C_R$  values, a result of compression of soil around the tube probe that was particularly evident in a clay loam soil. The RMSE of regression ranged from 0.006 to 0.013  $\text{m}^3 \text{m}^{-3}$ . This variant is not recommended in soils that compress easily as soil in the sampler may be compressed or dilated during sampling. The USDA-SCS (now NRCS) method is similar except that the Madera probe is used to take a 60- $\text{cm}^3$  sample at each reading depth with hand augering to deepen the hole between samples (Dickey, 1982, 1990b). After sampling, the access tube is inserted to allow for NMM readings. In the study of Allen et al. (1993) the RMSE of regression ranged from 0.011 to 0.014  $\text{m}^3 \text{m}^{-3}$  for the SCS method; but  $C_R$  values were not raised by soil compression. Both of these methods (Allen et al., 1993) are designed for calibration during access tube installation so that the access tube may be used for subsequent moisture readings. But, both have the dual disadvantages that (i) the soil sampled is removed from the hole before NMM counts are measured, and (ii) there is only one sample per depth associated with each NMM count. The accuracy of this variant can be improved considerably by

taking cores at three or more places around the access tube and close enough to be within the measurement volume (Wright, 1990).

Table 3.1.3.10-1. Calibration of water content ( $\theta_v$ ,  $\text{m}^3 \text{m}^{-3}$ ) vs. count ratio ( $C_R$ ) for the Amarillo fine sandy loam using method 2 (Evetts and Steiner, 1995). A depth control stand was used.†

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

*Calibration for Near-Surface Readings.* The loss of a substantial fraction of neutrons from the surface soil during near-surface readings (<0.3-m depth) 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). However, the ordinary field calibration procedure (method 2) is quite adequate provided a depth control stand is used (see Table 3.1.3.10-1).

*Method 3: Calibration in Soils with Variable Clay Content.* The above calibration procedure, assumes that the dominant variable affecting the NMM response is soil water content. When a field has variable clay or organic matter content within the same horizon, the above calibration procedure often leads to unacceptable scatter in the calibration points. This is particularly evident where a clay horizon occurs at varying depth across a field, or where clay or organic matter, and thus nonwater H, vary across the field within a horizon. Greacen et al. (1981) reported an empirical approximation for nonwater H in 18 Australian clays (including swelling and nonswelling clays)

$$We = 0.124 (+/- 0.012)C + 0.015 \quad [3.1.3-55]$$

where  $C$  is fractional clay content of the soil in g/g, and  $We$  is water content equivalent to clay H ( $\text{g g}^{-1}$ ). Nonwater H was measured as the water released from initially oven dry soil heated to  $600^\circ\text{C}$  in an  $\text{O}_2$  atmosphere.

If clay (or organic matter) is likely to vary horizontally within a soil horizon then a modified form of the above field calibration method is used. Tubes are randomly placed across the field in pairs, one of each pair to be sampled while wet and the other in dry conditions. This makes use of the assumption that variation in a field will be less between two points that are near each other than for two points that are much further apart. The resulting calibration then comprises, not a scatter of unrelated wet and dry points, but a series of pairs of points each defining a calibration line for a location in the field. These lines might be termed *minicalibrations*.

If the field is uniform, then these minicalibrations will form a readily identifiable common line, the same line that would be obtained by the unpaired method. In a nonuniform field however, a common calibration line is not likely. But now additional information is available which may be used to map the minicalibrations to the field and improve the precision of the NMM method as applied to that field. Pairing of access tubes is strongly recommended as results will be little

different to the same number of randomly distributed single tubes in a uniform field, but will provide much greater information and precision in nonuniform fields.

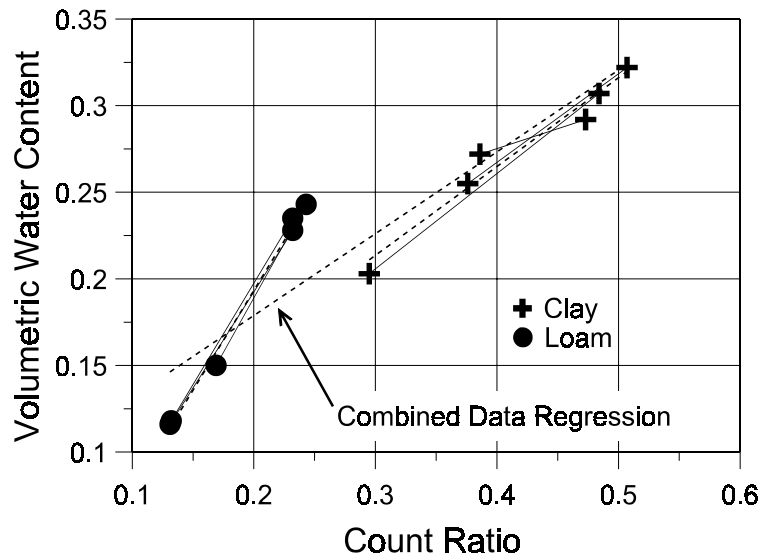


Figure 3.1.3.10-4. Field calibration in a soil with variable texture using three pairs of access tubes in each texture. Regressions (dashed lines) show clear differences in slope for loam and clay soils. The common regression shows a similar slope to the clay (offset by  $\sim 0.02$ ), but is biased for the loam. Profile water content change calculated using the common calibration will be considerably in error.

Figure 3.1.3.10-4 shows results of a calibration done for two extreme soil textures in a field (Table 3.1.3.10-2). The longest regression line (common calibration) includes all data points. The shorter lines are minicalibrations, each derived from a pair of tubes. Measures of water content using the common calibration will have a substantial error ( $RMSE = 0.03$ ), which would have to be tolerated if no additional data were available. Clay variation is commonly linked to soil horizons; and Method 2, if used with due attention to soil horization, would separate the calibrations for clay and loam horizons as a matter of course. Soil texture can often be identified by eye, or measured to sufficient precision by simple field texturing methods, so an access tube can be categorized as in a high clay or a low clay area and the appropriate mini-calibration selected for that site. In agriculture, this technique can provide additional precision. In larger scale work, the mini-calibration approach may be mandatory. An example is a catchment scale survey where soil properties at any given depth may change greatly over the catchment area and where it may be infeasible to apply Method 2 to each separate nominally uniform subarea.

Where a soil horizon has wide variation in density or clay there will be substantial variation in  $C_R$  that does not correspond to water content variation. Equation [3.1.3-55] indicates that, for example, variation from a sandy loam (15% clay) to a clay loam (30% clay) at an average density of  $1.4 \text{ Mg m}^{-3}$  would cause a change in  $C_R$  equivalent to  $0.025 \text{ m}^3 \text{ m}^{-3}$  in  $\theta_v$ . In the worst case, near



wilting point in the sandy loam ( $\sim 0.08 \text{ m}^3 \text{ m}^{-3}$ ), this suggests an error equal to 30% of the water content (0.025/0.08). Thus, for a soil with large horizontal variation in clay content or density, calibration by Method 3 is mandatory to produce the best calibration for estimation of water content that is possible under these conditions.

Table 3.1.3.10-2. Regression equations of water content ( $\theta_v, \text{m}^3 \text{ m}^{-3}$ ) vs. count ratio ( $C_R$ ) for Fig. 3.1.3.10-4.†

Soil texture	Depth (m)	Regression equation	RMSE	$r^2$	N
loam	0.3	$\theta_v = -0.037 + 1.150C_R$	0.005	0.99	6
clay	0.6	$\theta_v = 0.060 + 0.513C_R$	0.010	0.96	6
combined	0.3 to 0.6	$\theta_v = 0.084 + 0.472C_R$	0.027	0.85	12

† RMSE is root mean squared error, N is the number of samples, and  $r^2$  is the coefficient of determination.

*Transferring Calibration Coefficients Between Meters and Checking Meter Calibration.* Calibration of NMMs is time consuming whether done in the laboratory or the field. It is desirable to be able to transfer the calibration between a calibrated meter and a new or repaired one, and to be able to check a calibration. This can be done by preparing drums of media with sufficient volume that counts would not increase if further volume were added (quasi-infinite volume) and with media characteristics that produce widely different count numbers. Once a calibration is transferred to such a set of drums, the calibration may be transferred to NMMs of the same design, with some precautions (Reginato and Nakayama, 1988). Meters from different manufacturers have different source-detector configurations and respond to these media differently so that, in general, calibrations cannot be transferred between them. Even for a single manufacturer and model number, if the NMMs were manufactured many years apart, the internal characteristics may be sufficiently different that calibrations cannot be transferred in this manner (S.R. Evett, unpublished data). In any case, once a calibration is transferred, the NMMs involved should be used to obtain soil water content values in wet and dry sites in the field and those values checked for correspondence across meters. Of course, the transferred calibration will only be valid for the soil in which the initial calibration was done.

Media used have included water, aluminum sulfate ( $\text{Al}_2(\text{SO}_4)_3 \times 18\text{H}_2\text{O}$ ), urea ( $\text{NH}_2\text{CONH}_2$ ) (McCauley and Stone, 1972; Hodnett and Bell, 1991), ammonium alum ( $\text{Al}_2(\text{SO}_4)_3(\text{NH}_4)_2\text{SO}_4 \times 24\text{H}_2\text{O}$ ) (McGuinness et al., 1961), and high-density polyethylene plastic cylinders of various radii (Reginato and Nakayama, 1988). Depending on its size and constitution, each medium will represent a particular equivalent water content. At least two such media are required, one with a small equivalent water content and one with a large equivalent water content. For long term stability, the media should be prepared so that their properties do not change with time. For example, in the 10-yr study of Stone et al. (1995), urea was hygroscopic and took up water even though sealed in polyethylene sheeting and doubly sealed in a steel drum, while aluminum sulfate protected in the same way was quite stable. McGuinness et al. (1961) were able to create media with equivalent water contents ranging from 0.033 to  $0.434 \text{ m}^3 \text{ m}^{-3}$  by mixing ammonium alum with silica sand, and found the resulting mixtures to be very stable “even when exposed to air”. If a medium does not represent a quasi-infinite volume (e.g., the plastic cylinders of Reginato and Nakayama, 1988), then care must be taken to remove the meter shield and any other objects from the vicinity of the medium during counts.

To transfer a calibration to the media, the probe of a previously calibrated meter(s) is centered in each medium and a count is made of sufficiently long time to minimize count variance. Standard counts are also obtained (see above); and the equivalent water content for each medium is calculated from the calibration equation. Subsequently, the same meter or a very similar meter may be used to obtain counts in the media and standard counts, and a calibration may then be calculated. If three or more media (with three or more equivalent water contents) are used then linear regression may be used to calculate the new calibration equation, with the previously established equivalent water contents as the dependent variable and the new count ratios as the independent variable. If only two media are used then a set of two equations results, which may be solved for the slope of the new calibration equation:

$$b_1 = (\theta_{e2} - \theta_{e1}) / (C_{Re2} - C_{Re1}) \quad [3.1.3-56]$$

where  $\theta_{e1}$  and  $\theta_{e2}$  are the two equivalent water contents, and  $C_{Re1}$  and  $C_{Re2}$  are the corresponding new count ratios. The intercept of the new equation is then  $b_0 = \theta_{e1} - b_1(C_{Re1})$ .

Transfer of calibration between meters of different manufacture or internal design may be accomplished by using the calibrated meter to determine water contents at various depths in tubes in both dry and wet profiles of the same soil. Counts in these tubes with the other meter are used to compute count ratios for that meter corresponding to each depth; and the transfer calibration is established by linear regression vs. water contents from the calibrated meter (Nakayama and Reginato, 1982). Care must be used to establish the center of measurement at equivalent depths for both meters.

*Calculating Change in Water Content – the Effect of Calibration Bias.* A major application of the NMM is to measure crop water use, where measurement of water content is done as an intermediate step to calculation of change in soil water content over a time period. If change in water content is the primary aim of a project, then the calibration process should be optimized to produce minimum error in the slope of the calibration (Parkes and Siam, 1979). For the calculation of water content change, variable soils have particular relevance. In the example depicted in Fig 3.1.3.10-4, the combined calibration provides a measure of water content that appears acceptable, albeit with some error. The largest error is in the wet loam where the maximum water content of  $0.23 \text{ m}^3 \text{ m}^{-3}$  will be measured as  $0.19 \text{ m}^3 \text{ m}^{-3}$  by the NMM. Water content change calculations in the clay would be quite precise (the slope of the combined and the clay calibrations are similar). However, when the combined curve is used to calculate change in water content on the loam soil, the error is the ratio of the slopes from Table 3.1.3.10-2, which is  $1.150/0.472$  or 240%. In this example, the solution is to group mini-calibrations for the loams and clays. However, soil types are sometimes not so clearly differentiated, and the calibration may produce a range of mini-calibrations with a spectrum of slopes and intercepts. In this situation it is common that the combined calibration, while producing an apparently reasonable estimator for water content, will have a different slope to the mean of the slopes of the mini-calibrations and will produce a biased result when change in water content is calculated. When this situation occurs, a more accurate way to calculate water content change is to multiply change in  $C_R$  by the average slope of the mini calibrations.

### 3.1.3.10c Other Considerations

**Use of the NMM in Swelling Clay Soils.** Clays that swell and crack on a small scale (distance between cracks is  $<0.1\text{ m}$ ) can be treated like any other clay and require only the use of a depth control stand to adjust for differential movement of the access tube and soil. Soils that crack on a large scale (e.g. crack size  $>0.1\text{ m}$ ), require special techniques (Battikhi and Suleiman, 1997; Schindler, 1980). The very large sampling volume of the NMM means that it is the only practicable method to measure water in these materials that have extreme variability on the  $\sim 1\text{-m}$  scale. A major difficulty is that access tubes often form a nucleus for cracking and the soil may dry with the tube at the join of several wide cracks. Techniques have been developed however, for the successful measurement of water content in these soils which rely on the combined use of the NMM, simultaneous estimation of soil density by gamma ray absorption, and knowledge of the density vs. water content relationship for the soil to detect and correct for the massive density variability in the readings caused by cracking and uneven drying patterns (Hodgson, 1988; Hodgson and Chan, 1987; Jayawardane, 1984; Jayawardane et al., 1984).

Even when a measure of soil water content is obtained it must be interpreted with great care to obtain a meaningful measure of the water content of the field for crop water use assessment. The volumetric water content in a ped needs to be averaged across not only the volume of the cracks but assessed in relation to a depth datum sufficiently deep in the soil so that it is fixed as the soil material swells (Yule and Ritchie, 1980). The summation of volumetric soil water from the surface to, say, 2-m depth is a nontrivial calculation in these materials.

**Safety and Environmental Concerns.** 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 (S.R. Evett, 1999, unpublished data at Bushland, TX). Whenever trenching below 1 m for calibration, the trench walls should be shored up or stepped to prevent collapse. A meter should not be left unattended, even for short periods of time. Protective eyewear should be worn when changing batteries; and only batteries of like chemistry should be used as replacements. Charge only batteries for which the charger is designed. Batteries should be recycled as required. Radioactive sources may not be discarded, but must be returned to the manufacturer or a licensed waste handler.

Radiation safety involves safety for users, co-workers, and the general public. Most countries have regulations requiring licensing and training of users, and setting conditions of use such as requirements for personal dosimetry, leak testing every 6 mo, labeling of meters as to source content and strength for transportation, and locking of meters during transportation and storage to avoid theft. There has never been an accident leading to the breach of the stainless steel capsule containing the radioactive source. Simple precautions keep radiation dose for users below detection limits. Due to the low levels of radioactivity involved, the principle of reducing exposure to as low as reasonably achievable (ALARA) guides most 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 Evett

(2000b). 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/>).

**Advantages and Limitations.** Nearly 50 yr after its first use, the neutron method remains the best available method for repeated measurement of soil profile volumetric water content (IAEA, 2000). This is 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. The large zone of measurement means that fewer replicates are required than for other methods to produce a given level of precision, and that soil disturbance during installation has minimal effect on results (unlike most electronic sensor methods). The technology is mature with a wide literature base describing applications and problems.

Due to regulation, the method is not usable for automatic measurements and is therefore labor intensive. 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 very effectively for deeper measurements in conjunction with TDR measurement of the near-surface soil water content (Evetts et al., 1993). 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 the cost of obtaining necessary training and licenses for handling and transporting radioactive materials. Most users do not consider the radiation hazard a problem. Disposal of old sources has been a problem; but this can be solved by recycling them.

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