ACCURACY AND SOURCE STRENGTH IN SOIL
MOISTURE NEUTRON PROBES

The neutron method for measuring soil moisture entails three sources of error, assuming the measurements are made in a perfectly homogeneous material, chemically identical to that in which the instrument was calibrated. The error sources are:

1. Random variation of the count rate of slow neutron pulses, caused by random emission from the source.
2. Deviation of the calibration relation as found experimentally from the true relation between count rate and moisture content.
3. Failure of the counting equipment to measure the count rate or the total count and elapsed time accurately.

For the present, it is assumed that the error (3) is so small that it may be ignored, that is, we assume near-perfect counting equipment.

If, in the calibration procedure, error (1) was practically eliminated by counting for sufficiently long time periods, then the magnitude of error (2), here called the error of prediction, \( \sigma_p \), depends only upon the error of the moisture determination in the calibration procedure and the number of calibration points. Experience indicates that a typical value for error (2) is 0.01 volume fraction. In practice, this value may be smaller or larger but this matter will not be further considered.

Error (1), here called the counting error, \( \sigma_c \), depends upon:

(a). The strength of the neutron source.
(b). The efficiency of the probe design.
(c). The time constant or the time of counting when using a rate meter or a scaler, respectively.

Item (b) is fixed for any one type of probe and access tube, and item (c) is dictated by convenience or necessity. The maximum permissible value for error (1) is then obtained by choosing the right value for the strength of the source. This is an important issue because the strength of the source also determines the radiation hazard and the scope of precautionary measures.

In an article by Van Bavel et al., two commonly used probe designs were examined in detail as to efficiency and calibration. These data will be used here and we will further assume that a scaler is used and that the time of counting is 1 minute. A rate meter with a time constant of about 12 seconds would give similar results. The question posed here is what strength of the Ra-Be neutron source is required to obtain a random counting error equivalent to the error of prediction of the calibration curve, here taken to be 0.01 moisture by volume? A simple formula is derived as follows. Assume that a linear calibration obtains and let

\[
N = n \times S \times \theta
\]

in which \( N \) is the counting rate in cpm, \( n \) the efficiency in cpm per mc, \( S \) the source strength in mc and \( \theta \) the moisture content as a volume fraction.

From [1] we may conclude that:

\[
\sigma_N = n \times S \times \sigma_\theta
\]

in which \( \sigma_N \) is the standard error of the counting rate and \( \sigma_\theta \) the standard error in the moisture content attributable to \( \sigma_\theta \). But we also know that:

\[
\sigma_N = \sqrt{N/T}
\]

where \( T \) is the counting time in minutes. Combining [1], [2], and [3] shows that:

\[
S = \theta / \sqrt{[\theta T (\sigma_\theta)^2]}
\]

Equation [4] shows that the required source strength for a given, required precision is directly proportional to the moisture content. This is contrary to a common opinion that at low soil moisture content equal accuracy would require a greater source strength. Therefore, if the source strength is computed for a high moisture content value, say 0.40 by volume, a conservative result will be obtained.

Even though the calibration lines for the two probe designs mentioned before were not exactly linear, they may be so considered for the present discussion. Calculation gives values of 7,550 cpm per mc and 3,150 cpm per mc for the N-104 and the P-19 design, respectively. In order to use equation [4], \( \theta \) is set at 0.40, \( T \) at 1 minute, and \( \sigma_\theta \) at 0.01, equal to the error of prediction, \( \sigma_p \). Then we find a required source strength of 0.52 mc for the N-104 design and 1.24 mc for the P-19 design. These figures are smaller than what is generally considered as an adequate source.

The above calculation would result in an equal contribution to the total error of measurement from \( \sigma_\theta \) and \( \sigma_c \), the counting error and prediction error, respectively. If the source strengths were about doubled to 1.0 and 2.5 mc, respectively, the counting error would constitute only 1/5 of the total error. This demonstrates that, at present, neutron sources at least twice larger than necessary are employed with attendant and unjustified health hazard and cost.

The above is even more true at low soil moisture content. If, for example, \( \theta \) is 0.10 by volume, the contribution of the counting error to the total error is negligible when a source of 1.0 and 2.5 mc is used in the N-104 and P-19 design, respectively.

Many "field" calibrations of neutron equipment have errors of prediction in excess of 0.01 moisture as volume fraction. Neutron sources that are considerably smaller than those used at present would suffice for work dependent upon such calibrations, yet the data could have greater usefulness. Use of formula [4] will quickly show the required source strength.

The above considerations are equally true when, instead of absolute counting rates, the ratio to the count rate in a fixed standard is reported.

Conclusions

Assuming a near-linear calibration, the relation is analyzed between source strength and counting error for neutron moisture probes that are currently available. It is shown that, in order to maintain an absolute error of counting that is compatible with the precision of the calibration, neutron sources between 1 and 2 mc. Ra-Be are sufficient and lower soil moisture content implies lower required source strength. Both deductions are at variance with current practices and may serve to reduce the cost and health hazard involved in the use of the neutron method.

The conclusions reached apply only to general purpose applications of the neutron method. In special cases, higher count rates than suggested here may be useful. — C. H. M. VAN BAVEL, Chief Scientist, U. S. Water Conservation Laboratory, SW Branch, SWC, ARS, USDA, Tempe, Ariz.