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"Neutron Probes & Thier Use in Agronomy"

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NEUTRON PROBES AND THEIR USE IN AGRONOMY[1]

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1. INTRODUCTION

Neutron probes were developed to measure soil water contents in agricultural field soils. Soil water content, although being a very simple soil physics concept, is very difficult to be measured. Estimatives of soil water content obtained through many methods often deviate considerably from the "true" value, which, anyway, is never known. The main problem lies in sampling procedures. Once a soil sample is taken from the field, its soil water content can be estimated with a high degree of precision and accuracy. It is, however, neven known if the sample collected realy represents the soil at the desired depth, because of soil variability problems and sampling procedures.

Soil water content can be estimated on a weight or a volume basis. In this work we will use the following simbols and definitions:

a) soil water content by weight u (g H_2O/g dry soil)

$$u = \frac{\text{mass of water}}{\text{mass of dry soil}} = \frac{m_w - m_d}{m_d} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where: m_w = mass of wet soil
m_d = mass of dry soil

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b) soil water content by volume Θ (cm^3 H_2O/ cm^3 of bulk soil)

$$\Theta = \frac{\text{volume of water}}{\text{bulk volume of soil}} = \frac{m_w - m_d}{V} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where V is the volume of the sample. In this definition it is assumed that the density of water is 1 g/cm^3 and, therefore, $(m_w - m_d)$ is equal to the volume of water.

It can be shown that

$$\Theta = u \cdot d_b \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where d_b is the bulk density of dry soil (g dry soil/cm^3 of bulk soil), defined by:

$$d_b = \frac{m_d}{V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Example: In a soil profile, a soil sample was collected at the depth of 20 cm, with a volumetric cylinder of 200 cm^3, with a weight of 105.3 g. After handling the sample in the laboratory, eliminating all excess of soil and being sure that the soil was ocupying the volume V of the cylinder, the sample was weighed and the result was 395.6 g. The sample was then introduced into a ventilated oven at 105°C, until constant weight, and the final mass was 335.7 g. In this case:

$$u = \frac{395.6 - 335.7}{335.7 - 105.3} = 0.260 \text{ g/g} \quad \text{or} \quad 26.0\% \text{ weight}$$

$$\Theta = \frac{395.6 - 335.7}{200} = 0.300 \text{ cm}^3/\text{cm}^3 \quad \text{or} \quad 30.0\% \text{ volume}$$

$$d_b = \frac{335.7 - 105.3}{200} = 1.152 \text{ g/cm}^3$$

and it can be seen that $0.300 = 1.152 \times 0.260$.

There are several methods for the determination of soil water contents and bulk densities. They differ mainly in the form of sampling, but equations 1 to 4 are always applicable when information is available. The greatest difficulty lies in the measurement of V. Sampling soil with a simple auger destroys the structure of the soil and the information about V is lost. In this text we will not discuss all these "classical" methods of soil water measurment. The reader is refered to any basic soil physics text, or specifically to "Methods of Soil Analysis", part I, American Society of Agronomy, Monograph nº 9, 1986.

We will, however, discuss some aspects of the classical methods in order to compare them with the neutron probe method, which will be treated in detail. One great disavantage of the classical methods is their destructive feature. We have to sample the soil at each measuring event and interfere severely in the soil profile. Even sampling with a simple auger, after several samplings the field or plot will be very disturbed. Another problem is soil variability. At each sampling event, even collecting soil at the "same" depth, another location is sampled. A third problem, which might be minor, is the time spent for one measurement, which is almost never below 24 hours.

With neutron probes, which we will discuss in detail in the following pages, we disturbe less the soil profile. Only once an access tube has to be introduced into the soil to the desired depth and, thereafter, measurements are taken at any depth and time in a matter of minutes. Of course, there are also disadvantages in the use of neutron probes. At the end of this text we will spend some time discussing advantages and disadvantages of the use of neutron probes.

2. INSTRUMENT DESCRIPTION AND WORKING PRINCIPLE

A neutron probe consists essentially from two parts: (a) shield with probe, and (b) electronic counting system. In some models these parts are separable and in others not.

(a) Shield with probe

The probe is a sealed metalic cylinder of diameter 3 to 4 cm [illegible] 20 to 30 cm. It contains a radioactive source which emitts fast

neutrons, a slow neutron detector and a pre-amplifier. The signal of the pre-amplifier goes through a 5 to 20 m long cable to the electronic counting system.

The geometry of the probe, type and activity of neutron source, types of detector and pre-amplifier vary considerably from manufacturer to manufacturer. Neutron sources are the mixure of an alfa particle emitter (like Americium, Radium) and a fine powder of Berilium. Alfa particles bombard Berilium nuclei and the following reaction takes place:

$$ {}^{2}_{4}\alpha + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{1}_{0}n + {}^{12}_{6}\mathrm{C} + \text{energy} $$

The neutrons ${}^{1}_{0}n$, which are a product of the reaction, are called fast neutrons, having energies of the order of 2 MeV ($1\ \mathrm{eV} = 1.6 \times 10^{-12}$ erg).

The strength of the sources are generaly given by the activity of the alfa emitter, in milicuries (mCi). Most of the sources have an activity in the range of 5 to 50 mCi. Since the alfa emitter also emitts some gamma radiation, the sources emitt alfa particles, gamma radiation and fast neutrons. Therefore, radiation protection in an important issue. The shield, which is a case for the probe, has to be designed in order to protect the user from the radiation. Manufactured probes that are sold have a shield that exposes the user to permissible radiation levels, when in the shield. When the probe is not in the protection shield, the user is exposed to gamma radiation and neutrons. This should be terminantely avoided. The design of the probes is done in such a way that when the probe leaves the shield it goes immediately into the soil, avoiding any excessive exposure.

Shilding of gamma radiation is most efficiently made by lead and of fast neutrons by parafin, poliethylene or any other material with high H content. Neutron probe shields have,therefore, some metalic shield and some high Hydrogen content material.

During measurements, the probe is lowered to the desired depth in the soil, inside of an aluminum access tube. Aluminum is "transparent" to fast neutrons and so they are scattered into the soil, not going further than 30 to 50 cm away from the source. This interaction with the soil (and soil water) is used to estimate soil water content, as it will be seen later.

Next to the source is a slow neutron detector. This detector does not count fast neutrons, it detects only slow neutrons which are a result of the interaction of the fast neutrons with the soil. There are several slow neutron detectors available, e.g. Boron tri-fluoride detectors, Helium-3 detectors, and scintillation detectors. Each manufacturer makes its choice because all have advantages and disadvantages.

The pulses comming from the detector are first preamplified, which also occurs in the probe. Only these, slightly amplified pulses, are sent to the electronic counting system, through the cable which connects parts (a) and (b) of the neutron probe.

(b) Electronic counting system

The electronic counting system varies a lot from type of probe to type of probe. In simple words, it constitutes of amplifier, high voltage source, counter, timer, rechargeable bateries, microprocessor, etc. Since counting time is important for statistics, most probes have several options, e.g. 0.5, 1 and 4 min counting time. The microprocessor processes data and gives results in counts per minute (cpm) or counts per second (cps). Each count corresponds to one impulse originated from one slow neutron that reached the detector.

Recent neutron probes have a microprocessor to which one can feed the equations of calibration for several soils, and the results are given directly in soil water content (%, g/g, cm^3/cm^3) or even in terms of a water storage in a given soil layer (mm/10 cm, inches/foot).

Each manufacturer gives details of the operation of their probe and, therefore, we will not discuss this matter here. Figure 1 is a schematic diagram of a depth neutron probe, in the field, in a measurement position at depth L. Figure 2 is a schematic diagram of a surface neutron probe, also in measurement position. These probes are made only for surface (0-15 cm depth) measurements and do not need access tubes. They are placed, between rows, on the soil surface.

The working principle of neutron probes is very simple and straightforward. The neutron source emitts fast neutrons (of the order of 2 MeV) which interact with the matter which sourounds the probe. Since neutrons have no charge, there are no electric fields to counteract their movement. Three processes occur during this interaction: neutron absorption by nuclei, neutron scattering through collisions, and neutron desintegration.

Neutron absorbtion by nuclei depends very much on its energy and of the type of target nucleus. The "probability" of this process is

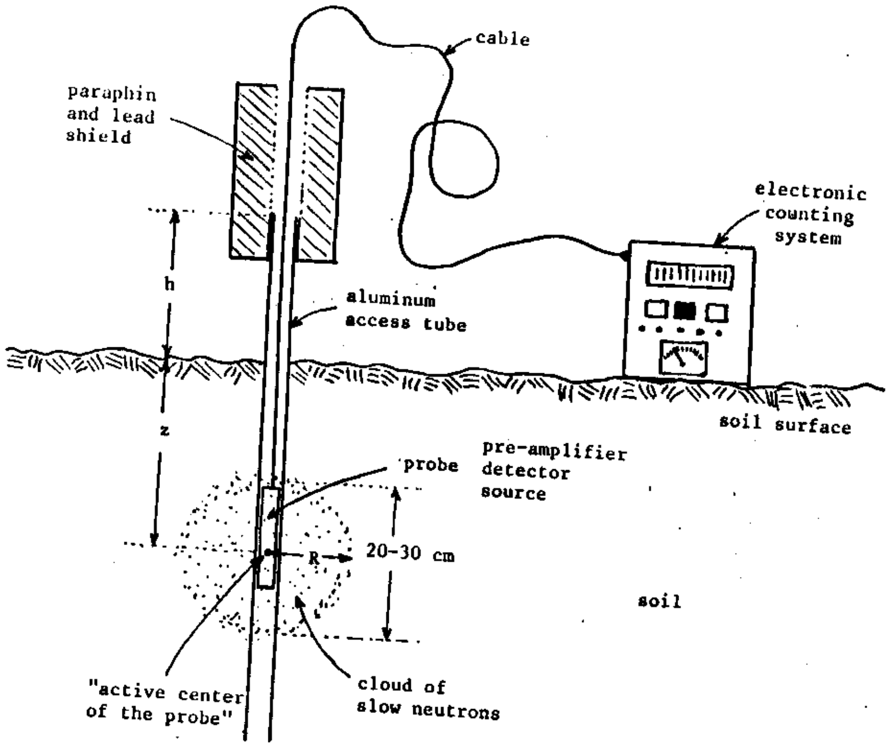

FIGURE 1 - Depth neutron probe

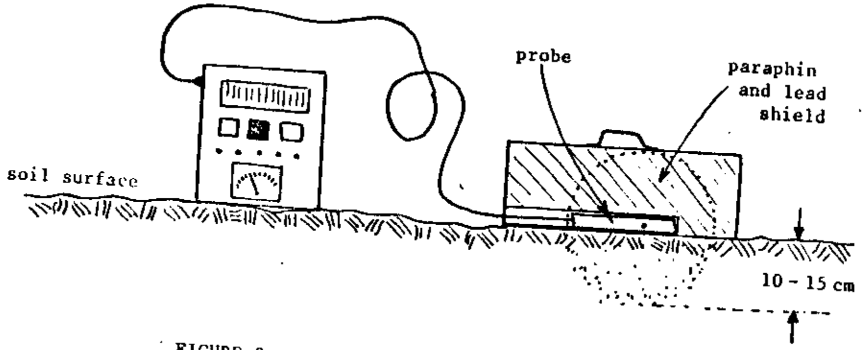

FIGURE 2 - Surface neutron probe

measured through the cross section of the reaction, which in general, for most of the elements present in soils, is very low. If the reaction occurs, one neutron is absorbed by a nucleus ${}^{Z}_{A}X$ according to:

$$ {}^{0}_{1}n + {}^{Z}_{A}X \rightarrow {}^{Z}_{A+1}X . $$

where the new nucleus ${}^{Z}_{A+1}X$ is, in some cases, unstable and desintegrates emitting radiation. This is the same principle of neutron activation. The process, however, occurs only with a few nuclei present in the soil, e.g., Ag, Au, In, Fe, Al, Mn, etc, most of them having a very low concentration in soil. Also the neutron flux emitted by the source has a very low intensity so that the probability of a neutron capture is extremely low. In many cases ${}^{Z}_{A+1}X$ is stable (e.g., ${}^{12}C + n \rightarrow {}^{13}C$; ${}^{14}N + n \rightarrow {}^{15}N$) and in the cases it is radioactive (e.g., ${}^{23}Al + n \rightarrow {}^{24}Al$, half life of 2.3 min) its half-life is very short. Due to these facts there is virtually no activation of soil material when a neutron probe is placed into the soil. Also the Aluminum access tubes, which might become slightly active during one measurement, decay in a few minutes.

Neutron scattering by collisions (elastic or non-elastic) is the most important process, on which the working principle of the neutron probe is based. Through collisions fast neutrons (high energy, about 2 MeV) loose energy (moderation) and might become slow or thermal neutrons (low energy, about 0.025 eV). If collisions are elastic, the heavier the target nucleus, the less energy is lost by the neutron. Table 1 illustrates this fact.

TABLE 1 - Number of elastic collisions necessary to reduce the energy of a neutron from 2 MeV to 0.025 eV.

Target Isotope	Number of Collisions
${}^{1}H$	18
${}^{2}H$	25
${}^{4}He$	43
${}^{7}Li$	68
${}^{12}C$	115
${}^{16}O$	152
${}^{238}U$	2172

It can be seen that ${}^{1}H$ is the most efficient target atom for reducing neutron energy. It is said that Hydrogen is a good neutron moderator. Since Hydrogen is a constituint of water, water is also a good neutron moderator. So, in a given soil, the wetter it is, the more slow neutrons will be present when a fast neutron source is introduced. Other soil materials also have Hydrogen as a constituint but, in this case, its Hydrogen content is constant, and is taken into account during calibration.

Neutrons when free are unstable, they desintegrate with a half-life of 13 seconds. So, if a neutron is not captured it will, after some time, desintegrate.

Due to these processes, after few fractions of second, a stable "cloud" of slow neutrons is developed around the source, having a spherical shape, with a variable diameter of 15 to 30 cm. The number of slow neutrons per unit volume at each point of the cloud remains constant and is proportional to the water content in the soil within the cloud. Since the slow neutron detector is placed inside the cloud volume, the count rate (cpm or cps) is proportional to the soil water content θ of the same volume. The instrument is then calibrated with samples of known θ. More details about neutron moisture meter theory can be found in Greacen (1981) and IAEA (1970).

3. SAFETY AND MANTAINANCE

As already stated, neutron probes available in the marked are tested for radiation exposure and the opperator is exposed to radiation levels below the international permissible dosis. Attention has, however, to be given to:

a) Neutron probes, like any other activity with radioactive material, should not be opperated by people with less than 18 years of age or not well instructed people.

b) During use opperator has to use a dosimeter for neutrons and gamma radiation.

c) Special attention to radiation exposure should be given when the probe is not in its shield. This should be avoided to a minimum and, when necessary, a radiation protection expert should be around.

d) Repair of problems in the probe (e.g., preamplifier, changing detector, fixing cable connection) should only be done by authorized people.

e) Probes should be stored in special dry places, designed for radioactive material storage, far from the circulation of other personnel.

f) For mantainance, each manufacturer gives details for their probe, but it is very important to mantain the probe in continuous use. Charging of batteries is very important. Therefore, even in periods when no experimental work is being developed, probes should be serviced once a week by an authorized technician, making at least a few standard counts.

4. ACCESS TUBES AND THEIR INSTALLATION

Size and type of access tubes depend on the diameter of the probe in use, cost and availability of tubing. Unfortunately diameters of probes have not been standardized internationally by manufacturers so that practically each probe has his diameter and requires a specific tubing size.

The best material is aluminum since it is very transparent to neutrons. Only in a few soils aluminum can corrode and be a problem for long term experiments. Other materials can also be used, e.g. steel, iron, brass, and also polyethilene and other plastics. It has only to be recognized that these different materials have different behaviour with respect to neutron interaction and count rates will be altered. Once one kind of tubing is chosen, calibration and all experimental work have to be done with the same material.

It is known that steel and brass tubings affect slightly the sensitivity of probes due to the greater absorbtion of neutrons by iron and copper. Polyethilene and other plastic materials contain significant amounts of Hydrogen and, therefore, give a higher count rate.

Tube size is normally specified by each manufacturer through inside and outside diameter. One should keep the closest possible to these specifications, mainly to the inside diameter. Probe shoud not enter tightly into tubing and a great air-gap between probe and tube wall affects sensitivity.

Tube length depends on measurement depths which depends on the objectives of the experiment. Access tube should always be 10 to 20 cm longer than the greatest measurement depth because the "active center" of the probe is never at its end. Tubes should also extend 20 to 40 cm above soil surface, in order to avoid entrance of soil material and to facilitate the installation of the shield case on top of the tube. Top end of the tube should be covered with rubber stoper or an inverted Aluminum beer can, to avoid water and dirt entrance. The botton of the access tube has also to be sealed (with rubber stoper or other material) if water table level is high. For very deep soil profiles this is not necessary.

There are several methods of installation of access tubes (Greacen, 1981) but essentially they all consist in drilling an auger hole into which the access tube is driven down to the desired depth. The main point in this procedure is to avoid an air-gap between the soil and the tube. This might be achieved by using an auger with a smaller diameter than the outside diameter of the acces tube. In this case, the tube is introduced with difficulty into the soil and some soil might enter inside the tube. With a second auger, with a diameter slightly smaller than the inside diameter of the tube, the soil that entered inside the tube is removed. Some people prefere to introduce the access tube with impacts into the soil, in steps of about 20 cm and then eliminate the soil inside the tube with an appropriate auger. In this case, there is very good contact between soil and access tube.

In special cases, however, many problems might occur. As an example we refer to stony soils, heavy swelling soils and extremely layered soils. In each case, the researcher has to use his own experience and do his best. It should only be remenbered that the installation of an access tube is done only once for a given experiment and, therefore, it has to be done with much care, even if it takes a few hours. A badly installed access tube will compromise all measurements made in future. It should also be remenbered that one of the great advantages of the neutron moderation method is the fact that the only disturbance made on the soil is during access tube installation and that, thereafter, quick measurement can be made over long periods, always "sampling" the same "point" in the field.

Repeating, time should therefore be spent to install in the best way possible each access tube. More details about access tube installation can also be found in IAEA (1976).

5. CALIBRATION

The calibration of a neutron probe consists in finding a relation between probe output: cpm (counts per minute) and soil water content Θ (cm^3 of water per cm^3 of bulk soil). To do this, samples of a given soil having a wide range in moisture are used to measure cpm with the probe and Θ in the classical way. It is a simple procedure in theory but it might be difficult and tedious depending on the choosen experimental design and of the properties of the soil profile. First we will discuss an easy case of the construction of the calibration curve for one depth of a homogeneous soil, and then extend it to more difficult situations.

Sampling is the main problem in calibration. In theory, the same sample should be "exposed" to the neutron probe to obtain cpm, and to the classical soil moisture method to obtain Θ. This is very difficult in practice, mainly because the neutron method "sees" a great volume which is not well defined (assumed to be a sphere of 20 to 30 cm diameter, see page 17) and the classical soil moisture methods use small samples (20 to 50 times smaller). This problem is minimized by taking several soil samples for Θ determination around the access tube in which cpm was obtained. In any case, we are never sure that both methods sampled the same total volume of soil. This becomes worse in heterogeneous soils, like layered or stony soils.

Another problem is finding the same soil in a wide soil moisture content range. By wetting (irrigation or rainfall) and drying (evaporation or drainage) a good range can be obtained, but always over a long period of time and wide range of space, and with tedious opperations. Since the neutron probe "explores" a great sample, during wetting and during drying, we never know if the whole sphere of influence was submitted to the same intensity of drying or wetting.

Assuming we did our best and we have a good collection of pairs of cpm and Θ we can start constructing our calibration curve. First, in order to avoid electronic drifts, temperature and other effects on the electronics of the neutron probe, we do not use cpm obtained in soil directly, but use the count ratio CR defined as:

$$CR = \frac{\text{cpm in soil}}{\text{cpm in standard material}} \qquad \text{.............. (5)}$$

Every time the neutron probe is used, it is checked for stability making a counting in a standard material which in most cases is taken with the probe inside its protection shield, sitting on the wooden probe case to mantain standard condition. Others recommend a standard count in water. In this case a sealed access tube is placed in the center of a large water container. The standard count C_s (total number of counts taken over a time t_s) should be constant over long periods of time, oscilating only within the statistical deviations, normally taken as $\pm \sqrt{C_s}$ (Poisson's distribution). Each manufacturer gives details for these procedures for their probes.

Table 2 shows field data obtained for the calibration of a probe for the 20 cm depth.

TABLE 2 - Calibration data for probe SOLO 25 (made in France) with a 40 mCi Am/Be source. Soil: Terra Roxa Estruturada (Alfisol) of Piracicaba, SP, Brazil. Depth: 20 cm below soil surface.

nº Points n	Θ ($cm^3.cm^{-3}$)	Count (cpm)	Count Ratio CR*
1	0.424	79,650	0.507
2	0.413	75,541	0.481
3	0.393	76,169	0.485
4	0.387	71,143	0.453
5	0.378	67,846	0.432
6	0.375	69,259	0.441
7	0.306	59,208	0.377
8	0.287	57,637	0.367
9	0.291	62,035	0.395
10	0.283	58,109	0.370

* Count in water N_s = 157,050 cpm taken as standard.

Figure 3 shows the linear graph of Θ versus CR. The solid line follows the equation $\Theta = -0.0954 + 1.0424CR$ obtained through classical linear regression, using Θ as the dependent variable y and CR as the independent variable x. The linear regression coefficient was R = 0.9644.

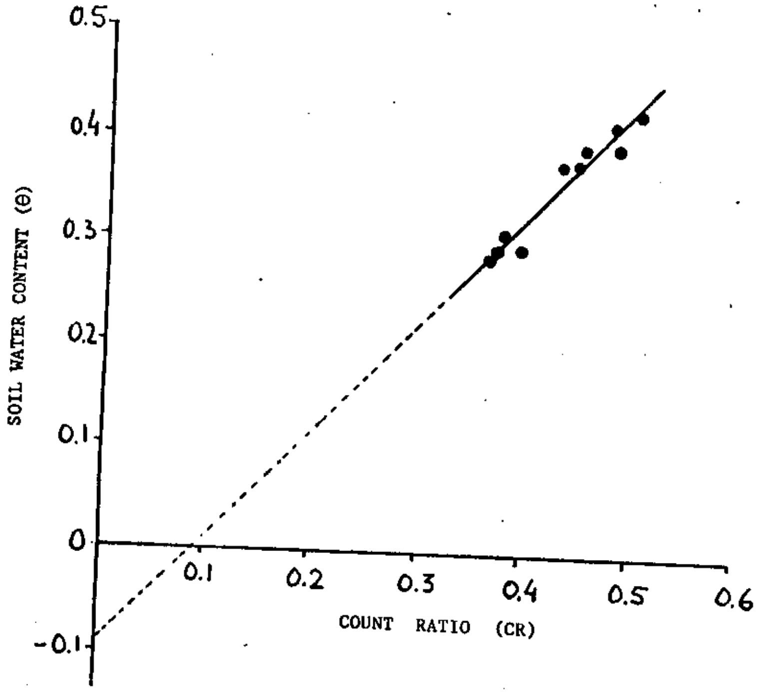

FIGURE 3 – Example of calibration curve (data of Table 2)

In the following chapter, on error analysis, we will have to use all variances envolved in the establishment of the linear regression equation $y = a_o + a_1 x$ and, therefore, we list below the respective equations. We use the symbol $s^2(\alpha)$ for the expected variance of α, and other well known statistical symbols, also used by Havercamp et al. (1984):

1. Variance of stochastic disturbance therm $s^2(e_o)$

$$s^2(e_o) = MSE \qquad (6)$$

2. Variance of intersept $s^2(a_o)$

$$s^2(a_o) = MSE \left[\frac{1}{n} + \frac{\bar{x}^2}{\Sigma x^2} \right] \qquad (7)$$

3. Variance of slope $s^2(a_1)$

$$s^2(a_1) = \frac{MSE}{\Sigma x^2} \qquad (8)$$

4. Covariance of linear regression $s^2(a_o, a_1)$

$$s(a_o, a_1) = -\bar{x}\, s^2(a_1) \qquad (9)$$

where n is the number of calibration points (in our example = 10) and MSE given by:

$$MSE = SSE / (n-2) \qquad (10)$$

and

$$SSE = \left[\Sigma y^2 - (\Sigma y)^2/n \right] - \frac{\left[\Sigma(x.y) - (\Sigma x \,.\, \Sigma y)/n \right]^2}{\left[\Sigma x^2 - (\Sigma x)^2/n \right]} \qquad (11)$$

For the data of Table 1 the following results were obtained:

$\Sigma x = 4.3080$
$\Sigma x^2 = 1.8797$
$\Sigma y = 3.5370$
$\Sigma y^2 = 1.2788$
$\Sigma x,y = 1.5486$

$\bar{x} = 0.4310$
$\bar{y} = 0.3537$
$n = 10$
$a_o = -0.0954$
$a_1 = 1.0424$

$SSE = 1.8099 \times 10^{-3}$
$MSE = 2.2624 \times 10^{-4} = s^2(e_o)$
$s^2(a_o) = 1.7884 \times 10^{-3}$
$s^2(a_1) = 9.506 \times 10^{-3}$
$s(a_o, a_1) = -4.0970 \times 10^{-3}$

As will be seen in next chapter, the variances of a_o and a_1 and the covariance $s(a_o, a_1)$ will contribute to a calibration error. This is one of the main errors in the use of neutron probes and, therefore, have to be minimized. In general, the closer to 1.0000 the value of R, the lower are these variances. This can be achieved by increasing the number of calibration points n, but they have to be "good points", that is, they should follow a straigh line behaviour. The best way is increasing n with points that widen the water content range, taking very wet (close to or at saturation) and very dry points.

The intersept a_o of a calibration curve varies from soil to soil and from probe to probe. It has not to be zero or close to zero. Since it is an extrapolated value, out of the calibration range, no strong theoretical meaning should be given to a_o.

The slope a_1 also varies from soil to soil and from probe to probe. It represents the sensitivity of the probe, being the derivative of the calibration line $y = a_o + a_1 x$, that is, $a_1 = dy/dx$. It is therefore the change in water content (dy = dΘ) per unit change in count ratio (dx = dCR). The lower its value, the more sensitive is the probe. It means that for small changes in water content we have great changes in count ratio, which is the variable we measure.

Because of the processes of neutron interaction in the soil, geometry of the probe, type of neutron detector, electronics, etc, each soil has a specific calibration relation for a given neutron probe. Soil characteristics also affect the calibration relation, mainly soil chemical composition and soil bulk density. Therefore, for a specific soil, calibration curves are related to different soil bulk densities d_b (figure 4). In general, the calibration lines for different bulk densities of the same soil are paralel, having the same slope a_1. For very layered soils, with layers of different composition, like some alluvial soils, the slopes for each layer might be different.

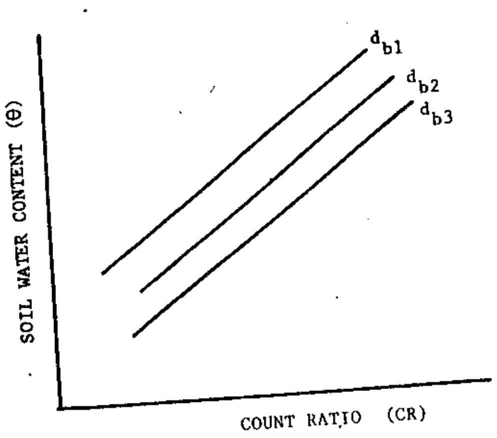

FIGURE 4 - Calibration relations for different soil bulk densities d_b.

Stony or gravely soils are a special problem. To begin with, access tube installation is difficult. The definition of Θ is also difficult, some authors use as bulk volume the total sample volume, including gravel, others exclude the volume occupied by gravel since it is a "dead" volume

Every case is a different case and the neutron probe user will have to find out by himself details of the calibration curves. The necessity of different calibration curves for slightly different soils or for slightly different bulk densities will depend on the objectives of each experiment. The accuracy needed for the determination of Θ will the most important criterium for judgement.

In a very broad sense we can divide all calibration methodologies in three groups: laboratory, field and theoretical calibration.

Laboratory calibration envolves the use of packed soil samples with descrete levels of soil water content Θ and soil bulk density d_b. For this great amounts of soil are packed into drums of 80 to 120 cm diameter and 100 to 150 cm height. Packing should be done carefuly in order to obtain a homogeneous sample in Θ and d_b. This is a very difficult task. The access tube is placed in the center of the drum.

Many neutron probe manufacturers have a collection of these sealed drums in order to calibrate each new probe. This data is given to the user and, normally, it is called factory calibration curve. Its use is very limited since it is done for one given soil. However it gives useful information to the user, when comparing this calibration relation to his own for a given soil. Commonly the slope a_1 of these calibration curves is very similar. Because of this fact, many times one can use the factory calibration curve when the interest is only in measuring soil water content changes ΔΘ, and not absolute values of Θ.

Field calibration envolves the installation of access tubes directly in the field and, at a certain soil water content situations, measurements of cpm are made with the probe and immediately after this soil samples are collected, at the same depths, around the access tube, to measure Θ by any classical method. This procedure is repeated to obtain the desiered number of replicates, and repeated with the soil at different moisture conditions. Under field conditions it is difficult to find the soil in a wide range of soil moisture. To obtain very wet situations irrigation is the best measure. Dry points are more difficult to obtain; it might take several weeks for the soil to become dry and, if it rains, one has to wait for another dry spel. The great problem lies in the fact that soils do not dry at a same rate at every depth and, as soil dries out it becomes heterogeneous with respect to moisture. This introduces an error in the calibration.

Theoretical models have also been developed in order to establish calibration relations, based on neutron diffusion theory. One of the most recent models (Couchat et al., 1975) is based on the measurement of neutron absorbtion and diffusion cross sections in a graphite pile. Soil samples have to be sent to a specialized laboratory that has a graphite pile and that will establish a linear calibration equation as a function of Θ and d_b.

Another great problem is establishing a calibration relation for the top surface layers. Many people recommend not to use the depth neutron probe for measurements close to soil surface, and use any other classical method. There are surface neutron probes, as shown in figure 2, which are specially designed for surface measurements.

Another approach is to obtain separate calibrations for shallow depths, which would take into account the escape of neutrons to the atmosphere. Some authors suggest to use neutron reflector/absorbers, which are parafin or poliethylene blocs, in the form of discs with a central whole, which are placed through the access tube on top of soil surface. Calibration is performed with the reflector. The use of these reflectors in routine measurements has, however, showed to be impractical in many situations.

6. "SPHERE OF INFLUENCE"

The slow neutron cloud which is formed immediatly after the probe is placed at a desired depth (see page 8) defines a sphere which is the volume of soil that the probe "sees". This sphere is called "sphere of influence" or "sphere of importance" of the probe. Unfortunately this sphere is not constant, not even for the same soil using a given probe. Theoretical studies (IAEA, 1970) show that its diameter is a function of the Hydrogen content (soil water content) of the medium. It is minimum in high Hydrogen content materials, like pure water, where it can take values of the order of 10 to 15 cm. In very dry soils, in which Hydrogen content is very low, the diameter of the "sphere of influence" can go up to 80 cm or more. Olgaard's (1969) theoretical model suggests that for values of $\Theta = 0.1$ cm^3/cm^3 (which are extremely low for agronomic purposes) the diameter

of the sphere is not greater than 90 cm.

This fact indicates a great sampling problem for every measurement made and also for calibration. It means that for each soil water content Θ, the probe "sees" a different volume of soil. This is a problem we have to live with, and be careful, mainly when working a shallow depths in dry soils. It is therefore recommended to know the diameter of the "sphere of influence" as a function of Θ, and then, place the probe at the correct depth not to loose neutrons to the atmosphere.

To measure the diameter of the sphere of influence, the medium has to be homogeneous, and so it is best done with soil packed in drums. If a field soil is faily homogeneous (also in Θ) the measurement can also be done in the field. The experimental procedure is very simple. The probe is lowered to a depth much greater than the radius of influence R. Since R is not known, and it should not be greater than 45 to 50 cm, we lower the probe down to 100 cm. Count rates are taken in very short depth intervals (if possible cm to cm, if not each 5 cm) bringing the probe up to soil surface. While the probe is at great depths, the sphere of influence is completely in the homogeneous medium, and count rates should be fairly constant, fluctuating only within the statistical permissible deviations ($\pm \sqrt{N}$, Poissons distribution). As the active center of the probe reaches soil surface, some neutrons start to escape to the atmosphere and the count rate starts to decrease. The decrease is first slow but soon goes exponentially close to zero, when most of the sphere is in the air. Due to this escape of neutrons the operator should take care of his protection, standing as far as possible from the probe. From the graph of the count rate as a function of depth it is possible to estimate the radius of the sphere of importance. At the depth where the count rate starts to decrease, the sphere starts to come out of the soil. This depth is its radius. Figure 5 and Table 3 ilustrate the procedure.

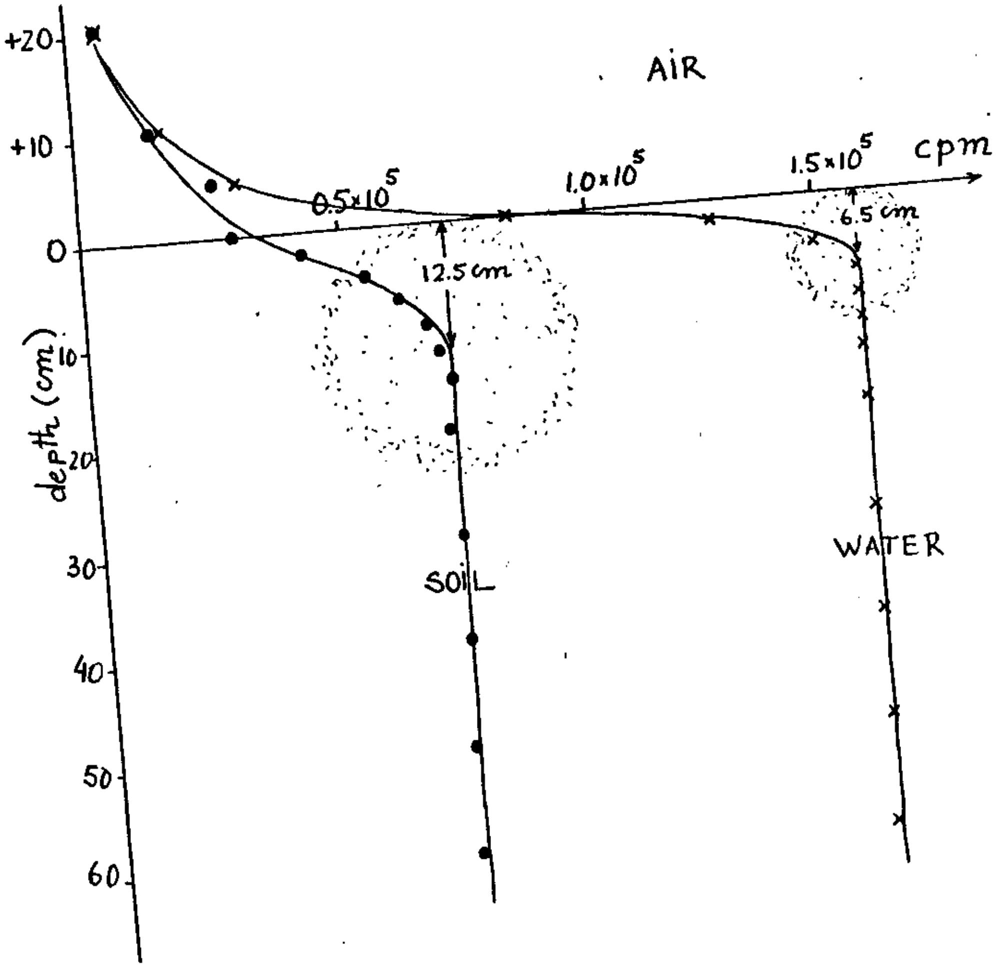

FIGURE 5 - Count rates as a function of depth, showing the radius of the sphere of influence for two homogeneous media (data from Table 4).

TABLE 3 - Count rate as a function of depth (counted from soil surface) for two homogeneous media: water and soil with $\Theta = 0.35\ cm^3/cm^3$.

depth (cm)	count rate (cpm)	
	water	soil
100	157,230	67,100
90	157,110	67,030
80	157,130	66,880
70	157,020	66,950
60	156,890	67,230
50	157,150	67,310
40	156,970	68,910
30	157,080	68,370
20	157,160	67,250
15	157,020	68,630
12.5	157,240	66,870
10	157,000	64,150
7.5	156,540	59,800
5	145,230	54,360
2.5	125,810	42,550
0	75,440	29,120
+ 5	30,770	26,670
+10	15,300	14,590
+20	5,110	5,670

7. ERROR ANALYSIS

Figure 6 shows schematically a depth neutron probe, in a measurement position. The "active" center of measurement is located at a point A, at a depth z (cm) measured from soil surface. If a soil water content Θ ($cm^3.cm^{-3}$) measurement is made at this point, several sources of error contribute to the final result. These are (without priority):

- a) counting time T (min)
  - a_1) for measurement T_c (min)
  - a_2) for standard T_s (min)
- b) calibration
- c) instrument performance
- d) active center depth
- e) sphere of influence of slow neutrons
  - e_1) effect of diameter
  - e_2) effect of proximity of soil surface
- f) access tube installation
- g) relative location in the field
- h) others

Some of these sources of error are inter-related and an analysis can only be made in a global form. We will discuss them separately as much as possible, but our final error analysis will lump some together or even neglect some.

Conting time error arise due to the physical processes by which neutrons are produced by the radioactive source, by which they are diffused and slowed down in the medium and by which they are detected. Here is an overlaping with instrument performance, due to geometry of the probe, source strength, electronics, etc. For a matter of simplicity, the whole counting process is assumed to follow Poisson's distribution, mostly the neutron emission process, and so, in a general sense, the longer we count, the smaller the standard deviations of the measurements. In practice, however, times greater than 5 minutes are seldomly used. The most common counting times T_c are 1 or 0.5 min. For the standard count T_s it is common to use longer times, from 3 to 5 minutes. If the true count rate is N, $\hat{N}$ one estimate and $\bar{N}$ the average of several estimates, then we can say for the standard count:

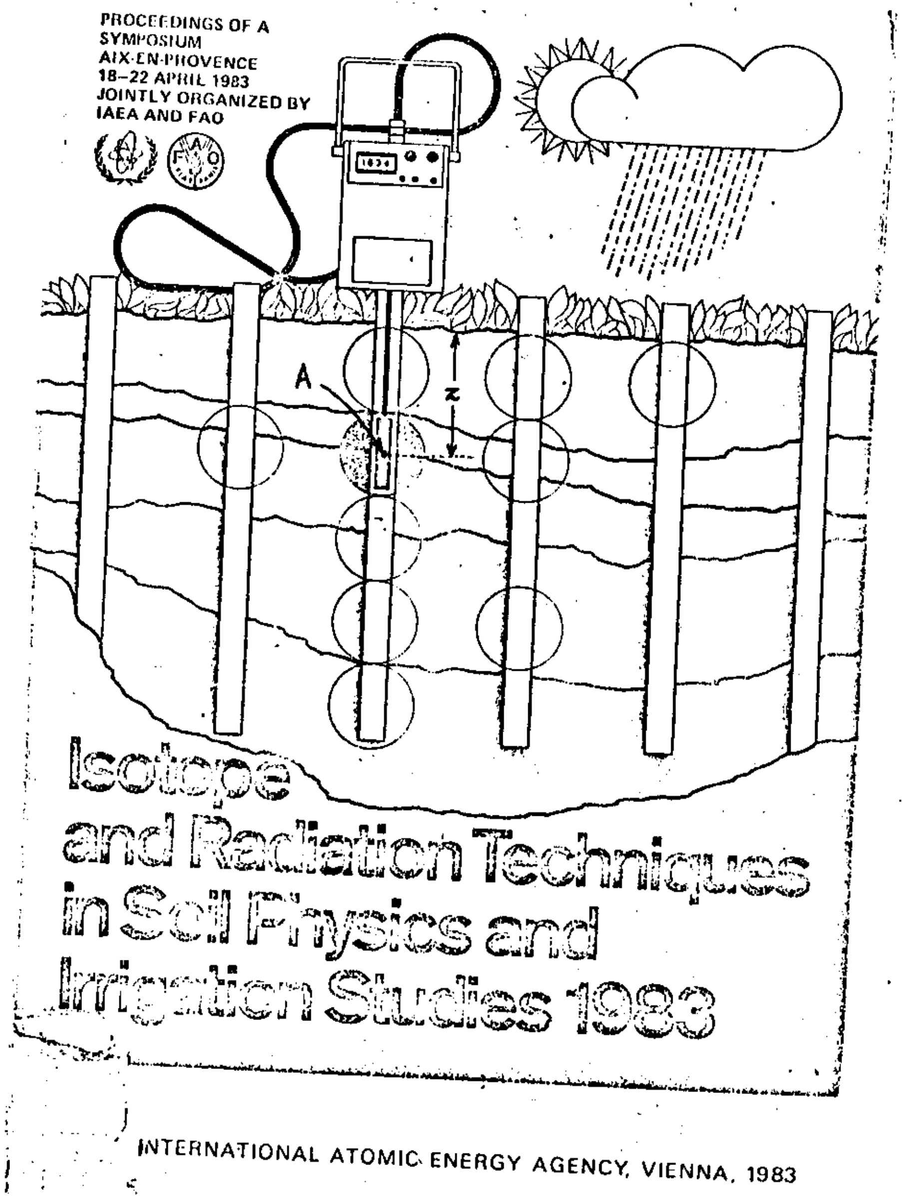

FIGURE 6 - Schematic design of a depth neutron probe

$$s^2(\bar{N}_s) = \frac{1}{q} \cdot \frac{\bar{N}_s}{T_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

and for the measurement count:

$$s^2(\bar{N}_o) = \frac{1}{p} \cdot \frac{\bar{N}_o}{T_c} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

where s^2 stands for variance, p and q number of replicates taken for counting times T_c and T_s, respectively. We should be aware that N is a count rate (cpm or cps), obtained dividing the total count C by the counting time T.

So, if five measurements of $\bar{N}_o$ are made in a soil at the same access tube and at the same depth, for counting times of 2 min, we have:

TABLE 4

Replicate	Count ($\hat{C}_o$)	Count Rate ($\bar{N}_o$)
1	30,003	15,002
2	30,105	15,053
3	30,152	15,076
4	29,906	14,953
5	29,817	14,909
ave	29,997	14,999

$$\bar{N}_o = \frac{29{,}997}{2} = 14{,}999 \text{ cpm}$$

$$s^2(\bar{N}_o) = \frac{1}{5} \cdot \frac{14{,}999}{2} = 1{,}500 \text{ cpm}$$

$$s(\bar{N}_o) = 38.7 \text{ cpm}$$

In order to diminish electronic and other instrumental drifts, it is common to use count ratios. The count ratio $\hat{CR}_o$ is given by the ratio between the mean count rate $\bar{N}_o$ (cpm) of p replications recorded at the same soil depth during T_c, and $\bar{N}_s$(cpm) of q replications recorded in a standard constant absorber (water, parafin shield, etc.) during T_s:

$$\hat{CR}_o = \frac{\bar{N}_o}{\bar{N}_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

The variance of the count ratio is given by the variance of a ratio, which is:

$$s^2(\hat{CR}_o) = \left(\frac{\bar{N}_o}{\bar{N}_s}\right)^2 \cdot \left[\frac{s^2(\bar{N}_o)}{\bar{N}_o^2} + \frac{s^2(\bar{N}_s)}{\bar{N}_s^2}\right] \quad \ldots (15)$$

Along with the five measurements of the previous example, one measurement $\hat{C}_s$ was taken for 5 minutes and the result was: 90,875 counts.

$$\bar{N}_s = \frac{90{,}875}{5} = 18{,}175 \text{ cpm}$$

$$s^2(\bar{N}_s) = \frac{1}{1} \cdot \frac{18{,}175}{5} = 3{,}635 \quad \text{(equation 12)}$$

$$s(\bar{N}_s) = 60 \text{ cpm}$$

$$\hat{CR}_o = \frac{14{,}999}{18{,}175} = 0.825$$

$$s^2(\hat{CR}_o) = 0.825^2 \left(\frac{1{,}500}{14{,}999^2} + \frac{3{,}635}{18{,}175^2}\right) = 1{,}2 \times 10^{-5} \quad \text{(equation 15)}$$

$$s(\hat{CR}_o) = 0.0035$$

It is easy to be seen that increasing T_c and/or T_s that the variance of $\hat{CR}_o$ decreases.

In order to measure soil water contents with a neutron probe, the instrument has to be calibrated. There are several procedures to make the calibration of a neutron probe, which we have discussed in a previous section. In any case, however, a set of Θ and $\hat{CR}_o$ data is obtained. The volumetric water content data Θ are obtained through classical soil physics methods sampling within the volume of "sphere of influence" of the neutron probe, in which also the value of $\bar{N}_o$ is measured.

In most cases, the relation between Θ and $\hat{CR}_o$ is linear, and a "calibration curve" is established through linear regression, with an equation of the form:

$$\theta_o = \hat{a}_o + \hat{a}_1 \hat{CR}_o \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (16)$$

which is the neutron probe calibration curve, where the parameters $\hat{a}_o$ and $\hat{a}_1$ are respectively, intersept and slope of the straight line.

The variances associated to $\hat{a}_o$ and $\hat{a}_1$ which are obtained directly from the regression analysis, depend on how well the θ_o measurement represents the soil volume at which $\hat{CR}_o$ is measured (sphere of influence) and depend on type of soil, soil stratification, soil variability, acess tube installation, etc. Therefore a careful sampling by classical soil physics methods to measure θ_o is recommended.

For the calibration and for any soil water content measurement it is also important that the "active center" of the probe is located at the desired depth z. This is also a source of error. We call "active center", the center of the sphere of influence, which represents the volume in which neutrons diffuse in the soil and therefore represents the soil volume "sampled" by the probe in each measurement. The catalogues of some probes are very detailed and give you the exact location of the active center, which not always is the center of neutron source and/or detector.

Knowing the position of the center in the probe, it is easy to establish a procedure to lower the probe to a desired depth z. This of course will depend on the height of the aliminium access tube which is above soil surface. We should also remember that when most probes are sitting on an access tube, 2 to 10 cm of the tube enter the probe's case. Of course, the levelling of soil surface will also introduce errors of a few centimeters. It has, however, to be recognized that these small errors are not of very great importance since neutron probe measurements are not punctual measurements, they are average values over the volume of the sphere of influence, which is relatively large, of the order of a soccer ball.

For a given access tube the error of the position of the active center is mainly a systematic error, and if we are careful it can be minimized easily. From access tube to access tube, however, we get again a random variation, which should be minimized.

Further problems are related to the sphere of influence itself. This sphere of influence is a function of soil water content. The higher the water content the smaller the sphere, its smallest value being in pure water. It varies also from probe to probe due mainly to source strength and varies slightly from soil to soil, even at the same water content. There are great problems, intimately related to the calibration.

Another source of error stems from the access tube instaliation. It is important to say again that a good installation will imply in as little disturbance as possible of the soil profile during auger operation, and that no air-gaps should be left between the wall of the access tube and the soil. These two aspects vary a lot from soil to soil. Again, for a given access tube we will have mainly a systematic error. From access tube to access tube, however, a random variation will be obtained.

Disregarding the relative location in the field (which we will discuss later) let us see how we could develop an expression to estimate the error in making a soil water content determination with a neutron probe. This was very well done by Havercamp et al. (1984). We will assume that we make no systematic errors in the position of the probe and that the sphere of influence is completely inside the soil.

Let equation (16) be an estimate of the true calibration curve, given by equation (17), which we do not know

$$\theta = a_o + a_1 CR + e \qquad \ldots\ldots\ldots\ldots\ldots \ (17)$$

where e is a stochastic disturbance term such that its expected value E{e} is zero.

Since the determination of θ and CR is bound to experimental measurement errors, only estimates of true values are obtained:

$$\hat{\theta}_o = \theta_o + \mu_i$$

$$\hat{n}_o = n_o + v_i$$

and using these values in the linear regression we obtain estimates of a_o and a_1, given in equation (16) as $\hat{a}_o$ and $\hat{a}_1$.

By subtracting equations (16) and (17) we obtain the difference between the true value of θ_o and the estimated $\hat{\theta}_o$, and an error analysis can be done. Details of this procedure are given in Havercam et al. (1984).

They arrive at a final equation of the form:

$$s^2(\theta_o) = \left[\hat{a}_1^2 - s^2(\hat{a}_1)\right] \cdot \left[\frac{\widehat{CR}_o}{pT_c} + \frac{\widehat{CR}_o^2}{qT_s}\right] \cdot \frac{1}{\bar{N}_s} + \ldots$$

$$\ldots + s^2(\hat{a}_o) + \widehat{CR}_o^2 s^2(\hat{a}_1) + 2\widehat{CR}_o s(\hat{a}_o, \hat{a}_1) + s^2(e_o) \quad \ldots\ldots\ldots (18)$$

which shows that the total variance of θ_o, equal to $s^2(\theta_o)$ is composed of two parts, one which we will call "instrument component" $s_I^2(\theta_o)$ since it is related to the counting procedure and related errors, and another, which we will call "calibration component" $s_c^2(\theta_o)$ since it takes into account the variances of the regression between θ_o and $\widehat{CR}_o$. In equation (18) we define:

$$s_I^2(\theta_o) = \left[\hat{a}_1^2 - s^2(\hat{a}_1)\right] \cdot \left[\frac{\widehat{CR}_o}{pT_c} + \frac{\widehat{CR}_o^2}{qT_s}\right] \cdot \frac{1}{\bar{N}_s} \quad \ldots. (18a)$$

$$s_c^2(\theta_o) = s^2(\hat{a}_o) + \widehat{CR}_o^2 s^2(\hat{a}_1) + 2\widehat{CR}_o s(\hat{a}_o, \hat{a}_1) + s^2(e_o) \quad \ldots.. (18b)$$

The parameters $\hat{a}_o$, $\hat{a}_1$, $s^2(\hat{a}_o)$, $s^2(\hat{a}_1)$, $s(\hat{a}_o, \hat{a}_1)$ and $s^2(c_o)$ are obtained directly from the linear regression on θ_o and $\widehat{CR}_o$ data. An example is given in page 14. For this set of data, applying equation (18b) we obtain the calibration variance of θ_o, which is assumed constant for all subsequent measurements of θ_o with this probe in this soil. If $s_c^2(\theta_o)$ is too high, additional calibration data has to be obtained in order to decrease $s^2(\hat{a}_o)$ and mainly $s^2(\hat{a}_1)$, which are the main contributers to $s_c^2(\theta_o)$. It can also be seen from equation (18b) that $s_c^2(\theta_o)$ depends on $\widehat{CR}_o$, which means that variance is different for different levels of soil moisture. For the above data, let us calculate the variance for $\widehat{CR}_o$=0.431, which is the average value over the soil moisture range found during calibration. So:

$$s_c^2(\theta_o) = 1.7884 \times 10^{-3} + 0.431^2 \, . \, 9.506 \times 10^{-3} + 2 \, . \, 0.431 \; (-4.097 \times 10^{-3}) +$$

$$+ 2.262 \times 10^{-4} = 2.462 \times 10^{-4}$$

$$s_c(\theta_o) = 0.0157$$

In our calibration equation we can see that for $\hat{n}_o$ = 0.431 corresponds a θ_o of 0.354 $cm^3.cm^{-3}$, and so we can calculate a calibration coefficient of variation CV%, which will be:

$$CV\% = \frac{0.0157}{0.354} \times 100 = 4.4\%$$

The above calibrated probe was used in a field (same soil of calibration) and at the same depth (20 cm) in the same access tube and five measurements of 2 minutes each were made. Also one measurement of the standard was made for 2 minutes:

TABLE 5

Measurement		C (count)	T (min)	$\bar{N}$ (cpm)	$\widehat{CR}_o$
1	soil	140,800	2	70,400	0.444
2	soil	138,200	2	69,100	0.436
3	soil	140,500	2	70,250	0.443
4	soil	139,900	2	69,950	0.441
5	soil	139,100	2	69,550	0.439
6	water	317,000	2	158,500	-
					0.4406

Using equation (18a) we can estimate the instrumental variance $s_I^2(\theta)$:

from page 14: a_1 = 1.0424; $s^2(a_1)$ = 9.506 x 10^{-3} $T_c = T_s$ = 2 min

$p = 5$ $q = 1$

$\widehat{CR}_o$ = 0.4406 $\bar{N}_s$ = 158,500

$$s_I^2(\theta) = (1.0424^2 - 9.506 \times 10^{-3}) \cdot \left[\frac{0.4406}{5 \times 2} + \frac{0.4406^2}{1 \times 2}\right] \cdot / 158{,}500 =$$

$$= 9.59 \times 10^{-7}$$

$$S_I(\theta_o) = 0.00098 \; .$$

which is two orders of magnitude smaller than $s_c(\theta_o)$. The instrumental coefficient of variation will be (9.8 x 10^{-4} / 0.364) x 100 = 0.3%. This example shows the relative importance of the instrumental and calibration errors in relation to the total error in estimating θ_o. For this case:

$$s(\theta_o) = 0.00098 + 0.0157 = 0.0167$$

What we have just seen is the variance involved in the measurement of θ at one depth in one access tube. In most cases, however, we are interested in a mean value $<\theta_o>$ of k measurements of θ_o made in k different access tubes (replicates). This mean value is now also affected by the "location" of the access tube, which depends on the spatial variability of the soil itself. Vauclin et al. (1984) treat this problem. They show that making the proper statistical analysis, equation (18) receives an additional term which takes into account the location and which can be expressed as:

$$s_L^2(<\theta_o>) = \left[\hat{a}_1^2 - s^2(\hat{a}_1) \right] . \frac{s^2(L_o)}{k\,\bar{\bar{N}}_s} \qquad \text{........ (18c)}$$

It should be noted that in the case of several access tubes, also in equations (18), (18a) and (18b), θ_o should be substituted by $<\theta_o>$.

Since it is difficult to calculate independently the location variance, Vauclin et al. (1984) suggest it should be calculated by difference:

$$s_L^2(<\theta_o>) = s^2(<\theta_o>) - s_c^2(<\theta_o>) - s_I^2(<\theta_o>) \qquad \text{... (19)}$$

where $s^2(<\theta_o>)$ is the total variance, given by:

$$s^2(<\theta_o>) = \left[\bar{a}_1^2 - s^2(\hat{a}_1) \right] . s^2(<\hat{CR}_o>) + s^2(\hat{a}_o) + <\hat{CR}_o^2>\, s^2(\hat{a}_1) + 2<\hat{CR}_o>\, s(\hat{a}_o,\hat{a}_1) \qquad \text{...... (20)}$$

Comparing equations (18) and (20) we see that the last one does not have the term $s^2(e_o)$. This is because equation (20) is the variance of a mean and the expected value of e is zero. Therefore $s^2(<e>) = 0$.

In equation (20) $s^2(<\hat{CR}_o>)$ takes into account location variability, estimated by:

$$s^2(<\hat{CR}_o>) = \frac{1}{k}\, s^2(\hat{CR}_o) = \frac{1}{k} \left[s^2(\bar{N}_o) + <\hat{CR}_o^2>\, s^2(\bar{N}_s) \right] . \frac{1}{\bar{N}_s^2} \qquad \text{.... (20a)}$$

To illustrate the use of equations(18c), (19), (20) and (20a), 30 measurements of CR_o were made in 30 access tubes, radomly distributed in the same field. All measurements were taken at the same depth of 20 cm. The data is given in Table 6.

TABLE 6 - Count ratios for neutron probe measurements at 30 different locations (z = 20 cm).

Tube nº	$\hat{CR}_o$	Tube nº	$\hat{CR}_o$
1	0.476	16	0.464
2	0.507	17	0.511
3	0.508	18	0.490
4	0.515	19	0.488
5	0.515	20	0.486
6	0.535	21	0.489
7	0.528	22	0.497
8	0.513	23	0.479
9	0.494	24	0.467
10	0.504	25	0.485
11	0.469	26	0.452
12	0.497	27	0.487
13	0.484	28	0.485
14	0.487	29	0.478
15	0.477	30	0.475

Using the data of Table 6 we will demonstrate that the larger k (number of locations) the lower is the local variance, given by equation (18c). First we give a complete example for k = 5, taking at random 5 measurements out of the 30 given in Table 6: They are from access tubes 6, 14, 26, 29 and 30. In this case we have:

$<\hat{CR}_o> = 0.4854$

$s^2(\hat{CR}_o) = 5.2768 \times 10^{-4}$, using classical statisitcs assuming that the 5 measurements are independent and normally distributed

$s^2(<\hat{CR}_o>) = (1/5) \times 5.2768 \times 10^{-4} = 1.0554 \times 10^{-4}$ (equation 20a)

$\hat{a}_o$, $\hat{a}_1$, $s^2(\hat{a}_o)$, $s^2(\hat{a}_1)$ and $s(\hat{a}_o,\hat{a}_1)$ as before (page 14)

$T_c = 1$; $T_s = 1$; $p = 5$; $q = 1$; $N_s = 157{,}050$

$s^2(<\theta_o>) = 16.4446 \times 10^{-5}$ (equation 20)

$s_I^2(<\theta_o>) = 2.2817 \times 10^{-6}$ (equation 18a)

$s_c^2(<\theta_o>) = 5.0771 \times 10^{-5}$ (equation 18b, without $s^2(e_o)$)

$s_L^2(<\theta_o>) = 10.7720 \times 10^{-5}$ (by difference)

Table 7 shows how the variances change as the number of replicates increase, from 5 to 30, in steps of 5.

Figure 6 also shows the variance change as a function of number of replicates (or access tubes). It should not be forgotten that these values are specific for this neutron probe and this soil. From these results it can be seen that instrumental variance is very small with respect to the others; calibration variance is relatively constant since it is not affected by k; and that the total and local variances decrease exponentially with k, having the tendency to become constant for very large values of k.

Figure 7 is extremely important in order to help us to answer the basic question: "how many access tubes do we need for each treatment of an experiment ?" For the data of Table 6, $<\hat{CR}_o> = 0.4913$, which corresponds to a value of $<\theta_o> = 0.417\ cm^3.cm^{-3}$. If we would like that this value of $<\theta_o>$ would be measured with a CV of 3%, we would have:

$$CV\% = \frac{s(<\theta_o>)}{<\theta_o>} \times 100$$

$$s<\theta_o> = \frac{3 \times 0.417}{100} = 0.0125$$

and

$$s^2<\theta_o> = 15.65 \times 10^{-5}$$

From Figure 7 we see that to have a total variance of this order, we need 6 access tubes. If the desired CV is 5%, 3 access tubes would be needed, and if CV is 2%, more than 30 access tubes are needed. A CV of 1% can not be obtained because of the intrinsic variability of $<\theta_o>$, as mentioned before.

TABLE 7 - Variance behaviour as a function of number of replicates k, using Table 6 data.

k	Number of Selected Access Tube from Table 6	$<\hat{CR}_o>$	$s^2(\hat{CR}_o)$	$s^2(<\theta_o>)$	$s_I^2(<\theta_o>)$	$s_c^2(<\theta_o>)$	$s_L^2(<\theta_o>)$
5	6 14 26 29 30	0.4854	5.28×10^{-4}	16.44×10^{-5}	2.28×10^{-6}	5.08×10^{-5}	11.13×10^{-5}
10	4 5 9 11 15 20 23 24 26	0.4839	4.04×10^{-4}	9.28×10^{-5}	1.95×10^{-6}	4.92×10^{-5}	4.16×10^{-5}
15	2 3 5 7 8 9 10 12 16 18 19 24 27 28 30	0.4948	3.28×10^{-4}	8.49×10^{-5}	1.90×10^{-6}	6.13×10^{-5}	2.17×10^{-5}
20	1 2 3 4 5 6 9 11 13 14 15 16 17 18 19 20 22 23 26 28	0.4910	3.95×10^{-4}	7.81×10^{-5}	1.82×10^{-6}	5.68×10^{-5}	1.95×10^{-5}
25	all except 1, 3, 13, 15 and 28	0.4924	4.08×10^{-4}	7.60×10^{-5}	1.79×10^{-6}	5.85×10^{-5}	1.57×10^{-5}
30	all access tubes	0.4913	3.67×10^{-4}	7.04×10^{-5}	1.77×10^{-6}	5.72×10^{-5}	1.14×10^{-5}

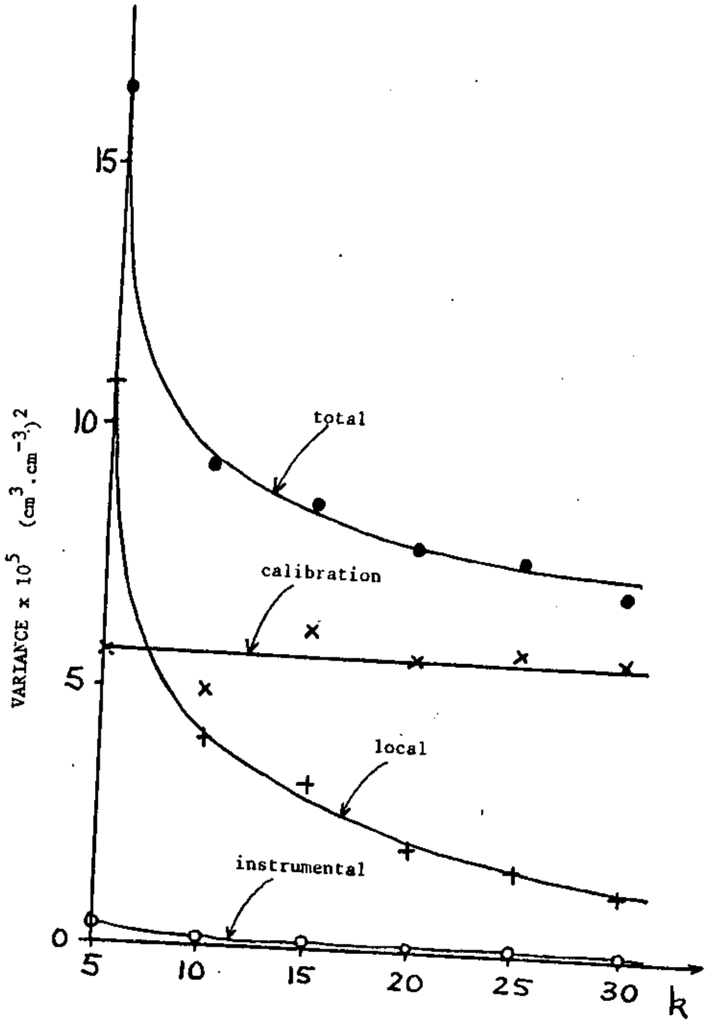

FIGURE 6 - Variances as a function of number of replicates in the field.

The only way to reduce the number of needed access tubes would be by reducing the calibration variance. A better calibration relation, with more points and over a wider range, will give lower calibration variance.

8. APLICATIONS

8.1. Soil Water Storages

The water stored in a soil layer at depths L_1 and L_2, at time t, is defined as:

$$A_{L_2-L_1}(t) = \int_{L_1}^{L_2} \theta \, dz \tag{21}$$

where θ is the volumetric soil water content given by equation 2, and z is the vertical position coordinate, measured downwards from soil surface.

Using θ in cm^3 of water per cm^3 of soil, and z in cm, the result of A is a height of water, given in cm. Each cm of stored water corresponds to a volume of 10 liters of water per square meter of soil surface, down to the integrated depth. The most common case is when $L_1 = 0$ (soil surface) and the integration is made over the whole soil profile, down to depth L_2.

Since in general the function $\theta(z)$ that describes the variation of θ along z is not known, one has to use numerical schemes of integration. Havercamp et al. (1984) and Vauclin et al. (1984) discuss the use of the trapezoidal and Simpson's rules. For most agronomical purposes, the simple trapezoidal rule is very adequate and, therefore, our example will cover this rule only.

According to the trapezoidal rule, equation (21) is simplified to:

$$A_{L_2-L_1}(t) = \bar{\theta}\,(L_2 - L_1) \tag{21a}$$

where $\bar{\theta}$ is the average value of θ in the interval $L_2 - L_1$.

Table 8 shows neutron moisture data collected at an access tube installed in a corn field. The neutron probe is the same as the one used for the calibration example in Figure 3.

TABLE 8 - Count ratios and soil water contents as a function of depth, for a corn crop, on September 7, 1988. Alfisol, Piracicaba, SP, Brazil.

Depth (cm)	Count Ratio (CR)	Soil Water Content ($cm^3.cm^{-3}$)
25	0.494	0.420
50	0.485	0.410
75	0.503	0.429
100	0.473	0.398
125	0.465	0.389
150	0.471	0.396

Using equation (21a) it is easy to calculate the following soil water storages:

$A_{0-150}(7/9/88) = 0.407\ (150-0) = 61.1\ cm = 611\ mm$

$A_{0-75}\ (7/9/88) = 0.420\ \ (75-0) = 31.5\ cm = 315\ mm$

$A_{50-100}(7/9/88) = 0.412\ (100-50) = 20.6\ cm = 206\ mm$

As already discussed in item 6, it is important to know the "sphere of influence" of the probe. This is specially true for the measurements close to soil surface. In the present case, the "sphere of influence" has a diameter of the order of 30 cm. This means that when the probe is placed at the depth of 25 cm, we are making a measurement from 10 to 40 cm depth; so we are loosing the top 10 cm. This introduces an error in our storage calculations that start at soil surface. On the other hand, it is good because we are sure that neutrons did not escape from soil surface, which also introduces errors. Therefore many times we take gravimetric samples at soil surface.

It is also important to note that the measurements of the probes are not punctual but, in actual fact, are averages over a soil layer of the thickness of the sphere of influence. Figure 7 illustrates this for the data of Table 8. This fact has advantages when calculating soil water storages because, as shown by equation (21a), the calculation is based on averages. Even the overlaping of spheres does no harm, on the contrary, it improves the sampling of the profile.

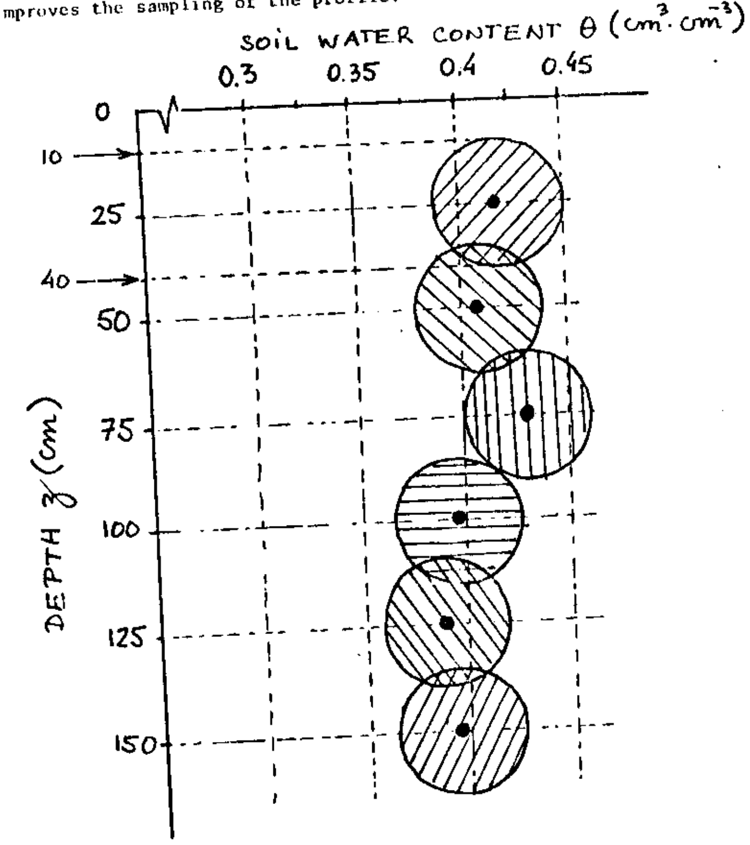

FIGURE 7 - Soil water content profile in a corn crop (7/9/88) showing "sampling volumes" of the neutron probe.

In our example, if measurements would have been taken in 10 cm intervals, the overlaping would be greater and the estimative of soil water storage, better. Attention must only be taken at soil surface. If we start measuring at the depth of 10 cm, part of the "sphere of influence" would be outside the soil.

Modern models of neutron probes have microprocessors that calculate automatically the soil water storage, giving results in mm of water. Others, more sophysticated, move up and down in the access tube, at a constant rate, making an excellent integration of the soil water profile.

Very important are also soil water content changes in time. As soil gains water by rainfall or irrigation or as soil looses water by evapotranspiration or internal drainage, soil water storage changes in time. For the same corn crop illustrated in Table 8 and Figure 7, neutron probe measurements made at different dates gave the following storages:

A_{0-150} (14/9/88) = 579,5 mm

A_{0-150} (21/9/88) = 543,8 mm

A_{0-150} (28/9/88) = 575,8 mm

From 7 to 21/9 there was no rain or irrigation. The average rates of water loss were:

$$\frac{\overline{\partial A}}{\partial t} \simeq \frac{A_{0-150}(14/9) - A_{0-150}(7/9)}{14 - 7} = -4.5 \text{ mm/day}$$

$$\frac{\overline{\partial A}}{\partial t} \simeq \frac{A_{0-15}(21/9) - A_{0-150}(14/9)}{21 - 14} = -5.1 \text{ mm/day}$$

It is however impossible to partition these losses into evapotranspiration and drainage below 150 cm. If the soil was at the beginning at field capacity, we can be sure that 100% of the losses were evapotranspiration. Above field capacity, this is not true and fair amounts of water can be lost by deep drainage.

In the period 21 to 28/9 there was rain, therefore soil water storage increased.

8.2. Field soil water retention curves

Combining neutron probe readings with tensiometer readings, at the same depth, it is possible to establish soil water retention curves, that is, relations θ versus ψ_m. Tensiometers should be installed as close as possible to neutron access tubes but not within the "sphere of influence" of the probe, because the tensiometer cup, being full of water, can interfere significantly in the readings of the probe. A distance of 20 - 30 cm should be ideal to avoid the interference. In many soils, however, bulk densities and water contents may vary significantly over these short distances. This was observed by Greminger et al. (1985) and Villagra et al. (1988) that obtained very scattered points in their field soil water retention curves due to soil spatial variability. IAEA (1984) also presents soil water retention curves obtained with tensiometers and neutron probes, for soils of several countries. Figures 8 and 9, below,are two examples of soil water retention curves obtained from neutron probe and tensiometer data.

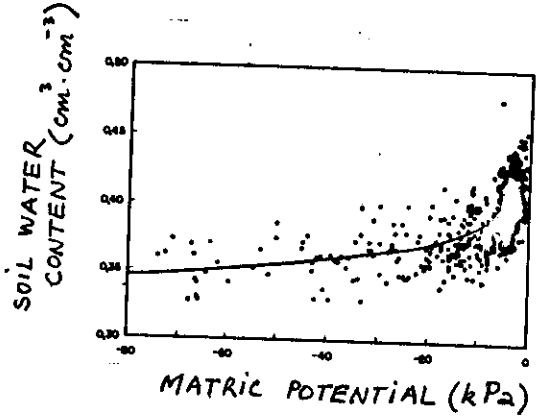

FIGURE 8 - Soil water retention curve for "terra roxa estruturada", depth of 20 cm, Piracicaba, Brazil. Villagra et al. (1988).

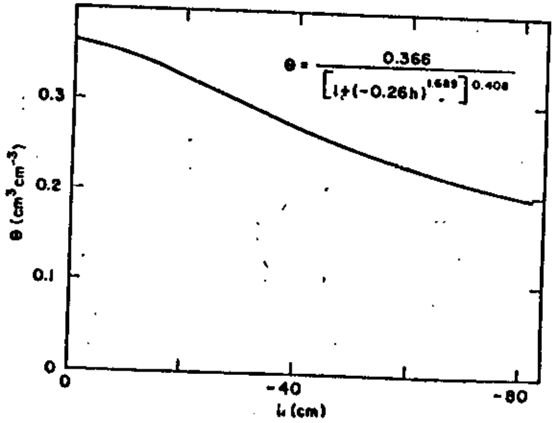

FIGURE 9 - World average soil water retention curve (average of 11 countries over 6 depths). IAEA (1984).

8.3. Soil Hydraulic Conductivities

Soil hydraulic conductivity K being a parameter that indicates the hability of the soil in transmitting water, is strongly dependent on soil water contents (Θ). Therefore, for a given porous material we define the function K(Θ), and all methods used to measure hydraulic conductivity envolve the measurement of soil water contents. Among these methods several are adapted to use neutron probes, specially those developed for field conditions. As an example we will illustrate this section with one method presented by Libardi et al. (1980).

In a 5 x 5 mm plot, 3 to 5 neutron access tubes are installed down to the desired depth. Water is ponded until steady state infiltration. At this time neutron probe readings should be constant in time and indicate the saturated soil water contents of the profile. Steady state infiltration rate should also be recorded, which is assumed to be the saturated hydraulic conductivity of the profile K_o.

After infiltration of the ponded water, soil surface is covered with plastic to avoid water evaporation, and internal drainage of the profile is observed through periodic soil water content measurements. Frequency of measurements is high at initial times (about twice a day) and becomes low as time passes (about twice a week), finishing the experiment after about one month. For these measurements neutron probes are extremely adequate because "same sites" are "sampled" each time of measurement. With auger techniques soil has to be uncovered each time and samplings are made every time at different locations. Auger holes disturb internal drainage process. During ponding and at early stages of infiltration, when soil is very wet and muddy, it is impossible to sample soil with an auger.

Figure 10 shows plots of soil water content as a function of the natural logarithm of time, for two selected depths of a yellow-red latosol from Piracicaba, Brazil, measured with a SOLO 25 neutron probe. According to the procedure of Libardi et al. (1980), linear regressions of plots of Θ versus ln t yield the coefficients γ of the exponential K(Θ) relation:

$$K = K_o \exp\left[\gamma(\Theta - \Theta_o)\right] \tag{22}$$

For the two examples of Figure 10, the values of γ are 23.077 and 27.273 the value of K_o is 85.6 cm/day and the values of the saturated water content are 0.481 $cm^3.cm^{-3}$ and 0.439 $cm^3.cm^{-3}$. Therefore we have:

z = 50 cm $\quad K = 85.6 \exp\left[23.077\ (\Theta - 0.450)\right]$

z = 150 cm $\quad K = 85.6 \exp\left[27.273\ (\Theta - 0.501)\right]$

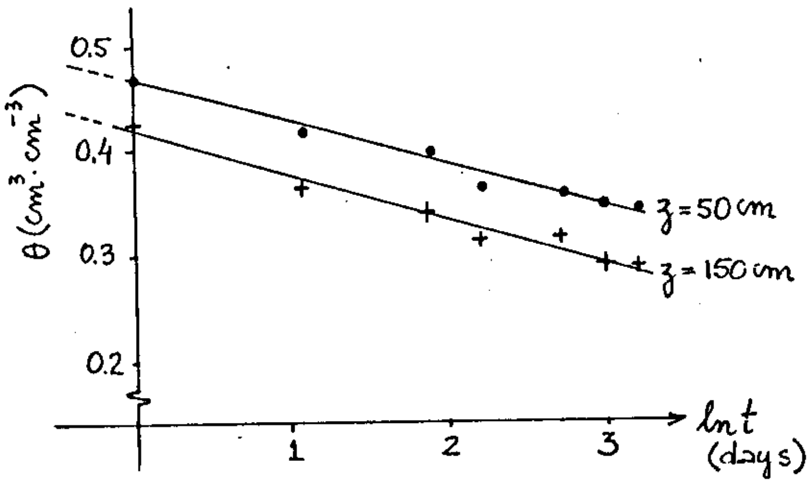

FIGURE 10 - Plot of Θ versus ln t

8.4. Soil Spatial Variability

When the problem is to study spatial variability of soil water contents and better understand their variances, their dependence on space, etc, neutron probes are very suitable. These studies can be performed with advantages using the theory of regionalized variables and, in this context, a large number of sampling points are needed. Sampling schemes may be transects or grids, with points separated of constant lag h.

Figure 11 shows several neutron probe measurements of soil water contents, made over a transect of 25 access tubes, with a lag of 5 m, located in an Alfisol, Piracicaba, Brazil. The parallelism between curves of different days shows that the neutron probe really "samples" the same location at each time.

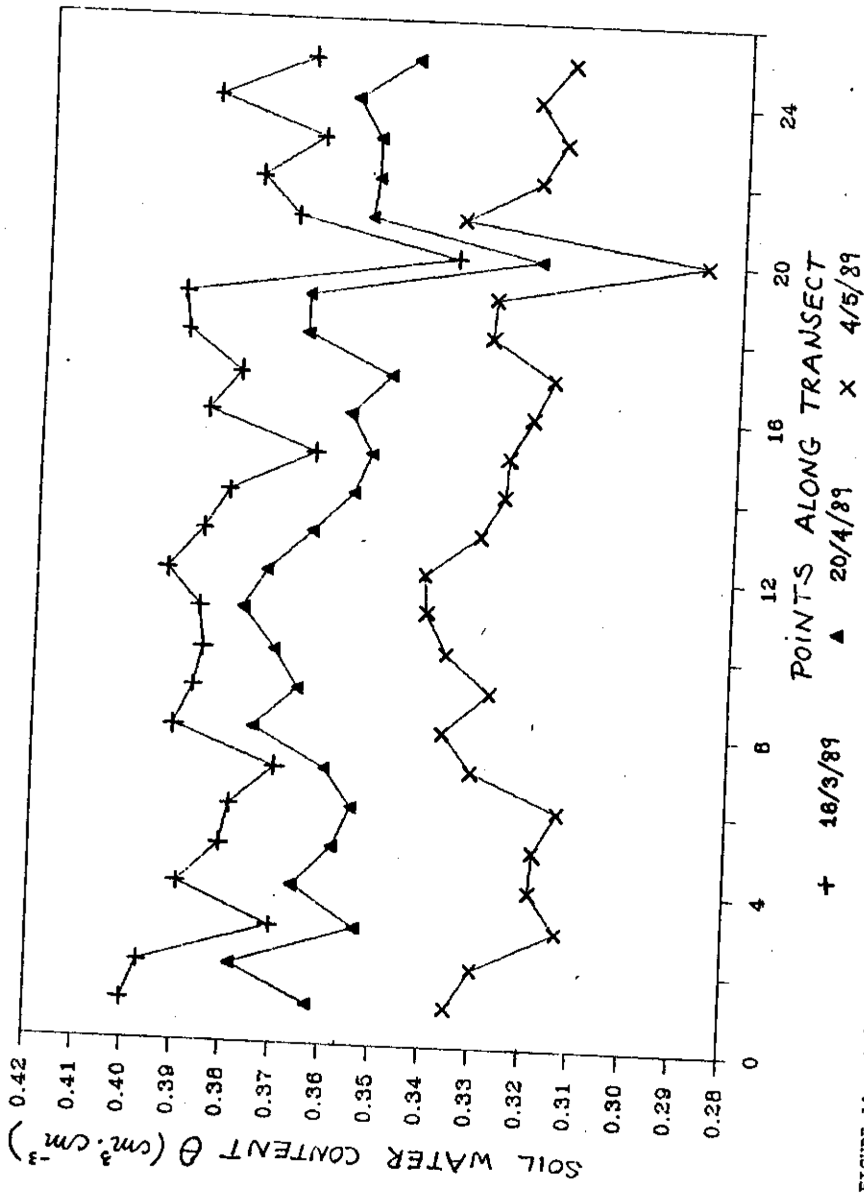

FIGURE 11 - Soil water content measurements along a transect of 25 points with lag of 5 m. Alfisol, Piracicaba, Brazil.

8.5. Water Extraction by Trees

In a rubber tree plantation tensiometer measurements of soil water potential ψ_m and neutron probe measurements of soil water content Θ indicate patterns of soil water extraction (Figures 12 and 13). Measurements were made at several locations and at different depths so that it was possible to construct isolines of ψ_m and Θ.

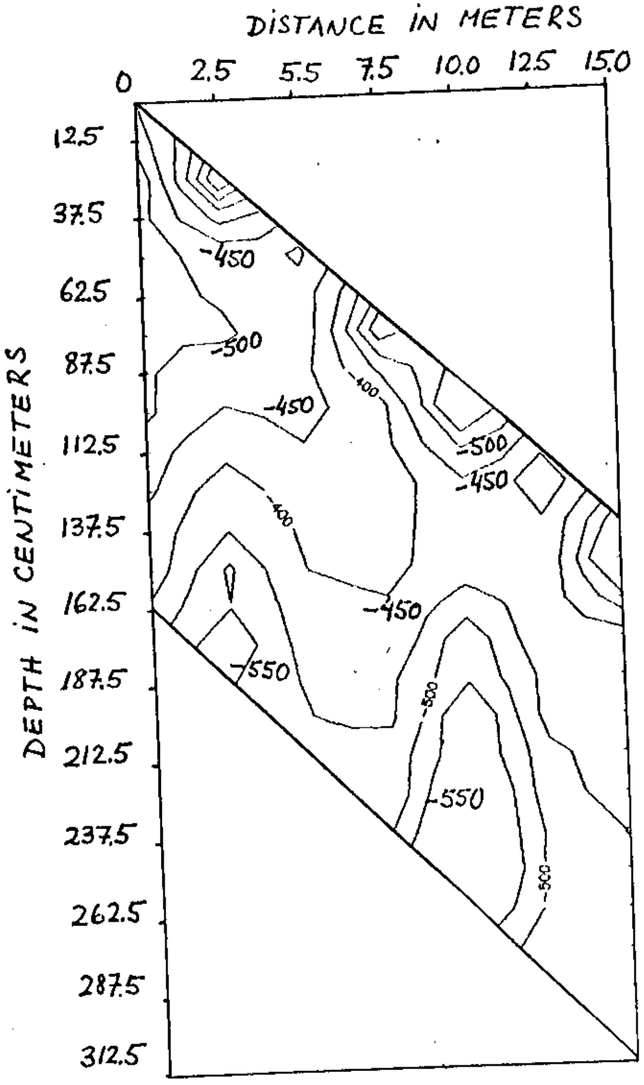

FIGURE 12 - Soil water potential isolines in a rubber-tree plantation (23/8/89)

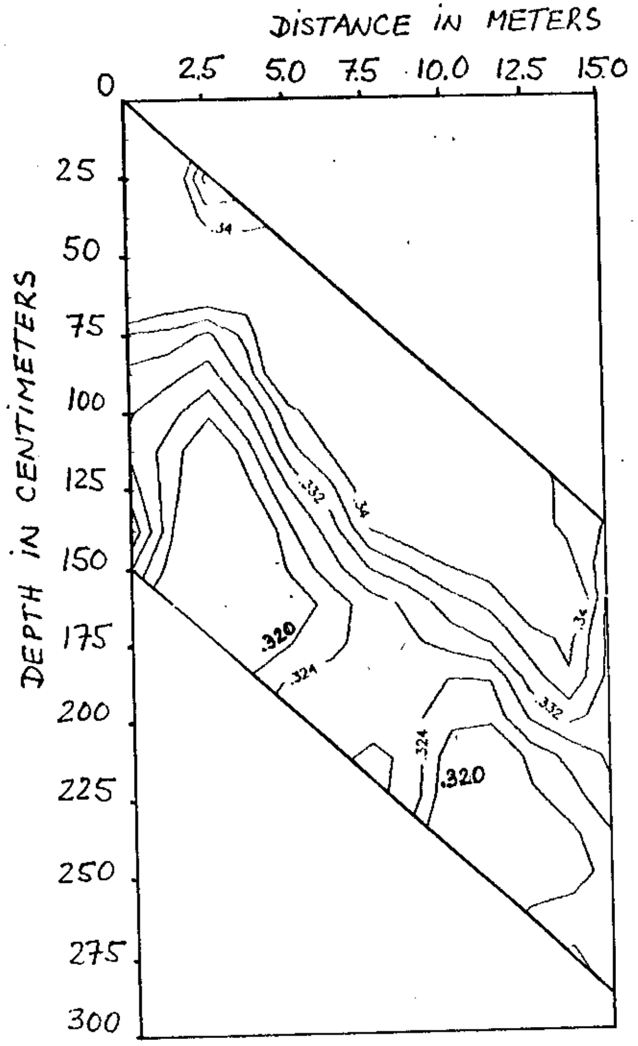

FIGURE 13 - Soil water content isolines in a rubber-tree plantation (23/8/89).

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