INSTITUTE
OF
HYDROLOGY

USER'S HANDBOOK FOR THE INSTITUTE OF HYDROLOGY NEUTRON PROBE SYSTEM

THE NATURAL ENVIRONMENT RESEARCH COUNCIL

REPORT No 79

October 1981

CONTENTS

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INTRODUCTION

The neutron probe is designed as a field instrument for measuring *in situ* the volumetric water content of the soil and of the underlying unsaturated zone. The measurement is made by means of a probe which is lowered into an access tube installed vertically in the soil profile. Soil moisture is determined at specific depths to provide a "soil moisture profile".

Because the probe has to be calibrated for each soil and because the access tubes are semi-permanent and must be installed with great care, the neutron probe method is best used in situations where repeated measurements of soil water change are required over an extended period of time.

The neutron probe is essentially a research tool. Although entirely suitable for routine use, the field procedure must always be carefully supervised and carried out with full knowledge of the theory and practice of the technique, including an awareness of its limitations. The method is then capable of producing consistently high quality data obtainable in no other way.

The Institute of Hydrology Neutron Probe System consists essentially of the probe and a ratescaler, connected together by a cable. The probe is housed in a carrier which incorporates a radiation shield, depth counter register, lock and cable clamp. The complete system forms a single unit which is easily carried over rough field terrain (Figure 1). The probe is lowered in the access tube to successive measurement depths by means of the cable (Figure 2) and the slow neutron count rate is determined at each depth.

FIGURE 1 The IH Neutron Probe being carried in the field

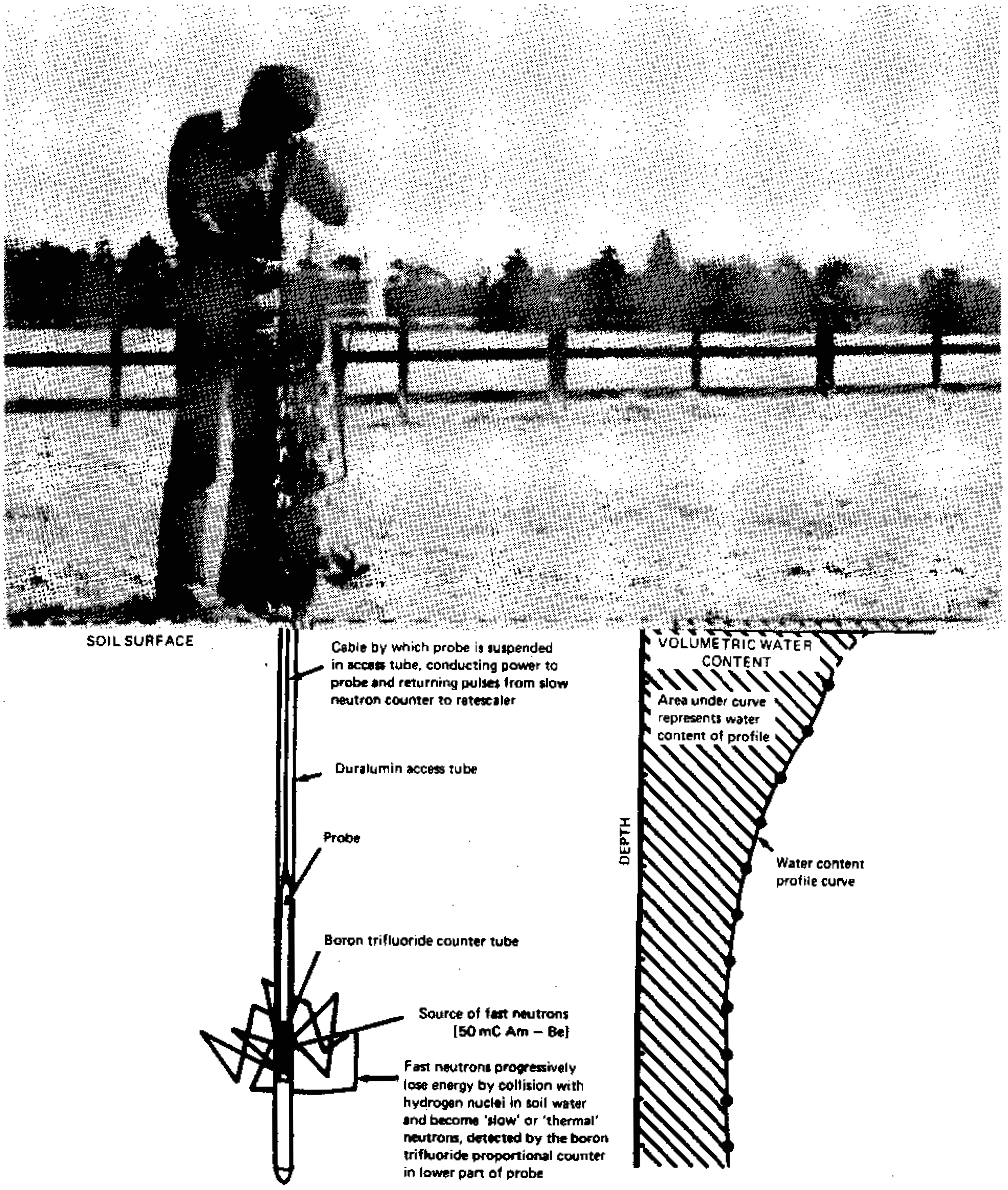


FIGURE 2 **The Probe in use in the field, showing diagrammatically the scattering of fast neutrons and return of slow neutrons in soil around the centre** ***of sensitivity of the probe; the graph shows an example of a*** **soil moisture profile.**

The probe contains a sealed Americium-Beryllium radioactive source from which fast neutrons are emitted into the soil. Collisions with the nuclei of the soil atoms, predominantly those of the hydrogen of the soil water, cause the neutrons to scatter, to slow and to lose energy. When they have slowed to the so-called "thermal" energy level they are absorbed by other nuclear reactions. Thus a "cloud" of slow (ie thermal) neutrons is generated within the soil around the source. The density of this cloud, which is largely a function of the soil water content, is sampled by a boron trifluoride slow neutron detector in the probe. The electrical pulses from the detector are amplified and shaped before passing up the cable to the ratescaler where their mean count rate is displayed digitally as counts per second. The count rate for each depth is converted into volumetric soil moisture content by means of an appropriate calibration curve.

Although it is the hydrogen in the soil, including that of bound water and organic material, which exerts the principal effect on the count rate, the nuclei of other soil elements also influence the count rate, but to a much smaller extent. Every soil therefore has a unique calibration relationship between count rate and water content, depending on its chemical composition. However, the general form of the calibration for soils ranging between clays and sands is well-known and for most purposes it is necessary only to establish one or two points so as to define the gradient of the calibration line and also its approximate intercept. A much fuller account of all the procedures involved in using a neutron probe is given in IH Report No. 19, "Neutron Probe Practice".

DESCRIPTION OF THE SYSTEM

The Institute of Hydrology Neutron Probe System II was designed jointly by the Didcot Instrument Company and the Institute of Hydrology, Wallingford. The system has been designed throughout for field use, with emphasis on simplicity of operation, robustness, lightness and ease of carrying.

Particular attention has been paid to electronic stability, "warm up" having been virtually eliminated and thermal effects reduced to less than ± 0.75% in the range $-10^{o}C$ to $+50^{o}C$. Cable problems have been minimised by generating inside the probe the very high voltages necessary to drive the BF_3 detector tube, so that the cable carries only very low voltages. The cable and the plug connections at either end are therefore much less vulnerable to damp and dirt than are those of many other systems. The electronic circuitry within the probe has been reduced to a single 3 mm thick printed circuit board offering the possibility of simple exchange of boards if failure occurs when the user has no access to a skilled electronic engineer. This is particularly valuable for the overseas user who cannot accept the long delays inherent in returning the entire system to the manufacturer if failure occurs.

The components of the system are:

The probe carrier. This incorporates a socket in its base (Figure 3) by means of which it is fitted onto the access tube so that the probe may be lowered directly from the carrier into the access tube. The carrier is cylindrical in form and made from tough PVC, and contains in its lower part a spherical polypropylene moderating shield for the fast neutrons.

An internal brass liner provides shielding against the relatively low level of gamma radiation which the source produces in addition to fast neutrons. The polypropylene sphere also serves as a rough standard to check that the probe is functioning. The upper part of the carrier contains the depth register and the

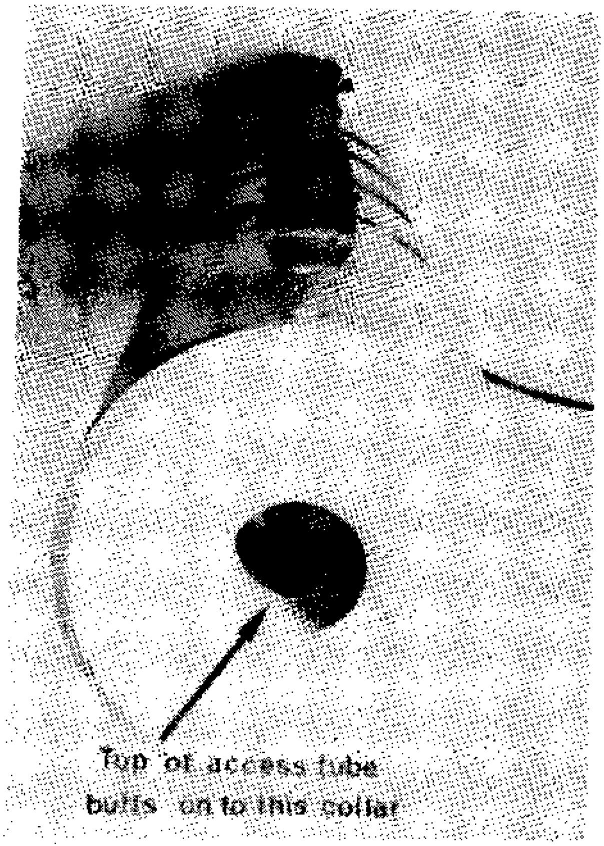


FIGURE 3

The basal socket of the probe carrier into which the upper 38 mm of the access tube fits.

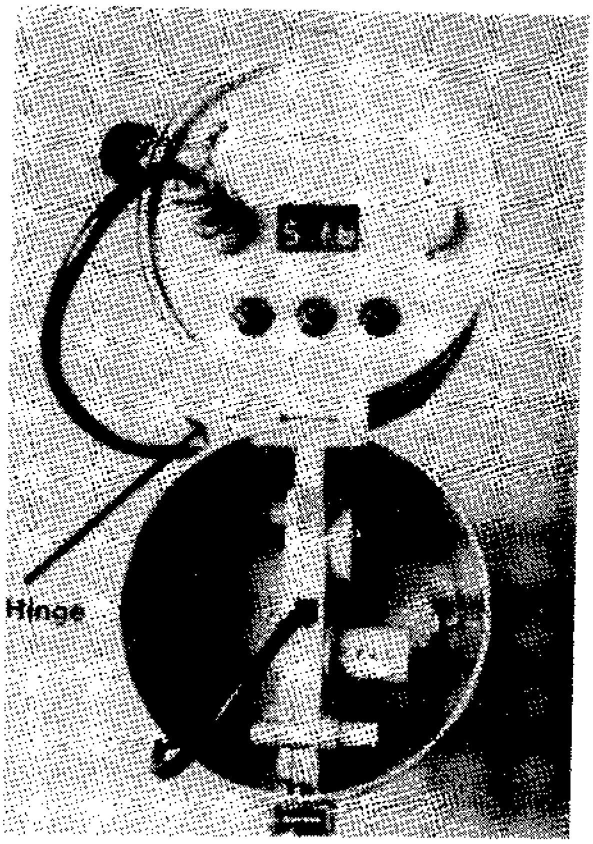


FIGURE 4

The Mk II E ratescaler mounted on the carrier in the "open" position, ready for use.

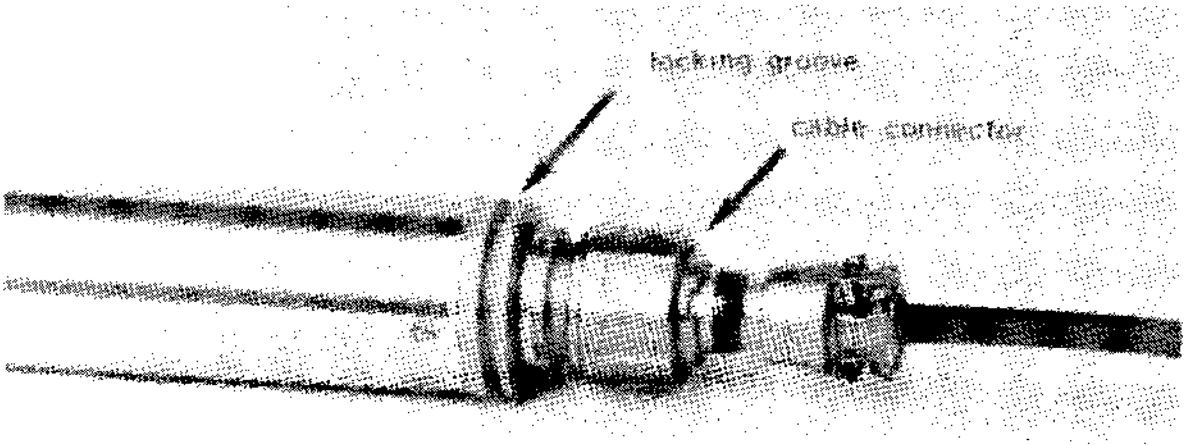


FIGURE 5 The upper end of the probe showing cable connection and locking groove.

cable clamp mechanism (Figures 4 and 6). A lock is provided to lock the probe in its carrier and this operates by advancing a flat bolt which ingages in a groove in the top of the probe (Figure 5). The key can only be withdrawn if the probe is fully retracted into its carrier with the locking bolt engaged in the groove. Cleats are provided on the side of the carrier to store the cable (Figure 7) and the body is perforated with a grid of 5 cm holes which enable the instrument to be handled more easily in wet or cold conditions. The holes allow a visual check that the probe is present and clean. A carrying strap is fitted to the side of the carrier.

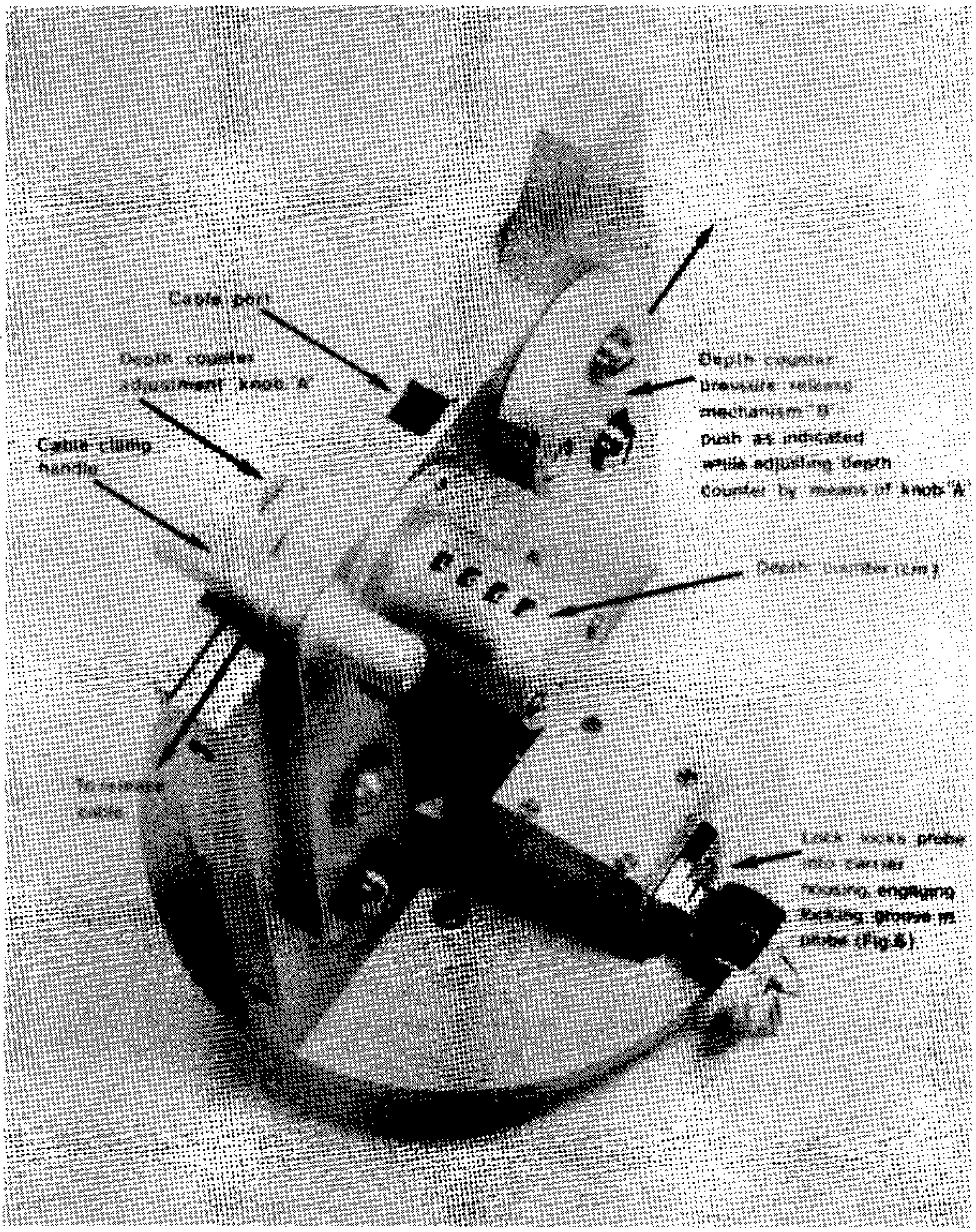


FIGURE 6 Lock, cable clamp and depth register assembly (removed from the carrier housing)

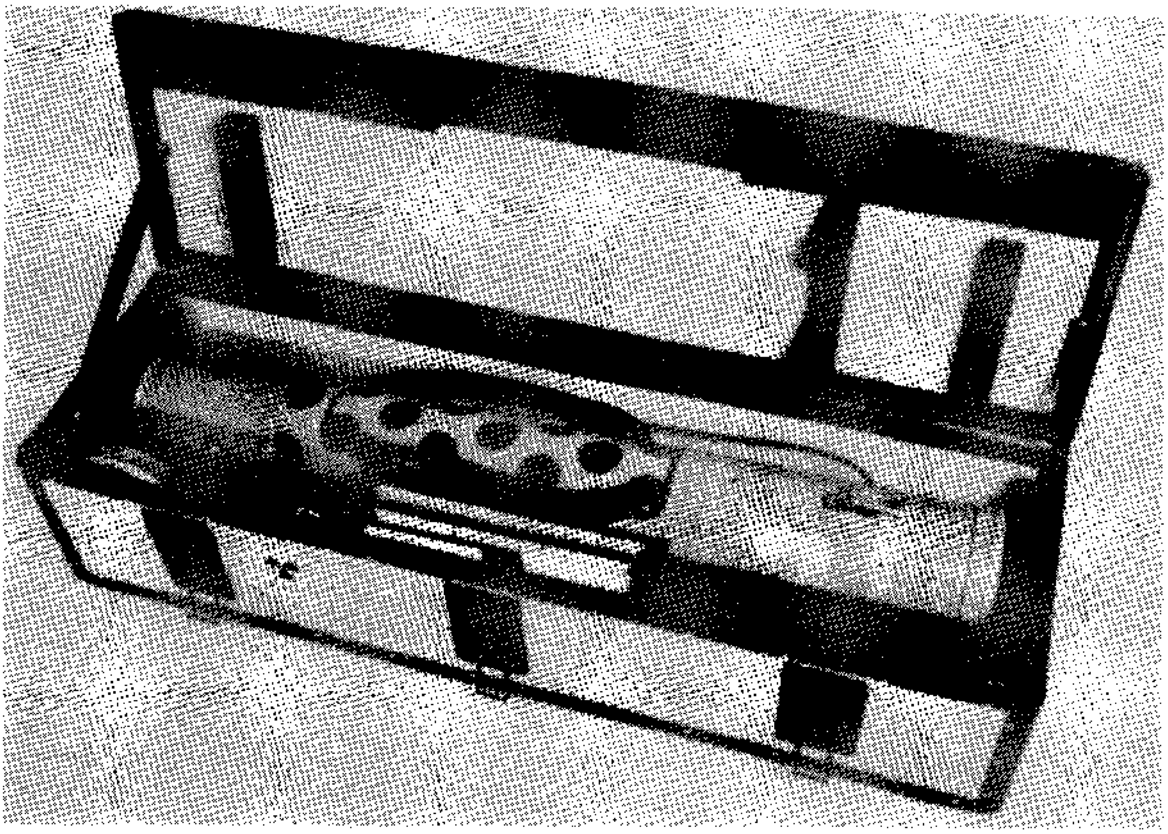


FIGURE 7 **Probe and accessories in the transport case (the earlier Mk II E ratescaler shown here).**

One half of a quick-release hinge is fitted to the top of the carrier. This engages the other half of the hinge mounted on the ratescaler, the two being joined (Figure 4) by a threaded screw pin with a knurled head which enables the two parts to be separated easily.

The ratescaler is a short cylindrical unit which is attached to the upper end of the carrier body by means of the hinge. When not in use the ratescaler is shut back over the end of the carrier, where it is secured by a toggle clip. A single unit is thus created which is easily carried and which protects all the controls (see Figure 1). When in use the ratescaler is hinged back to expose the controls and display (Figures 4 and 8). The hinge pin is easily unscrewed by hand so that the ratescaler can be detached.

The liquid crystal display gives the mean count rate at the conclusion of the preset counting time, in counts per second.

The 'probe socket' to the left of the display provides a nominal 13 V supply to power the probe and an input to the ratescaler for the returning pulses.

To the right of the display is the "bleeper" which sounds when a count is completed.

The sound level can be varied by screwing the cover in or out.

The 'charge/ext supply' socket above the display is used to charge the NiCd cells, using a maximum rate of 200 mA; higher rates are permissible but only for short periods (see specification). The socket may also be used to input an external 6 V power supply (NB: 7 V must not be exceeded: if an external power supply is used the cells must first be removed - see below).

The input is protected by a diode so that damage cannot be caused by incorrect polarity of the charger or power supply. Thus, battery voltage cannot be measured across the pins of this socket.

There are three switches. The right hand switch is used to initiate a counting sequence and to switch off the entire system. It is spring loaded in the central position and should be pushed in the appropriate direction and then released. The other two switches must be used to select the appropriate counting time, which may be either 16 sec, 64 sec, 16 min or 64 min.

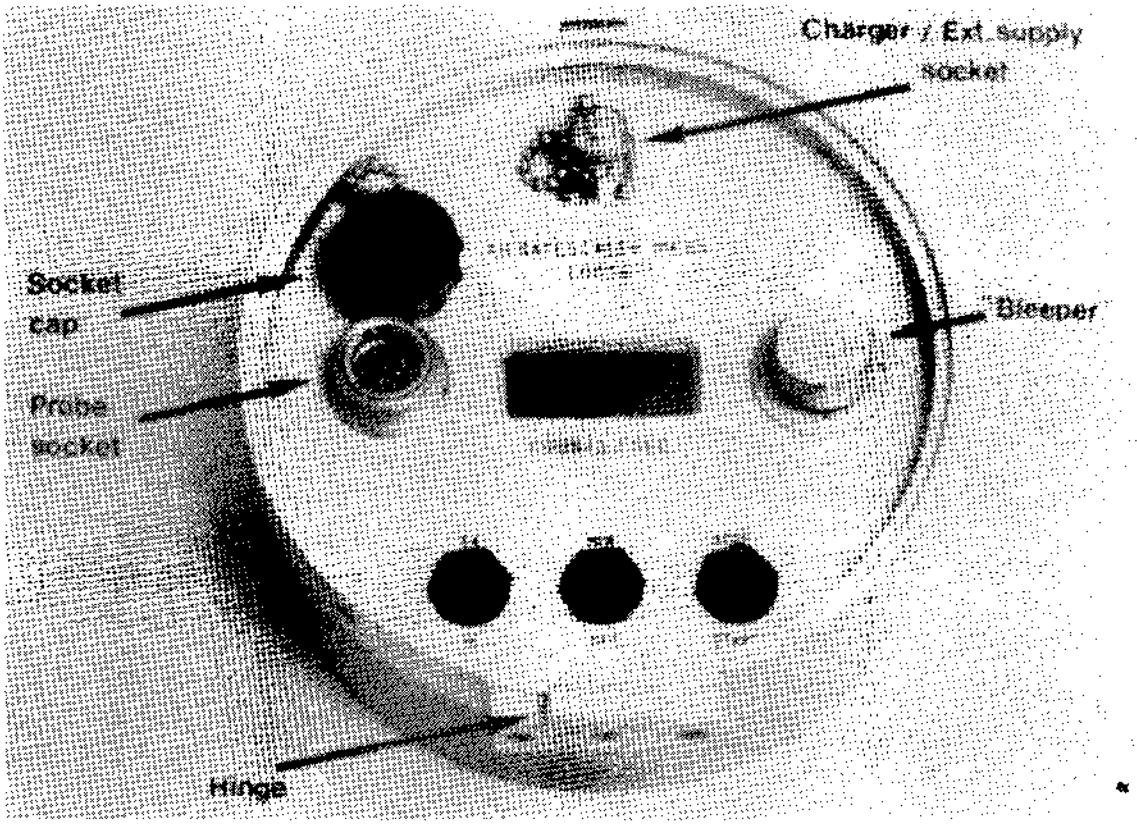


FIGURE 8 **The Mark II L Ratescaler showing the controls, display and connecting sockets.**

A fully charged battery should permit approximately 12 hours of continuous operation although this depends on the age and treatment of the battery and the operating temperature.

When the battery voltage has dropped to a voltage level at which the batteries are nearly exhausted, a buzzer inside the ratescaler is automatically actuated and a colon (:) is displayed intermittently between the second and third digits of the display. Readings taken while this is happening are perfectly acceptable, the buzzer simply warns that the battery will very soon fall below the critical voltage at which the display will be suppressed (4.0 V). The four NiCd cells are linked in series to give a fully charged voltage of about 5.3 V.

To gain access to the cells the back panel of the ratescaler is removed by unscrewing the central knurled knob at the rear (Figure 9). The cells may be easily removed and replaced, either by rechargeable NiCd cells or any dry cell of the same physical dimensions, of up to 1.5 V per cell. Polarity is designated beneath each cell. A fuse is placed in the circuit to protect against incorrect polarity and a spare fuse is mounted adjacent. The battery compartment is entirely separate from the electronics and the partition is water- and leak-proof.

The entire system switches off automatically 8 minutes after the completion of a count if START has not been repeated in the interim.

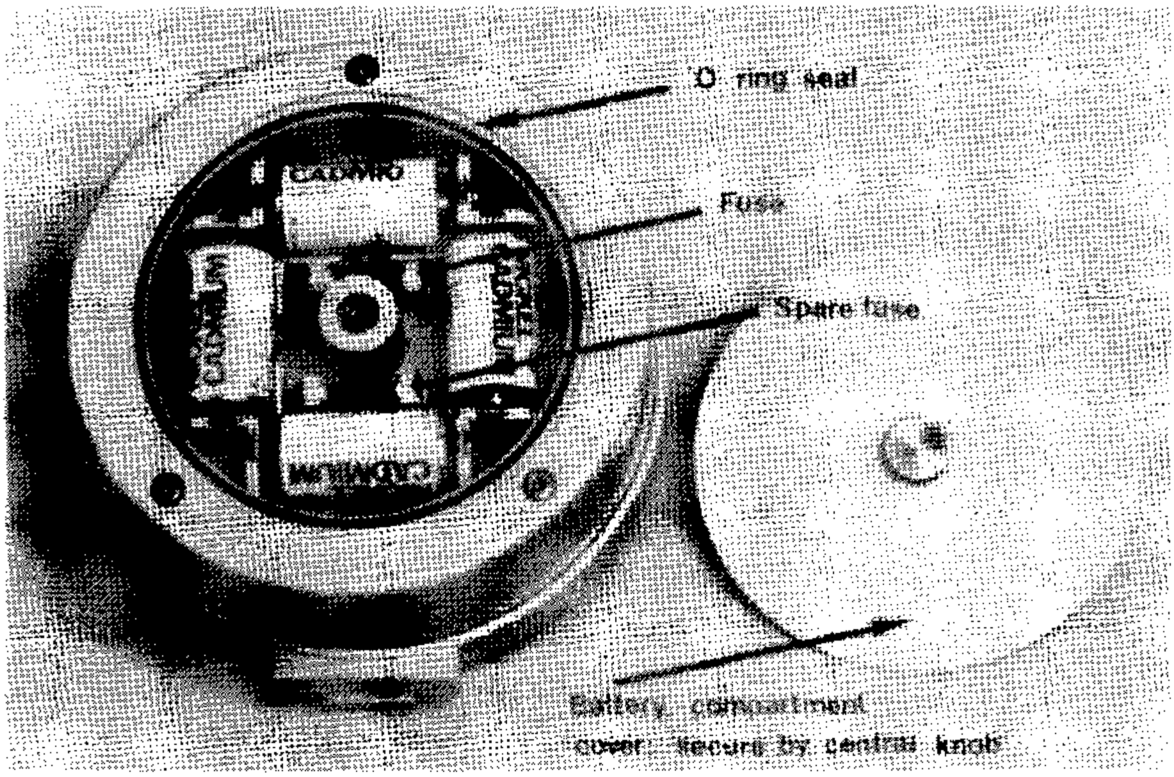


FIGURE 9 **The underside of the Mark II L Ratescaler - the battery compartment is open to show the internal features.**

The cable which connects the ratescaler to the probe is normally supplied in a 5 m length, permitting readings to be made to 4 m, but longer cables can be supplied if required. Although the cable is triaxial, it utilises only the inner two conductors. The probe is lowered down the access tube and supported by means of this cable, which also drives the mechanical depth register, accurate to ±1 cm in 5 m. The cable clamp holds the probe at any required depth. Waterproof connectors terminate the cable at both ends. The cable conducts the 13 V supply to the probe and returns 11 V pulses at the correct count rate to the ratescaler. It should be noted that the output pulse amplitude is approximately 1 V less than the D.C. supply voltage, which may be allowed to vary between 14 and 10 V without loss of counts. The cable is not reversible. The connector with the red marking fits the probe socket.

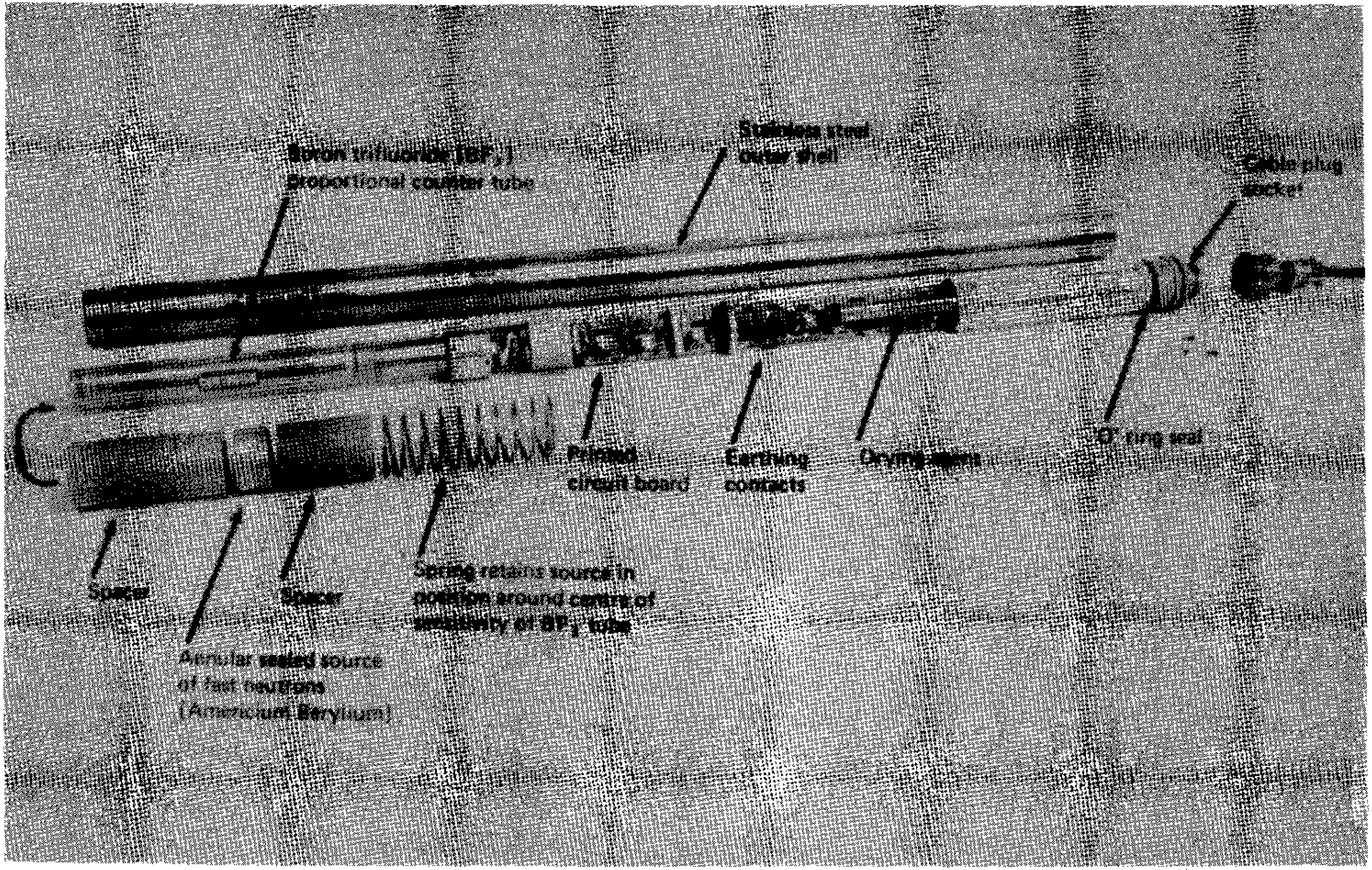


FIGURE 10 Internal components of the probe

The probe consists of a stainless steel cylinder 38 mm in diameter and 750 mm long overall. The cylinder is marked with a line at the mid-plane of the source, representing the centre of sensitivity. The internal layout is shown in Figure 10. The upper end incorporates a socket for connection to the cable plug. The probe contains the annular Am-Be source of fast neutrons, which is positioned around the boron trifluoride (BF_3) proportional counter tube at the mid-point of its sensitive length, and a single printed circuit board. This board incorporates a stabilised 2.3 kV power supply for the BF_3 tube. The additional circuits provide discrimination against low level noise and shape and amplify the count pulses generated by the BF_3 tube. These pulses return up the cable to the ratescaler. The probe may be operated below water to depths not exceeding 100 m. (Instruments for use at greater depths can be supplied if required). The nominal activity of the source is 50 mCi.

The battery charger Separate instructions are provided with this as the charging conditions vary with the type of cells and charger.

The transport case (Figure 7) is designed to serve as a store for the probe in its carrier and is physically and legally suitable for transporting the probe by road or air. It conforms with Type A specification (see section on radiological safety). It contains compartments to house spare cells, spare cable, field record forms, the charger, etc.

TAKING A READING

The procedure outlined here applies to both taking readings of soil water content in the field and to taking standard count readings. The bung is removed from the access tube (Figure 11) and the probe carrier fitted to the access tube by means of the socket in its base. The ratescaler is hinged open and the cable is unwound from the cleats and connected to the socket on the ratescaler front panel. The tightness of the cable connector at the probe end is checked.

The depth counter (Figure 6) is checked and adjusted with the probe locked in the carrier. It should read 9994, indicating that the centre of sensitivity is 6 cm above the top of the access tube (now located against the internal shoulder of the base socket). At this stage the source is still in the centre of the polypropylene shield. If the depth counter does not read 9994 it should be adjusted to do so by turning the knurled end of the protruding depth counter adjustment knob ("A" in Figure 6) whilst at the same time disengaging the pressure wheel by pressing back the drum "B" adjacent to the depth counter.

With the probe carrier fitted onto the access tube and the probe locked, a shield count can be taken to check that the system is functioning correctly. The count rate displayed should agree reasonably with the figure stamped on the carrier housing as "Shield Count". This is not only subject to random counting error but also varies with temperature and the proximity of external objects. Also, there is inevitably some slight dimensional variability between different shields. For these reasons therefore the shield count should not be used as a standard count. The shield count should be within plus or minus 10 counts per second or thereabouts of the stated figure; this is all that should be expected. Even with a 64 second count there is always a small probability (about 2%) that the reading may be outside this limit. If this happens the measurement should be repeated several times to establish that the readings are distributed reasonably within the limits of error. If doubt remains a more comprehensive test sequence should be carried out in the water

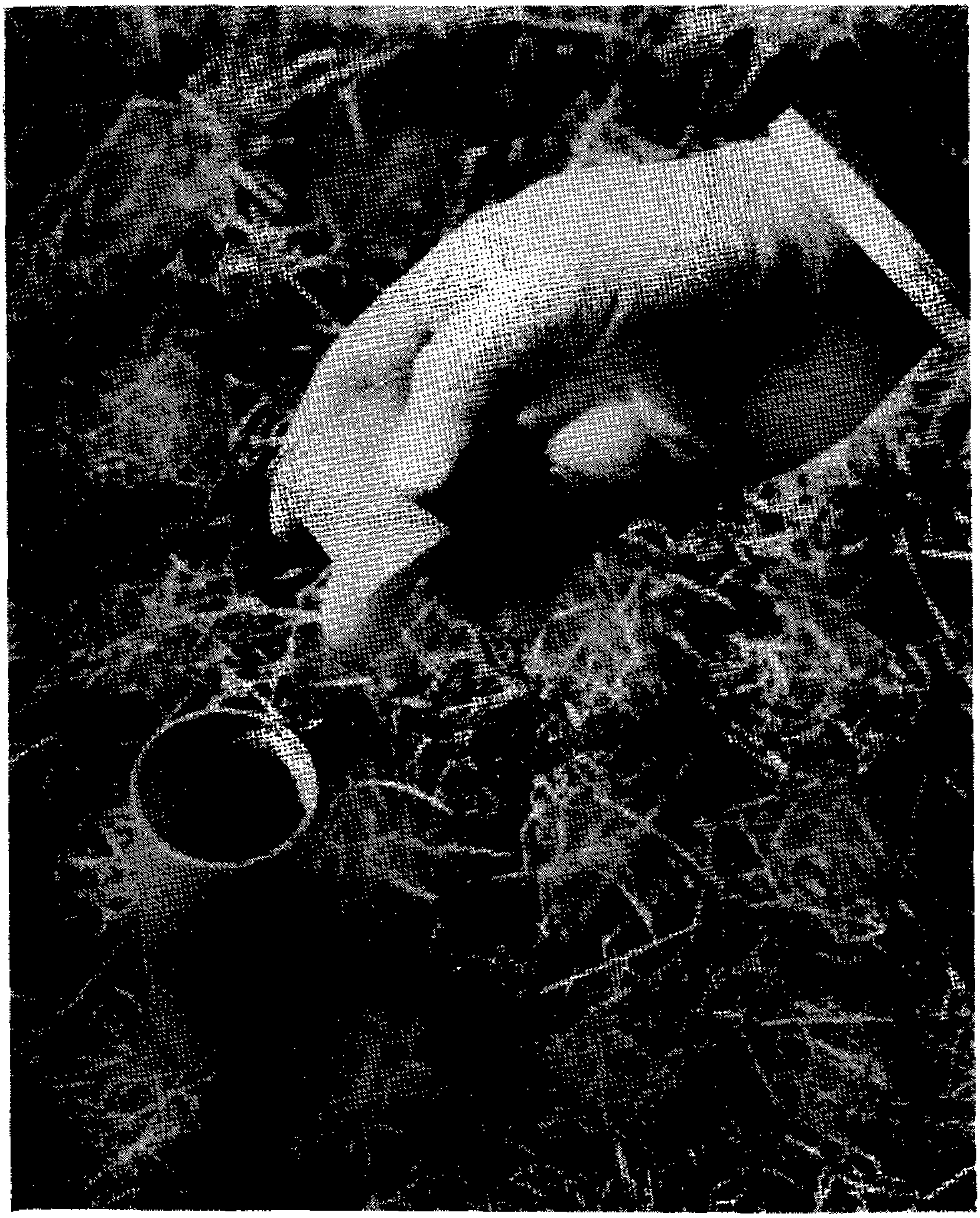


FIGURE 11 Top of access tube installed in grassland; in this case 10 cm has been left to protrude, allowing the probe carrier to be fitted into place without disturbing the grass or the soil surface.

standard and the standard deviation for a large number of repeated readings calculated and compared with the theoretical value.

The probe is unlocked from the carrier by turning the key to the horizontal position, disengaging the locking bolt from the groove in the top of the probe (Figure 5). To lower the probe into the access tube the cable should be held firmly in one hand about 50 cm vertically above the clamp aperture. The cable clamp should then be released by placing the first two fingers of the other hand over the T-shaped control bar with the thumb on the outside of the carrier, pulling back the bar until the cable runs free. The cable is then lowered steadily through the clamp until the required depth is reached. Releasing the control bar clamps the cable and holds the probe at the indicated depth. Care should be taken to lower the cable smoothly and to avoid bending it where it enters the aperture in the depth measuring gear, otherwise errors may be introduced in the depth reading. If initially the probe fails to lower, the carrier housing should be rocked gently until the probe enters the access tube. As the probe enters the tube the depth counter readings will increase from 9994 to 9999 and then to 0000. This indicates that the mid-plane of the measuring system, ie the source and detector centre, or "Centre of Sensitivity", is level with the rim of the access tube. Futher lowering will cause the reading to increase thus: 0001, 0002, 0003, etc indicating the depth in centimetres of the reading point below the access tube rim.

The probe is set at the first depth, the count time set and a reading is taken by pressing the START/STOP switch to "START" and then releasing it. At the end of the counting period the mean count rate will be displayed for eight minutes, or until START is reselected. This is repeated at each depth as required, recording depths and count rates on an appropriate field record form (Figures 12 and 13).

A count cannot be re-started while counting is in progress unless "STOP" is first selected, which turns the entire system off and removes any accumulated count from the display.

It is suggested that the first reading after the probe is switched on should be discarded as the circuitry takes a few seconds to stabilize.

It should be noted that in defining the depth of the probe below ground level, allowance should be made for the length of access tube protruding above the ground surface, ie if 20 cm of access tube protrudes and the first reading depth below ground level is (eg) 30 cm, the depth register will read 50 cm (ie 20 + 30) when the probe centre of sensitivity is at that depth.

The reading sequence may be either upwards or downwards although it is recommended that a standard procedure should be followed. The reading depths in any one tube should always be the same.

When the reading sequence is completed the probe is withdrawn into its carrier and locked. The depth register should again read 9994. If there is any unacceptable difference from this the whole sequence must be repeated, taking more care that the cable is fed vertically and smoothly through the clamp.

Before removing the carrier from the access tube the cable is wound round the cleats; it need not be disconnected as the ratescaler can be shut with the cable attached, taking care not to strain the cable where it enters the connector.

The ratescaler is hinged over into the shut position and clipped into place, the probe in its carrier is removed and the bung replaced in the access tube.

If the access tube is sited in pasture with cattle or sheep, additional precautions may be necessary to prevent the bung from being removed and lost.

DATE: 13.11.78　SOIL MOISTURE PROFILE: HKU　SITE NO: 1

PROBE: 162　RATE SCALER: 337 (Mk II E)　OPERATOR: 76

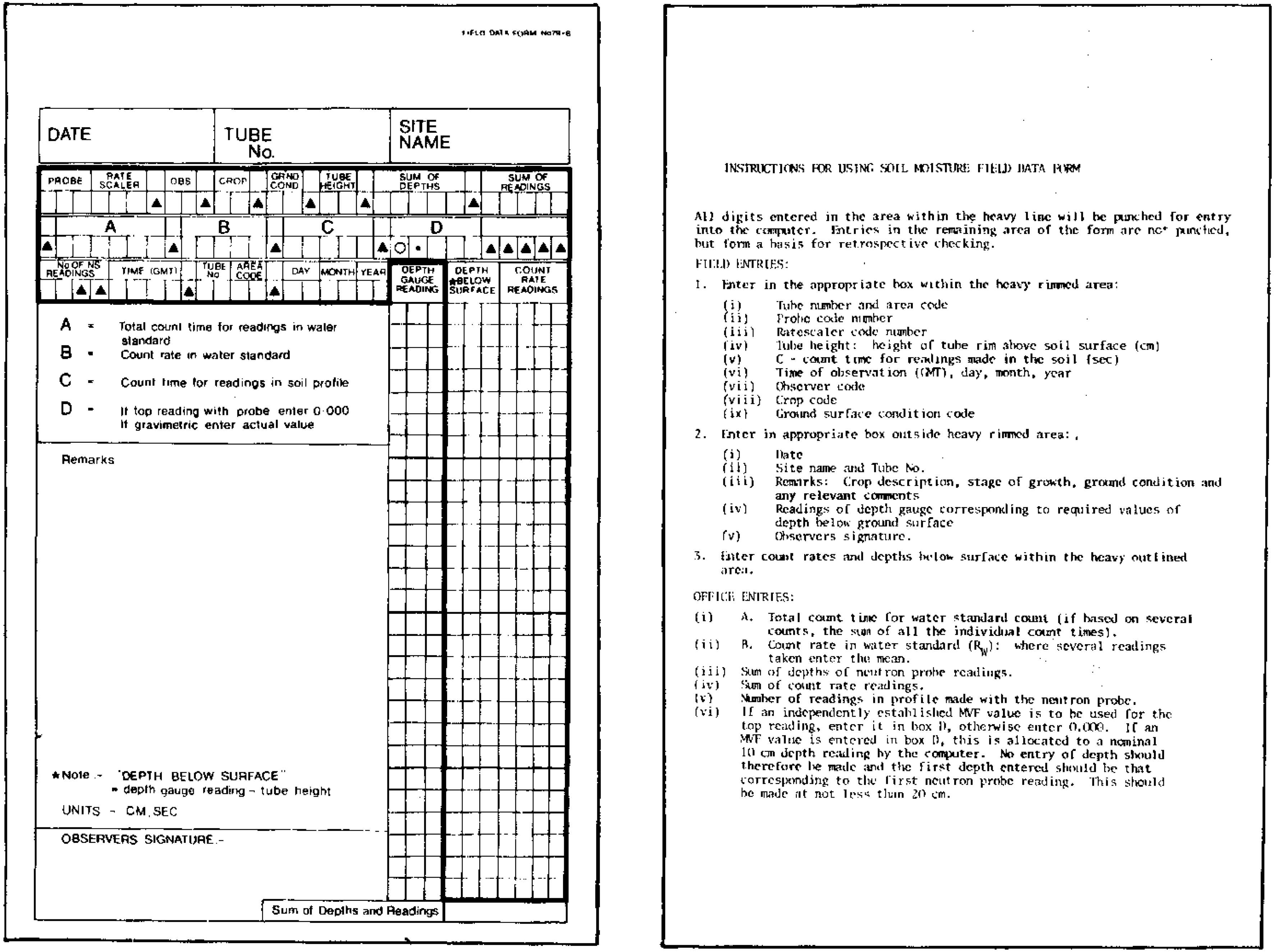
PRESET TIME FOR WATER STANDARD: 10 x 64 sec　COUNT RATE IN WATER: 964

PRESET TIME FOR SOIL: 64 sec　ACCESS TUBE HEIGHT ABOVE GROUND: 10 cm

Depth from top of tube	Depth from ground level	R	R/R_W	M.V.F. θ	Std Dev MVF	Layer Factor	Water cm	Std Dev
20	10	296	.307	.250	.002	15.0	3.75	.03
30	20	358	.371	.305	.002	10.0	3.05	.02
40	30	342	.355	.292	.002	10.0	2.92	.02
50	40	277	.287	.232	.002	10.0	2.32	.02
60	50	221	.229	.182	.002	10.0	1.82	.02
70	60	314	.326	.267	.002	10.0	2.67	.02
80	70	348	.361	.297	.002	10.0	2.97	.02
90	80	309	.321	.262	.002	10.0	2.62	.02
100	90	306	.317	.258	.002	10.0	2.58	.02
110	100	327	.339	.278	.002	10.0	2.78	.02
120	110	398	.413	.342	.002	10.0	3.42	.02
130	120	396	.411	.340	.002	10.0	3.40	.02
140	130	407	.422	.350	.002	10.0	3.50	.02
150	140	429	.445	.370	.002	10.0	3.70	.02
160	150	445	.462	.381	.002	10.0	3.81	.02
170	160	393	.408	.338	.002	10.0	3.38	.02
180	170	395	.410	.339	.002	10.0	3.39	.02
190	180	376	.390	.322	.002	10.0	3.22	.02
200	190	340	.353	.290	.002	10.0	2.90	.02
210	200	469	.487	.406	.002	10.0	4.06	.02
							61.83 ±	0.09

Calibration: $\theta = 0.865\ R/R_W - 0.016$

FIGURE 12　Example of a combined field data and processing sheet for soil moisture data to be processed manually: the final error figure (0.09) is the square root of the sum of the squares of the individual standard deviations and represents the probable error due to the random counting effect with 68% probability.



FIELD DATA FORM No78-6

DATE
TUBE No.
SITE NAME

A = Total count time for readings in water standard
B = Count rate in water standard
C = Count time for readings in soil profile
D = If top reading with probe enter 0·000
If gravimetric enter actual value

Remarks

*Note.- "DEPTH BELOW SURFACE"
= depth gauge reading - tube height

UNITS - CM, SEC

OBSERVERS SIGNATURE.-

Sum of Depths and Readings

Front side

INSTRUCTIONS FOR USING SOIL MOISTURE FIELD DATA FORM

All digits entered in the area within the heavy line will be punched for entry into the computer. Entries in the remaining area of the form are not punched, but form a basis for retrospective checking.

FIELD ENTRIES:

1. Enter in the appropriate box within the heavy rimmed area:
   - (i) Tube number and area code
   - (ii) Probe code number
   - (iii) Ratescaler code number
   - (iv) Tube height: height of tube rim above soil surface (cm)
   - (v) C - count time for readings made in the soil (sec)
   - (vi) Time of observation (GMT), day, month, year
   - (vii) Observer code
   - (viii) Crop code
   - (ix) Ground surface condition code
2. Enter in appropriate box outside heavy rimmed area:,
   - (i) Date
   - (ii) Site name and Tube No.
   - (iii) Remarks: Crop description, stage of growth, ground condition and any relevant comments
   - (iv) Readings of depth gauge corresponding to required values of depth below ground surface
   - (v) Observers signature.
3. Enter count rates and depths below surface within the heavy outlined area.

OFFICE ENTRIES:

(i) A. Total count time for water standard count (if based on several counts, the sum of all the individual count times).
(ii) B. Count rate in water standard (R_W): where several readings taken enter the mean.
(iii) Sum of depths of neutron probe readings.
(iv) Sum of count rate readings.
(v) Number of readings in profile made with the neutron probe.
(vi) If an independently established MVF value is to be used for the top reading, enter it in box D, otherwise enter 0.000. If an MVF value is entered in box D, this is allocated to a nominal 10 cm depth reading by the computer. No entry of depth should therefore be made and the first depth entered should be that corresponding to the first neutron probe reading. This should be made at not less than 20 cm.

Reverse side

FIGURE 13 Example of a field data form for use when data are processed by computer

THE STANDARD COUNT PROCEDURE

On each occasion that the probe is used in the field, either before or after use, a "standard count" R_W is taken in a water standard (Figure 14). The water standard count rate is used to "normalise" the field counts, all of which are divided by R_W.

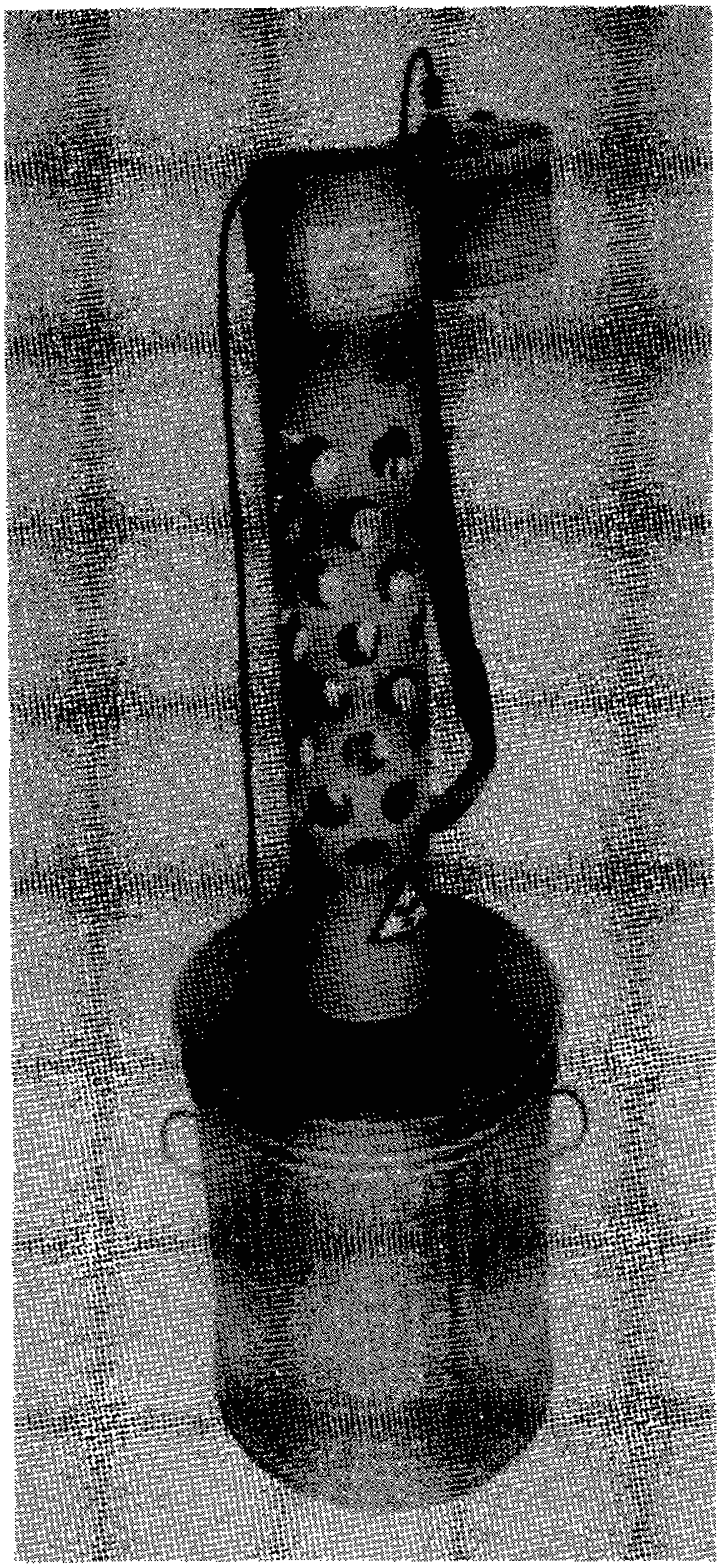


FIGURE 14

Water drum standard with the probe lowered into position for determination of the standard count rate in water, R_W

This is necessary because the probe is calibrated in terms of R/R_W against volumetric soil water content, θ, where R is the count rate in the soil (Figure 15). This procedure compensates for any electronic drift which might occur as the probe ages. It also maintains continuity of data if a different probe (of the same geometry) is used or if there is a change in the count rate response arising, for example, from repairs to the probe. If inspection of water counts for a period show no significant drift it may be considered better to use a single R_W value derived from the mean of all the R_W determinations over the period.

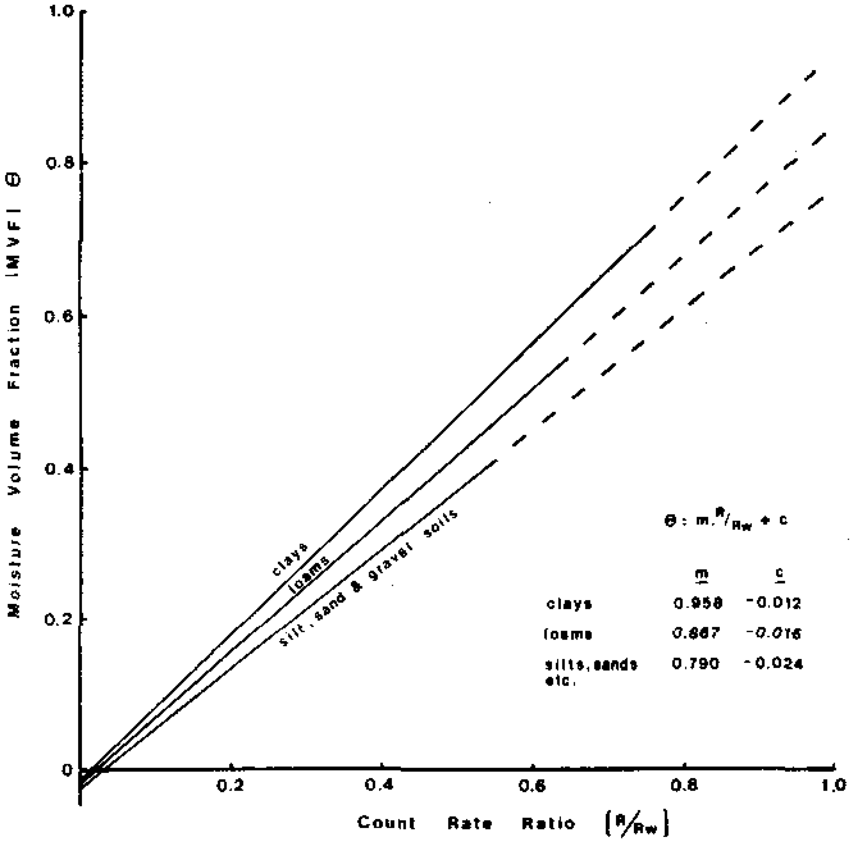


FIGURE 15 **Examples of calibration lines for the IH Neutron Probe system, showing textural dependency**

The standard count is performed with the probe suspended in an access tube placed axially in a drum of water. The drum must be sufficiently large such that the count rate produced is the same as would be produced in an infinite body of water. In practice, the minimum dimensions should be 45 cm diameter and 60 cm depth, but wider if possible. The drum may be made of any material which will not contaminate the water, such as plastic or painted steel. The probe should always be lowered to a standard depth, normally the mid-point between the water surface and the base of the drum. It should not be forgotten that the length of the access tube protruding above the water level should be added to the required depth below the water surface to define the correct depth register reading (as for reading in the soil). The optimum depth setting should be defined initially by plotting a count rate profile for the drum, ie a graph of count rate against depth below water surface (Figure 16). From this the depth corresponding to the mid-point of the plateau is defined, the plateau being the section of the curve with least variation in count rate. The drum should always be kept filled to a standard reference level and the water should be clean. In particular, no trace of neutron absorbers such as chlorine (in salt, for example) or iron (rust from the drum) should be present. The access tube should be checked to verify that it is dry internally. If there is a large diurnal or seasonal fluctuation in temperature, the drum should be kept in a place where this is minimised.

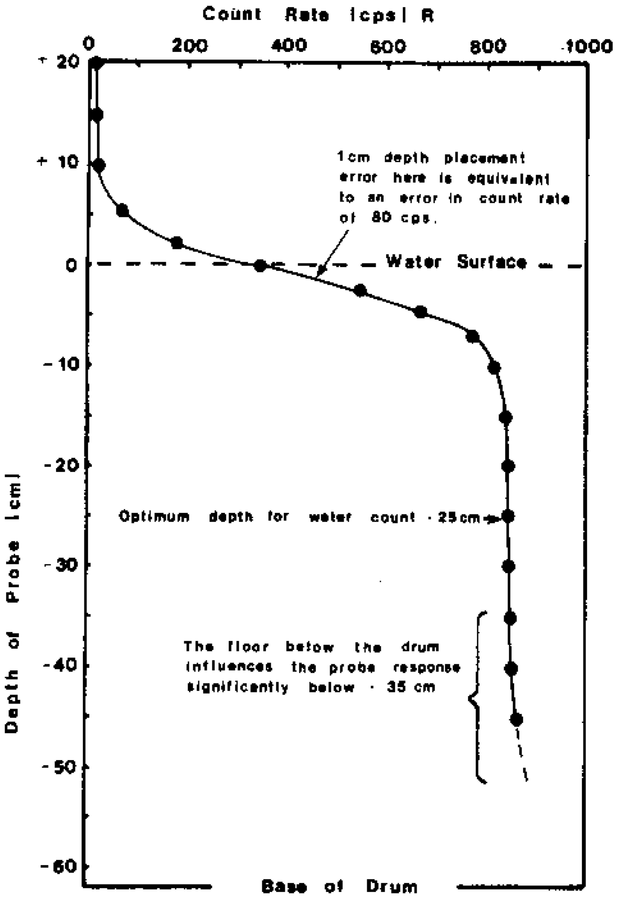


FIGURE 16

An example of a count rate profile in a water drum standard, showing the mid-point of the plateau where the reading should always be taken

For most purposes it is sufficient to take one 16 minute count, although for very precise work, a 64 minute count may be preferable. The R_W values should also be plotted on a graph which will reveal any sudden or progressive changes in the performance of the probe over a period of time. The choice of counting time used for the R_W determination is dealt with more fully in "counting statistics".

It should be noted that the polypropylene radiation shield does not, for reasons mentioned earlier, provide a satisfactory alternative to the water drum standard and should not be used for this purpose.

ACCESS TUBES AND THEIR INSTALLATION

The material for the access tubes should be selected for low neutron cross section of absorption for both fast and slow neutrons. To facilitate easy installation the material should also be mechanically strong and resistant to corrosion. For some years, the Institute of Hydrology has used aluminium alloy tubing, type HT30WP, external diameter 1¾" (44.45 mm), wall thickness 16 s.w.g. (1.63 mm). Pure aluminium has a smaller neutron cross section but is mechanically inferior. Hard drawn copper should also be quite satisfactory.

The use of stainless steel or brass tubing will result in a loss of count rate of the order of 10%, but this may be acceptable in some circumstances, as for example, in alkaline soils which corrode aluminium. Plastic tubing has been used successfully but chlorine-based plastics such as PVC have a high cross section of absorption for slow neutrons and should not be used. The hydrogen content of the plastic will introduce an increase in the count rate for which allowance must be made in the calibration. Some plastics are also liable to become very flexible at high temperatures or may tend to become brittle after prolonged exposure to sunlight.

The lower end of each tube must be sealed against entry of water with a nose cone, which also facilitates insertion into the soil. A neoprene bung should be used to seal the upper end when not in use.

Correct installation of the access tube is vital because recurrent errors can be created if the soil in contact with the access tube is unduly compressed or if the hole is too large. Ideally, the hole should be exactly the same size as the access tube but in practice a slightly tight fit is best. The installation technique recommended by the Institute of Hydrology for most soils is the guide tube method. Steel guide tubes with the same external diameter as the access tube are used to make the hole. These have at their lower end an internally bevelled cutting edge and at their upper end a reinforced head. This has holes for a tommy bar to be inserted, used when removing the guide tube. They are made in sets of 1.15 m, 2.15 m, 3.15 m, etc. and used in conjunction with augers of 1.3 m, 2.3 m and 3.3 m, etc. The auger is worked through and 15 cm ahead of the cutting edge and the guide tubes are then rammed down in 0.15 m stages in alternation with the auger. The auger removes the reamed out soil and cuts a pilot hole ahead of the guide tube. The guide tubes are used in sequence until the required depth is reached; the guide tube is then replaced by the access tube. For installations deeper than 3 or 4 m it may be an advantage to use a mechnical hammer to drive in the guide tubes and this works well even in consolidated sediments such as chalk.

MEASURING A SOIL WATER PROFILE IN THE FIELD

The procedure for using the probe is described under "Taking a reading". A series of measurements are made in each access tube at pre-determined depth intervals down the profile. The optimum depth interval is probably 10 cm and nothing is gained by making closer measurements, although in deep profiles with no steep moisture gradients it may be more efficient to increase the interval to 20 or even 30 cm.

A compromise has to be made between minimising the random error at each measured profile by taking longer and more numerous counts, and maximising the number of access tubes read in order to obtain the best estimate of the areal mean (and the variance about that mean) in the time available. Clearly the size of the area and the distance between access tubes (and hence the time spent in transferring the probe from tube to tube) are also factors in the compromise that has to be made.

Because the probe responds to slow neutrons returning from an indefinite volume, known as the "sphere of influence", the measurement obtained is not a point measurement. Most of the counts are generated within 10-15 cm of the source (farther in very dry soils) so that readings spaced at depth intervals of 10 cm tend to form a smoothed version of the true soil moisture profile. The area beneath the profile curve so defined represents the total water in the profile between the surface and the depth of the lowest measurement (eg Figure 2 and Figure 16). Where a sharp interface occurs, as between soil layers of different moisture content, the introduction of small errors is unavoidable. The worst such case is the soil/air interface at the soil surface, which greatly affects readings taken in the surface layer. Neutrons are lost from the soil when the probe is within about 25 cm of the surface (35 cm for dry soils) and the normal calibration curve no longer applies. Various ways round this problem have been used, including the use of "reflectors", "surface extension trays" and special calibration curves. None of these are entirely satisfactory and this is a major limitation of the neutron probe principle. Probably the best solution is the use of a specially derived calibration line for a specific depth below the surface, for example 10 cm (and perhaps also 20 cm in dry sandy soils). Because the count rate gradient is so steep across the interface, small depth location errors in the surface layer create large count rate errors. Further errors will arise from differences in distribution of water in this layer. For example, a given amount of water in the top 20 cm immediately after rain, when most of the water will be in the top 5 cm, may give a different count rate some hours later when the same water has infiltrated to the base of the layer. Thus, the data in time series will be more "noisy" for the surface layer than for deeper measurements, but if the special calibration is correct there should be no bias in the surface layer readings.

For most soils the use of a single calibration for all depths below 20 cm is justifiable, but in strongly layered soils such as, for example, a podzol or a clay loam overlying a gravel, the use of different calibration curves for each principal soil layer may be necessary.

Where only a modest amount of data is being collected and processed, computation by means of a simple programmable calculator is probably quickest and simplest. The recording of data in the field and its processing may be combined into a single field/analysis sheet, an example of which is shown in Figure 12. Because there is overlap of the sphere of influence of successive measurements, a smoother profile is produced, rather analogous to a running mean. The area under this curve represents the total profile water content and the simplest way to calculate this is to assume that each reading represents a layer of soil extending to the half interval between the measurements above and below. The thickness of each layer so defined, multiplied by its moisture volume fraction, gives the water content of that layer expressed as a depth of water. The sum of the individual layer water contents is the water content of the entire profile.

Organisations which have access to a computer and who produce large quantitities of soil moisture data on a routine basis might wish to quality control and process their data by computer and store them in a data bank for various forms of analysis. Listings of the processed data in various forms and graphs are then easily obtainable. An example of a field data form suitable for this purpose is shown in Figure 13. Data are punched directly from this form, thus avoiding the need for transcription.

CALIBRATION

The count rate of the probe, R, is linearly related to the volumetric water content of the soil, θ.

The slow neutron flux detected by the BF_3 tube and represented by the count rate is generated primarily by collisions between neutrons and the nuclei of hydrogen in the soil, this mainly in the form of water. The wetter the soil the greater the chance of collisions near to the detector and hence the greater the probability of slow neutrons entering the detector. Hence, the count rate is proportional to the soil water content. However, every element present in the soil matrix has some scattering and absorbing properties for neutrons which, although individually much less than those of hydrogen, together influence the count rate to an extent that cannot be ignored. Every soil therefore has, in theory at least, a unique calibration curve. In practice however, unless strong neutron absorbers such as cadmium, boron, chlorine (and iron to a much lesser extent) are present in the soil, the calibration line is unlikely to fall outside the envelope provided by the lines given below for clay and sand. The required precision in terms of moisture change must be considered by the intending user when deciding how much attention should be devoted to calibration and, indeed, whether or not it is necessary to calibrate at all.

The calibration relationship between count rate and volumetric water content is reasonably represented by a straight line equation of the form:

$$\theta = m.{}^{R}/R_W + c$$

where θ = the volumetric water content of the soil expressed as a fraction, ie volume of water per volume of soil (moisture volume fraction: MVF)

m = the gradient of the line

R = count rate in soil (counts per second)

R_W = count rate in the water standard (c.p.s.)

c = the intercept on the moisture axis (the y axis).

Three typical calibration lines are shown in Figure 15, the equations for these lines are:

sandy, silty or gravelly soils (ie predominantly silica)	$\theta = 0.790\ {}^{R}/R_W - 0.024$
loams	$\theta = 0.867\ {}^{R}/R_W - 0.016$
clay soils (also peat)	$\theta = 0.958\ {}^{R}/R_W - 0.012$

For most purposes it is the <u>change</u> in water content between successive time intervals that is required and it is therefore only the <u>gradient</u> of the calibration line that is important. Very little error will result from the adoption of the nearest relevant of the above three lines, or some intermediate compromise. This is likely to result in less error that in attempting to perform special calibrations which, unless very carefully performed, are likely to introduce a greater error.

If, however, good absolute accuracy is necessary, as for example if the data are being used to measure *in situ* the unsaturated hydraulic conductivity or moisture release characteristics, a full calibration procedure may be unavoidable. Either a field calibration or laboratory calibration may be performed, depending on circumstances.

A field calibration is done by taking known-volume soil cores from around the counting depths in temporary access tubes near to the permanent tube (Figure 17). The mean moisture content of each set of cores (usually 6), determined gravimetrically by oven drying, is plotted against $^R/R_W$ to obtain a point on the calibration graph. A number of such points are obtained over the seasonal range of water change for each soil type and the equation of each calibration curve is then established by means of a regression calculation.

FIGURE 17

Removing one of six known-volume cores from around a temporary access tube in which, prior to the coring, a precise count has been taken at a depth corresponding to the mid-point of the set of cores.

To perform such a calibration properly is an exacting, time consuming and expensive procedure and should not be undertaken unless essential.

A laboratory calibration is performed on a large sample of the soil which is dried, mixed and packed into a large drum to its original bulk density. The drum must be at least 1 m deep and 1.5 m in diameter to give a valid result. An access tube is inserted in the centre of the drum and count rates determined, first in the dry soil and subsequently in the same soil saturated with a measured volume of water. Two accurate calibration points are thus derived and these are joined with a straight line on the assumption that any non-linearity is negligible. This method is only suitable for soils which are reasonably homogeneous and can also be repacked to their original dry bulk density. Sands and gravels usually satisfy these criteria and clay soils do not.

COUNTING STATISTICS

The emission of neutrons and their collisions with various atomic nuclei are random in time and this means that repeated determinations at the same point in the soil or water standard will vary in a random way about the true mean count rate. The distribution of individual estimates of mean count rate (as determined by the ratescaler) about the true mean count rate is given by the standard deviation, σ_R.

$$\sigma_R = \sqrt{\frac{R}{t}}$$

From this expression it can be seen (for example) that by quadrupling the count time the standard deviation is halved. Thus, the count time determines the precision of the measurement. It also follows that σ_R is larger in wetter soils because R is larger and hence that a longer count time is required in a wet soil to give the same absolute precision of measurement as for a drier soil.

A choice of four counting times is offered with the MK IIL ratescaler, but intermediate or longer times can be obtained by averaging a number, n, of replicate determinations of count rate, $\bar{R}$, each of counting time, t, ie:

$$\sigma_R = \sqrt{\frac{\bar{R}}{n.t}}$$

Expressed in terms of soil moisture, θ, this expression becomes:

$$\sigma_\theta = g\sqrt{\frac{R}{t}} \quad \text{or} \quad \sqrt{\frac{g\theta}{t}}$$

where g is the gradient of the calibration curve $^{d\theta}/dR$. (The inverse of this, $^{dR}/d\theta$, is known as the "sensitivity" of the probe). The standard deviation of the water standard count R_W must also be included in the equation which now becomes:

$$\sigma_\theta = m.\frac{R}{R_W}\left\{\frac{1}{R.t} + \frac{1}{R_W t_W}\right\}^{\frac{1}{2}}$$

where m is the gradient of the calibration line, $^{d\theta}/d(^{R}/R_W)$.

For example, if $m = 0.790$

$R = 500$ c.p.s.

$R_W = 950$ c.p.s. (the mean of ten 64 sec counts)

$t = 64$ sec

$t_W = 640$ sec (ie 10 x 64 sec)

then $\sigma_\theta = 0.002$ MVF (0.2% on a volume percentage basis)

ie there is a 68% probability that any individual determination will be within 0.002 moisture volume fraction of the true moisture content. For 95% probability the error is doubled and for 99% probability it is trebled.

This probable error excludes other sources of error which might arise from probe location, temperature, probe malfunction, etc.

From the foregoing equations it may be seen that the only control which the operator has on the random counting error is through the selection of the appropriate counting time for determining both R and R_W. It is particularly important to minimise the random counting error attached to R_W because one R_W value is involved in many $^R/R_W$ values, all of which will be biased by any error in R_W.

RADIOLOGICAL SAFETY

It is important not to over-emphasise the health hazards involved in the use of a neutron probe. The radiation level received is very low indeed provided that the probe is used, carried, transported and stored in full accordance with the various regulations and codes of practice.

As an example of the radiation levels emerging from the IH II probe with a 50 mCi Americium-Beryllium source, the maximum total dose rate at the surface of the shield is approximately 3 mrem/hr. This figure was measured at the Institute of Hydrology by the National Radiological Protection Board, the gamma and neutron monitors being held in contact with the shield as close to the source as possible. When the monitors were held in contact with the unshielded probe (and therefore 7.5 cm nearer the source), they gave a dose rate of 23 mrems/hr. These figures are quoted as correct to within a factor of 2. The figures for probes containing larger or smaller sources will be in proportion to those given above.

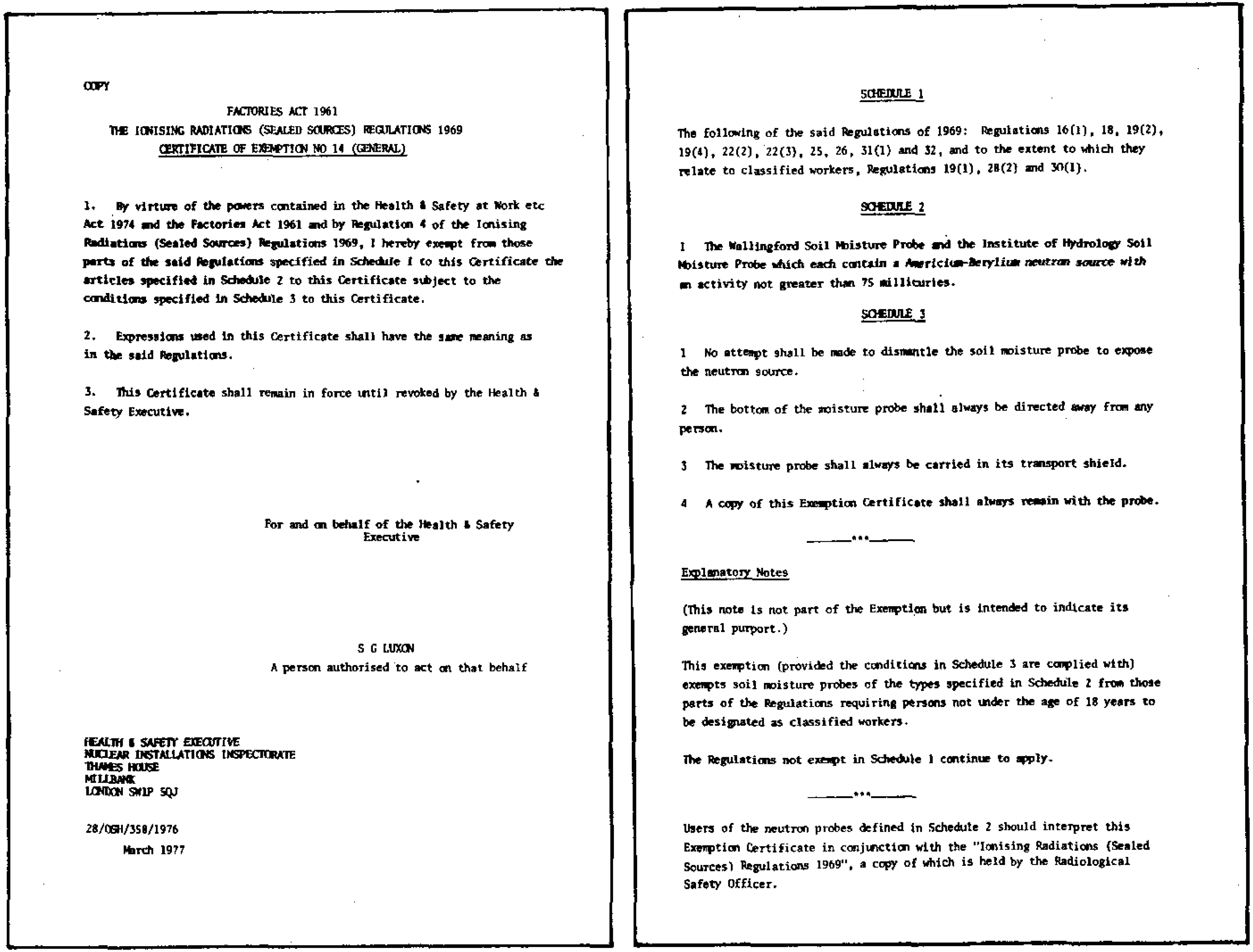
It is essential that owners and users of neutron probes are fully acquainted with the numerous regulations governing their use, storage and transport.

The regulations, in essence, have four objectives:

- to prevent loss of the source
- to prevent breakage and leakage of the source
- to prevent persons not involved with the use of the probe from being exposed to radiation levels exceeding 0.75 mrem/hr
- to prevent probe users from receiving more than a known, controlled and acceptable level of radiation.

The main difficulty arises in extracting from the all-embracing regulations those which are of relevance to neutron probe users. Once this has been achieved the situation is then much simpler. It is further simplified for users of the Institute of Hydrology Neutron Probe System because an Exemption Certificate (Figure 18) for this design has been issued by the Health and Safety Executive which exempts the user, subject to a few simple constraints, from the necessity to be a classified radiation worker. This means that under normal conditions of use there is no legal requirement for the wearing of film badges, medical examinations, the keeping and transferring of dose records, etc. In certain circumstances of use it may also be necessary to apply for an "approved scheme of work" from HM District Inspector of Factories, whose advice must always be sought before the neutron probe is acquired.

Relevant laws and regulations controlling the use of radioactive substances in the UK are:



COPY

FACTORIES ACT 1961
THE IONISING RADIATIONS (SEALED SOURCES) REGULATIONS 1969
CERTIFICATE OF EXEMPTION NO 14 (GENERAL)

1. By virtue of the powers contained in the Health & Safety at Work etc Act 1974 and the Factories Act 1961 and by Regulation 4 of the Ionising Radiations (Sealed Sources) Regulations 1969, I hereby exempt from those parts of the said Regulations specified in Schedule 1 to this Certificate the articles specified in Schedule 2 to this Certificate subject to the conditions specified in Schedule 3 to this Certificate.

2. Expressions used in this Certificate shall have the same meaning as in the said Regulations.

3. This Certificate shall remain in force until revoked by the Health & Safety Executive.

For and on behalf of the Health & Safety
Executive

S G LUXON
A person authorised to act on that behalf

HEALTH & SAFETY EXECUTIVE
NUCLEAR INSTALLATIONS INSPECTORATE
THAMES HOUSE
MILLBANK
LONDON SW1P 3QJ

28/OSH/358/1976
March 1977

SCHEDULE 1

The following of the said Regulations of 1969: Regulations 16(1), 18, 19(2), 19(4), 22(2), 22(3), 25, 26, 31(1) and 32, and to the extent to which they relate to classified workers, Regulations 19(1), 28(2) and 30(1).

SCHEDULE 2

1 The Wallingford Soil Moisture Probe and the Institute of Hydrology Soil Moisture Probe which each contain a Americium-Berylium neutron source with an activity not greater than 75 millicuries.

SCHEDULE 3

1 No attempt shall be made to dismantle the soil moisture probe to expose the neutron source.

2 The bottom of the moisture probe shall always be directed away from any person.

3 The moisture probe shall always be carried in its transport shield.

4 A copy of this Exemption Certificate shall always remain with the probe.

***

Explanatory Notes

(This note is not part of the Exemption but is intended to indicate its general purport.)

This exemption (provided the conditions in Schedule 3 are complied with) exempts soil moisture probes of the types specified in Schedule 2 from those parts of the Regulations requiring persons not under the age of 18 years to be designated as classified workers.

The Regulations not exempt in Schedule 1 continue to apply.

***

Users of the neutron probes defined in Schedule 2 should interpret this Exemption Certificate in conjunction with the "Ionising Radiations (Sealed Sources) Regulations 1969", a copy of which is held by the Radiological Safety Officer.

FIGURE 18 Copy of certificate of exemption No. 14, issued by the Health and Safety Executive

"The Health and Safety at Work Act 1975" *HMSO*

"The Ionising Radiations (Sealed Sources) Regulations 1969:
No. 808 - Factories" *HMSO*
This covers requirements under the Factories Act.

"The Radioactive Substances (carriage by road) (Great Britain)
Regulations 1974 No. 1735" *HMSO*

"The Radioactive Substances Act 1960" *HMSO*

These documents are interpreted and explained more fully in:

"The Radioactive Substances Act 1960 - An explanatory memorandum for persons keeping or using radioactive materials" *HMSO*

"Code of Practice for the protection of persons exposed to Ionising Radiations in Research and Teaching" *HMSO*

Users outside the UK should seek advice in their own country as to the relevant regulations. Advice may also be sought from the International Atomic Energy Agency, Kartner Ring 11, P O Box 590, A-1011 Vienna, Austria. For users in the UK, advice may be sought from the Department of the Environment and from the National Radiological Protection Board, Harwell, Didcot, Oxfordshire.

It should be noted that it is a requirement of the 1960 Act (Section 3) that radioactive material must not be kept on any premises without prior authorisation. Before the probe is acquired, application must be made for registration as a source holder on Form RSA2 to the appropriate address, as below:

Wales
Welsh Office
Pearl Assurance House
Greyfriars Road
CARDIFF CF1 3RT   0222-44151

England
Department of the Environment
Beckett House
Lambeth Palace Road
LONDON SE1   01-211-3000

Scotland
HM Industrial Pollution Inspectorate
for Scotland
Pentland House
47 Robb's Loan
EDINBURGH EH14 1TY   031-443-8681

N. Ireland
Department of the Environment for
N Ireland
Parliament Buildings
Alkali & Radiochemical Inspectorate
Stormont 4
BELFAST BT4 3SS   Belfast 63210

The 1975 Act defines the responsibilities of both the supplier and the user under that Act. The user is responsible for safe storage and use; the Didcot Instrument Company is responsbile for supplying the user with sufficient information for him to comply with the Act.

The user is also obliged by law to have the source tested for leakage - the so-called "wipe test" - at intervals of not more than two years. The Didcot Instrument Compan will advise users in the UK as to how this requirement may be met.

The X20 source capsule, Capsule Design No GB/SFC/29, used in the probe qualifies as "special form radioactive material" and conforms to specifications listed under reference HS 5002/2/SFC 29 of 24 June 1969. The certificate is issued by the Radiological Adviser of the Department of Transport, St Christopher House, Southwark Street, London SE1. Copies of the certificate are required if the probe is exported by air from the UK.

The probe should be carried in the field in a horizontal position by means of the shoulder strap (Figure 1), the source to the rear, using the forearm on the same side to steady the probe. Other persons should not be permitted to approach within 0.6 m of the source end of the carrier. The probe should not be removed from its carrier other than when it is lowered directly into the access tube. The source should not be removed from the probe other than by an authorised "classified radiation worker" who must take full precautions to prevent its loss and to preclude the possibility of unsuspecting persons approaching within a distance (about 0.6 m) such that they could receive a dose of more than 0.75 mrem/hr.

The probe should never be left unattended.

The user and his helpers should always attempt to minimise the time that they are within 0.6 m of the probe, although closer contact is unavoidable when the probe is being carried and manipulated. Such brief exposure is quite acceptable providing that the user does not become progressively careless when using the instrument.

The probe (in its carrier) may be stored vertically or horizontally, either in a locked room prominently marked on its door with the radiological trefoil sign and the words "DANGER - RADIOACTIVITY", or in a locked box or cupboard similarly marked. In the latter case the room need not be locked providing that the radiation at the outside of the cupboard does not exceed 0.75 mrem/hr, ie the probe source should be at least 0.6 m away from any external surface of the cupboard.

SPECIFICATIONS

Probe

Weight	:	1.63 kg
Dimensions	:	Overall length 75 cm Diameter 3.8 cm Centre of sensitivity 10 cm ± 1 mm from bottom of probe case
Neutron source	:	50 mCi (nominal). Am 241-Be sealed, annular "special form source" Code AMNK595 Intensity : 1.54×10^5 N/sec 3-10 Mev Background 0.175 mR/hour at a radius of 1 m when unshielded
Detector	:	Enriched Boron Trifluoride Proportional Counter Type : 20th Century 12EB70G Operating voltage 2-3 KV range
D.C. Input voltage	:	9V - 15V via 43 ohms load resistor (probe case negative)
Output	:	2 µS pulses across load resistor in series with positive supply terminal. Pulse amplitude = (supply voltage - 1) volts. NB: the 43 ohms load resistor is normally fitted into the waterproof 3-way socket at ratescaler end of cable. The probe is actually a two terminal device but has been modified to operate via a 3-core tri-axial cable. Operation of probe without a load resistor will destroy output transistor.
Connector	:	A.B. Electronics Brass Mk 4 3-pin plug (Coded 1) Type SB4 BS 3PXO/RF
Typical count rates	:	Air 8 c.p.s. Water 1000 c.p.s. (This varies as individual sources vary somewhat in strength)
Sealing	:	Hermetic

The Probe Carrier

Weight : 6 kg

Dimensions : Length 93 cm
Diameter 16 cm (20 cm overall, including hinge, etc.)

Access tube socket : 45 mm diameter, 38 mm depth

Radiation shield/moderator : 6" diameter polypropylene sphere bored through and fitted with an internal brass liner which also acts as an access tube stop

Depth monitoring counter : This has a ball-bearing mounted fluted stainless steel drum of 10 cm perimeter, driving a nylon drum revolution counter. A spring-loaded ball-bearing mounted wheel pinches the cable against the fluted drum which then rotates as the cable moves. The system is simple and accurate in use provided that the cable is not so jerked as to cause slip.

Cable clamp : This is a flat-ended, spring-loaded stainless steel bolt, the serrated face of which grips the cable against the flat wall of the cable guide. It is controlled with a lever having a 3 to 1 mechanical advantage and is easy to use with either hand.

Probe lock : This is a cam action flat bolt 3 mm thick and 15 mm wide which slides into a groove in the top end of the probe, locking it positively in the probe carrier when the key is turned. The key can only be removed when the probe is correctly located and locked.

Liquid Crystal Display Ratescaler Mk IIL

This instrument is watertight and is tested by immersion in water at 55°C.

Weight : 1.9 kg

Dimensions : Height 8.5 cm
Diameter 16.5 cm

Preset counting times : 16 or 64 minutes or seconds, controlled by a quartz crystal clock

Display : 4 digit, 7 segment, numeric liquid crystal, reading to 9999 counts per second whilst the count period is 16 or 64 minutes. A colon (00:00) will be displayed if the battery is low. The reading will display for 8 minutes, then the ratescaler and probe will automatically turn off unless previously re-started.

Audio signals : A sounder emits a 1024 Hz bleep twice per second at the completion of the count period. A 512 Hz continuous tone will sound if the battery is low.

Battery : 4 cells, either 1.2 V 2AH NiCd rechargeable or 1.5 V U11 type dry cells (preferably managanese alkaline) in an integral sealed compartment. NiCd cells may be recharged via the small BNC connector on the front panel via the cable provided.

External power : A 6 V (± 1 V) external power supply may be connected via the charging socket; the internal batteries must be removed if this is done.

Current consumption : 150 mA at 4.8 V (including probe)

Supply voltage : 4.5 to 6.5 V. The low voltage warnings will occur when the battery falls below 4.5 V. Below 4 V the instrument will cease to function.

Connector : A.B. Electronics Brass Mk 4 3-pin plug (Coded 1) Type SB4 BS 3 PXO/RF

Compatibility : The L.C.D. ratescaler is compatible with all type IH II neutron probes but not with the earlier 'Wallingford' probe manufactured by D. A. Pitman Ltd.

Battery Charger : As supplied: see separate specification

Battery Charging : For NiCd cells as supplied : 500 mA for 2¼ hours for fully discharged cells. For partially discharged cells, charge at 200 mA max. for up to 14 hours; longer charging at this rate will not cause damage. Do not attempt to recharge dry cells.

Cable

Weight : 0.68 kg

Length : 5 m standard. Other lengths to order.

Diameter : 6 mm

Type : Amphenol triaxial cable

Connector : A.B. Electronics Brass Mk 4 free socket
Type SB4 BS 3SEO
(Probe end coded 1 and marked with a red band)

Sealing : Two-component cold setting silicone rubber

<u>Transport case</u>

Weight : 21.5 kg

Dimensions : Length 116 cm
Depth 29 cm
Width 35 cm

<u>Weight of complete system</u>

Probe carrier, probe, ratescaler and cable 10.5 kg

<u>Overall length</u>

Length of probe carrier fitted with Mk IIL ratescaler 100 cm

<u>Note:</u> Any of the above specifications may be changed by the manufacturer at any time, without notice.