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THE USE OF GYPSUM RESISTANCE BLOCKS FOR MEASURING SOIL WATER POTENTIAL IN THE FIELD

by

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ABSTRACT

This Report describes the calibration and installation of commercially available gypsum resistance blocks for the field measurement of soil water potential in the range -0.4 to -15 bars. The use of ceramic pressure plate apparatus for calibration is described in detail. A method of temperature correction is described, and data handling, errors and interpretation are discussed. Providing blocks are individually calibrated and temperature corrected, soil water potential can be measured to, at best, 10% of a nominal matric potential in the working range. Block construction and design aspects are not disucssed in detail.

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1 INTRODUCTION

There are several methods available for measuring soil water potential, as reviewed, for example, by Marshall and Holmes (1979). Ceramic cup tensiometers are used in the range 0 to -0.8 bars (Richards, 1965; Webster, 1966) and thermocouple pyschrometers in the range -2 to -60 bars (Rawlins, 1976). However, measurements in the range -0.8 to -2 bars are not possible by either method but are important in many applications. Two methods are available for use in this range, the gypsum resistance block and the heat dissipation diode (Phene *et al.*, 1971). The latter were very expensive until recently (see Appendix A1). Gypsum blocks are cheap but suffer from a number of disadvantages which limit their usefulness, as discussed in this report.

History

The electrical resistance of a soil will change when the water content changes. The soil water, which will contain solutes, is much more conductive than the soil solids. Whitney *et al.* (1897) first suggested measuring the electrical resistance of soil to measure its water content. Because the potential of soil water also changes with soil water content, it is possible in principle to measure soil water potential from soil electrical resistance. Because of the inherent variability of all soil properties, it is better to measure the resistance of a porous block in hydraulic contact with the soil. Such a block is called a resistance block tensiometer, and consists of two electrodes separated by a porous material. The water content, and hence electrical resistance, of a block varies with its water potential, which tends to maintain equilibrium with the water potential of the surrounding soil. Variations in water content of the porous material also result in variations in its electrical capacitance, and it is possible to calibrate a block to relate either its resistance or its capacitance to its water potential, and hence the water potential of the soil with which it is in contact.

Block construction and its development

Methods of block construction are not discussed in this report. Recipes for making blocks have been published by Pereira (1951) and Fourt and Hinson (1970). We have used two types of commercially available blocks, made by the Soilmoisture Equipment Corporation, California, USA (SMEC), and by Beckman Instruments Inc., New Jersey, USA.

A number of different electrode materials, electrode shapes and porous materials have been tried (Bouyoucos and Mick, 1941; Taylor *et al.*, 1961). The electrodes are normally made of a metal, either single wire or wire mesh, (Bouyoucos and Mick, 1940), usually stainless steel, although other metals, e.g. silver coated with graphite (Fourt and Hinson, 1970) have been tried. Various electrode configurations have also been tried (Pereira, 1961; Taylor et *al.*, 1961) but parallel rectangular and concentric cylindrical are the most popular, as shown in Figure 1.

Bouyoucos and Mick (1940) first suggested using gypsum as the porous material. Bouyoucos (1953) and Fourt and Hinson (1970) reinforced the gypsum with nylon, by immersing the finished blocks in an alcoholic nylon solution. Other porous materials have been tried, e.g. nylon fabric (Bouyoucos, 1949; Farbrother, 1957; Verplancke and Hartmann, 1969) and fibre-glass (Colman, 1946). Other workers have tried such instruments and measured their electrical capacitance (Anderson

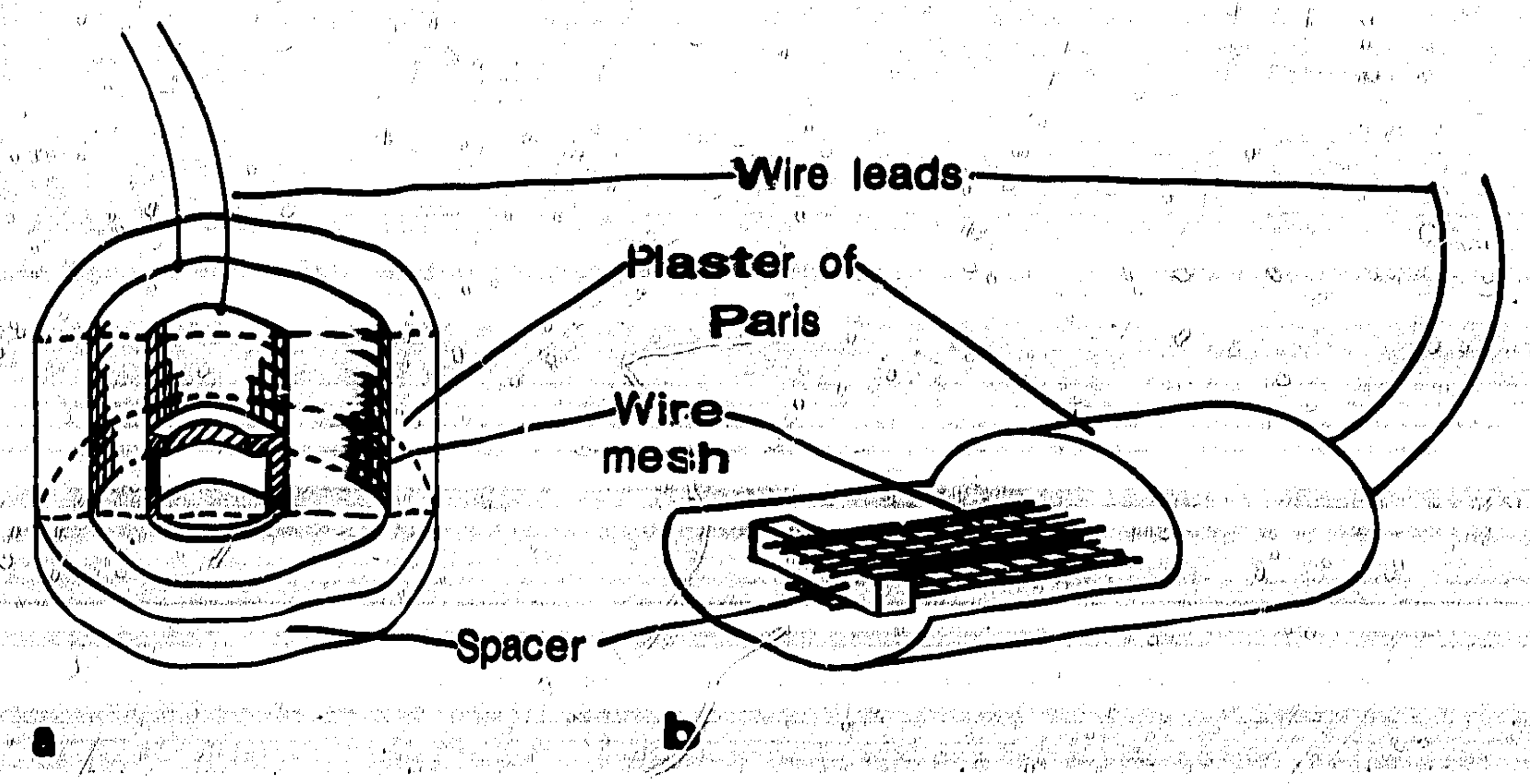


FIGURE 1 Cutaway diagram of two types of gypsum block tensiometer. a. Concentric cylindrical electrode. b. Parallel rectangular electrode.

and Edlefson, 1942). Most progress has been made using measurements of block resistance, however. Gypsum is preferred for the block material because it can be cast easily into any shape, and it has the advantage that the water in the block is always saturated with calcium sulphate. At 20°C this has a solubility of approximately 1000 mg l^{-1}. In temperate non-saline soils the total concentration of inorganic ions is likely to be less than a tenth of this. The gypsum thus buffers the electrical conductivity of the water in the block against changes in soil solution concentrations. In soils of low pH, gypsum dissolves rapidly. In saline soils the salts present would decrease block resistance. Correcting for this is likely to be difficult (Aitchison *et al.*, 1951).

Aitchison *et al.* (1951) reported their procedures for calibrating blocks, field installation and correcting resistance values for temperature. Only detailed improvements have been made since then. Greater advances have occurred in measuring the resistance using modern electronics, e.g. Schlub and Maine (1979), Goltz *et al.* (1981) and a new method suitable for automatic use with magnetic tape cassette data loggers was described by Strangeways (1983). Another method for both manual use or with solid state data loggers is described below.

Measurement of soil water content or potential

Gypsum blocks have been used to measure both water content and potential. For example, Kelly *et al.* (1946) used them to measure water content to control irrigation; Cary and Fisher (1983) used them to measure water potential to control irrigation. Knapp *et al.* (1952) measured water contents beneath natural forest, and Binns *et al.* (1965) beneath forest plantation. Davy and Taylor (1974) and Herbel and Gile (1973) measured potentials beneath natural vegetation, and Wellings and Bell (1980) beneath grass and cereal crops.

Most of the development work on resistance block tensiometers was done between 1935 and 1955. They have fallen out of favour in the past 20 years due to a tendency to confuse their poor performance as water content sensors with their much better performance for measuring soil water potential. While resistance blocks can in many conditions provide a good measurement of soil water potential, their use for measuring soil water *content* is only semi-quantitative due to the hysteresis of the relationship between water content and potential of the soil and of the block itself, and the spatial variability of soil water content. However, provided that blocks are individually calibrated on a drying cycle, and used for potential measurements only during drying, quite accurate measurements of potential can be obtained. For example, Wellings and Bell (1980) used them to measure total potential gradients in a study of water movement in unsaturated Chalk, to define the position of the zero flux plane (Arya *et al.*, 1975; Wellings and Bell, 1982). Most of these measurements were during the drying cycle; those made during the wetting cycle were regarded only as approximate.

The working range of potential

The relationship between water potential and block resistance is shown by Figure 2. Data are shown for two types of gypsum blocks, the SMEC (concentric clyindrical electrodes, No. 1) and Forestry Commission (parallel rectangular electrodes, (Fourt and Hinson, 1970); Nos. 2 and 3), at eight pressures in a ceramic pressure plate apparatus. If the relationship between resistance and water potential can be expressed by equation 3 (q.v.) then the working range of a block is where the curves of Figure 2 are closest to a straight line. The upper limit of potential varies between -0.4 and -0.8 bars, and the lower limit about -10 bars. Their use is best restricted to the range -0.7 to -10 bars. At high matric potentials the sensitivity rapidly decreases as the potential rises to saturation (Figure 2). Matric potentials are expressed as cm water head but as other units are sometimes used, conversion factors are given in Appendix A2. While not conforming to the practice of using S.I. units, the use of these units is most useful for soil hydrophysical purposes.

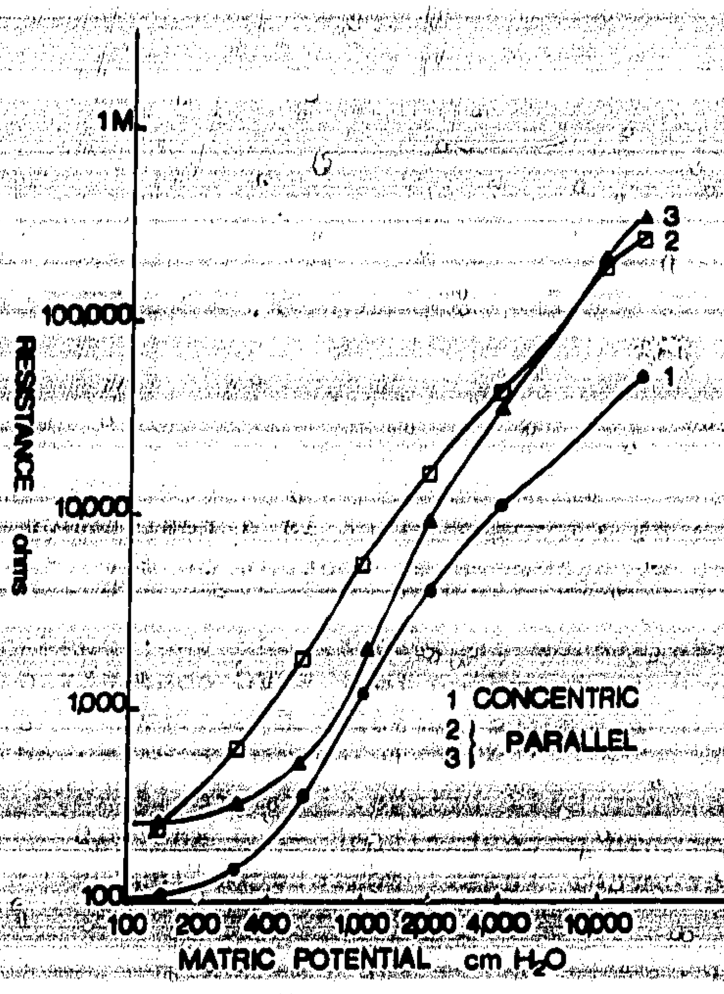


FIGURE 2

Relationship between resistance and matric potential at eight potentials for blocks with two types of electrodes

The slope of the log resistance versus log potential curve varies considerably between blocks, as shown in Figure 3, in which three-point calibration curves for twelve Soilmoisture Equipment Corp. blocks are given. Taylor *et al.* (1961) also found a similar variation. Because of this variation, blocks have to be individually calibrated for quantitative work. Although the calibration is more or less described by equation 3 for most blocks, some behave differently and must be discarded.

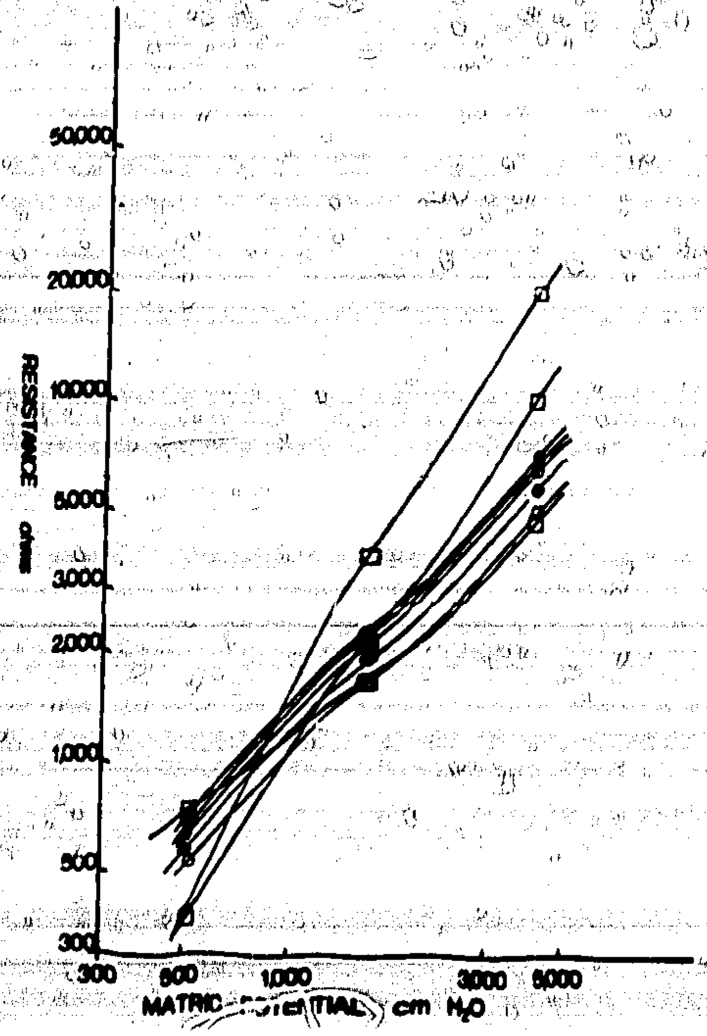


FIGURE 3

Variation of the slope of the log resistance versus log potential in a three-point calibration of eight blocks

2 MEASUREMENT OF BLOCK RESISTANCE

A useful, though not exact, electrical analogue of a gypsum block is a resistance and capacitance in parallel, both of which vary with the water content of the block. As the water potential of the surrounding soil decreases, the water potential of the block also decreases; the block resistance increases, and the capacitance decreases. This is shown by Figures 4 and 5, in which four SMEC concentric electrode gypsum blocks were placed in a ceramic pressure vessel and allowed to equilibriate at different pressures. Resistance and capacitance were measured simultaneously and independently with a Wayne-Kerr B642 bridge. The resistance varies typically by two orders of magnitude between potentials of -0.4 and -10 bars, whereas capacitance varies only by one order or less. Resistance is there-

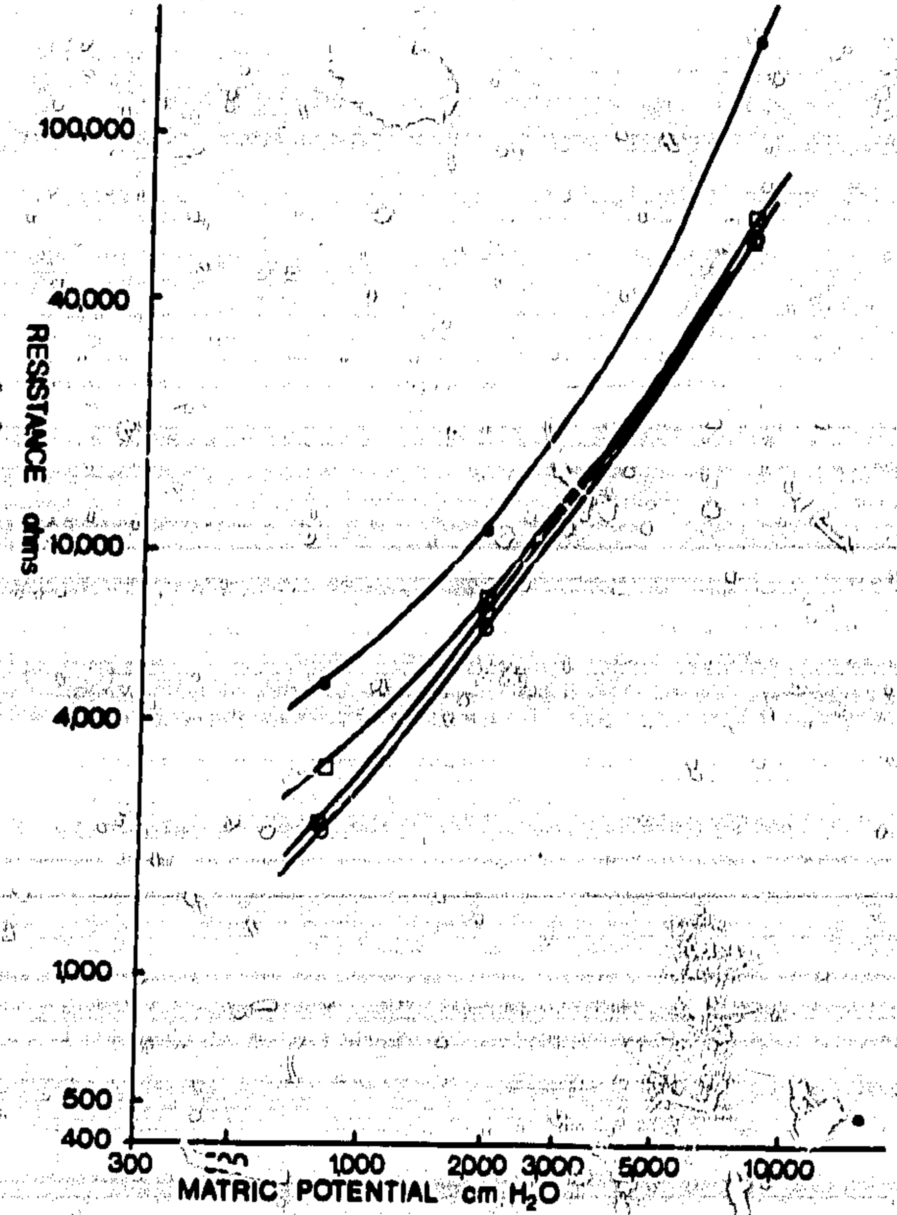


FIGURE 4

Relationship between resistance and matric potential for four concentric electrode blocks

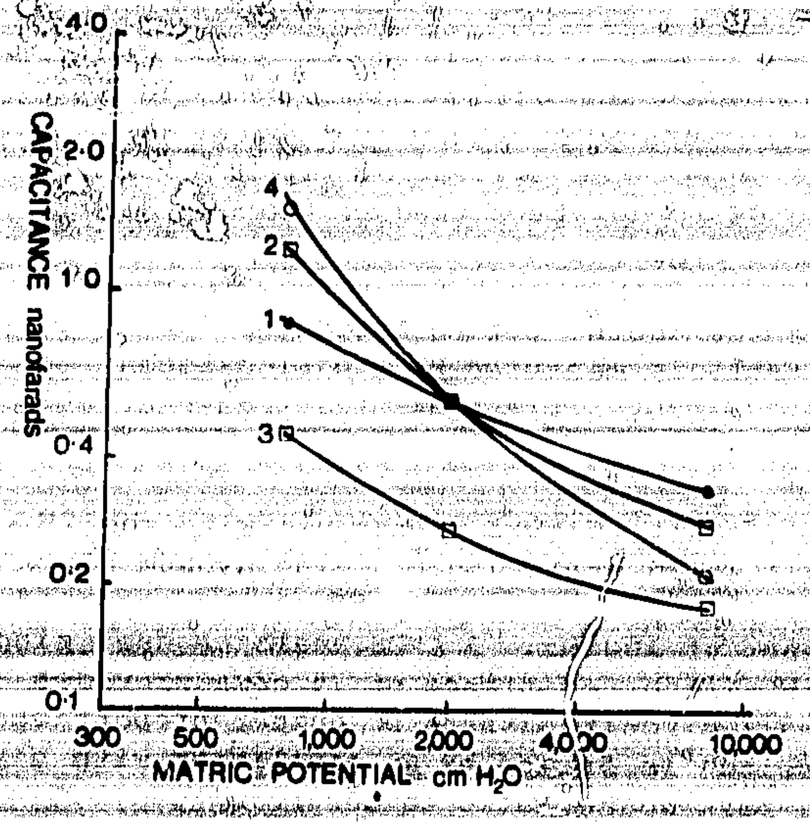


FIGURE 5

Relationship between capacitance and water potential for the blocks of Fig. 4

fore the more sensitive index of soil water potential. It is also more straightforward to measure in the field, conveniently by means of one of several commercially available, manually balanced AC bridges operating at around 1.5 kHz. Alternating current (AC) is used to avoid electrolysis within the block (polarisation) which would occur if DC were used directly (but see below). Polarisation causes an instantaneous and rapid increase in resistance due to gas bubbles forming on the electrodes.

Manual methods

Since it is preferable to measure the resistance component of the total reactance of a block, a bridge circuit is normally used, with a balancing capacitance in the bridge. Circuits have been devised using manual alternators (Pereira, 1951; Farbrother, 1957), thermionic valves (Aitchison et *al.*, 1951), and semiconductors (Kitching, 1965). Instruments are available in which the balancing capacitance is either fixed (the Soilmoisture Equipment Corp. Salinity Bridge 5500) or variable within ± 2% (the Beckham SMB -1A). These two have been found to be accepably accurate when compared in the laboratory with a bridge (such as the Wayne-Kerr B642) as a standard. More recent circuits have used different principles from the AC bridge (Schlub and Maine, 1979; Goltz et *al.*, 1981; Cary and Fisher, 1983). With modern solid-state circuitry a field instrument can be made small, light and water-proof, with very low power consumption.

Automatic methods

A bridge circuit is not suitable for automatic measurement as usually required for data logging at field sites. The circuits of Schlub and Maine (1979) and Goltz et *al.*, (1981) are suitable for adaption to data loggers. Two new circuits are described below, which are suitable for use with data loggers already available commercially.

Strangeways (1983) at IH has developed a method for use with Microdata magnetic tape cassette data loggers (Strangeways, 1972; Smart and Walker, 1979). In this method, four volts is switched to the block, in series with a fixed resistor, for 120 ms, during which time the voltage across the resistor is measured and logged. The block is then shunted with a low resistance to prevent any gradual build-up of polarisation. The profile of blocks are switched in isolation from each other to prevent the conductivity through the soil between them from affecting the reading. This system was developed for use with an automatic weather station in an arid climate in Libya, to detect the arrival of wetting fronts at specific depths in the soil. In the UK it has been used at the Gog Magog Golf Course near Cambridge (Wellings and Cooper, 1983), to follow water potential changes in a study of the unsaturated zone of the chalk aquifer. Figure 6 shows daily total potential values at three depths during the summer of 1982, together with rainfall. The rising potentials measured by the blocks can be seen to follow the rainfall of June 23-28th. Potentials fell again after July 2nd as the profile dried by evaporation and drainage.

Baty and Turner at IH have developed a circuit (Figure 7) for use with the IH designed Computing Techniques 12 channel solid state logger. The gypsum block is in the feedback loop of an operational amplifier and in effect the sense of the connections is reversed at a frequency of 100 Hz. A CMOS analogue dual single pole double throw switch, HI-5043, with switch resistance of 75 ohms provides interconnection reversal and the overall circuit gives a DC output proportional to the resistance of the block. The switch is driven by an oscillator with divide-by-2 output to provide an accurate 1:1 mark space ratio to ensure no cumulative polarisation. In Figure 7, amplifier A_1 ensures a low output impedence for the range adjustment control. A_2 is an operational amplifier with the gypsum block in the feedback loop. A_4 gives zero offset control by providing voltage by amplifier A_4. A circuit incorporating this principle has been combined with a liquid crystal display to be used as a manual reader for field use, reading directly in kilohms.

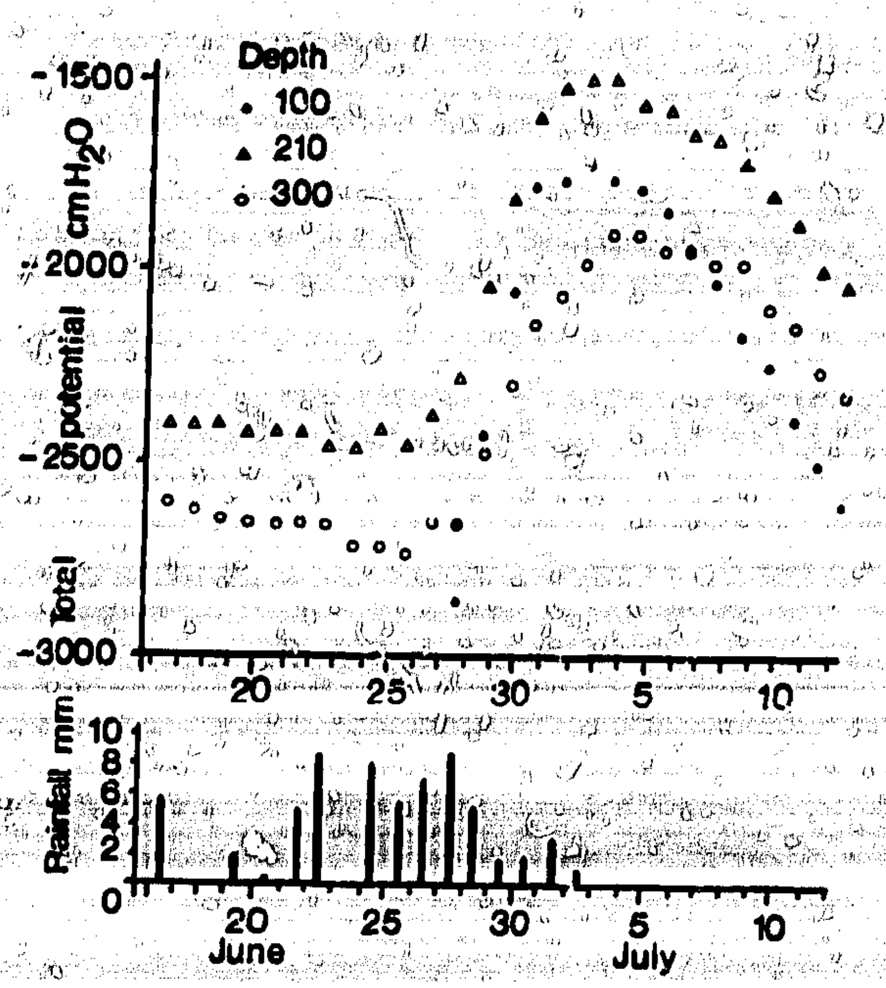


FIGURE 6

Total potential changes with time at 100, 210 and 300 cm depth at a chalk site near Cambridge, UK, measured with the Strangeways method on a Microdata logger

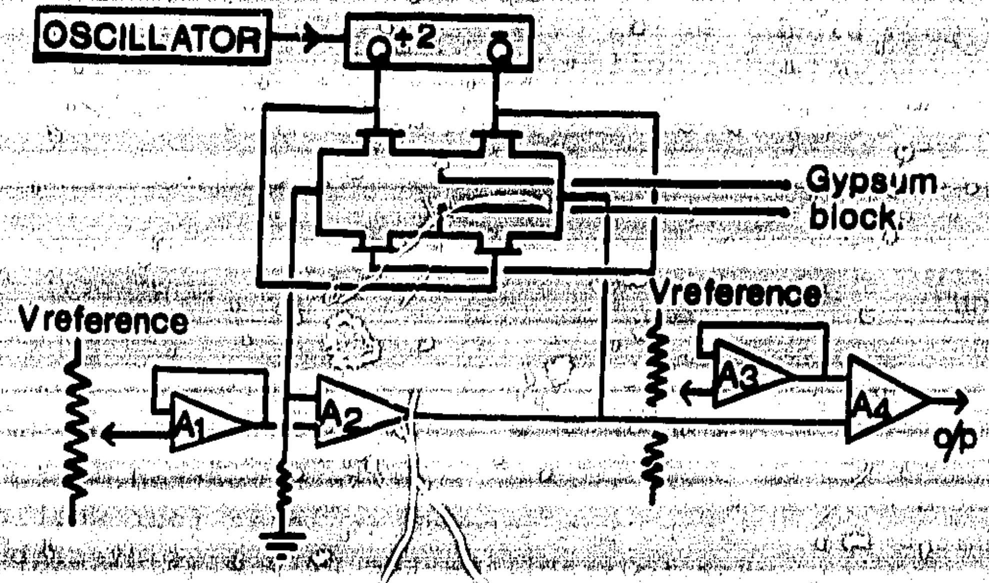


FIGURE 7 Schematic diagram of a pulsed DC method for measuring block resistance with the Turner & Baty circuit

An example of data from a solid-state logger using the Turner and Baty circuit is given in Figure 8. This shows the resistance of four gypsum blocks measured every hour during calibration. At 1605 (P in Figure 8) pm 2nd February, the pressure in the vessel was changed from 1.43 to 2.88 bars. By 1200 on 4th, the resistances had risen to within 90% of their final values, taken on 4th March. These data give an idea of the propable responsivemess of blocks to rapid potential changes in the field.

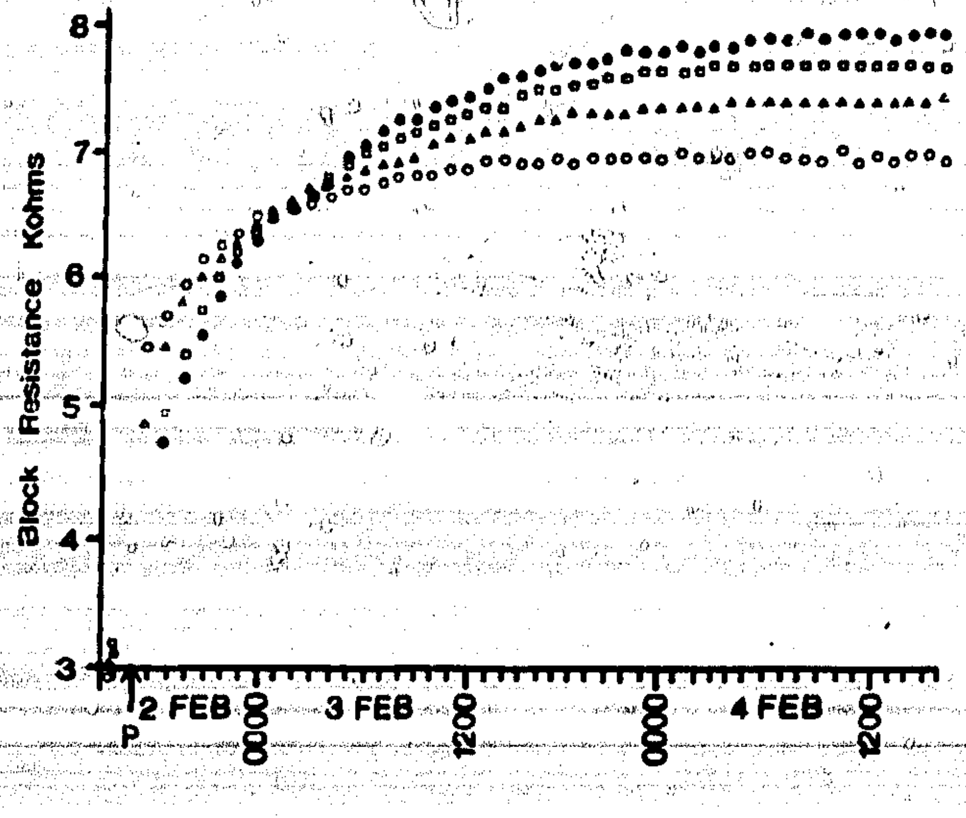


FIGURE 8 Resistances of four gypsum blocks during calibration, measured with the Turner & Baty circuit on a solid-state logger.

3 PROCEDURES FOR CALIBRATION

Because blocks are calibrated on a drying cycle, they must first be wetted. It has been found (Fourt, 1977) that blocks must be put through at least four wetting and drying cycles before calibration in order to stabilise the pore size distribution of the gypsum. Marked drift in calibration occurs during the first few cycles; subsequently the drift is much less, although it can be appreciable (see page). The blocks are wetted by standing them in 2-3 mm of water in a dish for 24 hours (i.e. only partly submerged), so that no air is trapped within the block while the water is absorbed. They are then allowed to air-dry for 24 hours. This procedure is repeated four times, and followed by a final wetting for 24 hours before calibration. It has been found that a more complete wetting is obtained if this is done in a low pressure chamber. Tanner *et al*. (1948) calibrated blocks by measuring the resistance at saturation. For this to be accurate, the slopes and forms of the log resistance versus log potential curves would have to be constant. Figure 2 shows that they are not, but this method may be used if only semi-quantative data are needed.

Haise and Kelley (1946) first proposed calibrating blocks in a pressure membrane apparatus. At IH blocks have been calibrated using a ceramic pressure plate apparatus with a 15 bar ceramic plate apparatus, manufactured by Soilmoisture Equipment Corporation (Figure 9). Calibration should be done in conditions of as near constant temperature as possible (23.0°C ± 0.5° at the Institute) and proximity to sources of radiant energy gain or loss (e.g. windows) should be avoided. A number of blocks are laid sideways on a 15 bar ceramic plate and covered entirely in a thick aqueous slurry of a powder containing a high proportion of silt-sized particles, such as a soil, silica flour or chalk (a soft Cretaceous limestone, 95% $CaCO_3$, of uniform silt-size particles). This ensures good hydraulic continuity between the blocks and the plate. The 15 bar pressure vessel used is equipped with three Amphenol 9-way lead through connectors. Using eight pins on each connector, in four pairs, a maximum of twelve blocks may be calibrated at once. A common earth connection must not be used; each block must have entirely separate electrical connections.

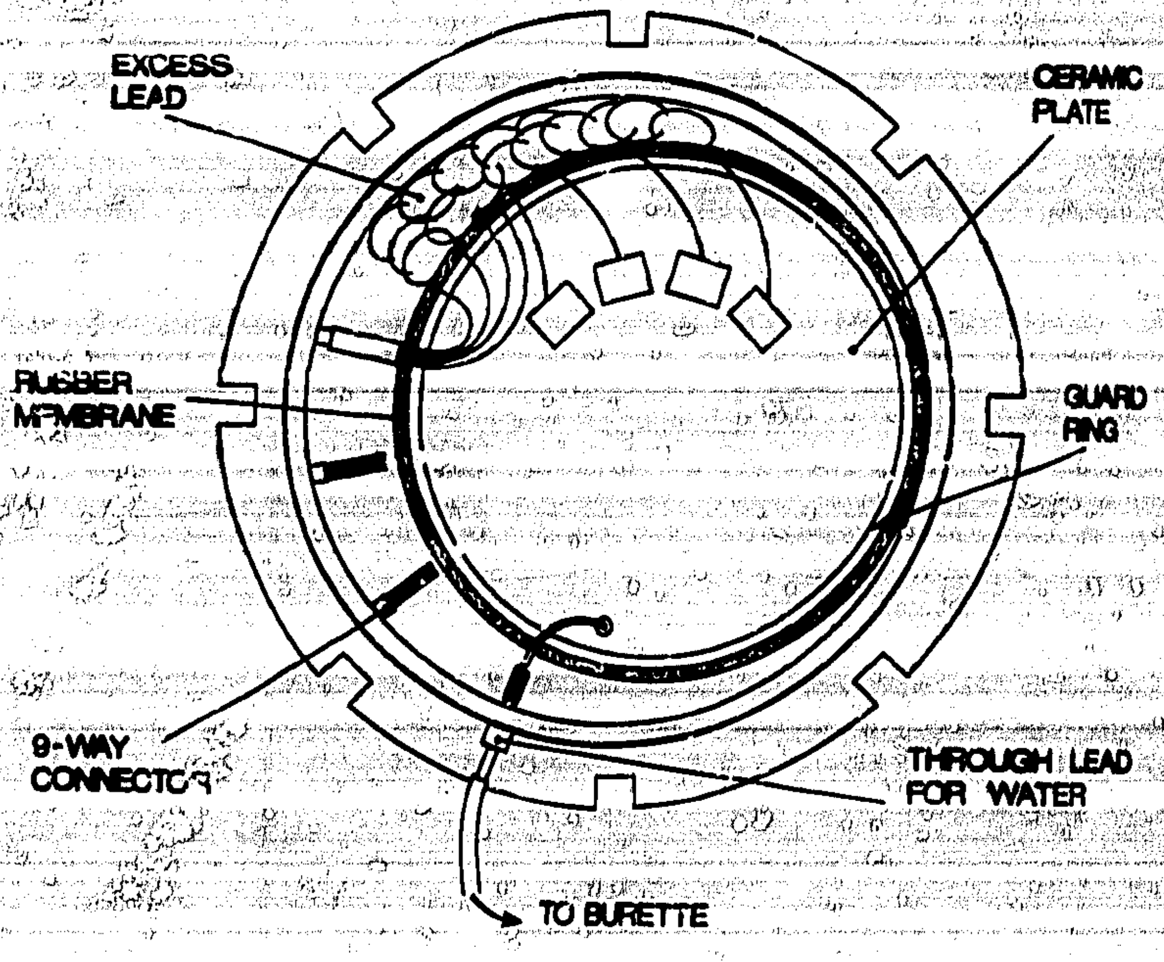
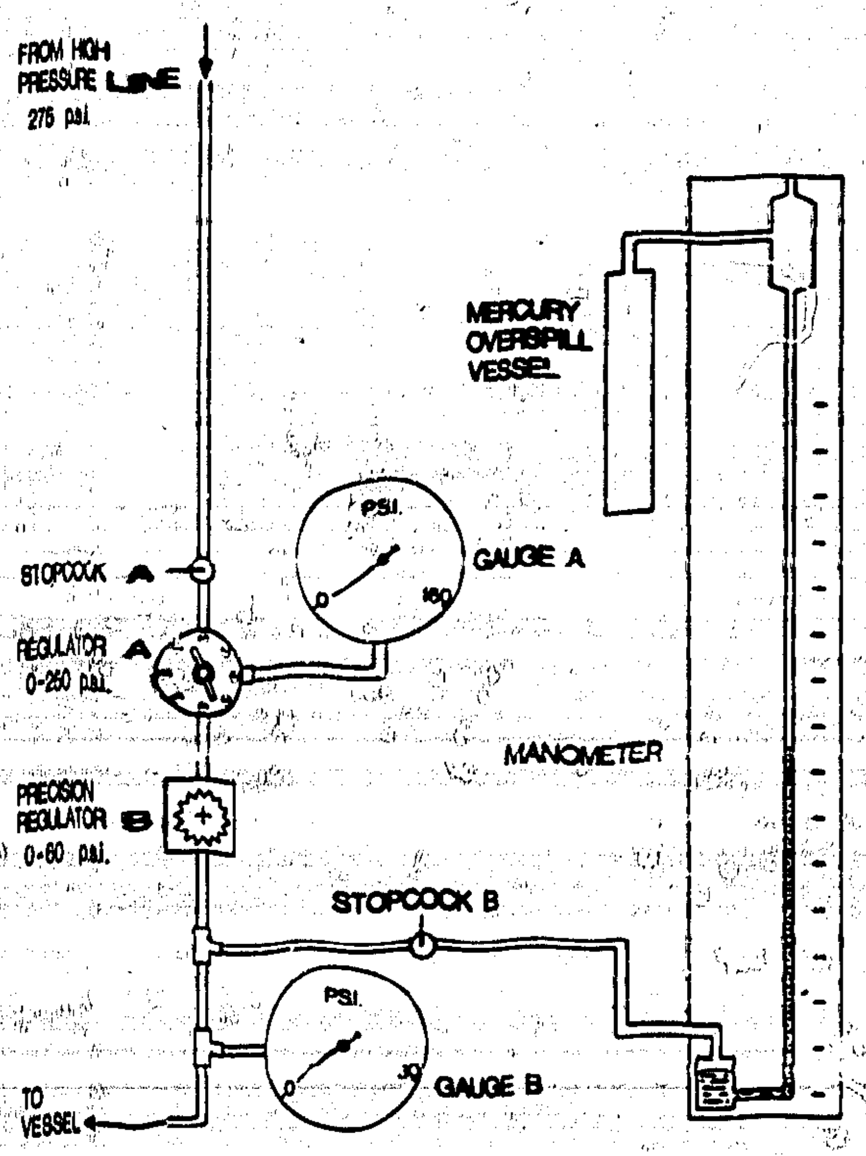


FIGURE 9 Arrangement of ceramic plate, blocks and electrical leads in the pressure plate vessel.

The compressed air regulation equipment as used by the Institute is shown in Figures 10 and 12. Figure 10 shows the equipment used to pressurise the vessel up to a maximum of 2 bars, and Figure 11 shows the equipment used from 2 bars to 10 bars. Figure 12 shows a simpler arrangement for use only at 15 bars. A mercury manometer is used to measure pressures up to 1 bar; a precision pressure gauge is used in the range 1-15 bars. It should be noted that many commercial "precision test gauges" are unsatisfactory, suffering from mechanical hysteresis and backlash.

FIGURE 10

Compressed air line for operation at 0 to 2 bars



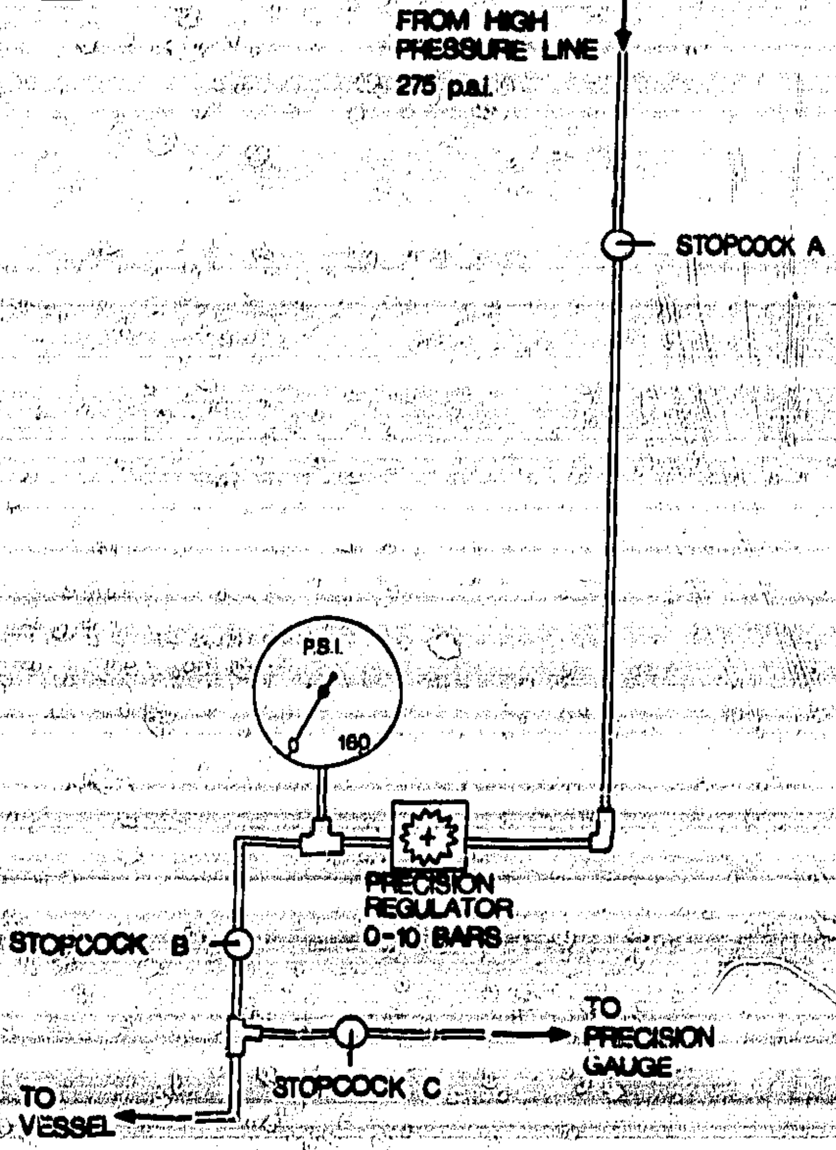
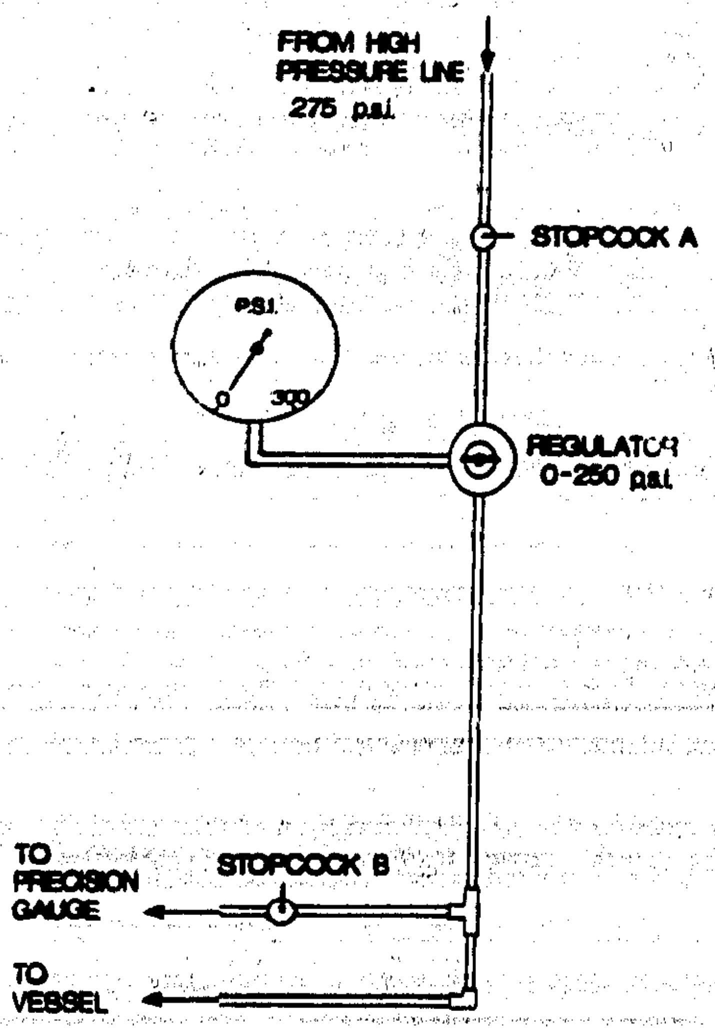


FIGURE 11

Compressed air line for operation from 2 to 10 bars

FIGURE 12

Compressed air line for operation at 15 bars



Wetting the ceramic plate

The ceramic plate must be completely saturated so that no air bubbles are trapped within the pores. The plate is wetted up from inside by connecting a water supply, for example a burette, to the brass water outlet of the plate (Figure 13), and slowly running in about 200 ml of water in about an hour, until the whole of the inner face of the plate is wetted. It is essential that while doing this that absolutely no water is allowed to wet the outer surface of the plate before it is fully saturated by soaking through from the inside. Failure to observe this precaution may trap air within the ceramic and allow air to pass through when pressure is applied.

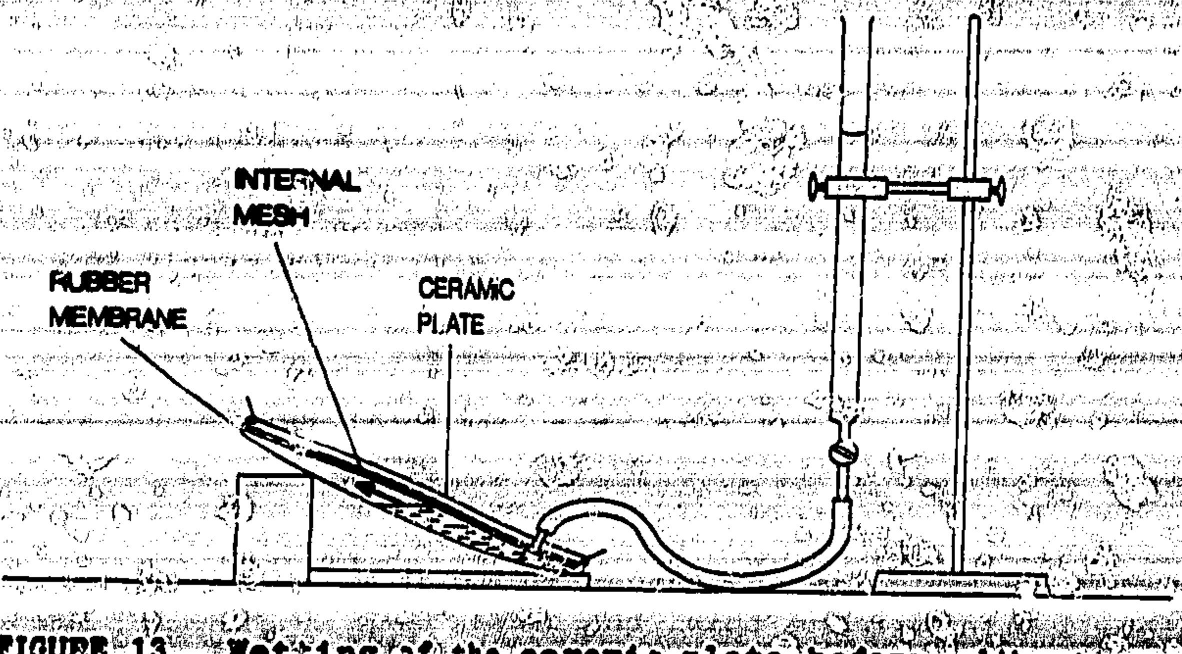


FIGURE 13 Wetting of the ceramic plate before calibration.

Preparation of a slurry

Chalk is used at IH to make the hydraulic contact between block and plate, although any medium-textured soil could be used. It must be readily available and easy to make into a slurry, and must retain a sufficiently high unsaturated hydraulic conductivity at low potentials to conduct water away from the blocks and to the plate. In principle the nature of the slurry should not affect the resistance of the blocks at a given potential. A comparison between calibration done in chalk and silica showed differences no greater than between repeated calibrations (see page 18).

About 750g of dry, finely ground chalk is mixed into a paste with water. This is sufficient for embedding twelve blocks on a plate.

Arrangement inside the pressure vessel

The arrangement of the blocks in the vessel immediately before closing the lid is shown in Figure 9. The wetted ceramic plate is placed on a triangular wire support on the bottom of the pressure vessel, so that the maximum space between the edge of the plate and the wall of the pressure vessel occurs nearest the connectors. An aluminium retaining ring, slightly smaller in diameter than the plate, is placed on it so that the 9-way connectors protrude inwards through cut-outs in the ring. The water outlet of the plate is connected to the lead-through in the vessel wall. A little water is sprayed on the surface of the wetted plate, and a thin layer (2-3 mm) of chalk slurry is smeared over the surface of the plate. The blocks are then laid out on the plate and the slurry poured over them until they are just covered, making sure that no block projects above the level of the O-ring seat. Failure to observe this may result in the ceramic plate being cracked when the lid is secured.

The excess length of electrical leads is placed between the retaining ring and the vessel wall. When all twelve blocks have been laid on the plate and embedded in chalk slurry, a polythene sheet is so arranged that any water condensing on the lid and falling onto the sheet runs off it and down the side of the vessel under the plate.

Electrical connection of the blocks

The 9-way connectors are arranged so that the male pins protrude into the vessel. Before placing the blocks on the plate, the leads of four blocks are soldered to the pins of a female connector, using pin pairs AB, CD, EF and HJ.

Observation of numerous calibration curves over many years had led us to conclude that water may condense on and between the pins of the lead-through connectors, resulting in the introduction of a component of resistance between the pins of these connectors in parallel with the block resistances; this would result in an underestimate of the block resistance during calibration. This would be more serious at high resistances (low potentials). Typical insulation resistances of moist connectors varied between more than 10 megohms and 350 kilohms. For a block resistance of 40 kilohms in parallel with this, the total resistance would be lowered respectively to between 39.8 kilohms and 35.9 kilohms.

The extent to which condensation on the connectors occurs is uncertain and it seems to vary over a period, probably due to changes in humidity. We have not yet devised a satisfactory way to overcome this, but it may help to seal the male to female connector join with silicone rubber before closing the vessel.

Closing and pressurising the pressure vessel

The seat of the O-ring, and the O-ring itself, are freed from all water and dust, and the O-ring is placed evenly on the seat. After the electrical connections are made and the water outlet of the plate is connected to the lead-through, the lid of the vessel is closed and all bolts are tightened evenly with a torque-wrench. If the vessel manufacturer does not specify a tightening sequence, the opposite pairs should be tightened, in clockwise sequence. A torque of 4 metre kg is suggested for the 15 bar pressure plate apparatus used by IH manufactured by the Soilmoisture Equipment Corporation, Santa Barbara, California, USA.

Before the vessel is connected to the equipment, all stopcocks and regulators are fully closed. A burette is connected to the lead-through to measure the quantity of water flowing out of the apparatus. The airline of the vessel is then connected to the compressed air equipment. While the vessel is pressurised, a small amount of air escapes through the burette. The rate is normally about 1 ml minute^{-1}, and is probably due to air diffusing through the water in the plate. Air escaping at a rate higher than this is probably due to leaks in the lead-through (which can be sealed with silicone rubber), that the cerramic plate is cracked or that it has not been wetted correctly and a dry spot has been left.

Operation at 0-2 bars

Refer to Figure 10. Before pressurising the system, check that regulators A and B, and stopcocks A and B, are fully closed. Stopcock A is first opened, and regulator A is opened to give a pressure on gauge A that is 10-15% above the required vessel pressure. This is necessary so that regulator B operates properly (a regulator should have a pressure difference across it of at least 10%).

Ensuring that stopcock B is fully closed, regulator B is slowly opened to expel excess water between the ceramic plate and rubber membrane. The rate of flow of water out of the vessel should not be too rapid. By progressive operation of regulator B the pressure is raised to a little below the required pressure, read on gauge B. Only if this pressure is below 1 bar (15 psi) can stopcock B be opened, bringing the mercury manometer into use. The pressure in the vessel should be checked about an hour after the initial application, and the pressure adjusted carefully and slowly to its correct level.

Operation at 2-10 bars

Refer to Figure 11. Before pressurising the system all stopcocks and the regulator are closed fully. Stopcocks A and B are opened and the regulator is opened slowly until the gauge indicates that the required pressure has been attained. The precision gauge can be connected to the vessel via stopcock C when desired to check the pressure precisely.

Operation above 10 bars

For water potentials below -10 bars (ie. pressures greater than 10 bars, -149 psi) a simpler, less precise pressure regulator is used (Figure 12), and the procedure is otherwise as for 2-10 bars. Less precision can be tolerated at the dry end of the range because the sensitivity of the blocks is less (Figure 2).

When the pressure is first applied, block resistance increases rapidly, to about 85% of the final equilibrium value in 48 hours (Figure 8). If this does not happen, the cause is usually a blocked water outlet. Depending on the potential (pressure applied) at each stage of calibration, the gypsum block may take from 10 to 60 days to reach final equilibrium. To determine when equilibrium is achieved, readings of block resistance, applied pressure and volume of water outflow are taken every few days. The attainment of equilibrium will depend on the pressure, composition and amount of the slurry, and the hydraulic conductivity of the blocks. It is advantageous to plot the readings against time when equilibrium has been achieved. This is most important for pressures above 3 bars, when it takes longer to achieve equilibrium. Judgement is subjective as it depends on the required precision for use in the field. A three-point calibration, at potentials -0.7, -3 and -10 bars may take up to four months.

Because of the long time needed to reach equilibrium, the smallest number of calibration points necessary to define a calibration curve adequately must be assessed. Figure 2 shows that the operational range can differ between blocks. The highest potential that can be measured is about -0.4 to -0.7 bars, varying from block to block. To obtain a good overlap with tensiometer measurements (range 0 to -0.8 bars) the authors considered that a three-point calibration, at -0.6, -1.5 and -4 bars, for Soilmoisture Equipment Corporation blocks was adequate for use in the Chalk. Calibration at a higher pressure (eg. 10 bars) may be necessary where potentials lower than -4 bars can be expected. Calibrations at the Institute have been determined on the drying cycle, starting at the lowest pressure (highest potential).

4 INSTALLATION OF BLOCKS IN THE FIELD

We have installed blocks using methods similar to those described by Pereira (1951). Gypsum blocks are small enough to be installed with minimum disturbance to the surrounding soil*, leaving only a twin-core cable running to the soil surface and along the ground to a suitable measuring point. Blocks should be saturated prior to installation. A vertical hole to the required depth is first made with the tools used to instal neutron probe access tubes (Bell, 1976), namely an auger and a suitable length of steel guide tube used as a reamer. These tubes are 44.5mm (1¼") OD and 3.6 mm wall thickness, driven manually through the soil and chalk with a 9 kg rammer. Cylindrical blocks can be lowered down the hole by their electrical leads. Rectangular blocks have to be installed by threading their lead through a 1" PVC pipe. This is then inserted down the hole while pulling upwards gently on the leads to hold the block in place at the end of the pipe. This ensures that the block does not wedge itself across the hole before reaching the required depth. The pipe is gently withdrawn, leaving the leads protruding from the hole. The pipe is then used to push both types of block gently against the base of the hole, which is then back-filled for about 50 cm with soil slurry, tamped with the PVC pipe, and then back-filled to near the surface with dry soil sieved to pass a 2 mm mesh. No problems have been experienced over lack of contact between block and soil with this method, and blocks have been installed satisfactorily at depths down to 5 metres in the Chalk (Wellings and Bell, 1980).

Mazery (1960) devised a variation of this installation method when controlling the overhead irrigation of sugar-cane in Mauritius. To improve contact between block and soil, he devised a conical block which was inserted into the base of a conical hole in the soil formed with a special auger; the access hole was inclined at 45° to the vertical to reduce the likelihood of irrigation water entering the disturbed soil. Rutter and Fourt (1965) have also installed blocks through inclined access holes.

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*SMEC blocks are 3 cm diameter and 2.5 cm high; Beckman blocks are 4 by 3 by 1.5 cm.

Recovery of blocks

With the installation methods described above, blocks have to be recovered by excavation; this is not economical for blocks deeper than about 60 cm. However, a method has been tried at IH to enable blocks to be recovered from the soil for re-use. 'Windows' 5 cm long by 4 cm wide are cut through the wall of a length of 2 inch diameter PVC pipe, centered at the required depths. A block is placed in the pipe opposite each window and the leads brought up the pipe. Plaster of Paris is then poured into each window to encase the blocks with plastic discs to prevent the plaster spreading up or down the pipe. The plaster is allowed to set, and then is smoothed to about 1 mm proud of the original surface of the pipe. A profile of blocks can thus be installed in a single pipe, which is installed in a hole made by tools similar to those used for installing neutron probe access tubes. Matric potentials measured by these blocks agree with those installed by the more conventional method described previously.

Blocks have been used at IH to measure water potentials in chalk to 20 m depth in unsaturated chalk (Wellings, 1984). Below 6 m depth, blocks were mounted with pressure transducer tensiometers on an aluminium mast in an unlined 150 mm borehole, and read manually every week. This method is specialised and expensive, however.

5 TEMPERATURE DEPENDENCE AND CORRECTION

The resistance of a gypsum block at constant water potential varies with temperature (Bouyoucos and Mick, 1940; Aitchison *et al.*, 1951). For measuring water potential in the field, a correction has to be applied. This has been done by measuring soil temperature with thermistors. For example, Wellings (1984) used thermistors calibrated to ± 0.5°C, installed at the same depths as the blocks, and read simultaneously with the blocks using a multimeter.

Figure 14 shows the results of a study made at IH to quantify the effect of temperature on block resistance. Three separate groups of 12 blocks were kept at 0 (saturation), -3 bars and -10 bars in ceramic pressure plate extractor. The mean resistances of each group of 12 were measured at different temperatures by placing each apparatus in a small chamber with independent temperature control. From the slope of the log resistance versus temperature data of Figure 14, the relationship:

$$R_1 = R_2 e^{-\alpha(T_2 - T_1)} \qquad (1)$$

was derived, where R_1 and R_2 are the block resistances at temperatures T_1 and T_2 respectively. For the calculation of block resitances corrected to calibration temperature, the equation:

$$R_c = \text{alog}_{10}[\log_{10} R_s + \beta (T_s - T_c)] \qquad (2)$$

has been used. R_c is the block resistance corrected to the calibration temperature T_c which is normally 23°C at IH. R_s is the resistance of the block in the soil at a temperature T_s. The data of Figure 14 gave a β value of 0.0123. After

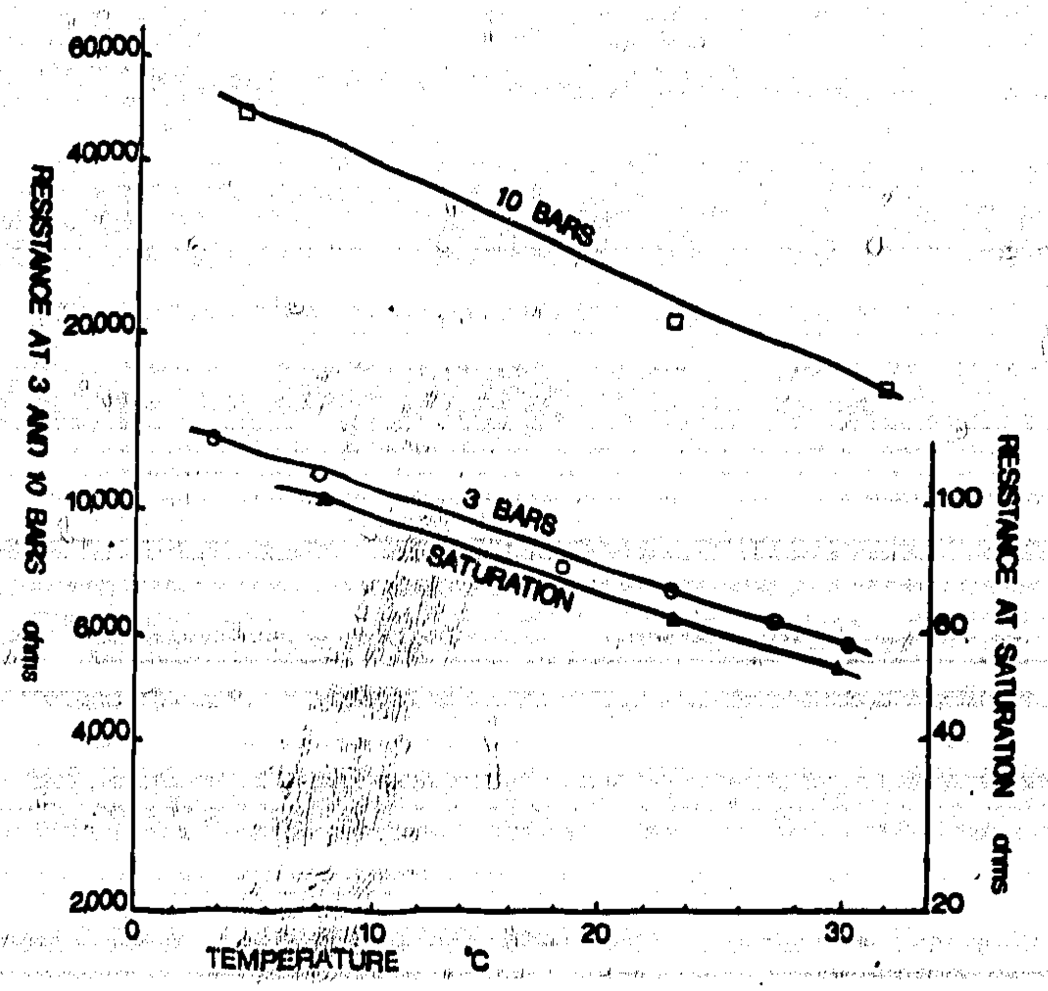

FIGURE 14

Relationship between the mean resistance of twelve blocks and temperature at three water potentials

temperature correction, the laboratory calibration data can be used to obtain the field soil water potential. Aitchison *et al.*, (1951) obtained a β value of 0.002 by a similar method, and presented a nomogram for correcting field-measured resistances. Davy and Taylor (1974) obtained a β value of 0.0036 by a similar procedure using blocks at saturation only.

6 DATA HANDLING AND INTERPRETATION

The calibration equation

Figure 15 shows that the relationship between block resistance and matric potential is not linear. If only semi-quantitative data are needed, then a linear calibration equation may be adequate. For greater accuracy, however, a log-log calibration equation is more appropriate.

The relationship between resistance and matric potential is approximately linear on a log-log scale over the working range (Figures 2 to 4). The calibration can thus be used to obtain a straight-line equation of log potential versus log resistance:

$$\log_{10} \psi_m = x.\log_{10} R_c + \log_{10} y \qquad (3)$$

Thus ψ_m is given by:

$$\psi_m = \mathrm{alog}_{10} [x.\log_{10} R_c + \log_{10} y] \qquad (4)$$

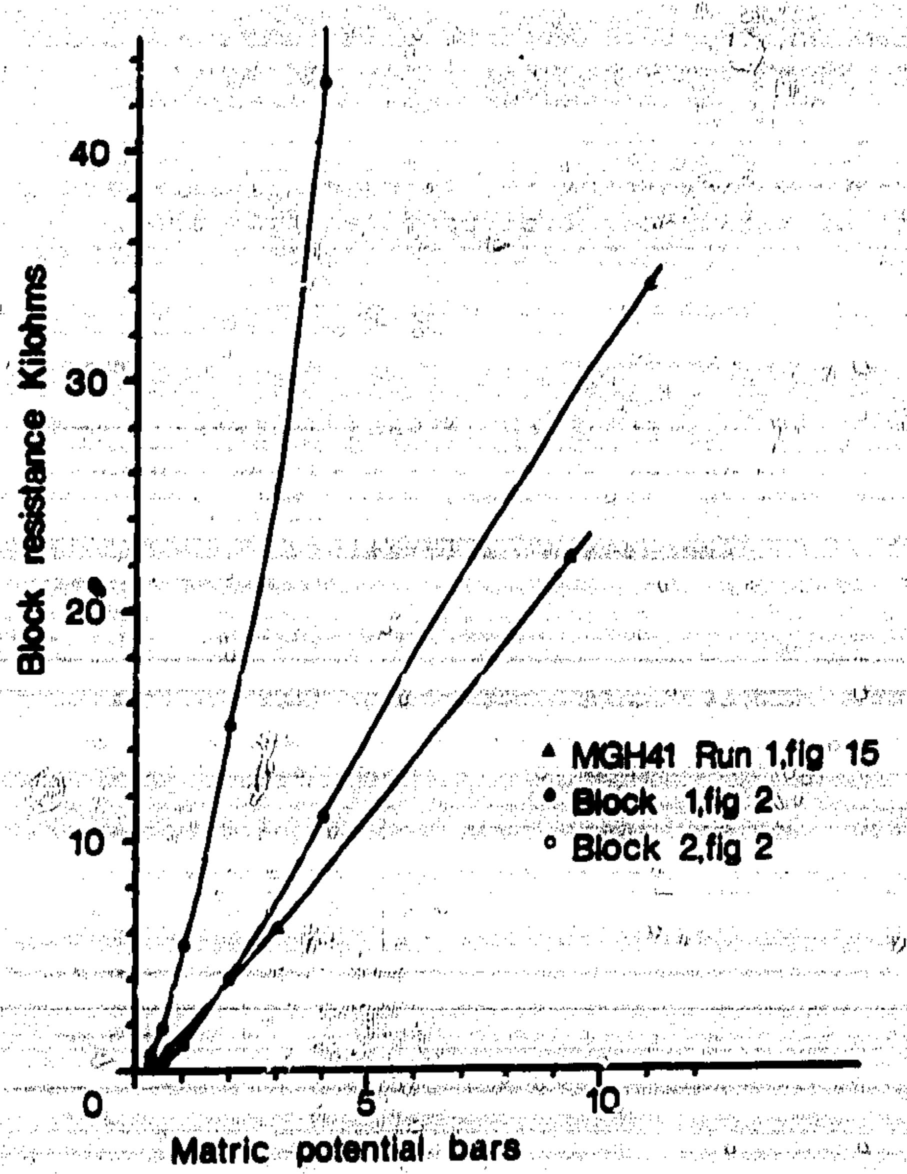

FIGURE 15

Relationship between resistance and potential for three blocks, on a linear scale

where ψ_m is soil matric potential, ψ = block resistance, and x and y are constants unique for each block. After correcting for soil temperature with equation (2), equation (4) can be used to calculate the matric potential. When R_c is in ohms and ψ_m is in cm water, typical values of x are between 0.5 and 1.1, and of y between -0.2 and 1.2. Both of these equations can be solved with a slide rule, using a calibration graph, or either a pocket programmable calculator or microcomputer. Programs have been written in Fortran for microcomputers to calculate potentials from field resistance data, and for storage of data on floppy magnetic disks. An example in Microsoft Fortran 80 for the Research Machines 380Z, using the Digital Research CP/M disk operating system, is given in Appendix A3.

Response time

The response time of gypsum blocks is difficult to assess as we have not used an independent method for measuring the potential. However, if the changes in resistance are considered in relation to rainfall, there appears to be a surprisingly quick response (Figure 6). Changes in resistance with time after a stepwise pressure increase during calibration (Figure 8) also suggest a quick response.

Potential profiles

Gypsum blocks have been used at IH mainly to measure total potential profiles in unsaturated soil and chalk (Wellings and Bell, 1980; Wellings, 1984). The main use of these data has been to determine the depth of the zero flux planer during the growing season. [This is a plane at which the gradient of potential (and hence, the soil water flux) is zero. Above it water moves upwards to plant roots, and below, downwards to the water table (Arya *et al.*, 1975; Wellings and Bell, 1982).] Measurements of water content can then be used to determine water content changes above and below the ZFP with time. Upward moving water is apportioned to evaporation, and downward moving water to drainage. This can be seen in Figure 16, which shows a pair of total potential profiles from the same blocks one year apart.

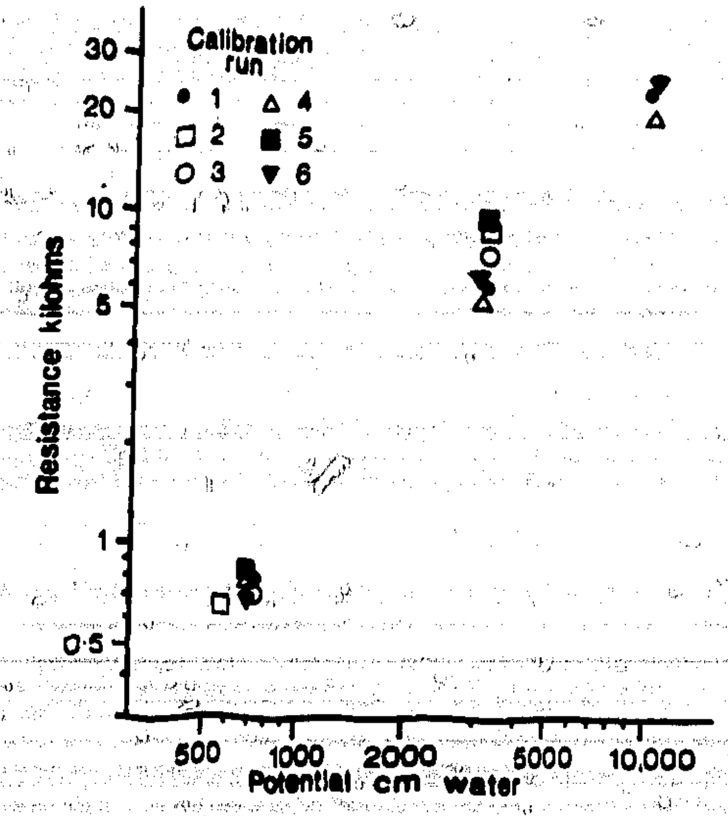

FIGURE 16

Relationship between resistance and potential for Soilmoisture Equipment block MGH41 during six successive calibrations

Errors

There are six principal sources of error in measuring soil water potential from gypsum block resistance.

(a) Application of a single calibration curve to all blocks

There is always a variation in the resistance of different blocks at the same potential, due to differences in the dimensions of the electrode, and in the porosity of gypsum (Figure 3: Tanner and Hanks, 1951). This can amount to a standard error of at least 75% of the mean for uncalibrated blocks but obviously is eliminated by calibrating each block.

(b) Calibration drift

Individual blocks have been recalibrated repeatedly to determine whether any drift in calibration occurs in successive wetting and drying cycles. Figure 17 shows the relationship between resistance and potential for one Soilmoisture Equipment block calibrated six times, and air dried between calibrations. Table 1 gives resistance and potential data for the successive calibrations. These are used to calculate the coefficients x and y of equation 3. Potentials are derived from these at the high potential (1000 ohms), mid-range (7000 ohms) and low potential (30K ohms) of the working range. At a resistance of 7000 ohms, for example, the derived potential varies considerably, having a coefficient of variation of 19% of the mean; this increases to 34% at 30K ohms. As the blocks were air-dried between calibrations, a greater drift may have occurred than in the field where they would be wetted between successive drying cycles.

TABLE 1 RESISTANCES IN OHMS AND APPLIED PRESSURE EXPRESSED AS [illegible] IC POTENTIALS IN CM WATER FOR ONE SOILMOISTURE EQUIPMENT BLOCK C[illegible] SIX TIMES The calibrations are expressed as the coefficien[illegible] of Eq. 3

CALIBRATION RUN	BLOCK RESISTANCES AND MATRIC POTENTIALS DURING CALIBRATIONS						CALIBRATION FACTORS		DERIVED POTENTIAL FOR 3 RESISTANCES		
	R_c	ψ_m	R_c	ψ_m	R_c	ψ_m	x	y	1K	7K	30K
1	784	709	6170	3035	22,100	9371	0.7666	0.6164	825	3668	11,200
2	667	646	8790	3014	-	-	0.6625	0.8661	714	2591	6,790
3	718	687	6670	3083	-	-	0.6736	0.9132	859	3186	8,490
4	751	692	5760	3185	19,000	9933	0.8165	0.4761	843	4127	13,500
5	808	692	6810	2960	-	-	0.6112	1.0632	788	2590	6,300
6	728	692	6030	2946	24,400	9796	0.7489	0.6797	844	3025	10,800
MEAN							0.7132	0.7691	812	3297	9,510
S.D.							0.0766	0.2183	53.9	623	2,800
C.V.%							10.7	28.1	6.6	18.8	34.0

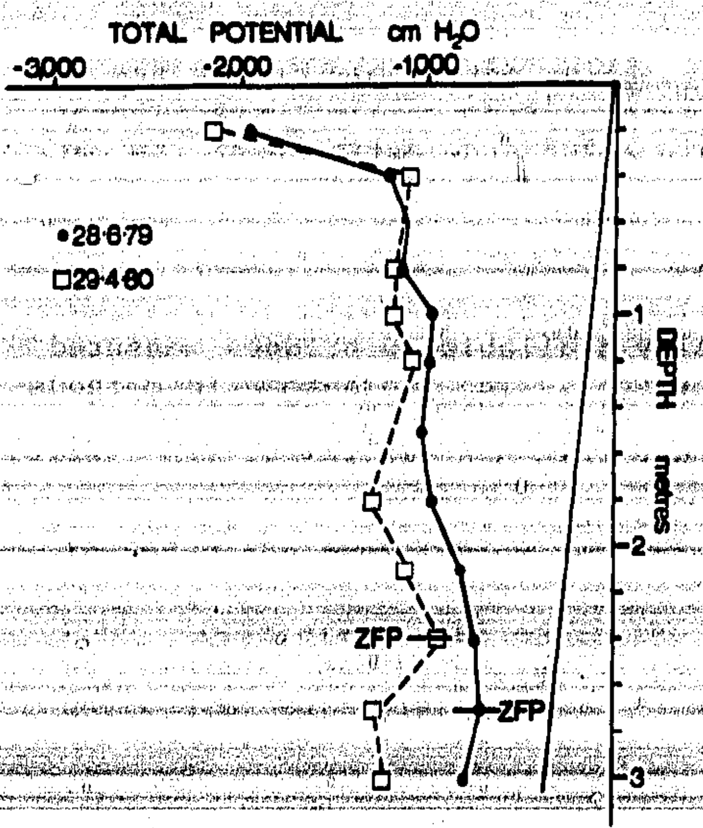

FIGURE 17

The presence of a zero flux plane in two total water potential profiles a year apart, using the same blocks and the same calibrations

Blocks do drift in the field, however, leading to an increasingly irregular potential profile with time. If data are taken from a set of blocks in two successive years (Figure 16), drift can be seen as a difference in the potential profile at closely similar soil water contents. The error due to calibration drift of each block can then be estimated by the differences in potentials between years, using the same calibration for both years. Although this results in errors, the shape of the potential profile - and the position of the ZFP - may still be determined if drift is not too severe, as in Figure 16. The absolute matric potentials may be in error by as much as ± 20%, however. Calibration drift probably represents the largest source of error in determining matric potentials but if only the ZFP depth is required for estimating actual evaporation in water balance calculations, this error may be acceptable.

(c) Assumption of an incorrect calibration equation

The assumption of equation (3) to represent the relationship between block resistance and matric potential is obviously a simplification which results in some errors. Figure 2 shows that this relationship is simplistic although satisfactory in the working range (see page). The error resulting from using equation (3) varies according to the departure of the resistance versus potential curve of a particular block from equation (3). A typical error is 5% of the potential at a given resistance, and no error greater than 10% has been found. This error may be reduced by assuming a different relationship. Davy and Taylor (1974), for example, used a seventh-order polynomial, although this cannot be recommended as it suggests unwarranted accuracy.

(d) Hysteresis

As with all porous media, there is hysteresis in the relationship between the water content and water potential of a gypsum block, seen in the difference between the resistance versus potential relationship when the block dries and when it wets (Bourget *et al.*, 1958; Tanner and Hanks, 1952). This is not serious providing blocks are used on the same part of the wetting-cycle for which they were calibrated. At IH, blocks were calibrated on the drying cycle as the pressure in the ceramic plate apparatus was increased. Field data were used to follow the downward progress of ZFPs as a crop dried out the soil and underlying rock. The error of using a drying calibration for estimating potentials during the autumn rewetting of the soil could not be estimated. From earlier work (Tanner and Hanks, 1952) the error could easily result in a 20% underestimate of the matric potential.

(e) Incorrect measurement of block resistance

As mentioned in section 2.1, the two commercially available AC bridges measured resistance to within ± 2% of a laboratory instrument. The two automatic methods described earlier measured block resistance to ± 50 ohms. This is an error of ± 10% at the high potential end of the range, but only ± 0.25% at the low potential end of the range.

7 CONCLUSIONS AND RECOMMENDATIONS

Our conclusions from the field use of gypsum resistance blocks agree generally with those of Holmes, Taylor and Richards (1967). Even though resistance units may be imperfect in some of their characteristics, they appear to be well suited for measuring water potentials in the -0.7 to -10 bar range. Blocks are also relatively cheap, between $3 and $10 each. However, they do suffer from the following limitations:

Calibration drift appears to occur with time.
Blocks must be individually calibrated for quantitative work.
The effect of soil salinity is not yet well defined.
Field resistance readings must be temperature corrected.
Blocks cannot easily be recovered for re-use without excavation.

Despite these problems, studies such as defining the depth of the zero flux plane can be done, even though the measurement of precise water potential values may not be possible. We disagree with Holmes *et al.* (1967); we do not recommend their use for measuring water content changes in soil because of the effect of hysteresis in both block and soil.

Our recommendations for calibrating and using gypsum blocks are as follows:

1. A constant temperature laboratory or chamber must be used for calibration, with temperature control ± 0.5°C within the pressure vessel.

2. A ceramic pressure plate apparatuus must be used, with two-stage pressure regulations to 1-0.5% of the nominal applied pressure.

3. A precision pressure gauge must be used to measure the vessel pressure. The Wallace and Tiernan Model FA 234 has been used at IH.

4. Precision constant-bleed pressure regulators must be used to control the vessel pressure. Norgren regulators nos. 11-818-100 and 11-818-110 have been used at IH.

5. A minimum of three points must be used to establish the calibration curve, and these must span the anticipated field soil water potential range.

6. The blocks in the pressure vessel must have each lead connected independently to the outside, with no common electrical ground. The connectors on the inside of the vessel must be electrically insulated against water condensing on the pins.

7. The change in block resistance with time must be followed during calibration to judge the equilibrium resistance.

8. When blocks are installed in the field, the soil must be disturbed as little as possible, eg. by using the tools for installing neutron probe access tubes devised by Bell (1976).

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I C Strangeways:	Advice on installation of his Microdata logger-based system.
G Bell & K B Black:	Software for reading and analysing the data.

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APPENDICES

A1. A list of suppliers of equipment

The following supply gypsum blocks and manual instruments to read them:

Beckman Instruments Inc.
Cedar Grove Operations
89 Commerce Road
New Jersey 07009
U S A

Soil Moisture Equipment Corp.
P O Box 30025
Santa Barbara
California, 93105
U S A

In the U.K.:

Beckman-Rill Ltd
6 Stapleton Road
Orton
Southgate
Peterborough
PE2 0TB

The following supplies solid state data loggers:

Computing Techniques (Mfg) Ltd
Brookers Road
Billingshurst
Sussex
RH14 9RZ

For pressure line equipment, pressure regulators, gauges and accessories:

Norgren Pneumatic Products Ltd
Shipston on Stour
Warwickshire
CV36 4PX
UK

Wallace and Tiernan Ltd
Priory Works
Tonbridge
Kent
TN11 0QL
UK

For the magnetic tape cassette data loggers:

Microdata Ltd
Monitor House
Station Road
Radlett
Herts WD7 8JX
UK

The following supplies Phene-type matric potential sensors:

Agwatronics
PO Box 55100
Riverside CA 92517
U S A

A2. A Table of Pressure and Water Potential Equivalents

	Pa	cm H_2O	Bar	Cm Hg	P.s.i.	kg cm	J Kg^{-1}	Atm
1 Pa	-	0.01017	10^{-5}	7.501 $\times 10^{-4}$	1.450 $\times 10^{-4}$	1.0197 $\times 10^{-5}$	0.0010	9.869 $\times 10^{-5}$
1 cm H_2O	98.32	- -	9.832 $\times 10^{-4}$	0.07375	0.01426	1.003 $\times 10^{-3}$	9.832 $\times 10^{-2}$	9.704 $\times 10^{-4}$
1 Bar	10^5	1017.1	-	75.01	14.50	1.0197	100.0	0.9869
1 cm Hg	1333.2	13.56	0.01333	-	0.1934	0.01359	1.333	0.01316
1 P.s.i.	6895	70.125	0.06895	5.171	-	0.07031	6.895	0.06805
1 kg cm^{-2}	9.807 $\times 10^4$	997.4	0.9807	73.56	14.22	-	98.07	0.9678
1 J Kg^{-1}	1000	10.17	0.0010	0.7501	0.1450	0.01019	-	9.869×10^{-3}
1 Atm	1.013 $\times 10^5$	1030.6	1.0133	76.00	14.69	1.0333	101.3	-

1 Atm is the standard atmosphere of 76 cm of mercury. The density of mercury is taken 13.56 g cm^{-3}, and the density of water is taken as 1.00 g cm^{-3} (Kaye and Laby, 1973).

To convert from the units in the vertical tow to another unit, multiply by the factor given, eg.:

1 Pound per square inch = 6895 Pa = 5.171 cm Hg, etc.

For more information see Rose (1979).

A.3 A Microsoft Fortran 80 program for calculating matric potentials from block resistances, and storing the data on magnetic disk.

This program is written in Microsoft Fortran 90, for the Research Machines 380Z microcomputer, using the Digital Research CP/M disk operating system. The block resistances read in the field are corrected to laboratory calibration temperature (23°C) using thermistor readings taken simultaneously at the same depths as the blocks. The temperature - corrected block resistances are written with their date and daycode, to random access files called ssGYpp.DAT on floppy disk, where ss is a two-letter site index, and pp a two-figure plot number.

The first record of each data file contains the site name, plot number, the data file name, the number of blocks in the profile (INO) and the total number of records in the file (NREC). The block depths, and the slope and intercept of the calibration equation 3 are stored in order of increasing depth from the 2nd to the (INO+1)th record. The block resistance data are stored in subsequent records.

This program stores the data only; other programs have been written to print out matric and total potentials, and to plot total potential profiles using graphics routines.

```
        PROGRAM GYPO
C
C    S. Wellings   4  January  1984  Version 1.0  for RML 380Z
C
C    Program to calculate temperature-corrected matric
C    potentials from gypsum block resistance values, and
C    to store data on disk. Temperature correction is done
C    using soil temperatures, calculated from thermistor
C    resistance values in subroutine TEMPS.
C
C     ARRAYS:
C      CALI     calibration line intercept
C      CALS        "           "  slope
C      IMO      no. of days in each month
C      IFILE    array containing data file name ssGYpp.DAT, where
C               ss is site index, pp is plot number.
C      POT      matric potentials, cm H2O
C      TEMP     soil temperatures in deg. C
C      RESC     temp-corrected block resistance
C      RESF     block resistances read in field, SMEC bridge, in ohms
C      RDG        "         "        "   "    "  , IH block reader, in
C               500 ohm steps (1.0=500 ohms)
C     REALS:
C      E       log to base E of 10
C      RESC    log10 of temp-corrected block resistance
C      RESL    log10 of field resistance of block
C      TEMPL   lab temperature at which blocks were calibrated
C      TFACT   factor for temp. correction of blocks
```

```
C      INTEGERS:
C        ID,IM,IY        date as ddmmyy, read in 3I2 format
C        IDAY            daycode
C        INO             no. of blocks in profile
C        IOK,ICONT,IDO   integers to control  function of program.
C        ILEAP,IYEAR     integers to allow for leap year
C        ICSR,IB         integers to control  cursor movements
C        IRV1,IRV2       reverse video on/off
C
       LOGICAL IFILE(11),ANAME(24),APLOT(4)
       DIMENSION POT(20),RESF(20),IDEP(20),CALS(20),CALI(20),
      &IMO(12),RESC(20),RDG(20)
       COMMON TEMP(20)
       DATA IFILE/2*' ','G','Y',4*' ','D','A','T'/,IRV1/18/,IRV2/20/
       DATA E/2.30259/,TEMPL/23.0/,TFACT/0.0123/,IB/8/,ICSR/31/
       DATA IMO/31,28,31,30,31,30,31,31,30,31,30,31/
 5     WRITE(1,1000)ICSR,IRV1,IRV2
       CALL TEMPS(TEMP)
C
C    Read the site and set number (into array IFILE), and disk drive.
C
 7     WRITE(1,1013)IB,IB,IB,IB,IB,IB,IB
       READ(1,105)IFILE(1),IFILE(2),IFILE(5),IFILE(6),NDRIV
       NDR=NDRIV-64
C
C   Read the first record of the ssGYpp.DAT file. This contains the
C   site name (ANAME), plot number (APLOT), the file name (IFILE),
C   the number of blocks in the profile (INO), and the number of
C   records in the file (NREC).
C
       CALL OPEN(6,IFILE,NDR)
       READ(6,101,REC=1)(ANAME(I),I=1,24),(APLOT(I),I=1,4),
      &(IFILE(I),I=1,11),INO,NREC
C
C   Read last observation date in the file. Read date of next
C   observation from the VDU, and calculate daycode.
C
       READ(6,1012,REC=NREC)IDL,IML,IYL,IDAYL,(RESC(I),I=1,INO)
       WRITE(1,1018)(ANAME(I),I=1,24),IDL,IML,IYL
       WRITE(1,1010)IB,IB,IB,IB,IB,IB
       READ(1,106)ID,IM,IY
       WRITE(1,1017)ID,IM,IY,IB
       READ(1,107)IOK
       IF(IOK.EQ.1)GO TO 23
       IDAY=0
       IYEAR=0
       IYEAR=IY+1900
       ILEAP=IYEAR/4
       IYEAR=ILEAP*4
       IF(ILEAP.EQ.IYEAR)IMO(2)=29
       K=IM
       IF(K.EQ.1)GO TO 11
       K=1
 13    IF(K.EQ.IM)GO TO 11
       IDAY=IDAY+IMO(K)
       K=K+1
       GO TO 13
 11    IDAY=IDAY+ID
```

```
C
C   Read block depths and calibration parameters from ssGYpp.DAT file.
C   The block depths (IDEP), calibration slopes (CALS) and intercepts
C   (CALI) are read from record numbers 2 to (INO+1).
C
      DO 3 I=1,INO
      II=I+1
3     READ(6,102,REC=II)IDEP(I),CALS(I),CALI(I)
C
C   Enter block resistance values, one at a time.
C
      WRITE(1,1001)IB
      READ(1,107)IBOX
4     IF(IBOX.EQ.2)GO TO 20
      DO 1 I=1,INO
30    WRITE(1,1009)IDEP(I),IB,IB,IB,IB,IB,IB
      READ(1,100)RESF(I)
      WRITE(1,1015)RESF(I),IB
      READ(1,107)IDO
      IF(IDO.EQ.1)GO TO 30
1     CONTINUE
      WRITE(1,1002)(RESF(I),I=1,INO)
      GO TO 22
20    DO 21 I=1,INO
31    WRITE(1,1014)IDEP(I),IB,IB,IB,IB
      READ(1,108)RDG(I)
      WRITE(1,1015)RDG(I),IB
      READ(1,107)IDO
      IF(IDO.EQ.1)GO TO 31
21    RESF(I)=RDG(I)*500
      WRITE(1,1016)(RDG(I),I=1,INO)
22    WRITE(1,1011)IB
C
C   Check on VDU to see if data entered are OK.
C
      READ(1,107)IOK
      IF(IOK.GT.0) GO TO 4
      WRITE(1,1003)
C
C   Calculate temperature-corrected matric water potentials (POT)
C   in cm. water from calibration line, from temperature-corrected
C   resistance values, using the equation:
C       POT = alog10[((log10(RESC))*CALS)+CALI]
C
      DO 2 I=1,INO
      RESL=(ALOG(RESF(I)))/E
      RESCC=RESL-(TFACT*(TEMP(I)-TEMPL))
      POTL=(RESCC*CALS(I))+CALI(I)
      POTL=POTL*E
      POT(I)=EXP(POTL)
      RESC(I)=EXP(RESCC*E)
2     CONTINUE
      WRITE(1,1004)(IFILE(I),I=5,6),ID,IM,IY,IDAY
      DO 6 I=1,INO
6     WRITE(1,1005)IDEP(I),POT(I)
C
C   Write the date, daycode and the temp-corrected resistances
C   to the file ssGYpp.DAT, at record number NREC. Update NREC
```

```
C   in the first record.
C
      NREC=NREC+1
      WRITE(6,101,REC=1)(ANAME(I),I=1,24),(APLOT(I),I=1,4),
     &(IFILE(I),I=1,11),INO,NREC
      WRITE(6,1012,REC=NREC)ID,IM,IY,IDAY,(RESC(I),I=1,INO)
      ENDFILE 6
C
C   Any more data to analyse? Present the menu.
C
23    WRITE(1,1006)ICSR,IB
      READ(1,107)ICONT
      IF(ICONT.EQ.0)GO TO 7
      IF(ICONT.EQ.1)GO TO 5
      IF(ICONT.EQ.2)GO TO 8
8     WRITE(1,1007)
100   FORMAT(F6.0)
101   FORMAT(1X,24A1,1X,4A1,1X,11A1,1X,I2,1X,I3)
102   FORMAT(I4,1X,F6.4,1X,F7.4)
103   FORMAT(21F5.2)
104   FORMAT(21F6.0)
105   FORMAT(2A1,1X,2A1,1X,A1)
106   FORMAT(3I2)
107   FORMAT(I1)
108   FORMAT(F4.1)
1000  FORMAT(1X,A1,20X,A1,' ****  PROGRAM GYPO  ****',1X,A1//' Data
     & should be entered for all plots on each date, in time
     &sequence.'/' The thermistor readings are entered first. If
     & there are no thermistor'/' readings for a given date, use
     & the data from the previous date.'//)
1001  FORMAT(' Enter resistance values of each block according to
     & the instrument.'//' What was the instrument used ? Enter
     & 1 if a SMEC bridge  :'/31X,' Enter 2 if an IH block
     & reader :   -',A1)
1002  FORMAT(' Resistance values are :'//1X,14(1X,F6.0))
1003  FORMAT(' Program continues to calculate potentials.')
1004  FORMAT(' MATRIC POT. DATA FOR PLOT ',2A1,' DATE ',3I2,
     &' DAY NO. ',I4)
1005  FORMAT(2X,I5,2X,F6.0)
1006  FORMAT(1X,A1,' Potential data written to disk file.'//
     &' Any more data for processing ?  Options are :'//
     &' More data on same date          ',32X,' Press RETURN'/' Data
     &from a different date, without new thermistor readings  Press
     & RETURN'/' Data from a different date, with new thermistor
     & readings   Enter          1'/' Finish processing            ',
     &32X,' Enter          2'/' Enter : -',A1)
1007  FORMAT(' CALCULATIONS COMPLETE.TA-TA FOR NOW!'/)
1008  FORMAT(/5X,I5)
1009  FORMAT(1X,I5,' cm reading, ohms: ------',6A1)
1010  FORMAT(' Enter date of readings, ddmmyy : ------',6A1)
1011  FORMAT(/' All correct ? Press RETURN if yes; enter 1 if no
     & -',A1)
1012  FORMAT(3I2,1X,I3,1X,20F6.0)
1013  FORMAT(//' Enter site index, plot no., and drive of data disk :
     & -- -- -',7A1)
1014  FORMAT(1X,I5,' cm reading, IH reader units:  --.-',4A1)
1015  FORMAT(' Is ',F7.1,' correct ? Press RETURN if yes; enter 1
     & if no : -',A1)
```

```
 1016  FORMAT(1X,20F5.1)
 1017  FORMAT(' Date of new data is :',3I2//' Do you want to
      &continue ? Press RETURN if yes; enter 1 if no : -',A1)
 1018  FORMAT(' Last data entered for',1X,24A1,', on ',I2,1X,I2,
      &'    19',I2/)
       STOP
       END
```

```
       SUBROUTINE TEMPS(TEMP)
C   S. Wellings   4 January  1984  Version 1.1 for RML 380Z
C
C   Subroutine for use with program GYPO, to calculate soil
C   temperatures (t) from thermistor resistances (r) using
C   a second order  polynomial:
C        t=A-Br+C(r*r)
C   where A,B and C are coefficients given below, for the
C   thermistors in use at West Ilsley.
C
       DIMENSION A(14),B(14),C(14),REST(14)
       COMMON TEMP(14)
       DATA A/54.74,51.60,50.25,52.01,51.82,51.90,51.39,51.16,
      &       52.04,51.14,52.09,52.43,51.83,51.49/
       DATA B/8.784,6.686,6.851,7.764,7.351,7.945,7.551,6.321,
      &       8.959,7.673,7.767,8.554,8.388,7.595/
       DATA C/0.3522,0.2077,0.2229,0.2779,0.2499,0.2915,0.2654,
      &       0.1869,0.3679,0.2765,0.2785,0.3337,0.3257,0.2687/
       DATA IB/8/
       WRITE(1,2002)
       DO 9 I=1,14
       WRITE(1,2001)I,IB,IB,IB,IB,IB
 9     READ(1,202)REST(I)
       DO 10 I=1,14
       TEMP(I)=A(I)-(B(I)*REST(I))
       SRES=REST(I)**2
       CRES=SRES*C(I)
 10    TEMP(I)=TEMP(I)+CRES
       WRITE(1,2005)
       WRITE(1,2003)(TEMP(I),I=1,14)
 202   FORMAT(F5.2)
 203   FORMAT(3F8.4)
 2001  FORMAT(' TH',I2,' : --.--',5A1)
 2002  FORMAT(' Subroutine TEMPS.'//' Enter thermistor
      & resistances in kilohms :')
 2003  FORMAT(14F5.1)
 2005  FORMAT(' Temperatures are, in deg.C, in order of
      & depth :')
       RETURN
       END
```