

L. A. RICHARDS<sup>2</sup>

U.S. Department of Agriculture

Received for publication November 18, 1941

A porous cup when filled with water and connected to a suitable gage may be used for measuring the pressure in soil water (1, 5). This pressure may be either greater or less than atmospheric pressure, which is ordinarily taken as the pressure reference. At points below a water table the pressure is positive, but in unsaturated soil the water in a porous cup must be under negative or vacuum pressure in order to be in equilibrium with the water in the soil. The combination of a porous cup and a vacuum gage for measuring the *equivalent negative pressure*<sup>3</sup> or tension of water in unsaturated soil has been called a "tensiometer" (1).

Improvement in both the design and materials for tensiometer construction will undoubtedly continue, and no one design will be best for all types of use. Care must be exercised in the selection of materials and in the construction of any tensiometer if it is to give trouble-free operation, and sometimes difficulties develop which are not easy to anticipate.

Numerous requests have come to the writer for information on the design and construction of tensiometers. Since these units are not commercially available at present, it is hoped that this paper will be of assistance to those who wish to construct tensiometers for their own use. Three units that have performed satisfactorily under field and laboratory conditions are described.

#### TENSIO METER CUPS

Porous cups suitable for use with tensiometers and of almost any desired shape can be made up in the laboratory by the drain-casting process. Experimentation with different clays and firing processes may be necessary to obtain a suitable porous structure. The cup wall should be permeable to water, and yet when the wall is wet the "air-entry value" must be greater than one atmosphere. This value is simply the pressure difference required to produce an air leak through the cup wall when it is saturated with water. There is to a certain extent, a reciprocal relation between these two properties; when one is high the other is low. Experience indicates that the permeability should be as high as possible and still have the air-entry value greater than one atmosphere.

<sup>1</sup> Contribution No. 23 from the U. S. Regional Salinity Laboratory, Bureau of Plant Industry, Riverside, California, in cooperation with the 11 western states.

<sup>2</sup> Senior soil physicist.

<sup>3</sup> The expression "equivalent negative pressure" is used because it is not known over what range of soil moisture contents less than saturation, water is actually present in a liquid phase and outside the range of the adhesive force of the soil particles. Actually a tensiometer measures the negative pressure or tension to which the cup water must be subjected to give it the same free energy as the adjacent soil water with which it is in equilibrium.

The air-entry value may be determined by observing the air pressure required to produce air leaks through a tensiometer cup which is submerged in water after it is connected to a controllable compressed air source.

The water conductance of a tensiometer cup is the rate at which a cup transmits water at unit pressure difference. This appears to be a significant constant for a tensiometer and involves the area and thickness of the cup wall as well as the permeability of the porous body. Various methods have been suggested for measuring cup conductance (2).

The porous cups described in this paper are commercially<sup>4</sup> available, and the properties of the porous body appear to be almost ideal. The air-entry value is about two atmospheres, i.e., 30 pounds per square inch. The water conductance for the cups shown in figure 1 averages 0.05 cc. sec.<sup>-1</sup>atmos.<sup>-1</sup> for the larger spout top cup K 948, and 0.025 cc. sec.<sup>-1</sup>atmos.<sup>-1</sup> for the small gasket seal cup K 980.

#### TENSIOMETER FOR FIELD USE

A number of factors underlying good tensiometer design have been discussed elsewhere (2) and will not be repeated here. The system should be vacuum-tight, rugged, and arranged so that filling the system completely with boiled hot (air-free) water is a simple operation. Also, convenient means should be provided for detecting and removing any air that subsequently accumulates in the system.

The tensiometer shown in figure 1 A and B is suitable for field installations or where soil space is not limited. The steel tube to which the porous cup is secured by set screws serves as a handle for installing and removing the cup without stressing the vacuum joints. The mercury manometer is supported on the S-foot length of channel iron which is welded to the steel tube.

A glass air-trap is provided so that air accumulating in the system can be readily detected and removed. Trouble has been experienced with the joint at the ends of the copper tube which connects the porous cup with the air trap. Certain kinds of rubber tubing become hardened and blackened in contact with the copper. Tubing specified in the drawing has been found comparatively free from this reaction. Coating the outside of the copper with solder, tin, shellac, or bakelite varnish also prevents this trouble. Shellac and varnish will plug or foul the inside of the capillary manometer if allowed to get inside the tensiometer system.

A number of considerations enter in determining the size of the copper tubing used for connecting the porous cup with the air trap. Water can be poured into and will replace air from  $\frac{3}{8}$ -inch O.D. (0.030-inch wall) copper tubing, whereas smaller diameters require special filling arrangements. On the other hand unnecessarily large diameters increase "thermometer action" of the tensiometer water during the diurnal temperature swing (2). To avoid telescoping and breakage, the glass air-trap should have the same outside diameter as the adjoining copper tubing. Using  $\frac{3}{8}$ -inch copper tubing specified in figure 1 A and B

<sup>4</sup> Manufactured by the General Ceramics Company, Keasbey, New Jersey.

makes it necessary to use special microstoppers (18 mm. high, 12 mm. top diameter, 7 mm. bottom diameter) in the air trap. If  $\frac{7}{16}$ -inch copper tubing is used, the air traps can be large enough to take No. 00 rubber stoppers, which are commonly available in the laboratory. The air trap can be flared to take the large stopper, but less trouble has been experienced with leaks when the glass is finished with a light fire polishing and the right sized stopper is used.

A bore of 1.5 mm. is recommended for the capillary glass manometer tube. With a smaller bore it is difficult to avoid errors unless considerable care is used to keep the manometers and the mercury clean; a larger bore decreases sensitivity. A mercury column rising in the manometer will be broken by intervening sections of air or water if the glass capillary is allowed to rest squarely in contact with the bottom of the mercury pot. This may be prevented as shown in the figures by boring out the mercury cavity with a twist drill so as to leave a sloping bottom in the mercury pot. Mercury pots made from 1-inch maple dowel and boiled in paraffin are satisfactory; plastics such as lucite have also been used.

Copper tubing (0.095-inch O.D., 0.040-inch I.D.) is flexible and convenient to use for the water connection at the top of the manometer. A 48-inch length of this tubing is required for the tensiometer shown in figure 1 A and B. It is desirable for added strength to wrap the small tubing as shown in B if the joint to the  $\frac{3}{8}$ -inch tubing is made with soft solder. If the end of the small tube extends appreciably into the large copper tube the free transit of air and water through the latter will be impeded. The diameter of the small tube is increased to the diameter of the glass capillary by soldering on a  $\frac{3}{4}$ -inch length of 8-inch O.D. brass or copper tubing.

Rubber, when exposed in the field, weather-checks unless protected from sunlight. The Koroseal tubing<sup>5</sup> used for making the connection at the top of the glass capillary is virtually unaffected by sunlight and is considerably less pervious to gas than is rubber. This material is a thermoplastic and should be heated in boiling water at the time the connection is made.

The aluminum sunshield is worthwhile for protecting the air trap stoppers from the action of sunlight. Wood caps made by boring out maple dowels are equally satisfactory for this purpose. Phosphor-bronz clips retain the glass capillary tube and manometer scale in the channel iron support and also hold the small copper tube against the outside edge of the channel, as shown in figure 1 A.

Holes for the installation of these tensiometers in soil can be made with the standard sized King-tube. Field installations have been made to depths of 15 feet. Since the units can be completely assembled, tested, and have the scale zeros set in the laboratory, the task of field installation consists simply in setting the unit in a King-tube hole in the soil, packing the surface soil around the unit with a  $\frac{1}{4}$ -inch iron rod, and filling with boiled hot water. A recent

<sup>5</sup> In case Koroseal tubing is not available, the following kind of rubber tubing has been found almost as satisfactory: No. RG 001— $\frac{1}{8}$ -inch bore,  $\frac{3}{32}$ -inch wall. Redman Scientific Company, Los Angeles, California.

installation of 36 units at depths ranging from 6 inches to 5 feet was made by two men in less than two hours.

TENSIO METER WITH SMALL CUP

It is sometimes desirable to use tensiometers where soil space is restricted or where a minimum of soil disturbance is desired. The gasket-seal tensiometer cup shown in figure 1 C and in detail in figure 1 D and E was designed for such

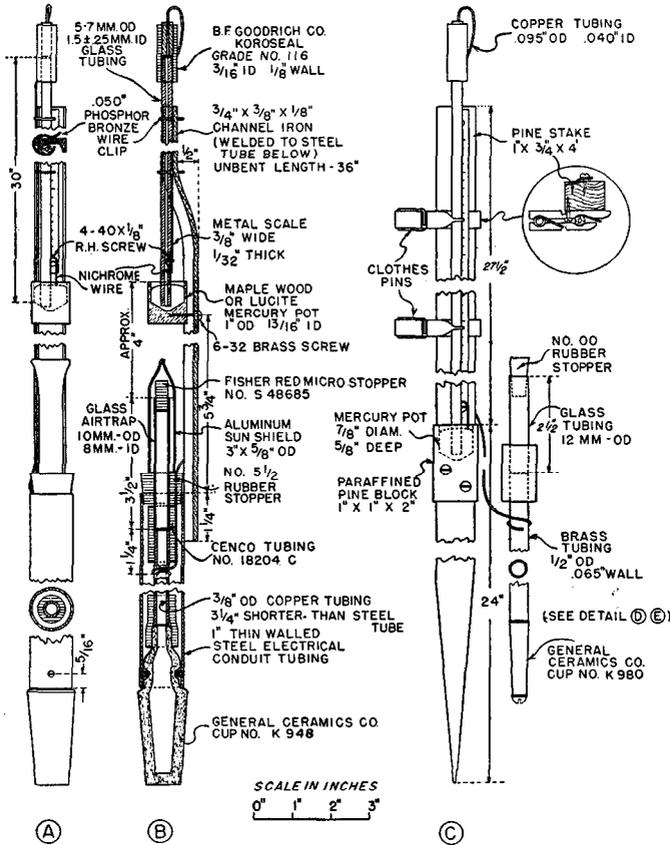


FIG. 1. A AND B, TENSIO METER FOR FIELD INSTALLATION ; C, GASKET-SEAL TENSIO METER CUP FOR USE IN RESTRICTED SOIL SPACE; D AND E, DETAILS OF GASKET-SEAL CUP FITTINGS; F, TENSIO METER FITTED WITH BOURDON GAGE

use. A hole for inserting these units can be made by a properly pointed steel pin. The gaskets may be cut on a lathe from Koroseal tubing, and no particular trouble is experienced in obtaining a vacuum seal if the holding screw is gently tightened when the cup and gaskets are boiling hot. The ends of the cup should be smoothed on fine sandpaper or an emery wheel. The flexibility of the gaskets makes this cup mounting surprisingly rugged, and no trouble has been experienced with breakage during installation. Care must be exercised to keep the

opening at the lower end of the glass capillary off the bottom of the mercury pot, because if breaks occur in the mercury column, mercury may be sucked over into the porous cup and will eventually disintegrate the brass fittings.

The wooden stake manometer support shown in figure 1 C may be used in place of the channel iron support shown in A and B.

When precise readings are not required, a Bourdon gage may be substituted for the mercury manometer. Such a tensiometer is shown in figure 1 F. The arrangement of the porous cup and steel tube is the same as that shown in figure 1

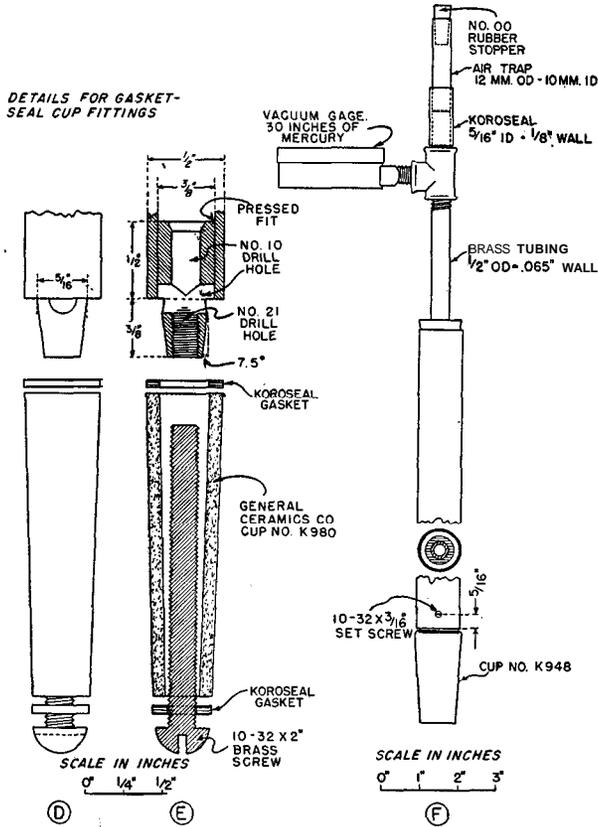


FIG. 1. (Continued)

A and B. On such units the air trap stopper should be inserted slowly so as not to damage the vacuum gage.

FILLING AND TESTING

All tensiometers should be tested for air leaks before being put in service. A single-piece ear syringe with a soft rubber pointed spout may be conveniently used for filling tensiometers with hot distilled water.<sup>6</sup> The syringe should be

† Distilled water should be used in testing work so that the water conductance of the porous cup will not be impaired by evaporation deposits. Distilled water is unnecessary when the cup is in the soil.

inserted in the air trap and water forced up the small copper tube and out past the mercury in the pot. By use of an aspirator or by mouth the mercury column should then be pulled up several times and suddenly released so as to remove air from the glass-to-metal junction at the top of the manometer.

The following are two procedures that may be used to test for leaks: 1. Pull the mercury column up by applying suction at the air trap and clamp off. The mercury meniscus in the capillary should remain 65 cm. or more above the mercury pot. The water in the tensiometer must be allowed to cool and excess water must be removed from the outer surface of the porous cup before a column this high can be maintained. 2. Completely fill the tensiometer with boiling water as above and insert the rubber stopper in the air trap. The mercury column will then begin to rise if evaporation is allowed to take place from the surface of the porous cup. This evaporation may be accelerated by use of an electric fan. The mercury meniscus in the manometer should rise at least 65 cm. above the mercury in the reservoir and remain above this point while the water disappears from the air trap. With either of these methods it is likely that air absorbed on the inner surfaces of the tensiometer will collect in the air trap and will have to be replaced once or twice with boiled water before the required test pressure can be attained.

#### MANOMETER SCALES AND ZERO SETTINGS

Ordinarily when the manometer scale on a tensiometer is read, either the negative pressure or the hydraulic head (3,4) of the cup water is wanted. These are usually expressed in mercury-column or water-column units. Since a counterbalancing water column comes into action as the mercury column rises in the capillary, the "effective" density of the mercury in the manometer is 12.5 instead of 13.5 (3). To simplify reduction of the measurements the writer has used manometer scales which are graduated in special units. On one scale, units were 8 per cent longer than centimeters and were divided in tenths. This scale, when used on manometers like those shown in figure 1 A, B, and C, corrects for the 'counterbalancing effect of the water and indicates changes in cup-water tension directly in centimeters of mercury. The other type of scale is calibrated to read cup-water tension directly in centimeters of water. The main divisions on this scale are 0.8 cm. apart, each corresponding to 10 cm. of water, with five subdivisions, each corresponding to 2 cm. of water. Both of these scales were made on nickel-silver stock  $\frac{1}{32} \times \frac{3}{8} \times 27\frac{1}{2}$  inches.' Inexpensive inch or centimeter scales, of course, may be used (2).

There is advantage in using water-column units whenever hydraulic head and hydraulic gradient are being considered in relation to soil moisture movement. Also, centimeters of water are the units commonly used for plotting sorption curves showing the relation between soil moisture tension and moisture content.

The elevation of the zero point of a manometer scale must be definitely located with respect to the mercury surface in the pot if correct readings are to be

<sup>1</sup> These scales were made by the Kennedy Name Plate Company, 4509 Pacific Blvd., Los Angeles, California.

obtained. The displacement of the zero point is required to compensate for the capillary depression of the mercury meniscus in the glass manometer tube and for the pressure change occurring in the water column which extends from the meniscus to the porous cup. A piece of 18-gage Nichrome or Chrome1 wire fastened to the lower end of the metal scale by a 440 x  $\frac{1}{8}$ -inch screw has been used for the zero indicator.

The elevation that the scale zero must have above the mercury pot for correct reading of cup-water tension may be determined by adjusting the scale so that the mercury meniscus in the manometer tube comes opposite the correct reading on the scale for any given and known cup-water tension. It is important to have a tensiometer completely filled with water before the zero position of the scale is determined. With assembled tensiometers like figure 1 A, distance from the scale zero to the end of the index wire is equal to the equilibrium mercury-column reading when the porous cup is half immersed in a vessel of water. A more generally usable procedure for determining the length of the scale zero-index wire is to leave out the air-trap stopper after the tensiometer is installed in the soil and filled with water. Under this condition the cup-water tension is negative (pressure is greater than atmospheric pressure) and equal to the hydrostatic pressure of the water column extending from the air-trap opening to the center of the porous cup. The scale zero, therefore, should stand above the manometer meniscus by the number of scale units corresponding to this water column. In other words, the correct length for the zero-index wire is equal to the elevation of the manometer meniscus above the mercury surface in the pot with the air trap stopper out plus the number of scale units equivalent to the vertical water column extending from the air trap opening to the porous cup.

The manometer scale can be set to read directly the hydraulic head of the cup water using the soil surface as the reference datum (3, 5). In this case, the length of the scale zero-index wire is equal to the elevation of the manometer meniscus above the mercury surface in the pot with the air trap stopper out plus the number of scale units equivalent to the water column extending from the air trap opening to the soil surface. When the length of the index wire is once properly determined, the elevation of the manometer scale should be adjusted before each reading so that the end of the index wire just touches the mercury surface in the pot.

#### USE AND LIMITATIONS OF TENSIO METERS

In the one-atmosphere soil moisture tension range, tensiometers provide direct information on the security with which water is held by soil, on whether the moisture content is increasing or decreasing, and on the direction of movement of soil moisture. Before tensiometer data can be used for determining the actual amount of moisture stored in or removed from the soil, or for determining the rate of moisture flow, it is necessary to have information on the way in which both the moisture content and the permeability are related to the soil moisture tension.

Even though tensiometers will not operate successfully over the whole soil-

moisture range that will permit the growth of plants, field experience indicates that they are useful for indicating the depth and rate of penetration of water in soil and for indicating the comparative rate at which moisture is extracted from soil at various depths. They appear also to have definite usefulness for studying and controlling moisture movement in connection with irrigation, and have been found to stay on scale throughout the year at moisture contents found under commercial irrigation practice for some crops.

#### REFERENCES

- (1) RICHARDS, L. A., AND GARDNER, W. 1936 Tensiometers for measuring the capillary tension of soil water. *Jour. Amer. Soc. Agron.* 28: 352-358.
- (2) RICHARDS, L. A., RUSSELL, M. B., AND NEAL, O. R. 1938 Further developments on apparatus for field moisture studies. *Soil Sci. Soc. Amer. Proc.* 2: 55-64.
- (3) RICHARDS, L. A., NEAL, O. R., AND RUSSELL, M. B. 1939 Observations on moisture conditions in lysimeters: II. *Soil Sci. Soc. Amer. Proc.* 4: 55-59.
- (4) RICHARDS, L. A. 1941 Hydraulics of water in unsaturated soil. *Agr. Engin.* 22: 325-326.
- (5) ROGERS, W. S. A. 1935 A soil moisture meter. *Jour. Agr. Sci.* 25: 326-343.