THE SORPTION-BLOCK SOIL MOISTURE METER AND HYSTERESIS EFFECTS RELATED TO ITS OPERATION[1]

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DAVIS and Slater (1)[3] in a note to this JOURNAL described a "direct weighing method for sequent measurement of soil moisture under field conditions". Independently the authors have been working on a moisture meter using the same principle and, although our results are not complete or conclusive, all the information we have obtained appears to be favorable to the method. Since our work on this project has been interrupted by the war, it is the purpose of this paper to report the progress we have made.

The method is based on the fact that a suitably disposed porous block will sorb (sorbeo-to suck in) moisture and come to equilibrium when placed in contact with moist soil. The rate at which equilibrium is attained and the degree of correspondence between the weight of the sorption-block and the moisture content of the soil are pertinent to the success of the method.

APPARATUS

Of the various forms of the apparatus tried by the authors, that shown in, Fig. 1 appears to be the most promising. A piece of tubing (A) inserted in the soil serves as the mounting for the system.[4] The soil surface at the bottom of the tube is leveled, packed gently, and covered by a disc of long fiber asbestos paper (B) which is cemented to the top of a short section of thin-walled brass tubing (c). This asbestos (0.008 inch thick) should be washed in water to remove sizing material. Three short legs of copper wire (D) soldered to the inside of the ring help to keep the asbestos cover in place. The sorption block (E) consists of a short cylinder of porous ceramic material mounted on a brass pin and covered with a disc of mica. We have used 36 gage copper wire rolled to a ribbon for the suspension.

A No. 5 rubber stopper (F) is mounted on the end of a section of steel tubing (G) (3/8 inch outside diameter, 1/32 inch wall). A washer is soldered on the tube to transmit the thrust to the stopper. The rubber stopper serves the double purpose of making a vapor seal to the sorption block chamber and also supplies a continuous elastic force to hold the block in contact with the soil when the small tube is lowered and clamped in place by the set screw in the threaded

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[3]Numbers in parenthesis refer to "Literature Cited", p. 1011.

[4]We have used 1-inch thin-walled steel electrical conduit tubing. The inside of the lower end must be polished and carefully coated with tin or solder to prevent. corrosion. The rest of the interior should be freed from burrs and coated with waterproof paint.

collar. A disc of mica (H) supports the upper end of the suspension and also helps to exclude extraneous material from the sorption block chamber. The turned wood cap (I), which is impregnated with paraffin, forms a closure for the top of the system and has a felt insert (J) to make a dust seal.

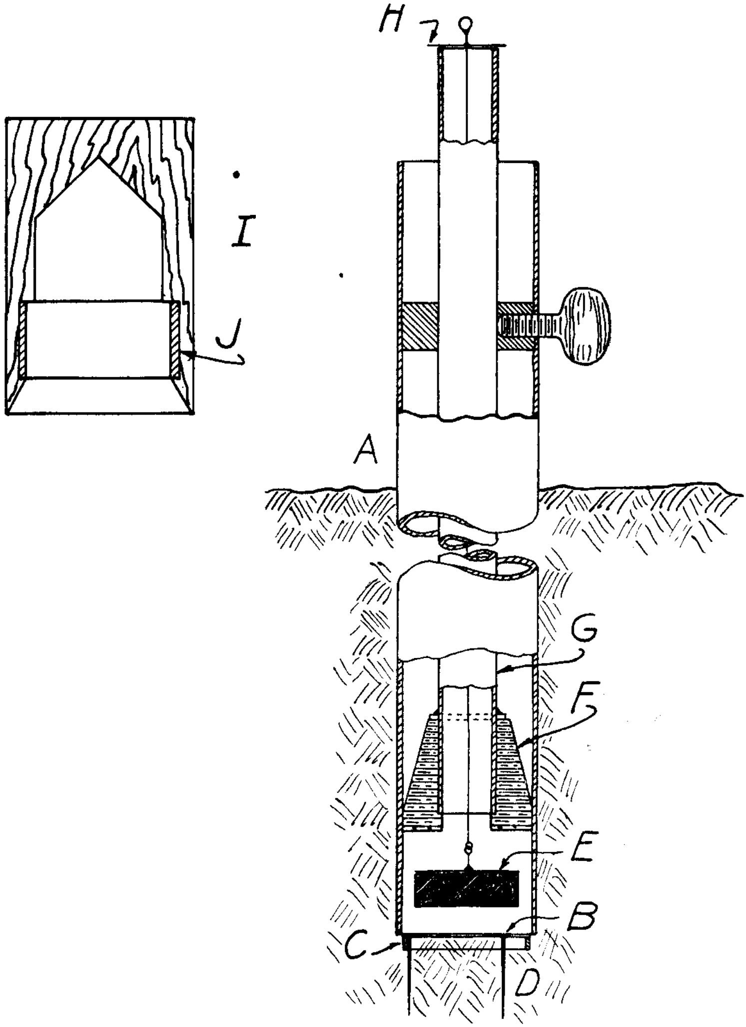

FIG. 1.-Sorption block assembly for a soil moisture meter.

We have used sorption blocks ¾ inch in diameter and ¼ inch thick which were plaster cast from a slip made from 90% common brick earth and 10% diatomaceous earth. After drilling holes for the brass pins, the blocks were brought to 850° C in an electric muffle furnace and allowed to cool. Abrasion of the blocks during handling was effectively prevented by lightly vitrifying the peripheral surface with an acetylene torch.

The sorption block weighings can be quickly made. The procedure is simply to (a) remove the wood cap, (b) unclamp the set screw and raise the rubber stopper (shown in the raised position in Fig. 1) and, (c) mount the weighing device on the top of the tube and attach the suspension system.

EXPERIMENTS

A preliminary experiment was set up in a constant temperature room (21° ± 1.0° C) to get information on the rate of transfer of water between sorption blocks and soil. Four 4-gallon crocks were filled with Fallbrook loam at four different moisture contents ranging from 15-atmosphere-percentage (near the wilting percentage) to the third-atmosphere-percentage (near the moisture equivalent). The soil for the crocks at low moisture levels was thoroughly mixed during and after wetting and was packed to field density. Three sorption block tubes were installed in each crock, the soil surface was heavily sealed with paraffin, and the pots were allowed to stand several weeks to approach equilibrium before experiments were started. The sorption-block installations were similar to those shown in Fig. 1. An analytical balance supported on a track was used for the weight measurements and weighings were made to 0.1 milligram. Lack of change of weight of each sorption block was considered indicative of equilibrium between block and soil.

Results from a considerable number of measurements may be summarized as follows:

1. Blocks saturated with water come to constant weight in wet soil in less than a day.
2. Dry blocks come to constant weight in wet soil in less than 3 days.
3. Wet blocks come to constant weight in dry soil in less than 5 days.
4. Blocks transferred between adjoining moisture levels either wetter or dryer generally reach equilibrium within 2 days.
5. For blocks having the composition given above there was found to be a hysteresis effect. That is, the equilibrium weight of a given block in a given soil depended on whether the block initially was wet or dry. This hysteresis effect was largest in wet soil. If the variation in the weight of the block from saturation to the wilting condition is taken as 100%, the block weight at equilibrium in 'wet soil (½ atmosphere tension) was found to vary through approximately 4% of this range, depending on whether equilibrium was approached from the wet or the dry side.

SORPTION-BLOCK OPERATION UNDER PLANTS

Sorption-block assemblies like those shown in Fig. 1 were installed at a depth of 6 inches in 4-gallon crocks containing Fallbrook loam. The crocks which were planted to maize and placed in the greenhouse are shown in Fig. 2. Block weight readings were taken usually just once daily between 8 and 9 o'clock in the morning. Fig. 3 shows

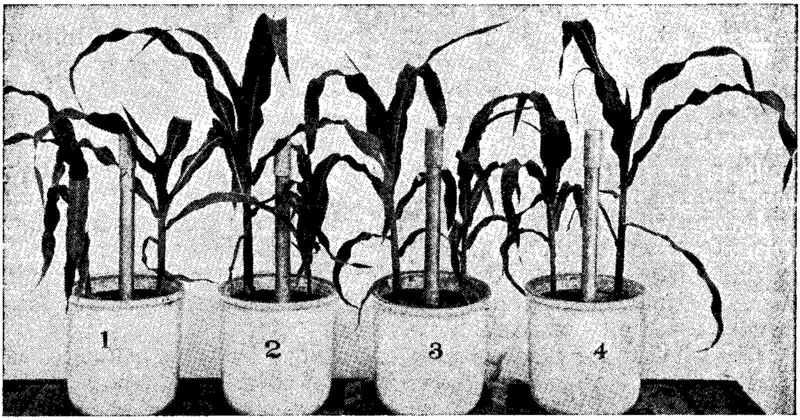

FIG. 2.-Sorption-block moisture meters in greenhouse pots. The photograph shows the condition of the maize on July 21, one day after irrigation.

the gross weight vs. time curves for these four moisture meters. When the plants were badly wilted, enough water was applied to the pots to produce some drainage outflow. The open circles on the curves indicate the day on which the plants developed wilting symptoms before noon. Fig. 2 shows the condition of the plants on July 21, one day after irrigation. It is seen that block weight corre-

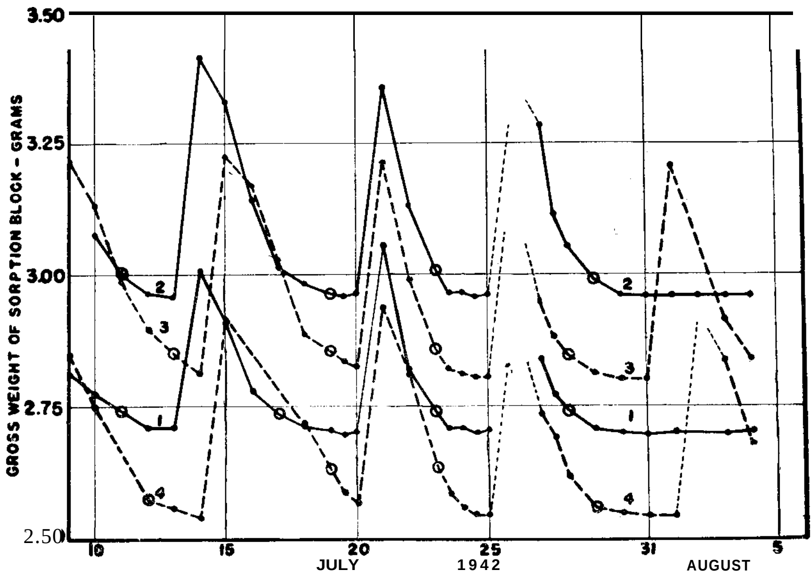

FIG. 3.--The variation of sorption block weight with time. The blocks were installed at a depth of 6 inches in four soil pots in which maize plants were grown. The open circles on the curves (one curve for each pot) indicate the days when wilting occurred before noon.

lates nicely with wilting, the variations in the weight of a block at the successive wiltings being generally less than weight losses during one day's time. There is reason to believe the blocks were not lagging far behind the soil even under these conditions of rapid soil moisture extraction. It is seen further that after permanent wilting the block weight soon attains a minimum value and that this minimum is the same for subsequent dryings. For the sorption blocks used in this experiment this minimum weight was not far above the oven-dry weight so these blocks were not suitable for studying moisture losses in the wilting range. Gross pot weight readings were not taken so the relation between block weight and soil moisture content was not established, but the curves in Fig. 3 resemble weight loss curves for soil pots containing plants (7).

It is seen that the range of moisture change for the blocks used is 300 to 400 milligrams. The gross weight of these blocks and suspension systems was kept small because the weight readings were made with a low capacity spring balance[5] free from the thermal effects. The authors have not studied the weighing problem sufficiently fully to make recommendations on a weighing device for general field use, but this appears to be only an incidental technical problem. In the future we plan to use sorption blocks about 3/8 inch thick.

HYSTERESIS

In the absence of temperature gradients it appears that gravity and gradients in the equivalent negative pressure or soil moisture tension are chiefly responsible for the movement of water through soil and hence into and out of sorption blocks. The relation between the soil moisture content and soil moisture tension for the block and the soil is thus of some interest.

It appears to be well established experimentally that there is a hysteresis effect in the relation between soil moisture tension and moisture percentage (4). This is indicated by the moisture content differences found at the same tension for various soils as shown in Table 1. Fig. 4 is a graphical representation of the data for the Yolo fine sandy loam. The soils are surface samples, 0 to 6 inches, and the series names were taken from the soil maps. The Vale sample is from plot B of the alkali experimental plots of the Oregon Agricultural Experiment Station at Corvallis.

These results were obtained with 6-inch double-walled irrigator pots by a method which has already been described (4). The experiment was conducted at a temperature of $21 \pm 1^\circ$ C and the equilibrium moisture content of the soil for the successive soil moisture tension values was calculated from the initially determined tare weight and the successive equilibrium gross pot weights. The soils were screened and packed in the pots at approximately field density. The initial moisture content and the date of starting of the experi-

[5]The spring was the Isoelastic type manufactured by John Chatillon Company. It was 0.32 cm in diameter and 12.5 cm long, with a spring constant of 5 cms per gram. A conventional jolly balance mounting was used and weighings could be quickly made to within ± 2.5 milligrams. The authors have also used inexpensive jolly balance springs, but these are subject to temperature effects for which we did not wish to make adjustments in this preliminary work.

TABLE 1.—*Hysteresis data for six soils from western United States.**

Equilibrium attained	Fallbrook loam S-40-1			Ritzville loam S-40-18			Yolo fine sandy loam S-40-23			Indio very fine sandy loam S-40-4			Vale plot B S-40-16			Imperial clay S-40-3		
	Date	Tension	Pw	Date	Tension	Pw	Date	Tension	Pw	Date	Tension	Pw	Date	Tension	Pw	Date	Tension	Pw
Start	Mar. 12, '41	—	4.17	Mar. 11, '41	—	2.14	Mar. 11, '41	—	9.02	Mar. 11, '41	—	5.37	Mar. 12, '41	—	12.40	Mar. 12, '41	—	9.34
1	June 12	610	5.23	July 10	610	10.20	July 10	610	17.16	Aug. 5	609	12.49	July 10	610	21.28	June 12	610	28.28
2	Aug. 18	305	5.86	Oct. 27	306	13.14	Sept. 30	304	19.10	Sept. 30	305	14.65	Sept. 30	304	23.90	Aug. 18	305	29.71
3	Jan. 7, '42	152	7.75	Feb. 20, '42	153	19.60	Dec. 23	154	22.00	Dec. 23	153	18.50	Dec. 23	153	27.97	Oct. 15	153	31.89
4	Feb. 20	2	23.05	Mar. 20	0	39.01	Feb. 20, '42	0	42.39	Feb. 20, '42	0	40.09	Feb. 20, '42	0	48.47	Jan. 7, '42	0	52.31
5	Mar. 25	153	14.44	Mar. 25	153	33.47	Mar. 20	152	25.47	Mar. 20	153	28.62	Mar. 19	153	34.17	Feb. 20	152	35.24
6	Apr. 1	306	8.54	Apr. 1	305	18.53	Mar. 24	305	22.46	Apr. 20	306	24.05	Mar. 25	305	29.37	Mar. 20	305	32.83
7	Apr. 17	610	6.02	Apr. 17	611	12.77	Apr. 1	610	19.82	May 5	610	21.42	Apr. 1	610	24.96	Apr. 1	610	30.69
8	Apr. 27	774	5.55	Apr. 27	775	11.60	Apr. 11	776	18.64	May 29	777	19.22	Apr. 8	777	23.27	Apr. 8	776	29.79
9	May 3	611	5.63	May 12	611	12.15	Apr. 27	611	18.72	June 10	610	18.63	Apr. 17	611	23.61	Apr. 24	614	29.90
10	May 12	306	6.53	May 25	307	15.05	May 5	305	20.24	June 20	306	19.14	Apr. 22	306	26.08	May 5	305	30.95
11	May 25	153	10.27	June 15	153	21.80	May 18	154	22.80	June 26	152	19.90	Apr. 27	153	30.15	June 2	1	45.58
12	June 10	1	20.06	July 8	0	33.91	May 29	305	20.97	July 8	0	33.40	May 5	0	42.56	June 10	152	33.92
13	June 20	153	13.34	July 22	153	26.72	June 10	610	19.10	July 22	152	25.83	May 12	153	31.99	June 20	305	32.04
14	July 1	306	7.63	July 27	304	17.91	June 20	776	18.60	Aug. 3	306	23.12	May 18	306	27.87	July 1	612	30.09
15	July 8	612	6.14	Aug. 3	613	12.88	June 24	611	18.68	Aug. 10	611	21.59	July 8	777	23.17	July 8	777	29.64
16	July 15	781	5.63	Aug. 11	775	11.96	July 8	306	20.17	Aug. 20	776	20.07	July 15	610	23.36	July 15	611	29.75
17	July 22	610	5.74	Aug. 16	612	12.33	July 15	610	18.95	Aug. 26	610	19.64	July 22	305	25.79	July 22	296	30.84
18	Aug. 3	305	6.73	Aug. 22	306	15.38	July 22	776	18.49	Aug. 30	307	19.86	July 29	153	29.93	July 31	154	32.49
19	Aug. 10	153	10.23	Aug. 28	154	21.76	July 27	610	18.60	Sept. 2	152	20.32	Aug. 8	0	41.54	Aug. 8	0	44.15
20	Aug. 22	0	19.59	Sept. 4	0	32.40	July 31	307	19.75	Sept. 4	0	31.12	—	—	41.4†	—	—	43.7†
21	—	—	19.6†	—	—	32.6†	Aug. 10	153	22.49	—	—	30.5†	—	—	—	—	—	—
22	—	—	—	—	—	—	Aug. 22	0	36.75	—	—	—	—	—	—	—	—	—
23	—	—	—	—	—	—	Aug. 26	152	24.17	—	—	—	—	—	—	—	—	—
24	—	—	—	—	—	—	Aug. 30	306	21.54	—	—	—	—	—	—	—	—	—
25	—	—	—	—	—	—	Sept. 3	776	19.02	—	—	—	—	—	—	—	—	—
									18.6†									

*Soil moisture tension is expressed in cm of water. Pw is grams of water per 100 grams of dry soil.
†Check value of Pw determined by drying at the termination of the experiment.

ment are given in the first row of data in Table 1. The successive dates for the successive equilibria are also given. In many cases the pots were allowed to stand longer than was necessary to attain equilibrium, but from intermediate gross pot weight readings it was made certain that equilibrium was attained before the tension

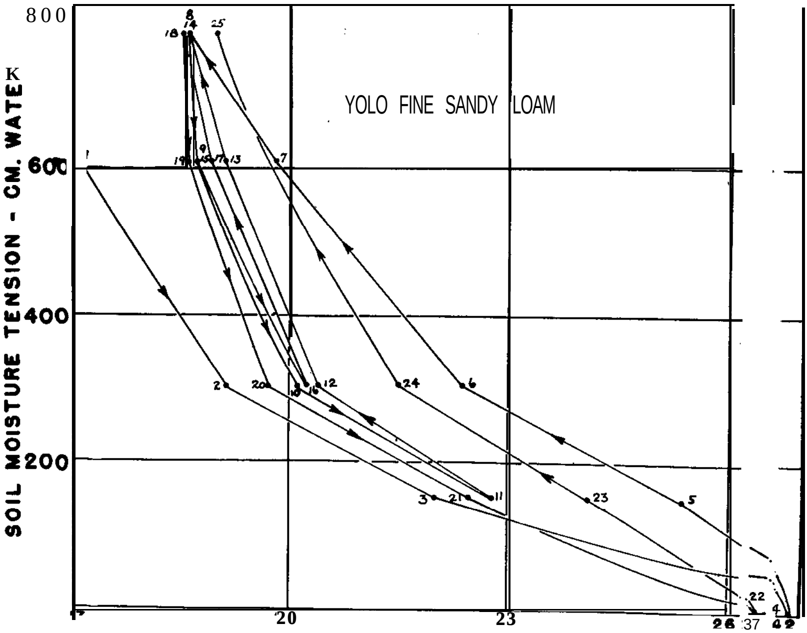

FIG. 4.-Curves showing equilibrium moisture sorption data for Yolo fine sandy loam. The numbers on the curves indicate the chronological order in which the various equilibria were obtained.

changed.[6] At the end of the experiment the moisture percentage was determined by drying as a check against the value calculated from the gross pot weight. These check values are given at the bottom of the moisture percentage columns. The soil moisture tension is given as the distance from the center of the soil mass (approximately 2.5 kilos) to the free water surface in the supply reservoir. This distance seldom varied more than ±2 cm from the desired value.[7]

[6]It will be noted that for equilibria following 9 and 17 for the Indio soil, a decrease in tension resulted in a decrease in the moisture content. This is inconsistant with all past data and throws some doubt on whether points g and 17 were actually equilibria points.

[7]Table 1 gives the average moisture content and the average soil moisture tension in the soil mass, but because of the height of the soil column (18 cm) there is a tension difference at each equilibrium of 18 cm of water between the top and bottom of the column and at low tensions this results in a very appreciable moisture content gradient. Small changes in the level of the water in the supply reservoir at the zero tension setting produce corresponding changes in the water table in the soil pot with consequent large changes in the calculated (average) moisture percentage. This fact accounts in large part for the spread in moisture content values at zero tension.

As has been indicated by Haines (2) and by S. J. Richards (3) for sands, it is apparent from Fig. 4 that equilibrium between soil moisture tension and moisture content can be attained at any point within the hysteresis loop. Thus, any method for estimating soil moisture content that is based on a soil moisture tension measurement will involve an uncertainty as large as the width of the hysteresis loop, unless something is known of the moisture history of the soil. However, the amount of hysteresis found for the soils in Table 1 is probably considerably larger than occurs for these soils under field conditions. It is not known, for instance, to what extent the difference between the initial and subsequent wetting curves is due to the structural change occurring during the first wetting. Also, field experience and the time required to obtain the first three equilibrium points for the soils in Table 1 indicate that seldom is any appreciable fraction of the soil profile in the moisture states represented by the left hand curve in Fig. 4. On the other side of the hysteresis loop it will be noted from the data in Table 1 that the extreme curve is usually connected with the highest moisture content attained in wetting. Field experience with tensiometers indicates that seldom are well-drained soils beneath the surface few inches wetted to zero tension, even under basin irrigation. A hysteresis loop such as represented by points 9, 10, 11, 12, and 13 is more commonly to be expected in the field. Furthermore, as indicated by the data in Fig. 3, if the soil moisture is replenished with an ample application of water, the wetted part of the profile will exist in moisture states represented by drying (desorption or moisture retention) curves most of the time. For the extreme case, when the soil inoisture fluctuates between fixed limits, the moisture regime will be represented by a single drying curve.

Little information seems to be available on hysteresis effects in porous media having fixed structure. Our experiments indicate, as would be expected, that the effect does exist and it appears that this should be an advantage rather than a disadvantage in the operation of sorption-block moisture meters. Hysteresis in the block will be in the same phase as hysteresis in the soil and hence will make the block weight more nearly correspond to soil moisture content.

DISCUSSION

At equilibrium the soil moisture tension in a sorption block approaches equality with the tension in the contiguous soil. For agricultural purposes the most useful information that can be obtained from readings with a sorption-block soil moisture meter would be (a) an indication of the rate and time of approach to the wilting condition, and (b) an indication of the amount of available moisture present in the soil, expressed either as volume of water per unit depth of soil or as a fraction of the available range for the soil.

Recent experiments at this laboratory (5, 6) indicate that the first of these objectives can be achieved with sorption blocks. Readings for a series of sorption-block installations can be quickly interpreted if the blocks are tared so as to have the same weight at, the wilting condition. To attain the second objective may require the selection of sorption blocks with a moisture retention characteristic related in a fairly definite way to the characteristic curve for the soil. This, however, should not be difficult to do.

When the U. S. Weather Bureau was first established to obtain information of use to farmers, the moisture reserve in the soil was proposed as one element in the crop environment to be widely measured and reported. The difficulties encountered did not make this feasible. For such purposes as crop yield forecast, a representative indication of moisture reserves available in the soil for maturing a crop would be useful and the sorption block moisture meter may prove suitable for this kind of work. A more immediate and practical application, of course, would be its use as an aid in soil moisture control under irrigation.

As Davis and Slater (1) have indicated, the sorption-block type of moisture meter makes possible the "sequent measurement" of moisture changes at a given location which is of particular advantage in following continuously the depletion of available moisture. When properly built, these units should require little servicing or attention and accurate results should be immediately obtainable even with long periods of neglect or elapsed time between readings. The units are not susceptible to frost injury or to disturbances from salt effects in soils. This latter feature is of considerable importance to the work of the Salinity Laboratory where the moisture regime of plants in saline and alkali soils is under study. The authors are inclined to favor ceramic sorption blocks, thus avoiding troubles that may arise from the solubility and low mechanical strength of gypsum.

The temperature of the sorption block, as well as the temperature of the adjacent chamber and soil, should be representative of the surrounding soil so as to prevent condensation in the sorption block chamber and to prevent moisture gradients in the soil adjacent to the block which might arise in response to temperature disturbances introduced by the tube. We have used steel tubing in our units. This may be expected to give trouble with shallow installations, especially where the temperature of the exposed part of the tube differs considerably from the soil temperature. We have not made a careful study of temperature disturbances, but for installations at a depth of 6 inches in greenhouse pots (Fig. 3), data for morning and evening readings lie on a smooth curve.

Experiments should be conducted to determine the characteristics of porous ceramic material best suited for sorption block use and to determine more precisely what correspondence there is between block weight and soil moisture content for various wetting and drying rates and limits. We have used the pressure-membrane apparatus for obtaining the moisture retention curves for various porous ceramic materials, but this work has not proceeded far enough to make specific recommendations. It appears that a reasonably satisfactory test of the relation between sorption block 'weight and moisture content can be made in soil pots containing a uniformly distributed plant root system. Under proper conditions the moisture throughout the pot is depleted fairly uniformly and the soil moisture content at the block can be inferred from the gross pot weight.

SUMMARY

A porous ceramic block if protected from evaporation will come to moisture equilibrium with soil with which it is in contact. A description is given for a sorption-block soil moisture meter based on weighing the block while suspended in the soil, thus avoiding exposure to evaporation. Various tests made indicate that this type of apparatus can be used for measuring the condition and amount of moisture in soil.

Data on the hysteresis effect for six soils are given. The occurrence of hysteresis in ceramic sorption blocks is noted, and this, being in phase with that of the soil, should improve their action for measuring soil moisture.

LITERATURE CITED

I. DAVIS, WENDELL E., and SLATER, C. S. A direct weighing method for sequent measurements of soil moisture under field conditions. Jour. Amer. Soc. Agron., 34:285-287. 1942.

2. HAINES, W. B. Studies in the physical properties of soils. The hysteresis effect in capillary properties, and modes of moisture distribution associated therewith. Jour. Agr. Sci., 20:97-116. 1930.

3. RICHARDS, STERLING **J.** Soil moisture content calculations from capillary tension records. Soil Sci. Soc. Amer. Proc., 3:57-64. 1938.

4. RICHARDS, L. A. Uptake and retention of water by soil as determined by distance to a water table. Jour. Amer. Soc. Agron., 33:778-786. 1941.

5. ——— and WEAVER, L. R. Moisture retention by some irrigated soils as related to soil moisture tension. In press in Jour. Agr. Res.

6. ———. The relation between the fifteen atmosphere percentage and the permanent wilting percentage In press in Soil Science.

7. TAYLOR, C. A., BLANEY, H. F., and McLaughlin, W. W. The wilting-range in certain soils and the ultimate wilting-point. Trans. Amer. Geophys. Union, Fart 1934.