COMPARISON OF TECHNIQUES FOR CALIBRATION OF GYPSUM AND FIBERGLAS ELECTRICAL RESISTANCE UNITS FOR SOIL MOISTURE MEASUREMENT

by

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INTRODUCTION

Increasing demands for available water for irrigation have arisen because of expansion of irrigated acreage in both the arid and humid areas of the United States. To keep abreast of the ever-expanding demand it becomes increasingly necessary to use the available water in the most efficient way possible. Efficient and economical irrigation requires a knowledge of when to irrigate and how much water to apply. At present, on a large proportion of the irrigated acreage, irrigation is practiced without suitable means for obtaining this knowledge. This leads to the possibility of over-irrigating or under-irrigating, either of which may result in reduced production and higher irrigation costs as well as undesirable chemical, physical, and biological reactions in the soil. Better guidance to economical and intelligent irrigation is therefore needed.

Accurate measurements of soil moisture are essential for determination of irrigation requirements and soil moisture reserves. Soil moisture records aid in the evaluation of plant-soil-water relations governing the growth and yield of economic crops. The need for this information has led to the development of a number of methods for soil moisture measurement. Among these are several which measure soil moisture "in situ". These methods make it possible to obtain frequent measurements of the soil moisture status at essentially a point in the soil and obviate the difficulties inherent in direct sampling: the immense expenditure of labor, the variations in soil samples, and the impossibility of taking a sample without destroying the sampling point.

The electrical method of measuring the resistance to a current passing between two electrodes buried in a soil is one of the methods that has been developed and is used with various modifications. One of the first and most widely used methods was to cast the electrodes in a porous medium which was then called an electrical resistance block. Although there are several types of electrical resistance blocks on the market, their reliability is still questioned. At present the electrical resistance method of measuring soil moisture is a semiquantitative method.

Some of the problems needing investigation to improve the quantitative aspects of electrical resistance methods are (1) the proper choice of porous materials, (2) the geometric design of the block and electrodes, and (3) the methods of calibration. Correlation of electrical resistance of the blocks with soil moisture content or soil moisture tension has been determined by various calibration methods, none of which have been accepted as entirely satisfactory.

The general objective of this study is to obtain information for evaluating various methods of calibration of selected blocks.

REVIEW OF THE LITERATURE

Development of Electrical Soil Moisture Measuring Instruments

The procedure involved in the electrical resistance method of measuring soil moisture is that of measuring the electrical resistance between two electrodes embedded in a porous medium buried in the soil. The measured resistance is a function of the moisture content of the medium surrounding the electrodes, which in turn is a function of the soil moisture tension. The medium, in which the electrodes are embedded, may consist of such materials as gypsum (plaster-of-paris), fiberglas, or nylon. The electrodes being embedded in the porous material, making a single unit commonly known as a block, provide better contact with the surrounding soil when buried than do bare electrodes in the soil. While the common unit is a rectangular gypsum block with parallel electrode, various modifications and combinations of these blocks exist, for example, cylindrical blocks with concentric electrodes, rectangular gypsum-fiberglas blocks with rectangular electrodes, and rectangular nylon-gypsum blocks with rectangular electrodes.

Bouyoucos and Mick (10, pp. 455-465) were the first to propose the rectangular gypsum block. Bouyoucos (16,

p. 449) 17, p. 135) later suggested improvements and modifications to increase the durability and sensitivity of his original unit. Gypsum blocks similar to the Bouyoucos pattern but different in material and preparation were made by Aitchison et al (5, pp. 72-73). These were reported to be more sensitive than the Bouyoucos and Mick blocks, over a wider range of soil moisture.

Since some electrical flow takes place outside the rectangular gypsum blocks with parallel electrode and this outside flow is affected by soil texture and salts, Slater (42, p. 285) presented a modified concentric electrode resistance unit for soil moisture measurement. A similar type of gypsum unit was used by Pereira (37, p. 213) for deep soils in Africa. The concentric electrode, with a slight difference in the geometry of the electrode system, was used by Croney et al (26, p. 86, 91) who felt that in designing accurate soil moisture measuring instruments the type of electrode system is of secondary importance to that of the absorbent used. Bouyoucos (18, p. 340) also inserted a new type of electrode into his rectangular gypsum block to lessen external conductance. All the above workers encountered difficulties in the construction of concentric electrode systems due to shapes, spacing, and arrangement of the electrodes.

A new soil moisture absorbing unit and soil moisture resistance meter was introduced by Colman in 1946 (23, p. 85) 24, pp. 1-20). Colman states that his fiberglas unit has its greatest potentialities in studies of hydrologic and forestry problems because of its rapid response to changes of soil moisture near saturation.

Bouyoucos (13, p. 327) devised nylon and fiberglas electrical resistance blocks; of these, the nylon block gave superior performance and smoother calibration curves than the fiberglas.

Youker and Dreibelbis (51, p. 448) constructed a rectangular fiberglas-gypsum block, patterned somewhat after the design of Bouyoucos and Mick, that is useful over the soil moisture range from saturation to the wilting point. The gypsum serves as a buffer and assures contact with the soil while the resistance responses of the fiberglas are such as to furnish reliable data in the wet range which the gypsum alone does not give.

A combination of several gypsum units into a cylindrical stake unit that can be inserted into the soil to a depth of two feet in one operation was introduced by Abd-El-Samie and Marsh (2, p. 404).

Factors Affecting Soil Moisture Measurements by Electrical Resistance Methods

There are many factors that influence the variability and behavior of soil moisture measuring instruments (34, p. 781) 47, pp. 1-5). Slater and Bryant (43, pp. 146-147) noted that differences in soil, instrument response, and variability among instruments themselves were important factors. The merits of each instrument depended on the sensitivity of the individual units at various soil moisture tensions. In detailed comparisons of the performance of gypsum and fiberglas units for soil moisture determinations, Albareda et al (6, pp. 579-673) found for soil moisture tensions less than 0.3 atmospheres that the fiberglas units were the most sensitive. However, the electrical resistance measurements with all the blocks tested became less accurate as the sand and organic matter contents of the soil increased.

Fiberglas, nylon, rectangular gypsum, and fiberglas-gypsum blocks were tested by Palpant and Lull (36, p. 12). The electrical resistance of fiberglas blocks was found to respond to relatively small changes in moisture content throughout the range of available moisture, whereas that of the rectangular gypsum block was not responsive in the wet range. They believe that with the exception of this insensitivity of the rectangular gypsum unit there is little reason to say that one type of unit is more sensitive than another: "within their limitations, all...units respond similarly to changes in soil moisture." (36, p. 14).

Croney et al (26, p. 91) reported that their concentric electrode units were insensitive from 0 to 0.3 atmospheres of tension and at 10 atmospheres the resistance became too large to measure. Tanner and Hanks (46, pp. 49-50) demonstrated with gypsum blocks that an appreciable resistance-hysteresis may occur: for instance, block resistance of 6,200, 23,000 and 58,000 ohms may correspond, respectively, to tensions of 1.16 to 2.5, 2.45 to 2.65, and 4.7 to 7.4 atmospheres. Bouyoucos and Mick (12, p. 539) maintain that the rectangular gypsum block shows the least hysteresis between drying cycles. Perieria (37, p. 218) noted that hysteresis effects were encountered with his concentric gypsum blocks unless each wetting and drying cycle began at saturation.

The electrical resistance of a medium is a function of the temperature of the medium; therefore, all moisture measuring units using the electrical resistance principle are temperature sensitive. Consideration was given by Aitchison (3, pp. 418-426) to the accuracy of measurement of soil temperature, and to temperature corrections to be applied to the rectangular gypsum blocks. An alinement chart was designed by Bethlahmy (8, p. 379) to adjust resistance of fiberglas blocks to a temperature of 60° F in one time-saving operation.

Electrical resistance also depends upon the salt concentration in the block and in the soil. Gypsum is used to diminish the effect of salts in the soil; however, limitations must be placed on the use of the units in saline soils. Soil salinity causes an appreciable shift in the relation between electrical resistance of the unit and soil moisture content of the soil. There was a very significant drop in the resistance of fiberglas units when Ewart and Baver (30, pp. 58-60) increased the salinity level of the soil from 0% to 0.1%. However, their results indicated that resistance values of gypsum blocks are sufficiently reliable for use in moderately saline regions but will show a lag in resistance in soils on which all crop growth is restricted by higher salinities. Weaver and Jamison (48, pp. 603-605) reported that the resistance of fiberglas units is little affected by salts in the wet range near saturation but the effect becomes greater as the tension increases. Bouyoucos (14, pp. 509-511) reported that for practical purposes, from wilting percentage to field capacity, the electrical resistance measurements of gypsum blocks is believed to be reasonably accurate in soils which have received fertilizer applications of 1000-2000 lbs of a 10-10-10 ($N-P_2O_5-K_2O$) fertilizer mixture per acre.

Variations in resistance between individual blocks arises from difficulties in manufacturing. Croney et al (26, p. 91) emphasized the importance of producing instruments of uniform characteristics because very small differences in mixing and curing of gypsum units have an important influence on the moisture tension-resistance relationship of the unit. Cummings and Chandler (27, p. 84) found 25 to 50 percent variations in resistance readings of individual rectangular gypsum blocks under comparable conditions in water, and at higher tensions as much as 100 percent variation. Fiberglas units (32, p. 420) did not shift in their relation between soil moisture and resistance after 15 months exposure and six drying cycles. To prevent any shifting in calibration of new gypsum blocks, due to alternate wetting and drying which alters the pore size distribution of the units, Bouyoucos (18, pp. 341-342) suggested that new gypsum blocks be put through a process of drying and wetting to attain maximum curing.

Resistance units with a parallel electrode geometry are affected by electrical current conductance outside the block. This was demonstrated to be of considerable magnitude on the block resistance readings as obtained by measured differences in water, soil and air (27, pp. 81-84). These effects are eliminated by the concentric electrode systems.

Soil differences which affect block behavior can be minimized if the resistance is expressed as a function of tension or free energy of the soil moisture: the resistance of any type of electrical resistance unit, in a soil of negligible salinity, is believed to be a measure of the free energy of the water (28, p. 279) 29, p. 112). This free energy is a function of the tightness with which the water is held in the soil mass.

Cummings and Chandler (27, p. 85) demonstrated the possibility of expressing the resistance values of gypsum blocks in terms of soil moisture tension. The electrical resistance moisture-tension relationship should be constant for any given type of electrical soil moisture measuring instrument, because any type of unit will hold its water with the same tightness with which the water is held in the soil mass. Differences that are encountered can be traced to differences in salt concentrations of the soil or to the disturbance of the soil structure (25, pp. 429-433).

Calibration of Electrical Resistance Soil Moisture Measuring Instruments

The electrical resistance-soil moisture percentage or soil moisture tension relationship must be determined for each individual unit. Slater and Bryant (43, p. 147) stated, "reliance can be placed on an instrument to indicate a correct moisture level only if it is first individually calibrated." Block calibrations can be considered in two categories, namely, laboratory procedures and field techniques.

Laboratory Procedures: Bouyoucos and Mick (11, pp. 224-225) proposed a shallow pan method for determining the soil moisture-resistance relationship. In this method, blocks are placed in a pan (1 x 2 x 2 inches), filled with 50 grams of soil and saturated with water. Resistance readings and weighings are made at varying intervals throughout the drying cycle. Kelley (33, p. 433) found this method to be unsatisfactory. Anderson and Edlefsen (7, p. 416) substantiated Kelley's conclusion with the reason that there is a lag of response to moisture changes in the vicinity of the wilting point by the Bouyoucos calibration method. Kelley (33, pp. 433-434) proposed a rapid method for calibrating various units. In this method (50, p. 23) a block is placed in a wire basket (1 1/2 x 2 3/8 x 3 1/2 inches), filled with soil and saturated with water. The contents of the basket are allowed to partially dry in air, and then the basket is placed in an equilibrium chamber before reading and weighing. Several points are obtained at successive stages of dryness.

Calibration curves were obtained by Haise and Kelley (31, pp. 413-414) for gypsum blocks by use of the pressure membrane extraction apparatus. Tanner et al (45, p. 63) modified the Haise and Kelley calibration method by placing the gypsum units on a rubber dam in the pressure membrane apparatus to prevent any influence of external conductance. Aitchison and Butler (4, p. 258) could not interpret the Haise and Kelley method in terms of the characteristics of gypsum blocks embedded in a soil mass. Aitchison, et al (5, p. 66) installed gypsum blocks in a pressure membrane extraction apparatus embedded in 5 kg. of soil. This required long periods of time for units to come to equilibrium with the applied tension.

The calibration procedures previously discussed require disturbed samples of soil. Hendrix and Colman (32, p. 421) found these methods were unsatisfactory because field bulk density and structure could not be exactly reproduced in the laboratory. They recommended laboratory calibration of units be made in cores of undisturbed soil obtained in the field. Although this calibration technique was tried by Youker and Dreibelbis (51, p. 448), field calibrations were found to be superior.

Abd El-Samie (1, pp. 21-22) calibrated gypsum blocks by placing the units in metal cans which were sealed after filling with soil which contained varying amounts of moisture. After the resistance readings had become constant a soil moisture sample was obtained. Difficulties were encountered with condensation and uniform moisture contents within the cans.

A procedure is described by Bethlahmy (9, pp. 699-706) in which laboratory calibration curves are first determined for fiberglas blocks. This gives the general shape and slope of curve for the units. The curves are then altered to fit a particular soil by laterally shifting the line of regression along the soil moisture axis an amount determined by a few field samplings. The alteration accounts for soil and plant differences.

Closs (22, pp. 333-338) introduced a rapid procedure for calibrating gypsum blocks by determining the freezing point depression of the water held in the medium of the units. In this method thermocouples are embedded in gypsum blocks which are then saturated with water and placed in a refrigerator. Readings of temperature and resistance are taken at intervals until the freezing point depression has been determined.

Field Calibrations: The Western Soil Research Committee (49, pp. 1-3) reported that gypsum block calibrations performed in the field with growing plants give better results than without plants and laboratory calibrations are satisfactory with 20 kg. or more of soil with growing plants. This calibration procedure is an outgrowth of a study conducted by Anderson and Edlefsen (7, p. 425). A steep soil moisture gradient is developed and maintained in the boundary layer surrounding the block where plants are growing.

Carlson (20, pp. 31-39) 21, pp. 34-42) did not find laboratory calibrations sufficiently accurate to supplant field calibration of fiberglas units. He reported that the failure of the laboratory and field calibration curves to coincide was owing to discrepancies in leaching of salts, hysteresis, moisture gradient, and swelling of the soil. Therefore, field calibration by soil sampling were recommended because of the inherent errors in laboratory calibrations.

None of the above calibration procedures for electrical resistance blocks are reliable enough to be accepted as a standard method for determining the soil moisture percentage or the soil moisture-tension. There is much to be desired, for improvement certainly can be made in several of these methods. With this in mind, the following specific objectives were chosen.

SPECIFIC OBJECTIVES

The first objective of this study was to evaluate selected methods for the calibration of the blocks shown in figures 1 and 2. Figure 1 is a photograph showing the units of interest with a part of each unit broken away to expose the internal design. Figure 2 is a diagrammatical sketch of the units, drawn to scale. Unit 1 in the figures represents a rectangular gypsum block[1] with parallel electrode of the same general design as the original Bouyoucos block and the most commonly used of the electrical resistance soil moisture measuring blocks.

Unit 2 represents the 12-inch unit in the Rayturn multiple unit gypsum stake[1] shown in figure 3, which is to be described later in detail. These stakes are being extensively used by the Soils Department of Oregon State College for field research. The 12-inch unit was chosen for this study since there is more information available from field experiments on the calibration of this unit than on any other unit in the stake. In field studies comparisons have been made between the 12-inch unit and the units for the other three depths. The 12-inch unit as well as the units for other depths has a large tapering

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[1] Manufactured by Rayturn Machine Corp., Portland, Oregon.

cylindrical shape and parallel, circular electrodes.

Unit 4 is similar to unit 2 but has two screens that serve as concentric electrodes. This unit[2] is being produced commercially at present. The concentric electrode arrangement confines more of the electrical flow within the block as emphasized in the literature review.

All gypsum blocks used in this study were constructed using a mixture of eight parts water to seven parts hydrocal white, which is a neutral base gypsum.

Colman fiberglas blocks[3] are represented by unit 3 in figures 1 and 2. These blocks contain no buffering medium such as gypsum and are smaller than the other units. The electrodes are two flat, parallel, monel metal screens separated by two thicknesses of fiberglas cloth. The electrodes are enclosed in a metal case and separated from the case by fiberglas cloth. This unit is also produced commercially and is in common use.

The second specific objective dealt with the influence of different soil environments on the calibration of the blocks described above. Can a single calibration curve be used for several soils was the question on which information was desired.

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[2] Manufactured by Rayturn Machine Corp., Portland, Oregon.

[3] Manufactured by Beckman Instruments, Inc., Berkeley Division, Richmond, California.

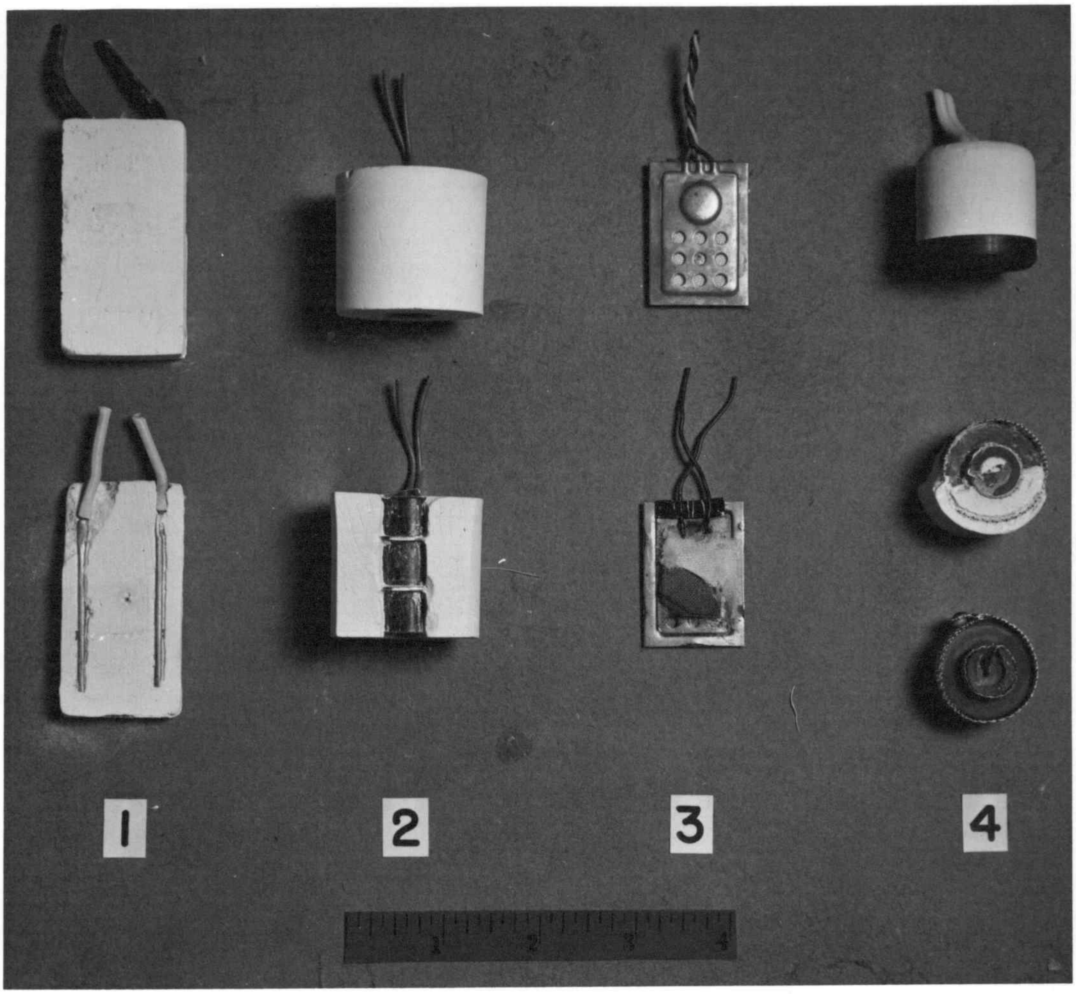

Figure 1. Soil moisture measuring units used in this study.

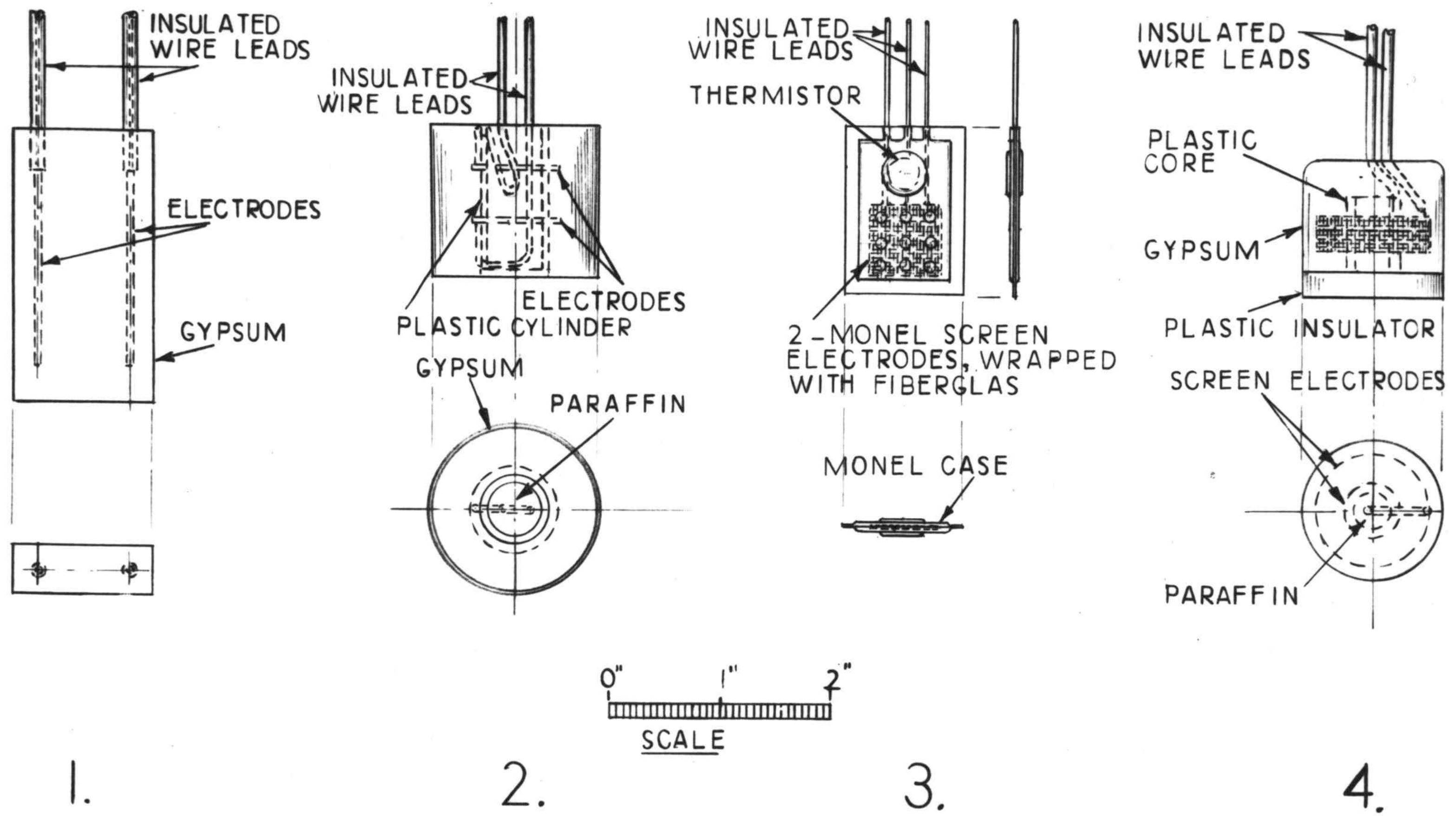

Figure 2. A diagrammatic sketch of soil moisture units in figure 1.

The third and last objective involved a study of the variability encountered in the use of the gypsum stake shown in figure 3 in place in the soil. The stake is composed of moisture measuring units at 6, 12, 18 and 24-inch distances from the top of the stake. The measuring units are the same as unit 2 in figures 1 and 2 except that they vary somewhat in size due to the amount of gypsum encompassing the unit. The stake tapers from two inches in diameter at the top to one and one-eighth inches at the bottom. The electrical resistance measuring units are separated from each other by gypsum spacers and plastic insulators. The stake is similar to the one described by Abd El-Samie and Marsh (2, pp. 404-406).

These stakes were new on the market when this study was initiated and it was necessary to know the behavior of these stakes in the field. A measure of the variability among stakes and among units within the stake was desired in order to predict the number of stakes necessary to estimate the soil moisture tension within a given percentage.

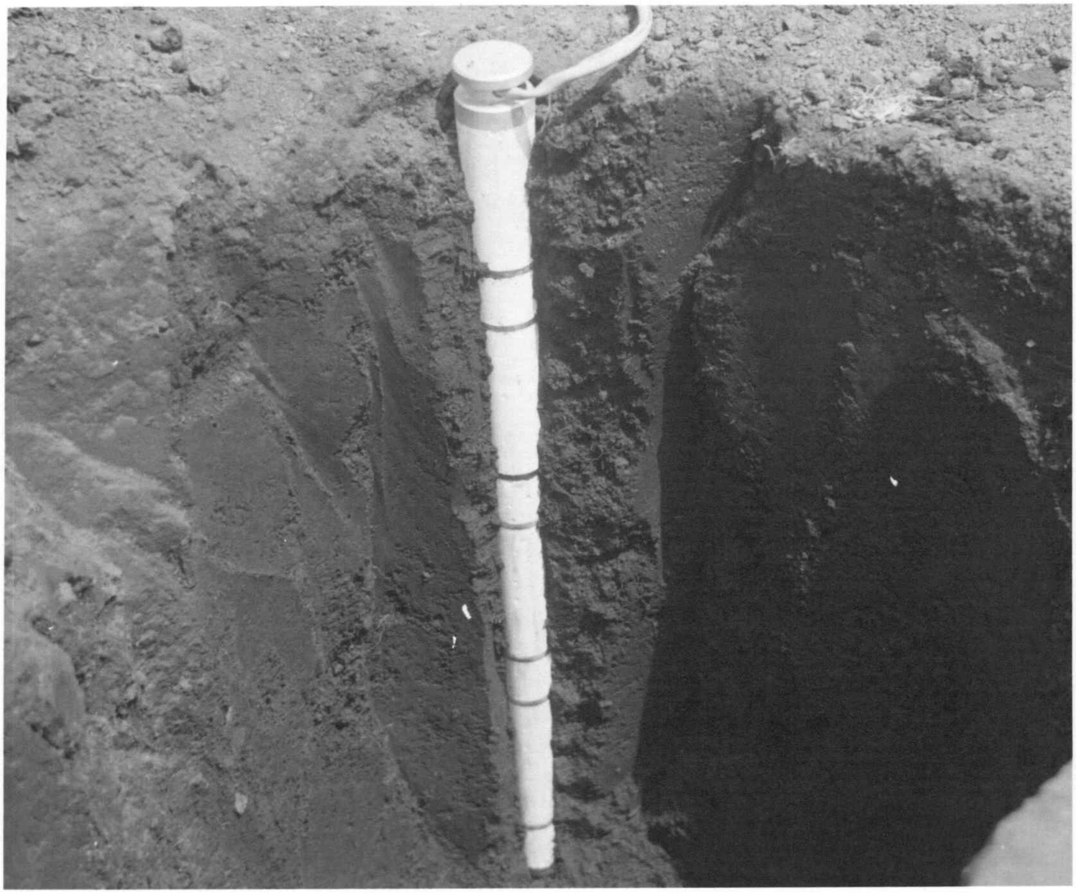

Figure 3. A view of gypsum stake in place in the soil. (Courtesy of Marvin Shearer)

EXPERIMENTAL AND STATISTICAL PROCEDURES

Information on the above objectives was obtained through greenhouse, field, and laboratory techniques. For calibration and comparison of the units in figures 1 and 2 in two different types of soil, a greenhouse study was conducted in the winter and spring of 1955. A laboratory procedure for calibrating electrical resistance-soil moisture measuring units was studied with the same soils used in the greenhouse study. A field experiment for obtaining information on the behavior of gypsum stakes was carried out and completed in the summer of 1954.

Greenhouse Calibration and Comparison of Selected Blocks

Each of the four types of units shown in figures 1 and 2 were calibrated under greenhouse conditions by the following procedure. Two units of each particular type were located near the center of a 10-inch clay pot which was filled with one of four soils. Four types of units and four soils were factorially combined in one of three replications. There was, therefore, a total of 48 pots.

The four soils used in this study were (1) a Newberg sandy loam, 0- to 12-inch depth, (2) a Newberg sandy loam, 12- to 24-inch depth, (3) a Chehalis clay loam, 0- to 12-inch depth, and (4) a Chehalis clay loam, 12- to 24-inch depth. Soil moisture-tension relationships for these soils were obtained by determining the equilibrium moisture content of disturbed samples at tensions of 0.3, 1, 2, 5, 10, and 15 atmospheres. Moisture equivalent was determined as an approximation of field capacity using the standard Briggs-McLane method (19, pp. 1-23), and was assumed to represent 0.33 atmospheres tension as suggested by Richards and Weaver (40, p. 221). The porous plate apparatus (39, pp. 105-110) was used for determination at 1 atmosphere and the pressure membrane apparatus was employed for the greater tensions (38, pp. 377-386). Soil moisture content was determined by oven drying the sample at 105° C for 24 hours. Results are expressed as moisture percentage on a dry weight-basis. The soil moisture-tension relationships for these soils are shown in the Appendix, figure 15.

Alta fescue was grown in the pots to cause a variation in soil moisture tension with time. The resistance of individual units was read with a Colman meter[4] at regular intervals of time during each of three drying cycles. At the time resistance readings were made duplicate soil moisture samples were taken at predetermined locations with each pot to a depth of 7 inches, using a

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[4] Manufactured by Beckman Instruments, Inc., Berkeley Division, Richmond, California.

5/8-inch diameter tubular soil core sampler; the top 3 inches of the core was discarded. Soil moisture was determined by weighing, oven-drying, and reweighing. The resulting holes were plugged with corks for the remainder of the drying cycle. At the end of the drying cycles, these holes were backfilled with soil from the same bulk sample originally used to fill the pot. The pots were then irrigated and allowed to dry down so that the soil in the backfilled holes had a chance to come to equilibrium with the surrounding soil. After this drying period, the next sampling and reading cycle was started.

Soil temperature measurements were also made with thermistors included in some of the fiberglas blocks and block resistance readings were later corrected to the equivalent resistance value at 60° F, following corrections as determined by the Bouyoucos Soil Temperature-Moisture Slide Rule (41, p. 163).

The procedure used in analyzing the data is discussed later.

Laboratory Calibration

A laboratory calibration method was studied which utilized the principle involved in the pressure membrane (38, pp. 377-386) and the pressure cooker apparatus (39, pp. 105-110). Blocks surrounded by soil are placed in a pressure chamber constructed so that a portion of the chamber is porous to allow movement of moisture but not air through the wall of the chamber. The soil and blocks are saturated and a certain air pressure applied within the chamber. When equilibrium conditions are reached, that is, when movement of moisture ceases, resistance readings of the blocks are compared with the soil moisture content.

For tensions between 2 and 15 atmospheres, a pressure cell was used which is six inches in diameter and four inches in height. The flat top and bottom is sealed to the cylindrical wall by the use of "O" rings and bolts. A fine stainless steel screen was soldered to the inside of the cell wall and bottom. Holes were placed in the wall behind the screen to facilitate the removal of water. A cellophane membrane is fitted against the screen. This arrangement gives contact between the soil and membrane along the walls of the cell as well as the bottom thereby increasing the rate of water removal from the soil. Consequently, when a pressure is applied within the cell the time for equilibrium is lessened.

The wire leads of the blocks are attached to insulated electrical fittings in the lid of the pressure cell. A plastic sealing compound[5] was molded around the

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5. "Duxseal" manufactured by Johns-Manville.

bare electrical connections to prevent condensation of water vapor. The cell was filled with soil to a depth of about three inches, after which the blocks were installed in the center of the soil mass. The soil and blocks were then saturated with water. The cell was closed and the desired pressure applied and held constant until equilibrium had been established.

Resistance readings of the blocks were taken at regular intervals and when the block resistances became constant and the moisture extraction had ceased, equilibrium conditions were believed to have been reached. At the end of each equilibrium period, soil moisture samples were taken and the moisture percentages converted to tension by the soil moisture-tension curves discussed earlier to compare with the resistance of the unit at equilibrium.

In the lower pressure range of 0.1 - 1.0 atmospheres the porous plate apparatus (39, pp. 105-110) was modified to permit electrical contact with the block leads through insulated fittings in the cooker wall. All connections were made air tight with rubber stoppers and "Duxseal". The procedure for obtaining data was similar to the procedure followed with the pressure cell.

Variability and Field Calibration of Gypsum Stakes

Behavior of gypsum stakes (figure 3) under field conditions was observed by the following experimental procedures. The stakes were installed in sweet corn rows, at tasseling stage, in a Chehalis clay loam soil near Corvallis, Oregon. The stakes were installed on a 7 foot grid in a 35 x 35 foot area within the corn. Soil moisture measurements and readings of electrical resistance with the Rayturn "Irrigage" meter[6] were made at six different times during the latter part of August and early September, 1954. Moisture in the soil was determined by sampling with a soil core sampling tube and oven drying in the same manner as in the greenhouse study. The sampling site for each time was chosen at random from three sites on each side of the row and a distance of four inches from the particular gypsum stake. Soil moisture samples were obtained at depths of 3-9, 9-15, 15-21, and 21-27 inches to correspond to electrical resistance unit readings at 6-, 12-, 18-, and 24-inch depths, respectively.

Disturbed soil samples from four depths at each of six different locations in the plot were obtained for

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[6] Manufactured by Rayturn Machine Corp., Portland, Oregon.

determination of soil moisture-tension relationships. The observed relationships are summarized in figure 16 of the Appendix.

Statistical Analysis of Calibration Data

In order to prepare the data for statistical analysis, a mathematical equation was calculated relating soil moisture tension and resistance for each soil and unit. The following example from the greenhouse study illustrates how these relationships were obtained.

Block resistance readings and the corresponding soil moisture percentages were plotted on semilog graph paper as illustrated in figure 4. It can be noted in this graph that a linear relationship exists between 14 and 21 percent moisture. In the procedure followed, only this interval is used since it represents the sensitive range of the block and difficulty was encountered when the entire range was used. Consequently, the data from the insensitive portion of the moisture percentage-resistance curve, e.g. from 21-28 percent moisture, were not used. Linear regression analysis (44, pp. 103-137) was used to determine the equation for the best fitting regression level. The equation has the form

$$\text{Log } R = b(M) + a \qquad [1]$$

where R is the resistance in ohms, M the percent soil moisture and a and b are constants. The regression line and the equation for the example are shown in figure 4.

When soil moisture tension is plotted on semilog paper against soil moisture content, as in figure 5, a nearly linear relationship is observed. This is true for all soils used in this study. Therefore, by linear regression analysis a mathematical expression of the form

$$\text{Log } T = b'(M) + a' \qquad [2]$$

may be obtained, where T is the soil moisture tension in atmospheres, M the percent soil moisture and a' and b' constants.

By solving equation [2] for M and substituting into equation [1] , the following equation is obtained:

$$\text{Log } R = \frac{b}{b'}(\text{Log } T) + a - \frac{a'b}{b'} \qquad [3]$$

Equation [3] can be simplified to the final form,

$$\text{Log } R = B(\text{Log } T) + A \qquad [4]$$

where A and B are constants. Therefore, with this development, one would expect a linear distribution of points on log-log paper of tension versus resistance if the soil moisture data are converted to tension by equation [2].

Figure 6 shows this to be true for the example, since the soil moisture data of figure 4 was converted to tension by the equation in figure 5.

In practice, soil moisture percentages were converted to tension by equation [2] with the appropriate constants a' and b' for the particular soil. A regression equation was then calculated for the distribution of points. By first converting the data, it allows the comparison of equations for different soils and units by statistical means.

Further statistical analysis of the data will be presented under RESULTS AND DISCUSSIONS.

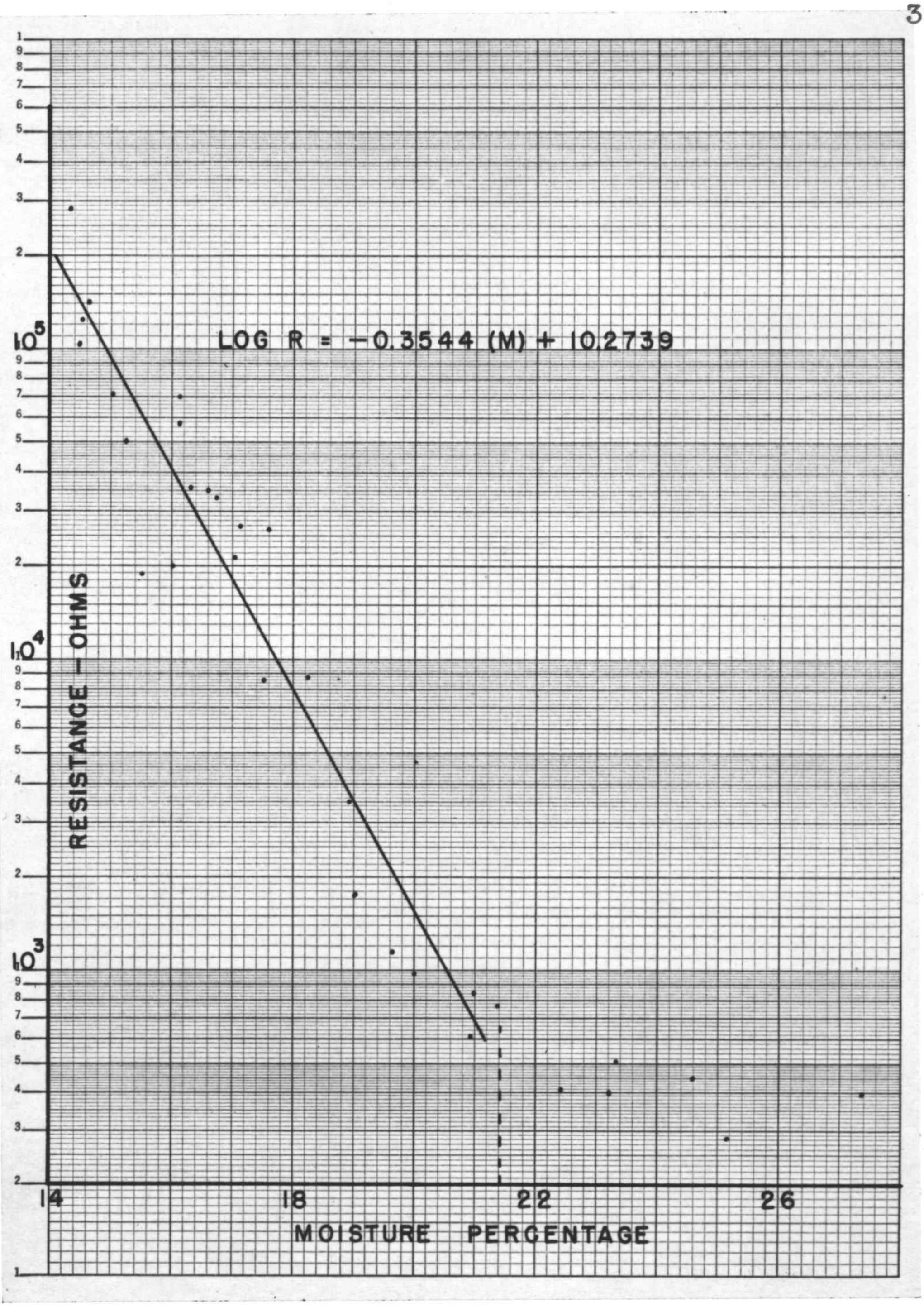

Figure 4. Soil moisture versus resistance for cylindrical gypsum unit having 2-screen concentric electrodes in Chehalis (0-12 inches) soil from greenhouse study.

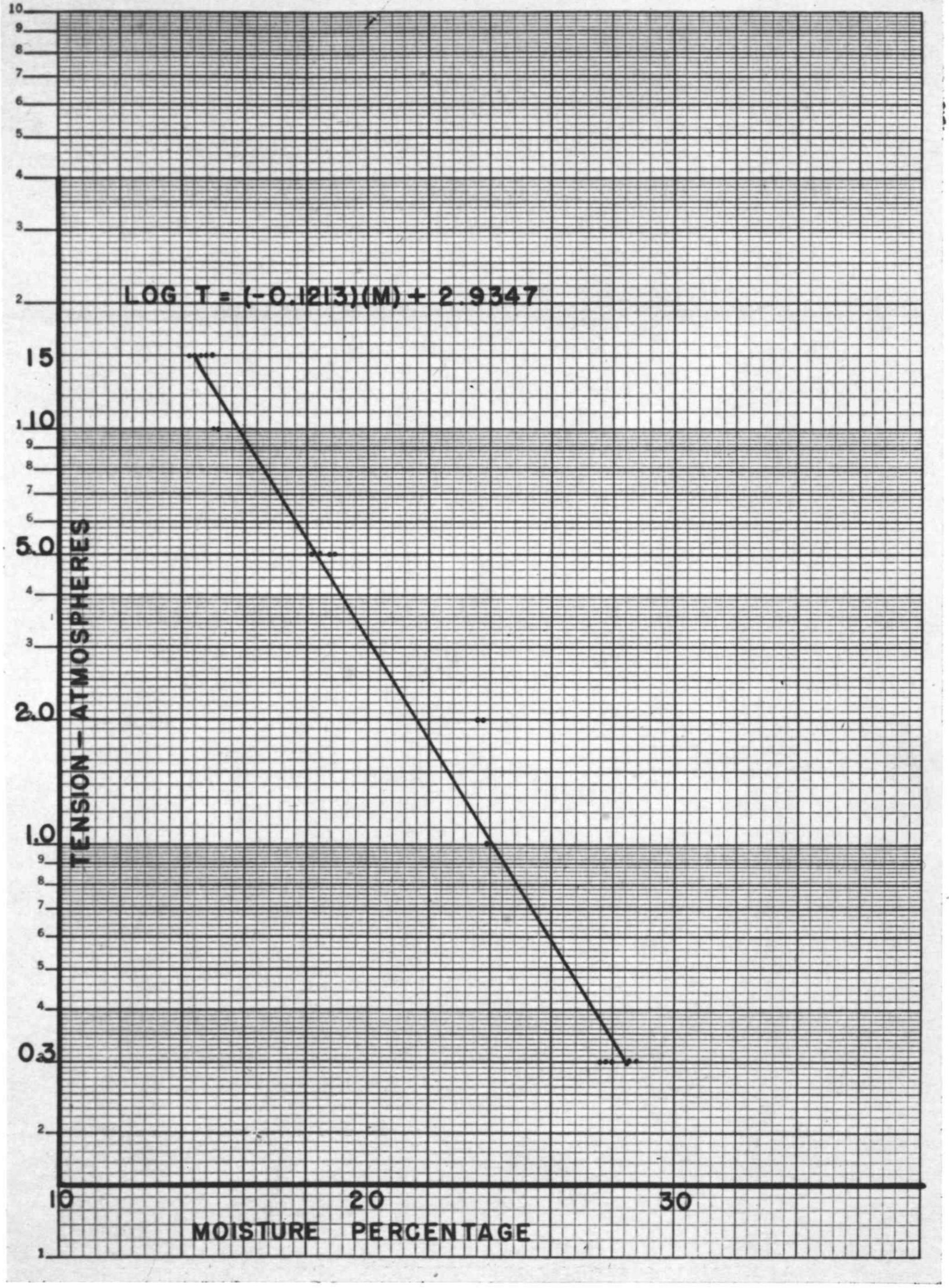

Figure 5. Soil moisture-tension curve for Chehalis (0-12 inches) soil used in greenhouse study.

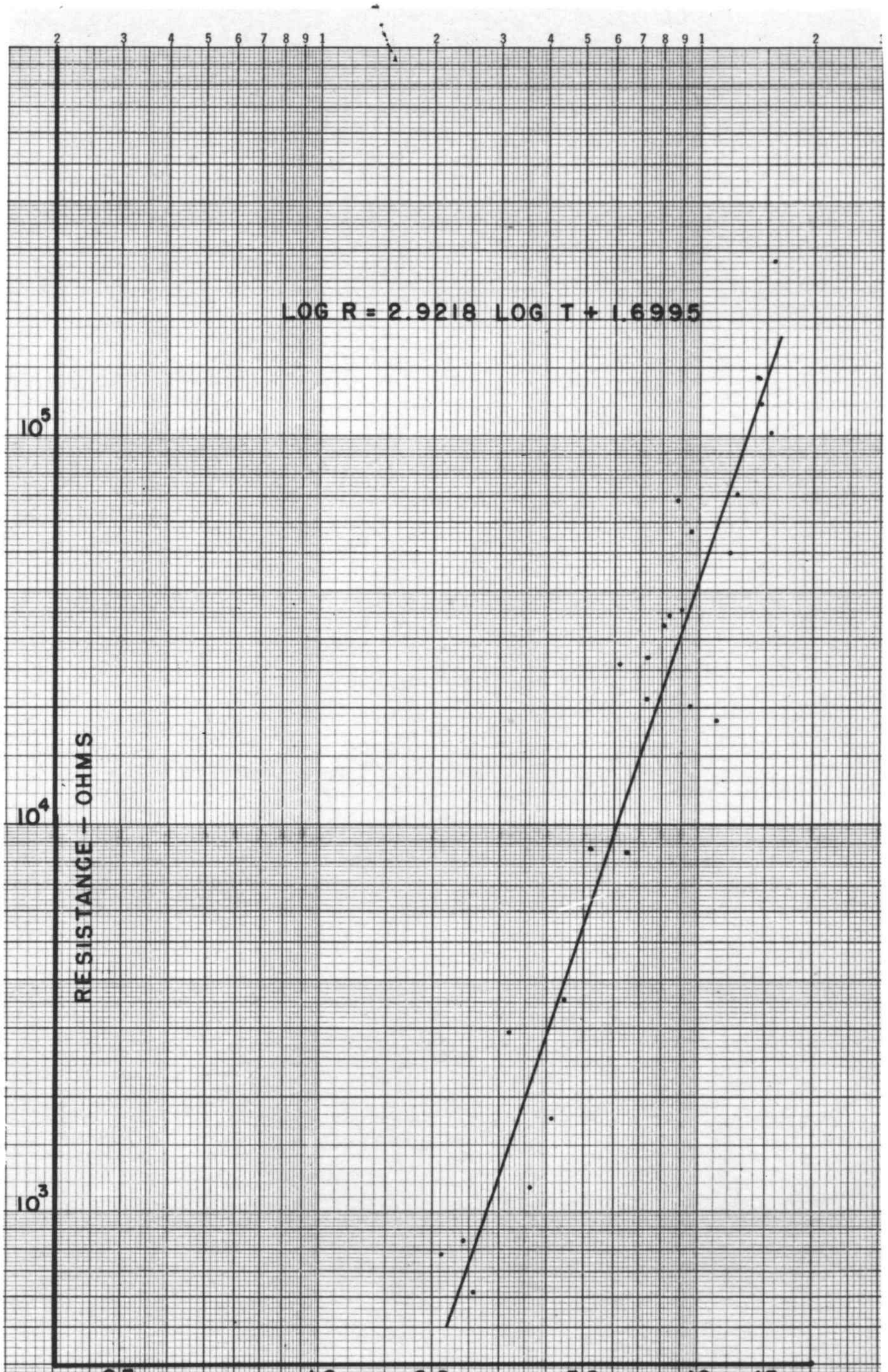

Figure 6. Tension versus resistance for cylindrical gypsum unit having 2- screen concentric electrodes for Chehalis (0-12 inches) soil from greenhouse study.

RESULTS AND DISCUSSION

Greenhouse Calibration and Comparison of Selected Blocks

The statistically computed A's and B's for equation [4] relating resistance (corrected to 60° F) to tension are reported in table I for each kind of unit in each of the four soils used in the greenhouse study. The correlation coefficients, number of readings, and the variance are also presented in this table to indicate the reliability of the calculated line. An analysis of variance of the B's in table I showed significant differences (1% level) among soils, among units, and a significant interaction, soils times depth. These differences will be considered more specifically in the following discussion.

The regression curves for the resistance of the rectangular gypsum unit with parallel electrodes as a function of the soil moisture tension are presented in figure 7. It can be seen that the curves generally have the same slope for all four soils but are displaced from one another, especially the Chehalis (12-24 inches). A test for homogeneity (35, p. 19-7) of B's across soils was made since B is the slope of the line. The test showed no significant differences; therefore, it may be considered that the slopes of the regression lines

Table I. Data associated with the calibration curves of units studied in the greenhouse study.

Soil and Depth	Type Unit	B*	A*	No. of samples (n)	Correlation Coefficient (r)	Variance (s^2)
Chehalis (0-12 inches)	Rectangular gypsum unit with parallel electrodes	2.0798	2.7589	32	0.972	0.04526
	Cylindrical gypsum unit with parallel electrodes	2.5038	2.5524	26	0.939	0.07972
	Cylindrical gypsum unit with 2-screen concentric electrodes	2.9218	1.6995	25	0.961	0.05138
	Colman fiberglas unit	0.9072	3.7646	29	0.947	0.03546
Chehalis (12-24 inches)	Rectangular gypsum unit with parallel electrodes	1.8196	3.6109	34	0.950	0.06734
	Cylindrical gypsum unit with parallel electrodes	2.6158	2.5496	31	0.949	0.09872
	Cylindrical gypsum unit with 2-screen concentric electrodes	2.9669	1.6460	31	0.940	0.1016
	Colman fiberglas unit	1.0013	3.8703	35	0.980	0.01944

* A and B are constants for equation [4]

Table I Con't. Data associated with the calibration curves of units studied in the greenhouse study.

Soil and Depth	Type Unit	B*	A*	No. of samples (n)	Correlation Coefficient (r)	Variance (s^2)
Newberg (0-12 inches)	Rectangular gypsum unit with parallel electrodes	2.1397	2.8410	25	0.957	0.06449
	Cylindrical gypsum unit with parallel electrodes	4.8633	0.2919	18	0.866	0.2222
	Cylindrical gypsum unit with 2-screen concentric electrodes	2.5049	2.2692	22	0.949	0.07776
	Colman fiberglas unit	0.8298	3.8391	24	0.965	0.02507
Newberg (12-24 inches)	Rectangular gypsum unit with parallel electrodes	1.8763	3.0634	21	0.944	0.04785
	Cylindrical gypsum unit with parallel electrodes	4.1392	0.8152	18	0.799	0.3352
	Cylindrical gypsum with 2-screen concentric electrodes	2.7862	1.8299	18	0.957	0.08508
	Colman fiberglas unit	0.5342	4.1611	23	0.883	0.03611

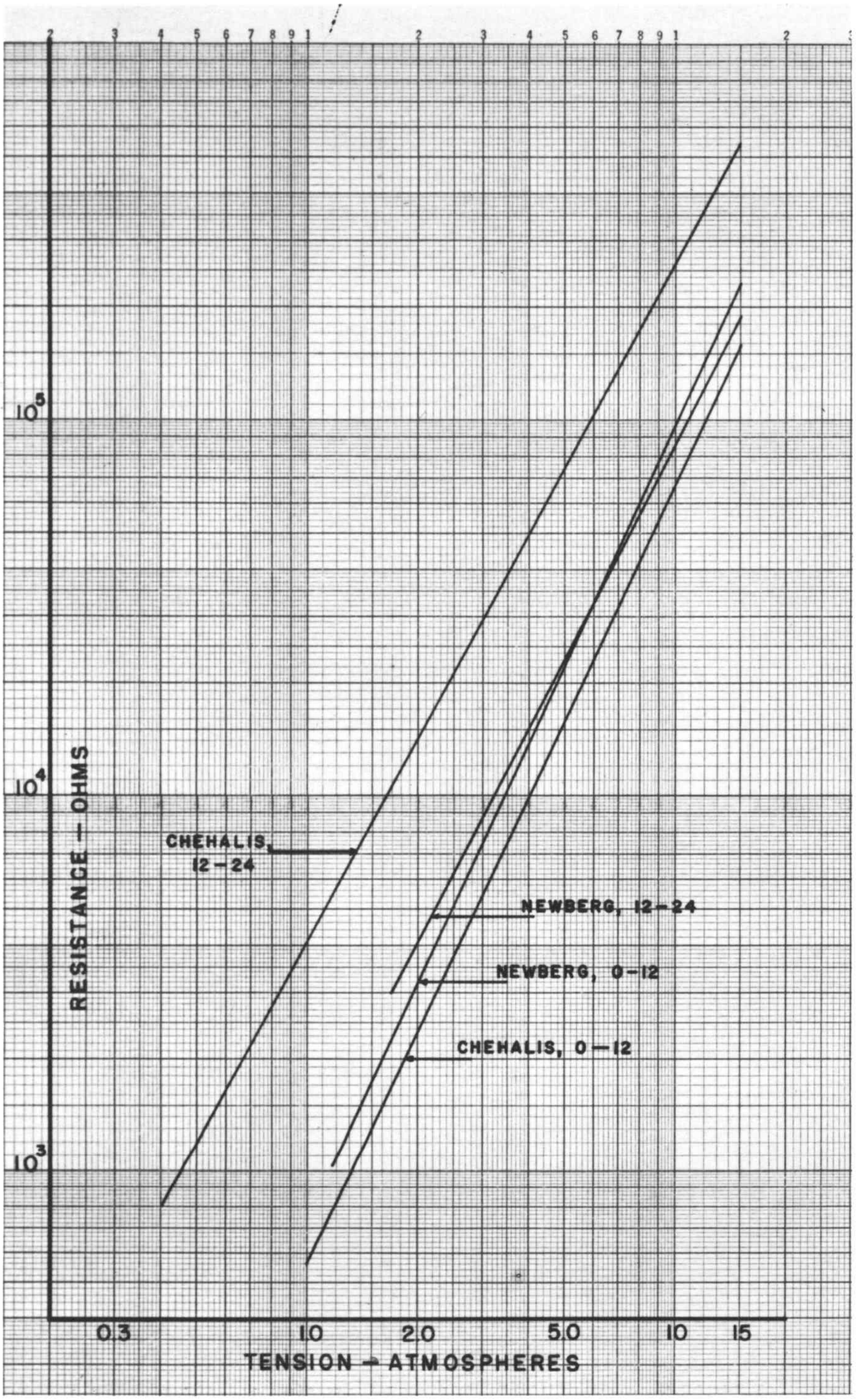

Figure 7. Greenhouse calibration curves for rectangular gypsum unit with parallel electrodes.

relating resistance of the rectangular unit and soil moisture content are similar for all soils of this study.

Since the slopes of these lines are statistically the same, we are justified in testing the A values for differences, the value A being a measure of the vertical displacement of the curves. The test used here was the test for homogeneity of the adjusted means (35, p. 19-15). This test gave an F value that indicated a significant difference among the adjusted means (1% level). When the Chehalis soil (12-24 inches) was omitted the level of significance changed to the 5% level, indicating that there still existed a difference among the remaining three curves. Thus, it cannot be said that the rectangular unit behaves similarly in all soils, nor can a single calibration curve be used for resistance versus tension in all soils.

The lines in figure 7 terminate at the lower tensions where the units become insensitive. It can be seen that, with the exception of the Chehalis (12-24 inches), the rectangular units are sensitive only above one atmosphere of tension. In the Chehalis (12-24 inches), the units showed response to four-tenths of an atmosphere. The curves are not carried beyond 15 atmospheres since no data were obtained above this tension.

The curves for the cylindrical gypsum unit with parallel electrodes (unit 2 in figures 1 and 2) are shown in figure 8. For this unit distinct differences (1% level) were noted by the test for homogeneity of the B's. Further testing showed that the two soil types gave different B's but there was no differences between depths within a soil type. The A values were then tested within the depths for each soil and there were no differences. Therefore, a pooled linear regression equation was calculated for each soil. The B's, A's, and variance associated with the pooled linear equation for the Chehalis soil are 2.5741, 2.5475, and 0.09011, respectively. For the Newberg the values are 4.4695, 0.5810, and 0.2787. Thus it may be said that the resistance of the cylindrical gypsum unit with parallel electrodes reacts similarly to moisture changes through the 0-24 inch depth of Chehalis soil. The relationship is constant also throughout the 0-24 inch depth of Newberg, but is different from that for the Chehalis soil.

The differences in values for B in the regression equation indicates that the sensitivity of the cylindrical gypsum unit with parallel electrodes in the Chehalis was somewhat less than in the Newberg soil, although the range of measurement of soil moisture-tension was greater in the former soil than the latter. The range

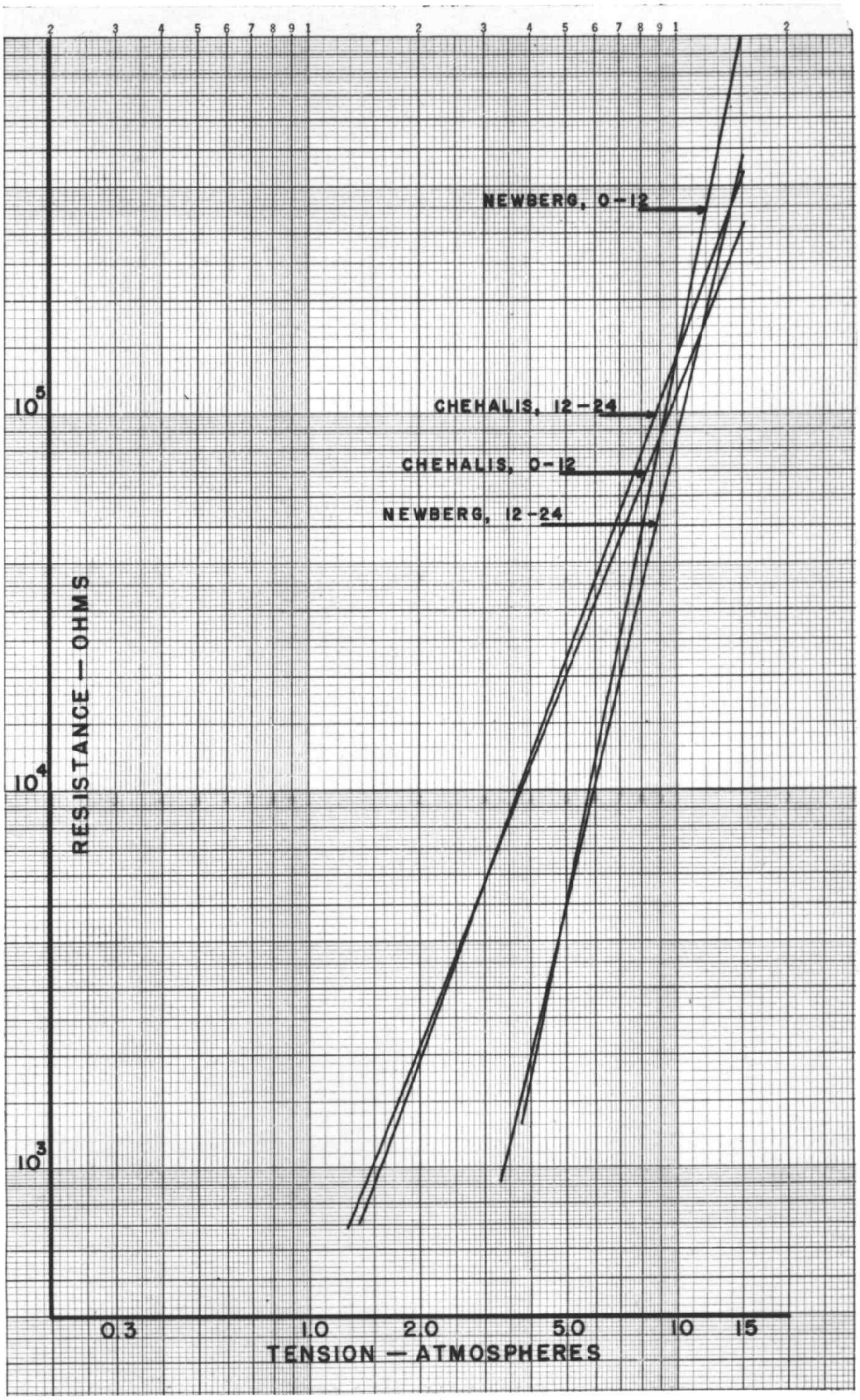

Figure 8. Greenhouse calibration curves for cylindrical gypsum unit with parallel electrodes representing the 12-inch position in the multiple unit gypsum stakes.

of response in the Newberg started at three atmospheres, at which point much of the available water in this soil had been depleted. In the Chehalis the range of response extended upwards from 1.5 atmospheres.

The third gypsum unit, the cylindrical gypsum unit with concentric electrodes, exhibited more uniformity across soils. The statistical test of the B's and A's demonstrated no significant differences in the B values but there was a difference among the adjusted means (5% level). This difference exists between the Newberg (0-12 inches) and the other three soils. However, the difference is small from a practical standpoint (see figure 9). Therefore, a pooled regression equation for all four soils was calculated with B equal to 1.9472, A equal to 1.8599, and a variance equal to 0.08039. The pooled calibration curve for this cylindrical gypsum unit having 2-screen concentric electrodes should serve in a variety of soils with similar characteristics to the soils used in this study. This decided advantage is offset somewhat by the usable range of this unit being limited to tensions above two atmospheres.

The Colman fiberglas units presented the smallest B values and the largest A values of any of the four units. Also, there were greater differences among soils and

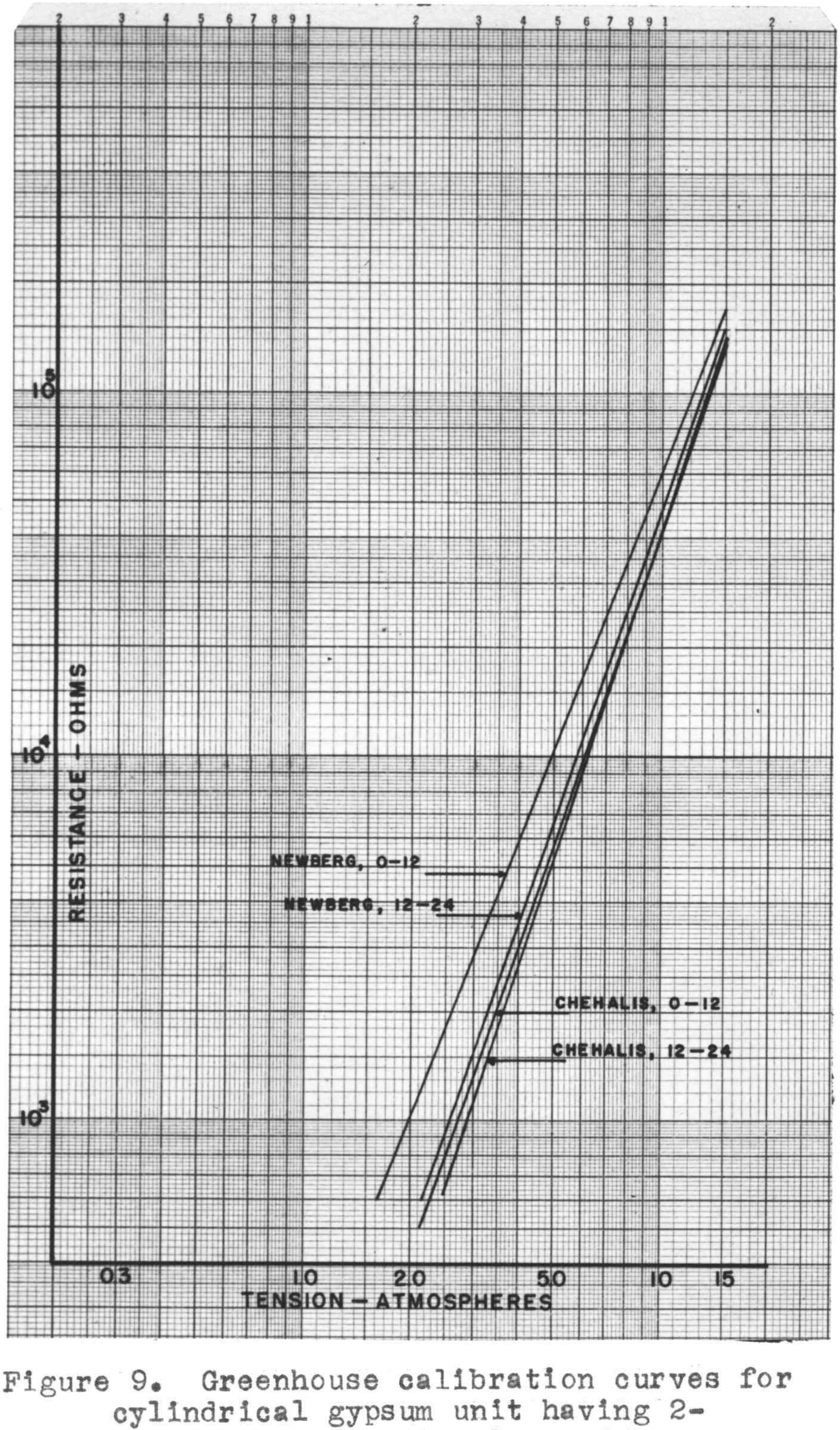

Figure 9. Greenhouse calibration curves for cylindrical gypsum unit having 2-screen concentric electrodes.

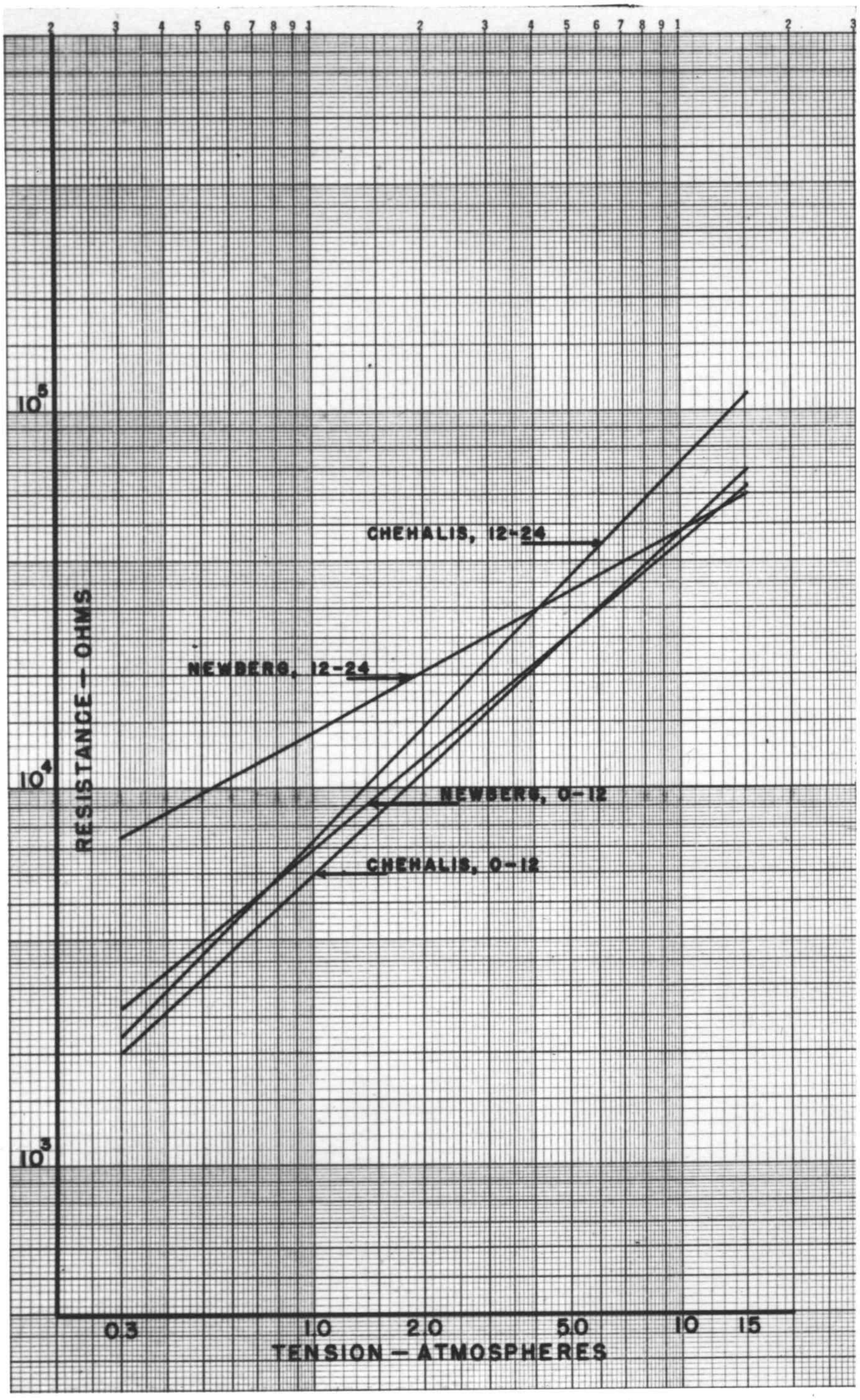

Figure 10. Greenhouse calibration curves for Colman fiberglas unit.

depths (see figure 10). It can be seen in figure 10 that this unit has greater sensitivity at lower tensions than the previous discussed gypsum units. The fiberglas blocks were sensitive down to at least one-third of an atmosphere. It should be mentioned that the data from the first cycle were not used in this analysis. These data differed from later cycles since the resistance was always lower for a given tension value. The general recommendation is to condition these units before use. For the Colman fiberglas blocks we can conclude that (a) separate calibrations are needed for both soils and depths and (b) they have the advantage of greater sensitivity in the low tension range.

As a practical evaluation of the four types of blocks, a calculation was made of the number of units of each type necessary to estimate the soil moisture tension within plus or minus 0.5 atmosphere at five atmospheres tension. The calculations were made using the following formula (44, pp. 41, 61).

$$N = \frac{s^2}{y^2 \; p^2} \times 10^4 \qquad [5]$$

where N is the number of blocks needed to estimate a given y within a certain percentage p and s^2 is the variance. For our calculations y must be expressed in log of ohms, the variance is taken from table I, and p can be chosen arbitrarily from practical considerations. However, it is the estimation of tension rather than resistance which is wanted. Therefore, y was selected to correspond to five atmospheres of tension, since this tension is near the center of the sensitive range of most of the units. The percentage p was calculated by considering the range in log of resistance associated with the range of 4.5 to 5 atmospheres of tension. The following equation was then used to calculate p:

$$p = \frac{y - y'}{y} \times 100$$

where y and y' are the log of the resistance in ohms corresponding to five and four and one half atmospheres, respectively.

By substituting the calculated value of p into equation [5] , N was calculated for each type of unit used in the greenhouse study. The results are given in table II. The calculated N in this table is the number of units required to estimate a true mean of five atmospheres within one-half of an atmosphere approximately 67 percent of the time.

Less gypsum units are generally required than Colman fiberglas units, although the variance of the fiberglas units was less. The reason for this is that the variance and sensitivity both influence N. The fiberglas units

Table II. Number of each type of unit used in the greenhouse study required to estimate the soil moisture tension at 5 atmospheres with an accuracy of ±0.5 atmospheres.

Type Unit	Soils			
	Chehalis (0-12 inches)	Chehalis (12-24 inches)	Newberg (0-12 inches)	Newberg (12-24 inches)
Rectangular gypsum unit with parallel electrodes	5	10	7	7
Cylindrical gypsum unit with parallel electrodes	6	7	5	9
Cylindrical gypsum unit with 2-screen concentric electrodes	3	6	6	5
Colman fiberglas unit	21	9	17	60

had less variance but the sensitivity was also less. The combination of the two results in less gypsum units required than fiberglas units for these experimental conditions.

The calculated N's in table II apply only to conditions similar to the greenhouse conditions of this study. Also, as the tension increases, N will also increase; therefore, the maximum number of units needed in an experiment may be calculated in a similar manner as above for the greatest allowable tension.

Laboratory calibrations

Although the laboratory method of calibration is still in the development stage, there are indications that demonstrate the merits of continuing the investigation. The only unit used in the laboratory was the Colman fiberglas unit. Figures 11 and 12 show calibration curves obtained in the laboratory for the unit in the Chehalis (0-12 inches) and the Newberg (0-12 inches) soils along with the curves obtained for the same unit and soil in the greenhouse. The curves obtained for this unit in the greenhouse were corrected to 70° F to correspond to the laboratory temperature. In both graphs it may be seen that the laboratory calibration has lower resistance values than obtained in the greenhouse but the

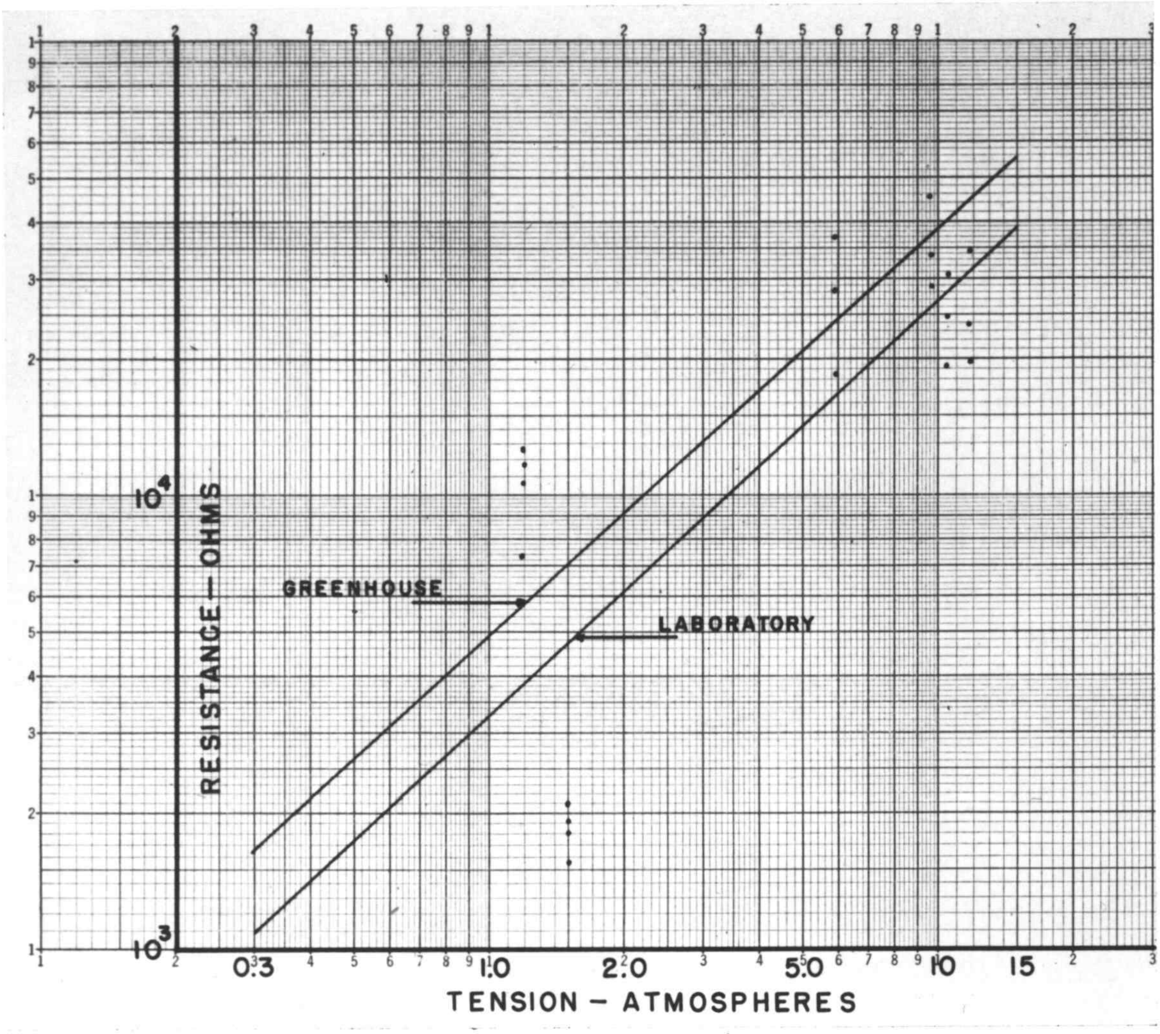

Figure 11. Comparison of greenhouse and laboratory calibrations for Colman fiberglas unit in a Chehalis (0-12 inches) soil.

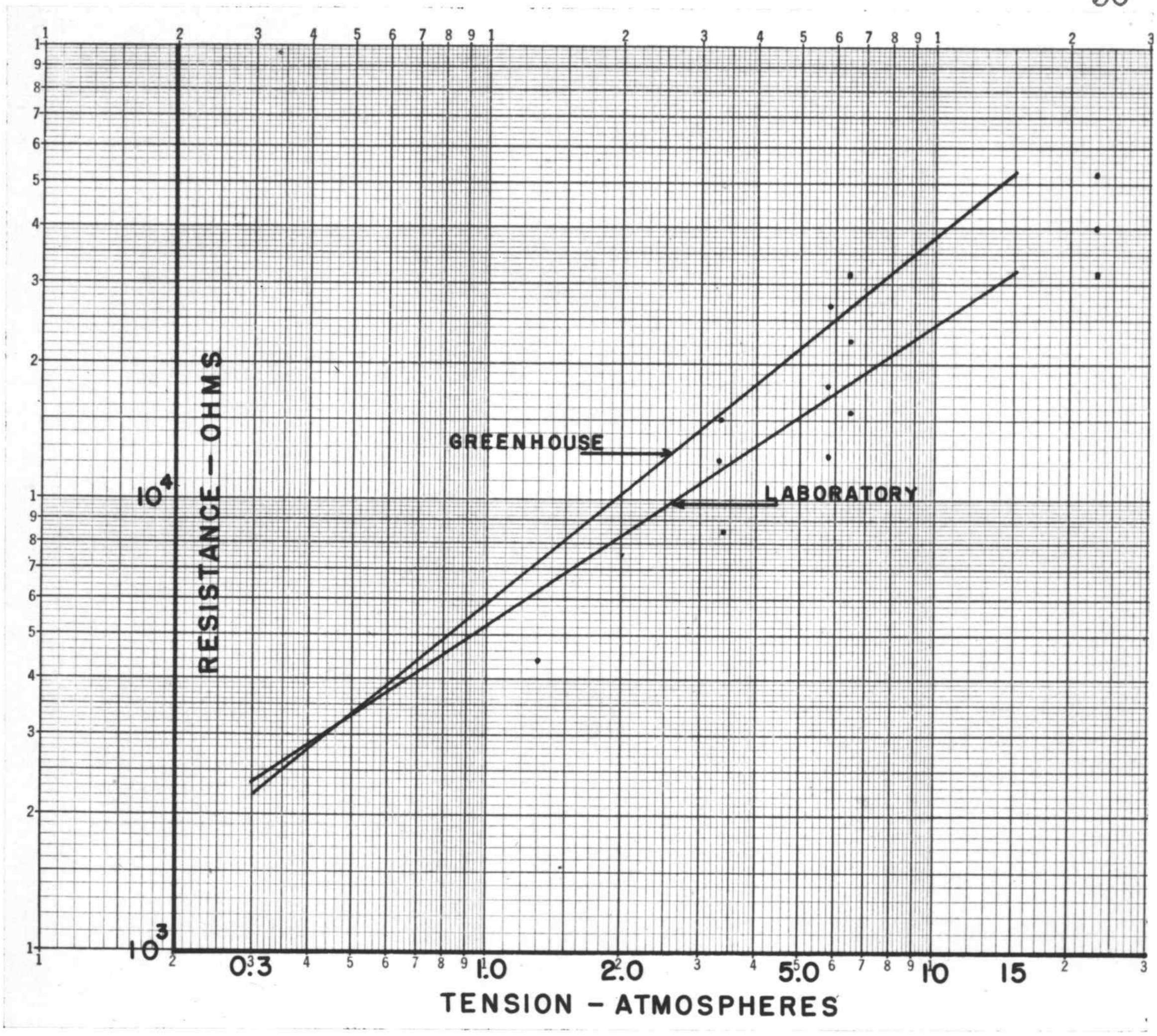

Figure 12. Comparison of greenhouse and laboratory calibrations for Colman fiberglas unit in a Newberg (0-12 inches) soil.

deviation is not great considering the limited amount of laboratory data. It is felt that some of the deviation of points from the line could be lessened by improvement in the technique. The points at 1.5 atmospheres in figure 11 and the point at 1.3 atmospheres in figure 12 were secured using the porous plate apparatus.

For comparison of variance of the laboratory data with that obtained in the greenhouse and given in tables I and II, the variance for the Chehalis soil was 0.09457 while for the Newberg soil it was 0.01905.

If this laboratory procedure can be shown to give the same results as other calibration methods, it will have the advantage that it can be carried out in the laboratory under controlled conditions in a relatively short time. It takes approximately two weeks to get resistance readings at equilibrium for several units at one applied tension.

Variability and Field Calibration of Gypsum Stakes

In this study we were able to evaluate some of the variance among the gypsum stakes and different depths besides obtaining a calibration of the four units within the stake. We will first consider the behavior of the four different size units of the stakes and later compare the calibration method to other techniques discussed in this study.

The comparison of the four units within the stake are seen in figure 13. The data from the regression equation [4] for the curves relating electrical resistances to soil moisture tensions in this figure are presented in table III. It is apparent that the behavior of the 6-inch unit is significantly different from that of those at the other three depths. The curves for the units at the 12, 18, and 24-inch depths have generally the same slope, as determined by the test of homogeneity for the B values. However, the adjusted means are significantly different (1% level) among these three units. Each unit of the stake must, therefore, have its own calibration curve. The range of the field curves does not extend to 15 atmospheres because of the wet conditions that existed during the summer of 1954, when the measurements were made. The field calibrations showed a lower limit of response at approximately 0.8 atmospheres.

The variability of the units at different depths may be expressed by N, the number of units necessary to estimate a given soil moisture-tension within given limits,in table III. It can be seen that the number of stakes needed increases very rapidly with depth from five units at 6-inches to 19 units at 24-inches.

The second point of interest in this study of the variability and field calibration of gypsum stakes was the comparison of the data obtained by the field technique with those from the greenhouse calibration studies. We are able to make this comparison with the 12-inch parallel electrode unit in the multiple unit gypsum stake (figure 13) with the same type unit used in the greenhouse study (figure 8), although the soil depths are not exactly the same. Figure 14 shows this comparison. The two curves appear quite similar, however, the B values are statistically different (1% level). The field calibration of the units exhibited greater responsiveness in the low tension range than in the greenhouse calibration.

There are several factors that may have been responsible for the differences in B values and the greater variation in the field than in the greenhouse. Among these are (1) differences in root distribution between Alta fescue and sweet corn, (2) differences in soil temperature between the field and greenhouse, and (3) differences in uniformity of soil in the greenhouse pots and in the field. Consequently, we can only say that for this particular calibration comparison in the field and greenhouse the curves are statistically different.

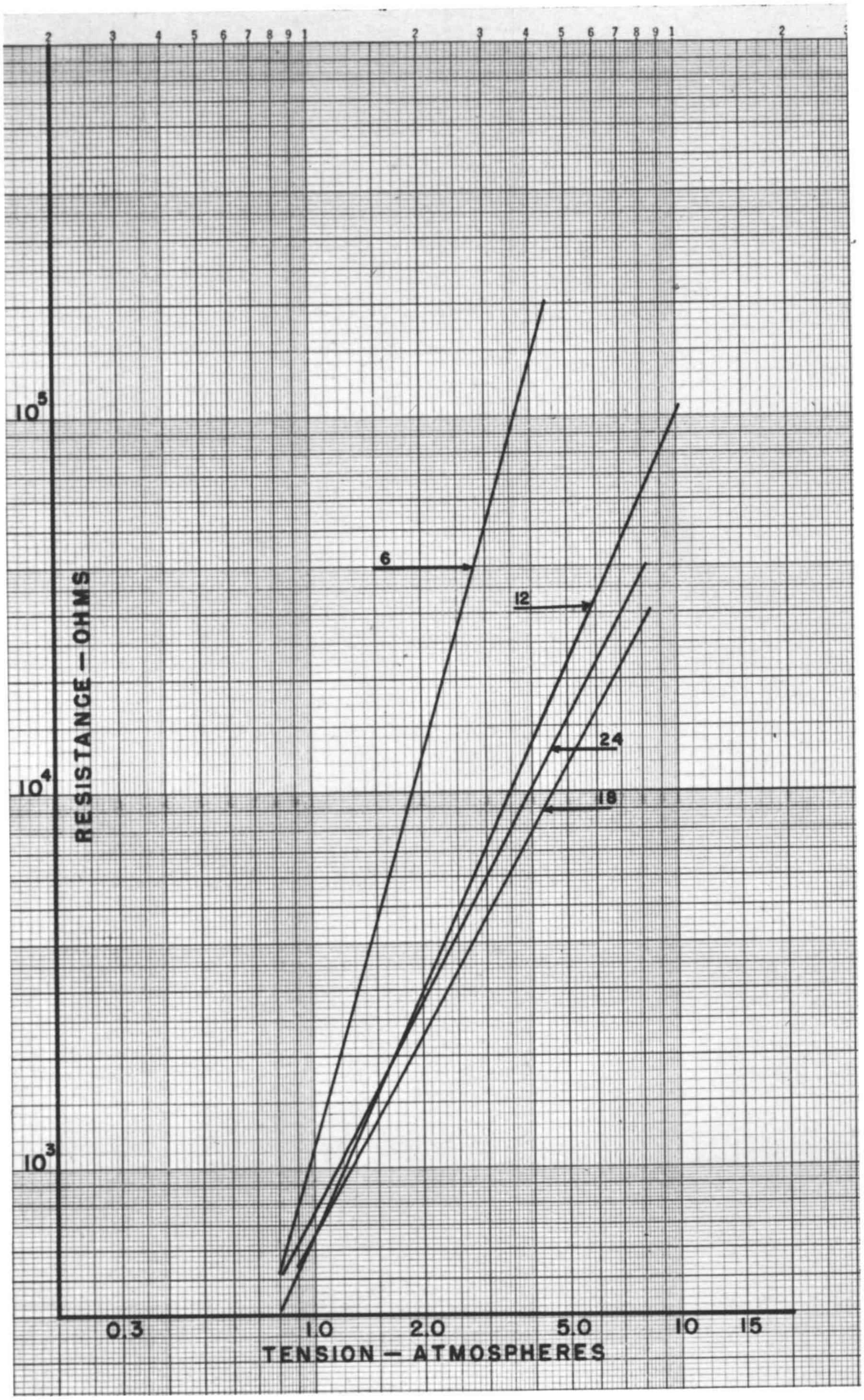

Figure 13. Field calibration curves of the four parallel electrode units in the multiple unit gypsum stake as determined in a Chehalis clay loam soil.

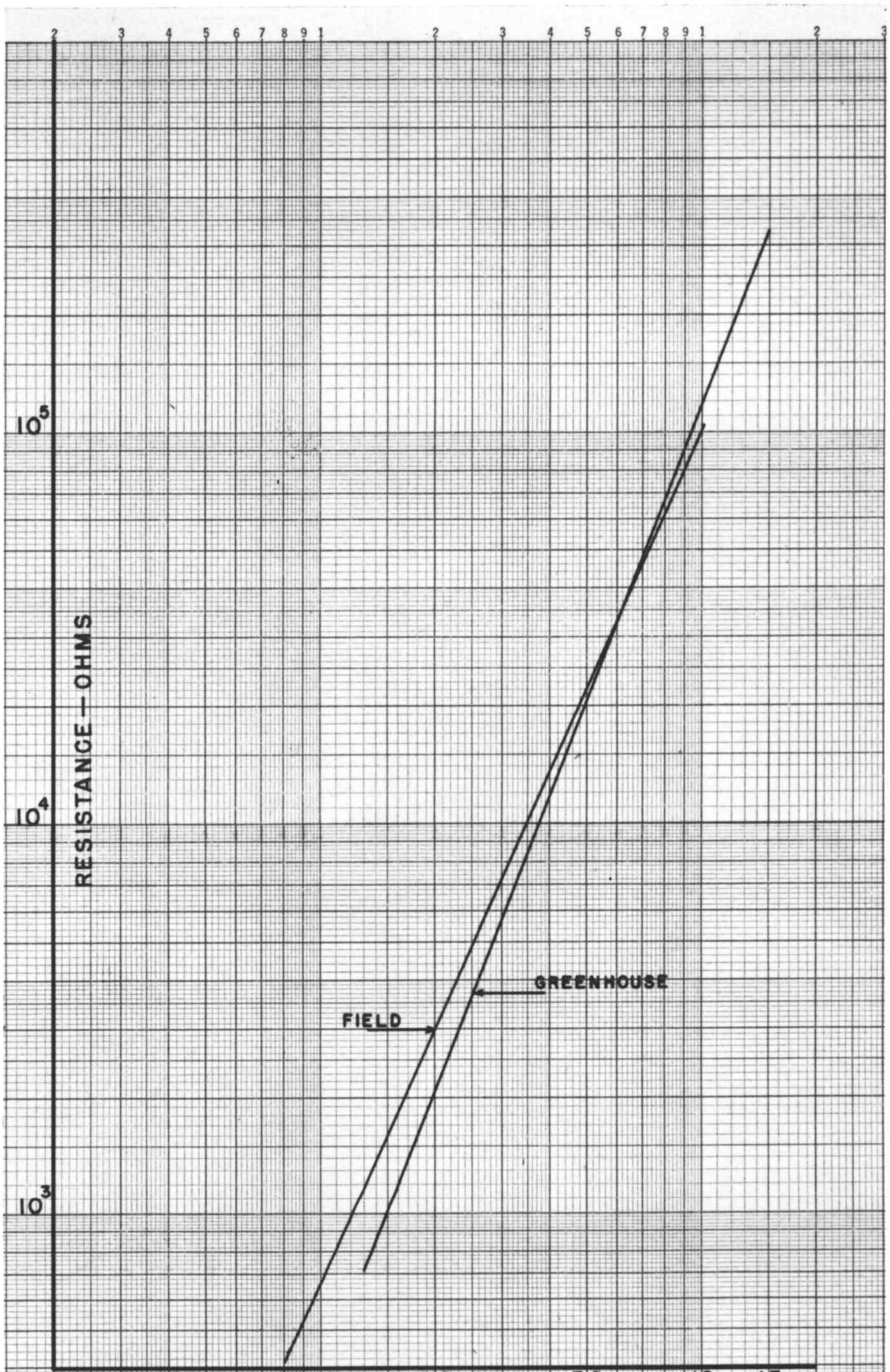

Figure 14. Comparison of field and greenhouse calibrations for the cylindrical gypsum unit with parallel electrodes representing the 12-inch stake in a Chehalis clay loam.

Table III. Data for field calibrations and variability study of multiple unit gypsum stakes in a Chehalis clay loam.

Depth of Units (inches)	B*	A*	No. of samples (n)	Correlation Coefficient (r)	Variance (s²)	No. of blocks needed to estimate 5 atmospheres of tension (N)
6	3.4595	3.0648	111	0.871	0.1215	5
12	2.1841	2.8213	140	0.847	0.1017	10
18	1.8115	2.8036	158	0.716	0.1243	18
24	1.8734	2.8880	166	0.718	0.1407	19

* Constants for equation [4]

SUMMARY AND CONCLUSIONS

Comparisons and calibrations of four different electrical resistance-soil moisture measuring units were made with the use of greenhouse, laboratory, and field techniques in a Chehalis clay loam and a Newberg sandy loam. The four types of units were (1) rectangular gypsum units with parallel electrodes, (2) cylindrical gypsum units with parallel, circular electrodes, (3) cylindrical gypsum units with 2-screen concentric electrodes, and (4) Colman units with parallel, screen electrodes separated by fiberglas. Data from the above calibrations for the various units were compared statistically by analysis of covariance.

In the greenhouse study the cylindrical gypsum unit with 2-screen concentric electrodes gave more nearly a single calibration curve for all soils than did the other three units, The resistances of the three gypsum units were sensitive to soil moisture tension changes from about 1 to 3 atmospheres at the lower limits on upwards to 15 atmospheres, with the rectangular gypsum unit with parallel electrodes giving the lowest limits. The Colman fiberglas unit was more sensitive than the gypsum units in the lower tension ranges. Generally, more fiberglas units are necessary than gypsum blocks to measure a given soil moisture-tension.

The laboratory procedure developed shows promise and is worthy of further investigation. Comparisons were made with the Colman fiberglas units in the greenhouse studies.

Field calibrations showed that a difference existed among the four units in the gypsum stakes. The variability of the stakes increased with depth. Comparison of the field and greenhouse calibration curves for the cylindrical gypsum unit with parallel electrodes showed a statistical difference, although they appear quite similar.

This study so far is inadequate to conclude that the laboratory or greenhouse methods may or may not be used to obtain calibration curves for field use. Field calibrations still remain, to the best of our present knowledge, as the calibration to be trusted because it duplicates the conditions under which these blocks are most commonly used in research investigations. The study has helped to amplify the need for knowing the fundamental behavior of these moisture measuring devices for proper interpretation of results. Research studies still in progress may add to our present knowledge in the next few years.

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APPENDIX

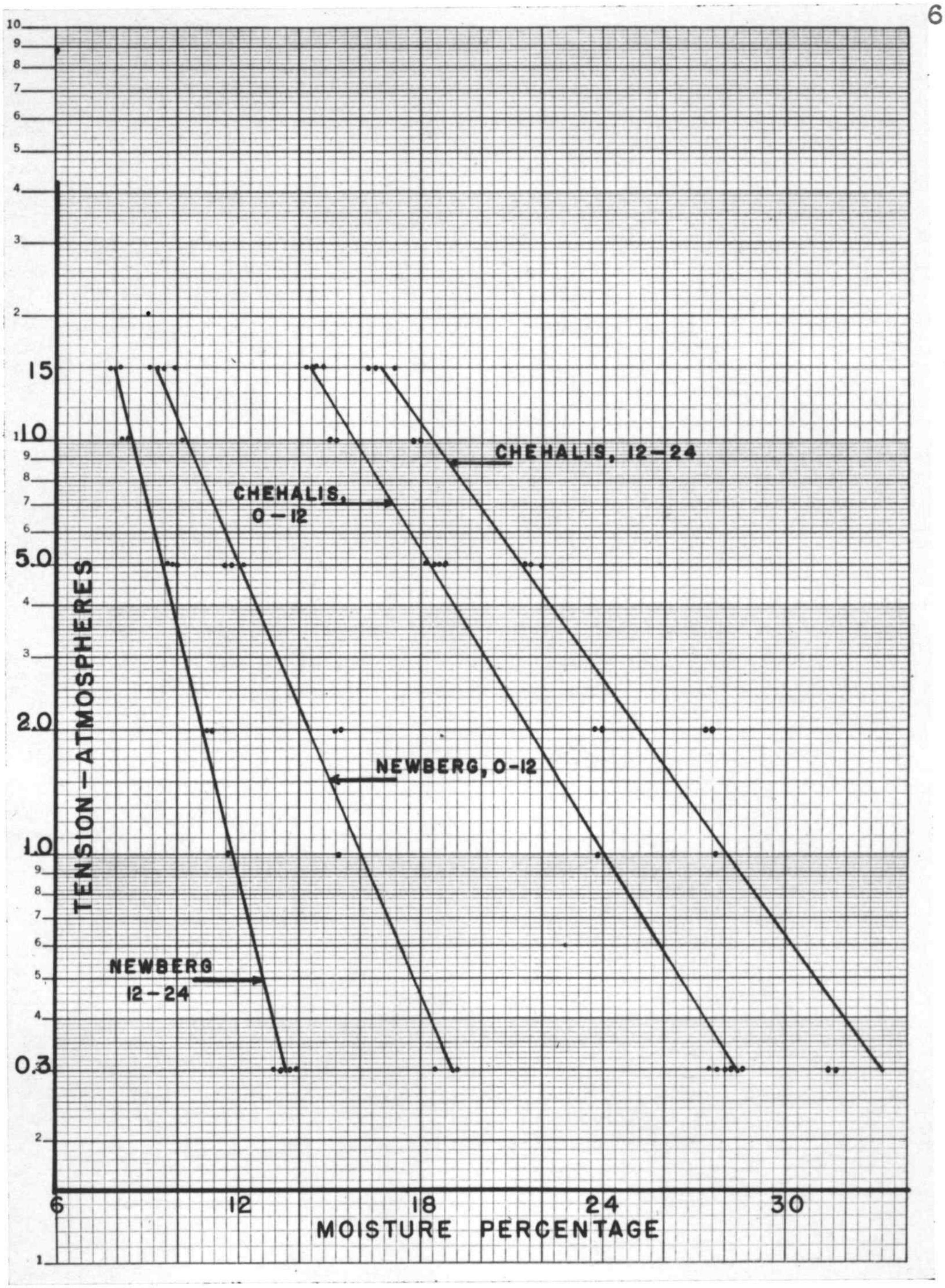

Figure 15. Soil moisture-tension curves for soils used in greenhouse and laboratory studies.

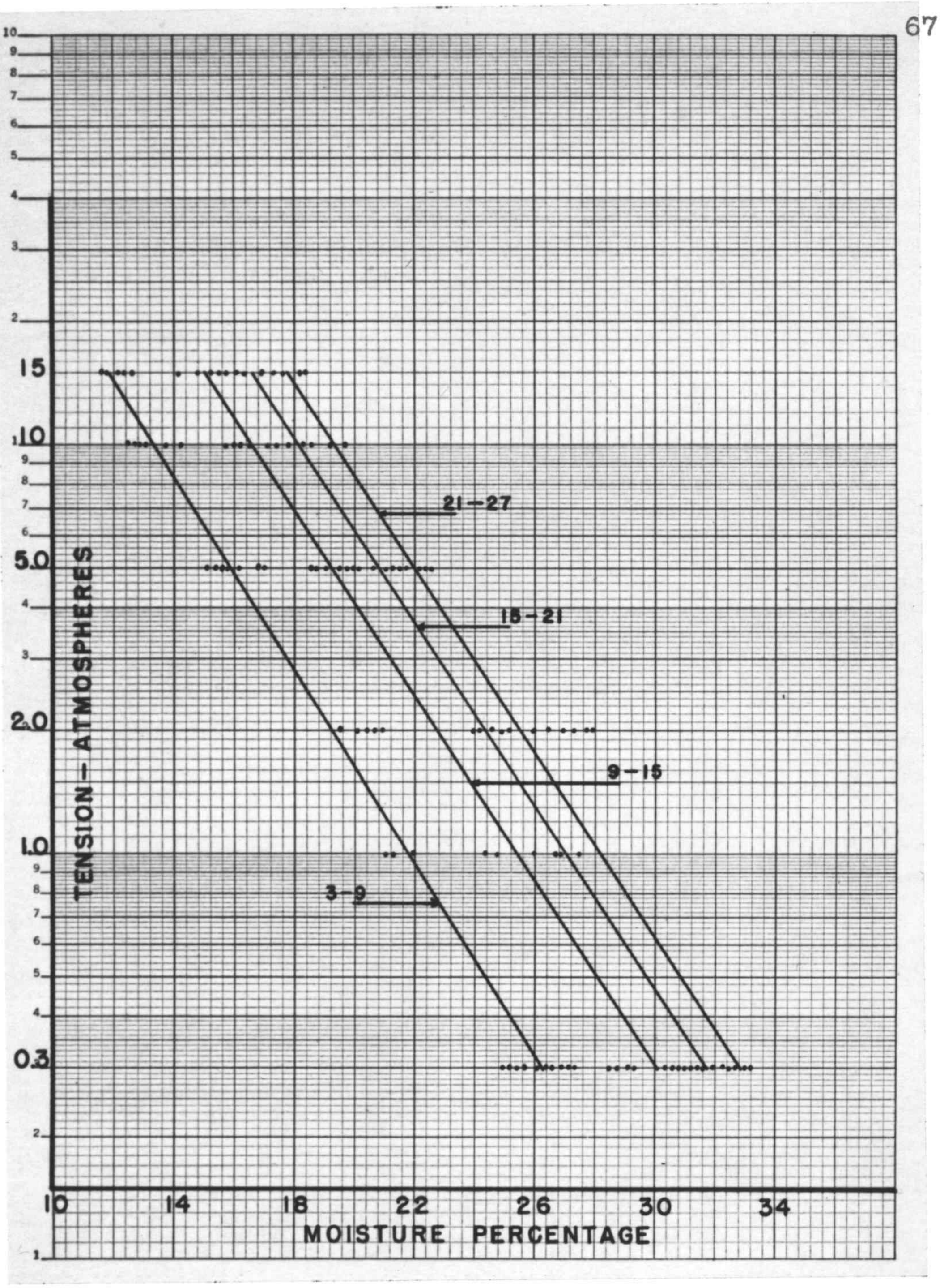

Figure 16. Soil moisture-tension curves for Chehalis soil used in field calibrations.

Table IV. The constants for equation [2] and number of measurements for curves in figures 15 and 16.

Soil	Depth (inches)	B	A	No. of samples (n)
Chehalis	0-12	-0.1213	2.9347	17
	12-24	-0.1037	2.9174	13
Newberg	0-12	-0.1744	2.8031	15
	12-24	-0.2949	3.5137	17
Chehalis	3-9	-0.1190	2.6046	48
	9-15	-0.1142	2.9205	44
	15-21	-0.1122	3.0439	48
	21-27	-0.1132	3.1984	44