5-1956

A Comparison of Devices for Measuring Soil Moisture Tension and their Effectiveness in Predicting Irrigation Requirements in the Field

Modesto Capiel
Utah State University

Recommended Citation

Capiel, Modesto, "A Comparison of Devices for Measuring Soil Moisture Tension and their Effectiveness in Predicting Irrigation Requirements in the Field" (1956). *All Graduate Theses and Dissertations*. 3615.
https://digitalcommons.usu.edu/etd/3615

A COMPARISON OF DEVICES FOR MEASURING SOIL MOISTURE TENSION AND THEIR EFFECTIVENESS IN PREDICTING IRRIGATION REQUIREMENTS IN THE FIELD

by

Modesto Capiel

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Agronomy

UTAH STATE AGRICULTURAL COLLEGE
Logan, Utah

1956

ACKNOWLEDGMENT

I feel most deeply indebted to Dr. Sterling A. Taylor for his valuable assistance and suggestions in the conduction of the experiments described in this thesis. I am also grateful to Dr. Rex L. Hurst for his valuable suggestions in the statistical analysis of this study.

Modesto Capiel

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF TABLES (cont.)

LIST OF FIGURES

LIST OF FIGURES (cont.)

INTRODUCTION

Many problems of management of irrigated soils require a knowledge of the soil moisture status and its relationship to plant growth before they can be solved.

The amount of water in the soil as indicated by moisture content gives no reliable information of its availability for plant growth. It is therefore desirable to obtain a direct measurement of the readiness with which soil water can be obtained by the plant.

The "field capacity" and the "wilting percentage" have been helpful in estimating the amount of soil water that can be used by plants.

Soil sampling has been used extensively to determine the irrigation requirements, irrigation efficiency, and the soil moisture depletion of the root zone between irrigations. By referring to corresponding soil moisture release curves, a crude estimate of the degree of availability can also be made. However, soil sampling is laborious and expensive, and if a continuous measure of the force per unit area that must be exerted to remove water from the soil is desired, the results are usually unsatisfactory.

A number of devices have been developed to estimate the soil moisture tension. So far, the tensiometer and the electric resistance unit have been most widely used. The former gives a direct relation of the tenacity with which moisture is held by the soil while the resistance units are indirectly related to moisture tension, and require proper calibration. Resistance units operate over a wider range of available soil moisture and do not require so much servicing as tensiometers.

More precise measurements of the soil moisture status in the root zone of the crop are frequently needed. Improved techniques and careful selection of measuring devices make possible some degree of improvement, but there are some inherent soil conditions which contribute to lack of uniformity. Variability of soil moisture within a given field or plot is certainly one of such conditions.

With an aim to improve the precision of field measurements of soil moisture, the response of some newly-developed resistance blocks within the soil moisture range from field capacity to the wilting point was investigated. Such desirable characteristics as uniformity, sensitivity, and precision of the units have been carefully studied.

Some of the more promising measuring devices were employed in a field experiment to indicate the moisture tension in the root zone of corn throughout its growing and fruiting stages. The data were also used to indicate when irrigation water was needed in plots receiving different moisture regimes. Moisture-fertilizer interaction on the yield of sweet corn and fodder was studied.

REVIEW OF LITERATURE

Volume or weight percentages of soil moisture measure the amount of water in the soil, but give no information about the proportion that a plant might use or the force per unit area with which it is retained.

The relative availability of moisture for plant growth has been estimated from measurements of soil moisture tension made in situ. A limited number of papers pertaining to this matter are herein reviewed. More consideration has been given to indirect measurements of tension and moisture content made with electric resistance units than with the direct method of measuring tension with the tensiometer.

The indirect determination of the "available moisture"

Potential functions are being used by soil physists to evaluate the forces involved in soil moisture movement. Edlefsen and Anderson (12) have pointed out the advantages of the free energy concept in the thermodynamic interpretation of soil moisture measurements. For the purpose of this study, the components of free energy arising from surface force action at the interface boundaries in the soil moisture system are expressed in terms of soil moisture tension. This concept is in accordance with the usage by Richards and Wadleigh (22) in reviewing the relation of soil moisture to plant growth.

In 1940, Bouyoucos (5) developed a device with which to measure the electrical resistance or capacitance of a porous absorption unit buried in the soil. He found it to have a reproducible relation to the soil moisture tension. After that different types of instruments have been proposed (1, 7, 4, 10, 11, 25, 3) which, with proper calibration, are suitable for indirectly measuring soil moisture tension within the plant growth range.

Bouyoucos and Mick (6) indicate that because the electrical resistance in a plaster of paris absorption block indicates the force with which moisture is held by the soil environment, it may be considered to portray the soil moisture conditions as they exist with respect to actively transpiring plants more accurately than conventional volume or weight percentages. They recall that conventional percentages have long been recognized as inherently fallacious in this regard because they cannot express free energy factors operating in moisture phenomena. They also add that unique features of the absorption block are that (a) the relationship between moisture in the soil and the block resistance is basically one of free energy, and that (b) the measurable range of sensitivity coincides with the critical variations of soil water. That is, the range of the technique corresponds with the quantity of moisture between permanent wilting and approximately the moisture equivalent.

Basic principles and performance characteristics. The electrical resistance of soils was first determined by placing in the soil 2 electrodes and measuring the resistance between the electrodes using an alternating current bridge to avoid polarization. Soil workers (1) found that the resistance between the electrodes and the soil was erratic because of the expansion and contraction of the surrounding soil which accompanied changes in moisture content. A multiple electrode (11) was proposed to eliminate this erratic contact. The possible influence of variations in salt concentration upon the electrical resistance was still unknown.

Bouyoucos and Mick (5) were the first to successfully control the immediate environment of the electrodes. This overcame the influence of soil texture, compaction, and—to a limited extent—the salt content.

They pointed out that after the porous absorption blocks are placed in the soil, their moisture content tends to come in equilibrium with the moisture content of the soil around, and from then on the blocks will loose or gain moisture with moisture changes in the soil. They overlooked the fact that the equilibrium established is one of relative suction and not moisture content directly. They further observed that the electrical resistance of the block does not begin to change until moisture has been lost to the extent that air occupies a part of the pore space, a condition which exists as the field capacity is approached. This, they explained, is because conductance makes a break near field capacity, and as the capillary moisture disappears, resistance of the block increases at a steady rate. They also explained that close to the lower limit of moisture availability the resistance changes for a slight loss of moisture are so great that the conductivity (reciprocal curve) approaches a constant.

Taylor (31) reported that the amount of water present in the surrounding matrix depends on (a) the relative attraction of the soil and matrix material for moisture, (b) the amount of moisture present, (c) the rate at which water transfer can be made from one material to the other, and (d) the electrical conductivity of the solution within the electrical influence of the electrodes.

Kelley, et al. (16) indicate that it is important that the pore size distribution of all blocks be very similar due to the fact that water drains faster from large pores at lower tension than from smaller pores.

Anderson and Edlefsen (1) agree with Kelley (16) in that an error up to 15 percent in the separation of the electrode during casting of the blocks should cause less than 5 percent variation in resistance reading. This theoretical consideration shows that for all practical purposes, not an excessive amount of care needs to be exercised in the spacing of the electrodes in the midplane of the block.

One characteristic, however, has been found (31, 7, 16) to limit the usefulness of absorption units. It is that they do not seem to operate over the entire plant growth range of soil moisture. Tensiometers, as described by Richards (19), have been used extensively to indicate the forces of retention in the moist range where resistance units lack precision. They have an additional advantage because they indicate tension directly while resistance units measure it only indirectly. However, a considerable portion of the plant growth range of soil moisture is left outside the limits of operation of a tensiometer (14, 16, 18, 20, 25). The region outside this limit is often very important in plant-soil moisture relationships.

Another limitation of the plaster block is encountered when they are buried in continuously wet locations. They begin to disintegrate immediately, and after functioning for some months under saturated conditions, they may have disintegrated to a point where they are no longer usable.

Another factor which has influenced the resistance reading of these blocks is changes in salt content of the soil. When Bouyoucos and Mick (5) designed their original block they studied the effect on resistance reading of treating soil with various amounts of fertilizer. They concluded that changes in the salt content of ordinary soil by fertilization will not greatly influence the relationship between the resistance of the block and soil moisture. These investigators repeatedly (8, 7, 6) attribute the failure of the changes in salt content of the soil solution to influence to any marked degree the block resistance, to result from the solubility of the $CaSO_4$. They indicate that the material is soluble up to 2400 p.p.m. A soil of average salt concentration will cause only a relatively small change in concentration of the block solution. It has been found that the fabric absorbent of nylon and fiberglass developed by Bouyoucos and Mick (7) and Colman and Hendrix (9), respectively, are more inert than plaster of paris and do not exhibit these buffering capabilities. This is especially true of nylon. Nevertheless, they recognized that changes in concentration of the soil solution in saline and alkali soils may be large enough to make the use of even the plaster units impractical.

Tanner and Hanks (28) report that appreciable resistance-tension hysteresis occurs in gypsum blocks. They indicate that the magnitude of the hysteresis at any tension will vary between different blocks. They claim that unless blocks are calibrated individually and unless they begin the drying cycle from a definite constant moisture condition, an estimate of soil moisture tension from block resistance may be in error by an amount equal to 0.5 to 1.0 times the estimated moisture tension. Holmes (14) includes hysteresis as one of 2 important sources of error in calibrating his blocks. Aging of the block is the other one, he mentioned.

The lag in response of resistance units might cause erroneous conclusions unless it is considered. Taylor (31) reports that the lag in response to moisture changes might be reduced when the moisture capacity of the units is made small and the transmission of water across the contact boundary between the unit and the soil is rapid.

It has been reported (5, 9, 25) that some variability in resistance reading may be traced to the fact that the electrical current conductance path is partially outside the block, and thus the resistance of the system changes, depending upon the conductance of the medium in which the block is placed and the contact between the unit and the soil. Slater (24) found that the conductance path may be confined wholly within the block by locating 1 electrode centrally in a cylindrical screen. The screen itself forms the second or outer electrode.

Bouyoucos (4) claims that his new screen electrode blocks develop a minimum amount of "stray currents" which he considers is less than one-third of that developed in his original block. No explanation is given why the new block exhibits this advantage over the old block.

Temperature changes have been reported (5, 6, 7, 31) to cause variations in the resistance of absorption blocks at a constant moisture content. Bouyoucos and Mick (5) report that the changes in block resistance is about the same for equal changes in temperature at all soil moisture contents. They prepared some correction curves which are in essential agreement with an equation developed by Slater and Bryant (25) for the same purpose. However, investigators (5, 7, 31) agree that variations resulting from temperature changes are small relative to other errors and can be ignored for many purposes.

Ashcroft and Taylor (2) express the opinion that increased resistance at the same tension, when units are allowed successively to wet and dry in normal use, results from recrystallization of gypsum in the plaster blocks. This will result in a change in the pore size distribution of the units. Another factor that could cause this drift is changes in contact between electrode and plaster.

Adding to the value of absorption blocks as soil moisture indicators for large-scale installations, Bouyoucos and Mick (6) mention the following advantages: (a) after the initial installation, which is relatively simple, the soil need not be disturbed, (b) reading may be made by unskilled labor, (c) single readings require a minimum of time, generally not in excess of 1 minute, thus several hundred readings could be made by a single operator in the course of a working day, (d) blocks may be completely buried so that their presence does not interfere with surface tillage or plant growth, or in any other way with crop production, and

(e) the plaster of paris units are not costly, which makes feasible a large number of replications.

Anderson and Edlefsen (1) have indicated that to ensure unquestioned similarity in characteristics of the blocks, such factors as the proportion of plaster of paris to water, mixing time, and pouring time must be carefully reproduced in the making of each block.

Matrix material and electrode. Many varieties of materials are marketed as plaster of paris.[1] Differences in both the chemical and physical characteristics of these materials are caused by varying the quantities of hasteners or retarders which are added to control setting speeds and otherwise modify a given product for commercial and technical uses. Bouyoucos and Mick (6) indicate that, in general, these regulating agents have an unfavorable influence on the soil water-resistance relationship of the blocks. They state that chemically-pure material exhibits a wider range of resistance changes for a given change in soil moisture and therefore contributes to the sensitivity of the method. To them, pure gypsum has proved extremely durable and the best material thus far investigated.

In 1942, Slater (24) reported he used hydrocal as the casting material for his modified cylindrical block. Although this material has been reported to be very hard, which might indicate greater durability, Bouyoucos and Mick (6) indicate that its extremely high density is complemented by a very low porosity which reduces not only the relative proportion of water that can be absorbed, but also the speed with which it moves within the block and between the block and the soil. They report that the sensitive range of these blocks is narrow, possibly because of their narrow pore size distribution characteristics. Besides, the low solubility of these hard materials reduces the buffer capacity of the block with respect to

---

[1] Manufactured by United States Gypsum Company.

salt concentration changes within the soil solution. Difficulties are encountered in casting such blocks with a high degree of uniformity.

However, Slater (24) reports that his coaxial design of blocks containing the concentrically arranged electrodes eliminated the effects of external electrical fields. Taylor (31) tested a concentric plug in comparison with other blocks and states it is apparent this unit has eliminated the effect of external contact.

Bouyoucos and Mick (6) state that the relative simplicity of the present rectangular pattern, and the ease and cheapness with which the blocks can be manufactured, appear to offset any theoretical advantage of a coaxial absorption unit.

In 1948, Bouyoucos and Mick (7) developed a fabric absorption unit embodying the principles of the plaster of paris block and which included nylon and fiberglass as absorbents. They point out that these units last longer under extremely wet conditions. They also claim these units measure the entire range of soil moisture from saturation to air-dryness. However, because of unique qualities which characterize plaster of paris, they made clear that the fabric units were not intended to replace plaster of paris blocks.

Comparing the fabric units and various others with different kinds of electrode and absorbent materials, Bouyoucos and Mick (8) report that the standard plaster of paris block, although operating over a smaller range of soil moisture than the other units, exhibited the smallest scattering within its range and thus allowed the smallest experimental error. Also, they report these units exhibited the least hysteresis between successive drying cycles, thus illustrating the unique buffering function of the slightly soluble gypsum absorbent.

Later in 1953, Bouyoucos (3), in an investigation on how to make more permanent his absorption units, reported that no block of the casting type had been produced so far, superior in performance and longevity to that made from plaster of paris. He reported that by impregnating the blocks with plastic resin, like nylon, not only the durability of the block is increased, but characteristics like buffer action, rate and amount of water absorption, electrical conductance, and sensitivity of the block to changes in soil moisture are not altered. This block was provided with a short, thick electrode which, in contrast with the old type, Bouyoucos claimed assured remarkable uniformity in the reading of the blocks.

Recently, as a result of recent studies, Bouyoucos (4) reports the introduction of a new type electrode. He states it probably constitutes one of the most important improvements on the blocks since their development. According to the results of experiments, it has led him to conclude that the new unit is superior in the following ways to his original block:

1. Exhibits little or no capacitance.
2. Develops a minimum amount of "stray currents" of electrical force.
3. Is slightly more sensitive at higher levels of moisture content. Definite sensitivity to changes in soil moisture at a tension ranging from 260 to 330 cm. of water is shown.
4. The screen electrode used in the new block assures closer, stronger, and more permanent contact between the matrix material and the electrodes. He also claims this electrode makes plaster of paris blocks more permanent and stable in their performance.

Taylor (31) reports that even if a material could be found that had exactly the same attraction for water as the soil over any given range in moisture content, there would still not be a 1:1 change in resistance of the units due to the fact that moisture content and resistance are not linearly related over all values of moisture.

<u>Calibration of units.</u> The relationship between soil moisture and electrical resistance of blocks as first determined by Bouyoucos and Mick (5)

has been the subject of various modifications. The method, depending fundamentally on moisture equilibrium between the block and the soil, is being objected to, principally because of the lag of the units in attaining equilibrium. Anderson and Edlefsen (1) report that they were unable to obtain equilibrium values for the electrical resistance of blocks at low moisture contents in the vicinity of the permanent wilting percentage. They investigated the lag in the response of the blocks to changes in soil moisture content when the roots of actively transpiring plants surrounded the units. Then they found surprising absence of lag in response for the 2 electrode blocks. The explanation they give is that in the soil where plants are growing, a very steep soil moisture content gradient is developed, the roots growing up to the face of the blocks. As the rate of movement of moisture, they explain, is proportional to the gradient of moisture content, the movement out of the blocks should be more rapid. Their figures showed that the electrical resistance corresponding to the permanent wilting percentage is around 200,000 ohms and that corresponding to the moisture equivalent is around 500 to 600 ohms. Tanner, et al. (27) and Bouyoucos and Mick (6) have reported similar figures. The latter suggest that for practical purposes, these resistance values will characterize the extremes of soil moisture from the wilting point to field capacity except where high osmotic potentials are encountered.

Tanner, et al. (27) calibrated various blocks previously tested for uniformity in a modified (13) pressure membrane apparatus. They found it to be the most versatile and rapid of all used. Haise and Kelley (13), who used the method originally, report that 1 to 7 days are required to reach equilibrium. However, they point out that this does not mean that the units would lag this much in the field if surrounded by soil in which moisture is being removed by roots of actively transpiring plants. Only one-third of the surface of the unit is exposed to the membrane, but if moisture were removed from the entire surface area they think that lag would be considerably reduced.

Taylor (31), in his comparison of various devices to determine soil moisture, calibrated different units in the pressure membrane. He reports that only in the case of the plain plaster blocks and the concentric plugs were the fluctuations between blocks low enough to permit the use of a single calibration curve to apply to many blocks.

Various investigators (5, 6, 31, 4, 27, 1) agree that uniformity of the blocks is essential in obtaining reproducible results from representative blocks of those calibrated in the laboratory. Bouyoucos and Mick (6) suggest that a good test for uniformity is to measure the resistance of the blocks when immersed in water. Tanner, et al. (27) recommend that for best results only blocks which check within 50 ohms be used in the field.

Bouyoucos (4) suggests that to prevent any shifting in calibration of new blocks, proper curing is essential. Fresh blocks should be put through a process of wetting and drying to attain maximum curing.

Suitability of units to field conditions. Various investigators (25, 10, 30, 2) have encountered the difficulties of unequal distribution of water, unequal removal by plants, marked changes in soil texture and structure, and cracks and discontinuities which cause unequal penetration.

Cummings and Chandler (10) indicate that other factors as (a) errors in field measurements, (b) temperature differences, (c) the various amounts of stray current flowing outside the block, and (d) variations in construction of the blocks contribute to reduce the precision of the instruments.

Ashcroft and Taylor (2) studied the variation in blocks and the random variation of soil moisture tension in potato plots. The coefficients of variability they determined for blocks, location, and the combined location and block variation, and they found that the smaller variation was among blocks themselves. The blocks they used were the standard Bouyoucos type and no attempt was made to select them to agree within 50 ohms when soaked in water. They indicate that such factors as drift of the blocks due to recrystallization of $CaSO_4$ in the units, the amount of electrolyte present in the soil, and the contact between the soil and the blocks that is obtained during installations are known to affect the precision and calibration of the instruments. They further suggest that by increasing the number of installations, the combined location plus block variability, which is an estimate of the precision with which the moisture tension is actually measured, can be reduced.

Taylor (31) indicates that since it seems unlikely that the coefficient of variability for field sampling of moisture plots can be reduced much below 10 percent of the true value, any method giving this precision would therefore seem to have a use in the field.

Slater (25) obtained a standard error of estimating soil moisture content by plaster blocks of 1.29 percent while for tensiometers he got 1.4 percent. Both methods of measurements were based on the respective moisture range in which the instruments are sensitive. In order to evaluate instrumental results, he made gravimetric determinations on soil samples taken from the plots, omitting an area of approximately 1 foot in diameter surrounding the instruments. He plotted log of ohms resistance because by the use of logarithms, linear relation between block resistance and soil moisture could be obtained. He found an essentially linear regression in the intermediate moisture ranges, but in the highest level of moisture he encountered a wide, horizontal dispersion of the data on the graphs. He did not determine the accuracy with which tension was estimated by the units.

Haise and Kelley (13) pointed out that the curves presented from laboratory calibration are for desorption only and it should be expected that the values would differ under field conditions, depending on the magnitude of the hysteresis effect. This factor might cause a considerably greater error in determining moisture content than in estimating tension since only the hysteresis in the blocks would be involved in the latter but both the soil and the blocks would be involved in the former. In the case of tensiometers there would be no hysteresis involved in tension measurements and only the soil hysteresis in determining the moisture content.

The direct method

Richards (20) describes soil moisture tension as a physical property of water, that within limits can be measured directly with soils in contact with a porous surface. Tensiometers provide a direct measure of the tenacity with which water is held by soils. The magnitude of the surface forces with which soil retains water can be expressed in terms of height of centimeters of a unit water column whose weight just equals the force under consideration. The mercury manometer in a tensiometer affords the greatest precision. On the measure no calibration against soil moisture tension is necessary because they are uniquely related to the work plants must do against surface force action to extract moisture from the soil.

However, tensiometer readings are unreliable unless it is known that the unit is substantially filled with water. Otherwise the volume of water that must be displaced through the cup wall to attain equilibrium with the soil will be excessive. A transparent air trap is therefore mounted above the ground and connected to the cup in such a manner that any air entering the system becomes visible in the air trap.

Essential elements of a tensiometer consist of a porous cup, a vacumn gage, and means for filling the system with water and removing air. Their form, size, and arrangement can be varied to suit individual requirements.

Cup conductance, as indicated by Richards (18), appears to be a significant constant for a tensiometer. It involves the area and thickness of the cup wall, as well as the permeability of the porous cup. The walls of the porous cup should be as permeable as possible and still have an air entry value greater than 1 atmosphere. That is, when the walls of the cup are saturated with water, they should withstand an air pressure difference of more than 15 pounds per square inch without leaking air. Suitable cups can be made from ceramic clay, by the drain-casting process. Air might enter through the cup walls or through the joints that are not vacumn-tight. Some kinds of plastic and rubber tubing are somewhat permeable to diffusion of some or all gases in the atmosphere, and when they are used, air entry is inevitable. Korseal tubing is the best material used today. It is thermoplastic and is unaffected by sunlight. After long periods of use, air gradually enters even the best-constructed tensiometers by solutions in the soil water which enter the instrument through the cup walls when rapid changes in tension from high to low values occur.

Tensiometers have been used for measuring soil moisture under field, laboratory, and greenhouse conditions. The tension range covered by them extends from 0 to about 850 centimeters of water. This is only a small fraction of the tension range over which soil moisture is available for plant growth. However, this limitation appears to be less severe when stated in terms of the available soil moisture-content range of the soil. Richards and Weaver (23) concluded that in the finest-textured soils the tension range of 0 to 0.85 atmosphere covers about half of the moisture content range between field capacity and the wilting percentage. Richards and Wadleigh (22) indicate that for coarser, sandy soils the tensiometer may cover more than 90 percent of this range.

Like electric-resistance units, a variability between tensiometer readings in a given plot area is usually associated with non-uniform soil moisture conditions.

There has been reported (25, 29) that one of the most common sources of error in tensiometer readings in the field results from the presence of air bubbles that appear in the system. The presence of air in the trap indicates that the instrument should be serviced. Distilled water, freshly boiled to remove dissolved air, should be used to refill the system. Otherwise, unreliable readings will be obtained from tensiometers.

Another source of error is caused by temperature variations in the field. It has been found that large, diurnal fluctuations occur in response to the heating and cooling of the metal portion of the instrument and the thermal conduction into the cup by the metal parts joining it. This sets up vapor pressure gradients and the distillation of water from cup to cold soil or vice versa, inducing differences in the readings from the true values. This can be partially corrected by eliminating metal parts to be in contact with the porous cup.

Slater and Bryant (25) reported that it was their experience that tensiometers are subject to mechanical failure. They added that their cost prohibits extensive replication, and that there is no way, once a tensiometer is installed under field conditions, to determine easily whether or not tensiometers are functioning correctly. In attempting to correlate soil sampling with corresponding tensiometer data, they indicated it was evident that an approximately linear relationship existed for the data at tensions of less than 60 centimeters of mercury, and that above that, little or no correlation is evident between soil moisture and instrument readings.

Conclusions from the review of literature

1. Electric resistance units indicate indirectly the force with which moisture is held by the soil environment. This, in turn, is an estimate of soil moisture conditions as they exist with respect to actively transpiring plants.

2. In the construction of the electrical resistance units it is important to obtain similarity in such characteristics as pore size distribution and water-holding capacity of the units. To do this, such construction factors as proportion of water in the mix, pouring, and mixing time must be carefully reproduced.

3. Units should be selected for uniformity so that they will give acceptable results from laboratory calibrations of representative blocks.

4. Plaster of paris blocks, because of their low sensitivity to salinity, low hysteresis effect, ease of fabrication and reproducibility, have thus far not been replaced by the other types of resistance units.

5. Some modifications have eliminated or reduced some undesirable characteristics in blocks of the casting type. Improvements have especially been accomplished by (a) eliminating or reducing greatly the capacitance of the blocks, (b) stray currents have been eliminated or reduced to a minimum, (c) slightly more sensitive units at a higher level of moisture content have been produced, and (d) new blocks seem to be more stable in their performance.

6. Calibrations in the pressure membrane apparatus have been found to be the most versatile of all methods used.

7. Unequal distribution of moisture in plots has been attributed to be one explanation for the variability in readings of the devices in the

field.

8. Tensiometers provide a direct measure of the tenacity with which water is held by soils. The magnitude of the surface forces with which soil retains water can be expressed in terms of height of centimeters of a unit water column whose weight just equals the force under consideration.

9. No calibration of tensiometer readings against soil moisture tension is necessary because of their unique property of being directly related to the work plants must do against surface force action to extract moisture from the soil.

10. The most common sources of errors in tensiometer readings in the field are caused by air bubbles that appear in the system and the temperature variations in the field. Whenever these conditions are present, they are inducing large differences in readings from the true values.

11. Tensiometers are subject to mechanical failure and require servicing. Also, their cost prohibits extensive replication.

LABORATORY METHODS AND PROCEDURE

Some weeks before installing the units to be used in the field experiment, blocks of different design were constructed in the laboratory in sufficient number to compare them by various calibration techniques and other tests. It was intended to collect enough data in the laboratory to select a block of apparently good characteristics for field use. However, this work was not completed before field work began, and selection was made on the basis of the limited results obtained.

A limited number of commercial units of the concentric type electrode[1] similar to Slater design (24) were included in the comparison, although not tested by all techniques.

Because only a few units of each kind of the commercial plugs were available, and because time and space in the pressure membrane were limited, some of the results herein obtained will necessarily require further investigations.

The units constructed in the laboratory were of a rectangular pattern, while those received commercially had a coaxial design and differed in the composition of their matrix material. In total there were 8 different devices which are described as follows:

1. Bouyoucos original block: For details of construction of this block refer to the literature (5).

2. Screen type electrode block: This block was constructed similar to the one developed lastly by Bouyoucos (4). The outside dimensions of this block are 2 by 1 9/16 inches. The electrodes are 1½ x 8/16 inches

---

[1] Obtained from Rauturn Corporation, Portland, Oregon.

in size. The electrodes are a 20-mesh stainless steel placed 3/16 inch apart. In this case, unlike the Bouyoucos type, they are arranged with the longest flat surface of the electrode parallel with the longest flat surface of the block. A good number of these blocks had been previously constructed and tested in the laboratory and were found to have promising characteristics. Gypsum casting plaster was used as matrix material for this and all blocks constructed in the laboratory. The plaster mix has 10 parts plaster and 7 parts water.

3. Screen type electrode block, impregnated: This block was constructed the same way as No. 2 except that the finished unit was impregnated in an alcohol solution of nylon resin (6 percent).

4. Concentric electrode plug (125): This unit was commercially available. The manufacturer[1] indicated it was made from straight hydrocal mix, in the proportion of 4 parts plaster to 5 parts water. To identify this and the following units, a number corresponding to the parts of water per 100 parts of plaster shall appear at the end of the names of these units.

5. Concentric electrode plug (100): This unit was also commercially available. The manufacturer indicated that the plaster of which it is made, designated as B-11 by United States Gypsum Company, is characterized primarily by its high alkalinity (pH 11). The plaster mix has equal parts of plaster and water.

6. Concentric electrode plug (60): This was also commercially available and manufactured from B-11 plaster. The plaster mix has 5 parts plaster and 3 parts water.

7. Concentric electrode plug, mixed plaster (60): Another unit that was also commercially available. The manufacturer indicated this was made

---

[1] Letter received from Mr. W. J. Turner, Rayturn Corporation, Portland, Oregon.

from hydrocal white mix and includes 1/30 of B-11 plaster. The mix has also 5 parts plaster and 3 parts water.

8. Gage stake sensitive cells. Units representing each depth level of commercial gage stakes. The mix used for these cells is also white hydrocal mixed with 1/30 of B-11 plaster. The mix has also 5 parts plaster and 3 parts water.

Calibration techniques

Various blocks of Nos. 1, 2, and 3 were constructed, tested for uniformity, and 4 of each kind were subjected to curing by alternate wetting and drying cycles as indicated in Figure 1. The commercial units underwent curing in the factory. Table 1 illustrates the uniformity of all blocks constructed in the laboratory, as well as that of the coaxial type units. Other data such as the coefficient of variability with additional wetting and drying cycles after curing are presented for units 1, 2, 3, 4, and 8. For the purpose of this comparison, the units were selected from those having the same or approximately equal readings in their first wetting. Information indicating the effect of external contact is also presented.

All the units to be calibrated by the different techniques were previously saturated with water. They were selected to check within 50 ohms as indicated by their saturated readings.

Pressure membrane apparatus. In order to plot the resistance readings against moisture tension in all curves obtained by the different calibration techniques, a moisture desorption curve was carried in the laboratory (Figure 2). For tensions from 0.1 to 1 atmosphere, the pressure plate apparatus described by Richards (23) was used. The procedure was also the same as that described by Richards and Weaver (19). For tensions above 1 atmosphere, the pressure membrane apparatus similar to that

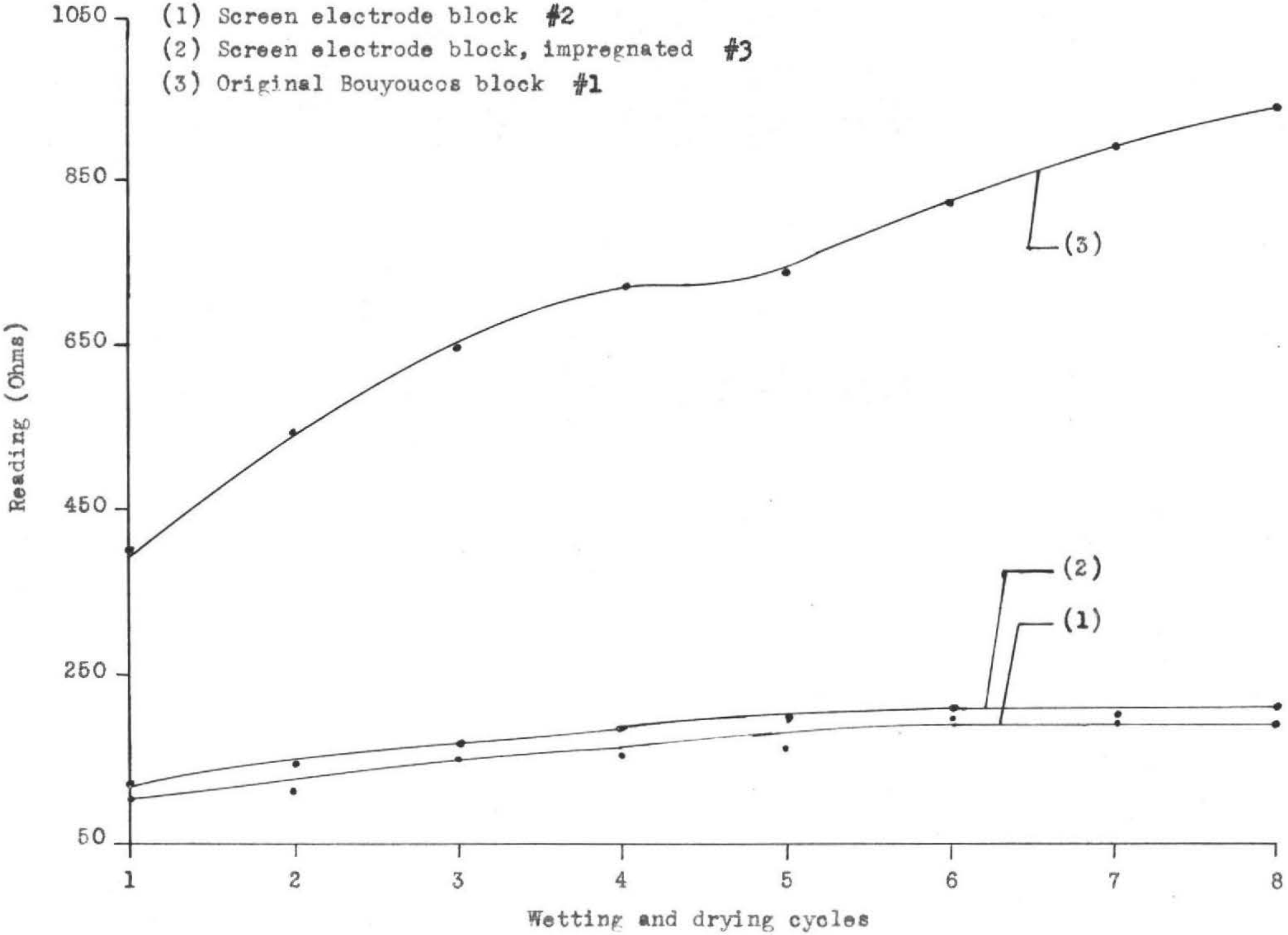

Figure 1. Response of various soil moisture measuring devices to attain equilibrium under alternate wetting and drying cycles.

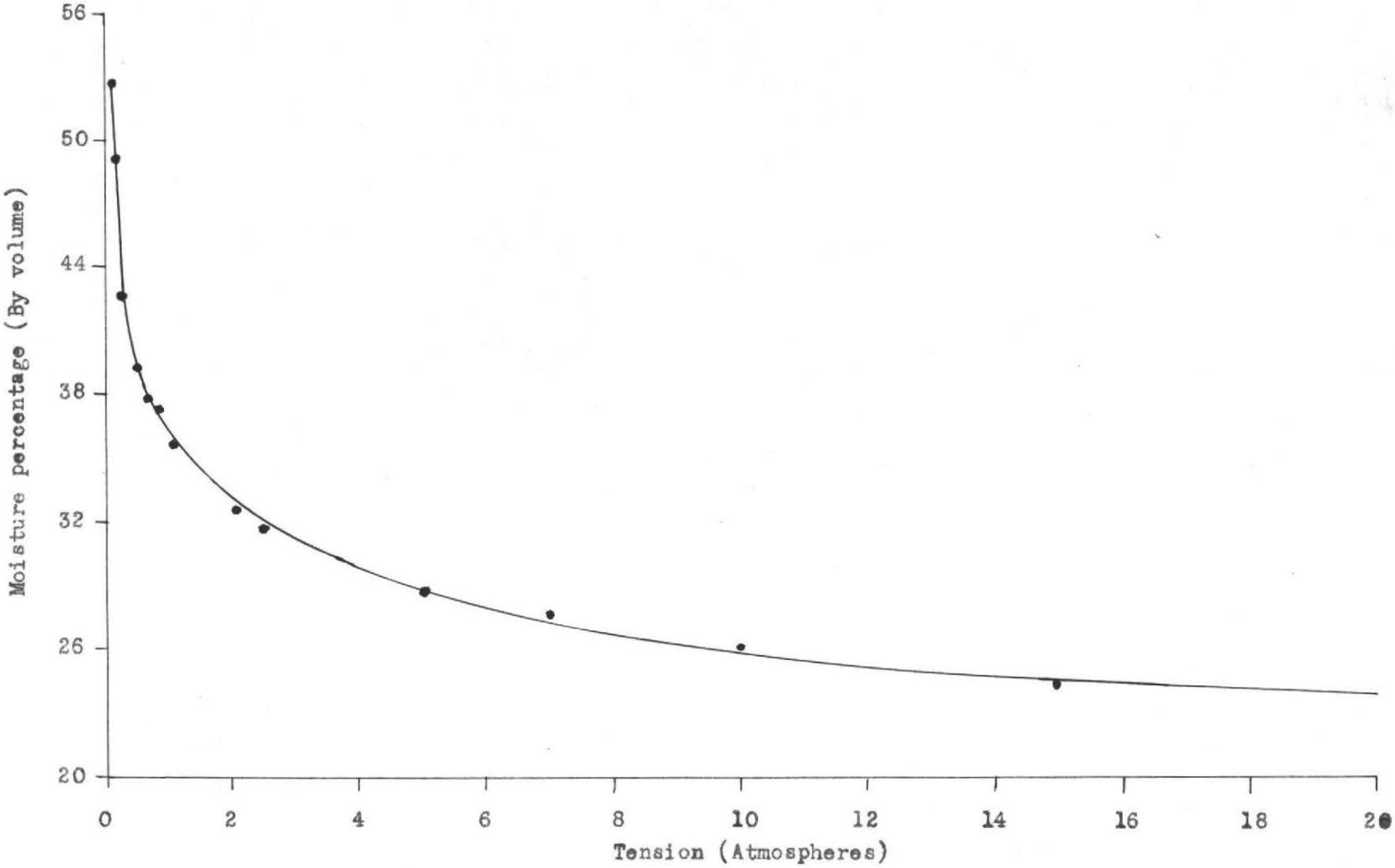

Figure 2. Soil moisture desorption curve obtained for Salt Lake silt loam with the use of the pressure plate and the pressure membrane apparatus.

modified later by Richards (20) was used. It has been found that by dipping the sausage membrane in warm water with a bit of mercuric iodide, the membrane can withstand tensions up to 15 atmospheres for a longer period of time.

Calibration curves for all the units, to be read in tension directly, were obtained in the pressure membrane apparatus. These cells had been slightly modified by Taylor (31) to permit electrical contact from the outside through insulated fittings in the cylindrical section. One-hole, double 0 rubber stoppers had been fitted into holes bored in the cylindrical walls. Machine screws of appropriate size to fit snugly in the hole through the rubber stopper were inserted. Washer and nuts had been placed then at each end of the machine screw and tightened enough to make a complete air-tight seal.

Except the Bouyoucos original block and the screen electrode block, impregnated, all other types were replicated as permitted by the number of available insulated fittings.

<u>Growing plants in pots</u>. Units 1, 2, 3, and 4 were calibrated by burying them in pots where actively transpiring corn plants were growing. These were kept in a greenhouse. Soil used for this and all other calibrations was Salt Lake silt loam, taken from the area where later a field experiment was carried on. It was previously passed (air dry) through a 2 mm. sieve in order to obtain fairly uniform structure in all pots. When the plants were big enough, resistance readings were taken twice every day with the Bouyoucos bridge (6). Temperature readings were taken every time to correct resistance readings to a uniform temperature of 60 degrees F. This was done by using the values on Table 8 (p. 347) of the <u>Soil Survey Manual</u> (26). Frequently, there were nights when temperature was more than 5 degrees higher than in the mornings, in which case, without corrections

for temperature, resistance readings were lower even though moisture had been lost during the day by transpiration and evaporation. Pots were wetted once to about field capacity, the day before the first readings were taken.

Friction top cans. In the constant temperature room all units were calibrated to read moisture content by placing them in 8 friction top cans with soil previously sieved and moistened uniformly to different moisture contents. The leads were brought through a hole in the top which was then sealed with cotton and wax. Readings were taken at intervals until no further change in resistance reading was noted; cans were then opened and the moisture content was determined. The remaining concentric plugs made with B-11 plaster were also calibrated by this procedure, modified to obtain several equilibrium readings from the same can. That is, only 2 friction top cans were used. When repeated resistance readings indicated equilibrium was obtained, a representative sample of soil for moisture determination was removed. The cans were then heated to about 70 degrees C. for about 3 to 4 hours to reduce the moisture content. They were then sealed and heated again to aid in obtaining a uniform distribution of moisture inside the cans. Units which were replicated twice inside the cans were placed 1 on top and the other on the bottom, so that their readings would give an indication of the distribution of the soil moisture inside. Two units of the screen type electrode block, not impregnated, having the same saturated reading, were buried also in each of the 2 cans.

RESULTS OF LABORATORY PROCEDURE

The attempt has been made to obtain data comparable for all devices on the basis of uniformity, precision, sensitivity, lag, drift, and weathering.

Under the curing process (alternate wetting and drying cycles), the screen type electrode blocks attained a constant reading apparently faster than the original Bouyoucos block. Their drift was also significantly less. There seems to be no significant differences between the impregnated and non-impregnated screen type blocks as to quickness in curing and drift (Figure 1). The impregnated block seems to be slightly more precise in its saturated reading once it is apparently "cured." Both screen type electrode blocks compare favorably in uniformity (Table 1) with the commercial units as indicated by their first saturated readings, even though all commercial units had undergone curing from factory. No significant changes in the saturated resistance readings of the screen type blocks were found when their external contact was varied. This agrees with Bouyoucos (4), who indicated that his screen type electrode block had practically eliminated the effects of "stray currents." None of the concentric plugs were affected in their readings with change in external contact.

Figures 3, 4, 5, 6, 7, 8, 9, and 10 represent the calibration curves obtained from all units by the 3 calibration techniques employed. All curves have been plotted on log paper, 3 by 3 cycles. It has been found that an approximately linear relationship exists between log ohms resistance and log tension over a part of the moisture range for many of the units, as shown in the figures. Slater and Bryant (25) used this or a

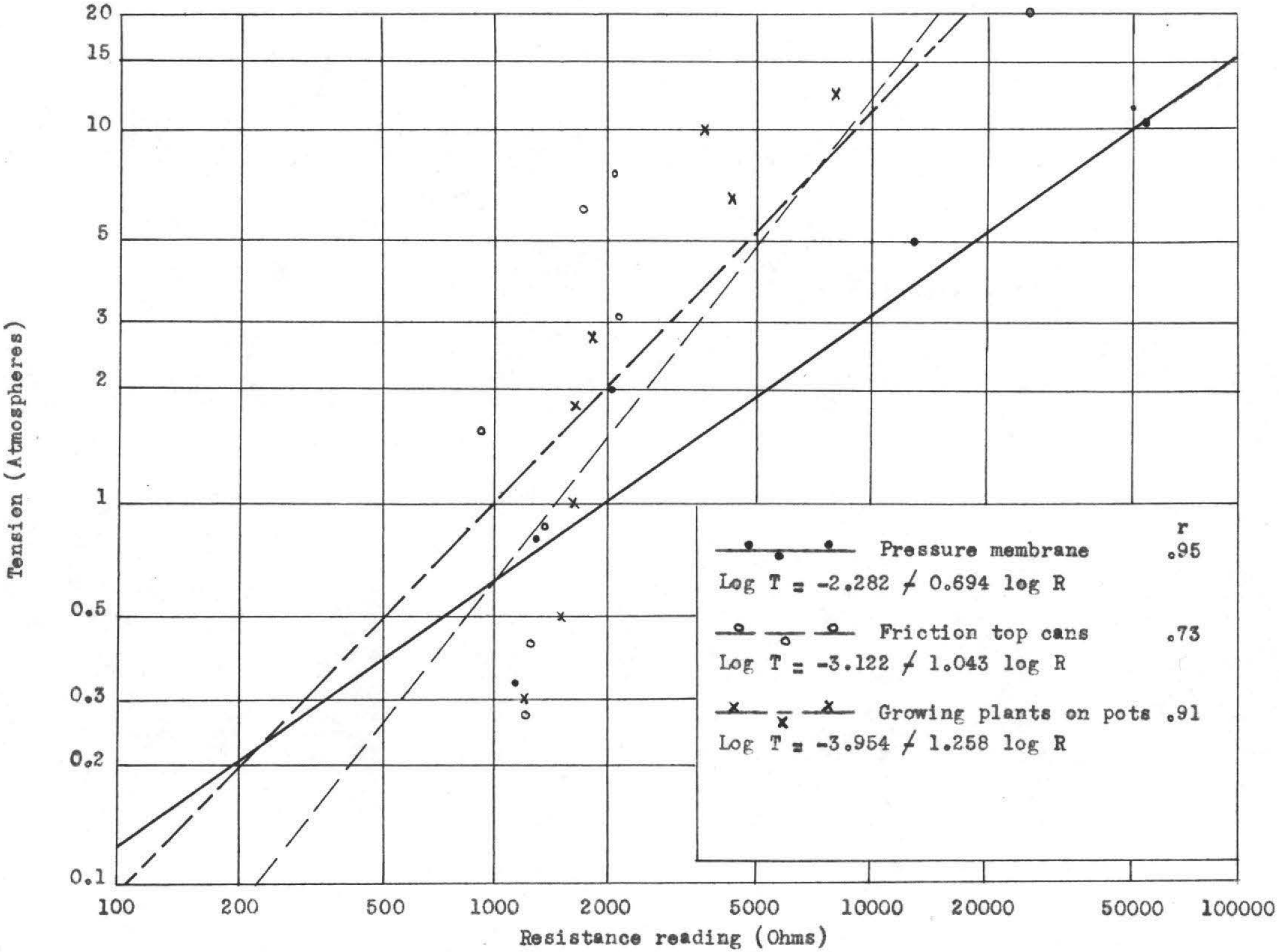

Figure 3. Calibration curves obtained by regression for Bouyoucos original block.

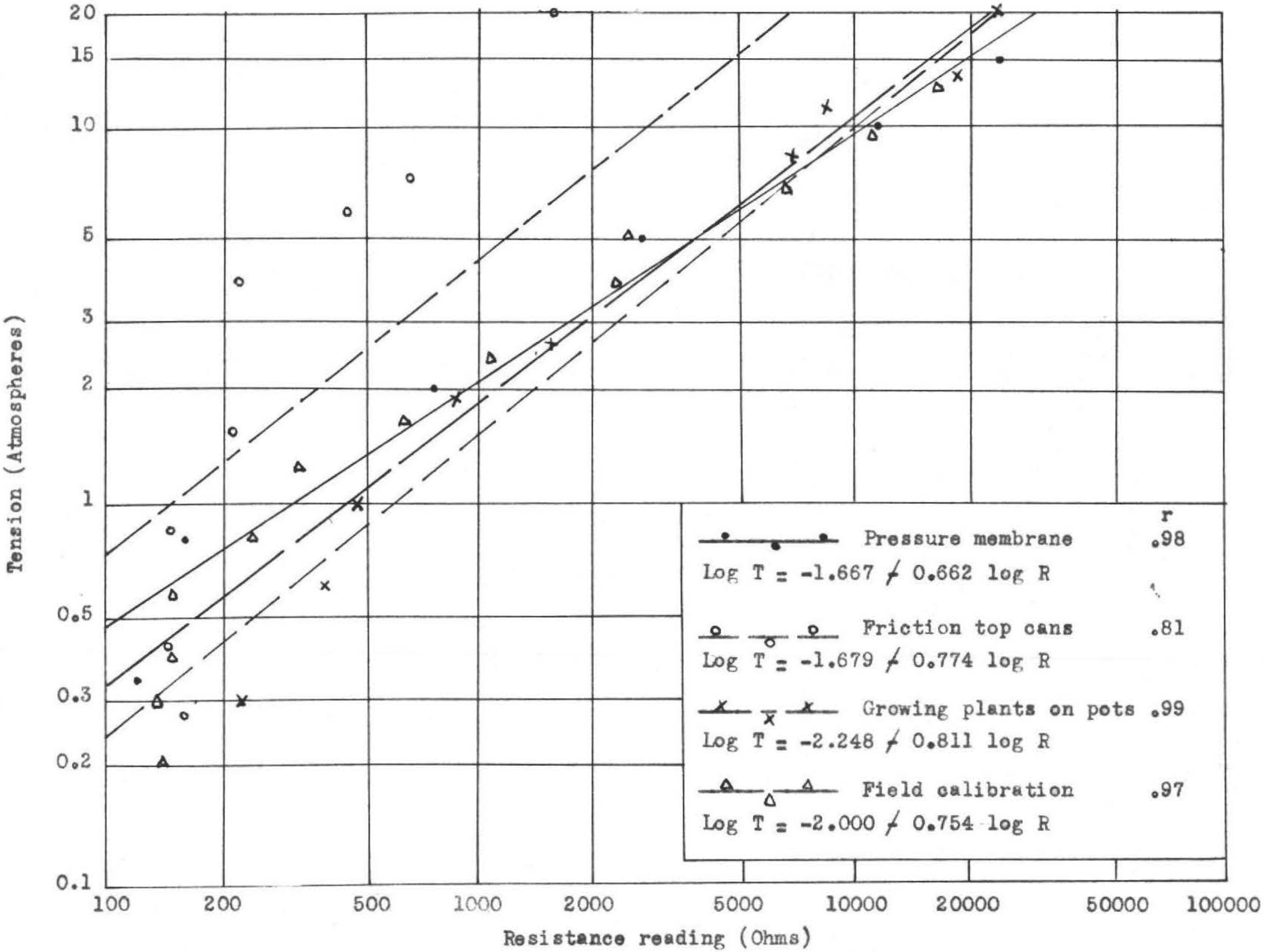

Figure 4. Calibration curves obtained by regression for the screen electrode block.

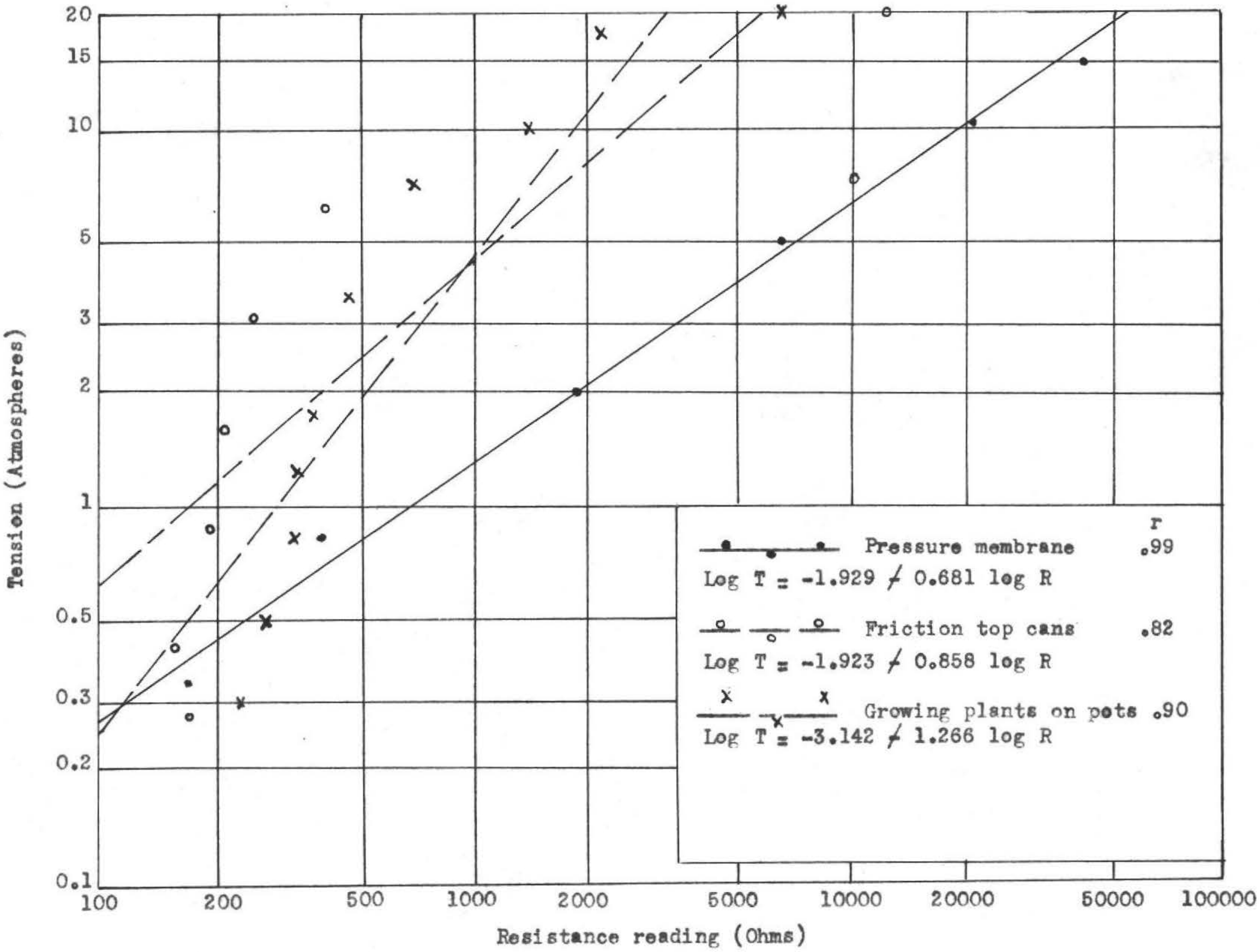

Figure 5. Calibration curves obtained by regression for the screen electrode block, impregnated.

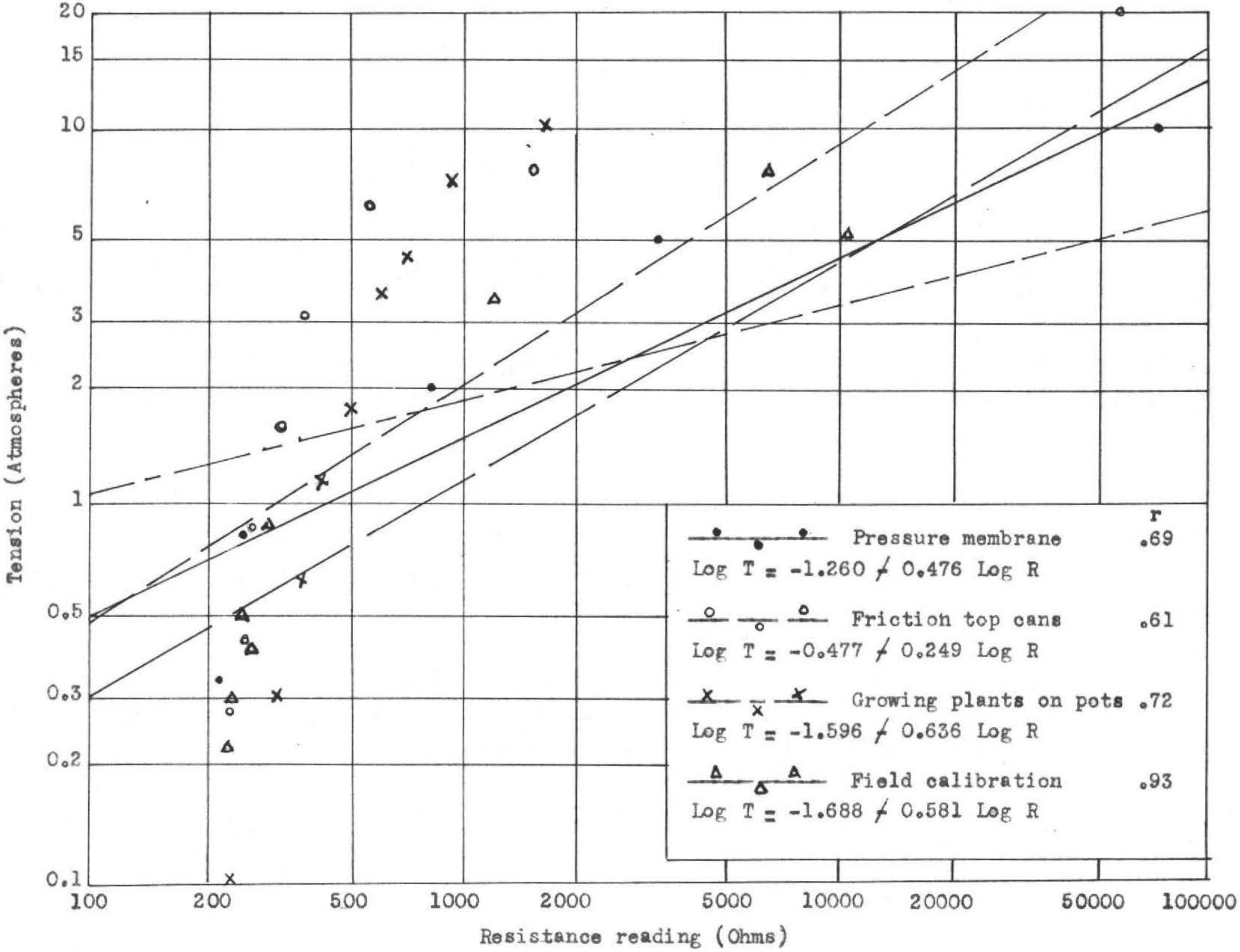

Figure 6. Calibration curves obtained by regression for the concentric electrode plug, (125).

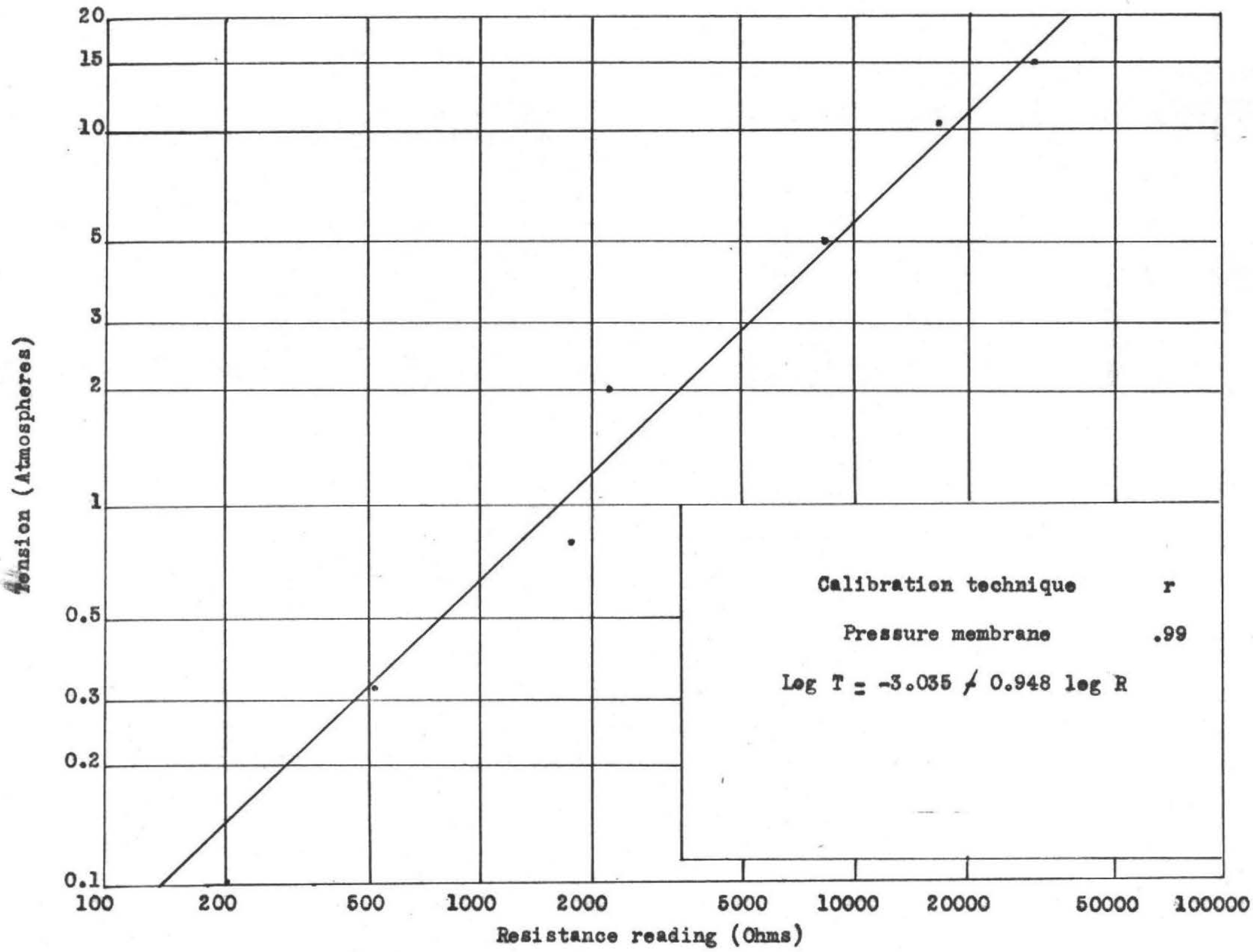

Figure 7. Calibration curve obtained by regression for the concentric electrode plug, (60).

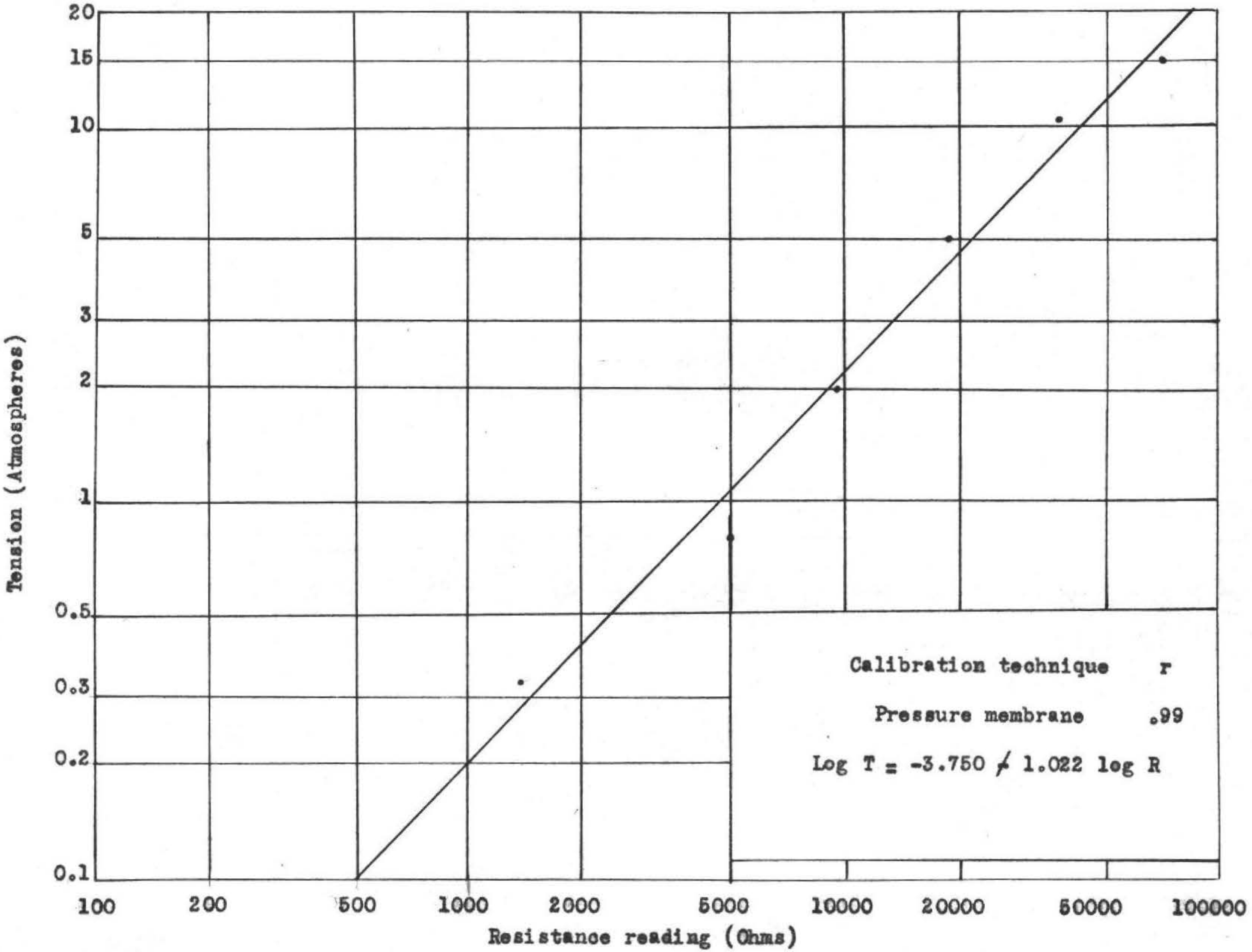

Figure 8. Calibration curve obtained by regression for the concentric electrode plug, (100).

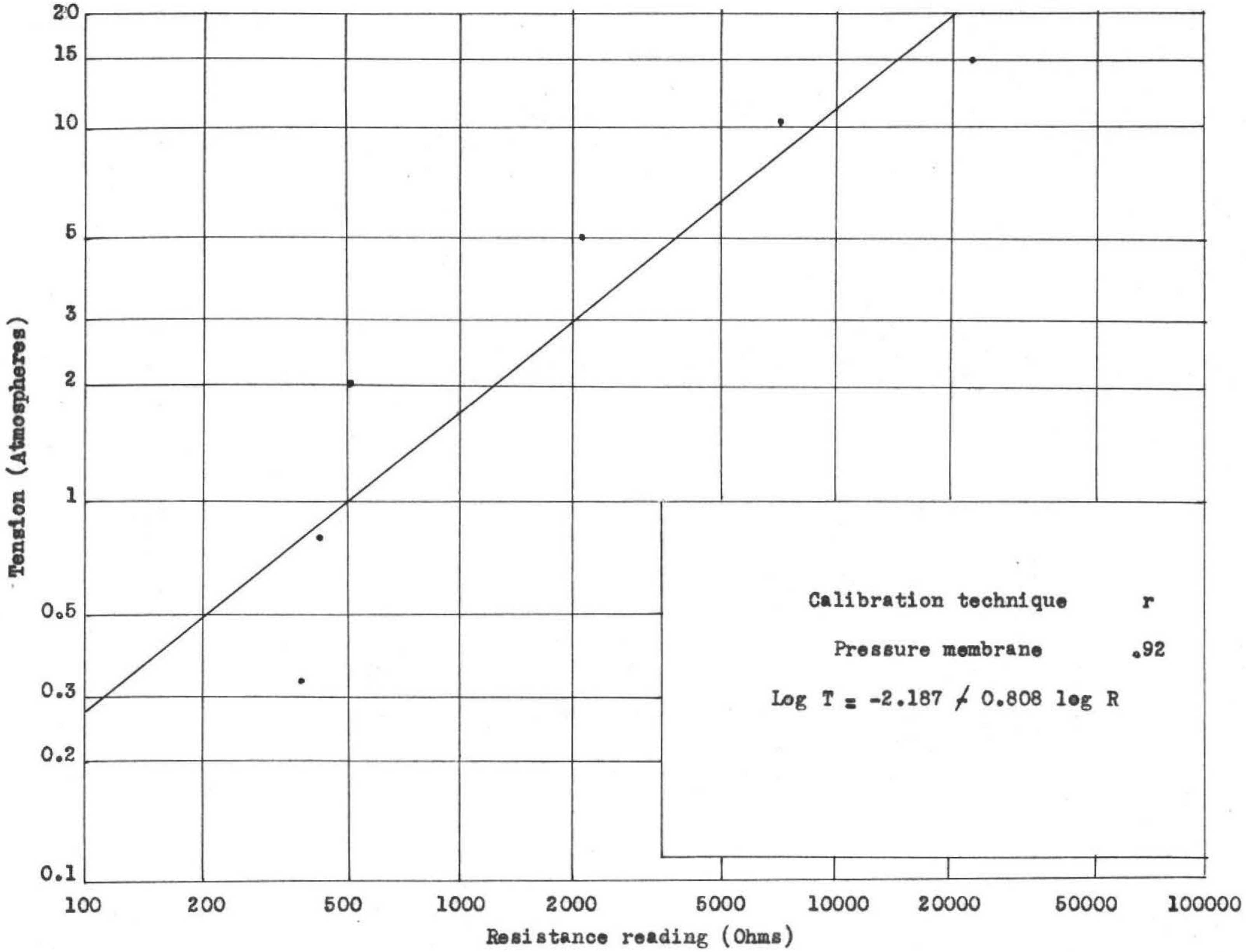

Figure 9. Calibration curve obtained by regression for the concentric electrode plug, mixed plaster, (60).

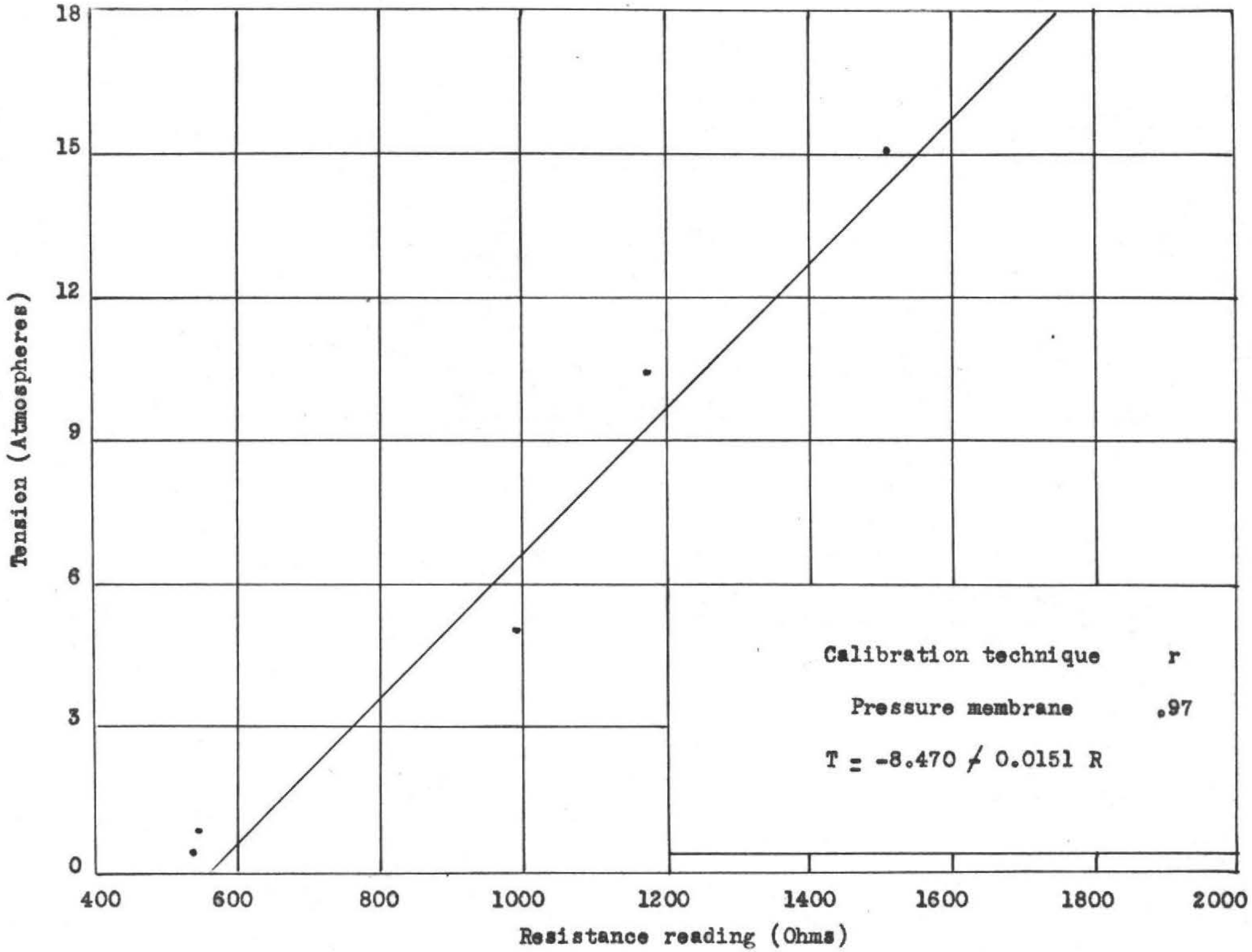

Figure 10. Calibration curve obtained by regression for the gage stake sensitive cells.

Table 1. Uniformity of units worked with in the laboratory and their relative saturated resistance reading in response to external contact

Unit	Coefficient of variability				Resistance reading (ohms) Mean of 3 cycles		
	Curing (5 cycles)		After curing (6th to 8th cycle)			External contact	
	Units	%	No. of units	%	No. of units	Water	Air
1	40	11.3	4	12.0	4	765	1,300
2	29	7.3	4	8.8	4	180	190
3	30	7.7	4	5.0	4	190	200
4	12*	8.7	4	5.4	4	285	285
5	3*	13.0	-	-	3	245	245
6	3*	5.9	-	-	3	335	335
7	6*	3.8	-	-	4	445	445
8	12*	9.5	4	8.1	4	555	565

*Were subjected to wetting and drying cycles in the factory.

similar method to compare various devices in a study which they carried out. All values plotted represent means. The fact that many of the true curves as indicated by the plotted points deviate considerably from a straight line is to be expected. When a curve does not deviate from the straight line, it is considered to be fortuitous.

Table 2 indicates the mean resistance readings obtained for all the devices calibrated in the pressure membrane apparatus. The concentric plug, mixed plaster (60), exhibited the greatest uniformity (least coefficient of variation). At the same time, they were characterized by the least sensitivity (Table 3) in the low tension range. The screen type electrode blocks exhibited their highest uniformity at the extremes of the available moisture range. They seem to compare favorably in sensitivity with the other devices

Table 2. Resistance reading and the coefficient of variability for all the devices calibrated in the pressure membrane apparatus

Measuring Devices	Tension (Atmospheres)					
	0.33	0.8	2.0	5.0	10.0	15.0
	Reading (ohms) corrected to 60° F.					
<u>Resistance reading</u>						
Original block (1 unit)	1,160	1,310	2,025	13,800	56,230	130,000
Screen type electrode mean of 3 units	120	160	750	2,570	11,700	24,900
Screen type electrode impregnated (1 unit)	170	380	1,830	6,600	20,900	43,000
Concentric plug (125) mean of 3 units	210	250	820	3,350	74,250	21,700
Concentric plug (60) mean of 2 units	515	1,780	2,220	8,850	17,210	31,460
Concentric plug (100) mean of 2 units	1,375	5,020	9,600	18,500	39,100	74,900
Concentric plug, mixed plaster (60) 2 units	380	420	515	2,150	7,330	22,780
Gage stake sensitive cells, mean of 6 units	535	545	800	990	1,175	1,510
<u>Coefficient of variation</u>	Percentage					
Screen type electrode	8.2	9.5	25.9	33.4	31.8	11.8
Concentric plug (125)	11.3	4.7	59.7	125.0	140.6	58.6
Concentric plug (60)	11.8	17.6	19.8	23.3	20.8	18.5
Concentric plug (100)	29.4	28.8	36.6	15.3	20.4	22.4
Concentric plug, mixed plaster (60)	0	2.6	0	7.2	6.8	5.4
Gage stake sensitive cells	10.0	10.7	11.4	11.7	3.6	19.4

Table 3. Relative sensitivity of all devices calibrated in the pressure membrane apparatus

Measuring Devices	Tension (Atmospheres)					
	0.33	0.8	2.0	5.0	10.0	15.0
			percentage			
Average rate increase: $\dfrac{(R_2 - R_1)/d}{R_2}$						
Original block	2.6	1.9	3.2	4.6	4.6	4.2
Screen type electrode	-	6.2	4.7	11.7	4.8	3.7
Screen type electrode, impregnated	-	7.9	8.5	4.4	4.8	3.4
Concentric plug (125)	-	4.0	4.9	-	-	7.8
Concentric plug (60)	2.5	9.3	5.6	3.4	4.2	3.1
Concentric plug (100)	10.2	9.4	5.4	2.7	4.0	3.1
Concentric plug, mixed plaster (60)	-	2.4	1.9	4.7	5.3	4.4
Gage stake sensitive cells	-	0.9	2.5	1.5	1.8	2.2
Percent increase in initial reading						
Original block	-	2.3	4.6	-	24.2	15.0
Screen type electrode	-	0	15.6	46.0	16.5	7.8
Screen type electrode, impregnated	-	40.5	15.0	-	15.0	9.8
Concentric plug (125)	-	0	10.0	8.3	18.6	8.8
Concentric plug (60)	-	74.0	9.0	-	5.0	6.3
Concentric plug (100)	-	108.0	10.0	-	7.5	5.5
Concentric plug, mixed plaster (60)	-	0	0	-	10.0	9.4
Gage stake sensitive cells	-	1.9	12.0	8.4	12.8	2.4

tested, except with changes in the low tension range. The impregnated block was slightly more sensitive with changes in moisture content in the low tension range. Their equilibrium readings at all tensions were also higher. However, the results obtained from the impregnated block are based on only 1 unit. For this reason these differences should rather not be considered conclusive.

The concentric plug (60) was more uniform in resistance readings at low tension than the same plug with lower density (100). Both of them exhibited the highest sensitivity at low tension values, especially the one with the lower density. In fact, this was extremely sensitive, a characteristic which was not so significantly exhibited at higher tension values. The concentric plug (125) made from straight hydrocal mix was characterized by a high variability at high tension, although very sensitive at this range. Besides, it was characterized with the greatest lag of all units. The Bouyoucos block was quite sensitive in the high tension range and came to equilibrium generally faster than the concentric plugs.

Table 4 indicates the drift exhibited by the different devices run in the pressure membrane apparatus. This covered a period of 2 months for the screen type blocks, not impregnated, and the concentric plugs (125). For this period only 1 desorption cycle was completed. Fortunately, the membrane did not break. For the other units, however, a period of 3 months and 13 days was covered in which the membrane broke twice. To calibrate the gage stake sensitive cells, it took only 1 month and 12 days, due to the fact that the units reached equilibrium rapidly and the membrane did not break. Figure 11 shows the arrangement of these units inside the pressure cell.

Tables 5 and 6 represent the resistance readings and lag obtained by calibrating the various devices in friction top cans. Under both

Table 4. Drift exhibited by the different devices calibrated in the pressure membrane apparatus

Device	Mean of	Saturated Reading (ohms) Before calibration	 After calibration	% drift
Original block	1	600	1,500	150.0
Screen type electrode block	3	143	162	13.3
Screen type electrode block, impregnated	1	130	220	69.0
Concentric plug (125)	3	255	313	22.7
Concentric plug (60)	2	352	487	38.4
Concentric plug (100)	2	310	360	16.1
Concentric plug, mixed plaster (60)	2	455	550	20.8
Gage stake sensitive cells	6	577	609	5.55

calibration procedures using friction top cans, none of the units showed as much sensitivity to moisture changes in the surrounding soil as that obtained from other calibration techniques. However, at the higher moisture levels, readings were quite similar to those obtained from other methods. As was suspected, the lag was considerably reduced when the cans were heated. Even though moisture movement in the vapor phase provoked by temperature gradient might have been responsible for a reduced lag, the results were still unsatisfactory. With the condensation of moisture on the walls of the cans, moisture equilibrium could not be obtained readily. That the resistance reading is probably not significantly changed, it was shown by the screen type electrode blocks which were tested under both procedures.

Table 7 indicates the resistance readings and the coefficient of

Figure 11. Arrangement of laboratory calibration in the constant temperature room. Indicated:

1. Pressure membrane extraction apparatus prepared for running a moisture desorption curve.

2. Arrangement of the gage stake sensitive cells for calibration in the pressure membrane apparatus.

3. Pressure membrane apparatus used to calibrate the screen electrode blocks and the concentric plugs shown on the cover.

4. Friction top cans assembled for calibration.

Table 5. Resistance reading obtained for various blocks calibrated in friction top cans and their lag attained to reach apparent equilibrium

Tension (atms)	Reading (ohms)	Lag (days)	Reading (ohms)	Lag (days)
	Screen electrode block		Screen electrode block impregnated	
0.3	160	3	175	1
0.4	145	1	160	3
0.8	150	2	195	5
1.5	205	1	205	2
3.1	220	8	255	6
6.0	460	12	410	12
7.4	655	18	1,000	18
21.0	15,730	20	11,400	20
	Bouyoucos original block		Concentric plug (125)	
0.3	1,210	4	235	3
0.4	1,255	4	260	4
0.8	1,340	6	260	4
1.5	940	5	320	4
3.1	2,080	15	380	8
6.0	1,735	14	570	12
7.4	2,025	16	1,570	18
21.0	26,220	20	58,140	19

Table 6. Resistance reading obtained for the concentric electrode plugs in friction top cans (heated) and their lag attained to reach apparent equilibrium

Tension (atms)	Reading (ohms)	Lag (days)	Reading (ohms)	Lag (days)	Reading (ohms)	Lag (days)
	Concentric plug (60)		Concentric plug (100)		Mixed plaster (60)	
0.1	410	1			315	1
0.3	410	1			315	1
0.6			1,010	1	370	2
1.2	1,020	1			330	1
2.0			1,825	1	390	1
2.3	1,660	1			330	1
3.6			2,890	2	430	2
5.2	3,130	2			440	1
8.1			5,940	3	590	4
10.2			11,100	5	1,380	9
34.0			100,000	4	36,150	15

Table 7. Resistance reading and coefficient of variation of the following devices calibrated with growing plants in pots: (1) original block, (2) screen type electrode, (3) screen type electrode, impregnated, and (4) concentric plug

Tension (atms)	Resistance reading (ohms) corrected to 60° F.				Coefficient of variation (%)			
					3 units			2 units
	Devices				Devices			
	1	2	3	4	1	2	3	4
.1				220				2.6
.3	1,200	220	235	310	14.5*	18.5*	10.2	13.3**
.5	1,510		280		29.5*		10.6	
.6		390		365		8.3		33.5
.8			335				10.0	
1.0	1,610	470			25.1	32.0*		
1.2			340	415			10.0	9.3**
1.8	1,650	885	380	500	31.7	39.8	9.0	4.9**
2.75	1,850	1,530			25.2*	38.2		
3.5			470	620			4.7	2.0
4.5				710				6.1
6.5	4,415				60.0*			
7.0			700	945			36.0	12.0
8.0		7,030				51.3		
10.0	3,730		1,410	1,700	15.1		66.9	30.6
11.0		8,775				46.8		
12.0	8,410				18.3			
13.0		18,620				45.6		
18.0			2,175				84.5	
21.0		29,030	6,690	166,000		33.7	109.0	55.6
27.0	18,600	38,060			39.2	24.7*		
35.0	41,100				40.6			

*Calculated from 6 units.
**Calculated from 4 units.

variation of the 4 different kinds of blocks calibrated by burying them in pots where actively transpiring plants of corn were grown. None of the B-11 plaster concentric plugs were calibrated by this method because the few available were used for calibration in the pressure membrane apparatus.

Although exhibiting somewhat greater variability than the other blocks tested by this method, the screen type electrode block, non-impregnated, still yielded a calibration curve apparently very similar to the corresponding curve for this type of block obtained with the pressure membrane calibration method.

Table 8. Relative precision observed by the various measuring devices under different calibration techniques

Calibration techniques	Degrees of freedom	Coefficient of variation (%)	Coefficient of determination (r^2)
Original block			
Pressure membrane	4	8.0	.899
Growing plants	8	6.2	.838
Friction top can	6	10.2	.535
Screen electrode block			
Pressure membrane	4	6.3	.965
Growing plants	8	3.7	.978
Friction top can	6	16.6	.656
Field calibration	11	6.5	.943
Screen electrode, impregnated			
Pressure membrane	4	3.6	.998
Growing plants	8	7.5	.821
Friction top cans	6	12.5	.682
Concentric plugs (125)			
Pressure membrane	4	13.8	.481
Growing plants	8	20.2	.528
Friction top cans	6	47.5	.371
Field calibration	8	13.1	.862
Concentric plug (60)*	4	3.2	.975
Concentric plug (100)*	4	2.8	.982
Concentric plug, mixed plaster (60)*	4	9.67	.856
Gage stake sensitive cells*	4	9.50	.957

*Calibrated in the pressure membrane apparatus.

Table 8 presents the coefficients of variation and determination (r^2) of the different units calibrated under different procedures. The variation between the individual units of the same type of block calibrated by each method (Tables 2, 7, and 12) is not reflected in this table. The coefficient of variation in this case refers to the variations from regression of mean resistance readings with respect to tension.

It is apparent that the screen electrode block was, in general, the most precise in measuring soil moisture under varied techniques. The concentric plug (125), on the other hand, exhibited the greatest variability of all units. The concentric plugs (60) and (100) seem to be promising. These units also indicate the highest sensitivity in the low tension range when calibrated in the pressure membrane apparatus, as indicated in Table 3.

In the laboratory, calibrations in the pressure membrane apparatus seem to give the highest precision. Calibration with growing plants in pots compared favorably with the pressure membrane for some of the units. The friction top-can technique was an unsatisfactory one for all units.

The concentric plug, mixed plaster (60), characterized by low sensitivity, seems to be the most likely to withstand weathering of all the units, as indicated by their external appearance after calibrated in the pressure membrane apparatus. The screen electrode blocks and concentric plug (60) also presented very nice weathering characteristics. The concentric plug (100) appeared slightly deteriorated. Under field conditions for long periods this might be significantly increased. The concentric plug (125) is apparently the most affected by weathering. The gage stake sensitive cells did not present any weathering effect. They are made of the same mix as the concentric plug, mixed plaster (60).

Table 9 indicates the relative consistency exhibited by the devices calibrated under different methods as reflected by the homogeneous nature of their variances. These variations refer to the squared deviations from regression. All units exhibited a more or less homogeneous variance, though the screen type electrode blocks, not impregnated, seem to be more homogeneous in this respect. This characteristic seems to be very much related to the precise reading of a block.

Table 9. Relative consistency (homogeneity of variance) of the measuring devices calibrated by different techniques

Calibration technique	Variance	Degrees of freedom	t value	
			(Bartlett's homogeneity test)	At 5% level
Bouyoucos original block			3.16	5.99
Pressure membrane	0.7830	5		
Growing plants on pots	0.2692	9		
Friction top cans	0.2109	7		
Screen type electrode block			0.75	7.81
Pressure membrane	0.9155	5		
Growing plants on pots	0.4683	7		
Friction top cans	0.6954	9		
Field calibration	0.5865	12		
Screen type electrode block, impregnated			3.48	5.99
Pressure membrane	0.9071	5		
Growing plants on pots	0.3957	7		
Friction top cans	0.2197	9		
Concentric plug (125)			2.21	7.81
Pressure membrane	1.6338	5		
Growing plants on pots	2.5451	7		
Friction top cans	0.6840	9		
Field calibration	1.2150	9		

The change in resistance reading with change in tension as exhibited by the gage stake sensitive cells (Table 2) resulted in a linear relationship between resistance and moisture tension over all values of moisture. The fact that moisture content and tension are not linearly related suggests that these results should be more fully investigated. A straight line relationship between resistance in ohms and tension is probably ideal. However, the devices would necessitate an extremely high degree of uniformity and precision.

METHODS AND PROCEDURE OF FIELD EXPERIMENT

The field experiment consisted primarily of studying instrument results and evaluating these on the basis of the response of the units under a differential irrigation experiment in a field of sweet corn.

Irrigations were applied when predetermined moisture tensions were reached in the root zone of corn as shown by the moisture measuring devices.

Yield data have been analyzed in search of more information relating irrigation frequency and resultant soil moisture status to prevailing soil fertility conditions and yield.

Description of area

The experimental area covered approximately 1 acre and is located on the Evans experimental farm of the Utah Agricultural Experiment Station near Logan, Utah. The surface soil has been classified as Salt Lake silt loam. It is underlain by a heavier clay or clay loam at a depth from 12 to 18 inches. Below 2 feet it abruptly changes to a light grayish, calcareous clay, plastic when wet and granular when dry. This layer goes down to more than 3½ feet, and is characterized by a distinct reddish and rust brown mottling which indicates imperfect drainage. No indications of the water table have been observed.

The area was left fallow last year, after being cropped with grains the previous year.

Experimental plan

A split plot type of experimental design was used (Table 10) with the main effects of moisture confounded. It consisted of 3 blocks, each

Table 10. Arrangement of the field experiment with moisture blocks and fertilizer plots randomized in a split plot design

Fertilizer		Replications											
		1			2			3			4		
		Blocks											
		1	2	3	1	2	3	1	2	3	1	2	3
		Moisture level											
N	P	Dry	Med.	Wet	Dry	Med.	Wet	Dry	Med.	Wet	Dry	Med.	Wet
		Plot number			Plot number			Plot number			Plot number		
0	0	2	3	2	2	6	4	3	1	2	6	1	2
1	0	3	1	3	5	3	5	4	6	3	5	2	4
2	0	5	5	5	6	4	1	6	4	6	2	5	3
0	1	4	2	1	4	5	2	1	5	5	3	4	5
1	1	6	4	6	3	1	3	5	3	1	1	3	6
2	1	1	6	4	1	2	6	2	2	4	4	6	1

to receive a differential irrigation. Six fertilizer combinations subdivided each block into 6 equal plots, and the whole experiment replicated 4 times, each replication thus comprising 18 treatments. Plots were randomized within blocks and these randomized within each replication. The individual plots were 15 feet wide (5 rows) and 10 feet long.

Hybrid sweet corn, F. M. cross variety, was selected for the experiment. Seven border rows were left between each block within each replication with 10 extra rows on each side of the experiment. Twenty feet of border were left at both sides between each replication.

The 6 fertilizer combinations used include 3 levels of nitrogen and 2 of P_2O_5. Ammonium sulphate was used as the nitrogen source at rates of 0, 80, and 160 pounds of N. per acre. Phosphorous was applied as treble superphosphate in the proportion of 0 and 40 pounds of P_2O_5 per acre. The available phosphorous in the soil as determined[1] by the sodium bicarbonate method was around 21 pounds per acre. It was assumed that the available soil potash was adequate for optimum growth. Fertilizer was broadcasted

---

[1] Courtesy of J. P. Thorne, Soil Conservation Service Laboratory.

and incorporated into the soil by harrowing. It was applied the same day previous to planting. Corn was planted with a 2-row planter on May 21. The planter was set to place the seeds about 8 inches apart in the rows and 36 inches between rows. A stand of about 17,400 plants per acre was obtained. Soil was wet enough for the seedling to sprout without any additional irrigation until the differential irrigations were applied.

The moisture desorption curve (Figure 2) obtained previously in the laboratory for the soil of this farm indicated that at 1/3 atmosphere this soil contained 42.6 percent moisture by volume. It can be observed that from very close to the .33 atmosphere point in the curve, the slope of the tangent to the curve changes rapidly, indicating that from this point additional increasing suction is required per unit amount of moisture removed. For the field experiment, this tension was assumed to represent the field capacity of the soil, although this value might vary under field conditions.

The wilting point of the soil was determined by the method of Veihmeyer and Hendrickson (32), using indicator plants. It was 21.6 percent by volume; thus the available moisture was 21.0 percent by volume.

The average bulk density was 1.4 gms. per cubic centimeter at 6 inches depth. The number of samples obtained for this determination was limited by time. About 14 samples from different locations taken on different days were averaged for this depth. For the 12, 18-24, and 30-36 inch depths, average values of 1.5, 1.55, and 1.5 gms./cc were obtained, all of them from a limited number of samples. Of the samples obtained later for moisture determinations, some of them were checked for bulk density and they agreed fairly well with the above figures.

Screen type electrode blocks constructed in the laboratory were buried between plots on the hills at 6, 12, 18, 24, 30, 36, and 42 inches deep, 2 sets on each moisture block. The high and low fertility plots in each block were selected for their location, although it was later found that some sets had not been placed exactly in these locations. All blocks, before being installed, were subjected to 4 wetting and drying cycles for curing, and were selected to check within 50 ohms for those to be buried at the same depths.

On the wet blocks and located in the high fertility plots, also in the hills between plants, tensiometers were installed at 6, 12, and 18 inches depths, 1 set per block. This experiment was set to rely mostly on the screen electrode block reading and to use tensiometers to check on block readings. It was realized that blocks do not compete in sensitivity with tensiometers within the limits of soil moisture range in which the tensiometers perform, but it was difficult to obtain enough tensiometers to be placed in all the replications at the different depths. Besides, as will be described below, the wet plots were to be irrigated when their moisture tension reached 0.8 atmospheres in the root zone. This tension is in the borderline, if not outside of the range of soil moisture in which tensiometers are reliable.

On the dry plots, 2 sets of concentric plugs (125) were buried at the same depths as the screen electrode blocks, and located close to these in the hills. The readings obtained from these units were also intended to check on the screen electrode block readings. These plugs were commercial units cured at the factory. Their saturated reading was also checked to select them for installation in the same manner as the screen electrode blocks. But with the limited number available, only those buried at the first 4 depths checked with 75 ohms, the others being less uniform.

Gage stakes with sensitive cells like those calibrated in the laboratory were buried, 1 in each block in the hills, close to the other devices.

The units are located in these stakes so as to determine the moisture tension at the 6, 12, 18, and 24 inches depths. The matrix material of the cells was made of hydrocal like the concentric plugs (125). They are also commercial devices. They were buried dry.

The 3 irrigation treatments were as follows:

1. Wet plots: Irrigated to field capacity when the screen electrode blocks and tensiometers, whichever was first, indicated that the tension in the active root zone was at or around .8 atmospheres. This tension indicated that 1/4 of the available moisture had been removed from the active root zone.

2. Medium wet plots: Irrigated to field capacity when the screen electrode blocks indicated that the tension in the active root zone was at or around 2.2 atmospheres. This tension indicated that 1/2 of the available moisture had been removed from the active root zone.

3. Dry plots: Irrigated to field capacity when the blocks indicated that the tension in the active root zone was at or around 8.2 atmospheres. This tension indicated that 3/4 of the available moisture had been removed from the active root zone.

Furrow irrigation application was selected for this experiment. The supply ditch was located on the west end of the field with the headgate at the northwest corner. The electrical conductivity of the irrigation water was reported to be 380 microhms (E.C. x 10^6), and is classified as class 1A water for irrigation purposes. Two irrigation furrows were opened for every corn row in order to wet the root zone readily and uniformly. Rubber pipes were employed as flow control on each furrow. They were leveled in the soil in groups of 10 (1/2 block) to permit uniform distribution of water. Feeding ditches were converted into equalizing bays with the location of turn-outs at the end of each block.

Canvas was placed half way to irrigate the first half of the left side of the block. The whole block was too long to maintain an equalizing bay all through and still distribute water uniformly. Every replicate was provided with 2 Parshall flumes (throat width = 2 1/8") to measure the inflow and outflow at the head and drainage ditches, respectively. Water flowed in 2 directions, northward and westward. Both slopes were gentle, especially the former, thus favorable for even distribution.

The field was cultivated when the plots were about 6 inches tall. From then on, weeds were removed by hand as they appeared.

Moisture control and irrigation

Resistance readings of blocks and plugs were taken with the Bouyoucos bridge used in the laboratory. Generally the wet and medium wet blocks readings were taken every other day and the dry ones every 4 days. Readings were corrected to a uniform temperature of 60 degrees F. using Table 8 of the Soil Survey Manual (26).

Gage stake readings were taken with the Irrigage meter,[1] which was especially adapted for stake readings. However, sometimes readings were also made with the Bouyoucos bridge which was always available. The Irrigage meter occasionally gave erratic readings which resulted in unreliable data. The unit of measurement of this meter is the "hydrohm." This corresponds very closely to the "microampere" unit. For uniformity, all readings in this study are expressed in ohms. However, Figure 12 is included to facilitate the conversion of ohms to hydrohms, or vice versa. It was prepared from readings made in the field with both meters at the same time. Irrigage readings were later checked with an ohmmeter to make sure Irrigage and Bouyoucos bridge agreed in the field.

Calibration curves for the screen type electrode block and the

---

[1] Manufactured by Rayturn Corporation, Portland, Oregon.

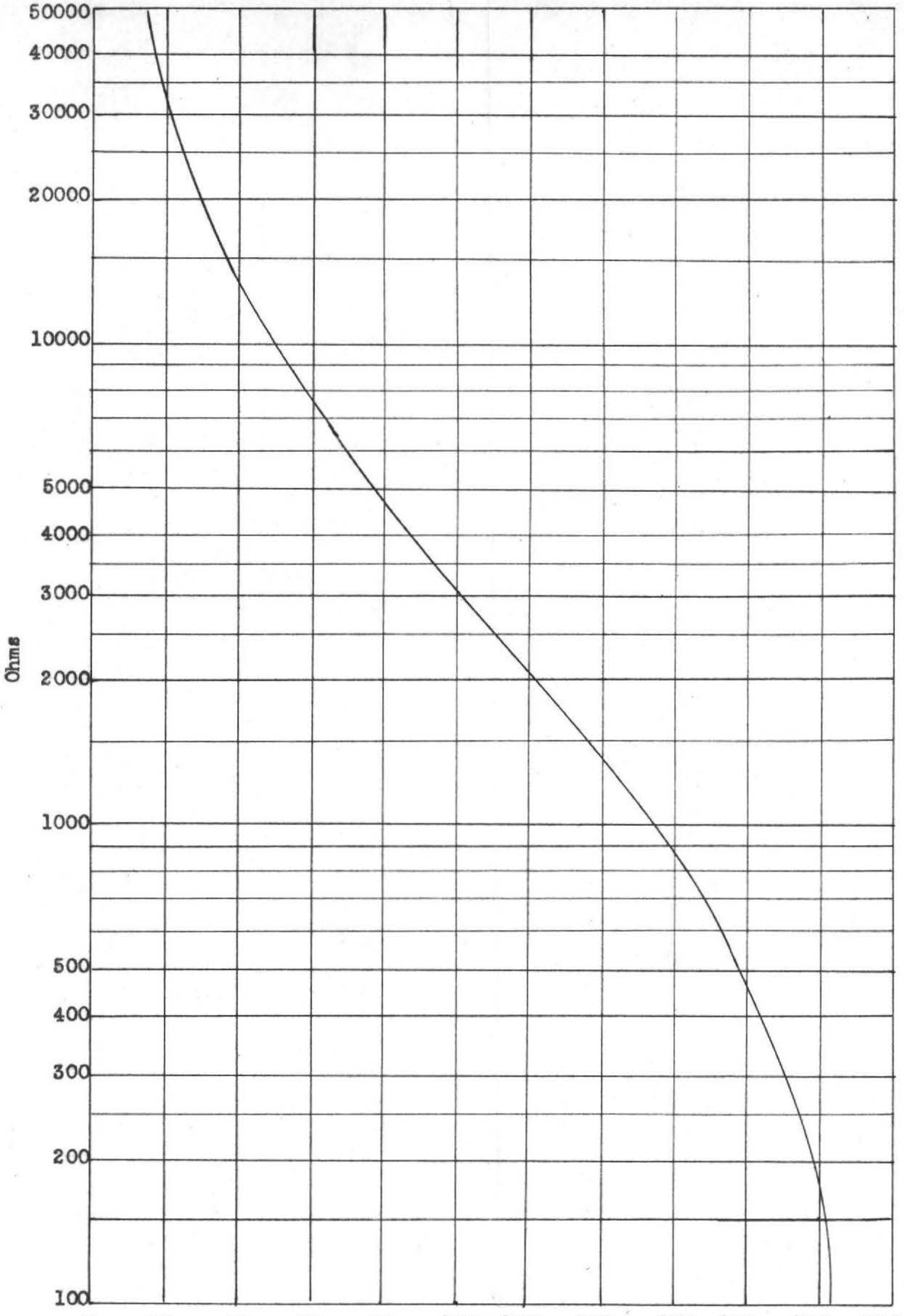

Figure 12. Conversion curve of hydrohms to ohms.

concentric plugs were plotted from the combined data obtained with the pressure membrane apparatus and field sampling done to evaluate moisture determinations. The curve obtained from the concentric plugs (125) was used also to calibrate the gage stakes readings. There was no time to calibrate them as these units were received too late. However, their saturated readings and those obtained after an irrigation were similar to the plug readings. Readings were made at the same hour early in the mornings to reduce to a minimum the temperature effects on tensiometer readings.

The resistance readings of all blocks and plugs, after corrected for temperature, were converted to tension values in atmospheres and recorded in I. B. M. punch cards.

The differential irrigations were applied from June 27 to August 23, about a week before harvesting. Wet blocks were irrigated 9 times, the medium wet 4 times, and the dry blocks 3 times.

A rough estimate of the water requirements previous to each irrigation was generally made. It was based on the tension shown by the devices to the depth to which their readings were changing. It was planned to irrigate when the integrated tension calculated on the I. B. M. machines indicated that moisture was being depleted to the limits assigned to the 3 different moisture levels. However, these data were never computed before any of the irrigations were applied.

Table 11 indicates the inches of water applied to every half block. Generally an average head of 4 inches was maintained in the Parshall flumes. However, the stream was sometimes reduced or increased for some reason, some blocks being more affected than others. This was generally a cause of unequal distribution of water to blocks receiving the same irrigation treatment.

Table 11. **Inches of irrigation water applied to each half block and amount of rainfall received during the experiment**

Day	Replications							
	Wet Blocks							
	1		2		3		4	
178*	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
180**	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
183*	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
189	1.34	1.73	2.54	2.51	3.03	2.83	2.95	2.85
196	1.69	1.45	1.83	1.67	2.63	2.35	1.39	2.20
200	2.79	3.04	3.43	3.13	3.47	4.03	1.71	2.64
206	2.61	3.20	2.25	2.83	3.07	2.76	2.79	3.18
210	2.73	3.19	2.32	2.45	2.47	2.90	1.41	1.42
217	3.76	3.28	2.01	2.32	6.33	5.87	3.56	3.75
224**	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
228**	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
229	8.35	4.71	5.95	6.55	7.59	7.94	6.05	7.23
237**	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Total	28.63	25.96	25.69	26.82	33.95	34.04	25.26	28.63
	Medium Wet Blocks							
180**	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
183*	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
196	3.31	3.66	5.99	5.43	4.09	6.45	4.33	4.33
206**	4.16	3.71	5.06	4.12	4.84	5.82	3.47	3.17
222	5.97	6.71	8.11	7.99	7.09	4.79	4.62	6.08
224**	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
228**	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
237**	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Total	17.80	18.44	21.52	21.90	20.38	21.42	16.78	17.94
	Dry Blocks							
180**	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
189	3.72	3.39	5.91	4.67	5.59	5.69	3.84	4.06
206	5.72	5.03	5.33	4.31	6.35	7.26	3.17	3.89
224	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
228	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
235	10.27	10.49	11.44	11.07	12.51	12.12	9.08	10.00
237	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Total	23.07	22.27	25.44	23.41	27.81	28.43	19.45	21.31

*Application was not measured.

**Rainfall.

Correction for submergence never seemed necessary in the flumes. Inflow and outflow were measured generally about every 10 to 15 minutes. Inflow was timed from the moment the water entered the pipes and the outflow from the time water reached the flume in the drainage ditch.

In order to evaluate instrument results, moisture determinations were made on soil samples taken from the different plots. These were taken as close as possible to the units, but avoiding any disturbance of them. At the beginning, samples were taken at the 6 and 12 inches depth, where the active root zone was concentrated. Toward the end of the season, samples were taken to greater depths, as deep as 36 inches. The number of samples taken to lower depths was very limited; even those taken at 6 and 12 inches deep were insufficient considering that there were 284 units for measuring soil moisture at all depths. But because of limitation of time, 320 samples were taken, some of which were unreliable for some reason.

Corn was harvested from August 31 to September 3, when it was judged ready for canning as indicated by the thumb nail test. Following the ear harvest, stover was cut. Data on ear and stover yield were taken.

RESULTS OF FIELD EXPERIMENT

Variability of devices

With the gravimetric determinations obtained from the 6 and 12 inches depths, calibration curves (Figures 13 and 14) for the screen type electrode blocks and the concentric plugs (125) were plotted. The scattering of points is indicated to give an idea of the variability which existed under field conditions. A comparison of this calibration technique has been presented under the laboratory results (Tables 8 and 9).

Table 12 indicates the mean resistance readings and the coefficient of variability obtained for the blocks and plugs calibrated in the field. Of 214 moisture determinations made to evaluate the screen electrode blocks results in the first foot, 182 or 85 percent were used for calibration. The others were too much erratic to be considered. Probably, these units were not wetted with the last irrigation previous to sampling because of uneven application of water. Their readings were exceedingly high. Still, very high coefficient of variability occurred, especially at medium high tension values. However, in the low tension range, their coefficient of variability was rather low. There seems to be no logical explanation for the extremely high variability at medium high tensions, even higher than near the wilting point of the soil.

Out of 75 moisture determinations made to evaluate the concentric plug results in the first foot, 59 or 79 percent were used for calibration.

A separate calibration curve was plotted with the data obtained from the screen blocks in the 18 and 24 inches depths to represent the second foot in the root zone. This curve was made for the purpose of comparison with the one obtained from the first foot. Figure 15 represents both

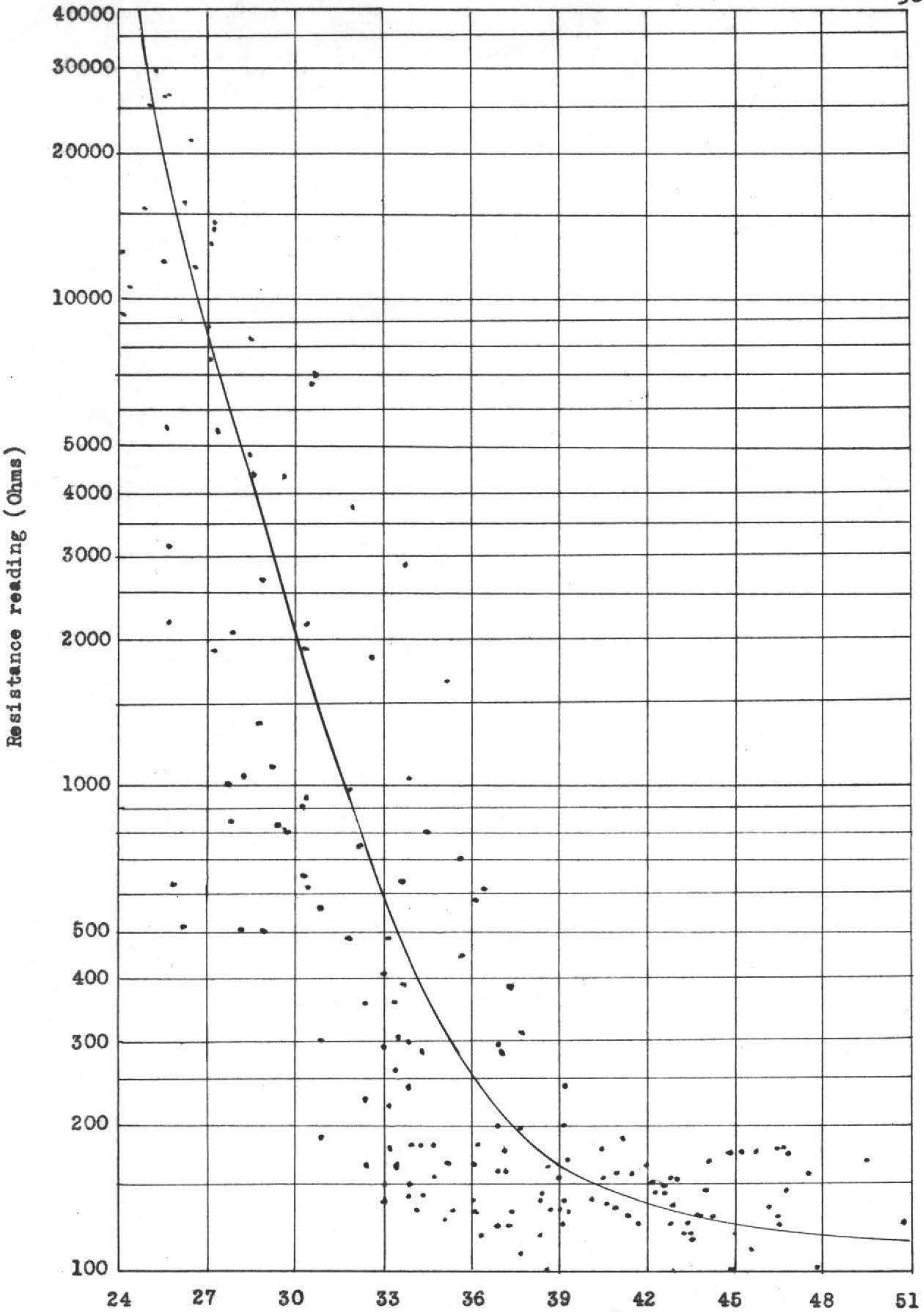

Figure 13. Field calibration curve of the screen type electrode block indicating the scattering of points.

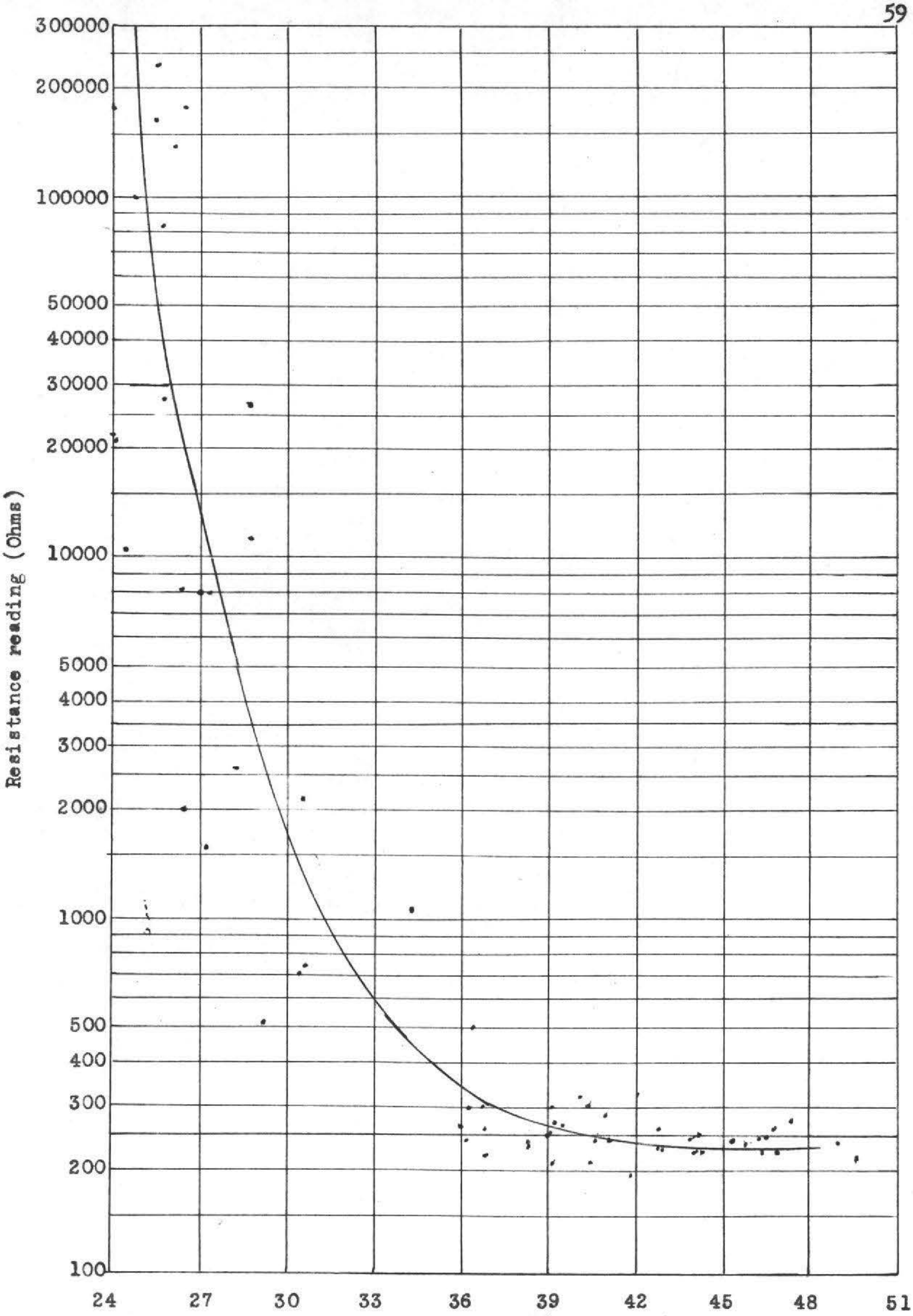

Figure 14. Field calibration curve of the concentric electrode plug (125) indicating the scattering of points.

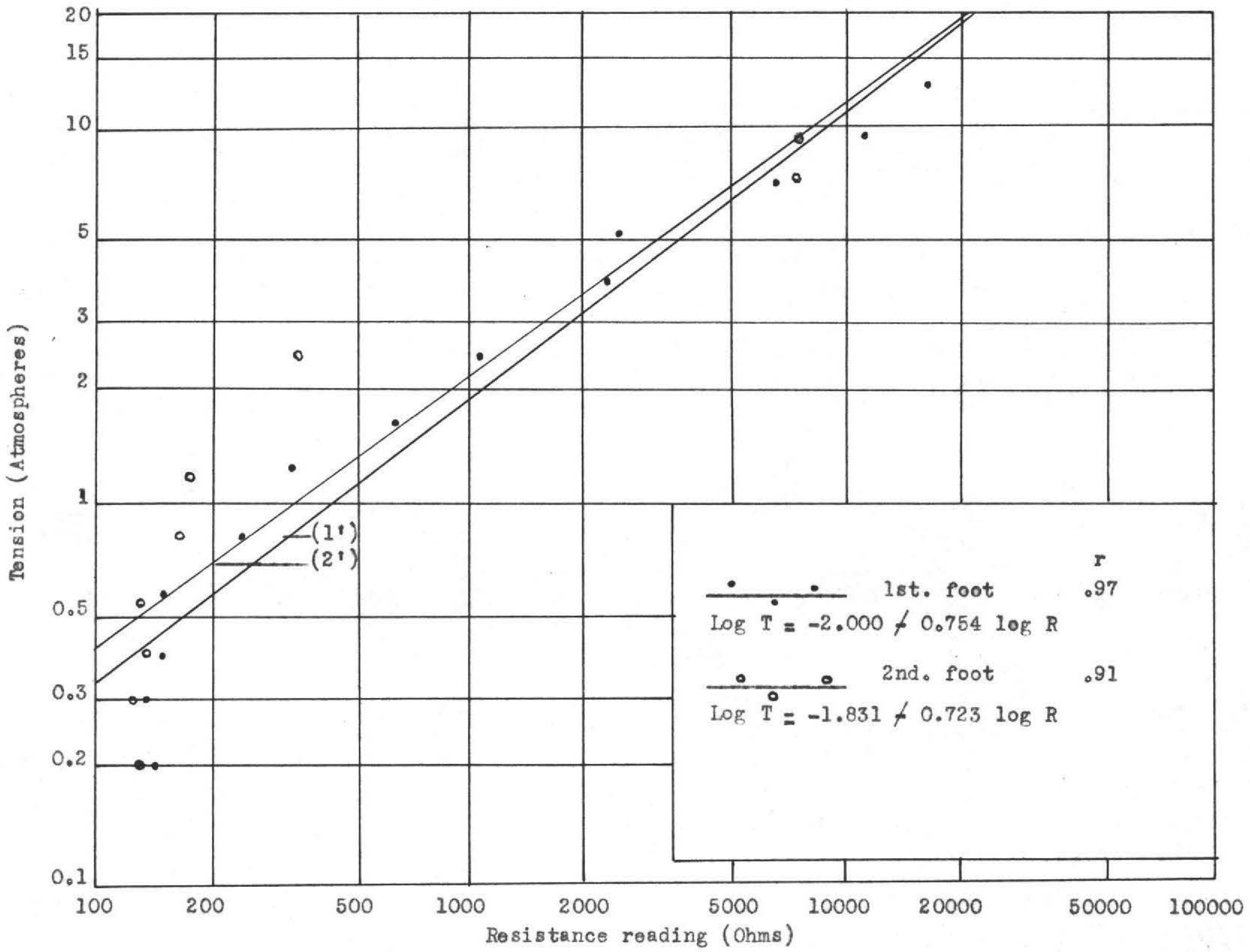

Figure 15. Calibration curves obtained by regression for the screen electrode block by sampling in the 1st. and 2nd. foot of the root zone in the field experiment.

Table 12. Mean resistance reading and coefficient of variation of the plugs and blocks buried at the 6 and 12 inches depths in the field

		Screen type block		Concentric plug (125)	
Moisture % (by vol.)	Tension (atmospheres)	Mean reading (ohms)	Coeff. of variation %	Mean reading (ohms)	Coeff. of variation %
47.2	0.2	145	18.6	240	8.3
43.4	0.3	135	16.2	240	13.3
40.7	0.4	150	12.7	265	11.6
38.5	0.5	160	32.5	255	11.9
36.7	0.8	240	64.2	300	18.7
34.8	1.2	345	120.0		
33.4	1.7	640	119.6		
31.7	2.5	1,085	141.0		
30.4	3.6	2,370	99.9	1,215	70.7
28.8	5.1	2,535	99.4	10,465	116.3
27.4	7.1	6,900	76.0	6,740	51.5
26.0	9.4	11,620	87.8	104,690	82.6
24.6	12.2	17,100	48.8		
24.2	12.9			122,370	123.0

curves plotted logarithmically. They appear to be relatively similar. Establishing confidence limits for the average resistance values in the 1-foot depth calibration curve, it was found that the mean values of the second foot curve, at 95 percent confidence interval, fall within the confidence limits of the former curve except at tension values above 10 atmospheres.

Instrument results below the second foot were only analyzed for coefficient of variability at the same depths (Table 13). Below the first foot depth for about the first 6 weeks, when roots were still shallow, readings were consistently around 100 for the screen electrode blocks and around 200 for the plugs. That is, both instruments were giving readings slightly below field capacity. Not having the sub-soil as good drainage characteristics as the top foot, it seems to be justified for the instruments to indicate tensions somewhat below field capacity until the roots

Table 13. The precision of soil moisture measurements with the screen type electrode block and the concentric plug compared to the gravimetric method as obtained from 2 locations per block with measurements made on different days

Moisture range	Coefficient of variability (percent)		
	Number of measurements	Gravimetric method	Screen electrode block
<u>Wet</u>			
Depth (inches)			
6	Mean of 10	3.6	17.5
12	" " 12	6.5	11.0
18	" " 8	5.9	7.1
24	" " 5	12.9	33.5
30	" " 2	4.1	4.3
36	" " 2	3.7	7.8
<u>Med. wet</u>			
Depth (inches)			
6	Mean of 16	7.5	51.4
12	1	3.2	67.0
18	Mean of 2	5.3	55.8
<u>Dry</u>			
Depth (inches)			
6	Mean of 12	5.0	41.6
12	" " 6	7.8	52.9
18	" " 5	5.3	66.5
			Concentric plug (125)
<u>Wet</u>			
Depth (inches)			
6	Mean of 4	2.7	5.4
12	" " 9	7.0	8.8
18	" " 6	4.9	31.5
24	" " 5	12.9	18.2
30	" " 2	4.1	7.5
36	" " 2	3.6	6.4

started deeper penetration.

To determine whether there should be significant differences in resistance readings with depth, because of changing soil textures and structure, moisture desorption curves were also obtained in the laboratory for the second, third, and fourth foot depths (Figure 16). It is apparent that the moisture desorption curves representing the first and second foot are the most dissimilar. Yet as indicated in Figure 15, their corresponding calibration curves are apparently similar.

Table 13 presents the coefficient of variation of block and plug resistance readings obtained from corresponding gravimetric determinations. In the wet range of soil moisture, it is apparent that greater precision was obtained by the gravimetric than by the instrumental method of soil moisture determination. On the basis of variability of soil moisture in the soil as indicated by the gravimetric method, it seems that blocks and plugs were relatively accurate in the low tension range. The coefficient of variation obtained with the limited number of moisture determinations from plugs at the medium wet and dry range, although not presented in the table, was extremely high. The variation obtained from blocks in the same range was not as high, but still significantly high if compared to the gravimetric method. However, it should be indicated that the coefficient of variability in Table 13 was estimated from resistance readings in ohms. Had readings been converted to atmospheres, variability on high soil moisture tension values would be reduced.

Instruments' response

The integrated moisture tension with depth was calculated with the I. B. M. machines for all the types of units used in the field.

Figure 17 is plotted to indicate the changes in mean integrated tension (averaged for the 4 wet blocks), with time and as affected by the 9 irrigation treatments applied in the season. It is apparent that tensiometers practically never agreed with the screen electrode blocks. After the day 195, the mean integrated tension for all blocks barely

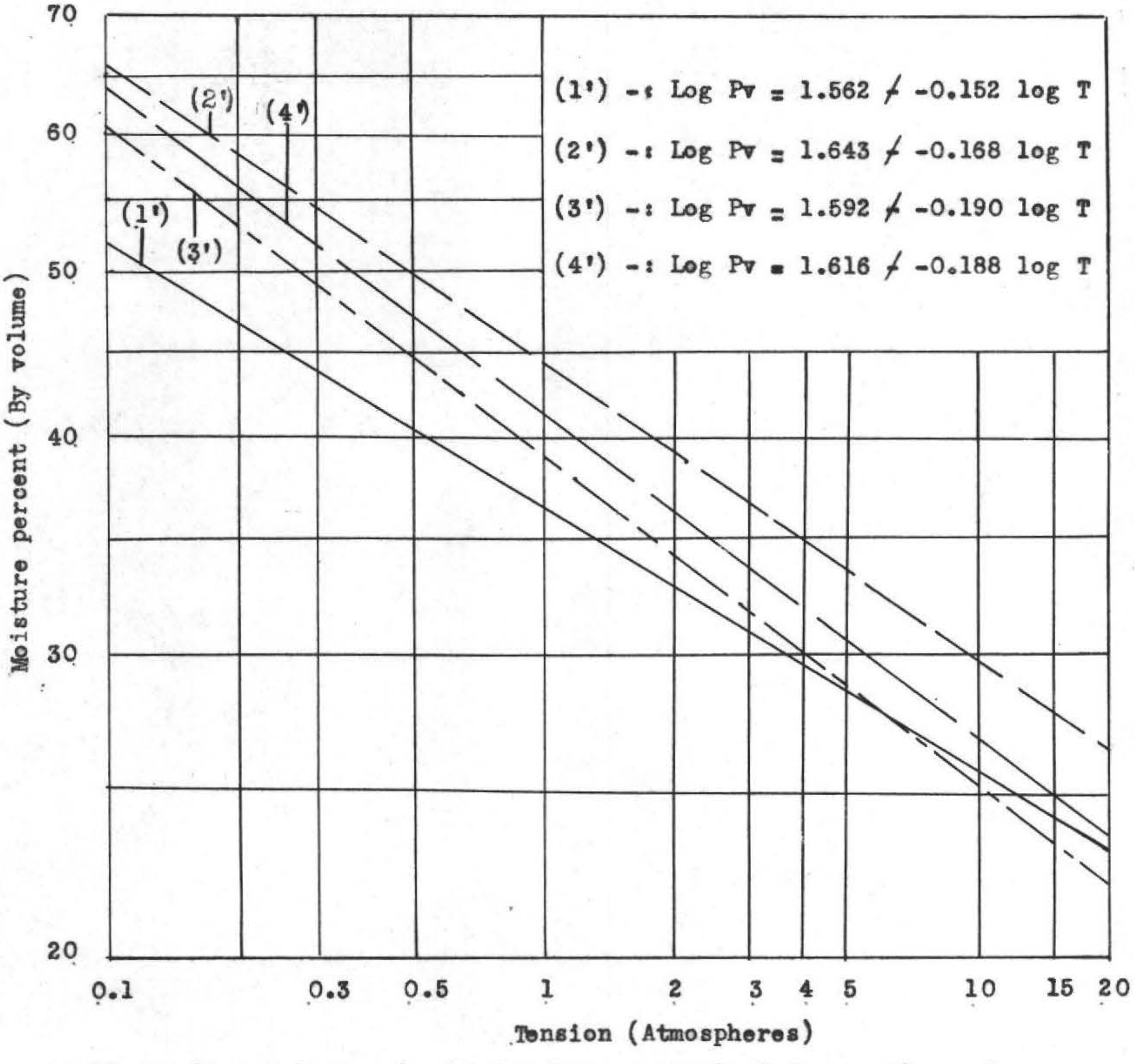

Figure 16. Moisture desorption curves obtained from soil samples representing the root zone of corn in the field experiment.

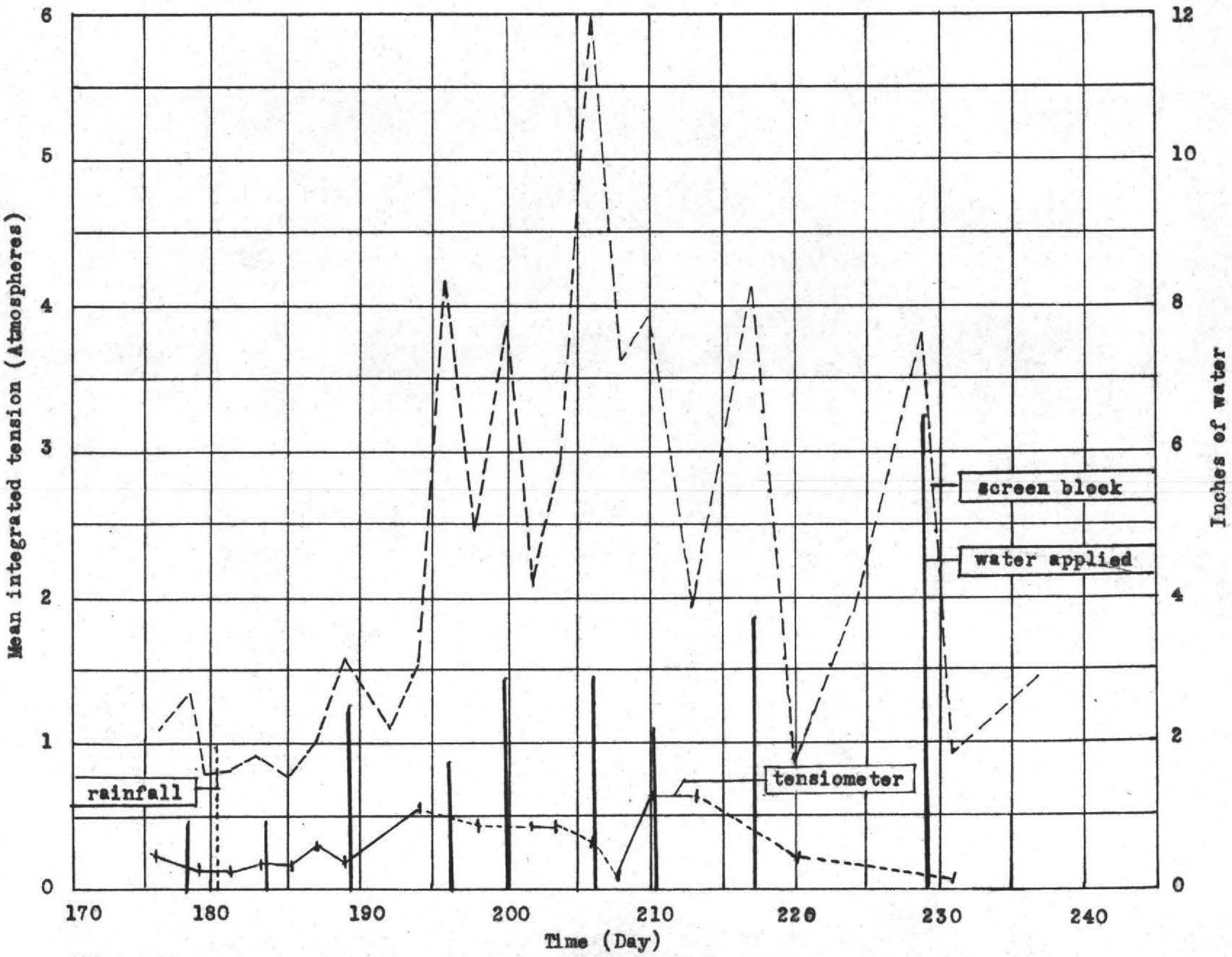

Figure 17. Mean integrated tension as a function of time in the wet plots.

dropped below 1 atmosphere after irrigations. However, readings were usually made 2 days after water was applied, which might have been sufficient time for plants to deplete moisture again to some extent. It also appears that the inches of water estimated to be applied for most irrigations were not sufficient to bring the root zone to field capacity. This fact probably contributed to the uneven distribution of moisture. This seems to have been reflected in the uniformity of instrument response after irrigations, as indicated in Table 14. Tensiometers, on the other hand, not even approached the 0.8 atmosphere tension until the day 194 (Figure 17). Broken lines show that through the indicated time, at least in 2 of the 4 sets, the mercury column had gone beyond the manometer scale readings. After irrigations, tensiometer readings generally came down to below 0.5 atmospheres. But when approaching the 600 cm. mark, they started leaking and did not seem very helpful in following the moisture depletion in the root zone.

Figure 18 presents the change in mean integrated tension (for depth) with time in the medium wet plots, and as indicated by the screen electrode blocks. The peaks indicated before irrigations suggest that irrigations should have been made more frequently for the type of moisture treatment assigned to these blocks. It is interesting to note the uniform pattern followed between irrigations. This is explained by the increasing demand for moisture when plants attain vigorous growth. It is apparent that blocks were consistent to indicate nearly the same integrated tension 2 days after each of the 4 irrigations.

Figure 19 compares the average directional trend of the mean integrated tension in the dry blocks as indicated by the screen electrode blocks and the concentric plugs (125). It is apparent that both devices consistently agreed from the time after the first application of water

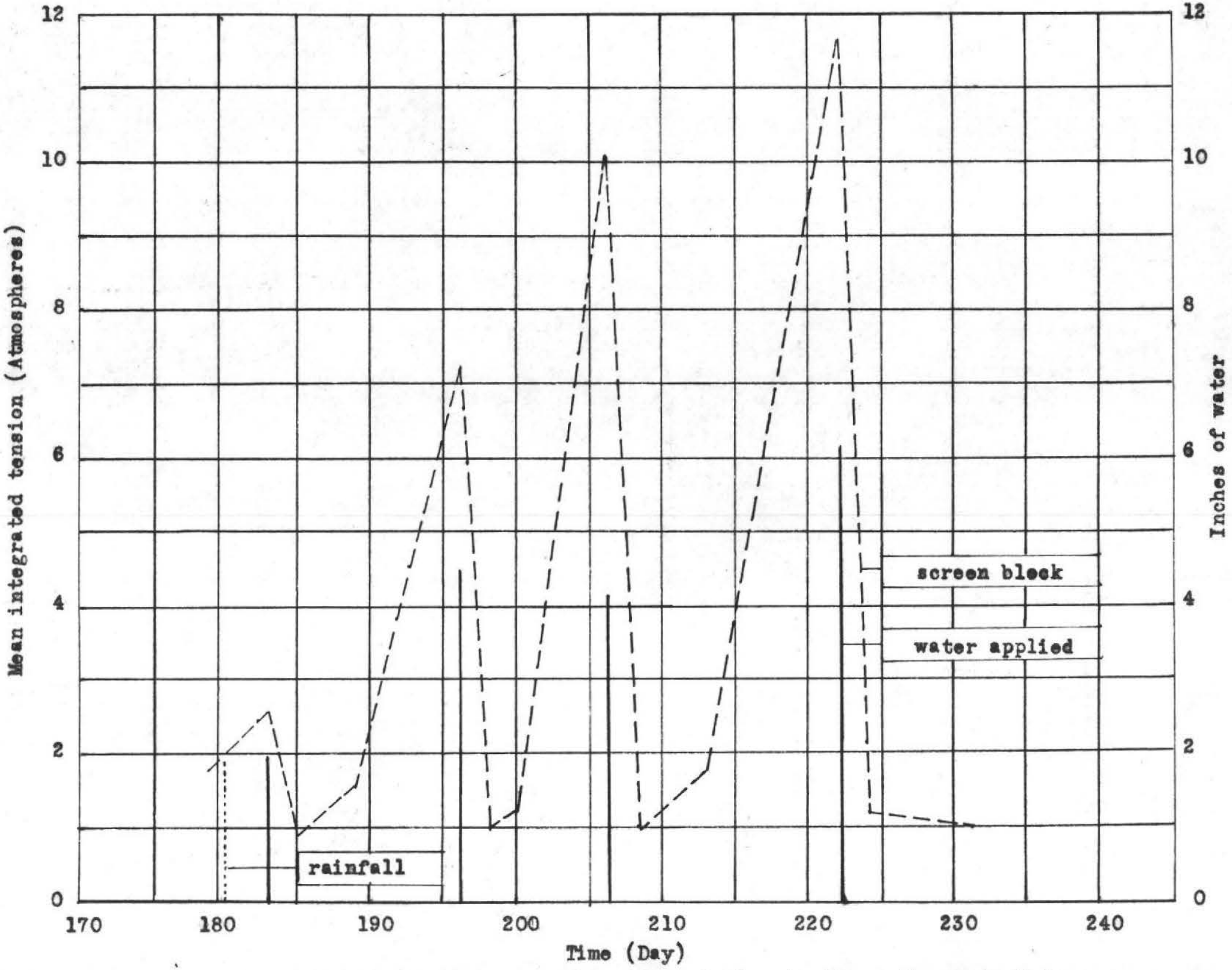

Figure 18. Mean integrated tension as a function of time in the medium-wet plots.

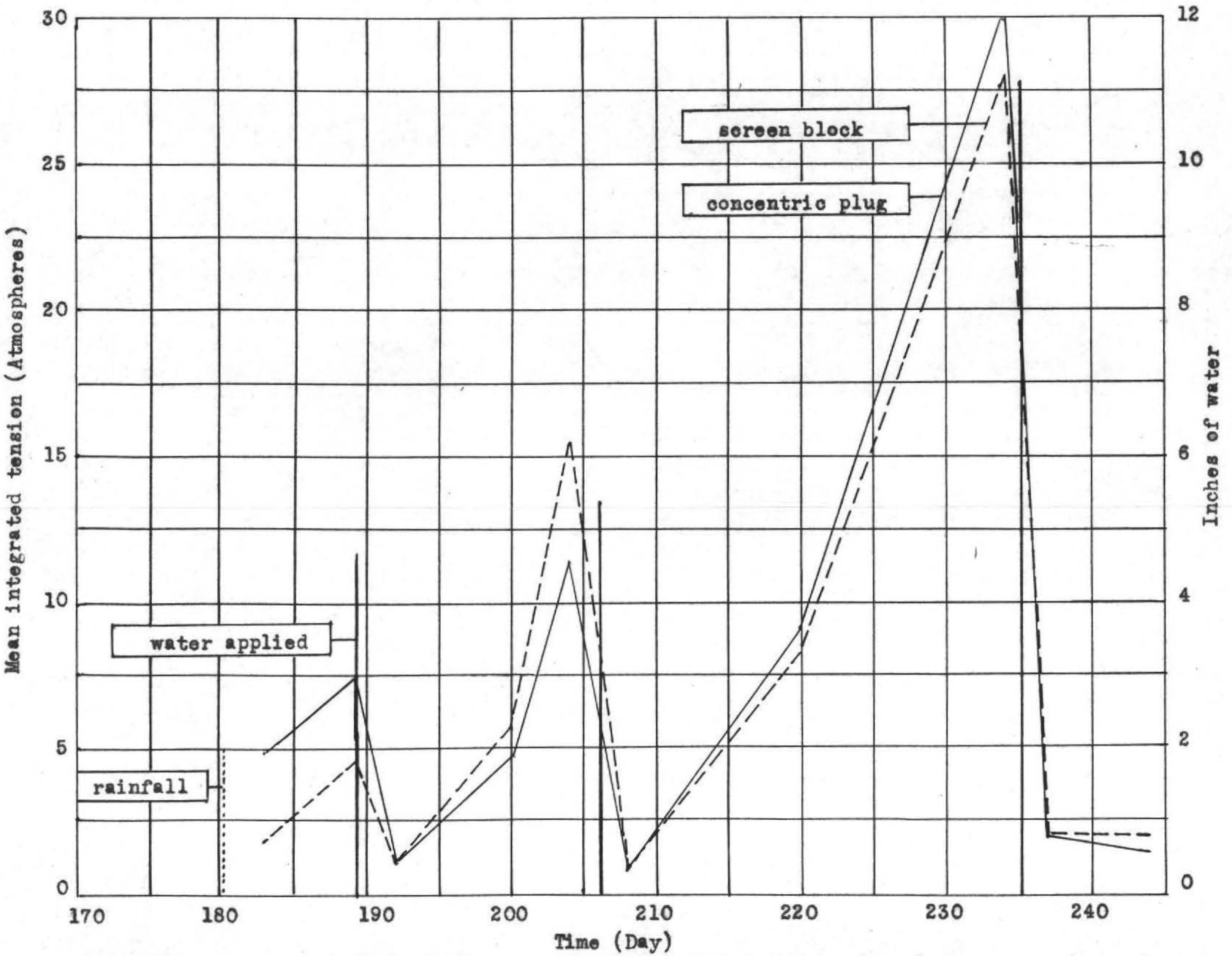

Figure 19. Mean integrated tension as a function of time in the dry plots.

Table 14. Variability of soil moisture among all devices after irrigations and as indicated by the mean integrated tension (M. I. T.) estimated with different instruments

Day	Coefficient of variability (%)					
	Tensiometers		Wet Blocks		Gage stakes	
	%	MIT	%	MIT	%	MIT
179	73.0	.13	45.2	0.7	36.5	3.03
185	49.3	.16	50.3	0.7		
192	8.3	.38	33.2	1.0	33.1	0.1
198	65.6	.44	82.1	1.8	35.1	0.9
202	37.4	.46	90.0	2.1	62.9	1.1
208	25.7	.12	133.0	3.2	29.2	2.7
213	21.8	.65	30.0	1.2	34.0	24.5
220	91.5	.21	15.7	0.9	13.0	10.5
231	8.0	.04	38.8	1.0	30.8	5.4
			Medium wet			
185			54.5	0.9		
198			28.6	1.0	25.4	0.6
208			19.3	1.0	51.0	1.3
224			30.6	1.2		
			Dry			
	Plugs					
192	28.6	1.2	17.5	1.3	16.1	0.8
208	30.7	1.1	18.0	1.1	96.5	1.8
237	42.2	2.0	41.8	2.3	40.1	0.9

was made. They coincide especially in the integrated tension indicated after every irrigation. They read approximately 1 atmosphere, as in the medium wet plots. The coefficient of variability of the integrated tension among blocks after each irrigation was lower for the dry plots, as indicated in Table 14.

It seems that, in general, the irrigations applied to the medium wet and dry blocks satisfied better the moisture demands of the root zone than in the wet blocks.

Table 15 indicates the coefficient of variability for soil moisture

Table 15. Variability of soil moisture after irrigations in the medium wet and dry blocks as indicated by the integrated tension estimated by electrical resistance units

Day	Coefficient of variability (2 sets per block)							
	Dry							
	Screen type block Replication				Concentric plug Replication			
	1	2	3	4	1	2	3	4
192	14.6	5.2	53.7	5.6	57.0	22.8	12.9	21.8
208	28.3	22.4	0	0	41.7	20.2	0	52.1
237	55.8	0	8.8	22.6	40.0	18.2	0	19.6
	Medium wet							
185	9.3	12.8	47.2	28.3				
198	14.1	6.1	40.4	34.4				
208	28.3	10.1	15.7	0				
224	20.2	30.3	7.4	37.7				

determinations after irrigations. It refers to that existing in the individual blocks (dry and medium wet) and estimated from the integrated tension of 2 sets of blocks or plugs per plot. As it should be expected, it resulted lower than when estimated for among the moisture blocks.

Few results are presented about the gage stakes' behavior. Sometimes they were not read because of difficulties with the bridges. Also, the last readings were mostly erratic. It seems that the units of these stakes deteriorate badly (Figure 20), thus the contact necessary between the soil and the unit to obtain reliable results is lost. The cells representing the 18 and 24 inches depths are apparently the most weathered because they are the most exposed to wet conditions throughout the season.

Figure 20. A gage stake used in the field experiment (right) as compared to the new one. Note that the outer concentric screen electrode is partly exposed on the cell representing the 24 inches depth in the used stake.

Crop response and yields

As the season progressed, plants showed differences in the rate of growth and in the darkening of the green color of the leaves. Those plants receiving the most frequent irrigation treatments in the high nitrogen level plots presented more vigorous growth than all other plants. Plants which received low or no nitrogen application indicated a yellowing of the lower leaves after they were about 50 days old.

Tables 16 and 17 indicate the yield of sweet corn ears and stover under different moisture and fertilizer treatments. Table 18 presents an analysis of variance from the data of Tables 16 and 17. It is apparent that the differential moisture treatments had no significant effect on the yield of sweet corn ears (Table 18). Neither was size of ear (Figure 21) significantly affected by moisture. However, nitrogen fertilizer was highly significant in the yield of corn ears. Moisture and nitrogen interaction was not significant on the yield of corn ears. However, as indicated in Table 16, in the high nitrogen plots, increased moisture resulted in higher corn ear yield of from 5.5 to 6.3 tons per acre. This may indicate that the effect of moisture-nitrogen interaction can only be significant

Table 16. Effect of moisture and fertilizer on the yield (tons per acre) of corn ears

Soil moisture level	Pounds of nitrogen added					
	0		80		160	
	Pounds of phosphorus added					
	0	40	0	40	0	40
Dry	3.3	2.5	4.8	4.5	5.5	5.5
Medium	2.4	2.8	4.0	4.7	5.4	6.0
Wet	2.7	2.3	4.8	4.6	6.3	6.2

if the amount of nitrogen applied is in a reasonable proportion with the water applied.

Table 17. Effect of moisture and fertilizer on the yield (tons per acre) of sweet corn stover

	Pounds of nitrogen added					
	0		80		160	
Soil moisture	Pounds of phosphorus added					
level	0	40	0	40	0	40
Dry	10.1	9.2	14.4	13.5	15.5	14.3
Medium	9.3	11.9	14.9	14.3	17.3	18.7
Wet	12.7	11.4	15.9	14.9	22.1	23.3

Table 18 indicates that moisture and phosphorus interaction was significant at a 5 percent level in the yield of corn ears. This is rather difficult to explain considering that phosphorus had no effect at all when considered under all other possible combinations. In the medium wet plots, however, corn ear yield was increased by phosphorus application.

At all fertility levels, increased moisture induced more stover (Figure 22 and Table 18). However, nitrogen fertilizer was still more significant in the yield of stover, as is indicated in Table 18. Moisture-nitrogen interaction was also significant in the yield of stover.

Figure 21. Size of ears harvested from the high fertility (3 on the left) and low fertility (3 on the right) plots. Each of the 3 ears from left to right represent the wet, medium wet, and the dry plots in the high and low fertility groups, respectively.

Table 18. Analysis of variance table for data on Tables 16 and 17

Source of variation	df	Yield of ears			Yield of stover		
		sum squares	mean squares	F value	sum squares	mean squares	F value
<u>Whole plots</u>							
Replications	3	1.82	0.61	0.22	140.67	46.89	3.73
H_2O (blocks)	2	2.06	1.03	0.37	785.53	392.76	31.24**
Error "a"	6	16.53	2.75		75.46	12.57	
<u>Sub plots</u>							
N	2	516.73	258.36	168.86**	3,104.09	1,552.04	103.47**
H_2O x N	4	11.31	2.82	1.8	389.24	97.31	6.49**
P	1	0.08	0.08	0.05	0.87	0.87	
H_2O x P	2	12.64	6.32	4.13*	60.23	30.12	2.01
N x P	2	3.16	1.58	1.03	22.24	11.12	0.74
H_2O x N x P	4	1.10	0.27	0.18	53.60	13.40	0.89
Error "b"	45	68.85	1.53		675.25	15.00	
Total	71	634.28			5,307.18		

*Significant at 5% level.
**Significant at 1% level.

Figure 22. Size of plants representing from left to right the wet (1 and 2), medium wet (3 and 4), dry plots (5 and 6). The high fertility plots in the order from left to right are represented by the odd number plants, while the low fertility plots are the even number ones.

SUMMARY AND CONCLUSIONS

Different types of electrical resistance units of the casting type have been tested in the laboratory.

For these units constructed in the laboratory, as well as the other commercial units received, an attempt has been made to evaluate them on the basis of uniformity, precision, sensitivity, lag, drift, and weathering.

The screen type electrode block and the concentric plug (125) were further tested under field conditions. Data concerning their behavior in the field and their response after irrigations are presented.

Crop response to different irrigation treatments and under varied soil fertility levels was measured by grain and stover yield.

The screen type electrode block was characterized with high uniformity and precision in the laboratory. The drift it undergoes is apparently not significant. The slight, but definite sensitivity shown by this block in the laboratory is present under conditions operating in the field, and makes the blocks less precise. Non-uniform distribution of soil moisture resulting from insufficient and uneven applications of water is possibly the main factor affecting the block accuracy.

The good weathering characteristics of the screen blocks, their low drift, reasonable accuracy, and the simplicity of constructing them indicate that it might justify a concentrated effort to increase somewhat more the sensitivity of the block in the low tension range (0.1 to 0.8 atmospheres). It seems that by reducing the density of the matrix material, that is, using a greater proportion of water in the mix, which thus increases the water-holding capacity of the finished block, higher sensitivity can be obtained. This was observed in those units constructed from the B-11 plaster. The fact that the concentric plug (125), although containing the highest proportion of water in the mix, was not sensitive to moisture changes below 1 atmosphere, was probably because it is made from straight hydrocal mix. This material is characterized for its extremely high density and very low porosity. These characteristics reduce the speed with which water moves within the block, even though the proportion of water added to the mix be high. This same unit, however, was extremely sensitive in the low moisture range. The weathering characteristics of the plug were, on the other hand, greatly affected. Therefore, if it is attempted to increase the sensitivity of a unit by increasing the proportion of water to mix, it should be kept in mind that at the same time the finished block will be more subject to weathering.

The good possibilities of constructing a large number of uniform screen blocks in a short time, as long as reasonable care is exercised in reproducing pouring and mixing time and in being consistent in the proportion of water to mix used, offset any advantage of a finished commercial plug.

The chief advantage of the coaxial design, in that the effect of external contact in the reading of the units is eliminated, has been accomplished now by the screen type electrode blocks. Greater sensitivity in the low tension range seems to be the only other important advantage of the concentric plug made with B-11 plaster. Apparently this advantage is derived from the plaster. Therefore, it is suggested that this matrix material be tried with the rectangular pattern screen electrode blocks. Although no definite conclusions were arrived at, there is also the possibility that the rectangular pattern assures better contact with the soil under field conditions, since it has slightly larger surface area in contact per unit mass of soil.

The fact that moisture content varies in the soil from place to place, especially near the limits in which it is critical to plant growth, implies that the more replications that are used, the greater should be the accuracy with which the moisture status in the root zone of crops can be estimated. Therefore, devices should be simple and easy to construct, or otherwise cheap and commercially available.

Of the commercial units of coaxial design, those manufactured from B-11 plaster should be studied more in detail because of their higher sensitivity in the low tension range. The manufacturer has indicated that this plaster seems to have undesirable weathering characteristics. However, this material--even mixed with water in the proportion of 5 parts plaster to 3 parts water--was characterized with relatively high sensitivity at the low tension range. From the laboratory results, this unit seems to compare favorably with those made from gypsum casting plaster.

The lag in speed of response of the devices to moisture changes seems to be associated with the water-holding capacity of the units after setting up. That is, if the size and distribution of the pore space in the units is equal, by reducing the proportion of water in the mix, lag characteristics could be improved. In fact, the plugs with consistency 125 and 100 were generally the last to attain equilibrium. It has been informed by the manufacturer of the concentric plug that B-11 plaster has apparently a desirable characteristic in that it seems to be relatively easy to control the moisture-holding capacity of the finished plaster. This characteristic should certainly tend to increase the uniformity of the unit. However, no conclusion on this respect was arrived at in the results of this experiment.

It is doubtful that the findings on this experiment might point out to definite conclusions. There seems to be no completely satisfactory unit for measuring soil moisture tension in the field. But it seems that we might be closer to develop or construct a unit which will meet with greater satisfaction such desirable characteristics as precision, sensitivity, uniformity, minimum drift, lag, and weathering. Until such a unit is devised, a large number of replications should be employed to detect more accurately the moisture status of the soil. It has been shown in the field experiment that, of the devices employed, the screen electrode unit is the most precise, but the concentric plug (125) followed it rather closely when the combined performance of all units was considered.

LITERATURE CITED

(1) Anderson, A. B., and N. E. Edlefsen. 1942. Laboratory study of the response of 2 and 4 electrode plaster of paris blocks as soil moisture content indicators. Soil Sci. 53:413-428.

(2) Ashcroft, G., and S. A. Taylor. 1953. Soil moisture tension as a measure of water removal rate from soil and its relation to weather factors. Soil Sci. Soc. Amer. Proc. 17:171-174.

(3) Bouyoucos, G. J. 1953. More durable plaster of paris blocks. Soil Sci. 76:447-451.

(4) ______ 1954. New type of electrode for plaster of paris moisture blocks. Soil Sci. 78:339-342.

(5) Bouyoucos, G. J., and A. H. Mick. 1940. An electrical resistance method for the continuous measurement of soil moisture under field conditions. Mich. Agric. Exp. Sta. Bul. 172.

(6) ______ 1947. Improvements in the plaster of paris absorption block electrical resistance method for measuring soil moisture under field conditions. Soil Sci. 63:455-465.

(7) ______ 1948. A fabric absorption unit for continuous measurements of soil moisture in the field. Soil Sci. 66:217-232.

(8) ______ 1948. A comparison of electrical resistance units for making a continuous measurement of soil moisture under field conditions. Plant Physiol. 23:532-543.

(9) Colman, E. A., and T. M. Hendrix. 1949. The fiberglass electrical soil moisture instrument. Soil Sci. 67:425-438.

(10) Cummings, R. W., and R. F. Chandler, Jr. 1941. A field comparison of the electrothermal and gypsum block electrical resistance method with the tensiometer method for estimating soil moisture "in situ." Soil Sci. Soc. Amer. Proc. 5:80-85.

(11) Edlefsen, N. E., and A. B. C. Anderson. 1941. The 4 electrode resistance method for measuring soil moisture content under field conditions. Soil Sci. 51:367-376.

(12) ______ 1943. Thermodynamics of soil moisture. Hilgardia 15: 31-298.

(13) Haise, H. R., and O. J. Kelley. 1946. Relation of moisture to heat transfer and electrical resistance on plaster of paris blocks. Soil Sci. 61:411-422.

(14) Holmes, V. W. 1953. Methods of measuring soil water status. Aus. Conf. of Soil Sci. 2:4.1-4.2.

(15) Hunter, A. S., and O. J. Kelley. 1946. A new technique for studying the absorption of moisture and nutrients from soil and plant roots. Soil Sci. 62:441-450.

(16) Kelley, O. J., et al. 1946. A comparison of methods of measuring soil moisture under field conditions. Jour. Amer. Soc. Agron. 38: 759-784.

(17) Richards, L. A. 1941. A pressure membrane extraction apparatus for soil solution. Soil Sci. 51:377-386.

(18) _______ 1942. Soil moisture tensiometer materials and construction. Soil Sci. 53:241-248.

(19) _______ 1947. Pressure membrane apparatus construction and use. Agric. Eng. 28:451-454.

(20) _______ 1949. Methods of measuring soil moisture tension. Soil Sci. 68:95-109.

(21) Richards, L. A., and M. Fireman. Pressure plate apparatus for measuring moisture absorption and transmission by soils. Soil Sci. 56:395-404.

(22) Richards, L. A., and C. H. Wadleigh. 1952. Soil water and plant growth. In soil physical conditions and plant growth. Byron T. Shaw, ed. New York: Academic Press, Inc. 491 pp. illus.

(23) Richards, L. A., and L. R. Weaver. 1944. Moisture retention by some irrigated soil as related to soil moisture tension. Jour. Agric. Research 69:215-235.

(24) Slater, C. S. 1942. A modified resistance block for soil moisture measurement. Jour. Amer. Soc. Agron. 34:284-285.

(25) Slater, C. S., and J. C. Bryant. 1946. Comparison of 4 methods of soil moisture measurement. Soil Sci. 61:131-155.

(26) Soil Survey Staff. 1951. Soil survey manual. U. S. Dept. Agric. Handbook. 18.

(27) Tanner, C. B., et al. 1948. Gypsum moisture block calibration based on electrical conductivity in distilled water. Soil Sci. Soc. Amer. Proc. 13:62-65.

(28) Tanner, C. B., and R. V. Hanks. 1952. Moisture hysteresis in gypsum moisture blocks. Soil Sci. Soc. Amer. Proc. 16:48-51.

(29) Taylor, S. A. 1952. Estimating the integrated soil moisture tension in the root zone of growing crops. Soil Sci. 73:331-337.

(30) ______ 1952. Use of mean soil moisture tension to evaluate the effect of soil moisture on crop yields. Soil Sci. 74:217-226.

(31) ______ 1955. A comparison of several methods of field determination of soil moisture. Agric. Eng. 654-659.

(32) Veihmeyer, F. V., and A. H. Hendrickson. 1949. Methods of measuring field capacity and permanent wilting percentage of soils. Soil Sci. 68:75-90.