Technical Report No. 76

MEASUREMENT OF THE ENERGY STATUS

OF WATER IN A GRASSLAND ECOSYSTEM

Bruce P. Van Haveren

Watershed Science Department

Colorado State University

Fort Collins, Colorado

TABLE OF CONTENTS

ABSTRACT

The concept of the free energy status of water in soil and plant systems is discussed together with the theory, instrumentation, and techniques involved in the measurement of water potentials. Preliminary soil water potential data collected on the Pawnee Site are included.

INTRODUCTION

Grassland areas are generally characterized by low to moderate annual precipitation amounts and high evaporative demands of the atmosphere. These two effects cause water to be an important, if not the most important, limiting factor regulating biological activity on the grasslands.

Many investigators have recently suggested that strong relationships exist between the energy or activity of water in the soil-plant complex and growth phenomena in plants (Barrs 1968; Boyer 1968; Ehlig and Gardner 1964; Gardner and Ehlig 1963; Gavande and Taylor 1967; Kramer 1963; Slatyer 1956, 1957).

This report discusses the concepts, terminology, and instrumentation involved in measuring water potentials in the soil-plant-atmosphere continuum together with the plans for studying the energy status of water on the Pawnee Intensive Site. Preliminary data collected on the Pawnee Site during the summer of 1970 are included.

STATE OF WATER IN POROUS MEDIA AND BIOLOGICAL SYSTEMS

A thorough consideration of the theory involved in describing the energy status of water in porous media and biological systems is beyond the scope of this report. The reader is referred to Slatyer (1967); Gardner (1965); Kramer, Knipling, and Miller (1966); Taylor, Evans, and Kemper (1961); Taylor and Stewart (1960); Taylor (1964, 1965); and Spanner (1964) for a more detailed treatment.

Water in any system can be discussed in terms of its free energy status. In the case of the free atmosphere or the atmosphere contained within a porous medium, the free energy status of water is analogous to relative vapor pressure or relative humidity, providing thermodynamic equilibrium exists. In biological systems water is often associated with solutes and the resulting solution has a lower free energy than pure free water. In other words, there is a "potential" for more pure water in the system. Thus, we may equate "free energy status of water" to "water potential". Water potential may be defined as the minimum additional work required to remove water from the soil, plant, or atmosphere in excess of the work required to remove pure free water from the same location and at the same temperature and ambient pressure. The relationship between water potential and relative vapor pressure of water can be seen in the following equation,

$$- \psi_t = \frac{RT}{\overline{V}} \ln \frac{e}{e_s} \tag{1}$$

where ψ_t is total water potential expressed in bars, T is absolute temperature in $^\circ K$, R is the universal gas constant, $\overline{V}$ is the partial molal volume of water, e is actual vapor pressure of water in the system, and e_s is the vapor pressure of pure free water. The reader will note that the above equation assumes that 1) thermodynamic equilibrium exists, and 2) water vapor acts as an ideal gas.

THE COMPONENTS OF WATER POTENTIAL

The total water potential of any system can be broken down into various component potentials, as seen in the following equation,

$$\psi_t = \psi_m + \psi_\pi + \psi_z + \psi_p, \tag{2}$$

where ψ_m is the matric potential, ψ_π is the osmotic potential, ψ_z is the gravitational potential, and ψ_p is the pressure potential. It should be mentioned here that the matric and osmotic components are negative quantities, the pressure component is a positive quantity, and the gravitational component may be either positive or negative depending on how the arbitrary reference point is chosen.

In most porous media the matric potential is the more important while in biological systems the osmotic potential is the dominant component. The pressure component becomes significant only when the system in question is subjected to pressures above or below atmospheric pressure. The gravitational component may either add to or subtract from the total water potential in both soil and plant systems. Consider the following relationship,

$$\psi_z = \rho gh, \tag{3}$$

where ρ is the density of pure free water at the temperature of the system in question, g is the acceleration due to gravity, and h is the vertical distance separating the system in question from some arbitrary reference point. Since 1.0 bars is equivalent to approximately 1022 cm. of water, the gravitational component is negligible in most soil and plant systems.

In the measurement of water potentials, the reference point is taken to be a pool of pure free water at normal gravity, a temperature of $25^{\circ}C$ and atmospheric pressure of 30 inches Hg at sea level. In studying water potentials along the soil-plant-atmosphere continuum, it has been common practice to arbitrarily choose the soil surface as the reference level.

WATER POTENTIALS IN SOIL AND PLANT SYSTEMS

In order to extract water from the soil, a plant must exert an energy above that energy at which the water is held in the soil. The same principle holds true for the transpiration and evaporation processes. In order for transpiration to occur, the relative vapor pressure of the air immediately above the leaf surface must be less than the relative vapor pressure of the leaf surface. Likewise, in order for evaporation to occur, the relative vapor pressure of the air above the soil surface must be less than that of the soil atmosphere. Thus, the driving force for water movement in the soil-plant-atmosphere complex is a gradient of decreasing free energy of water.

Total soil water potential is composed primarily of the matric and osmotic potentials, of which matric is the dominant component. In saline soils, however, the osmotic potential may contribute a significant amount to the total potential. Matric potential describes the effect of films of water adhering to soil particles. The tension at which water is held in the soil is dependent upon both the texture and structure of a given soil. It can be assumed for practical purposes here that a fine-textured soil will hold a given amount of water at a higher tension (lower potential) than will a coarse-textured soil, due to the increased surface area available for adhesion. Thus, soil water content becomes a doubtful indicator of the water available to plants, unless something is known of the physical properties of the soil in question.

As was mentioned earlier, the osmotic component of total water potential in biological systems is probably the dominant component force. The osmotic potential which reduces the chemical free energy of a solution is due to the presence of dissolved substances in the solution (Brown 1970). Sugars are the basic solutes found in solution in plant systems. The matric potential in plants is due largely to the presence of cellular colloids and the adhesion of water to cell walls. Turgor pressure, which is the positive pressure against vacuolar membranes and cell walls, is due to hydrostatic forces of water within the cell and constitutes a positive component of the total plant water potential. At permanent wilting the plant is essentially at zero turgor pressure. The total plant water potential at zero turgor pressure appears to take on characteristic values unique to each species and possibly unique to ecotypes within species (Brown, personal communication).

In theory then, if one were to measure total water potentials along the soil-plant-atmosphere continuum, establishing characteristic gradients for given species and given conditions, the status of water in an ecosystem could be used as a plausible predictor of water loss, growth processes, and even primary production.

MEASUREMENT OF WATER POTENTIALS

Conventional methods of obtaining soil water potential (i.e. tensiometers, resistance units, pressure chambers) for relatively undisturbed samples are designed to permit the measurement of the matric component only, ignoring the osmotic component. Early investigators working in the area of plant-water relations were restricted to measuring water contents of plant parts. A recent development in thermoelectric instrumentation has enabled researchers to measure accurately the energy status of water in plant tissues and soils using in situ methods. Spanner (1951) was the first to use the Peltier effect with a miniature thermo-psychrometer to measure water potentials. Since then a great deal of research has gone into perfecting this instrument and associated techniques for measurement. The present-day thermocouple psychrometer has distinct advantages over conventional instruments: 1) It is backed up by sound thermodynamic theory, 2) it measures the relative vapor pressure and thus the total water potential of the system in question, 3) it is extremely precise (relative vapor pressure to nearest 0.01%), and 4) its size allows it to be placed within the tissues of many plants. The thermocouple psychrometer has been used to measure soil water potential (Rawlins, Gardner, and Dalton 1968; Hoffman and Splinter 1968); the water potential within tree trunks (Wiebe, et al. 1970); the osmotic potential of human body fluids (Hunter, personal communication); and the relative vapor pressure of many other materials

(Richards 1965). This author has used a thermocouple psychrometer to measure the relative vapor pressure of the atmosphere within a mountain snowpack.

Two basic designs of thermocouple psychrometers are in use today. The "Spanner psychrometer" utilizes the Peltier cooling effect to obtain condensation at the wet bulb measuring junction (Spanner 1951; Monteith and Owen 1958). The Richards and Ogata or wet-loop psychrometer (Richards and Ogata 1958) cannot be used effectively for in situ measurements since the droplet of water must be added manually to the wet bulb junction. Modifications of both types have emerged recently. The wet-loop psychrometer will not be discussed further, since all psychrometers used on the Pawnee Site will be of the Spanner type. The basic design of a Spanner psychrometer is shown in Figure 1. The interested reader can find detailed construction criteria in Brown (1970) and a rigorous mathematical treatment of the theory of the Spanner psychrometer in Rawlins (1966) and Peck (1968, 1969).

The copper leads are attached to a psychrometric microvoltmeter capable of measuring outputs to the nearest 0.1 microvolt (1×10^{-7} volts). The voltmeter includes circuitry that allows one to reverse polarity of the sensing circuit and supply a current to the thermocouple using a 1.35 volt mercury battery. A current imposed upon a thermocouple in a direction opposite to the normal flow of current will cool the thermocouple junction down to a point depending upon the properties of the thermocouple wires used, and the length of the cooling period. This phenomenon is known as the Peltier effect. In the Spanner psychrometer the copper-chromel junction are imbedded in a piece of
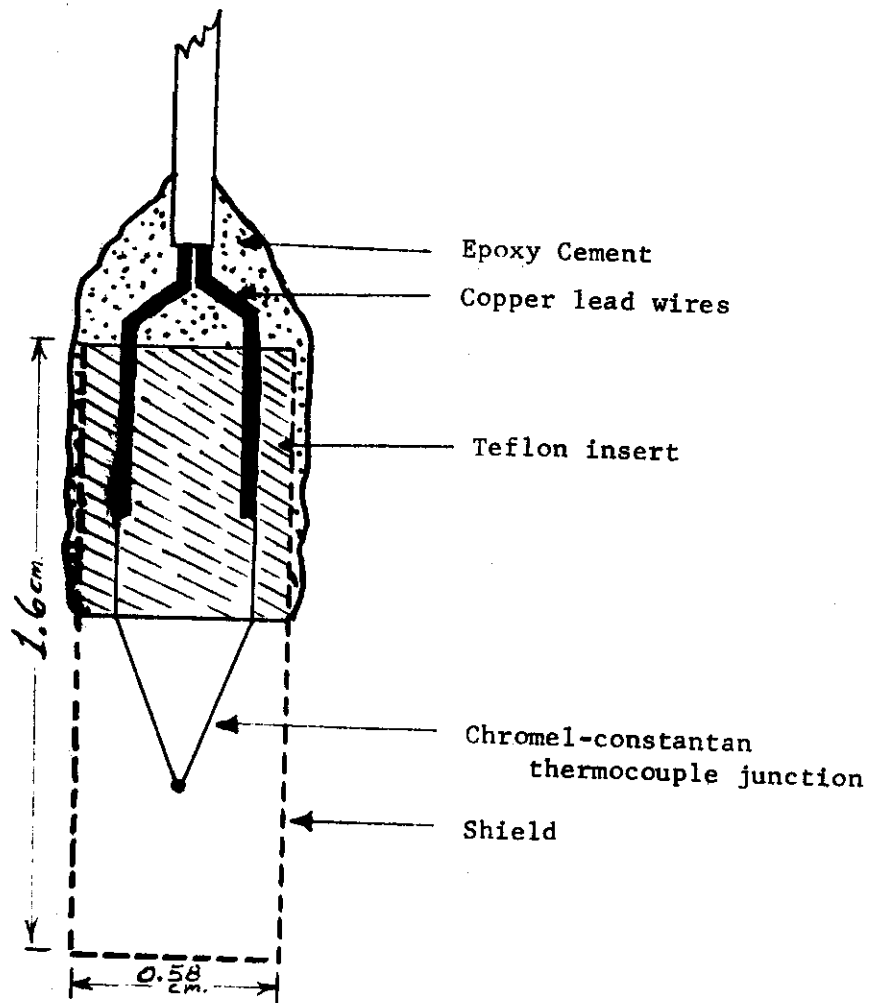
Figure 1.   The Spanner thermocouple psychrometer.

teflon and supposedly remain at the ambient temperature during the measurement period. These two junctions, then, act as twin reference junctions. The chromel-constantan junction is the actual sensing junction and is the junction subjected to the Peltier cooling. If the psychrometer is subjected to a system having a relative vapor pressure greater than 90%, the chromel-constantan junction can be cooled down to the dewpoint of the atmosphere within the system, and condensation will occur at the junction. The output of the thermocouple can then be monitored after the cooling current is turned off and evaporation begins. An electromotive force (EMF) is generated at the reference junctions and is proportional to the ambient or dry bulb temperature. The EMF generated at the measuring junction during evaporation of the condensate is proportional to the wet bulb temperature of the junction. The difference between these EMF's is read on the microvoltmeter and is essentially the wet bulb depression. When ambient temperature is not regulated at some known point (e.g. in the field), a copper-constantan thermocouple is positioned close to the psychrometer and used for the measurement of ambient temperature.

Three basic designs of the Spanner psychrometer are in use today. They differ only with respect to the type of enclosure used to shield the measuring junction. A ceramic cup thermocouple psychrometer used by Rawlins and Dalton (1967) and Wiebe et al. (1970) has been used primarily for soil water potential measurement. The hollow ceramic cup provides the shield and allows for a continuous film of water between the inside wall of the ceramic chamber and the soil matrix. However, in dry soils this contact may be broken and vapor equilibrium will depend on the vapor diffusion between the chamber and the soil

atmosphere. The ceramic wall then acts as a barrier to vapor flow. Brown (1970), in an attempt at minimizing this diffusion resistance, developed a screen cup psychrometer which utilizes a fine-mesh screen to enclose the measuring junction. This screen cup is constructed from 200-mesh stainless steel screen having a maximum opening diameter of 74 microns. The third design of the basic Spanner psychrometer is simply an open, unshielded psychrometer that is used with sample chambers and probes (Box 1965; Rawlins, Gardner, and Dalton 1968; Hoffman and Splinter 1968). Figure 2 is a graph developed by Brown (1970) showing the response times of the three types of Spanner psychrometers. All three types were enclosed in test tubes lined with filter paper that had been saturated with a 0.3 molal KCl solution at 25°C. (-13.7 bars osmotic potential). As seen from the graph, the ceramic cup psychrometer offers a great deal more diffusion resistance than either the screen cup or unshielded units. This past summer the author buried 4 commercial ceramic cup psychrometers beneath an infiltration plot at the 5, 10, 20, and 30 cm. depths. The data are plotted in Figure 3. From these data it appears that during the wetting cycle the response of the psychrometers involved a 15-20 minute lag. Once the units had been saturated, however, the lag time decreased considerably. The use of screen cup psychrometers in this experiment may have eliminated the lag entirely.

The calibration of thermocouple psychrometers is a fairly simple and straight-forward procedure. Salt solutions (commonly NaCl or KCl) of known osmotic potential are placed in a closed chamber with a thermocouple psychrometer. Vapor equilibrium is allowed to occur and readings are taken when both vapor and temperature have reached a steady state. Equilibrium may occur anywhere from 15 minutes to
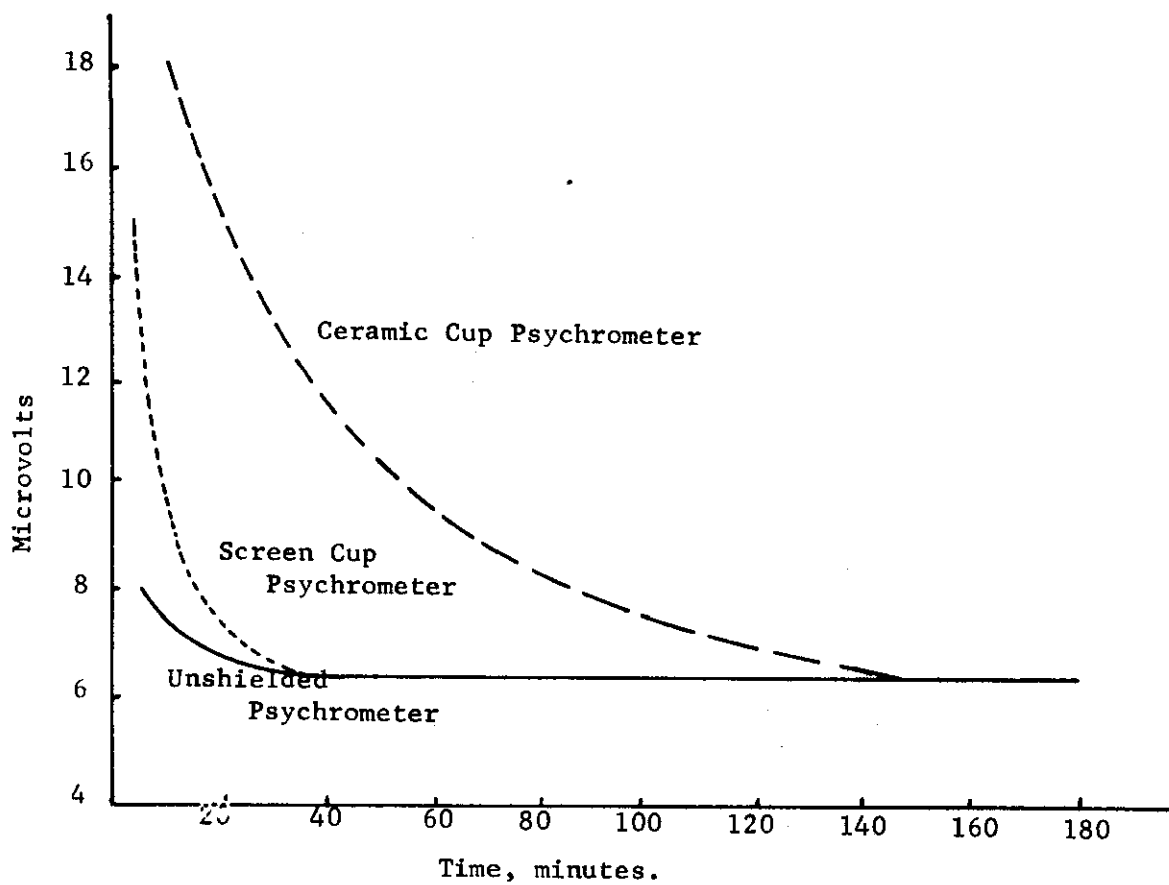
Figure 2.   Response time for three different thermocouple
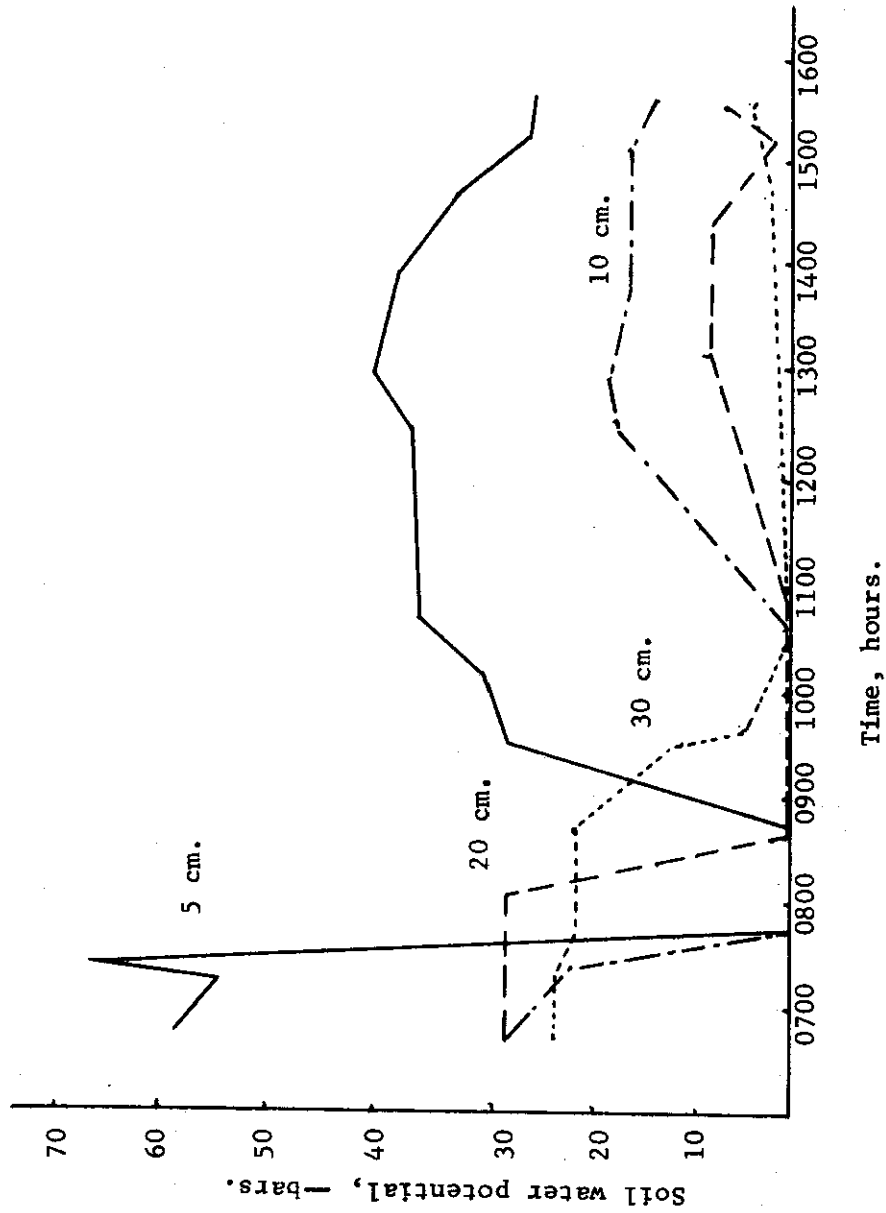   psychrometers (from Brown, 1970).

76

Figure 3. Soil water potential data collected during an infiltration run.

2 1/2 hours depending on the type of psychrometer being calibrated and the internal volume of the closed chamber. Since the osmotic potential varies linearly with temperature, each individual unit should be calibrated at a minimum of 3 osmotic potentials and 3 temperatures. A relationship between psychrometer output and osmotic potential is derived for each temperature. This relationship appears to be linear up to 20 microvolts or approximately -40 bars for most chromel-constantan psychrometers. A lower limit of -100 bars seems to be the lowest water potential value attainable with conventional thermocouple psychrometers. A typical calibration curve follows the relationship,

$$\psi_\pi = a(\mu v) + b \text{ (for a given temperature), } (4)$$

where μv is the microvolt output, a is the slope of the curve, and b is the y-intercept, which theoretically should be zero.

It has been common procedure to establish one calibration curve at $25^\circ C$ for each psychrometer and utilize a temperature correction equation to correct data to $25^\circ C$ when readings were taken at other temperatures. Weibe et al. (1970) developed the following temperature correction for ceramic cup chromel-constantan psychrometers,

$$\mu v \ 25^\circ C = \frac{\mu V_T}{0.027T + 0.325} \qquad (5)$$

where μV_T is the microvolt output at temperature T and $\mu V \ 25^\circ C$ is the microvolt output corrected to $25^\circ C$.

For accurate water potential measurements, a calibration curve and temperature correction equation should be developed for each thermocouple psychrometer.

WATER POTENTIAL MEASUREMENTS ON THE PAWNEE SITE

Early this past fall a calibration plot was constructed behind
the Pawnee Site laboratory on an Ascalon sandy loam soil. A galvanized
metal rim, 120 cm. in diameter and 25 cm. high, was pounded into the
soil to a depth of approximately 10 cm. Four neutron probe access tubes
were installed in the plot to a depth of 120 cm. At the 2, 15, 30,
45, 60, and 75 cm. depths thermocouple psychrometers (ceramic cup
type), Coleman resistance units, and Bouyoucos blocks were installed.
At 24 hour intervals 2 cm. depth increments of water were added to the
plot until all depths were eventually saturated.

Data were collected from all the instruments 24 hours after
adding each increment of water. The plot is presently drying out and
measurements are now being taken at monthly intervals. This study was
designed to investigate a field calibration procedure for the
resistance units using the soil psychrometers as the standard.
It was also an opportunity to look at the possibility of determining
soil water characteristic curves based upon in situ measurements of
water content and water potential. Preliminary data suggests that
the method may work. Data from the 45 cm. level collected during
the wetting cycle are shown in Figure 4.

A study of soil water potentials is being planned for the 1971
growing season on the Pawnee Site. A combination of 1 neutron probe
access tube and a stack of 5 soil psychrometers is located on each
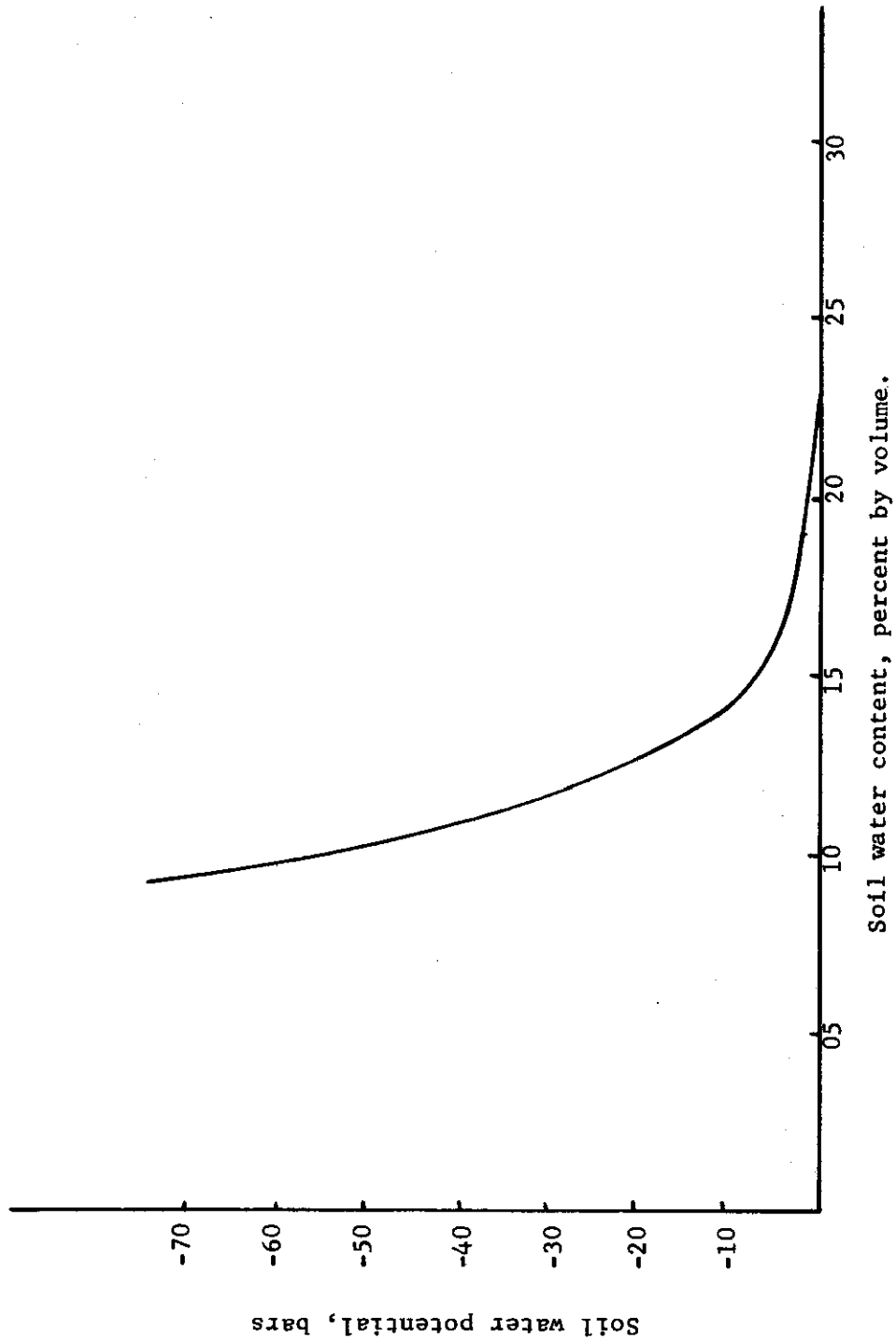major soil type in the medium-grazed pasture. This design will permit

76

Figure 4.   Soil water characteristic curve developed from in situ measurements at 45 cm. depth.

the determination of diurnal and seasonal soil water potentials for
each horizon within each major soil type. Hopefully, the data could
be used to construct soil water characteristic curves for each
horizon within each soil type.

In addition to soil water potential measurements, present plans
call for measurements of plant water potential to be taken during the
1971 growing season. Data from these studies should provide a
general idea of the free energy status of water in the soil and
plant systems on the Pawnee Site over an entire growing season.

LITERATURE CITED

Barrs, H. D. 1968. Determination of water deficits in plant tissues,
    p. 235-368. *In* T. T. Kozlowski [ed.] Deficits and plant growth,
    Vol. 1. Academic Press, Inc., New York.

Box, J. E. 1965. Measurement of water stress in cotton plant leaf discs
    with a thermocouple psychrometer. Agron. J. 57:367-370.

Boyer, J. S. 1968. Relationships of water potential to growth of leaves.
    Plant Physiol. 43:1056-1062.

Brown, R. W. 1970. Measurement of water potential with thermocouple
    psychrometers: construction and applications. USDA U.S. Forest
    Service Res. Paper INT-80. 27 p.

Ehlig, C. F. 1962. Measurement of the energy status of water in plants
    with a thermocouple psychrometer. Plant Physiol. 37:288-290.

Ehlig, C. F. and W. R. Gardner. 1964. Relationship between transpiration
    and internal water relations of plants. Agron. J. 56:127-130.

Gardner, W. R. and C. F. Ehlig. 1963. The influence of soil water on
    transpiration by plants. J. Geophys. Res. 68:5719-5724.

Gardner, W. R. 1965. Dynamic aspects of soil-water availability to plants.
    Annu. Rev. Plant Physiol. 16:323-342.

Gavande, S. A. and S. A. Taylor. 1967. Influence of soil water potential
    and atmospheric demand on transpiration and the energy status of
    water in plants. Agron. J. 59:4-7.

Hoffman, G. J. and W. E. Splinter. 1968. Water potential measurements of
    an intact plant-soil system. Agron. J. 60:408-413.

Kramer, P. J. 1963. Water stress and plant growth. Agron. J. 55:31-35.

Kramer, P. J., E. B. Knipling, and L. N. Miller. 1966. Terminology of
    cell-water relations. Science 153:889-890.

Monteith, J. L. and P. C. Owen. 1958. A thermocouple method for measuring
    relative humidity in the range 95-100%. J. Sci. Instruments 35:441-446.

Peck, A. J. 1968. Theory of the Spanner psychrometer. 1. The thermo-
    couple. Agr. Meteorol. 5:433-447.

Peck, A. J. 1969. Theory of the Spanner psychrometer. 2. Sample effects and equilibrium. Agr. Meteorol. 6:111-124.

Rawlins, S. L. 1964. Systematic error in leaf water potential measurements with a thermocouple psychometer. Science 146:644-646.

Rawlins, S. L. 1966. Theory for thermocouple psychrometers used to measure water potential in soil and plant samples. Agr. Meteorol. 3:293-310.

Rawlins, S. L. and F. N. Dalton. 1967. Psychrometric measurement of soil water potential without precise temperature control. Soil Sci. Soc. Amer., Proc. 31:297-301.

Rawlins, S. L., W. R. Gardner, and F. N. Dalton. 1968. *In situ* measurement of soil and plant leaf water potential. Soil Sci. Soc. Amer., Proc. 32:468-470.

Richards, L. A. and G. Ogata. 1958. Thermocouple for vapor pressure measurement in biological and soil systems at high humidity. Science 128:1089-1090.

Richards, L. A. 1965. A thermocouple psychrometer for measuring the relative vapor pressure of water in liquids or porous materials. Int. Symp. on Humidity and Moisture, Proc. Reinhold Publ. Corp., New York.

Slatyer, R. O. 1956. Evapotranspiration in relation to soil moisture. Netherlands J. Agr. Sci. 4:73-76.

Slatyer, R. O. 1957. The influence of progressive increases in total water potential on transpiration, growth, and internal water relations of plants. Australian J. Biol. Sci. 10:320-336.

Slatyer, R. O. 1967. Plant-water relationships. Academic Press, Inc., New York. 366 p.

Spanner, D. C. 1951. The Peltier effect and its use in the measurement of suction pressure. J. Exp. Bot. 2:145-168.

Spanner, D. C. 1964. Introduction to thermodynamics. Academic Press, Inc., New York. 278 p.

Taylor, S. A. and G. L. Stewart. 1960. Some thermodynamic properties of soil water. Soil Sci. Soc. Amer., Proc. 24:243-247.

Taylor, S. A., D. D. Evans, and W. D. Kemper. 1961. Evaluating soil water. Utah Agr. Exp. Sta. Bull. 426. 67 p.

Taylor, S. A. 1964. Physics of irrigated soils: soil-plant water relations. Utah State Univ., Logan.

Taylor, S. A. 1965. Soil-water movement in vapor and liquid phases, p. 159-163. *In* Methodology of plant eco-physiology. Montpellier Symp., UNESCO Proc.

Weibe, H. H., R. W. Brown, T. W. Daniel, and E. Campbell. 1970. Water potential measurements in trees. Bio-Science 20:225-226.