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Part I - Controlling the Soil Moisture Environment of Transpiring Plants, Part II - Prediction of Leaf Temperature Under Natural Atmospheric Conditions

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PART I
CONTROLLING THE SOIL MOISTURE ENVIRONMENT OF TRANSPIRING PLANTS

PART II
PREDICTION OF LEAF TEMPERATURE UNDER NATURAL ATMOSPHERIC CONDITIONS

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PART I

ABSTRACT

A technique for controlling the soil moisture potential in the root zone of transpiring plants was developed. The method uses the principles of unsaturated flow through a porous media to develop the desired moisture potential. In the case of non-steady state transpiration, the maximum possible fluctuation in the soil moisture potential can be determined by the techniques presented.

KEY WORDS: Transpiration, soil moisture.

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PART I

CONTROLLING THE SOIL MOISTURE ENVIRONMENT OF TRANSPIRING PLANTS

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Controlling the soil moisture environment of transpiring plants at specified levels of moisture potential is a problem that has bothered scientists for several decades. The soil moisture potential is commonly termed suction, tension or negative pressure. There are presently three methods being used for controlling soil moisture potential at relatively constant levels.

The first and most commonly used of these methods is to wet the soil to a certain moisture content, allow the soil to dry from the water abstraction of the plant and then to rewet the soil. This procedure is repeated for the duration of the experiment. The major disadvantage to the method is that the water potential of the soil is always changing and may vary between wide limits unless carefully monitored.

A second method of controlling the moisture potential is to saturate the soil with an osmotic agent made up of water and a solute. The osmotic solution simulates a negative soil-water potential. One commonly used solute is polyethylene-glycol (PEG). One disadvantage of this method is the possibility of toxic effects of the solute on plants (Jackson, 1962; Greenway et al.

1968). A second disadvantage is that plants are now growing in a saturated media so that water movement through the media cannot limit transpiration as it can in natural conditions and aeration of the roots is greatly hampered.

To overcome the disadvantages of growing plants in a soil saturated with an osmotic agent, Painter (1966) and Cox and Boersma (1967) have developed soil cells that use the osmotic potential of (PEG) to create a negative soil water potential in the soil by surrounding the soil with a semipermeable membrane. The membrane separates the soil from the PEG solution so the soil is not saturated. The membrane must be permeable to water but not to PEG which means the water potential of the soil will come to equilibrium with the osmotic potential of the PEG solution. One major disadvantage of this method is the semipermeable membranes tend to deteriorate with time due to the biologic activity in soil so that the moisture potential of the soil can be controlled for only about 12 days. This problem may be solved by using bactericide or by changing the membrane periodically.

In conjunction with some research on the effect of soil moisture potential on evapotranspiration another method for controlling soil moisture was developed. This method uses the principle of unsaturated flow through a porous media to control the soil moisture potential.

Operating Principles of Cell

A single plant cell and its water supply is shown in Figure 1. The purpose of the cell is to maintain a constant water potential ψ_t at the interface between the soil and the porous media. The design variables are the distance d that the water level is below the soil and the relationships between the water content, moisture potential and conductivity of the porous media (Θ - ψ - K relationship).

It is assumed that the moisture content in the soil surrounding the plant roots is uniform. For this assumption to be valid, evaporation from the soil surface must be prevented and the soil cannot be too deep. The plant roots will tend to grow toward the most readily available water and will thus distribute along the soil-porous media interface. To prevent the roots from penetrating the porous media a fine screen is placed between the soil and the porous media. A number 400 screen with 0.037 mm openings has been found satisfactory for this purpose.

The water level in the porous media is controlled by a bubble tube arrangement. The bubble tube is adjustable to permit raising or lowering the water level in the porous media. The rate water is being used can be determined from successive readings on the burette.

From Figure 1 it can be seen that predicting the movement of moisture from the water level to the plant is a problem in unsaturated flow. The relationship governing the movement of moisture in unsaturated soil is

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial z} \left[K(\Theta) \frac{\partial \psi}{\partial z} - K(\Theta) \right] \tag{1}$$

and the rate of flow is given by

$$V_z = -K(\Theta) \left[\frac{\partial \psi}{\partial z} - 1 \right] \tag{2}$$

where the z direction is taken as positive downward and V_z is the velocity of flow in the z direction.

Equations (1) and (2) can be solved by taking as boundary conditions constant moisture contents at $Z = 0$, the soil-porous media interface and at $z = d$, the water level in the porous media.

In general, numerical techniques such as described by Hanks and Bowers (1962) must be used to solve equations (1) and (2). Swartzendruber (1969) discusses the special case of steady state evaporation from a soil surface with a constant water table height when the hydraulic conductivity is defined by the following empirical relationship proposed by Gardner (1958).

$$K(\Theta) = K_s / (c\tau^m + 1) \tag{3}$$

where K_s is the saturated hydraulic conductivity, τ is the suction head ($-\psi$), and c and m are constants.

Using this notation, equation (2) becomes

$$V_z = K(\Theta)\left[1 + \partial\tau / \partial z\right] \tag{4}$$

which can be rewritten as

$$Z = -\int \frac{d\tau}{1 - V/K} + C_2 \tag{5}$$

In these relationships V is positive downward.

Gardner (1958) presents the solution for equation (5) for values of m equal to 1, 3/2, 2, 3 and 4. Swartzendruber presents the solution for the case m equal to 2 and the boundary condition that τ equals 0 at z equals d as

$$Z = d - \frac{K_s}{[-cV(K_s - V)]^{1/2}} \arctan \tau \left(\frac{-cV}{K_s - V} \right)^{1/2} \tag{6}$$

For a given V, equation (6) specified the distribution of τ with z. For example if a porous media 30 cm deep is found to have m equal 2, c equal .003 (cm water)$^{-2}$, and K_s equal 5 cm per day, the curves of Figure 2 result. Swartzendruber also shows that for these conditions the maximum rate of flow can be determined from the equation

$$-V_m (K_s - V_m) = \frac{K_s^2 \pi^2}{4c\, d^2} \tag{7}$$

If the porous media is such that equation (3) is not valid, numerical techniques can be employed on equation (1) to obtain curves like those shown in Figure (2).

Figure (2) shows that the moisture potential at the soil-porous media interface is a function of the transpiration rate and the depth to the water table. The depth to the water table is easily controlled. Thus for a given transpiration rate, the moisture potential in the soil can be controlled at selected values. For example for the porous media used to get Figure 2, if the transpiration rate is 2.8 cm per day and a moisture potential of 400 cm is desired, the water level would have to be 29.4 cm below the soil-porous media interface. If a tension of 200 cm was desired, the depth to the water level would be only 27.5 cm.

If the transpiration rate is 1 cm per day and a tension of 400 cm is desired, the cell of Figure 2 will not work since the maximum tension at 1 cm per day is only 45 cm. This means a coarser porous material such as used to produce Figure 3 would have to be employed. Here 400 cm of tension is reached when the depth to the water table is 19.5 inches. For high transpiration rates the depth to the water table would be quite small.

Discussion

The method presented here enables one to control the soil moisture potential at a constant level as long as the transpiration rate of the plant is constant. If the transpiration rate is varying, the upper and lower limits of moisture potential can be determined. For example for the situation used to produce Figure 2, if the water table depth is 25 cm and the transpiration rate is varying between 0 and 2 cm per day, the soil moisture potential will always be greater than 22 cm and less than 55 cm.

Figures 2 and 3 show that at relatively high tensions, the slope of the potential versus water table depth becomes very steep for these two soils indicating that a slight change in water table depth produces a large change in the moisture potential. If a finer porous media had been used, the slope would have been less steep; however, the depth to the water table for a tension of 1000 cm would have been very large. To overcome these difficulties a two layer porous media can be used with a fine material on top of a coarser material. The flow characteristics of the two materials, the moisture potentials desired and the total allowable depth to the water table would determine the depths of the individual layers of material.

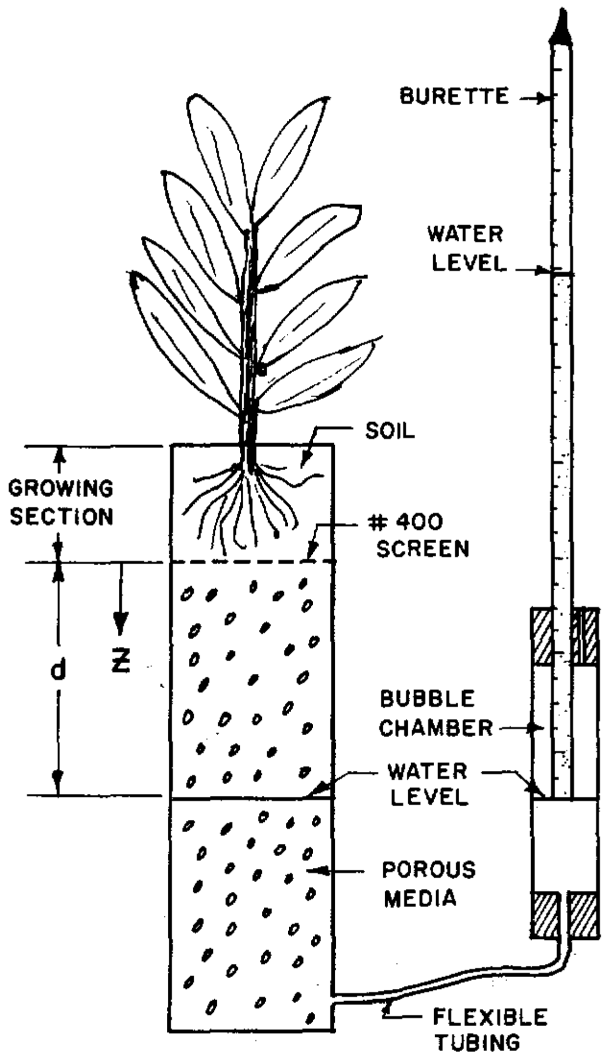

FIGURE 1. SCHEMATIC OF SOIL CELL

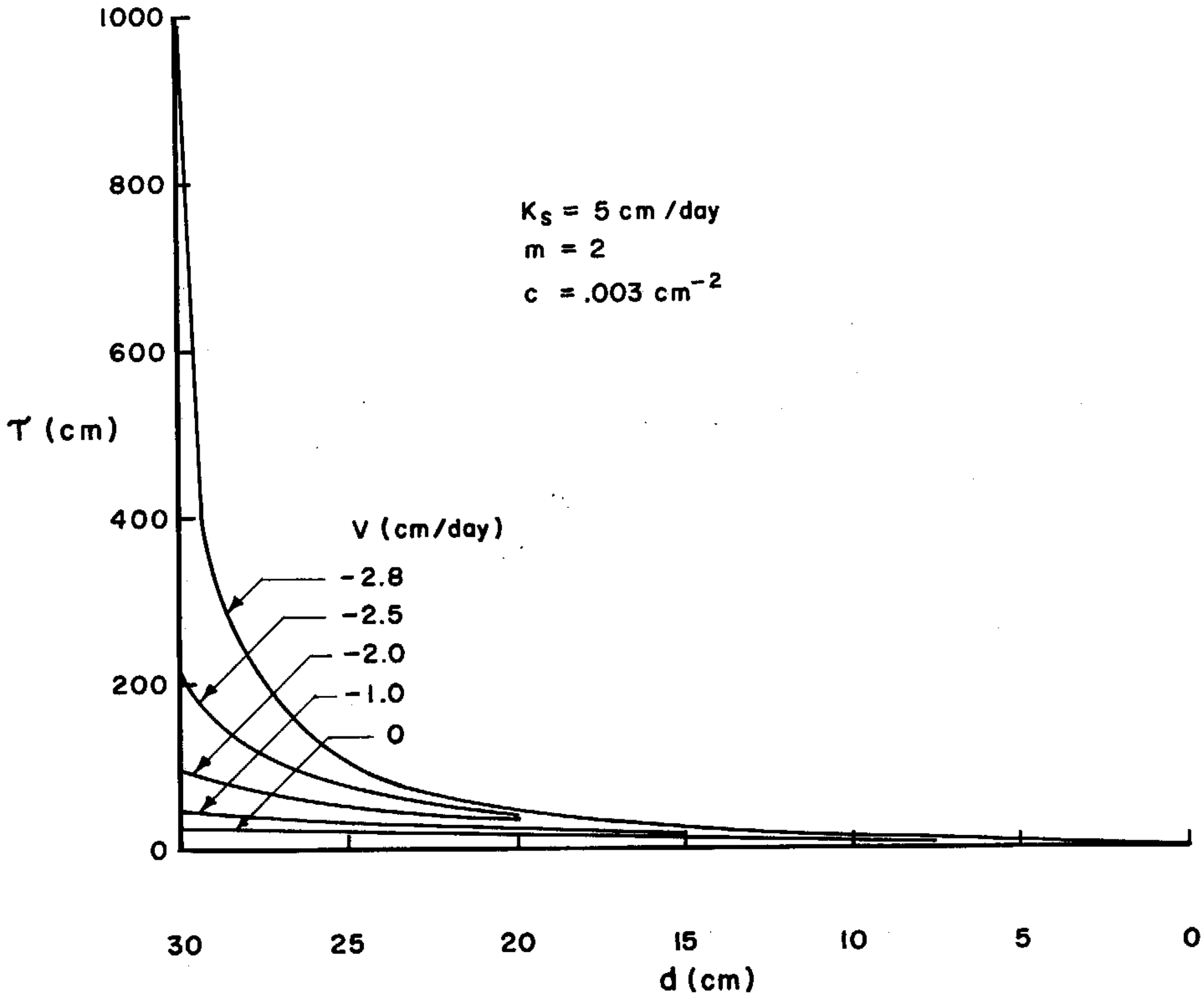

FIGURE 2. MOISTURE POTENTIAL - WATER TABLE DEPTH FOR SOIL 1

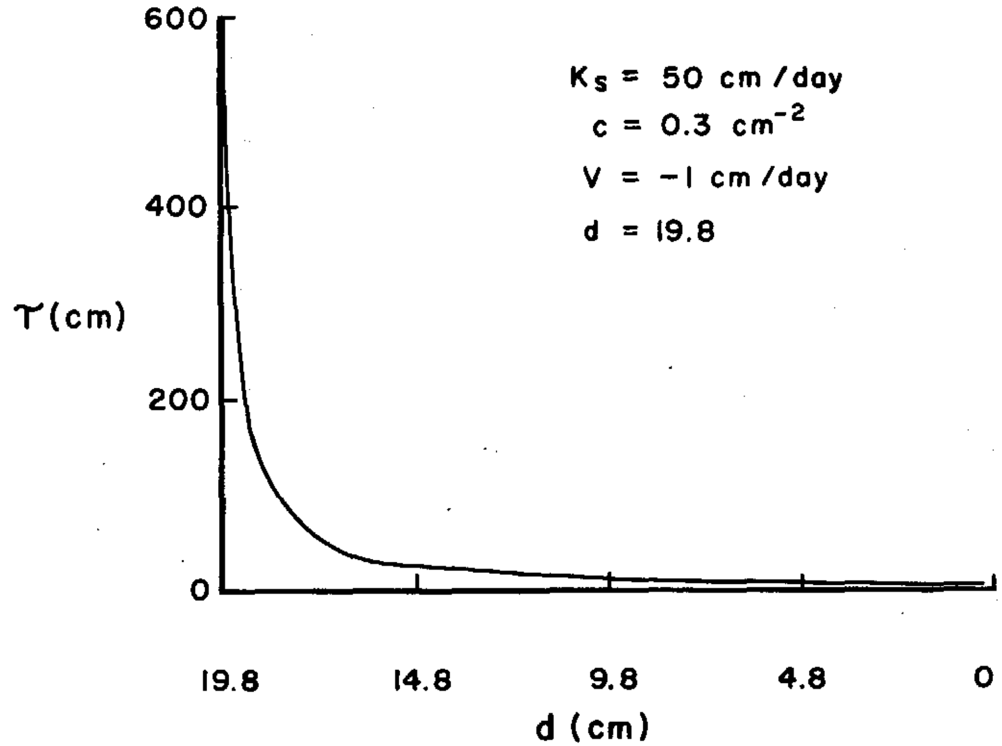

FIGURE 3. MOISTURE POTENTIAL - WATER TABLE DEPTH FOR SOIL 2

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PART II

ABSTRACT

Two implicit leaf temperature prediction equations were derived from the energy balance approach. The equations define sensible and latent heat transfer from a plant population as a two step process:

1. Transfer between the plant leaf and the canopy bulk air and
2. Transfer between the canopy bulk air and the atmosphere.

Boundary layer concepts were applied to leaf heat transfer in both equations. Turbulent atmospheric transfer by free and forced convection were considered.

Measurements of leaf temperature and wind velocity, temperature and humidity profiles for a cucumber plot were taken during ten tests. Richardson numbers to classify atmospheric stability were determined. The neutral wind velocity profile parameters, roughness height and zero displacement height were determined by a computerized least squares technique using data from the ten tests. Calculated Richardson's numbers indicated transfer by free convection. Comparison of predicted and measured leaf temperatures revealed the forced convection prediction equations considerably over estimated leaf temperature while the free convection predictions was much more accurate.

KEY WORDS: Leaf temperature, transpiration, mist irrigation, micrometeorology.

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CHAPTER I

INTRODUCTION

Modification of agricultural plant environment to increase productivity and net economic return holds promise for farmers. Because of the cost involved and possible detrimental effects of most modification methods it is advantageous to have a thorough knowledge of the natural processes influencing plant growth and to be able to predict the parameter modified under naturally varying environmental conditions. With this understanding, an efficient method for modification of plant environment may be selected and the desired results obtained. The modified parameter must limit plant growth in order for modification to be desirable.

Plant growth is very much a function of leaf temperature. Obviously, temperatures near freezing and those that cause heat damage are detrimental to growth. However, even more moderate temperatures may be a limiting growth factor because most biological reactions are temperature dependent. An optimum growth temperature has been shown to exist for most plants (11). In order to select a method to modify plant temperature, it is desirable to understand the interrelationship between environment and plant temperature.

In the natural environment leaf heat transfer occurs primarily in three forms: (1) radiant, (2) latent and (3) sensible. Since the recognition of these processes in 1875, they have received considerable study and their relative importance has been subject to much controversy (2). Quantitative expressions have been developed and tested by previous workers for these three transfer processes, for heat transfer from individual plant leaves and from plant canopies under natural atmospheric conditions (11, 9, 12, 15, 17, 1, 7, 14).

The purpose of this investigation was to develop a prediction relationship for leaf temperature under natural conditions and to test its validity under field conditions. This was accomplished by combining the transfer terms from the leaf and from the plant canopy to obtain an equation for the heat balance of a crop. The resulting equation is a transcendental function of leaf temperature in terms of meteorological and morphological variables.

Data required to test the equation and to classify atmospheric stability was taken during the summer of 1969 over a cucumber plot on the University of Kentucky Horticultural Farm.

CHAPTER II

LITERATURE REVIEW

HEAT TRANSFER FROM AN INDIVIDUAL LEAF

Early Work

The study of leaf temperature dates back to the second quarter of the 19th Century when Van Beek and Bergsma in 1838 found on one occasion a plant temperature to be 22°C warmer than the air (4). Askenasy in 1875 observed that thin leaves in sunshine were 4-5°C warmer than the air, while the thick leaves of succulent plants were some 20°C warmer than the air (2). Askenasy in the same paper attributed the cooling of leaves to back radiation, air movement over the leaf and transpiration. The main concerns of investigations following the recognition of these three transfer processes have been the relative importance of transpiration and the development of quantitative expressions to describe heat transfer processes.

Seemingly contradictory results were obtained regarding the importance of transpiration. Brown and Escombe calculated leaf temperature from the dispersal of available energy to the leaf and concluded that transpiration accounted for 80% of the heat transfer (21). Clum measured leaf temperatures only 2 to 4°C warmer on leaves whose transpiration had been checked by coating with vasoline or whose soil was dry and concluded that transpiration played a much less significant role in leaf heat transfer (4).

Radiant heat transfer was the subject of an early investigation by Curtis (8). His study was one of the first to focus attention on the infra-red wavelengths. Noting the transparency of atmospheric gases to infra-red radiation he stated that leaves may become cooler than the ambient air due to radiation to cooler objects or to space. Leaves may be warmer than surrounding air due to the receipt of radiant energy from warmer objects. Curtis sites as an example the condensation of water vapor onto plant leaves at night under clear skies.

In an extensive literature review and theoretical discussion written in 1960, Raschke established a sound basis for the analysis of heat transfer between an individual leaf and a well defined environment close to the leaf (15). Quantitative terms adopted from physics and micrometeorlogy were used to describe the three heat transfer processes.

Sensible Heat Transfer

Raschke used the "boundary layer" concept developed in 1904 by Pradtl to describe convective heat transfer. Transfer of heat, moisture, and momentum occurs within this boundary layer. Measurement of the temperature gradient and temperature field around the leaf confirmed the values calculated for the thickness of the leaf boundary layer. The boundary layer thickness varies inversely with wind velocity. According to Raschke, it is generally smaller than one centimeter and may be reduced to a fraction of a millimeter in a strong wind. Although the thickness of the boundary layer is small the air within the layer is constantly being replaced and large quantities of heat are transferred. The volume of environment influenced by this heat transfer process is very small.

Convective heat transfer is proportional to the temperature difference between the plant leaf and the ambient air. The effectiveness of the leaf boundary layer as a heat conductor defines the constant of proportionality known as the heat transfer coefficient. The thickness of the boundary layer increases with the distance from the leading edge of the leaf along the air-stream. As a result the heat transfer coefficient is not constant over the leaf surface. Raschke states, however, that it is practical to assign to a body one mean representative heat transfer coefficient. Substituting a diffusion resistance term which is equivalent to the reciprocal value of the heat transfer coefficient, convective heat transfer was defined by Raschke as:

$$H_s = -\rho C_p \frac{(T_b - T_L)}{r_a} \tag{1}$$

where
- H_s = sensible heat transfer
- ρ = density of dry air
- C_p = specific heat of dry air at constant pressure
- T_b = temperature of the air at the top of the boundary layer
- T_L = temperature of the leaf
- r_a = boundary layer resistance

Heat transfer between the plant and environment by conduction normally involves only the plant roots.

Latent Heat Transfer

Transpiration has been assumed to occur from saturated surfaces inside the plant leaf stomata normally called the substomatal cavity. Ignoring the vapor pressure depression caused by dissolved substances in plant water, the temperature of the plant determines the saturation vapor pressure of the moisture emitting surface. The gradient between the saturation vapor pressure and the partial pressure of the water vapor in the air initiates water vapor transfer. The liquid water within the leaf changes physical state and the transfer of water vapor is a form of heat transport. The movement of water vapor meets resistance to flow within the leaf stomata and a series resistance while moving through the leaf boundary layer. By using the above assumptions, Raschke showed that the flux of latent heat may be expressed by the equation:

$$H_1 = \frac{L}{R\bar{T}} \frac{(e_s - e_b)}{(r_a + r_s)} \tag{2}$$

where
H_1 = latent heat transfer
L = latent heat of vaporization
$\bar{T}$ = average boundary layer temperature, °K
R = natural gas constant for water vapor
e_s = saturation vapor pressure of the substomatal cavity
e_b = vapor pressure of the free air
r_s = stomatal resistance

Radiant Heat Transfer

The volume of environment which influences radiation exchanges is extremely large. Short wave radiation comes directly from the sun and is reflected from the ground and other reflecting surfaces. Long wave radiation environment includes the leaf and all bodies that are visible from it. Even the carbon dioxide and water vapor of the air absorb and emit from and to the leaf at certain wavelengths. The environment of radiation transfer may extend a short distance to the ground or into the higher atmosphere with clear skies. Brooks has given a good summary of the radiation exchange processes occurring in the atmosphere (3).

Radiant heat transfer increases with the fourth power of the absolute temperature as expressed by the well known Stefan-Boltzmann equation

$$H_R = \epsilon \sigma T_L^4 \tag{3}$$

where
H_R = radiant heat transfer
ϵ = emissivity of the leaf
σ = Stefan-Boltzmann constant
T_L = temperature of the leaf, °K

Total Energy Budget of an Individual Leaf

Plant heat transfer processes occur concurrently, therefore, a total treatment of the energy budget must be considered. A heat balance equation for studying energy exchange must consider net radiation and latent and sensible heat transfer.

The total heat transfer from a leaf is a non-linear function of leaf temperature as evidenced by equations 2 and 3. Hence the energy budget equation is a transcendental function of leaf temperature.

Gates, in a number of papers and in a book published in 1962, has pointed out the importance of energy budget concepts in biology and increased the understanding of leaf heat transfer processes in relation to leaf morphological and meteorological parameters (10, 11, 12). The book Energy Exchanges in the Biosphere, gives a very thorough explanation of radiant energy, radiation instruments, convective heat transfer and the influence of the energy balance on biological systems. Gates in 1968 showed that leaf temperature could be determined from an energy balance equation for a leaf in a well defined air stream. Response with variation of several meteorological and morphological parameters were simulated. The energy budget equation for a flat leaf used by Gates was:

$$Q_{ABS} = \epsilon\sigma T_L^4 + k_1 \left[\frac{u}{D_*}\right]^{0.5} (T_L - T_b) + L(T_L) \left[\frac{\rho_s (T_L) - r.h. \rho_s (T_b)}{r_s + k_2 \left[D_*^{0.35} w^{0.20} / u^{0.55}\right]}\right] \quad (4)$$

where	Q_{ABS}	=	net short wave radiation
	k_1, k_2	=	constants
	u	=	wind speed
	D_*	=	leaf dimension in wind direction
	w	=	leaf dimensions transverse to the wind
	r. h.	=	relative humidity of the free air

$L(T_L)$ = latent heat, a function of leaf temperature

$\rho_s(T_L)$ = saturated concentration of water vapor at the leaf temperature

$\rho_s(T_b)$ = saturated concentration of water vapor at free air temperature

and other terms as previously defined.

The coefficients, k_1, k_2 and other powers assigned to D_*, W, and u were determined by wind tunnel experiments on individual leaves. Equation 4 applied to forced convection. Gates considered free convection to occur at wind speeds less than 10 cm/sec, a rare event in nature. Based on the theoretical analysis Gates showed that:

1) with conditions that are common in warm, sunny, humid areas during the summer at midday: (a) a decrease in stomatal resistance by a power of ten in still air decreases leaf temperature 8°C and in a light wind (2.2 MPH) decreases leaf temperature less than 5°C; (b) at a certain stomatal resistance increasing wind speed has no effect on transpiration, at a larger stomatal resistance increasing wind speed decreases transpiration, at a smaller resistance increasing wind speed increases transpiration.

2) Given conditions typical of warm, humid, cloudy summer days at midday an increase in wind speed always produces an increase in transpiration rate.

The results given by Gates point out the complexity of energy balance relationship. More detailed review of the results reveal many seemingly inconsistent relationships between transpiration, leaf temperature and morphological and meteorlogical parameters. It is easily understood why the results of experiments through the years have lacked conformity. Variation in one parameter may influence the energy balance enough to produce first positive and then negative correlations between a second parameter and transpiration rate.

HEAT TRANSFER FROM THE PLANT CANOPY

Stability Criteria

Vertical transport of heat or any other atmospheric property commonly occurs in two ways, free and forced convection. Free convection occurs when the temperature gradient is such that buoyancy forces predominate. Forced convection occurs when forces causing movement (such as pressure gradient) predominate over buoyancy forces. Stability criteria have been used to define buoyant air properties. A stable air profile has buoyant properties retarding vertical motion of air, a neutral air profile has no buoyant properties and an unstable air profile has buoyant properties promoting vertical motion. Quantitatively, a neutral atmosphere is defined by a decrease in temperature with height or lapse rate of 1°C/100 meters or 5.4°F/100 feet. Smallet lapse rates indicate a stable atmosphere and larger lapse rates indicate an unstable atmosphere. Comparing the modes of convection with the states of buoyancy or stability one finds that forced convection occurs at or near neutrality and free convection occurs after some critical value of instability. Richardson's number has been used to define the stability state. It is a dimensionless parameter that expresses the ratio between buoyant and inertial forces of the atmosphere, or

$$R_* = \frac{g\,(\delta T/\delta Z)}{\overline{T}\,(\delta u/\delta Z)^2} \tag{5}$$

where R_* = Richardson number

g = acceleration of gravity

$\overline{T}$ = average temperature within the layer, °K

$\partial T/\partial Z$ = temperature gradient of the layer

$\partial u/\partial Z$ = wind velocity gradient of the layer

A Richardson number of zero denotes neutrality. A negative Richardson number indicates enhanced mixing due to instability and a positive Richardson number indicates supressed mixing due to stability. A detailed discussion of the Richardson number criteria is given by Sutton (19).

Heat Transfer with Forced Convection Conditions

Transport in the atmosphere is normally caused by the presence of eddys in turbulent flow. This transport can be measured in some idealized cases by a process known as the eddy correlation technique (17). It can also be calculated from aerodynamic relationships assuming a similarity between momentum, heat and mass transfer (17). These aerodynamic equations are:

$$\text{momentum} \quad \tau = \rho K_m \partial_u / \partial Z \quad \text{(a)} \qquad (6)$$

$$\text{heat} \quad H_s = -\rho K_h C_p \partial T / \partial Z \quad \text{(b)}$$

$$\text{mass} \quad E = -\rho K_v \partial \psi / \partial Z \quad \text{(c)}$$

where τ = shear

H_s = sensible heat transfer

E = evaporation

ψ = concentration of water vapor

K_m, K_h, K_v = turbulent transfer coefficients for momentum, heat and mass respectively

and other terms as previously defined.

Early work in turbulent transport argued that the transfer coefficients of all entities are equal (17). With this assumption the transfer coefficient can be determined from the wind speed profile and used with the vapor pressure gradient and temperature gradient to compute transfer. Attempts to express the momentum transport coefficient and the wind velocity profile in terms of measurable quantities produced a logarithmic variation of wind speed with height. Thornthwaite assumed the logarithmic profile and assumed (1) surface properties that can be expressed through a roughness constant Z_o and/or a zero plane displacement d and (2) vertical wind shear as invariant with height (17). Based on the Thornthwaite's analysis the following assumptions and deductions were made:

ASSUMPTIONS	DEDUCTIONS
$\tau/\rho = \tau_o/\rho = K_m \, \partial u/\partial z$	$K_m = uk^2 (Z-d) / \ln (\frac{Z-d}{Z_o})$
$u = \frac{1}{k} \left[\frac{\tau_o}{\rho}\right]^{1/2} \ln (Z-d)/Z_o$	$E = \rho k^2 (\psi_1 - \psi_2) u_2 / [\ln (\frac{Z-d}{Z_o})]^2$ (5)
$E = - \rho K_v \, \partial \psi / \partial Z$	$H_s = \rho C_p k^2 (T_1 - T_2) u_2 / [\ln (\frac{Z-d}{Z_o})]^2$ (6)
$H_s = - \rho C_p K_h \, \partial T/\partial Z$	
$K_v = K_m = K_h$	

where τ_o = shear at the surface

k = Von Karman constant

and the other terms as previously defined.

The log linear velocity profile extrapolated to zero velocity defines the roughness height or roughness constant (17).

The resulting equation for the calculation of evaporation was first proposed by Thornthwaite and Holzman in 1942 and is known as the Thornthwaite-Holzman equation or the aerodynamic equation. With additional work Thornthwaite and Kaser observed that the plot of height versus wind velocity changes with the stability of the air. During periods with neutral or near neutral lapse rates the log linear plot holds true but is concave downward during stable conditions and concave upward in unstable conditions (17).

Heat Transfer with Free Convection Conditions

The Thornthwaite equation discussed previously assumes a log linear velocity profile. This assumption has been shown to be valid only with neutral and near neutral atmospheric conditions (17). The prevalence of unstable conditions and the necessity of defining other atmospheric profiles has led workers to study other relationships.

Independent work by Priestly and Monin and Obukhov has resulted in an expression for sensible heat transfer in the free convection regime (14). Reasoning that a suitable expression would not contain wind speed or wind shear explicitly from the definition of free convection, Priestly used a dimensional analysis approach to derive his equation. By including seven independent variables on which the heat flux may depend, Priestly defined the free convection sensible heat transfer equation as:

$$H_s = \overset{*}{H} \rho C_p \left(\frac{g}{\bar{T}}\right)^{1/2} (Z-d)^2 \left(\frac{\partial T}{\partial Z}\right)^{3/2} \tag{7}$$

where $\overset{*}{H}$ = constant and other terms as previously defined.

The argument was made that purely thermal turbulence is self patterning because there is no scale length provided by the independent parameters in the atmosphere. The $\overset{*}{H}$ term in equation (7) is the non-dimensional sensible heat flux and has a value between 1.32 and 1.40 (14, 7).

Crawford has derived an analogous equation for latent heat transfer in the free convection regime as:

$$E = \overset{*}{E} \rho \left(\frac{g}{\bar{T}}\right)^{1/2} \left(\frac{\partial T}{\partial Z}\right)^{1/2} (Z-d)^2 \, \partial q / \partial Z \tag{8}$$

where $\overset{*}{E}$ = constant
q = specific humidity

and the other terms as previously defined.

The critical value of Richardson number at which free convection becomes the dominate mode of convection has been determined as negative 0.02-0.03. The transition from the forced convection regime to the free convection regime is gradual (14). The validity of equations (7) and (8) has been tested by experimentation (14, 7).

The work accomplished by previous workers can be summarized as follows: (1) Raschke and Gates have developed quantitative expressions for latent, sensible and latent heat transfer from a single leaf, (2) expressions for latent and sensible heat transfer from the canopy with forced convection conditions have been developed from aerodynamic considerations and (3) Priestly and Crawford have developed expressions for the transfer of sensible and latent heat from the canopy with free convection conditions.

CHAPTER III

THEORETICAL DEVELOPMENT

THE ENERGY BALANCE

The first step in the derivation of any energy balance equation is to define all the significant terms. Components for the energy balance equation of a bare ground surface are shown diagramatically in Figure 1.

Short wave radiation is received at the earth's surface as two forms: direct and diffuse radiation. Diffuse radiation is solar radiation that has been scattered by atmospheric particles and arrives at the earth's surface indirectly. A portion of the shortwave radiation arriving at the earth's surface is reflected by the ground and other reflecting surfaces. Net solar radiation is equal to the algebraic sum of direct, diffuse, and reflected solar radiation. All objects emit long wave radiation in an amount proportional to the fourth power of their absolute temperature. Net radiation is the algebraic sum of net solar and long wave radiation, and as the name implies, it is the net amount of radiation received at the earth's surface. In the energy balance equation net radiation is balanced by heat transfer with the ground and evaporation and convection with the earth's surface.

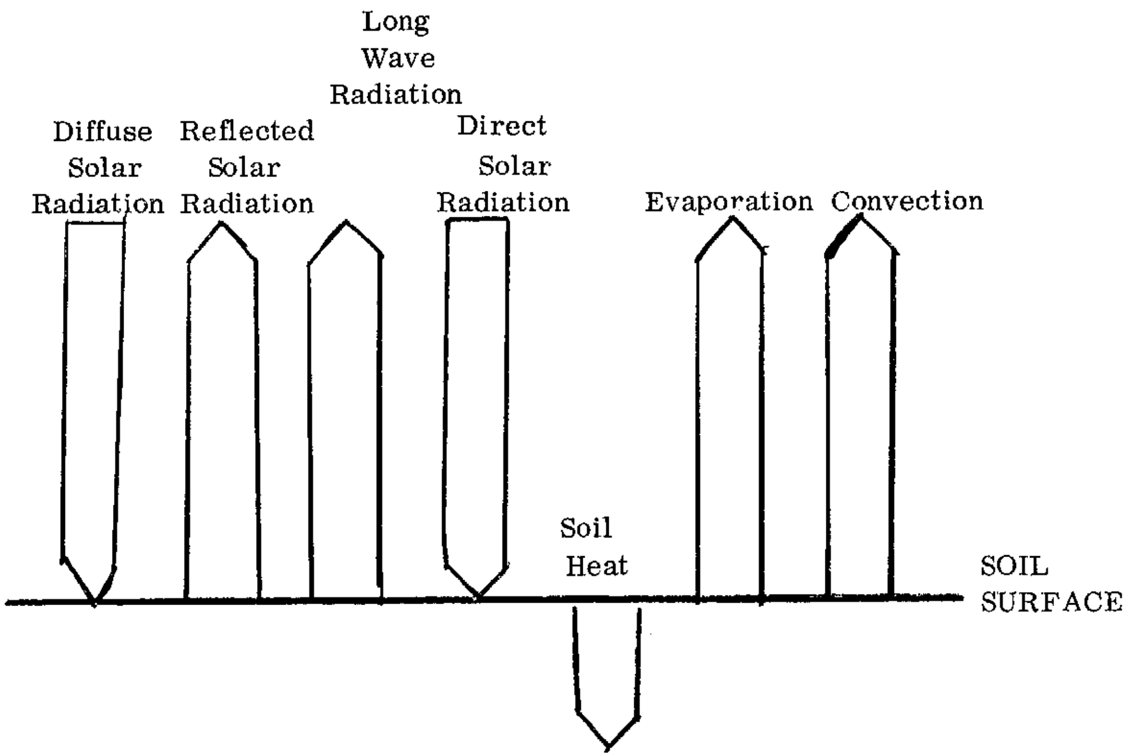

FIG. 1 THE DAYTIME ENERGY BALANCE OF BARE GROUND

The energy budget of a plant community is somewhat more complicated. Incoming solar radiation is reflected, absorbed and transmitted by the plant leaves. In addition, radiant energy is used by the plant in photosynthesis. Receipt of radiation at the soil surface occurs from diffused solar radiation and long wave radiation from the plant leaves (18). In general, over time periods of several days changes in soil heat are relatively small (18). Also over time periods of an hour or less there is relatively small variation in soil heat content (18). Photosynthetic energy use seldom exceeds 2-3% of total heat received by incident radiation (18). Therefore, net radiant energy is dissipated in plant communities predominately by convection and transpiration for short time periods.

DERIVATION OF PREDICTION EQUATIONS

Leaf Heat Transfer

The equations of Raschke, Gates and others in leaf heat transfer expressions contain a transfer coefficient term and a temperature or humidity gradient term. Basic expressions applicable for the transfer of latent and sensible heat in laminar flow are known as Fick's and Fourier's Laws, respectively, and may be written:

Fick's Law $$H_1 = - D_t \frac{L}{RT} \frac{\partial e}{\partial Z} \qquad (9)$$

Fourier's Law $$H_s = -\rho C_p D \frac{\partial T}{\partial Z} \qquad (10)$$

in which H_1 = the flux of latent heat

D_t = diffusivity of water vapor

L = latent heat of vaporization

R = specific gas constant for water

$\bar{T}$ = average temperature, °K

$\partial e/\partial Z$ = vapor pressure gradient

H_s = sensible heat flux

C_p = specific heat of dry air at constant pressure

D = diffusivity of sensible heat

$\partial T/\partial Z$ = temperature gradient

If one adopts Prandtl's boundary layer concept and assumes it has a constant thickness (δ), the steady state flux of vapor can be written as:

$$H_1 = -D_t \frac{L}{R\bar{T}} \frac{(e_b - e_L)}{\delta}$$

in which e_b = water vapor pressure at the top of the boundary layer

e_L = water vapor pressure at the leaf surface.

An air resistance to vapor transfer can be defined as $r_a = \delta/D_t$, hence equation (9) becomes

$$H_1 = -L\ (e_b - e_L)\ R\bar{T}\ r_a \tag{11}$$

in which $\bar{T}$ = the average of the temperature of the leaf (T_L) and the temperature of the canopy bulk air (T_b), °K.

For thin leaved plants the leaf surface temperature is approximately the same as that of the leaf interior.

The terms included in equation (11) are shown schematically in Figure 2. Equation (11) describes the transfer of water vapor between the leaf surface and the bulk air of the canopy. A similar equation can be obtained by considering water vapor transfer from the evaporating surface inside the leaf stomata to the leaf surface, or

$$H_1 = - \frac{L}{RT_L} \frac{(e_L - e_s)}{r_s} \qquad (11a)$$

where e_s is the saturation vapor pressure at temperature T_L. The term r_s refers to the leaf stomatal resistance which is a function of the stomatal area and the shape of stomatal opening. Equation (12) may be obtained by solving equation (11) for e_L, substituting into equation (11a) and solving for H_1.

$$H_1 = - L\,(e_b - e_s)/R\overline{T}\,(r_a + r_s) \qquad (12)$$

An air resistance to the flow of sensible heat can be defined in a manner similar to that of water vapor using the concept of air resistance to heat flow, the sensible heat flux from the leaf can be written:

$$H_s = - \rho C_p\,(T_b - T_L)/r_a \qquad (13)$$

Since the leaf surface temperature is approximately the same as that of the leaf interior, there is negligible sensible heat flow from inside the stomata to the leaf surface.

Radiant heat transfer from a leaf surface that "views" an open sky can de defined by the Stefan-Boltzmann equation as:

$$H_R = \epsilon \sigma\,(T_L)^4 \qquad (14)$$

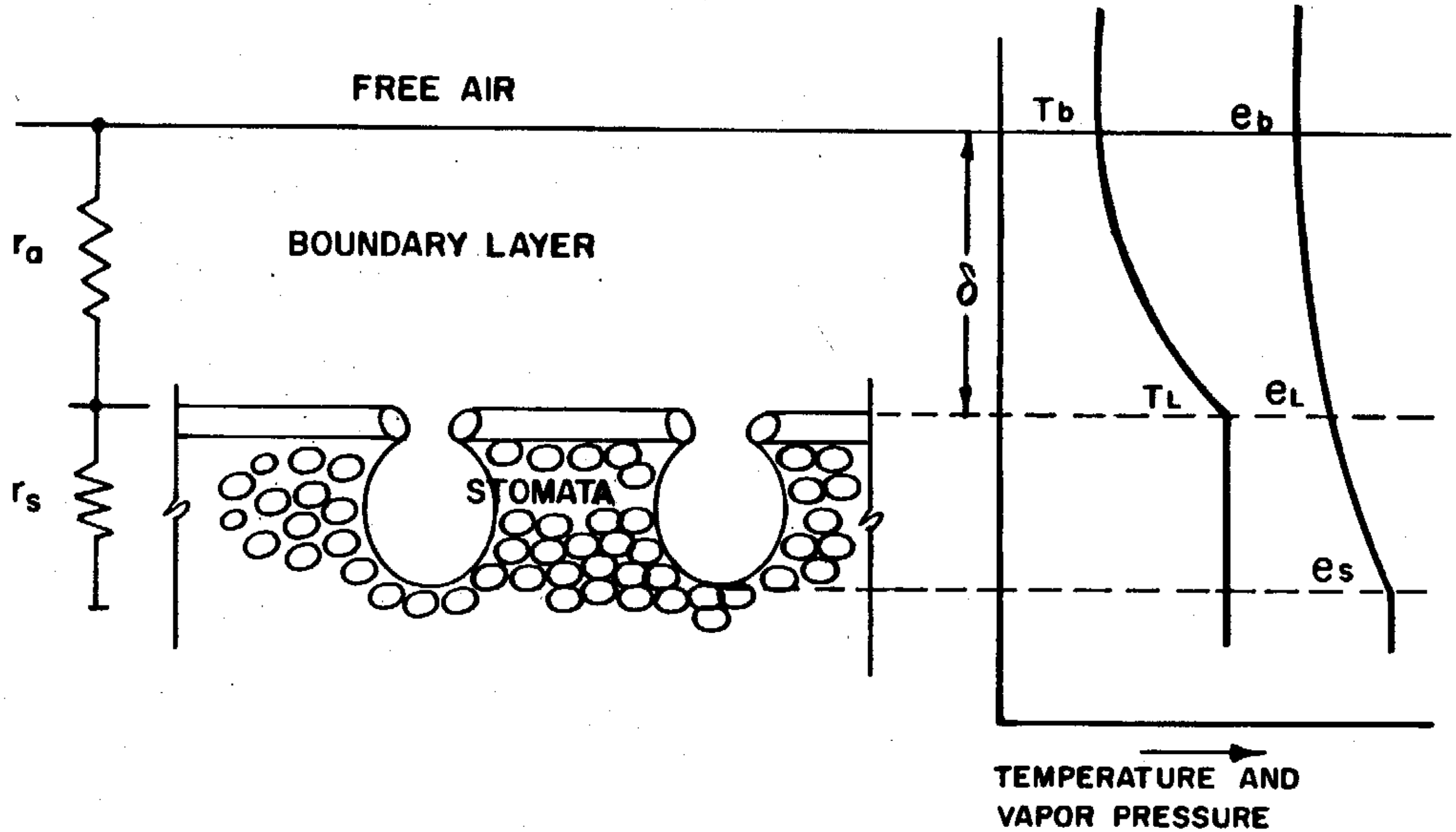

FIG. 2 THEORETICAL MODEL OF A LEAF

in which H_R = the flux of radiant heat

ϵ = emissivity of the leaf surface

σ = Stefan-Boltzmann constant

Transfer in the Atmosphere

Quantitative determination of transfer from a surface to the atmosphere requires definition of all sources and sinks as a function of height. Transfer from bare surfaces presents no problem as the ground itself is the source with the height of the ground defined as being zero. Also, the gradient of physical quantities such a momentum, moisture concentration, and heat within the plant canopy are complex functions of many variables. Error in assigning a value to an effective crop surface is related to crop height. Canopy resistance to transport is also directly related to crop height. The equations developed in this study apply to a short crop which fully covers the ground surface. The roughness height will be taken as the effective crop surface.

Transfer with a Neutral Atmosphere - A neutral atmosphere is one in which thermal gradients have little effect on mixing. The transfer of latent and sensible heat in the atmosphere may be expressed in a manner similar to Fick's and Fourier's laws. However, flow during most daylight hours is turbulent rather than laminar. The equations for the turbulent transfer of latent and sensible heat are expressed as (17):

$$H_1 = \frac{-L}{R\overline{T}} K_v \, \partial e / \partial Z \qquad (15)$$

and

$$H_s = -\rho\, C_p K_h\, \partial T/\partial Z \qquad (16)$$

Where K_v and K_h are the turbulent transfer coefficients for water vapor and sensible heat, respectively. The turbulent transfer coefficients are no longer properties of the fluid as in laminar flow but are variables that depend upon wind speed and the presence of buoyancy forces. The variation of wind shear with height can be defined for two dimensional flow as (17)

$$\tau/\rho = K_m\, \partial u/\partial Z \qquad (17)$$

where τ = wind shear

K_m = turbulent transfer coefficient for momentum

u = wind velocity

The velocity distribution with height has been found to be log-linear for a neutral atmosphere as depicted in Figure 3. This logarithmic velocity profile can be written as (17)

$$u_z = \frac{u_*}{k} \ln \left[\frac{(Z - d)}{Z_o}\right] \qquad (18)$$

in which u_z = wind velocity at some height Z

$u*$ = $(\tau/\rho)^{1/2}$, shear velocity

k = Von Karman constant

d = zero displacement height

Z_o = roughness height.

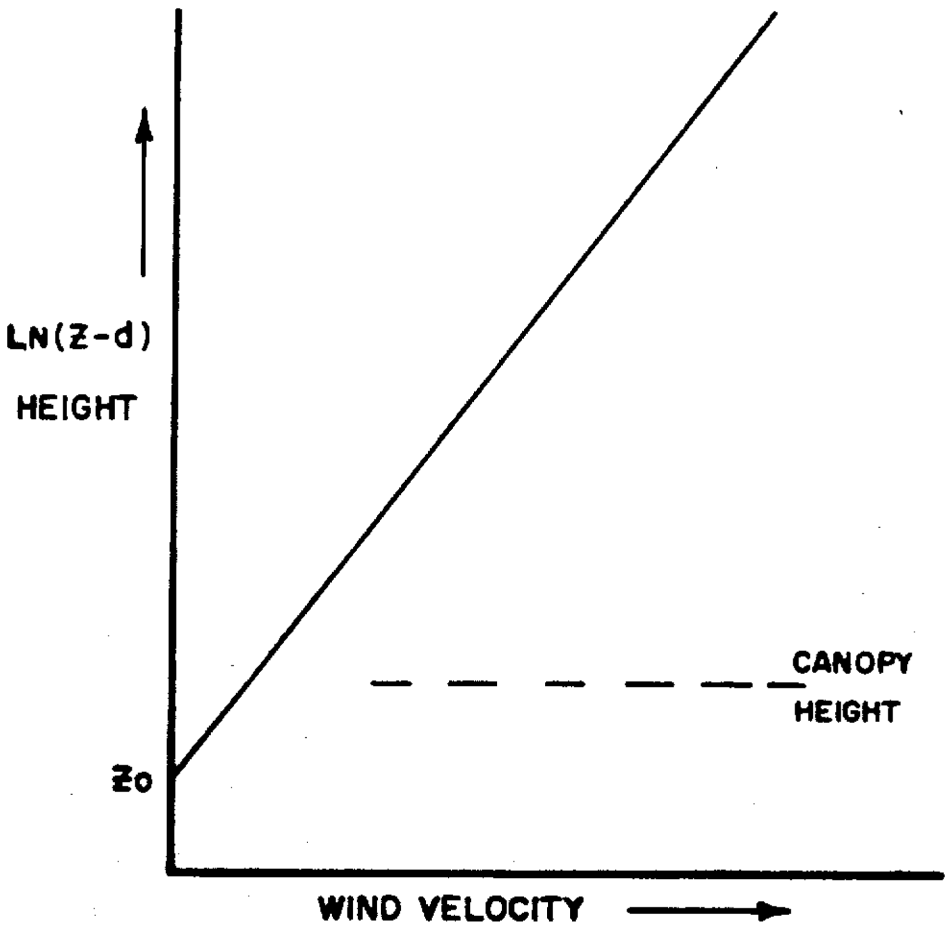

FIG. 3 LOG LINEAR VELOCITY PROFILE

If equation 18 is differentiated with respect to Z, one obtains

$$\partial u / \partial Z = \frac{u_*}{k\,(Z-d)}$$

This result can be substituted into equation (17) to obtain a value for the momentum transfer coefficient as

$$K_m = u_* k(Z-d) \qquad (19)$$

For a turbulent neutral atmosphere the assumption can be made that the momentum, mass and heat transfer coefficients are equal (17). Hence, one can substitute the value for K_m obtained in equation (19) into equations (15) and (16) to obtain:

$$H_1 = \frac{-L}{RT} u_* k(Z-d)\, \partial e/\partial Z \qquad (20)$$

and

$$H_s = -\rho C_p u_* k(Z-d)\, \partial T/\partial Z \qquad (21)$$

Equation (21) can be integrated and simplified to obtain

$$H_s = -\rho C_p u_* k\, (T_a - T_b)/\ln((Z-d)/Z_o) \qquad (22)$$

u_* can be eliminated from equation (21) by integrating the equation

$$u_*^2 = k(Z-d)u_*\, du/dZ$$

to obtain

$$u_* = ku/\ln\left(\frac{Z-d}{Zo}\right)$$

This can be substituted into equation (21) to obtain a final equation for heat flux in a neutral atmosphere,

$$H_s = -\rho C_p uk^2 (T_a - T_b)/[\ln((Z-d)/Zo)]^2 \qquad (23)$$

A similar expression can be obtained for latent heat transfer. For steady state conditions e_b and T_b of equations (12) and (13) can be equated to e_b and T_b of the equations for latent and sensible heat transfer described above to obtain the results

$$H_s = \frac{-f(Z_o)\rho C_p u (T_a - T_L)}{1+f(Z_o)ur_a} \qquad (24)$$

$$H_1 = \frac{-L}{R\bar{T}} \frac{(e_a - e_s) f(Z_o) u}{1 + (r_a + r_s) uf (Z_o)} \qquad (25)$$

in which

$$f(Z_o) = k^2/ [\ln ((Z-d)/Z_o)]^2$$

These equations are similar to those developed by Rijtema for daily estimation of transpiration (16).

An energy balance equation for neutral atmospheric conditions can be obtained by combining equations (24) and (25), an expression for long wave radiant heat, and the incoming solar radiation to obtain

$$R_i = \epsilon\sigma T_L^4 + \frac{f(Z_o)\rho C_p u(T_L - T_a)}{1 + f(Z_o) ur_a} + \frac{L}{R\bar{T}} \frac{(e_s - e_a) f(Z_o)u}{[1+(r_a + r_s)f(Z_o)u]} \qquad (26)$$

in which R_i = incoming solar radiation and the terms as previously defined.

Net radiation is equal to the algebraic sum of the first two terms of equation (26). The latent heat of vaporization is a function of leaf temperature(13). Since the water vapor pressure of the stomatal evaporating surface and the free air are functions only of leaf and air temperature and air relatively humidity equation (26) can be solved implicitly for the leaf temperature (19). Equation (26) is the proposed model for a neutral atmosphere.

Transfer with an Unstable Atmosphere - An unstable atmosphere is one in which thermal gradients are the primary cause of mixing. The transfer of sensible and latent heat in the atmosphere under unstable conditions have been expressed quantitatively by Priestly and Crawford (14, 7). These atmospheric transfer terms can be combined with the sensible and latent heat transfer terms from a leaf surface to define transfer from a leaf surface to the unstable atmosphere. Priestly's and Crawford's expressions for the transfer of sensible and latent heat are

$$H_s = \overset{*}{H}\rho C_p \left[\frac{g}{\overline{T}}\right]^{1/2} \frac{(Z-d)^2}{4} \left[\frac{T_b - T_a}{Z-d}\right]^{3/2} \qquad (28)$$

and

$$H_1 = \overset{*}{E}\rho L \left[\frac{g}{\overline{T}}\right]^{1/2} \frac{(Z-d)^2}{4} \left[\frac{T_b - T_a}{Z-d}\right]^{1/2} \left[\frac{q_b - q_a}{Z-d}\right] \qquad (29)$$

Where $\overset{*}{H} = \overset{*}{E} = 1.32$

g = acceleration of gravity

$\overline{T}$ = average temperature in the layer, °K

q = specific humidity

Equations (28) and (29) can be combined with equations (12) and (13) in a manner similar to that for the neutral atmosphere to obtain the following relationships (assuming $r_a = 0$):

$$H_s = \overset{*}{H}\rho C_p \left[\frac{g}{\overline{T}}\right]^{1/2} \frac{(Z-d)^2}{4} \left[\frac{T_L - T_a}{Z-d}\right]^{3/2} \qquad (30)$$

and

$$H_1 = \overset{*}{E}\rho L\left[\frac{g}{T}\right]^{1/2} \frac{(Z-d)^2}{4} \left[\frac{T_L - T_a}{Z-d}\right]^{1/2} \left[\frac{q_s - q_a}{Z-d+f_1 r_s}\right] \tag{31}$$

where $f_1 = \overset{*}{E}\rho \left[\frac{g}{T}\right]^{1/2} \frac{(Z-d)^2}{4} \left[\frac{(T_L - T_a)}{Z-d}\right]^{1/2}$

An energy balance equation can be formed for unstable conditions by combining equations (30) and (31), an expression for long wave radiant heat and the incoming solar radiation

$$R_i = \epsilon\sigma T_L^4 + \rho \overset{*}{H} C_p \left[\frac{g}{T}\right]^{1/2} \frac{(Z-d)^2}{4} \left[\frac{T_L - T_a}{Z-d}\right]^{3/2} + \overset{*}{E}\rho L\left[\frac{g}{T}\right]^{1/2} \frac{(Z-d)^2}{4} \left[\frac{T_L - T_a}{Z-d}\right]^{1/2} \left[\frac{q_s - q_a}{Z-d+f_1 r_s}\right] \tag{32}$$

The first two terms of equation (32) can again be combined to give the net radiation. Specific humidity of the stomatal evaporating surface and the air can be approximately expressed as functions of atmospheric pressure assumed constant standard conditions, leaf and air temperature and air relative humidity. Equation (32) can be solved implicitly for the leaf temperature. It is the proposed model for an unstable atmosphere.

WORKING APPROXIMATIONS

Implicit solution of the prediction equations for leaf temperature requires suitably accurate values for leaf and boundary layer resistances and roughness and zero displacement heights.

Roughness and Zero Displacement Heights

The roughness and zero displacement heights are most accurately obtained with wind velocity profiles taken at neutral atmospheric conditions. Collecting such data requires continuous readout or, as a close approximation used by some investigators the averaging of the two near neutral profiles taken on either side of neutrality. In the absence of either the continuous profile data or the averaged profile data the same analysis may be made but is susceptible to error due to deviations of the wind velocity profile from a log linear relationship under non-neutral conditions. The zero plane displacement and roughness height vary with wind speed, as wind speed increases flexible crops are bent down by the wind resulting in a smaller surface roughness. Variation of the zero displacement height with wind speed is proprotionally much less than the corresponding change in roughness height (20). Roughness height has been shown by Szeicz et al to be equal to one-tenth of crop height(20).

Boundary Layer Resistance

Boundary layer or aerodynamic resistance is dependent upon leaf dimensions, leaf surface characteristics and wind velocity. Measurement is usually accomplished in a wind tunnel with normal or simulated wetted leaves. Boundary layer resistance is inversely proportional to wind velocity. At high wind velocities boundary layer resistance becomes small. Gates states that boundary layer resistance becomes negligible at wind speeds greater than 2 mph (89.4 cm/sec). Neglecting the boundary layer resistance term can be justified either by the criteria stated by Gates and/or finding that the prediction equation is insensitive to neglecting it.

Transfer in the free convection regime is considered to be independent of wind velocity and aerodynamic resistance of the boundary next to the leaf has been neglected.

Leaf Stomatal Resistance

With moderate light intensities, little or no moisture stress, moderate temperature and carbon dioxide levels stomatal resistance is relatively constant (18). Stomatal resistance is generally evaluated with representative leaves in a wind tunnel (18). Literature contains numerous summaries of leaf stomatal resistance for different plants (18, 12). Stomatal resistance values can be chosen from literature and inserted into the equation for analysis. Moisture stress can be accounted for by changes in stomatal resistance.

CHAPTER IV

EXPERIMENTAL EQUIPMENT AND PROCEDURE

A plot of cucumbers was grown in the summer of 1969 on the horticultural farm at the University of Kentucky to test the validity of the equations proposed in Chapter III. Cucumbers are a low growing crop with thin leaves that adequately shade the entire ground area.

PLOT CHARACTERISTICS

A 50 ft. by 50 ft. plot of SMR-17 cucumbers was grown. The plot was surrounded by grassland and stubble that varied from 2-4 inches in height (see Figure 4). The shortest reach was 150 ft. to a cornfield to the west. The topography was gently rolling with a low ridge to the south. The cucumber canopy height varied from about 8-10 inches and provided fairly complete ground cover. Cucumbers were picked 9 days before the first observation. Damage to the vegetation was minor.

EXPERIMENTAL PROCEDURE

A telephone pole 15 feet high was erected in the center of the plot to support temperature and wind velocity profile sensors (Figure 5). Wind velocity was measured by *Disa 55Do1 constant temperature anemometer with

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*Disa- S&B, Inc., 779 Susquehanna Ave., Franklin Lakes, New Jersey.

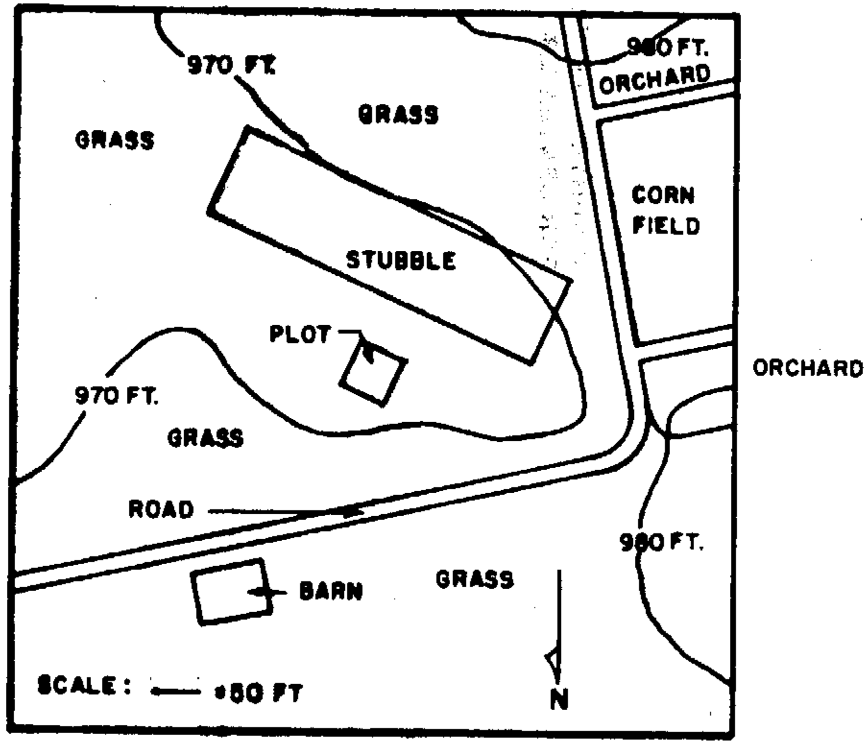

FIG. 4 PLOT AREA CHARACTERISTICS

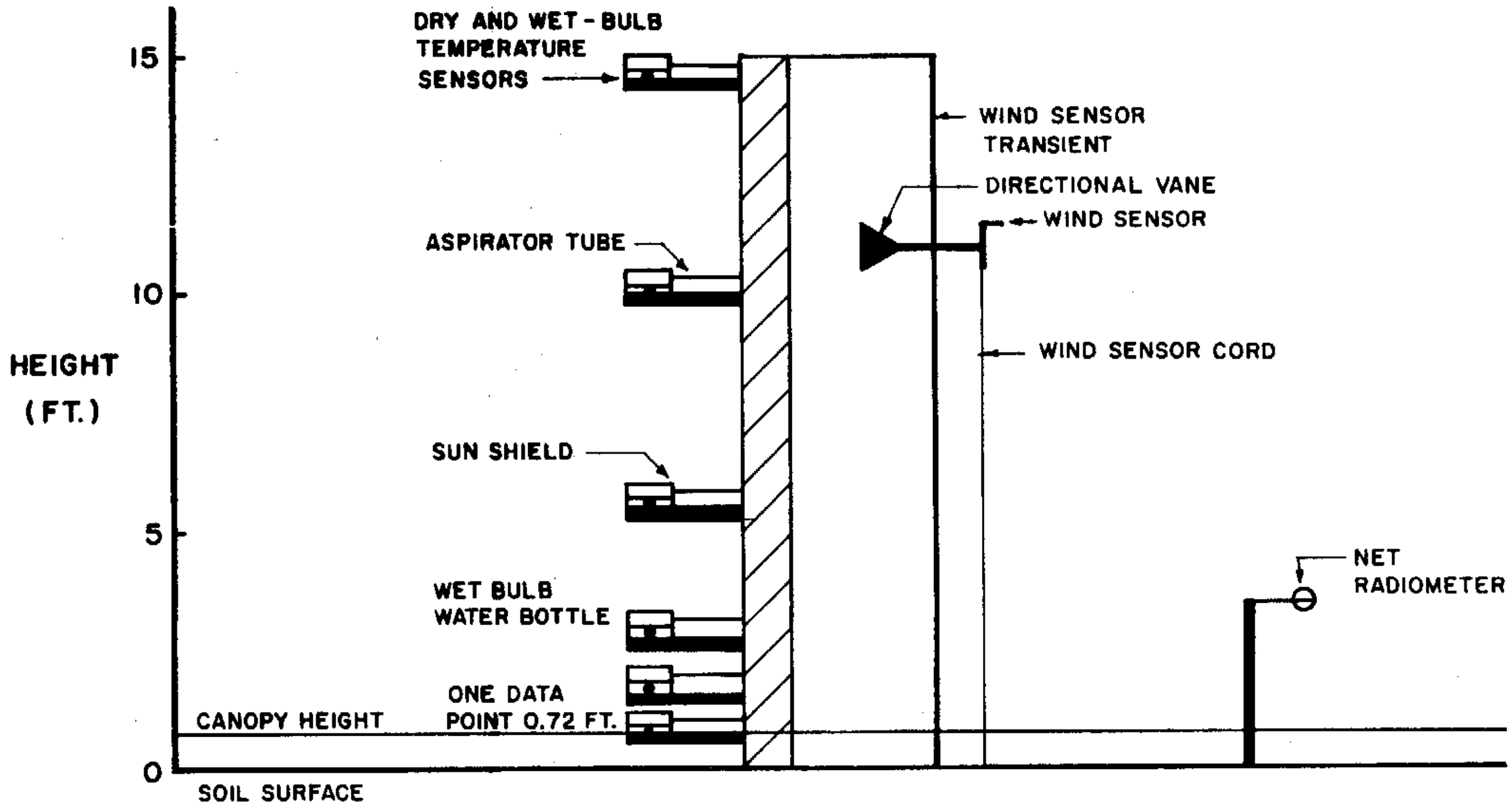

FIG. 5 VERTICAL CROSS SECTION OF INSTRUMENTS LAYOUT

a standard 55A22 hot wire sensor. The calibration curve for the sensor used was supplied by the company. The wind velocity sensor was held in a directionally sensitive transient vane on a metal rod mounted 3 feet to the southwest of the main pole. Seven dry and wet bulb temperature sensors were mounted on 2.5 foot supports, they were logarithmically spaced vertically and were oriented toward the northeast. The temperature sensors were copper-constantan thermocouples pushed into 3/8 inch clear plastic tubing. The wet bulb temperature sensor was covered by a wick moistened with distilled water supplied from a small glass jar. Required aspiration of the wet and dry bulb thermocouples was accomplished by a small exhaust fan connected to the plastic tubing (5). The temperature sensors were shaded from solar radiation. Leaf temperature was measured by fifteen 40-gauge copper constantan thermocouples inserted into leaves. Care was taken during leaf thermocouple placement to obtain readings throughout the plot to avoid edge influence (Figure 6). Leaf thermocouples were checked daily for proper insertion and normal leaf quality. Soil temperature readings were taken at three locations (Figure 6) at depths of 1/2, 2, 4 and 6 inches with copper constantan thermocouples. Details of equipment design are shown in Figure 7.

Net radiation was measured by a Thornthwaite model 601AA net radiometer. The radiometer is essentionally two thermopile units mounted back to back covered by two polyethylene hemispheres. The wavelength absorption and wavelength transmission characteristics of the thermopile

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C. W. Thornthwaite Associates, Route 1, Centerton, Elmer, New Jersey.

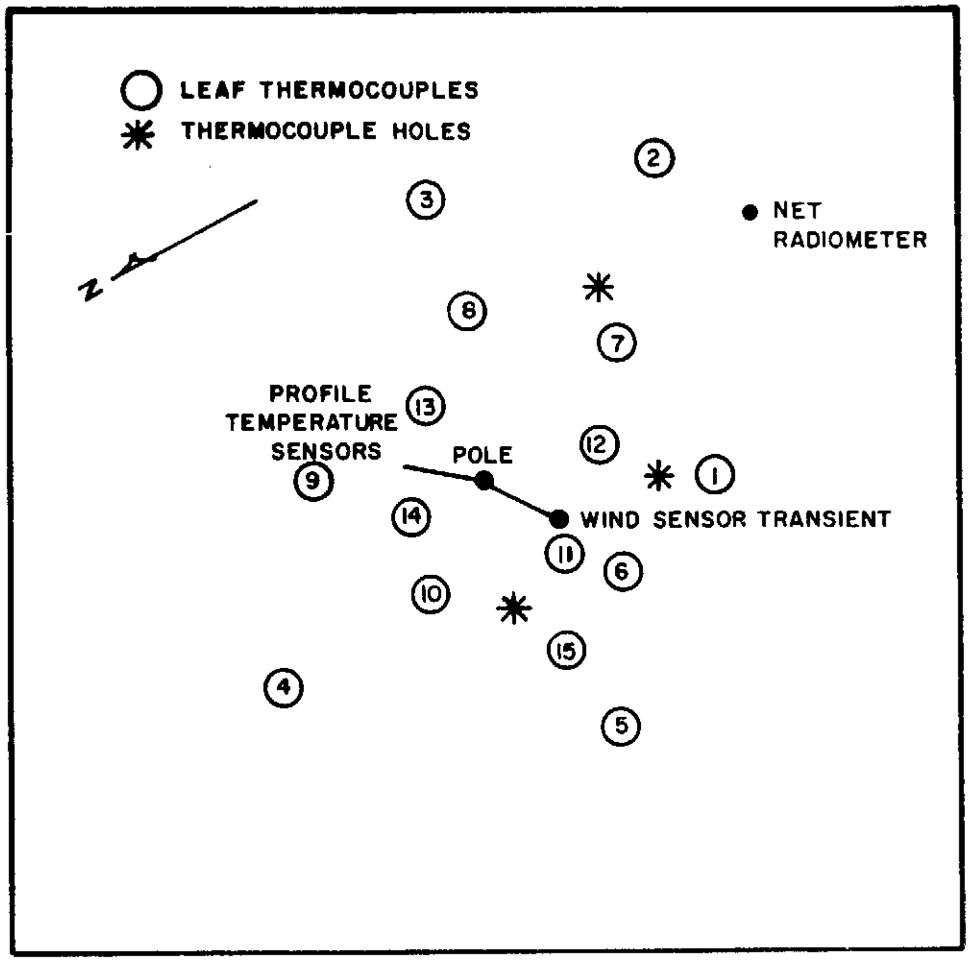


FIG. 6 TOP VIEW OF PLOT

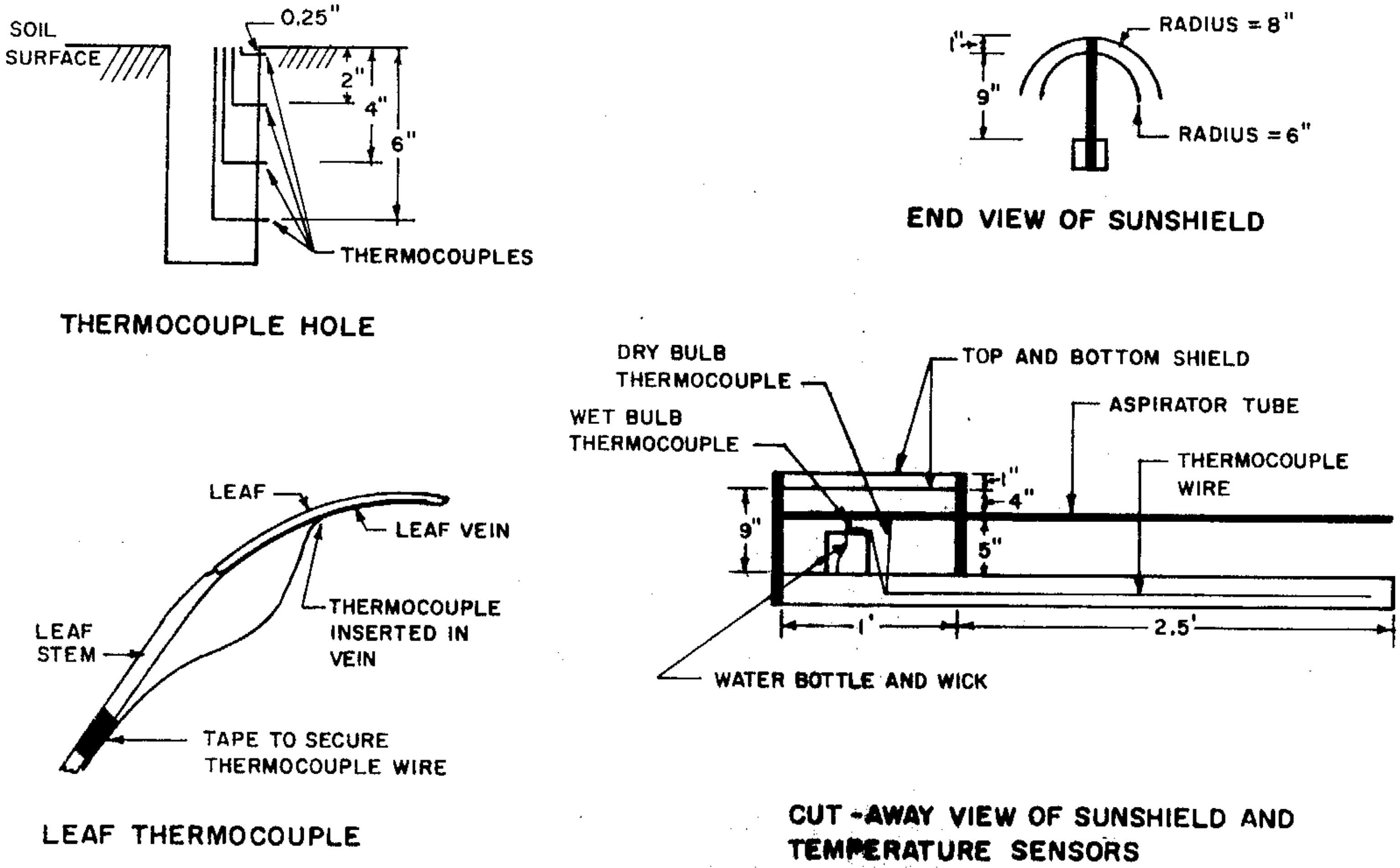


FIG. 7 DETAIL OF EQUIPMENT DESIGN

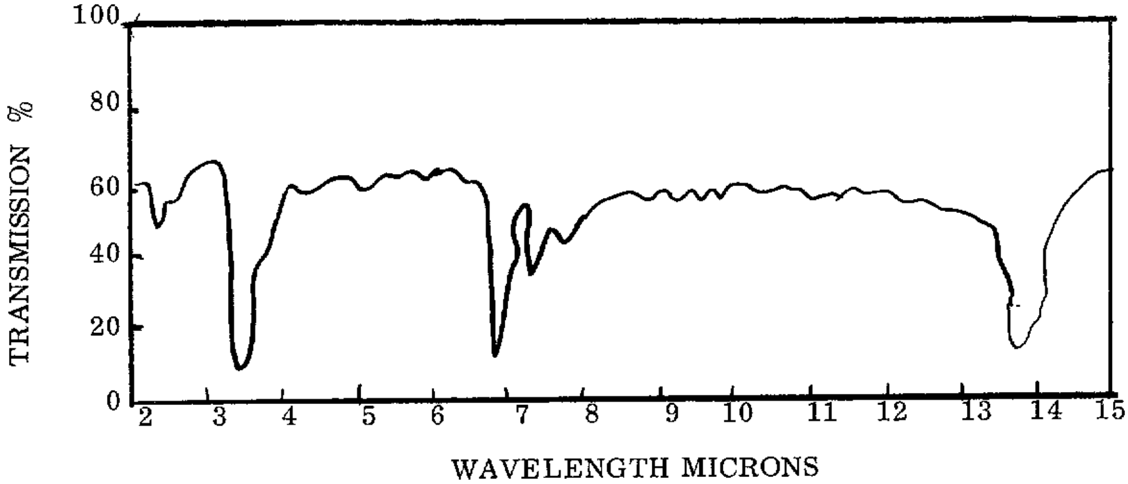
and polyethylene are shown in Figure 8. The radiometer provided a continuous recording of net radiation.

Net radiation measurements were taken for each profile by averaging the output of the net radiometer.

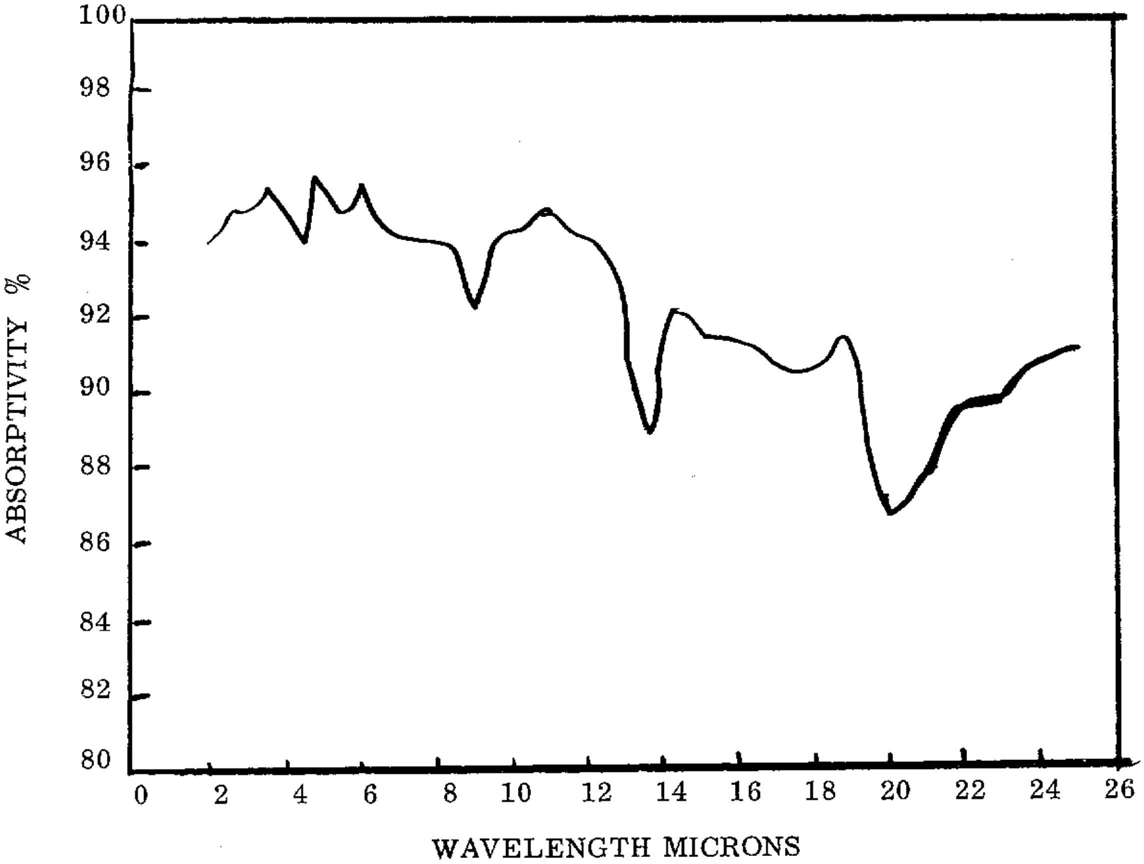
During each of ten tests made in the experiment, temperature recording was continuously cycled through the individual temperature readings. Tape punch recording provided means for later analysis. Wind velocity profile measurement required:

1. averaging numerous readings due to the wind's turbulent nature,
2. total time of test less than approximately one hour so steady state conditions could be assumed,
3. wind velocity reading at each height representative of the total time of observation.

To meet the requirements established, multiple profiles were taken for each test. A minimum of four profiles was taken for each test and all but two tests contained a composite of six profiles. Three wind velocity readings were taken at each of the six heights above the canopy for each profile. This procedure permitted: (1) 12 to 18 readings for each height, (2) total time of observation of about 48 minutes and (3) three readings for each height that were within 8 minutes of start or stop time. A net radiation measurement was recorded for averaging at each height of each profile measurement. Frequent rainfall and irrigation supplied sufficient moisture so plants showed no signs of soil mositure stress.



TRANSMISSION OF POLYETHYLENE RADIOMETER COVER



ABSORBTIVITY OF RADIOMETER THERMOPILE

FIG. 8 WAVELENGTH RESPONSE CHARACTERISTICS OF THORNTHWAITE 601AA NET RADIOMETER

CHAPTER V

RESULTS AND DISCUSSION

Ten tests were taken by the procedure described in Chapter IV to test the proposed prediction relationships. Wind velocity, temperature and net radiation measurements were averaged to obtain the most representative values. The averaged data for each observation are presented in Tables 6 and 7 in the Appendix. Data from measurements at 457.5 cm. (15 ft.) were inconsistent with lower profile measurements and were not used in analysis.

RICHARDSON NUMBER AND STABILITY

Wind velocity and dry bulb temperature profile data were used to calculate Richardson number as expressed by equation (5). A localized Richardson number was calculated for each layer of the profile. Richardson numbers are summarized in Table 1. The values are all negative ranging from 0.04 to 8.27. Detailed interpretation of the results is difficult because of the range of values. Variation of results can be attributed to the measurement error in relatively small wind velocity and height gradients and even smaller temperature gradients. The Richardson numbers are, however, below the 0.03 value which is the upper limit of free convection as given by Crawford and Priestly (7, 14).

TABLE 1

MEASURED RICHARDSON NUMBER

TEST	RICHARDSON NUMBER	TEST	RICHARDSON NUMBER
1	-8.27	6	-1.02
2	-0.04	7	-0.09
3	-0.61	8	1-.08
4	-0.12	9	-1.14
5	-0.29	10	-0.43

TABLE 2

AERODYNAMIC PREDICTION RESULTS

		Predicted T_L °C			
	OBSERVED	Z_o = 1.7		Z_o = 2.5	
TEST	T_L °C	r_s = 1.2	2.0	r_s = 1.2	2.0
1	29.5	39.7	42.3	38.6	41.1
2	31.1	39.6	42.5	38.6	41.4
3	25.1	33.6	36.2	32.6	35.0
4	28.5	37.7	40.7	36.7	39.5
5	29.3	37.3	40.0	36.3	39.0
6	26.7	35.1	37.7	34.0	36.5
7	30.1	37.7	40.4	36.7	39.6
8	28.9	36.3	39.0	35.3	37.8
9	31.3	41.1	44.3	39.9	43.1
10	30.7	36.8	39.5	36.0	38.6

ROUGHNESS HEIGHT AND ZERO DISPLACEMENT HEIGHT

The inputs of roughness height and zero displacement height were obtained by a least squares regression given by Covey (6). Results are presented in Table 7. Average values were calculated for both the roughness height and the zero displacement height. The average roughness height, 1.7 centimeters, was close to one-tenth of the minimum crop height of 20 centimeters (8 inches). The value for one-tenth of the maximum crop height of 10 inches, 2.5 centimeters, was also evaluated in the analysis. Zero displacement height was considered conservative with stability. The average value of zero displacement height, 35 centimeters, was used in the analysis. It should be pointed out again that the values of roughness and zero displacement height are best obtained at neutral or near neutral conditions when the logarithmic wind velocity profile approaches linearity.

VAPOR PRESSURE GRADIENT

Saturation vapor pressure can be expressed as a function of temperature by a log linear version of the Kirchhoff-Rankine-Dupré formula (19) as

$$\ln e_s = A + \frac{B}{T}$$

The vapor pressure gradient expression in dynes/cm^2 derived for use in the analysis as

$$e_s - e_a = 1.626\text{x}10^{12} \left(e^{\frac{-5.29\text{x}10^3}{T_L + 273}} - \text{r.h.}\, e^{\frac{-5.29\text{x}10^3}{T_a + 273}} \right)$$

in which e_s = saturation vapor pressure (dynes/cm^2) of the stomatal evaporating surface at leaf temperature T_L

e_a = saturation vapor pressure (dynes/cm^2) of the air at some reference height whose temperature is T_a and relative humidity is r.h.

AERODYNAMIC PREDICTION EQUATION

Equation (26) in the form used for evaluation is

$$R_n = f(Z_o)\rho C_p u (T_L - T_a) 60 + \frac{L}{RT} \frac{(e_s - e_a) f(Z_o) u (60)}{[1 + r_s f(Z_o) u]}$$

where $f(Z_o) = \frac{k^2}{[\ln((Z-d)/Z_o)]^2}$

r_n = net radiation, cal/cm^{2}min

k = Von Karman's constant, 0.40

Z = reference height, 320.5 cm

d = zero displacement height, cm

Z_o = roughness height, cm

ρ = density of dry air, 1.2×10^{-3} gm/cm^3

C_p = specific heat of dry air, 0.24 cal/gm °C

u = wind velocity at reference height, cm/sec

T_L = temperature of the leaf, °C

T_a = temperature of the air at reference height, °C

L = latent heat of vaporation 597.3 - 0.56 T_L cal/gm

R = natural gas constant of water vapor, 4.615×10^6 dyne cm/gm°K

$\bar{T}$ = $(T_L + T_a)/2+273$

r_s = stomatal resistance, sec/cm

e_s and e_a have been defined in the previous section.

The above equation was solved implicitly for leaf temperature. Results are presented in Table 2 and graphically in Figure 9 and 10.

Predicted leaf temperature values are larger than observed values 6-12 °C. The large error in prediction is probably due to the neglect of buoyant forces in the derivation of heat transfer equations for a neutral atmosphere. The large negative Richardson numbers indicate that buoyant forces are significant. By including the effects of buoyant forces, one would predict higher heat transfer rates for the same temperature gradient.

Sensitivity of Aerodynamic Prediction Equation to Inputs

The influence of roughness height, stomatal resistance and boundary layer resistance on predicted leaf temperature was tested by conducting the analysis with several combinations of representative values of these inputs. Techniques used in the experiment prohibited selection of any one value as absolute. Table 3 and Figures 11 and 12 demonstrate the variation of predicted leaf temperature with changes in roughness height, stomatal resistance and boundary layer resistance values. The tests selected for presentation (using meteorological parameters from Tests 3 and 9) are the tests with the lowest and highest predicted leaf temperatures.

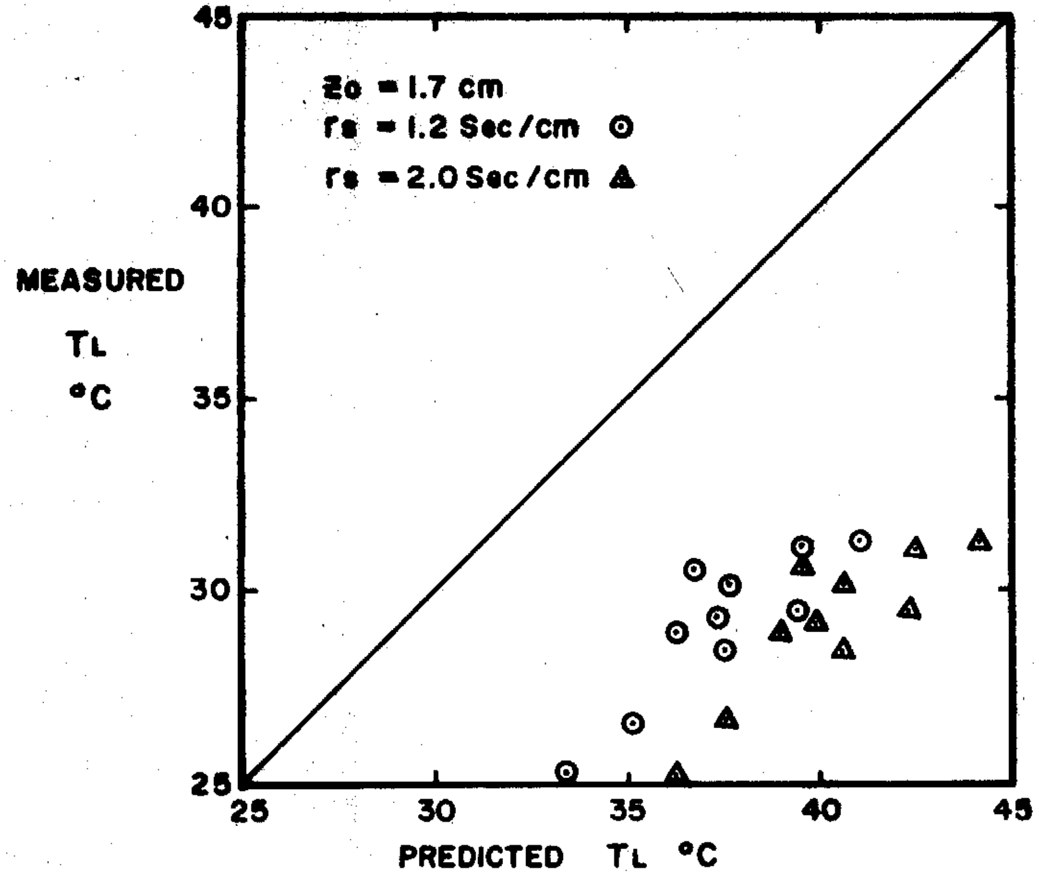


FIG. 9 AERODYNAMIC PREDICTION RESULTS

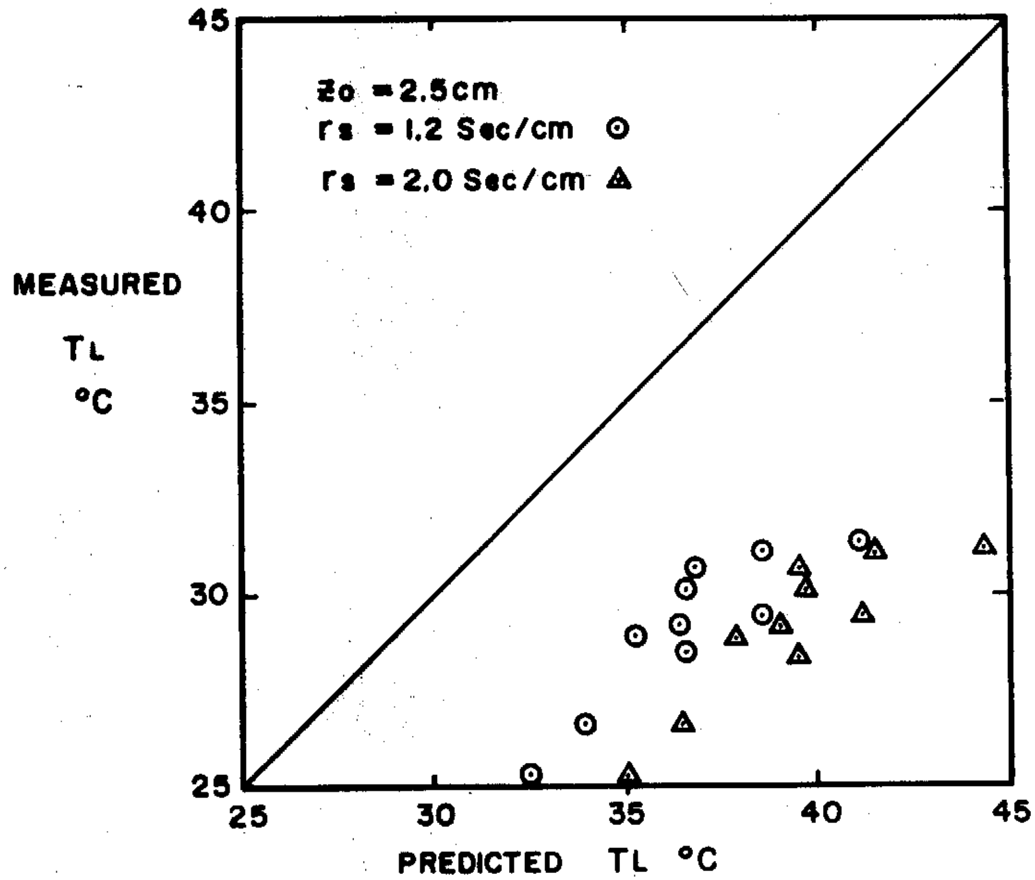


FIG. 10 AERODYNAMIC PREDICTION RESULTS

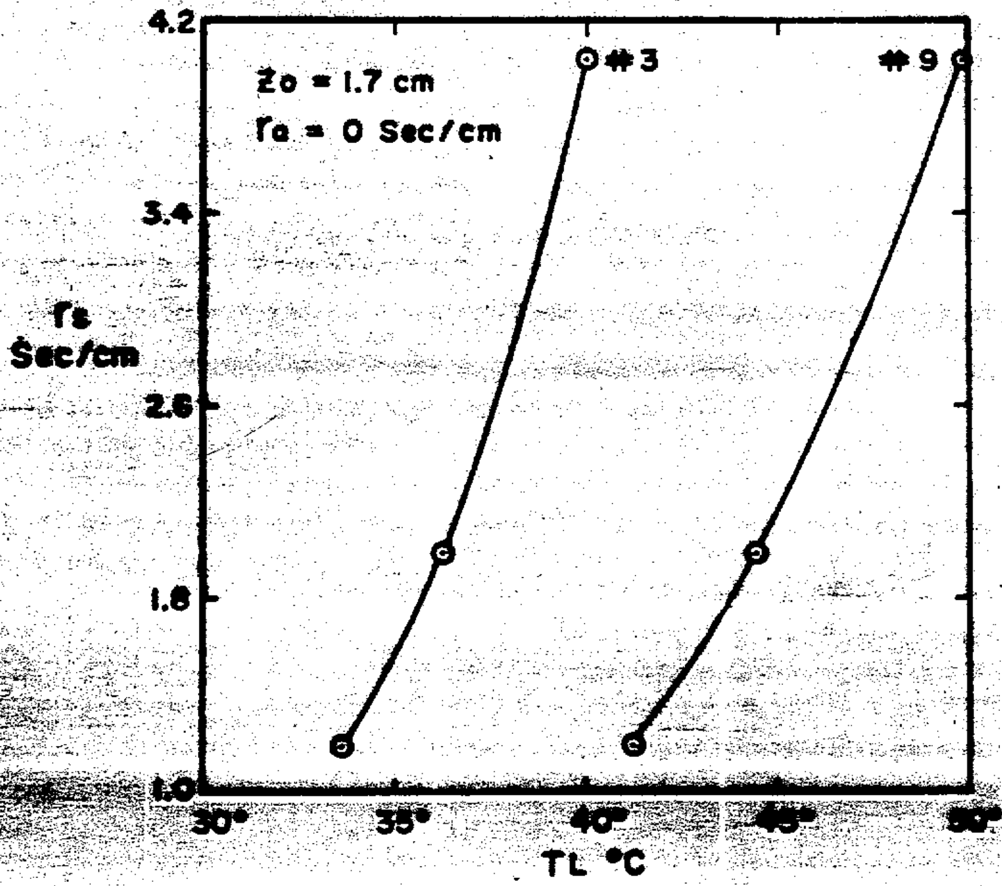


FIG. 11 SENSITIVITY OF AERODYNAMIC PREDICTION EQUATION TO STOMATAL RESISTANCE

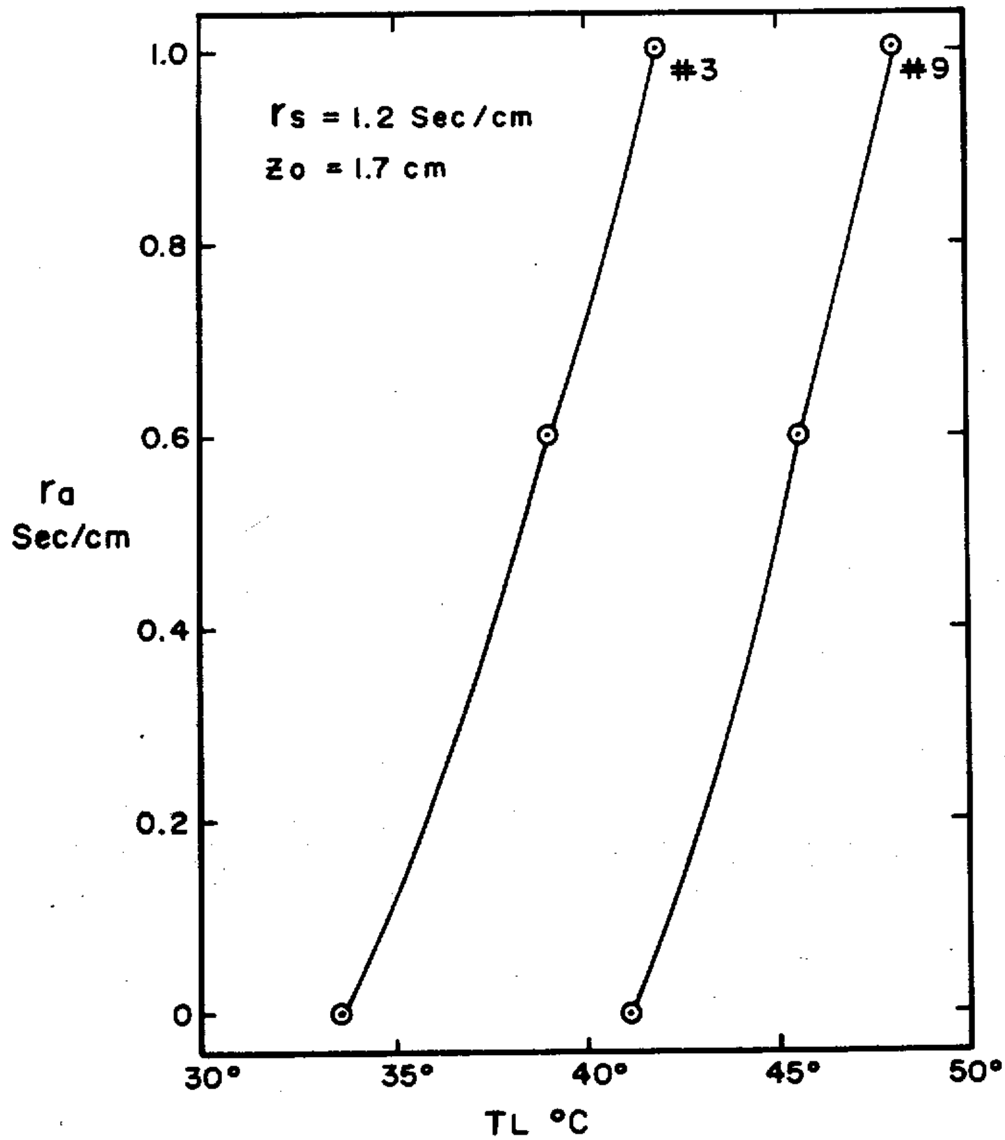


FIG. 12 SENSITIVITY OF AERODYNAMIC PREDICTION EQUATION TO BOUNDARY LAYER RESISTANCE

TABLE 3

Sensitivity of Aerodynamic Prediction Equation to Roughness Height (Z_o)
$r_a = 0$, $r_s = 1.2$ sec/cm

#9	Z_o (cm)	Predicted T_L (°C)	#3	Z_o (cm)	Predicted T_L (°C)
	1.7	41.1		1.7	33.6
	2.5	39.9		2.5	32.6

TABLE 4

Free Convection Prediction Results

Test	Observed	Prediction	
	T_L °C	$r_s = 1.2$	2.0
1	29.5	28.3	28.5
2	31.1	30.9	31.2
3	25.1	25.1	25.3
4	28.5	28.6	28.9
5	29.3	29.2	29.5
6	26.7	24.7	24.9
7	30.1	29.3	29.6
8	28.9	27.2	27.5
9	31.3	30.2	30.5
10	30.7	30.4	30.9

Sensitivity to Roughness Height - Leaf temperature is relatively insensitive to the range in roughness height. Increasing Z_o lowered predicted leaf temperature to some extent. Values for roughness height that would lead to approximation of observed leaf temperature do not meet the one-tenth value of crop height noted in the literature.

Sensitivity to Stomatal Resistance - Leaf temperature increased with increasing stomatal resistance. The sensitivity to stomatal resistance would be smaller if boundary layer resistance were different from zero. Lowering leaf stomatal resistance much below the 1.2 sec/cm minimum value used would be inconsistent with reported values in the literature and nearly eliminate plant influence on the heat transfer process.

Sensitivity to Boundary Layer Resistance - Leaf temperature increased with increasing boundary layer resistance. As mentioned previously Gates has stated that at wind speeds of 2 mph (89.4 cm/sec) or greater boundary layer resistance could be neglected (11). Observed wind velocities at 45.3 centimeters were generally larger than 89.4 cm/sec. Although this value did not occur at the leaf surface it was felt that boundary layer resistance could be assumed to be approximately equal to zero. Boundary layer resistance could not be varied to yield predicted leaf temperatures approximating observed leaf temperatures.

The analysis of predicted leaf temperature with changes in the values of input parameters whose absolute values were unknown showed that a predicted leaf temperature either could not be obtained by variation of a given input or the value of the necessary input was not consistent with literature.

FREE CONVECTION PREDICTION EQUATION

Equation (32) in the form used for evaluation is

$$R_n = \frac{\rho H^*}{4} \frac{g}{T}^{1/2} (Z-d)^{3/2} (T_L - T_a)^{1/2} \left[\frac{C_p (T_L - T_a)}{Z-d} + \frac{L(q_L - q_a)}{Z-d+f_1 r_s}\right]$$

where $H^* = E^* = 1.32$

g = acceleration of gravity

$\bar{T} = (T_L + T_a)/2 + 273$

$$q_L = \frac{0.612\, e_s}{P} = \frac{0.612}{P} (1.626 \times 10^{12})\, e^{\frac{-5.29 \times 10^3}{T_L + 273}}$$

$$q_a = \frac{0.162}{P} e_a = \frac{0.612}{P} (1.626 \times 10^{12})\, (r.h.)\, e^{\frac{-5.29 \times 10^3}{T_a + 273}}$$

$P = 1.013 \times 10^6$ dynes/cm^2

and the other terms as previously defined.

The results from the implicit solution of the above free convection equation are presented in Table 4 and shown graphically in Figure 13. Predicted leaf temperatures are slightly lower than observed leaf temperatures. However, results are easily within range of experimental error. Two reasonable values for leaf stomatal resistance are reported. The equation predicted a 0.2-0.5 °C increase in leaf temperature with stomatal resistance varying from 1.2-2.0 sec/cm. Best fit was obtained by the 2.0 value. The reference height used was 320.5 cm. The use of such a high value for Z decreased the sensitivity of both equations to zero displacement height.

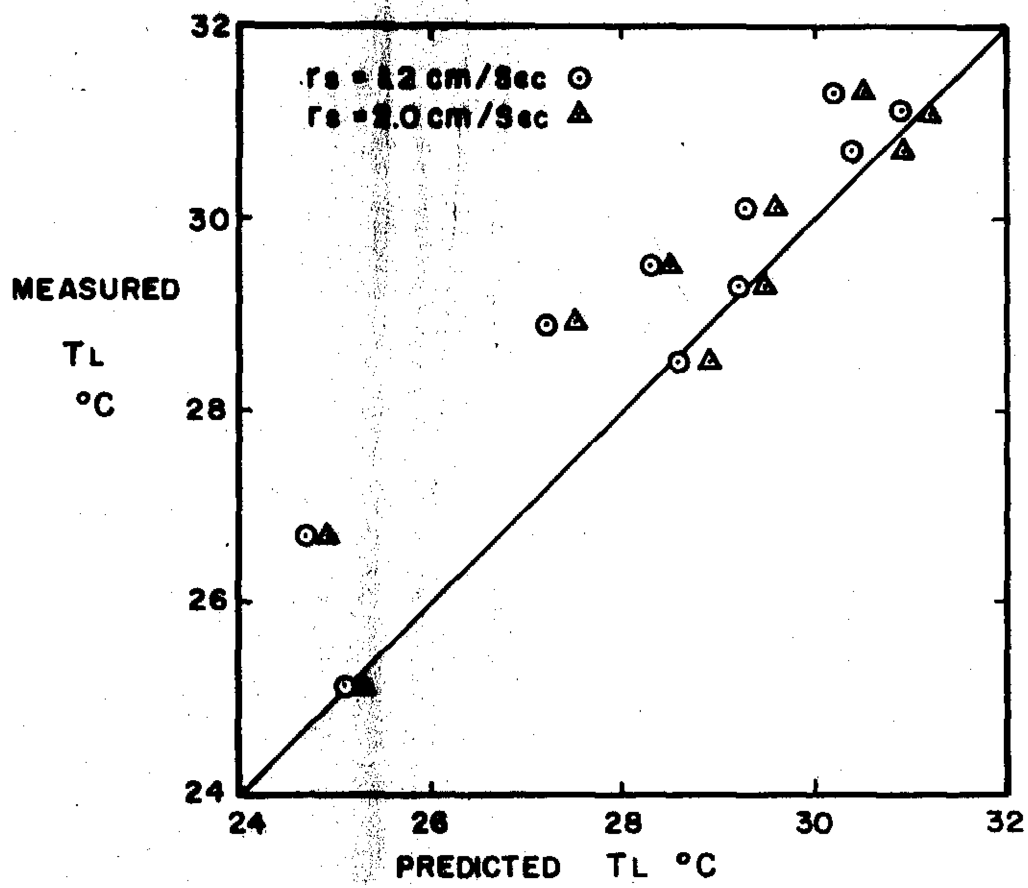


FIG. 13 FREE CONVECTION PREDICTION RESULTS

STATISTICAL ANALYSIS OF THE RESULTS

The Student t-test was used on the paired values to test the null hypothesis that the difference between the predicted and observed temperature was zero. Standard procedures were used to establish confidence intervals. Results are shown in Table 5.

Statistical Analysis of the Aerodynamic Prediction Equation Results

The null hypothesis of zero difference between measured and predicted leaf temperatures can be rejected at the 0.01 level of significance for all combinations of variables. Confidence limits indicate that 99 percent of the time predicted leaf temperature was at least 4.3° C above the measured leaf temperature.

Statistical Analysis of the Free Convection Prediction Equation Results

The null hypothesis of zero difference between measured and predicted leaf temperature for r_s equals 2.0 sec/cm. cannot be rejected at the 0.05 level. When r_s equals 1.2 sec/cm. the null hypothesis can be rejected at the 0.05 level. Confidence intervals for the two stomatal resistance values indicate that 99 percent of the time leaf temperature prediction values would be between 1.5° C lower than and 0.4° C above observed leaf temperature.

SOIL HEAT LOSS

The assumption of negligible heat loss to the soil was investigated. Soil profile temperatures for the first and last five cycles of readout during each run were averaged and plotted on graphs (Figure 14). The two resulting

TABLE 5

Results of Statistical Analysis

Prediction Equation	Variables		t Calculated	Confidence Intervals $t_{0.05}$	$t_{0.01}$
Aerodynamic	$r_s=1.2$	$z_o=2.5$	6.8	$5.5<\bar{x}_D<11.2$	$4.3<\bar{x}_D<12.4$
		$z_o=1.7$	21.9	$7.5<\bar{x}_D<9.2$	$7.1<\bar{x}_D<9.6$
	$r_s=2.0$	$z_o=2.5$	27.2	$9.1<\bar{x}_D<10.8$	$8.8<\bar{x}_D<11.1$
		$z_o=1.7$	27.9	$10.3<\bar{x}_D<12.1$	$9.9<\bar{x}_D<12.5$
Free Convection	$r_s=2.0$		1.8	$-1.0<\bar{x}_D<0.1$	$-1.2\bar{x}_D<0.4$
	$r_s=1.2$		3.1	$-1.3<\bar{x}_D<0.0$	$-1.5<\bar{x}_D<0.0$

$t_{0.05} = 2.26$ $t_{0.01} = 3.25$

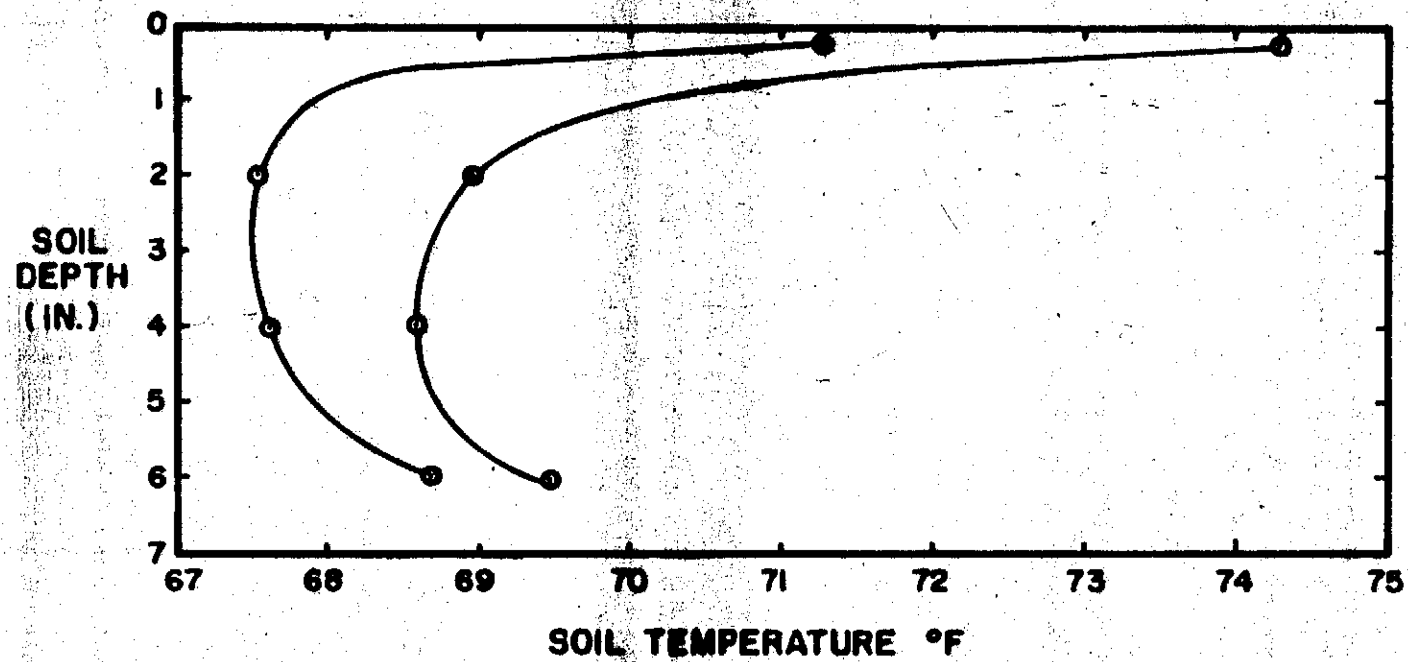


FIG. 14 ANALYSIS OF SOIL HEAT LOSS, AT TWO TIMES

curves represented beginning and ending soil temperature profiles. This temperature difference was multiplied by a specific heat for Maury silt loam calculated by a method described by Van Wijk to give an estimate of heat loss per square centimeter during the observation (22). This result was divided by the lapsed time between the third temperature cycle from the beginning and the third temperature cycle from the end of the observation. Results of this investigation are shown in the Appendix. Soil heat gain during the observation ranged from less than 0.01 to 0.06 cal/cm^2 min. Consideration of this soil heat gain would have lowered leaf temperature predictions by at most 0.2°C.

CHAPTER VI

SUMMARY AND CONCLUSION

Prediction equations were derived for the calculation of leaf temperature under natural conditions. The equations were based on two different modes of convective heat transfer, forced convection and free convection. Both equations consider heat transfer from the leaf to the bulk canopy air and from the bulk canopy air into the atmosphere. Values for leaf boundary layer resistance and leaf stomatal resistance were obtained from literature. Leaf boundary layer resistance was considered to be negligible and hence was neglected. Zero displacement height and roughness height values were obtained from computer analysis of measured wind speed profiles. The average value of computed roughness height agreed closely with the one-tenth canopy height value. Richardson numbers calculated from wind speed temperature profiles indicated that heat transfer was in the free convection regime. Results from analysis appear in Table 6.

Prediction of leaf temperature with the aerodynamic prediction was completed using 1.2 and 2.0 sec/cm stomatal resistance values and 1.7 and 2.5 cm roughness height values. The value of 1.7 cm derived from computation and 2.5 cm equal to one-tenth of maximum approximate crop height. Predicted aerodynamic equation temperatures were at least 6°C larger than observed values. Best results were obtained with a roughness height of 2.5 cm and a stomatal resistance value of 1.2 cm/sec. High prediction values were explained by the presence of buoyancy forces which enhance sensible and latent heat transfer.

Prediction from the free convection equation agreed closely with observed leaf temperature values. Confidence intervals with the t-test revealed prediction at the 99 percent level would be between 1.5°C below the observed leaf temperature for the poorest results. Stomatal resistance values of 1.2 and 2.0 sec/cm were used.

Based on the results, the following conclusions were drawn:

1. The aerodynamic prediction equation derived to define forced convection under natural conditions overpredicts leaf temperature when Richardson number indicates heat transfer in the free convection regime.
2. The free convection prediction equation derived to define heat transfer with free convection accurately predicts leaf temperature under most natural conditions.

For further work in the immediate subject area the following is suggested:

1. Refinement of instrumentation, primarily continuous readout of required data in a form available for computer reduction and analysis.
2. Addition of more data collection points in the profile; the five used lacked good continuity.
3. Installation of lysimeters to check evaporation that could be calculated by use of one of the two right hand terms in the prediction equation.
4. Use of a stomatal resistance meter to get an accurate value of stomatal resistance.

APPENDIX

TABLE 6

EXPERIMENTAL DATA

Test	1	2	3	4	5	6	7	8	9	10
Dry Bulb Temperature °C										
320.5 cm	26.4	28.7	22.8	26.2	27.2	22.7	26.9	25.3	28.0	28.8
183.1 cm	26.4	28.8	23.6	26.5	27.6	23.3	27.3	25.5	28.3	29.1
101.2 cm	27.2	29.0	23.9	26.8	27.8	23.8	27.8	26.4	28.8	29.5
70.7 cm	27.9	29.1	24.0	26.8	27.8	24.1	28.1	27.0	29.2	29.8
45.1 cm	28.6	29.2	24.6	27.1	28.0	25.1	28.2	27.7	29.6	30.1
22.0 cm	28.6	27.6	25.0	27.0	27.7	25.6	28.3	27.7	29.5	29.2
Wet Bulb Temperature °C										
320.5 cm	23.9	24.4	18.7	21.1	22.2	19.4	21.5	21.2	22.3	23.0
183.1 cm	23.6	24.1	18.3	20.5	21.8	19.2	21.5	21.1	22.0	22.3
101.2 cm	24.1	24.3	18.8	21.0	22.3	19.9	22.0	21.9	23.0	23.6
70.7 cm	24.7	24.9	19.3	21.5	22.9	20.2	22.7	22.7	24.1	24.9
45.1 cm	25.4	25.1	19.9	21.8	23.1	21.0	23.0	22.5	24.0	24.3
22.0 cm	26.0	25.7	20.4	22.6	23.7	21.6	23.7	23.5	24.9	24.5

TABLE 6 (Continued)

Test	1	2	3	4	5	6	7	8	9	10
Wind Velocity cm/sec.										
320.5 cm	128.0	231.6	280.4	262.1	228.6	167.6	274.3	216.4	176.8	211.2
183.1 cm	101.5	210.3	292.6	231.6	243.8	158.5	249.9	210.3	140.2	210.2
101.2 cm	103.6	176.8	249.9	210.3	176.8	146.3	182.9	176.8	134.1	146.3
70.7 cm	94.5	155.4	219.5	143.3	112.8	131.1	146.3	140.2	112.8	134.1
45.1 cm	57.9	115.8	109.7	97.5	67.1	85.3	115.8	100.6	70.1	79.25
Net Radiation ly/min.	0.62	0.83	0.76	0.89	0.75	0.62	0.89	0.72	0.87	0.64

TABLE 7

EXPERIMENTAL DATA

Test	1	2	3	4	5	6	7	8	9	10
Avg. Richardson Number	-8.27	-0.04	-0.61	-0.12	-0.29	-1.02	-0.09	-1.08	-1.14	-0.43
Zero Displacement Height cm	43.45	30.82	44.65	34.71	34.84	43.84	8.15	36.60	37.92	35.10
Roughness Height cm	0.014	0.735	0.010	1.623	3.296	0.005	8.980	0.518	0.539	1.430
Observed T_L °C	29.5	31.1	25.1	28.5	29.3	26.7	30.1	28.9	31.3	30.7
Aerodynamic Prediction T_L °C										
d=35 Z_o=1.7 r_s=1.2	39.7	39.6	33.6	37.7	37.3	35.1	37.7	36.3	41.1	36.8
r_s=2.0	42.3	42.5	36.2	40.7	40.0	37.7	40.4	39.0	44.3	39.5
Z_o=2.5 r_s=1.2	38.6	38.6	32.6	36.7	36.3	34.0	36.7	35.3	39.9	36.0
r_s=2.0	41.1	41.4	35.0	39.5	39.0	36.5	39.6	37.8	43.1	38.6
Free Convection Prodiction T_L °C										
d=35 r_s=1.2	28.3	30.9	25.1	28.6	29.2	24.7	29.3	27.2	30.2	30.4
r_s=2.0	28.5	31.2	25.3	28.9	29.5	24.9	29.6	27.5	30.5	30.9

TABLE 7 (Continued)

Test	1	2	3	4	5	6	7	8	9	10
Values corrected for Soil Heat Loss										
r_s=1.2	28.3	30.8	24.9	28.6	29.0	24.6	29.2	27.2	30.1	30.4
r_s=2.0	28.5	31.2	25.2	28.9	29.4	24.8	29.5	27.4	30.4	30.9
Soil Heat Gain ly/min	0.01	0.01	0.06	0.00	0.06	0.02	0.03	0.02	0.04	0.00

TABLE 8

EXPERIMENTAL DATA

Test	1	2	3	4	5	6	7	8	9	10
Dry Bulb Temperature °C 457.5 cm	28.2	29.4	28.1	26.8	28.3	24.7	27.7	27.5	29.2	30.6
Wet Bulb Temperature °C 457.5 cm	23.5	24.2	18.7	20.8	22.0	19.2	21.3	21.1	22.2	22.6
Wind Velocity (cm/sec) 457.5 cm	125.9	179.8	387.1	222.5	207.3	210.3	329.2	293.8	182.9	253.0

A, B	=	constants
C_p	=	specific heat of dry air at constant pressure
D	=	diffusivity of sensible heat
D_t	=	diffusivity of water vapor
D_*	=	leaf dimension in wind direction
E	=	evaporation
H_l	=	latent heat transfer
H_r	=	radiant heat transfer
H_s	=	sensible heat transfer
K_h	=	turbulent transfer coefficient for heat
K_m	=	turbulent transfer coefficient for momentum
K_v	=	turbulent transfer coefficient for mass
L	=	latent heat of vaporization
P	=	atmospheric pressure
Q_{abs}	=	net short wave radiation
R	=	natural gas constant for water vapor
R_i	=	incoming solar radiation
R_*	=	Richardson number
T_a	=	temperature of the air at reference height
T_b	=	temperature of the air at the top of the boundary layer
T_L	=	leaf temperature

T_S = temperature of the leaf surface

$\bar{T}$ = average temperature of the layer

Z = reference height

Z_o = roughness height

d = zero displacement height

e = water vapor pressure

e_a = water vapor pressure at reference height

e_b = water vapor pressure at the top of the boundary layer

e_s = saturation vapor pressure of the substomatal evaporating surface

g = acceleration of gravity

k = Von Karman Constant

k_1, k_2 = constants

q = specific humidity

q_a = specific humidity of the air at reference height

q_b = specific humidity of the air at the top of the boundary layer

q_s = specific humidity of the substomtal evaporating surface

r. h. = relative humidity of the air at reference height

r_a = boundary layer resistance

r_s = stomatal resistance

u = wind velocity at reference height

u_* = friction velocity

w = dimension of the leaf transverse to the wind

δ	=	boundary layer thickness
ϵ	=	emissivity
ρ	=	density of dry air
σ	=	Stefan-Boltzmann Constant
τ	=	Shear
τ_o	=	surface shear
ψ	=	water vapor concentration

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