

T H E S I S

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EFFECT OF DEPTH OF WATER TABLE  
ON EVAPORATION FROM FINE SAND

Submitted by  
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In partial fulfillment of the requirements  
for the Degree of Master of Science  
Colorado State University  
Fort Collins, Colorado

October 1957

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ENTITLED EFFECT OF DEPTH OF WATER TABLE  
ON EVAPORATION FROM FINE SAND  
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## Chapter I

### INTRODUCTION

As new uses for water are devised and as the population of the world continues to increase, men are becoming more conscious of the growing need for the conservation of water. If man is to continue to progress, more economical methods for the use of fresh water must be developed.

Fresh water is obtained either directly or indirectly from the rain which falls on the lands. Much of this water is not utilized because it is lost through evaporation before man is able to derive any useful service from it. Because water is often stored in open reservoirs, the problem of evaporation from a free water surface has attracted much attention. Probably a greater amount of useful water is lost through evaporation from soils, but there have not been as many systematic investigations concerning this problem.

This thesis is concerned with the rate of evaporation from soils and some of the variables which influences this rate. It is a preliminary study which is part of a comprehensive investigation of evaporation from soils.

Because this is a preliminary study, an attempt was made to reduce the complexity of the experimental set up, and for this reason the soil chosen for the study was a fine sand from which most of the clay fraction has been removed.

### Problem

How is the rate of evaporation related to the depth of the water table, and to what extent is the relationship influenced by the severity of the ambient evaporating conditions? What soil properties influence the interrelation between water table depth and evaporation rates, and how can these properties be evaluated?

### Analysis of Problem

Since the above problem will require years for its complete investigation with respect to all ambient conditions, water table depths, saturation histories, and soil types, this investigation has been confined to determining answers to the following questions:

1. How is the evaporation rate from a fine sand affected by independently varying the wind velocity and the depth of the water table?
2. Can the functional relationship between evaporation rates under specified ambient conditions and the depth of water table be related to easily measurable properties of the sand?

### Delimitations

A. The facilities of the wind tunnel place the following limitations on the investigation:

1. The maximum wind velocity will be 50 feet per second.
2. The water table will have a maximum depth of 42 inches.
3. There will be no control over the ambient temperature or ambient humidity.

B. For the initial phase of this problem the investigation will deal only with a fine sand from which the original clay fraction has been removed.

C. The surface will be maintained relatively smooth and level with the floor of the tunnel.

D. All evaporation measurements will be made on the drainage cycle. In other words, the sand will be initially saturated and then allowed to drain with the water table at particular depths.

### Definition of terms as used in this thesis

Pore volume -- The volume of a porous solid which is occupied by a mobile fluid.

Saturation -- The fraction or percentage of the pore volume which is occupied by a particular fluid phase.

Wetting phase -- That fluid phase which tends to be preferentially adsorbed by the solid surfaces and is at a lower pressure than other fluid phases that may occupy the same porous solid.

Non-wetting phase -- A fluid phase which is not preferentially adsorbed and is at a higher pressure than a wetting phase occupying the same porous solid.

Permeability -- A measure of the ability of a porous solid to transmit a fluid under a specified potential gradient. It is obtained from an equation relating the volume flux across an unit area of a porous solid to the potential gradient perpendicular to the unit area, the effect of viscosity being accounted for by a viscosity term in the equation. Usually the term permeability is used in reference to a system saturated with only one fluid phase unless it is preceded by the word "effective".

Hydraulic conductivity -- The ratio of the volume flux to the hydraulic gradient normal to a specified plane within a porous solid. Hydraulic conductivity is a function of the viscosity of the fluid as well as of properties of the porous solid. It usually refers to a system saturated with only one fluid phase unless preceded by the word "effective".

Effective Permeability -- This term has a meaning similar to permeability except that it refers to the permeability of a porous solid for a particular fluid phase when the pores of the solid contain more than one fluid phase, i.e., water and air.

Effective hydraulic conductivity -- This term is related to hydraulic conductivity in the same way that effective permeability is related to permeability.

Relative permeability -- The ratio of the effective permeability for a particular fluid phase to the permeability. The relative permeability will be a function of the saturation of the specified phase as well as of properties of the porous solid.

Residual saturation -- The saturation obtained by extrapolating the curve of non-wetting phase relative permeability to unity ignoring the convex portion of the measured curve which approaches unity. The residual saturation is expressed in terms of the wetting phase saturation. The relative permeability of the wetting phase at the residual saturation is very small, usually less than one percent.

Moisture equivalent -- The moisture content in an initially saturated soil sample after it is subjected

to a centrifugal force 1000 times that of the gravitational force.

Effective saturation -- The ratio  $\frac{S - S_r}{1 - S_r}$  where  $S$  is a particular wetting phase saturation and  $S_r$  is the residual saturation, both terms being expressed as fractions.

Desaturation -- The displacement of a wetting phase by a non-wetting phase, i.e., water being displaced by air.

Saturation history -- The process by which a porous solid has reached its present state of saturation, i.e., drainage or imbibition cycles or combinations of these.

Drainage cycle -- A saturation history in which a porous solid initially saturated 100% with a wetting phase is desaturated.

Imbibition cycle -- A saturation history in which a porous solid initially containing a non-wetting phase, imbibes a wetting phase as a result of capillarity.

Capillary pressure -- The difference in pressure across interfaces of separate fluid phases caused by interfacial forces. A non-wetting phase is at a higher pressure than a wetting phase.

Displacement pressure -- The capillary pressure for a

porous solid saturated with a single wetting phase which is just sufficient to initiate displacement of the wetting phase by a non-wetting phase. The displacement pressure is a property of the fluids involved as well as of the porous solid.

Air-entry pressure -- The displacement pressure when the wetting phase is water and the non-wetting phase is air.

Water table -- The locus of points where the capillary pressure across air-water interfaces is zero.

Free water surface -- A water table which is exposed to the ambient atmosphere, i.e., the surface of a lake or the surface of water in a large open container.

Barrier (semi-permeable) -- A porous solid which has a displacement pressure higher than the material with which it is in contact. Semi-permeable barriers are used to make tensiometers and similar equipment. They are called "semi-permeable" because they permit the passage of a wetting phase but not of a non-wetting phase.

Tortuosity -- The square of the ratio of the mean length of the actual flow path of a particular fluid phase to the corresponding distance between two points within a porous solid. The tortuosity

is a function of the saturation of the particular phase and the saturation history as well as of properties of the porous solid.

Moisture content -- The mass of water expressed as a percentage of the mass of dry soil within which the water is retained.

Unsaturated flow -- A term used by soil scientists which refers to the flow of water in a soil the pores of which also contain more or less air.

<u>Symbols</u>	<u>Definition</u>	<u>Dimensions</u>
b	exponent	dimensionless
e	rate of evaporation	L/T
e <sub>s</sub>	rate of evaporation from a soil surface when the water table is maintained at a constant level	L/T
e <sub>f</sub>	rate of evaporation from a free water surface	L/T
h	hydraulic head	L
w	specific weight of water	F/L <sup>3</sup>
z	elevation above the water table	L
z <sub>0</sub>	plane where the pressure of the water is zero	L
z <sub>1</sub>	elevation of plane at the top of the fully saturated zone	L
z <sub>2</sub>	elevation of plane at which the soil moisture is at field capacity	L
z <sub>3</sub>	elevation of plane above z <sub>2</sub>	L

<u>Symbols</u>	<u>Definition</u>	<u>Dimensions</u>
$C'$	constant of integration	not specified
$C$	hydraulic conductivity	$L/T$
$C_e$	effective hydraulic conductivity	$L/T$
$K_{rw}$	relative permeability of the wetting phase	dimensionless
$P_c$	capillary pressure	$F/L^2$
$P_D$	displacement pressure	$F/L^2$
$P_w$	water pressure	$F/L^2$
$S$	saturation	dimensionless
$S_e$	effective saturation	dimensionless
$S_r$	residual saturation	dimensionless
$\mu$	micron	$L$

## Chapter II

### REVIEW OF LITERATURE

Agriculturists in arid regions have been concerned for many decades with the conservation of soil moisture for plant growth. Loss of moisture from soils as high as seventy-five percent of the total precipitation has been attributed to evaporation. In the last 20 years great strides have been made in acquiring knowledge concerning the mechanism of evaporation from a free water surface. This information is now being utilized in studying the fundamental principles of the mechanism of evaporation from soils.

This chapter is concerned with methods of measurement and theories relative to evaporation from a free water surface, investigations of the factors affecting evaporation from soils, and equipment for measuring these factors.

#### Methods of Measuring Evaporation

Four methods (1:2) exist for determining the evaporation from a large body of water. One procedure (30:50) is known as the water budget method which is based on a material balance or conservation of matter. The

water budget method is often inaccurate due to the difficulties of measuring the inflow, outflow, and storage capacity with sufficient precision. A second procedure involves the use of evaporation pans to measure the rate of evaporation from the water surface. Much has been done to correlate evaporation from pans to that from lakes (40:31-33), but the "pan coefficients" used for this correlation have been determined under experimental conditions which often do not exist in the field. A third procedure, the energy budget method, applies the principle of conservation of energy in determining the energy available for evaporation. The fourth method is the mass-transfer method in which the evaporation rates are related to the diffusion characteristics of the atmospheric surface layer. These last two methods are discussed more fully below.

Energy-budget method. -- Anderson, Anderson, and Marciano (1:42) suggested an energy equation which is similar to an equation previously presented by Cummings (12). The equation of Anderson, Anderson, and Marciano is given as

$$Q_e = \frac{Q_s - Q_r - Q_b + Q_v + Q_p}{1 + R}$$

Here  $Q_e$  refers to energy used for evaporation,  $Q_s$  solar radiation,  $Q_r$  reflected solar radiation,  $Q_b$  effective

back radiation,  $Q_v$  energy advected into or out of a body of water,  $Q_p$  energy stored in the body of water, and  $R$  the Bowen ratio. Bowen's ratio (2) is defined as the ratio of the energy conducted away from the water surface as sensible heat to the energy used for evaporation. The effect of the wind velocity is eliminated when the Bowen ratio is incorporated in the equation. If this ratio is not used, a term for wind velocity would have to appear in the equation.

Mass-transfer method. -- The mass-transfer method (1:3-36) is based on evaluation of the parameters involved in the movement of water vapor away from the surface of the water. The variables involved in this phenomenon include the wind velocity, wind turbulence, temperature, humidity, and their gradients. The gradients of the variables for the laminar portion of the boundary layer will differ greatly from that of the turbulent portion, being steeper for the laminar sublayer than for the turbulent region. The wind speed, temperature, and humidity vary almost linearly with the height above the surface in the laminar sublayer and linearly with the logarithm of the height above the surface in the turbulent layer. Water vapor is transferred in the laminar layer mostly by molecular diffusion and in the turbulent layer by mass movement. The turbulent diffusion coefficient is approximately a thousand times greater than the molecular

diffusion coefficient (7:59). The boundary surface is either hydrodynamically smooth or rough depending on the relative thickness of the laminar sublayer and a characteristic height which evaluates the roughness (36, 37, 42). The laminar sublayer acts as a barrier to evaporation, while evaporation is much greater from a hydrodynamically rough surface where the laminar sublayer is practically non-existent. Two theories have been proposed regarding the mixing of gaseous vapor in the turbulent layer, i.e., Sutton's (37) continuous mixing theory and Prandtl's (31) mixing length concept.

The Reynold's analogy (7:7-14) has been used to relate an evaporation coefficient to the drag coefficient.

#### Investigation of Evaporation from Soils

Thorntwaite and Holzman (38:14-22) used Prandtl's mixing length concept and both Prandtl's and von Kármán's (42) logarithmic wind equations to derive an equation for evaporation from land and water surfaces. The total evaporation for an interval of time was expressed as

$$E = \frac{0.063 k_o^2 (\rho_{w_1} - \rho_{w_2}) (u_2 - u_1)}{\left(\log_e \frac{z_2}{z_1}\right)^2}$$

with E referring to the total evaporation for an interval of time,  $\rho_{w_1}$  and  $\rho_{w_2}$  to the average absolute humidities

at heights  $z_1$  and  $z_2$  above the surface,  $u_1$  and  $u_2$  to the wind velocity at heights  $z_1$  and  $z_2$  respectively, and  $k_0$  to von Kármán's universal constant. The variables of this equation include only those pertaining to the ambient atmospheric environment, and do not include those pertaining to the effects of the soil-water regime.

Many of the early investigations of evaporation from soils deal with methods of reducing evaporation loss and not on the fundamentals of the process of evaporation. Some of these early studies have resulted in many misleading assumptions and concepts concerning the factors governing evaporation. This section of the chapter deals with investigations of the factors which affect the rate of evaporation from soils.

Evaporation stages. -- Koliasev (24) has visualized evaporation from soil as occurring in three stages. He theorized that the rapid rate of evaporation from a near-saturated soil, the first stage, was governed by the ambient atmospheric conditions. Under these conditions the factors that influence the evaporation from a free water surface also control the evaporation from the soil, and the rate of evaporation from both are practically the same. The pertinent variables in the first stage are the wind speed, vapor pressure gradient, air temperature, and radiation.

The second stage described by Koliasev is the stage during which the rate of evaporation rapidly declines. During this stage the surface layer dries because the flow of moisture from the water table is less than the rate of evaporation. In other words, the internal factors of the soil, which had a negligible effect in the first stage, have a significant influence during the second stage.

According to Koliasev, the last stage is governed by the molecular attraction that the soil particles have for water which results in a slow decline in the rate of evaporation. The water film around each particle of soil is attracted so strongly that an extensive amount of energy would be required to evaporate the water.

Koliasev, in his studies, was concerned with shortening the first stage of evaporation in order to reduce the total amount of evaporation from the soil. His investigation revealed that stratified layers in the soil profile interrupted the capillary continuity, thereby reducing the moisture content in the loose layers and increasing the moisture held in the compacted layers which prohibits moisture moving readily to the surface either by liquid flow or gaseous diffusion. By the use of surface active additives he was able to reduce the moisture in the surface layer causing a dry layer to form which acted as a barrier to liquid flow. Koliasev also investigated

the affects of the height and spacing of wind-breakers on reducing the evaporation loss caused by winds.

Some of the work performed by Koliasev has been duplicated and verified by Lemon (26).

Effect of wind velocity. -- Harris and Robinson (21:449) and Kucera (25) in separate papers reported that evaporation rates increased with wind velocity up to 10 miles per hour beyond which increased velocities produced negligible increase in the rate of evaporation.

Turnage and Shreve (39) reported that in their experiments the rate of depletion of soil moisture increased only slightly with wind speeds greater than five miles per hour. Turnage and Shreve also stated that evaporation appears to be mainly a function of humidity and wind speed.

Effect of surface conditions. -- King (23) advocated strip cropping or planting of trees and shrubs in rows as windbreakers every 18 or 20 rods to reduce moisture loss caused by winds. From studies conducted in Wisconsin, he showed that evaporation rates due to wind were 30 per cent less 20 feet from a hedgerow than 30 feet away.

With a portable wind tunnel, Zingg, Woodruff, and Englehorn (45) conducted experiments on the effects of the orientation of windrows on the erodibility of land. They noted that along with reducing erodibility a saving of soil moisture was accomplished by plowing the field perpendicular to the direction of the prevailing winds.

In more recent work Woodruff (43:16) showed that the evaporation loss was reduced for a distance of 20 times the height of the wind barrier on the leeward side.

Effect of relative humidity. -- Harris and Robinson (21:447) performed research on the effect of relative humidity on evaporation. They were able to show by passing saturated air over a soil column that evaporation was less than when unsaturated air was passed over the column.

According to Cummings (11) there is no strong correlation between evaporation and humidity. In his study, he derived an equation evaluating the rates of change of evaporation with vapor pressure and eliminating the effects of insolation. The strong correlation which does exist between insolation and evaporation masks the small effect that changes of humidity have on evaporation changes.

Fukuda (15) studied humidity in terms of vapor diffusion in the soil profile. He observed that when the relative humidity was less than 100 per cent that it fluctuated considerably within a 24-hour period. He also observed that evaporation occurs first at the ground surface and afterwards at gradually increasing depths. When night comes, condensation occurs at the surface and proceeds in the same cycle as the evaporation had followed during the day.

Effect of radiation. -- Several investigators (3, 21, 29) have studied the effect of radiation on evaporation. Penman (29) compared the rate of evaporation of soils under simulated summer conditions (high radiation) with those under isothermal conditions. The columns were kept in a room with controlled atmospheric conditions and several columns were exposed to controlled radiation for eight hours each day. The columns were under free drainage. He observed that evaporation from the columns receiving radiation was very high until the surface dried. Evaporation after the surface crust had formed was slight. The total evaporation from the column under simulated summer conditions was less than the evaporation from the isothermal columns.

Effect of temperature. -- The response of water in soil to a temperature gradient was studied by Gurr, Marshall, and Hutton (20). The water in the warm end of a horizontal closed soil column vaporized and flowed toward the cool end. There the water vapor condensed creating a pressure gradient causing the liquid to flow towards the warm end where the water continued to vaporize.

Effect of water table. -- The effect of the depth of water table was studied by Ridgaway (35) at the Wyoming Agricultural Experiment Station. Steel cylinders were driven into the ground and were equipped for controlling the water table within certain limits. In comparing

evaporation from the soil with that of a free water surface he observed that where the water table was at a depth of 18 inches evaporation was 50 percent of that from a free water surface and when it was at a depth of 22 inches it was 35 percent. Ridgeway reported the chemical analysis of the top 18 inches of the soil where the columns were placed. A mechanical analysis was not given.

Effect of particles size and moisture content. --

Work has been performed by several investigators (3,21) on the effect of particle size and moisture content on the rate of evaporation. The majority have concluded that as the ratio of the surface area to the volume of the particles increases the rate of evaporation increases, other factors being held constant. As the moisture content of the soil is increased, it was found that the rate of evaporation increases. This increase occurs until a certain moisture content (usually between 25 and 30 percent) is reached after which the rate of evaporation becomes approximately constant (21:444).

Veihmeyer and Hendrickson (41) studied the rate of evaporation from wet and dry soils finding that the rates were constant until the moisture content fell below the permanent wilting point. At this moisture content, the rate of evaporation dropped sharply.

Effects of capillary pressure and permeability. --

Buckingham (3) contributed a great deal to the science of

soil physics by his theoretical analysis of capillary flow. He compared the flow of water through soil with that of an electric current flowing through a wire. He attributed the driving force for the flow of water to the different attraction that unequally moist portions of the soil have for water. The term "capillary potential" refers to the work required to move a unit mass of water from a free water surface to a position in the soil above the free water surface.

After the concept of capillary potential was introduced by Buckingham, no serious consideration was given to it until Gardner (16) expanded the concept in 1922. In his investigation, he presented evidence that the capillary potential was a linear function of the reciprocal of the moisture content over a considerable range of capillary potentials. The linear function is expressed by

$$\Psi = \frac{a}{\theta} + b$$

where  $\Psi$  refers to capillary potential,  $\theta$  moisture content and  $a$  and  $b$  are constant. According to the relationship the potential-moisture curve would be hyperbolic in nature.

The functional relationship between permeability and saturation of porous solids has been related to the potential-saturation curve by many investigators (4, 9, 10,

17, 18, 19, 27, 44). Burdine (4) was one of several investigators to relate "relative" permeability to the capillary pressure-desaturation curve. Relative permeability is the ratio of the permeability of an unsaturated soil to the permeability of the soil fully saturated. In measuring the relative permeability of a large number of porous rock cores he noted that the square root of the tortuosity parameter in the Kozeny-Carman equation was a linear function of the fluid saturation. Thus, Burdine was able to calculate the relative permeability of a liquid in a porous media by measuring only capillary pressure-desaturation curves. Burdine's equation may be expressed as

$$K_{rw} = \left( \frac{T}{T_1} \right) \left( \frac{A_1}{A} \right) = S_e^2 \left( \frac{A_1}{A} \right)$$

where

$K_{rw}$  = relative permeability of the wetting phase,

$T$  = tortuosity of the soil sample completely saturated,

$T_1$  = tortuosity of soil sample less than saturated,

$A$  = area under the  $\left( \frac{1}{P} \right)^2$  vs  $S$  curve,

$A_1$  = area under  $\left( \frac{1}{P} \right)^2$  vs  $S$  curve up to the saturation of the soil sample,

$S_e$  = "effective" saturation of the soil sample.

Effective saturation was defined by Corey (9) as

$$S_e = \frac{S - S_r}{1 - S_r}$$

where  $S$  is some saturation greater than  $S_r$  which is the "residual" saturation or saturation at which the permeability becomes very small.

Corey (9) after determining the relative permeability on numerous porous media by using Burdine's method observed that with sufficient accuracy the ratio  $\left(\frac{A}{A}\right)$  was proportional to the square of the effective saturation,  $S_e^2$ . Thus, Corey rewrote Burdine's equation as

$$K_{rw} = S_e^4$$

The work performed by Burdine, Corey, and the other investigators (4, 9, 44) was concerned primarily with porous rock and not with soil. Prior to these investigations Moore (27:410-417) studied the functional relationship between permeability, capillary pressure, and moisture content of soils. He observed that permeability of soil is maximum at, or near, a capillary pressure of zero, or at a saturation of 100 percent. With clays maximum permeability occurred at a moisture content less than saturation due to the swelling of the clays that reduced the pore space when fully saturated. Permeability declined very rapidly with decreasing moisture content and

became very small at the moisture equivalent of the soil. He measured the permeability of soils of various textures over the range of moisture content from saturation to field capacity. His data shows that the relative permeability of sand is higher during the initial stages of desaturation than clay. But before field capacity is reached the relative permeability of sand becomes less than that of clay. He also observed that the moisture content at the wetting front of moisture rising in a dry soil column is at field capacity. He interpreted the moisture content at the wetting front and at which permeability becomes nearly zero as being representative of the moisture content at which the moisture films in the soil become discontinuous.

Recently Gardner (18) has attempted an analytical solution for the steady-state movement of water from a water table during evaporation. Gardner and Fireman (19) have also conducted laboratory studies of evaporation from soil columns in the presence of a water table.

In his analytical approach, Gardner assumed a continuous functional relationship between conductivity and capillary pressure. The function which he used is given by

$$k = \frac{a}{(P_c^n + b)}$$

where  $a$  and  $b$  are constants,  $k$  is the hydraulic con-

ductivity, and  $n$  is a constant which Gardner took to be 2 or 3. He arrived at the values of  $k$  from measurements of outflow from a capillary pressure cell. (17) By means of the empirical equation for  $k$ , Gardner was able to compute maximum evaporation rates as a function of depth to a simulated water table.

In the paper dealing with the laboratory study, data were presented comparing theoretical and experimental rates of evaporation. The agreement was fairly good although some adjustment of the constant  $b$  appearing in the conductivity equation would have given a better fit.

It should be pointed out that Gardner's assumption of a continuous functional relationship between  $k$  and  $P_c$  does not agree with the observations of Corey (9, 10) and others (4, 44). The latter have pointed out that  $k$  does not change with  $P_c$  until  $P_c = P_D$ . Corey has also found that in the high liquid saturation region (low capillary pressures exceeding the displacement pressure) that the relative value of  $k$  varies inversely as the 8th power of  $P_c$ .

Gardner and Fireman's data shown in Fig. 4 of their paper (19) indicates a distinct change in the functional relationship between  $k$  and  $P_c$  at a  $P_c$  of about 1/3-atmosphere (which corresponds roughly to field capacity in most soils). They have drawn curves through the data in such a way as to ignore this change in the

functional relationship. A curve fitting their data better could have been made by using three separate equations for  $k$ , the first applying to the range wherein  $k$  is invariant with  $P_c$ , the second applying to the range between  $P_c = P_D$  and  $P_c$  corresponding to field capacity, and a third for  $P_c$  greater than at field capacity. Their data within the low capillary pressure range is somewhat erratic, however, and definite conclusions about this range is impossible.

At the greater water table depths, Gardner and Fireman obtained good agreement between actual evaporation rates and theoretical rates. Evidently, probable discrepancies between their empirical equation for  $k$  and the actual value of  $k$  in the low tension range did not materially affect the results when most of the resistance to upward flow occurred in the dry soil at the top of long columns.

### Instrumentation

This section of the literature review deals with several kinds of equipment used for measuring the variables in the evaporation equations.

Wind velocity. -- The whirling cup anemometer is probably the most common instrument now used for obtaining the average wind speed in the open air. For wind-tunnel studies where a greater precision is desired, the tungsten

hot-wire anemometer is often used. The construction and circuit for the hot-wire anemometer has been described in a previous publication (5:72-82).

Ambient temperature and relative humidity. --

There are four methods of determining moisture in the atmosphere which are in general use, i.e., (1) the chemical-absorption method, (2) the dew-point method, (3) psychrometric method, and (4) the hygroscopic expansion method. The most common and simplest method is the psychrometric method. The adaptation of this method with the use of thermocouples is discussed by Anderson, Anderson, and Marciano (1:50-54).

Soil temperature. -- Thermometers, thermistors, and thermocouples have been used for obtaining the temperature below the soil surface. Because of simplicity of installation, thermocouples have been used most widely. The construction and characteristic of several types of thermocouples are adequately presented by Dike (13).

Tensiometers. -- Tensiometers are used for measuring the capillary potential in the soil moisture. They were developed by Richards (32) and have since that time been improved upon by him and others, (8, 22, 33, 34). The reader is referred to the references for further information concerning them.

Water-loss measurements. -- For many years the only direct method for determining the water loss due to

evaporation was by noting the change in weight of the container over a time interval. Several years ago Parshall (28) made use of the Mariotte siphon for measuring the volume of water loss due to evaporation and also for controlling the water-table depth. This method seemed to be the best adapted for the present investigation.

Radiation. -- The incoming solar and reflected solar radiation may be measured by an Eppley pyrhelio-  
meter as described by Anderson (1:59). The pyrhelio-  
meter is a standard instrument used by the U.S. Weather Bureau. The measurement of the incoming/terrestrial radiation is accomplished by recording the differences between the readings of the Eppley pyrhelio-  
meter and the Gier and Dunkle flat plate radiometer. The Gier and Dunkle flat plate radiometer was recently developed by Gier, Dunkle, and co-workers (14).

Chapter III  
ANALYSIS OF THE PROBLEM

In the analysis of the problem a soil column is considered that contains a water table somewhere within the column. The column which is initially fully saturated is protected from evaporation and is insulated to eliminate radial temperature gradients. The column is then allowed to drain until water within the entire column is in equilibrium with the water table. At equilibrium, the mechanical potential, temperature, and free energy are everywhere the same. In other words, there is no mass flow or net diffusion occurring in the column after equilibrium has been reached.

When the water table is at a depth such that the fully saturated zone reaches the surface of the column, the capillary pressure  $P_c$  is nowhere greater than the displacement pressure. Capillary pressure  $P_c$  is defined as the difference in pressure,  $P_{air} - P_{water}$ , across the interface of water and air. The capillary pressure at which the air phase is just sufficient to displace the water phase in the largest pores of the soil is defined as the displacement pressure  $P_D$  of the soil. In considering the pressure difference across the air-water interface, the density of the air is considered to be negligible;

therefore, the pressure of the air is everywhere zero. This implies that  $P_c$  is given by  $P_c = -P_w$  where  $P_w$  is the pressure of the water. At the water table  $P_w$  is zero, therefore  $P_c$  is also zero. The pressure of the water decreases with elevation above the water table according to the relation

$$\frac{dP_w}{dz} = -w, \quad (1)$$

where  $w$  is the specific weight of water and  $z$  is the elevation above the water table. Consequently, it follows that

$$\frac{dP_c}{dz} = w. \quad (2)$$

Eqs. 1 and 2 apply to a column at equilibrium.

The hydraulic head  $h$  anywhere in a profile at equilibrium may be expressed as

$$h = z + \frac{P_w}{w} \quad (3)$$

or above the water table by

$$h = z - \frac{P_c}{w}. \quad (4)$$

When the surface of the soil column is exposed to the atmosphere allowing evaporation to take place, upward flow of water is induced. This flow occurs because

$h$  decreases in the upward direction. In the case of evaporation from soils the velocity head will be negligible and therefore, it is permissible to use Eqs. 3 and 4 for this situation.

The law of Darcy may be written in terms of evaporation rates as

$$e = - C \frac{dh}{dz} \quad (5)$$

where  $e$  is the rate of evaporation,  $C$  the hydraulic conductivity, and  $\frac{dh}{dz}$  the hydraulic gradient. By rearranging the terms in Eq. 5 and integrating, the head lost through the fully saturated zone is expressed as

$$h = - \frac{e}{C} z + C' \quad (6)$$

where  $C'$  is the constant of integration and is zero when  $h = 0$  at the water table where  $z$  equals zero.

The hydraulic head at any point is given by Eq. 4. The gradient of  $h$  may be expressed as

$$\frac{dh}{dz} = 1 - \frac{d(P_c/w)}{dz} \quad (7)$$

By substituting Eq. 5 into Eq. 7,

$$- \frac{e}{C} = 1 - \frac{d(P_c/w)}{dz} \quad (8)$$

Rearranging the terms and expressing the equation in terms of an integral gives

$$P_c/w = \left(1 + \frac{e}{C}\right) \int_{z_0}^{z_1} dz . \quad (9)$$

Defining  $z_0$  as zero, then

$$P_c/w = \left(1 + \frac{e}{C}\right) z_1 . \quad (10)$$

This is the equation for determining  $P_c$  in the fully saturated zone where  $P_c$  is a linear function of  $z$ . When  $P_c$  is greater than  $P_D$ , Eq. 10 does not apply.

When  $P_c > P_D$ , the hydraulic conductivity varies with the moisture content (27). Data presented by Burdine (4) and Corey (10) imply that for  $P_c$  less than that corresponding to field capacity but greater than  $P_D$

$$C_e \approx C \left(\frac{P_D}{P_c}\right)^8 \quad (11)$$

where  $C_e$  is the effective hydraulic conductivity applicable to unsaturated flow. Replacing  $C$  in Eq. 5 by the expression for  $C_e$ , the hydraulic gradient immediately above the saturated zone may be expressed by

$$\frac{dh}{dz} \approx - \frac{e}{C} \left(\frac{P_c}{P_D}\right)^8 . \quad (12)$$

Eq. 7 satisfies all points. Substituting Eq. 12 into Eq. 7 and rearranging the terms gives

$$\frac{d(P_c/w)}{dz} \approx 1 + \frac{e}{C} \left( \frac{P_c}{P_D} \right)^8 \quad (13)$$

For a particular soil and evaporation rate the only variables are  $P_c$  and  $z$ . Since the exponent for the parameter  $\frac{P_c}{P_D}$  is 8, there is no simple solution in closed form.

Eq. 13 may be solved by a numerical method but before discussing the details of this it is desired to rewrite the equation in terms of reduced (dimensionless) variables which will not change its validity. Multiplying both top and bottom of the left side of Eq. 13 by  $P_D$  and rearranging the terms gives

$$\frac{d(P_c/P_D)}{d(z/\frac{P_D}{w})} \approx 1 + \frac{e}{C} \left( \frac{P_c}{P_D} \right)^8 \quad (14)$$

This equation applies when the datum is taken at the top of the fully saturated zone and for moisture contents greater than field capacity.

Eq. 14 can easily be solved by making a plot of  $P_c/P_D$  vs  $z/\frac{P_D}{w}$ . The value of  $z/\frac{P_D}{w}$  is computed at the point where  $P_c = P_D$ . Examination of Eq. 14 will

reveal that the slope of the curve at this point is  $1 + \frac{e}{C}$  (usually only slightly greater than 1). A short tangent to the curve is plotted from which another value of  $z / \frac{P_D}{W}$  is obtained to calculate the value of the slope at this point. The slope at this point is extended a short distance to obtain new values of  $z / \frac{P_D}{W}$  and  $\frac{P_c}{P_D}$ , etc. If the tangent at these points are extended only a very short distance the error will be negligible. Fig. 1 presents solutions for arbitrary values of  $\frac{e}{C}$ .

For moisture contents below field capacity the same type of equation can be developed, i.e.,

$$\frac{d(P_c/P_D)}{d(z/\frac{P_D}{W})} \approx 1 + \frac{e}{C} \left(\frac{P_c}{P_D}\right)^b \quad (15)$$

The data of Gardner (18) and Gardner and Fireman (19) indicate that the value of  $b$  is between 2 and 3. The method of numerical solution used for Eq. 14 may be used for Eq. 15.

Eqs. 10, 13, and 15 may be combined to give  $h$  at any point in the soil profile (when  $h = 0$  at the water table) as

$$h = -\frac{e}{C} \int_0^{z_1} dz - \frac{e}{C} \int_{z_1}^{z_2} \left(\frac{P_c}{P_D}\right)^b dz - \frac{e}{C} \int_{z_2}^{z_3} \left(\frac{P_c}{P_D}\right)^b dz \quad (16)$$

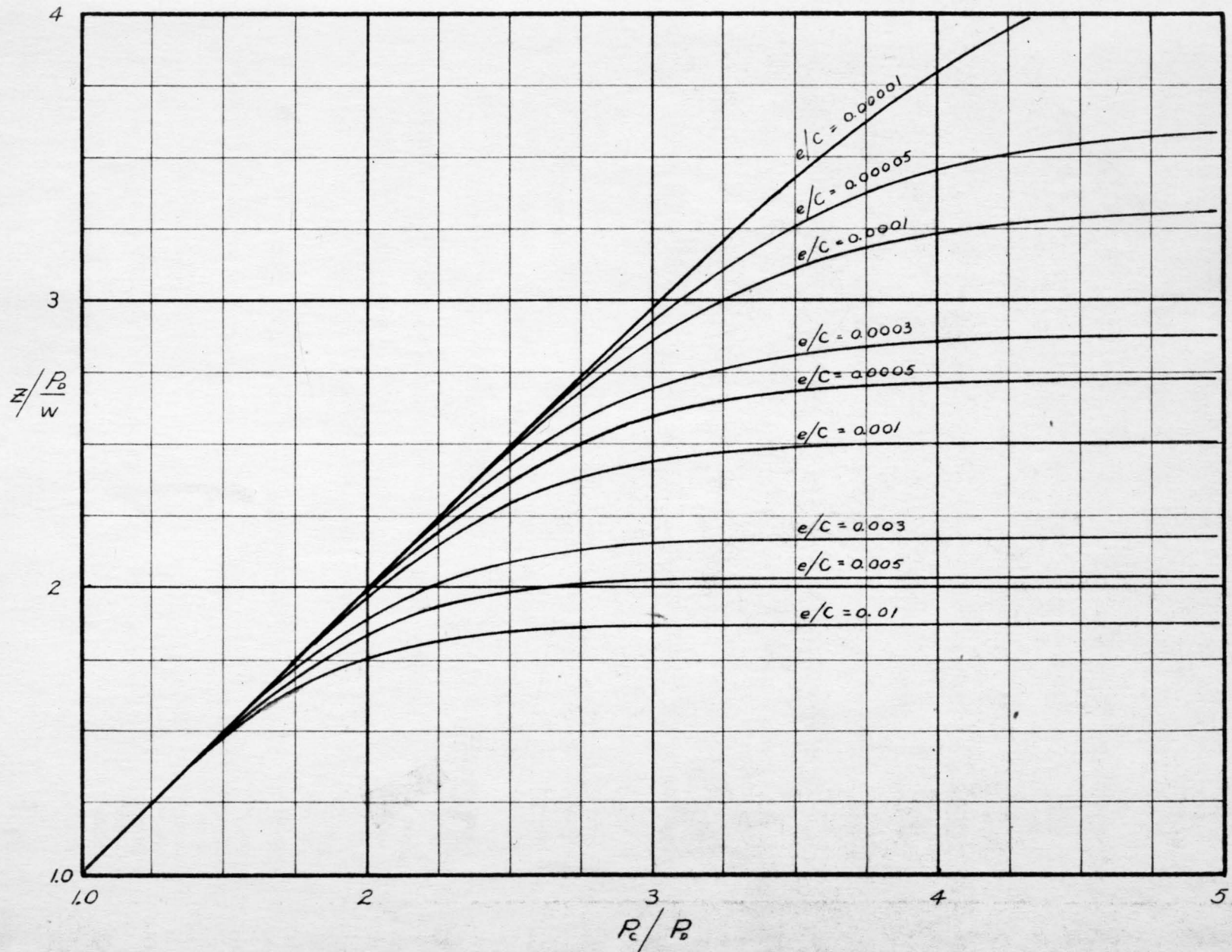


Figure 1 - Computed relationship between the parameters  $\frac{z}{P_0/w}$  and  $\frac{R_c}{P_0}$  for various values of  $e/C$ .

where  $z_1$  is the elevation at the top of the saturated zone,  $z_2$  is the elevation of the plane at which the soil moisture is at field capacity, and  $z_3$  is the elevation at some point above the plane of field capacity.

Though Eq. 16 is believed to be an approximate equation which could apply to all ranges of  $P_c$ , it will be assumed that a tensiometer could always be located in a region above the water table where the soil does not reach a moisture content less than field capacity. Consequently, this analysis will deal primarily with the first two integrals in Eq. 16 and particularly with Eq. 14.

It would have been possible to have arrived at the same set of dimensionless variables by dimensional considerations alone. The parameters,  $\frac{P_c}{P_D}$ ,  $z/\frac{P_D}{w}$ , and  $\frac{e}{C}$ , include all variables that would be included in a dimensional analysis of the problem, i.e.,

$$f(P_c, P_D, z, w, e, C) = 0. \quad (17)$$

The pertinent soil variables are accounted for in the variables  $P_c$ ,  $P_D$ ,  $z$ , and  $C$ ; the fluid variables are accounted for by  $w$  and  $C$ ; the ambient variables are accounted for indirectly by  $e$  in relation to all the other variables.

According to the Buckingham  $\pi$  Theorem these variables could be replaced by three dimensionless parameters involving the given set of six variables. The

three parameters arrived at by the analytical procedure previously described constitute one permissible set of dimensionless parameters out of a large number of such sets.

The set chosen is entirely rational and its significance is easily visualized. For example, the constant  $P_D/w$  which is used to scale the elevation above the water table represents the elevation at the top of the fully saturated zone; in other words, it is the  $z_1$  of Eq. 16. The parameter  $\frac{e}{C}$  is the evaporation rate divided by the hydraulic conductivity, and surely the pressure distribution and the resulting saturation distribution are affected by the evaporation rate in relation to the hydraulic conductivity. In the parameter  $P_c/P_D$ , the  $P_D$  which is a constant for a given soil serves as a scaling factor which accounts for gross differences in the functional relationship between  $P_c$  and  $C_e$  (effective hydraulic conductivity) for individual soils (10).

It is hoped that the experimental procedure will give results permitting an evaluation of Eq. 14, and that a valid functional relationship between the parameters  $P_c/P_D$ ,  $z/\frac{P_D}{w}$ , and  $e/C$  can eventually be established. If this objective could be realized, it should be possible to estimate average rates of evaporation from soils in contact with a water table by means

of tensiometers placed at strategic elevations above the water table and by measuring certain soil characteristics. These soil characteristics are the hydraulic conductivity when the soil is fully saturated and the capillary pressure-desaturation curves (9).

## Chapter IV

## EXPERIMENTAL EQUIPMENT AND PROCEDURE

The equipment described in this chapter is generally that which was specifically designed for this study. Only brief mention is made of the other equipment since a full description of it has appeared in previous literature (5, 6).

Experimental Equipment

Wind tunnel.--The investigation was conducted in the 6-ft. x 6-ft. test section of the wind tunnel of Colorado State University (5:49-107). A hot-wire anemometer, attached to a traversing mechanism, was used to measure the wind velocity and to obtain the profile of the boundary layer. Wet and dry-bulb thermocouples were also mounted on the traversing mechanism to measure the relative humidity. The traversing mechanism is electrically operated and can be controlled so that the sensing elements for measuring the wind velocity and relative humidity can be located in any position above the columns. A view of the inside of the wind tunnel is shown in Fig. 2, Plate I, along with the instruments for measuring the wind velocity in Fig. 3, Plate I.

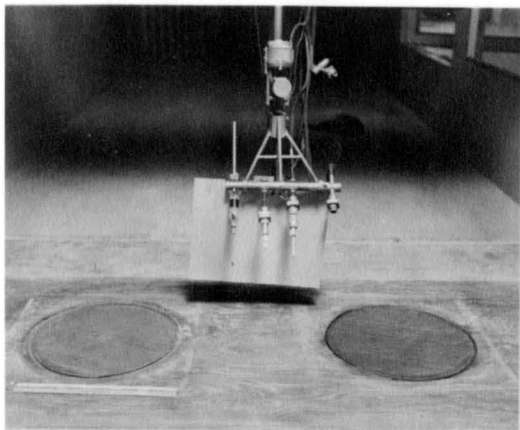


FIGURE 2 -- SURFACE OF THE SOIL COLUMNS IN THE WIND TUNNEL AND THE SENSING ELEMENTS ABOVE THE COLUMNS.

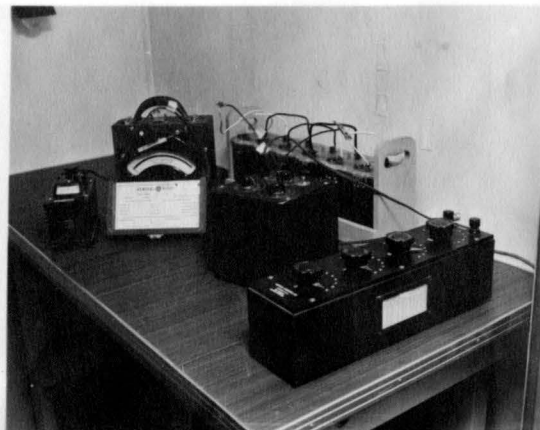


FIGURE 3 -- HOT-WIRE ANEMOMETER RECORDING INSTRUMENTS FOR MEASURING THE WIND VELOCITY.

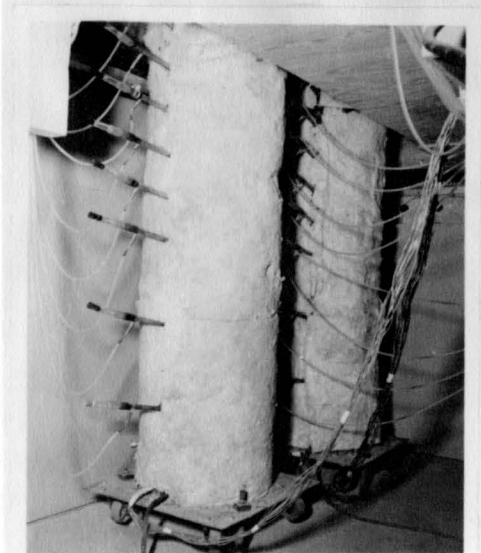


FIGURE 4 -- SOIL COLUMNS IN PLACE UNDERNEATH THE WIND TUNNEL.

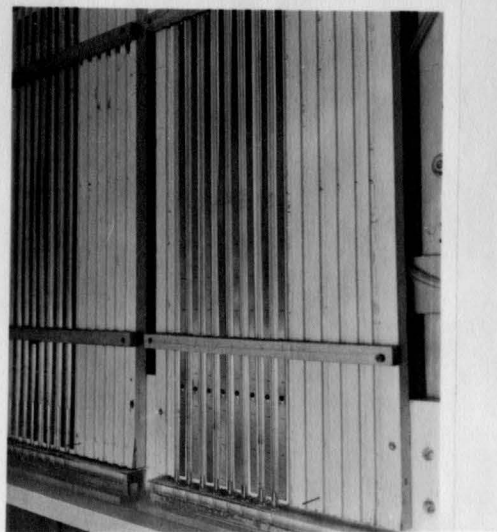


FIGURE 5 -- MERCURY MANOMETERS FOR MEASURING THE CAPILLARY PRESSURE OF THE FINE SAND IN THE SOIL COLUMNS.

Soil column.--The two soil columns were located side by side one and one-half feet from the walls of the tunnel and one foot apart. The columns consist of a 46-inch length of 14-gauge, straight seam, black steel pipe 12 inches in diameter which was welded to a steel dolly. Jack screws on the dolly were used for adjusting the column to the level of the wind tunnel floor. Rubber paint was used to prevent the columns from corroding. Glass-wool insulating material was glued to the column to protect it from radial temperature gradients. Fig. 4, Plate I, shows these columns in place under the wind tunnel.

Tensiometers.--Eight tensiometers, (Coors' #762 filter cylinder, porosity #3) were placed at various depths in the column and were connected to one-half inch brass tubes that extended through the side of the column at an angle of 11 degrees to the horizontal as shown in Fig. 4, Plate I. A glass air trap was placed on the end of the brass tube for trapping the air in the system during a test. Tygon plastic leads connected the brass tubes with the mercury manometers. Air was removed from the plastic leads before the tests by applying a head of hot water at the air trap and forcing the air through the mercury. The scales were adjusted to zero with the water table at the surface of the column. These scales were

graduated for reading the height of the mercury column in centimeters of water. See Fig. 5, Plate I.

Thermocouples.--A small plastic rod was placed in the center of the column to which copper-constantan thermocouples were attached at various depths for obtaining the temperature profile along the vertical axis of the column. Each thermocouple was coated with enamel and threaded through a plastic tube for protection against abrasion. The leads of the ten thermocouples from each column came together at a master switch. From here, the copper lead went to the potentiometer and then to the reference junction. The constantan lead was connected directly to the reference junction which was maintained at  $0^{\circ}$  C in an ice bath. The junction of the thermocouples in the soil columns was made by twisting the two wires and soft soldering them together. The thermocouples were calibrated by taping them to a thermometer and by placing them in a large bucket of water which was at room temperature. The potential of the thermocouples were measured and their corresponding temperature was compared to that of the thermometer. Good correlation was obtained.

Mariotte siphon.--The water was supplied to the bottom of the columns by means of Mariotte siphons. The ambient air line in one of the siphons was placed at the same level as the surface of the column in the wind

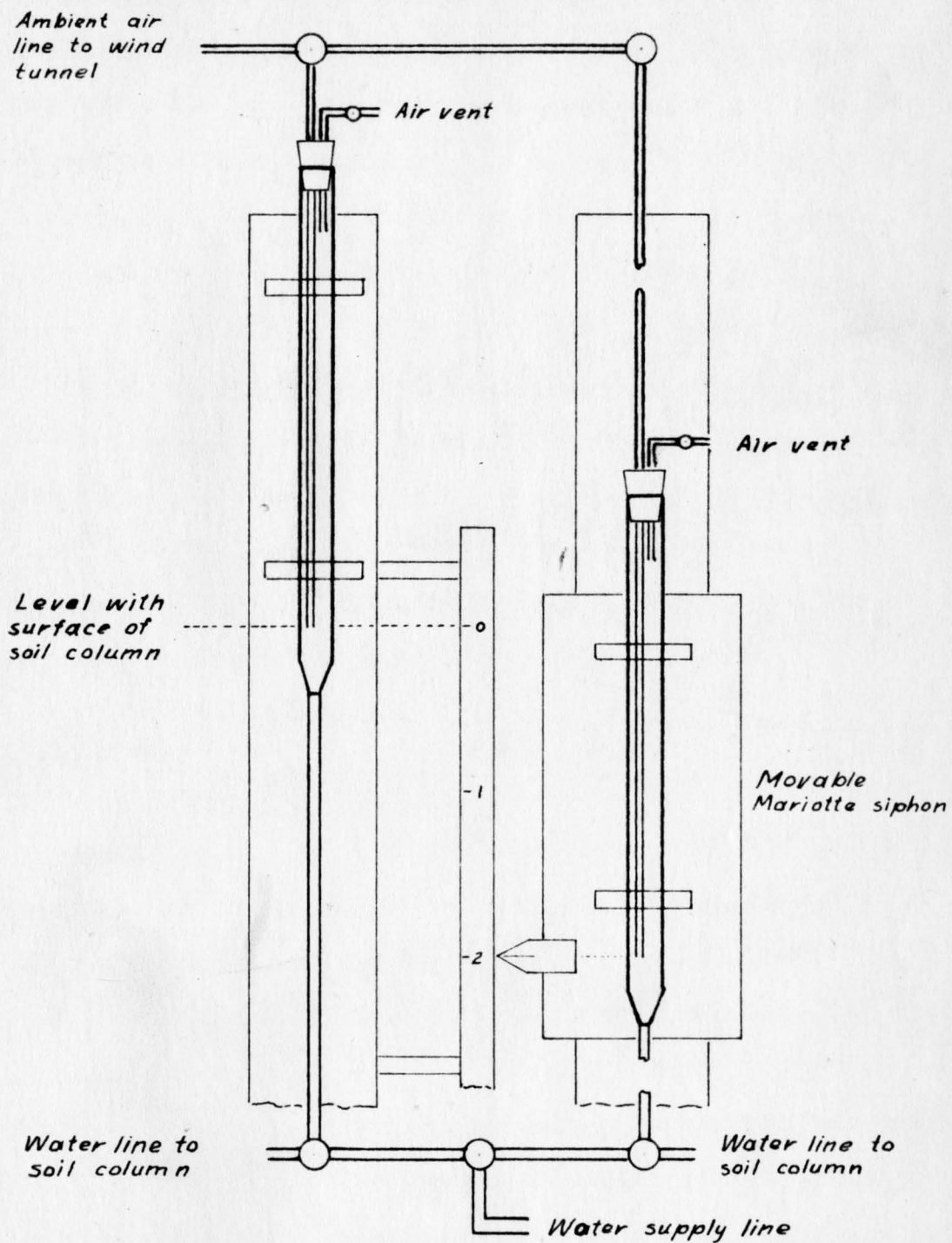


Figure 6 - Mariotte siphons for controlling water-table depth and measuring evaporation.

tunnel test section. The other siphon was movable in the vertical direction to facilitate the adjustment of the water-table depth in the second column. The burettes of the Mariotte siphons were calibrated to account for the volume that was occupied by the ambient air line. These burettes were supplied with water through a three-way stop-cock from a reservoir on top of the tunnel. A diagram of the Mariotte-siphon setup is shown in Fig. 6.

Sand used in the columns.--A fine sand with most of the clay fraction removed was used in the investigation. The fine sand came from the lake deposits in Loveland Lake near Loveland, Colorado. The mean particle size diameter of the sand was approximately 0.15 millimeters. Fig. 7 shows the mechanical analysis of the sand.

### Procedure

Preliminary steps.--A three and one-half inch layer of gravel was placed in the bottom of the columns to prevent the intake line from becoming plugged with fine sand and to reduce the head loss at the entrance. When the columns were filled with sand, the water surface was always above the surface of the sand. This aided in obtaining maximum compaction besides giving assurance that the columns of sand would be fully saturated. In order to obtain a more stable porosity a rubber mallet was used for vibrating the columns while the sand was being placed in

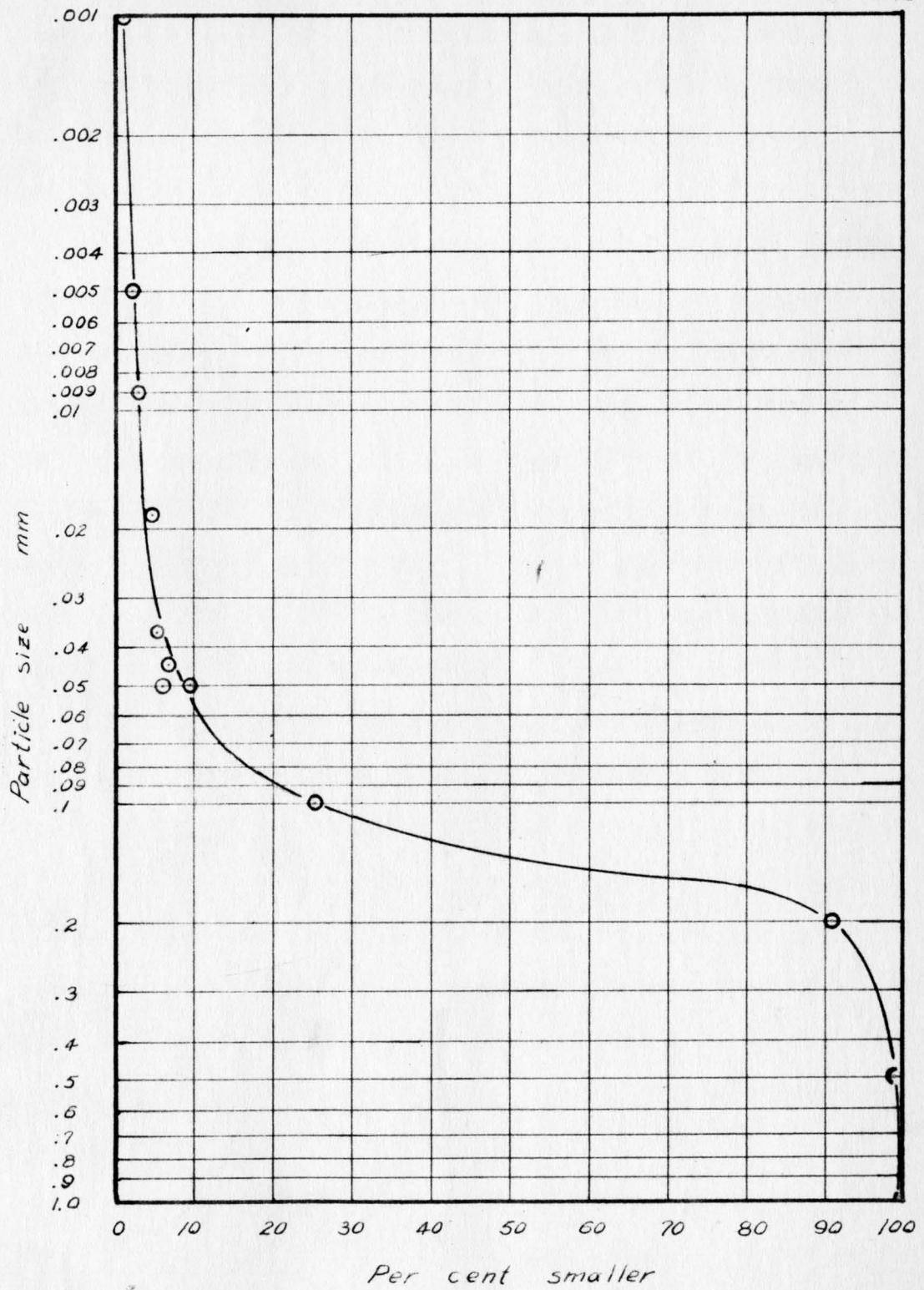


Figure 7 - Mechanical analysis for fine sand.

them. The east column contained 254.2 pounds of dry sand which resulted in a porosity of 0.442 while the west column contained 249.0 pounds of dry sand and a porosity of 0.444.

Permeability measurements were made on the two columns of sand under heads of 7 and 10.25 inches of water. The water flowed upward through the columns for approximately 30 minutes for each test. A graduated cylinder was placed at the overflow spout of the columns to measure the volume per unit time of the flow. The permeability of the columns expressed in units of square microns was found to be  $6.50 \mu^2$  for the west column and  $5.27 \mu^2$  for the east column.

Wind tunnel experimental procedure.---The water table was held at the surface of both columns as a wind velocity of 50 feet per second was created in the tunnel. Observations of water loss from the burettes were made at regular intervals along with the temperature and pressure profiles of the columns and the atmospheric conditions over the columns. When the rates of evaporation of both columns were the same and steady state had been obtained, this test was terminated.

The water table of one of the columns was lowered six inches below the surface and a series of tests were made with the water table at this depth. Tests were made at water table depths of 6, 12, 24, 26 and 29 inches

with the wind being maintained at speeds of 14, 25, 35 and 45 feet per second at each depth until steady state was established. The sensing elements on the traversing mechanism for measuring the wind velocity and the ambient humidity was located seven inches above the floor of the wind tunnel and midway between the two columns. Other data that were collected included the barometric pressure, soil temperature distribution along the vertical axis of the column, tension at various depths of the sand profile, and the volume of water being supplied to the water table from the burettes.

A plot of evaporation vs time was made of each column during each test. In addition to this plot, the ratio of evaporation from the two columns vs time was plotted to determine when steady state was obtained. When the ratio became constant with time, the columns were assumed to be at steady state. The tests were not terminated unless the columns had remained at steady state for approximately two hours. Fig. 8 is an illustration of these plots.

A correction factor was applied to the rates of evaporation due to the change in the volumes of the steel pipe, sand, and water caused by temperature fluctuations. The change in volume of both the sand and water together per degree centigrade is greater than the change in volume of the steel container. Therefore, a volume

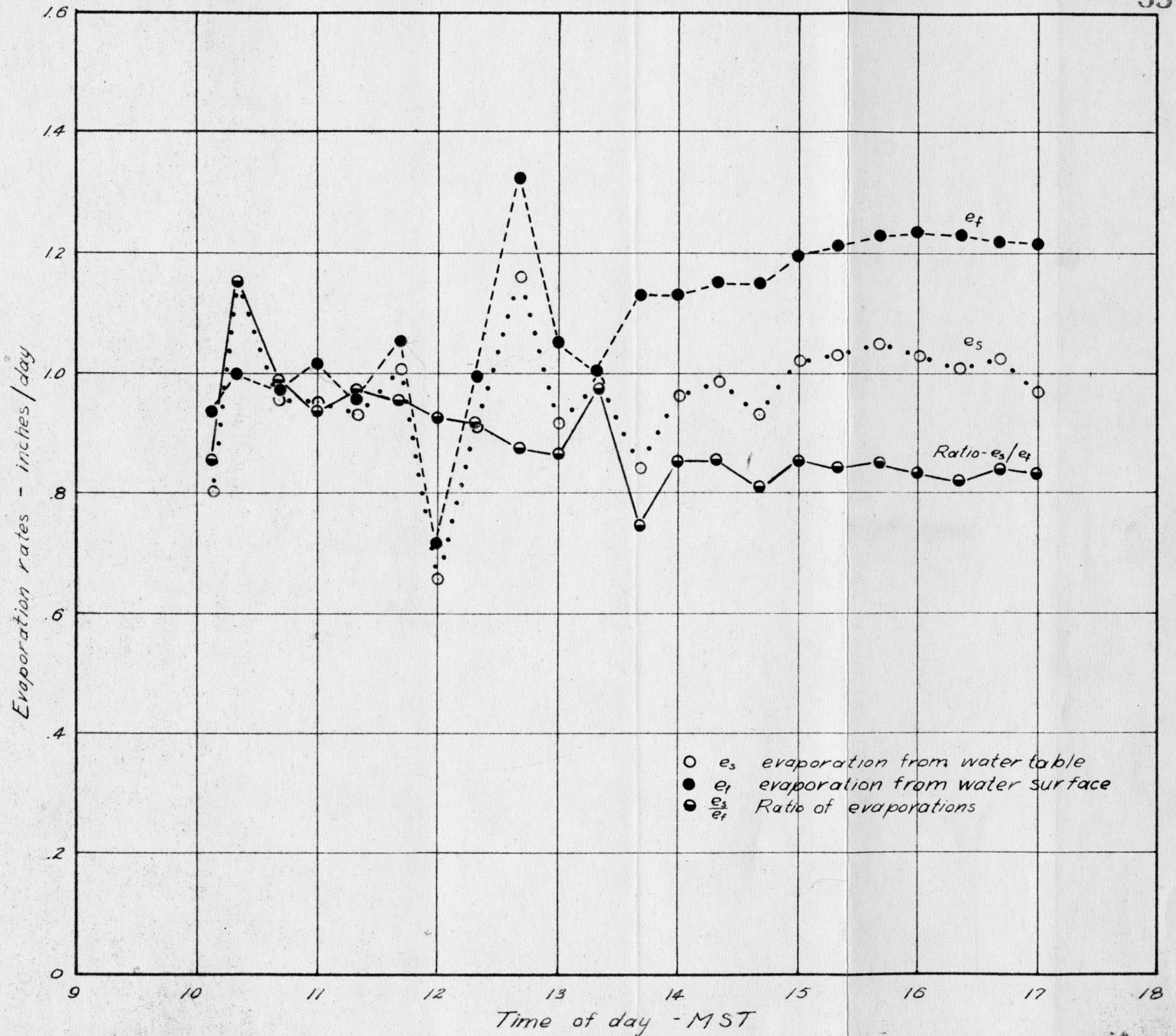


Figure 8 - Evaporation rates vs time of a typical run. Run 34.

correction was added to the volume of water lost from the burettes when an increase in temperature occurred and subtracted when the temperature decreased.

### Supplementary Tests

Height of capillary rise.--A 5-inch diameter plastic column, four feet high, was packed with dry sand. The water table was maintained within half an inch of the bottom of the column by adding water through a plastic tube connected to the bottom. The volume of water added and the rate of capillary rise was observed for a period of eight days.

Capillary pressure-desaturation curve.--In order to determine the functional relationship between capillary pressure and the degree of saturation of the sand in the columns, special equipment was designed to obtain capillary pressure-desaturation data. The equipment developed for this purpose is shown in Fig. 9, Plate II.

Representative samples of the air-dry sand (about 10 grams) were placed in small weighing bottles. The samples were covered with a volume of water sufficient to fully saturate the samples. The weighing bottles containing the sand and water were then placed in an evacuated flask attached to a vacuum pump. The flask was evacuated until virtually all the air was removed and then air

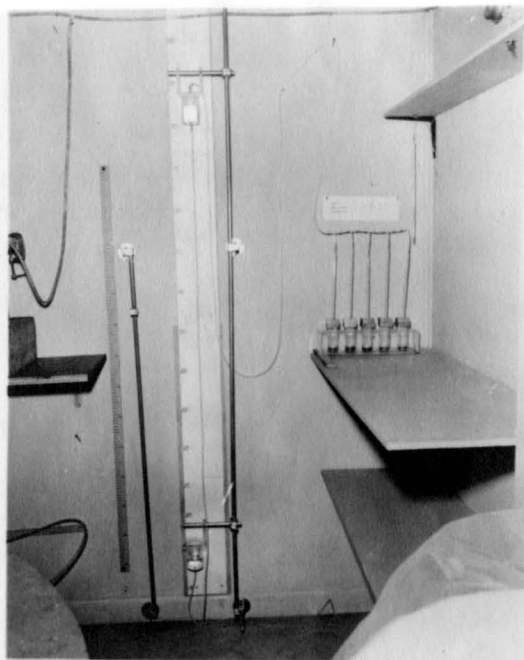


FIGURE 9 -- APPARATUS FOR OBTAINING THE  
CAPILLARY PRESSURE-DESATURATING  
CURVE OF THE FINE SAND.

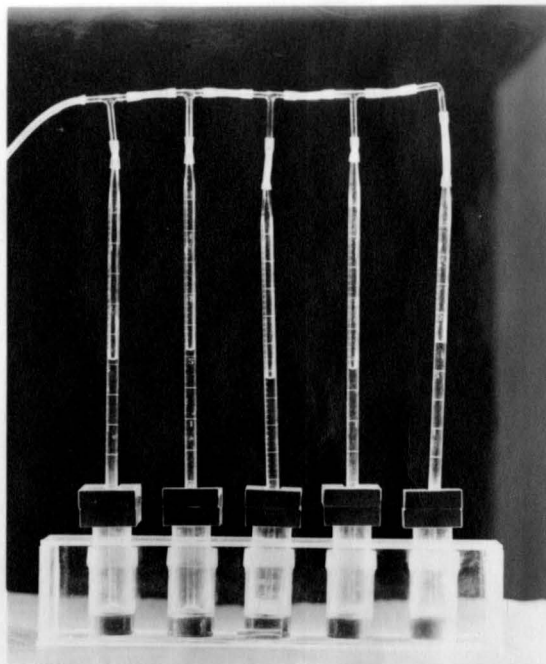


FIGURE 10 -- LUCITE PLASTIC BOX WITH PIPETTES  
ATTACHED TO LUCITE CYLINDERS  
WHICH ARE IN CONTACT WITH THE  
FINE SAND CONTAINED IN WEIGHING  
BOTTLES.

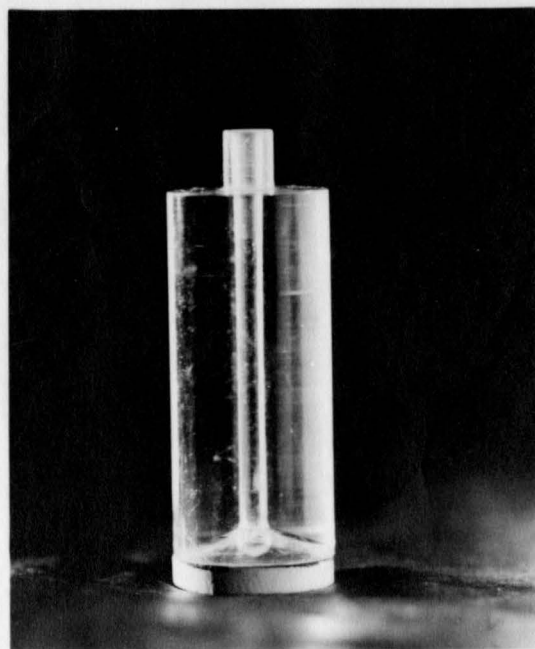


FIGURE 11 -- LUCITE CYLINDER AND SEMI-PERMEABLE  
BARRIER FOR CAPILLARY  
PRESSURE-DESATURATING APPARATUS.

was admitted quickly at atmospheric pressure. This procedure caused the samples to be fully saturated with water and also produced a porosity in the samples virtually the same as that obtained in the columns.

After the samples were saturated, the excess water was removed and the weighing bottles were placed in a lucite plastic box shown in Fig. 10, Plate II. Water-saturated semi-permeable barriers made of Sela ceramic having an air-entry pressure of one and one-half atmospheres were placed in contact with the samples through openings in the top of the box.

The barriers are connected with Armstrong adhesive (A-1) to the lucite cylinders as shown in Fig. 11, Plate II. The barriers are one-eighth-inch thick and one-inch in diameter. The plastic cylinders are also one-inch in diameter and the holes through the top of the box are just large enough for the cylinders to slip through without allowing space for appreciable diffusion of water vapor from the samples. Good contact between the barrier and soil is maintained by placing weights on top of the cylinders as shown in Fig. 10, Plate II.

A negative pressure on top of the barrier was produced by means of two leveling cells containing water and connected by a flexible Tygon tube. The upper cell which was initially filled with water was connected to five 5-ml pipettes for measuring the volume of water

removed from the samples. The pipettes in turn were connected to the lucite cylinders. The lower water cell was open to the atmosphere and in the beginning contained only a small amount of water.

At the beginning of the test, the difference in elevation of the two water cells was sufficient only to support columns of water above the samples as high as the lowest graduation on the pipettes. Thereafter, the difference in elevation of the two cells was gradually increased in small increments. Time was allowed for equilibrium to be reached between the soil and barrier as indicated by a constant volume of water in the pipettes.

As the pressure in the upper cell and in the leads to the barriers was decreased, the air in the leads expanded, causing some water to flow from the upper cell to the lower cell. Because the volume of air in the pipettes and leads was deliberately made as small as possible, the lowering of the water level in the upper cell was very slight (over the range of pressures used). The Tygon leads have an inside diameter of only 1/16-inch compared to an inside diameter of 2-inches for the leveling cells.

As the capillary pressure of the water was increased there was an initial removal of some excess water from the samples which was discounted. There was a range of capillary pressures over which virtually no increase

was observed in the water level in the pipettes. These levels were taken as zero readings from which to compute the amount of water subsequently removed from the samples at higher capillary pressures. The highest capillary pressure at which measurements were made was 200 cms. of water.

The capillary pressure was computed by subtracting from the difference in elevation of the water in the leveling cells the height of water above the samples in the pipettes. After the samples had apparently reached equilibrium at the highest capillary pressure applied, the samples were removed from the plastic box and were weighed. They were next oven-dried and weighed again to determine the amount of water remaining in the samples. The saturated pore volume of each sample was computed by adding to the volume of water remaining at the end of the run the volume of water removed during the run.

The volume of water in the sample (at equilibrium with each capillary pressure applied during the run) was computed and was expressed as a percentage of the saturated pore volume. The percentages of the saturated pore volumes were then plotted against the corresponding capillary pressure for that saturation to obtain the capillary pressure-desaturation curve. The capillary pressure at which the first desaturation of the sample occurred was designated as the displacement pressure, the

definition of displacement pressure being the pressure differential between air and liquid required to allow air to enter the largest pores of an initially liquid-saturated porous system.

## Chapter V

## PRESENTATION OF DATA AND DISCUSSION OF RESULTS

In the analysis of the problem appearing in Chapter III, the variables pertinent to evaporation from a soil column in contact with a water table were resolved into the parameters  $e/C$ ,  $P_c/P_D$ , and  $z/\frac{P_D}{W}$ . It was hoped that the experimental results would provide information relative to the functional relationship between these parameters. Accordingly, means were provided for measuring the variables appearing in the parameters at various points along the axes of the columns. In addition, the temperature profile within the column and the profiles of the relative humidity, temperature, and wind velocity above the columns were measured as previously explained.

Wind Velocity

Wind speeds of 15, 25, 35, and 45 feet per second were maintained with the water table being held at particular depths. Runs were continued until the ratio of evaporation from the two columns  $e_s/e_f$  became approximately constant;  $e_f$  is the evaporation rate from the column with the water table at the surface, and  $e_s$  is

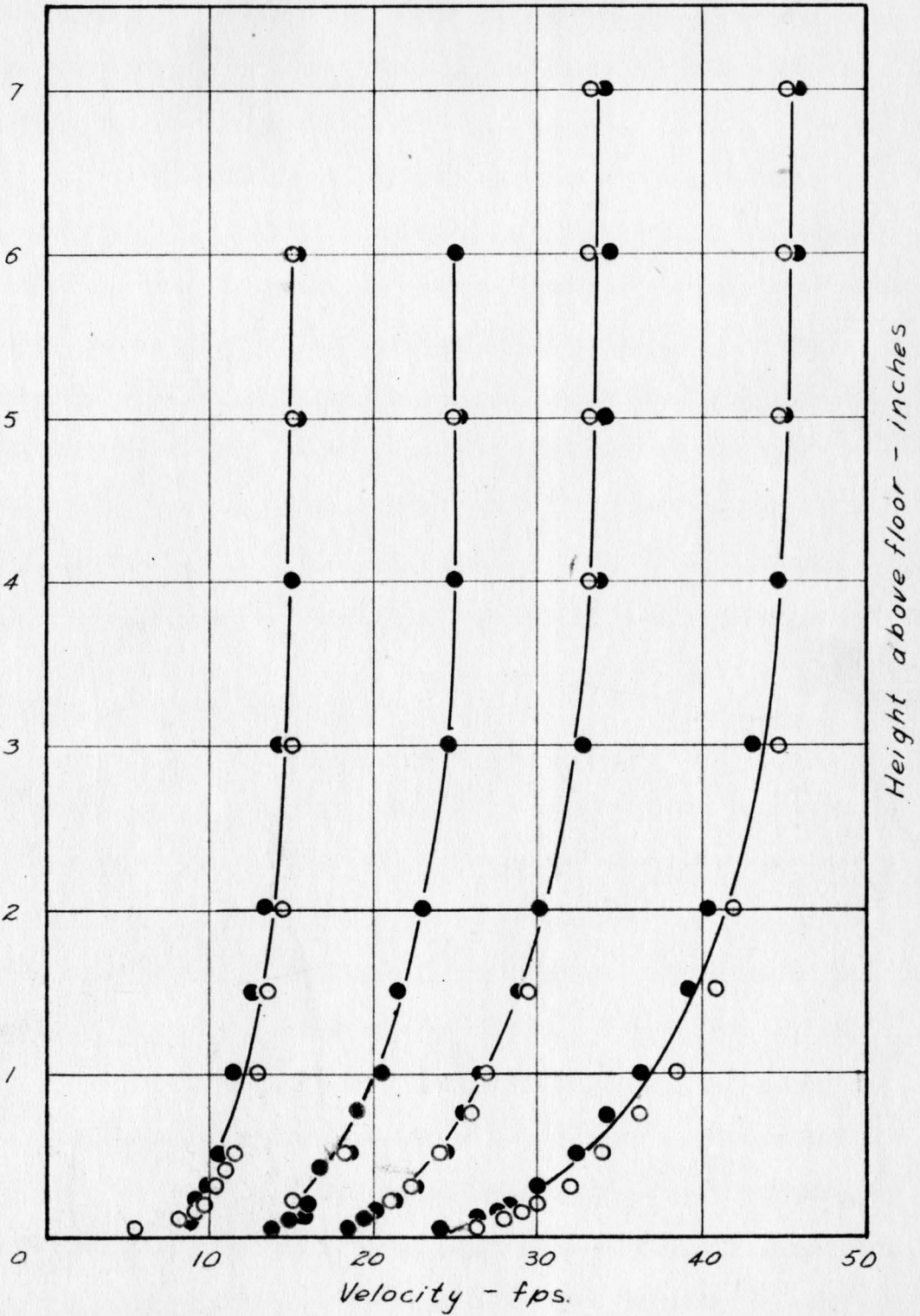


Figure 12 - Velocity profiles

the rate from the column with the variable water table. The velocity profiles above the columns at each of the speeds studied are shown in Fig. 12.

No attempt has been made to evaluate the Reynold's number or the shear resulting from the winds imposed. The evaporation rates from the column with the water table at the surface was used to integrate the effects of ambient factors. Because of the mechanical limitation of the driving mechanism and the lack of provision for providing additional radiant energy to the soil surfaces, the greatest evaporation rate obtained was 1.35 inches per day with the water table at the surface.

#### Temperature profiles

Typical temperature profiles are shown in Figs. 13 and 14. It will be noted that the surface temperature is lower on the column with the water table at the surface. Higher evaporation rate from this column resulted in a greater withdrawal of heat from storage producing a temperature difference between columns. Since the column which evaporates the most water must absorb the most heat, this temperature difference is maintained in the steady state. The drier soil becomes warmer at the surface and as a consequence loses more heat by radiation. A certain amount of heat is also absorbed in the process of moving water from the water table to the surface but this is

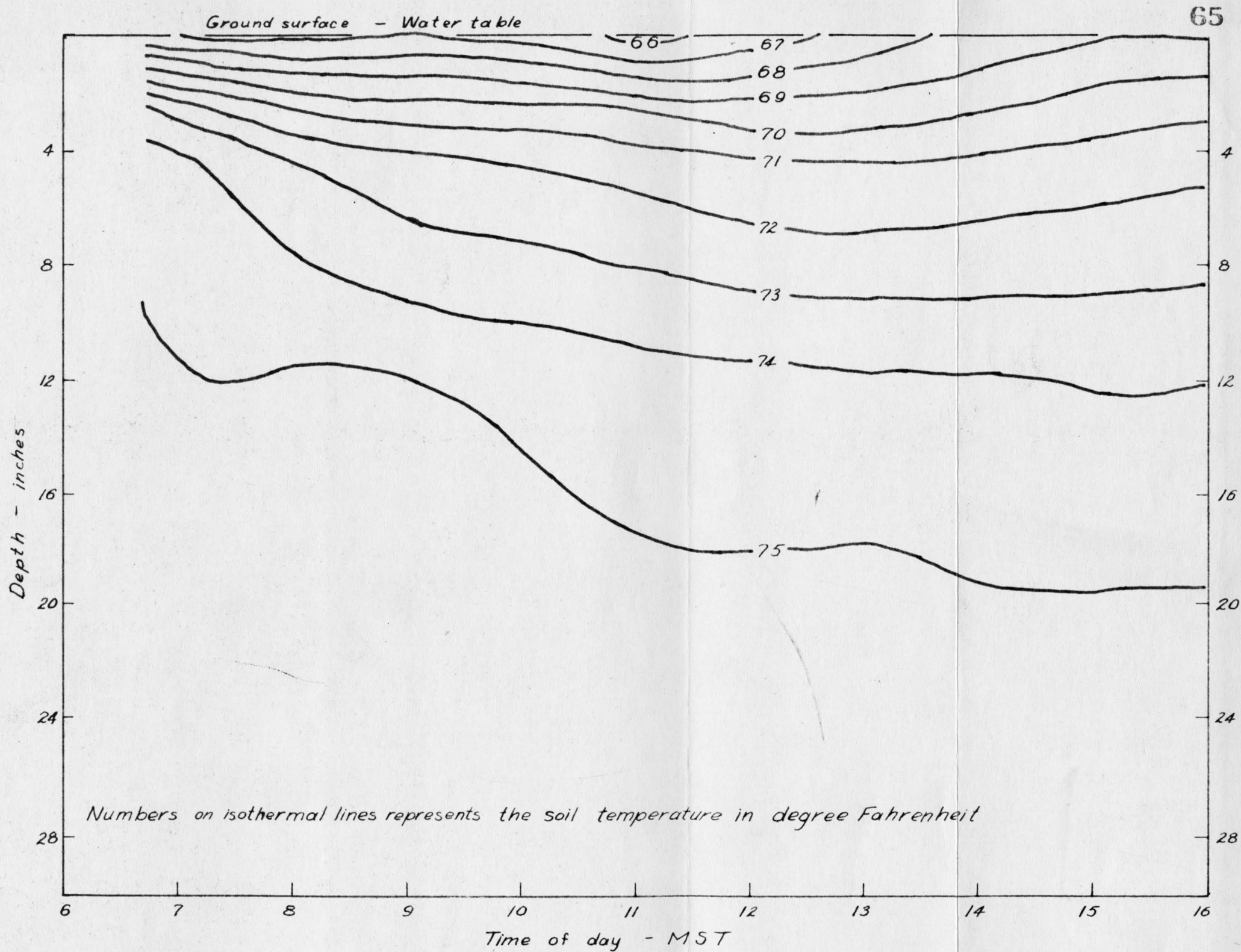


Figure 13 - Typical temperature profile - West column, run 30

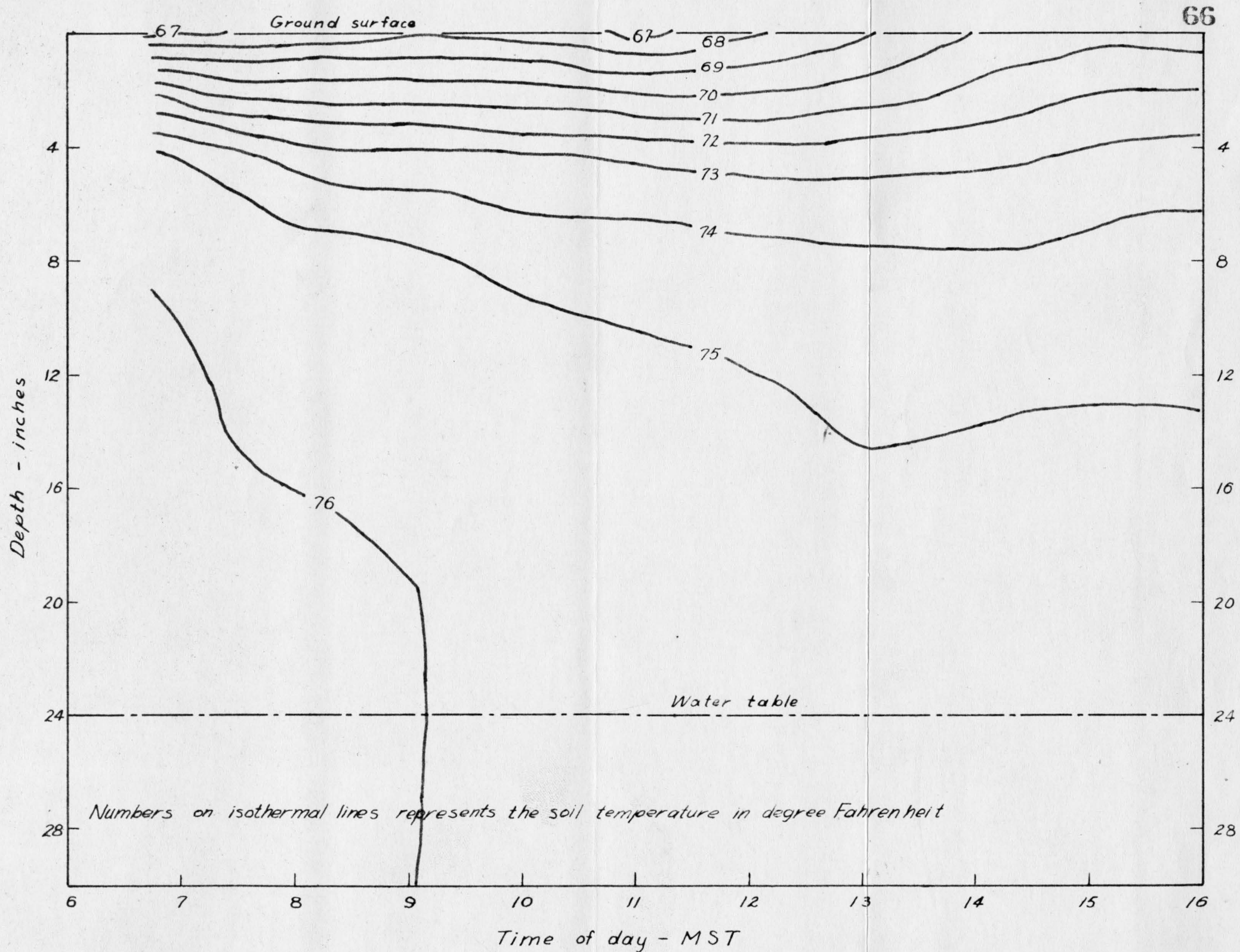


Figure 14 - Typical temperature profile - East column, run 30

negligible unless the soil becomes very dry to a considerable depth. An energy loss of the same magnitude as that required to evaporate the water would be produced by a drop in hydraulic head of about 154 miles.

Evaporation rates are very sensitive to radiant energy input. In this experiment the column with the water table at the surface apparently received slightly more radiant energy than the east column. This was probably due to reflection of light from the west wall that passed through a window on the east side of the test section. Evidence that the west column received more radiation is shown in Figs. 15 and 16. Note the slightly higher temperature at the surface of the west column. These temperatures were measured during a check run with the water table at the surface of both columns. The west column had a significantly higher evaporation rate. The slopes of the curves in Fig. 19 were probably influenced by this factor and undoubtedly each curve would have had a slightly greater slope had this not been the case.

As a source of additional evidence that this conclusion is correct some data are shown which were taken during a more recent experiment in which the same sand was used. In this experiment all columns were placed at equal radii on a revolving table in a controlled environment. There was no possibility of any column receiving more

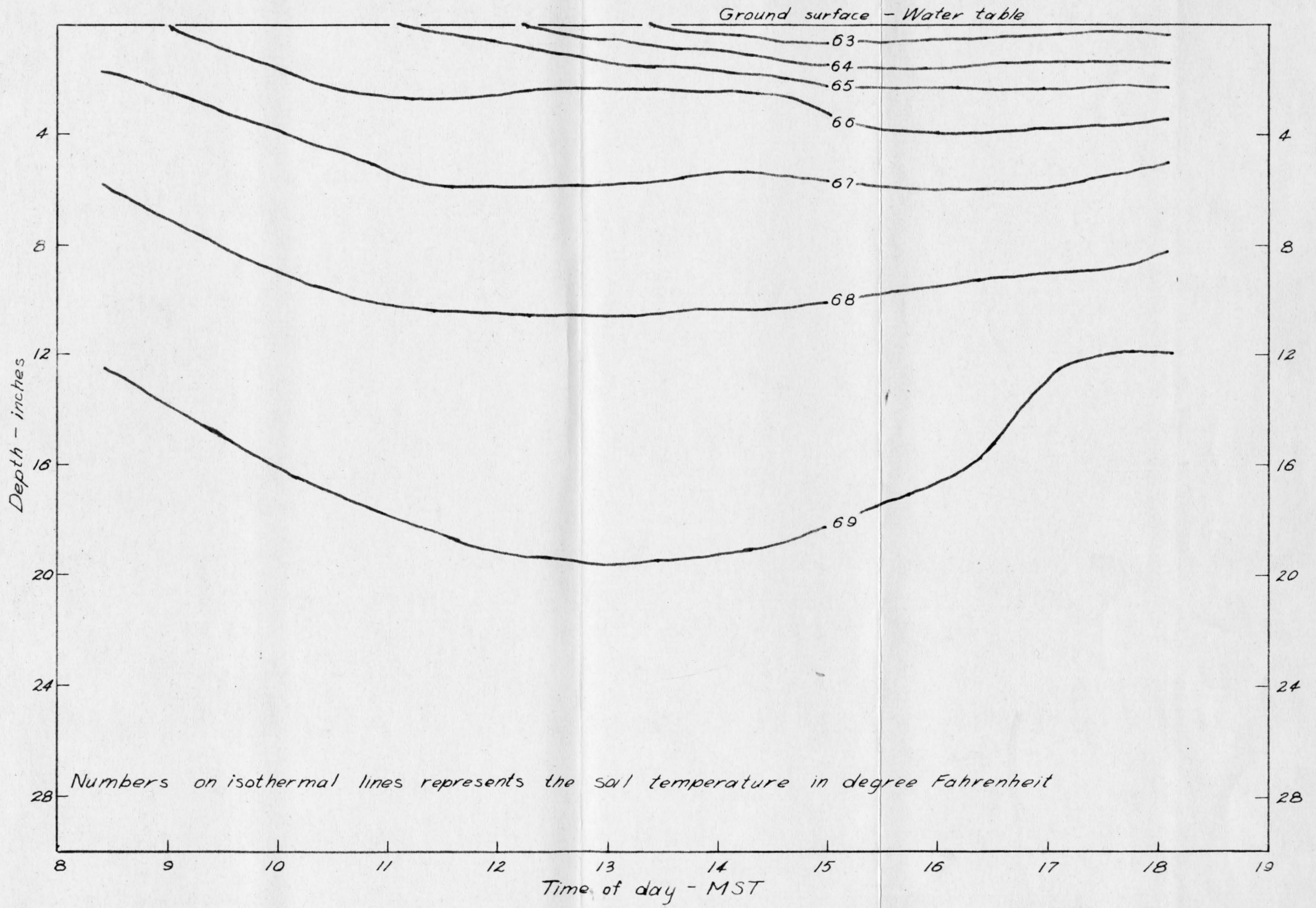


Figure 15 - Typical temperature profile - West column, run 49A

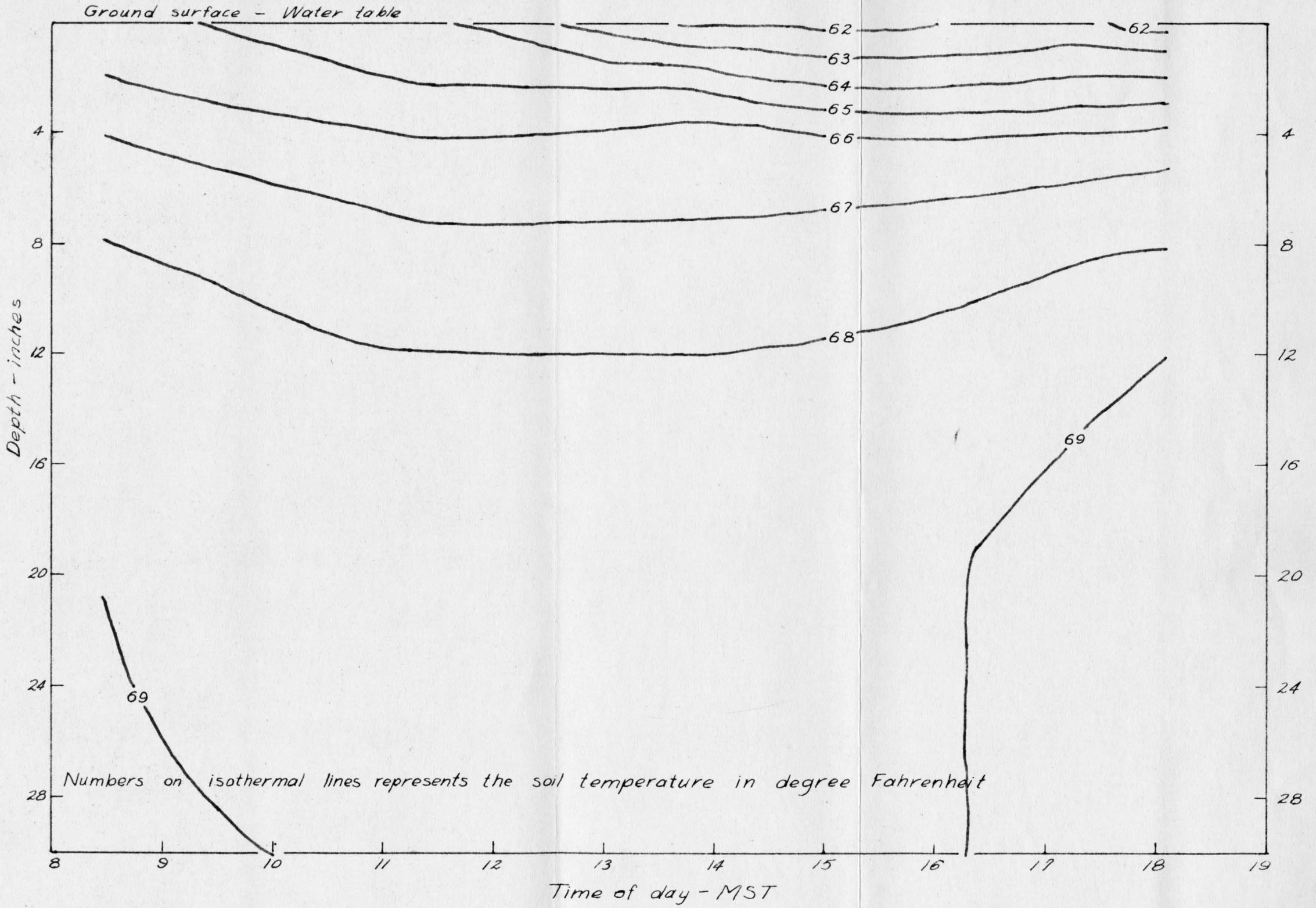


Figure 16 - Typical temperature profile - East column, run 49A

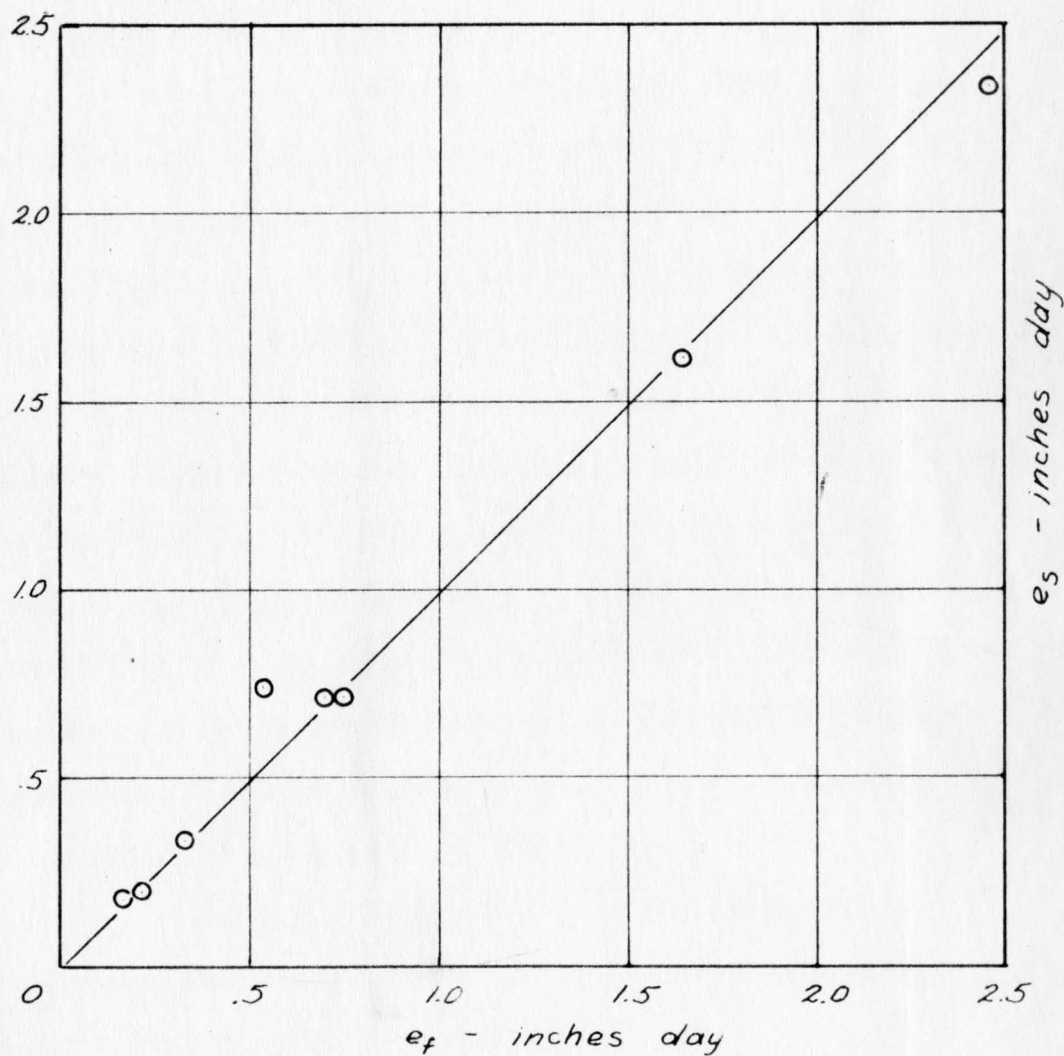


Figure 17 - Evaporation from fine sand with a water-table depth of 6 inches in comparison with evaporation from a free water surface with the columns in a controlled environment.

radiant energy than the other. Results from this experiment are shown in Fig. 17. Note that in this case the plot of  $e_s$  vs  $e_f$  with the water table at a depth of six inches gives a slope which is virtually one.

Another source of difficulty was the extreme variation in ambient temperatures during each run which made it impossible to obtain steady state in the usual sense. Expansion and contraction of the water, the soil, and the steel columns introduced an error in the computation of the evaporation rates such that reasonably accurate measurements of rates less than about 0.1 inch per day were impossible. A volumetric correction was applied depending on the direction and rate at which the temperature was changing, but the accuracy of the correction was always in doubt because of the impossibility of measuring the average temperature of all components of the system with sufficient precision.

Another difficulty was that data could be collected only during the frost-free season because of the danger of freezing the system.

### Relative humidity

Some typical profiles of relative humidity above the columns during evaporation are shown in Fig. 18. These indicate that the thickness of the relative-humidity boundary layer was not more than one-half inch. The

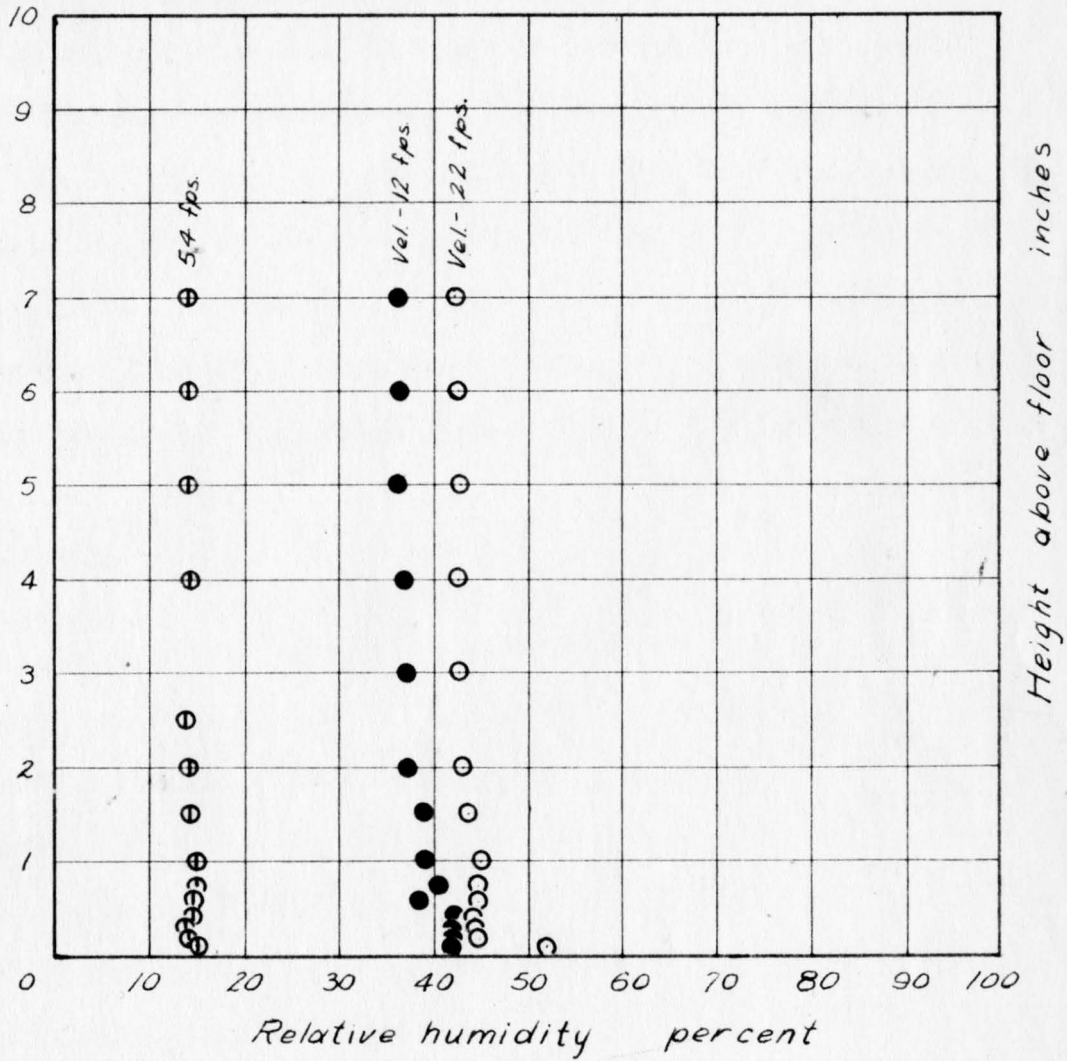


Figure 18 - Typical relative humidity profiles at different wind speeds.

relative humidity also varied considerably during most runs, which generally lasted for a period of 6 to 8 hours. Typically the relative humidity decreased during the day as the temperature within the wind tunnel increased. There was usually a particular sharp increase in temperature with a concurrent decrease in relative humidity about noon each day resulting from direct sunlight striking the return section of the wind tunnel. This greatly increased the difficulty in obtaining a steady rate of evaporation.

#### Capillary pressure distribution

Perhaps the most disappointing circumstance relative to the entire experiment was the failure of the mercury manometers to indicate the capillary-pressure gradient within the columns. There were several reasons for this failure. The first was that the sand used is very permeable and the head loss resulting from flow in the fully-saturated state was very small. It was not possible to measure small evaporation rates with sufficient accuracy, and consequently water-table depths which might have produced a substantial capillary-pressure gradient were not investigated. The mercury manometers used to read the capillary pressures were not particularly sensitive, and moreover, most of the head loss resulting from flow probably occurred above the top tensiometer.

As a result of these circumstances, the theory developed in the analysis of the problem could not be tested except by inference.

#### Depth of water table.

Perhaps the most interesting fact learned from the experiment was that there is a critical water-table depth for this sand. When the water table is below this depth there is an abrupt decrease in evaporation rates. Fig. 19 presents the evaporation rates as a function of depth of water table and of the evaporation rates from a free water surface. It will be noted that when the depth of water table was varied between 0 and 24 inches no great change in the rate of evaporation occurred. When the depth was increased to 26 inches, however, a considerable reduction in rates occurred at a higher value of  $e_f$ . When the depth was increased to 29 inches  $e_s$  was reduced to a value that could not be measured accurately with the experimental procedure employed. Consequently greater depths of the water table were not investigated.

Because of the abrupt reduction in evaporation as a water-table depth of 26 inches is approached, an effort was made to determine whether this could be explained in terms of the theory developed in Chapter III.

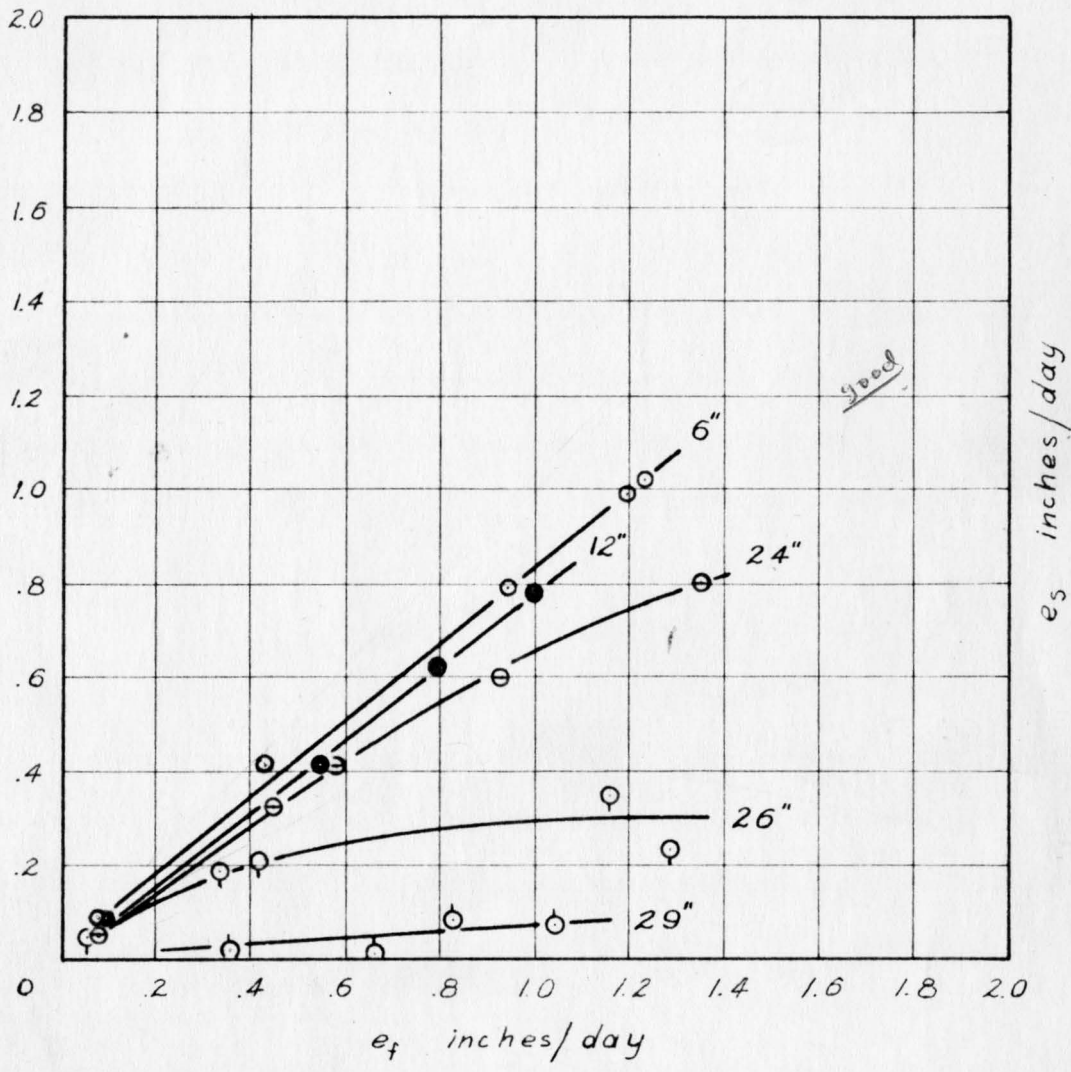


Figure 19 - Evaporation rates from fine sand at various water-table depths as functions of evaporation rates from a free water surface.

### Capillary pressure - desaturation curves

Fig. 20 shows the functional relationship between the capillary pressure  $P_c$  and the saturation  $S$  for the fine sand on the drainage cycle. It will be noted that this sand has a displacement pressure  $P_D$  of about 60 cm of water. This is a few centimeters higher than the capillary rise found for the sand as shown in Fig. 21. The range of the water-table depths, 24-29 inches, over which the evaporation rates underwent an abrupt decrease corresponds to the range of  $P_c$  for which the sand desaturates from 100 to 45 percent.

It will be obvious from Eq. 16 of Chapter III that during evaporation the value of  $P_c$  at the surface of the column is greater than the depth of the water table, but until  $P_c$  becomes greater than  $P_D$  at the surface, this difference will be slight. As soon as  $P_D$  is exceeded, however, the resistance to the flow will increase rapidly with increasing  $P_c$  and the difference between  $P_c$  for the static case and the  $P_c$  with evaporation will increase sharply.

In order to further clarify this situation, a relative permeability vs saturation curve was calculated for the sand using Burdine's method. This curve is shown in Fig. 22. Relative permeability to water  $K_{rw}$  is defined as the ratio of the effective conductivity  $C_e$  at the saturation  $S$  to the conductivity  $C$  when the saturation

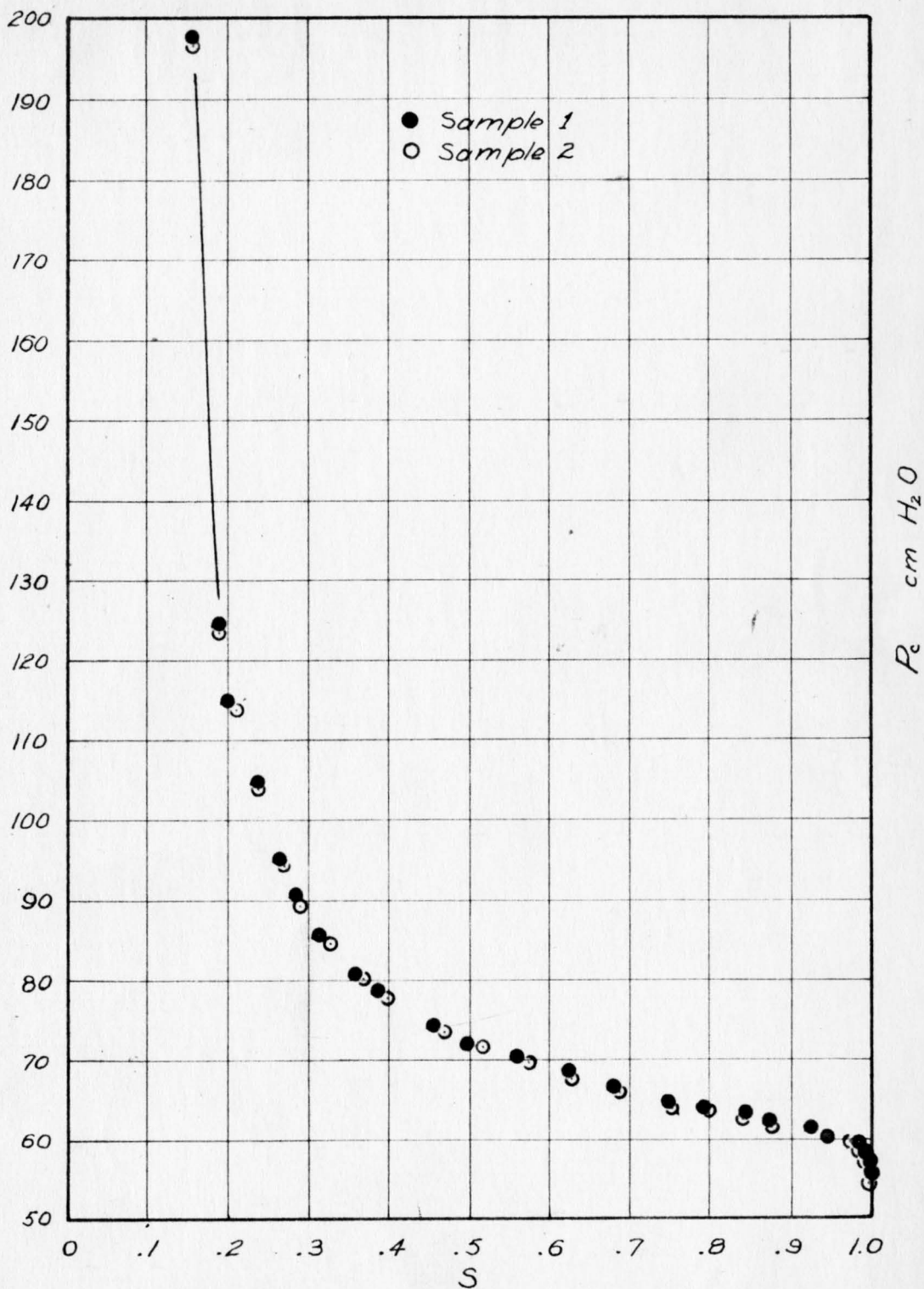


Figure 20 - Relationship between the capillary pressure and saturation of a fine sand

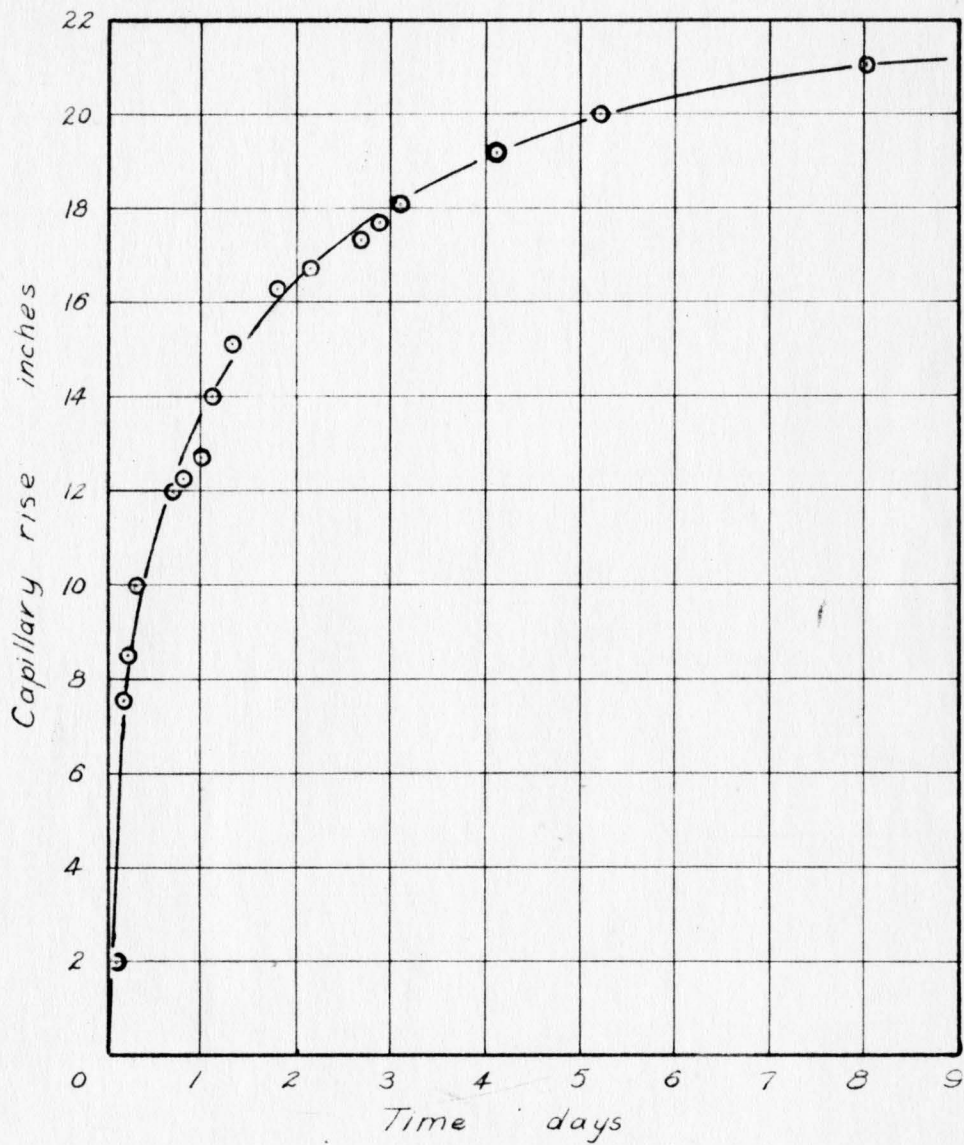


Figure 21 - Capillary rise in a fine sand from Loveland Lake.

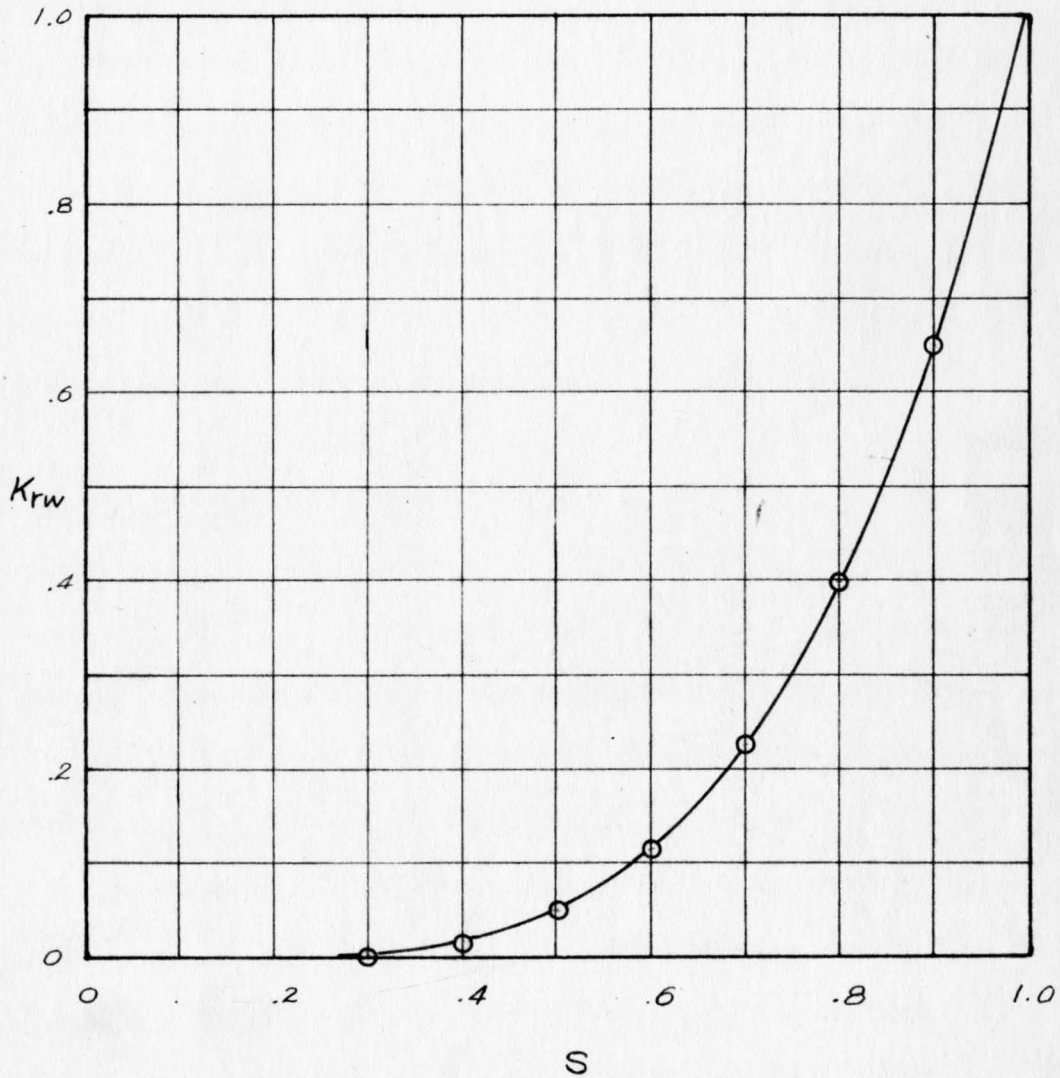


Figure 22 - Relative permeability to water as a function of water saturation. Computed by method of Burdine(4).

is unity or 100 percent. It will be noted by comparing Figs. 20 and 22, that  $C_e$  is the same as  $C$  until  $P_c = 60 \text{ cm H}_2\text{O}$ . The equation of Gardner (18) relating  $C_e$  to  $P_c$  obviously could not be valid for the sand used in this investigation. It can also be seen from Fig. 20 that by the time the water table has reached a depth of 29 inches (even if a static situation is assumed) the saturation at the surface will have been reduced considerably. Once the surface becomes dry, more of the heat supplied to the surface is lost by radiation.

In regard to Eqs. 11 and 14, in which Burdine and Corey found that  $K_{rw}$  is related inversely to the 8th power of  $P_c$  for porous rock cores, Fig. 23 shows that this relationship for the fine sand is to the 16th power. For saturations below field capacity, Gardner found that the relationship is to the 2nd or 3rd power. The abrupt desaturation as noted in Fig. 20 indicates that most of the pores are nearly the same size. The mechanical analysis, Fig. 7, of the fine sand reveals that most of the sand particles are also nearly the same size. The fact that the sand particles and pores are both of uniform size accounts for the sudden desaturation of the sand. This results in  $K_{rw}$  being proportional to the inverse of  $P_c$  to the 16th power.

Some idea of the exponential relationship between the parameters  $e/C$ ,  $P_c/P_D$ , and  $z \frac{P_D}{W}$  is given in

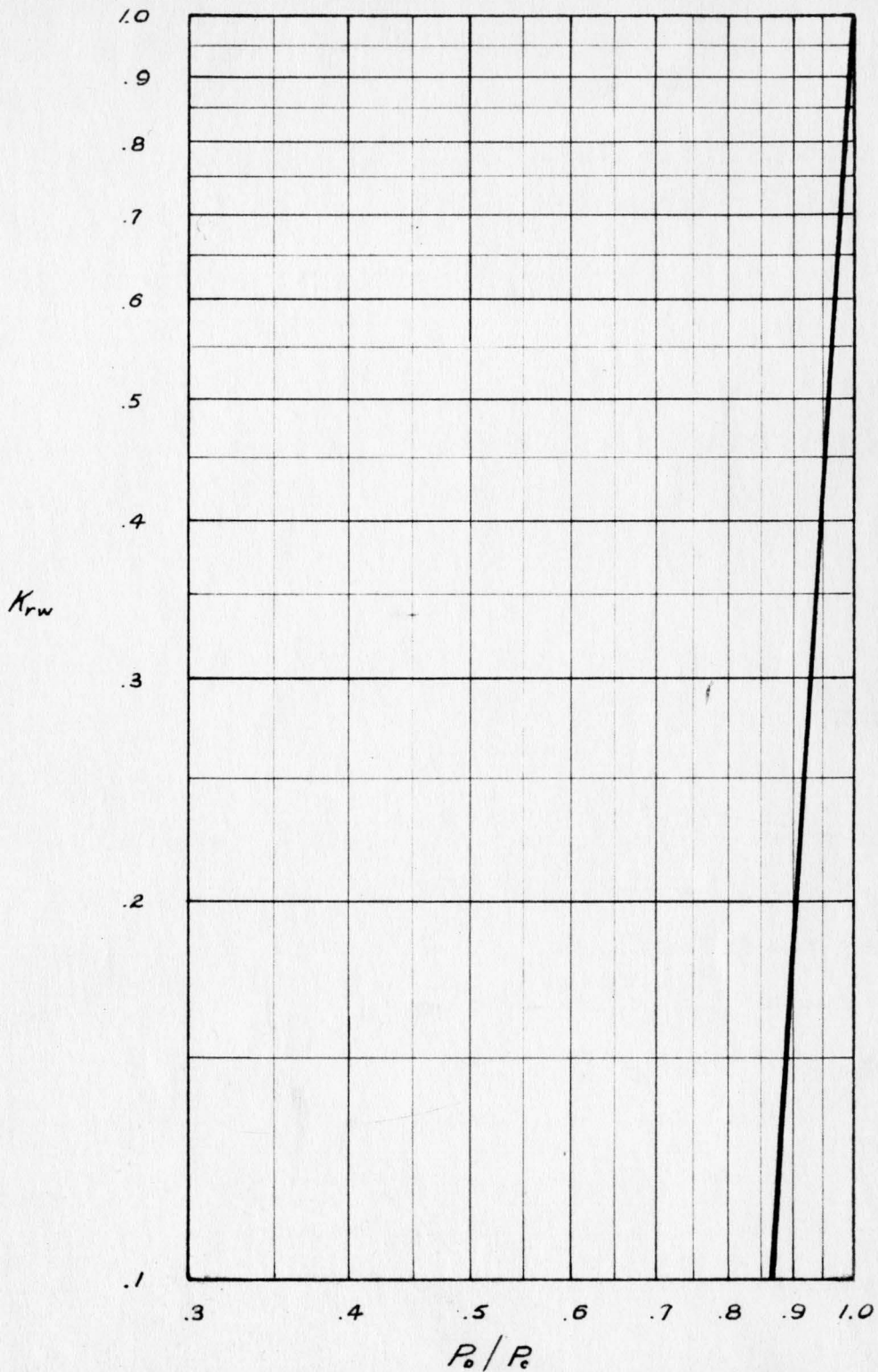


Figure 23 - Relationship between the relative permeability and the inverse of the capillary pressure on the sand. Computed by the method of Burdine (4).

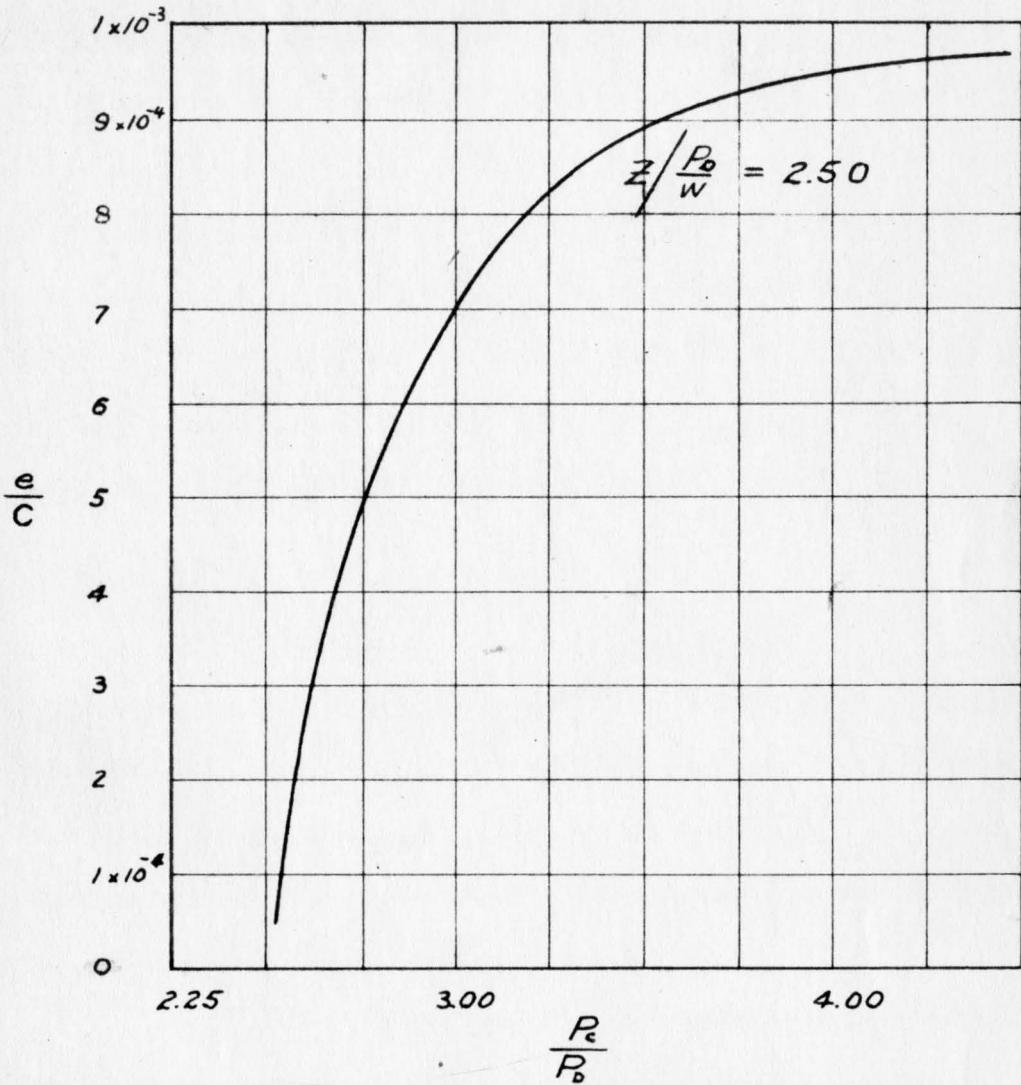


Figure 24 - Computed relationship between the parameters  $e/c$  and  $P_c/P_b$  at a particular value of  $z/P_b/w$ .

Fig. 24. This figure presents the same functional relationship as Fig. 1 presented in Chapter III except that in this case Eq. 14 was solved explicitly for  $e/C$  as a function of  $P_c/P_D$  for a particular value of  $z/\frac{P_D}{w}$ . Note that  $e/C$  tends to approach a maximum. The transition, moreover, between a rapidly changing value of  $e/C$  and a nearly constant value of  $e/C$  is abrupt. The fact that  $e_s$  does tend to reach a limiting value, depending on the water-table depth, is shown in Fig. 19. This fact has also been established by Gardner (18).

#### Suggestions for future studies

As previously stated, this thesis is a preliminary investigation of evaporation from soils in which the factors affecting the rate of evaporation from fine sand were studied. The following suggestions for future studies are a consequence of experience gained in carrying out the experiments described.

Similar experiments are needed on a variety of soils to determine if a critical depth of water table occurs and if a similar relationship exists between this depth and the characteristics of the moisture release curve as exists for the fine sand. Because the wind tunnel now in use does not permit control of ambient temperature, radiation, or humidity, it is recommended that future studies of evaporation be conducted in a facility

designed so that these variables can be controlled. Provision should also be made for measuring capillary pressures within the soil profile with greater precision so that the relationships between the several dimensionless parameters can be studied and the theoretical relationship can be evaluated.

Many additional experiments will be needed before the over-all objectives of the project of which this thesis is a part will be realized. One of the first things that comes to mind in this regard is an evaluation of the dynamic case, i.e., an initially wet soil (not necessarily in contact with a water table) which is dried by evaporation.

## Chapter VI

## SUMMARY

A preliminary investigation of steady-state evaporation was made to determine the effects of wind velocity and depth of water table on the rate of evaporation from a column of fine sand in contact with a water table. An attempt was also made to relate the rate of evaporation under specific environmental conditions to measurable properties of the sand.

Two columns of fine sand from deposits in Loveland Lake, washed free of most of the clay fraction, were placed in the 6 ft. by 6 ft. test section of the wind tunnel on the Colorado State University campus. One column was a check column in which the water table was maintained at the surface while in the other column the depth of the water table was varied.

Runs were made with the wind velocity varying from 0 to 50 feet per second while the water table varied independently between the surface and a depth of 30 inches. The runs were conducted in such a manner that the column with the variable water table was always on the drainage cycle. Each run was continued until steady state

was approached.

A critical depth of water table for the fine sand was found at about 24 inches. With the water table above this depth, evaporation rates were of the same order of magnitude as from the free water surface. With the water table at a depth of 26 inches, the evaporation rate was less than half that from the free water surface. When the water table was at a depth of 29 inches, the evaporation rate became too small to be measured accurately with the apparatus employed.

The critical water-table depth could be related to properties of the capillary pressure - desaturation curve, particularly to the displacement pressures which was about 23.6 inches of water for the fine sand. With the water table at any particular depth the evaporation rate apparently approached a limiting value as the wind velocity was increased.

By analyzing the flow of water through a column of fine sand from the water table to the surface, the variables affecting the flow were grouped into three dimensionless parameters:  $e/C$ , the ratio of the evaporation rate to the hydraulic conductivity;  $P_c/P_D$ , the ratio of the capillary pressure at any elevation to the displacement pressure of the sand; and  $z/\frac{P_D}{W}$ , the ratio of the elevation above the water table to the elevation

of the top of the fully-saturated zone under static conditions.

A differential equation relating these parameters was derived which was based on the assumption that the relative permeability of a sand to water (for  $P_c > P_D$ ) is proportional to  $(P_D/P_c)^b$  where  $b$  is an exponent. The equation which can be solved by numerical methods is

$$\frac{d(P_c/P_D)}{d(z/\frac{P_w}{w})} = 1 + \frac{e}{C} \left(\frac{P_c}{P_D}\right)^b .$$

Solutions applicable to  $P_c$  greater than  $P_D$  but less than one-third atmospheres were obtained by giving  $b$  the value of eight. The assumptions made were based on experimental data published by Corey (10) and Gardner and Fireman (19).

Calculations based on measurements of the  $P_c$  vs saturation function indicated that for the particular sand used in this experiment the value of  $b$  is probably about 16. It is believed that this is much higher than for most soils, the high value of  $b$  being caused by the unusual uniformity of pore sizes of the sand. Limitations of the equipment prevented a quantitative evaluation of the theory. The theory predicts a rather abrupt transition from moist soil to dry soil at the surface when the depth of the water table is increased beyond a critical

depth. The theory also indicates an abrupt decrease in evaporation rate when the surface dries. For a particular depth of water table, the evaporation rate should approach a limiting value as the severity of the ambient evaporating conditions increases. All of these predictions were verified qualitatively.

## A P P E N D I X

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TABLE I. -- DATA OF EVAPORATION FROM COLUMNS OF FINE SAND

RUN	WEST COLUMN						EAST COLUMN						RATIO $E_S/E_E$
	$\Delta V$ CM <sup>3</sup>	$\Delta \theta$ °F	TRUE* $\Delta V$ CM <sup>3</sup>	$\Delta T$ MIN.	$\frac{\Delta V}{\Delta T}$ CM <sup>3</sup> /MIN.	$E_F^{**}$ IN./DAY	$\Delta V$ CM <sup>3</sup>	$\Delta \theta$ °F	TRUE* $\Delta V$ CM <sup>3</sup>	$\Delta T$ MIN.	$\frac{\Delta V}{\Delta T}$ CM <sup>3</sup> /MIN.	$E_S^{****}$ IN./DAY	
15	131.8	-.30	132.8	50	2.657	1.991	132.1	-.34	133.3	50	2.665	1.937	.972
18	161.0	-.14	161.5	90	1.794	1.347	98.8	-.16	99.4	90	1.104	.801	.595
19	151.9	-.07	151.7	324	.468	.351	4.55	-1.60	10.15	295	.0344	.0250	.0712
20	156.8.	-.40	155.4	177	.878	.659	1.21	-.53	3.07	180	.0171	.0124	.0188
22	121.4	-.04	121.5	214	.518	.426	112.0	-.01	112.0	195	.574	.417	.979
23A	398.2	-.62	400.4	320	1.252	.938	346.6	-.67	348.9	320	1.090	.791	.844
24	236.8	-.78	234.1	326	.719	.538	173.6	-.37	172.3	298	.578	.420	.781
25	142.2	-1.12	146.1	1199	.122	.0913	140.5	-1.23	144.8	1187	.122	.0885	.970
26	512.4	-.73	509.8	478	1.044	.783	425.0	-1.01	421.5	492	.857	.622	.794
29A	307.2	-.54	305.3	515	.593	.445	230.8	-.04	230.9	515	.448	.326	.732
30	358.6	-1.62	352.9	458	.770	.577	281.3	-1.12	277.4	485	.572	.415	.718
31A	582.1	-.88	579.0	470	1.232	.924	399.3	-.01	399.3	482	.828	.601	.651
32	418.7	-.52	416.9	379	1.100	.825	40.70	-1.54	46.1	410	.112	.0816	.099
33	396.0	-.45	394.4	284	1.389	1.041	29.80	-1.16	33.9	325	.104	.0757	.0726
34	281.8	-.73	284.4	179	1.590	1.193	239.7	-.90	242.9	177	1.373	.996	.836
35	231.7	-.49	233.4	142	1.643	1.233	191.5	-.48	193.2	138	1.401	1.018	.824
36	348.2	-.40	346.8	262	1.324	.993	279.3	-.26	278.4	260	1.071	.778	.783
39	326.0	-.23	334.0	4301	.0776	.0582	318.6	-.35	330.8	4490	.0737	.0535	.919
40,42,42A	609.8	-.30	609.8	1392	.438	.328	367.2	-2.86	377.1	1464	.257	.187	.569
41	257.2	-.55	259.1	448	.578	.433	134.8	-1.15	138.8	470	.295	.214	.494
43	400.7	-.26	401.6	259	1.55	1.162	139.6	-2.11	147.0	310	.474	.344	.296
44A	471.1	-.08	471.4	275	1.713	1.285	84.0	-1.60	89.6	287	.312	.227	.177
46A	559.8	-.44	561.3	317	1.771	1.328	476.6	-.81	479.4	340	1.410	1.024	.771
49A***	174.9	-.29	175.9	231	.761	.553	151.8	-.65	154.1	247	.624	.468	1.182

\*  $\Delta \theta \times 3.5 + \Delta V = \text{TRUE } \Delta V$

\*\*  $\frac{\Delta V}{\Delta T} \times .75 = E_F$

\*\*\* CHECK RUN - EAST COLUMN WAS CONSIDERED THE FREE WATER SURFACE  $E_F$ . NOTICE THAT THE BURETTE COEFFICIENTS HAVE ALSO BEEN REVERSED

\*\*\*\*  $\frac{\Delta V}{\Delta T} \times .726 = E_S$

$\Delta V$  - VOLUME OF WATER TO MAINTAINED WATER-TABLE CONSTANT.

$\Delta \theta$  - DIFFERENCE IN TEMPERATURE FROM BEGINNING OF RUN TO END OF RUN.

$\Delta T$  - DURATION OF RUN

Table 2. -- WATER-TABLE DEPTH AND WIND VELOCITY MAINTAINED DURING EACH RUN AND THE RATIO OF  $e_s$  to  $e_f$  OBTAINED FROM THE COLUMNS OF FINE SAND

Run	Ratio $e_s/e_f$	Water-table depth inches	Wind Velocity fps
15	.972	0	50
18	.595	24	50
19	.0712	29	14
20	.0188	29	25
22	.979	6	14
23A	.844	6	25
24	.781	12	14
25	.970	12	Calm
26	.794	12	25
29A	.732	24	14
30	.718	24	25
31A	.651	24	35
32	.099	29	35
33	.0726	29	50
34	.836	6	35
35	.824	6	50
36	.783	12	35
39	.919	26	Calm
40, 42, 42A	.569	26	14
41	.494	26	25
43	.296	26	35
44A	.177	26	50
46A	.771	12	45
49A	1.182	0	14

TABLE 3. -- CAPILLARY PRESSURE-DESATURATION DATA FOR THE FINE SAND, SAMPLE #1

HEIGHT OF LEVEL B	HEIGHT OF LEVEL A	$\Delta$ HEIGHT INCHES	PIPETTE READING CM <sup>3</sup>	$\Delta$ VOLUME CM <sup>3</sup>	$\Sigma \Delta$ VOLUME CM <sup>3</sup>	BACK PRESSURE IN. H <sub>2</sub> O	$P_c$ IN. H <sub>2</sub> O	$P_c$ CM. H <sub>2</sub> O	$\frac{P_D}{P_c}$	$\left(\frac{P_D}{P_c}\right)^2$	PERCENT SATURATION	TEMP. OF.
125.0	108.0	17.0	0.48									82.2
125.0	99.5	25.5	0.49									81.0
125.0	99.0	26.0	0.50									80.0
125.0	98.5	26.5	0.50	0	0	4.44	22.06	56.0			100	80.0
125.0	98.0	27.0	0.51	.01	.01	4.45	22.55	57.3			99.6	80.0
125.0	97.5	27.5	0.52	.01	.02	4.47	23.03	58.5			99.3	80.0
125.0	97.0	28.0	0.54	.02	.04	4.50	23.50	59.7			98.5	76.0
125.0	96.5	28.5	0.65	.11	.15	4.67	23.83	60.5	.992	.984	94.5	80.0
125.0	96.0	29.0	0.71	.06	.21	4.76	24.24	61.6	.974	.948	92.4	80.0
125.0	95.5	29.5	0.85	.14	.35	4.96	24.52	62.2	.964	.930	87.3	80.3
125.0	95.0	30.0	0.93	.08	.43	5.10	24.90	63.2	.949	.900	84.4	80.0
125.0	94.5	30.5	1.07	.14	.57	5.31	25.19	64.0	.938	.880	79.3	78.1
125.0	94.0	31.0	1.20	.13	.70	5.52	25.48	64.7	.927	.860	74.6	82.2
125.0	93.0	32.0	1.38	.18	.88	5.80	26.20	66.6	.902	.813	68.0	80.1
125.0	92.0	33.0	1.54	.16	1.04	6.04	26.96	68.4	.877	.770	62.2	80.0
125.0	91.0	34.0	1.71	.17	1.21	6.31	27.69	70.6	.850	.722	56.0	80.7
125.0	90.0	35.0	1.88	.17	1.38	6.58	28.42	72.1	.832	.693	49.8	81.1
125.0	89.0	36.0	2.00	.12	1.50	6.76	29.24	74.3	.808	.653	45.4	80.6
125.0	87.0	38.0	2.19	.19	1.69	7.06	30.94	78.6	.764	.583	38.5	80.3
125.0	86.0	39.0	2.27	.08	1.77	7.17	31.83	80.8	.743	.552	35.6	80.0
125.0	84.0	41.0	2.39	.12	1.89	7.36	33.64	85.5	.702	.493	31.3	80.4
125.0	82.0	43.0	2.47	.08	1.97	7.49	35.51	90.2	.666	.443	28.3	80.9
125.0	80.0	45.0	2.53	.06	2.03	7.58	37.42	95.0	.632	.399	26.2	69.0
125.0	76.0	49.0	2.60	.07	2.10	7.69	41.31	104.8	.572	.328	23.6	79.0
125.0	72.0	53.0	2.70	.10	2.20	7.84	45.16	114.8	.523	.274	20.0	85.0
125.0	69.0	57.0	2.73	.03	2.23	7.89	49.11	124.6	.482	.232	18.9	82.0
125.0	39.0	86.0	2.82	.09	2.32	8.03	77.97	198.1	.303	.092	15.6	80.0

\*  $P_0 = 60.0$  CM.

TABLE 4. -- CAPILLARY PRESSURE-DESATURATION DATA FOR THE FINE SAND, SAMPLE #2

HEIGHT OF LEVEL B	HEIGHT OF LEVEL A	$\Delta$ HEIGHT INCHES	PIPETTE READING CM <sup>3</sup>	$\Delta$ VOLUME CM <sup>3</sup>	$\Sigma \Delta$ VOLUME CM <sup>3</sup>	BACK PRESSURE IN. H <sub>2</sub> O	$P_c$ IN. H <sub>2</sub> O	$P_c$ CM. H <sub>2</sub> O	$\frac{P_D}{P_c}$	$\left(\frac{P_D}{P_c}\right)^2$	PERCENT SATURATION	TEMP. °F
125.0	108.0	17.0	0.49									82.2
125.0	100.0	25.0	0.49									80.6
125.0	99.5	25.5	0.50									81.0
125.0	99.0	26.0	0.50	0	0	4.55	21.45	54.5			100	80.0
125.0	98.5	26.5	0.51	.01	.01	4.56	21.94	55.8			99.6	80.0
125.0	98.0	27.0	0.52	.01	.02	4.58	22.42	56.9			99.3	80.0
125.0	97.5	27.5	0.54	.02	.04	4.61	22.89	58.2			98.6	80.0
125.0	97.0	28.0	0.56	.02	.06	4.65	23.35	59.3			97.9	76.0
125.0	96.5	28.5	0.65	.09	.15	4.79	23.71	60.2	.997	.994	94.6	80.0
125.0	96.0	29.0	0.72	.07	.22	4.91	24.09	61.2	.980	.960	92.1	80.0
125.0	95.5	29.5	0.86	.14	.36	5.51	24.35	61.8	.970	.941	87.1	80.3
125.0	95.0	30.0	0.95	.09	.45	5.30	24.70	62.7	.957	.915	83.9	80.0
125.0	94.5	30.5	1.07	.12	.57	5.50	25.00	63.5	.945	.893	79.6	78.1
125.0	94.0	31.0	1.20	.13	.70	5.71	25.29	64.2	.934	.872	75.0	82.2
125.0	93.0	32.0	1.38	.18	.88	6.01	25.99	66.0	.909	.827	68.6	80.1
125.0	92.0	33.0	1.54	.16	1.04	6.28	26.72	67.8	.885	.793	62.8	80.0
125.0	91.0	34.0	1.70	.16	1.20	6.55	27.45	69.7	.861	.741	57.2	80.7
125.0	90.0	35.0	1.86	.16	1.36	6.82	28.18	71.6	.838	.702	51.4	81.1
125.0	89.0	36.0	1.99	.13	1.49	7.03	28.97	73.5	.816	.666	46.8	80.6
125.0	87.0	38.0	2.19	.20	1.69	7.37	30.63	77.8	.772	.596	39.7	80.0
125.0	86.0	39.0	2.27	.08	1.77	7.50	31.50	80.0	.750	.562	36.8	80.0
125.0	84.0	41.0	2.40	.13	1.90	7.72	33.28	84.5	.710	.504	32.2	80.4
125.0	82.0	43.0	2.49	.09	1.99	7.97	35.13	89.2	.673	.453	28.9	80.9
125.0	80.0	45.0	2.55	.06	2.05	7.97	37.03	94.1	.638	.407	26.8	69.0
125.0	76.0	49.0	2.64	.09	2.14	8.12	40.88	104.0	.577	.333	23.6	79.0
125.0	72.0	53.0	2.72	.08	2.22	8.25	44.75	113.7	.538	.290	20.7	85.0
125.0	68.0	57.0	2.77	.05	2.27	8.33	48.67	123.7	.486	.236	18.9	82.0
125.0	39.0	86.0	2.87	.10	2.37	8.50	77.50	196.8	.305	.093	15.4	80.0

\*  $P_D = 60.0$  CM

Table 5. -- COMPUTATION OF RELATIVE PERMEABILITY-SATURATION CURVE FOR THE FINE SAND USING SAMPLES 1 AND 2, COMPUTED BY THE METHOD OF BURDINE (4).

Saturation	$A_1$ inches <sup>2</sup>	$\frac{A_1}{A}$	$\frac{T}{T_1}$	$\frac{T}{T_1}$	$K_{rw}$
.144	-	0	0	0	0
.20	.212	.0143	.066	.004	.000
.30	1.152	.0777	.182	.033	.003
.40	2.50	.168	.292	.085	.014
.50	4.12	.278	.416	.173	.048
.60	5.95	.401	.532	.283	.113
.70	7.93	.533	.648	.420	.224
.80	10.07	.678	.767	.588	.399
.90	12.33	.831	.884	.782	.650
1.00	14.87	1.000	1.000	1.000	1.000

A = area under the curve  
T = tortuosity  
 $K_{rw}$  = relative permeability to water

## B I B L I O G R A P H Y

## BIBLIOGRAPHY

1. Anderson, E. L., L. J. Anderson, and J. J. Marciano. A review of evaporation theory and development of instrumentation (Lake Mead water loss investigations). Interim report. 1950. 71 p. (U. S. Navy Electronics Laboratory, San Diego, Calif. Report no. 159).
2. Bowen, I. S. The ratio of heat losses by conduction and by evaporation from any water surface. *Physical Review*, 27:774-787, June 1926.
3. Buckingham, Edgar. Studies on the movement of soil moisture. Washington, U. S. Government Printing Office, 1907. 61 p. (U. S. Department of Agriculture, Bureau of Soils, Bulletin, no. 38).
4. Burdine, N. T. Relative permeability calculations from pore size distribution data. *Journal of Petroleum Technology*, 5(3):71-78, March 1953. Cited by A. T. Corey (see bibliography reference 9).
5. Cermak, J. E. and H. J. Koloseus. Lake Hefner model studies of wind structure and evaporation. Final report, part I. Fort Collins, Colo. Colorado Agricultural and Mechanical College, Dept. of Civil Engineering. November 1953. 151 p.
6. Cermak, J. E. and P. N. Lin. Vapor transfer by force convection from a smooth, plane boundary. Fort Collins, Colo. Colorado Agricultural and Mechanical College, Dept. of Civil Engineering. January 1955. 127 p.
7. Cermak, J. E. and A. C. Spengos. Turbulent diffusion of momentum and heat from a smooth, plane boundary with zero pressure gradient. Final report, part II. Fort Collins, Colo. Colorado Agricultural and Mechanical College, Dept. of Civil Engineering. December 1956. 77 p.
8. Colman, E. A., W. B. Hanawalt, and C. R. Burck. Some improvements in the tensiometer design. *American Society of Agronomy. Journal*, 38:455-458, May 1946.

## BIBLIOGRAPHY. -- Continued

9. Corey, A. T. The interrelation between gas and oil relative permeabilities. Producers Monthly, 19:38-41, November 1954.
10. Corey, A. T. Measurement of water and air permeability in unsaturated soil. Soil Science Society of America. Proceedings, 21:7-10, January-February 1957.
11. Cummings, N. W. Relation between evaporation and humidity. National Research Council. Bulletin, no. 68:47-56, February 1929.
12. Cummings, N. W. The evaporation-energy equations and their practical application. American Geophysical Union. Transactions, pp. 512-522, 1940.
13. Dike, P. H. Thermoelectric thermometry. 2nd ed. Philadelphia, Leeds and Northrup Co., 1955. 90 p.
14. Dunkle, R. V., and others. Non-selective radiometers for hemispherical irradiation and net radiation interchange movements. Berkeley, Calif. University of California, Division of Engineering Research, 1949.  
Cited by Anderson, Anderson, and Marciano (see bibliography reference 1).
15. Fukuda, H. Diffusion of water vapor and its exchange between condensation and evaporation in soil. Soil Science, 81:81-95, February 1956.
16. Gardner, W. and J. A. Widtsoe. The movement of soil moisture. Soil Science, 11:215-232, 1921.
17. Gardner, W. R. Calculation of capillary conductivity from pressure plate outflow data. Soil Science Society of America. Proceedings, 20:317-320, July 1956.
18. Gardner, W. R. Some steady state solutions of the unsaturated moisture flow equation with application to evaporation from a water table.  
In press. Soil Science (Ms. used by permission)
19. Gardner, W. R. and M. Fireman. Laboratory studies of evaporation from soil columns in the presence

## BIBLIOGRAPHY. -- Continued

19. Continued  
of a water table.  
In press. Soil Science. (Ms. used by permission)
20. Gurr, C. G., T. J. Marshall, and J. T. Hutton.  
Movement of water in soil due to a temperature gradient. Soil Science, 74:335-345, November 1952.
21. Harris, F. S. and J. S. Robinson. Factors affecting the evaporation of moisture from the soil. U. S. Department of Agriculture. Journal of Agricultural Research, 7(10):439-461, 1916.
22. Hunter, A. S. and O. J. Kelley. Changes in construction of soil moisture tensiometer for field use. Soil Science, 61:215-217, March 1946.
23. King, F. H. Destructive effects of winds on sandy soils and light sandy loam. Wisconsin Agricultural Experiment Station. Bulletin, no. 42, 1894. 29 p.
24. Koliasev, F. E. Measures for the control of evaporation of soil moisture. Sbornik Rabot po Agronomicheskoe Fiziki, 3:67-81, 1941.  
(Translation in author's possession).
25. Kucera, C. L. Some relationships of evaporation rate to vapor pressure deficit and low wind velocity. Ecology, 35:71-75, January 1954.
26. Lemon, E. R. The potentialities for decreasing soil moisture evaporation loss. Soil Science Society of America. Proceedings, 20:120-125, January 1956.
27. Moore, R. E. Water conduction from shallow water tables. Hilgardia, 12(6):383-426, March 1939.
28. Parshall, R. L. Experiment to determine rate of evaporation from saturated soils and river bed sands. American Society of Civil Engineering. Transactions, 94:961-999, 1930.
29. Penman, H. L. Laboratory experiments on evaporation from fallow soil. Journal of Agricultural Science,

## BIBLIOGRAPHY. -- Continued

29. Continued  
31:454-465, October 1941.
30. Perry, J. J. and D. M. Corbett. Hydrology of Indiana lakes. Washington, U. S. Government Printing Office, 1956. 347 p. (U. S. Department of the Interior. Geological survey. Water-supply Paper, no. 1363).
31. Prandtl, L. The mechanics of viscous fluids. Aerodynamics Theory, Division G, 3:145-150, 1935.  
Cited by Anderson, Anderson, and Marciano (see bibliography reference 1).
32. Richards, L. A. and W. Gardner. Tensiometers for measuring the capillary tension of soil water. American Society of Agronomy. Journal, 28:352-358, May 1936.
33. Richard, L. A. Soil moisture tensiometer materials and construction. Soil Science, 53:241-248, April 1942.
34. Richard, L. A. Methods of measuring soil moisture tension. Soil Science, 68:95-112, July 1949.
35. Ridgaway, C. B. Experiments in evaporation. Wyoming Agricultural Experiment Station. Bulletin, no. 52:43-55, April 1902.
36. Schlichting, H. Boundary layer theory. New York, McGraw-Hill. 1955. 535 p.
37. Sutton, O. G. Convection in the atmosphere near the ground. Royal Meteorological Society. Quarterly Journal, 74(319):13-31, January 1948.  
Cited by Anderson, Anderson, and Marciano (see bibliography reference 1).
38. Thornthwaite, C. W. and B. Holzman. Measurement of evaporation from land and water surfaces. Washington, U. S. Government Printing Office, 1942. 143 p. (U. S. Department of Agriculture. Technical Bulletin, no. 817).
39. Turnage, W. V. and E. B. Shreve. Note on atmospheric aridity. Ecology, 20(1):107-109, January 1939.

## BIBLIOGRAPHY. -- Continued

40. U. S. National resources committee. Special advisory committee on standards and specifications for hydrology data. Deficiencies in basic hydrologic data. Washington, U. S. Government Printing Office, 1936. 66 p.
41. Veihmeyer, F. J. and A. H. Hendrickson. Rates of evaporation from wet and dry soils and their significance. *Soil Science*, 80:61-67, July 1955.
42. Von Kármán, T. Turbulence and skin friction. *Journal of the Aeronautical Sciences*, 1:1, 1934.  
Cited by Anderson, Anderson, and Marciano (see bibliography reference 1).
43. Woodruff, N. P. Shelterbelt and surface barrier effects on wind velocities, evaporation, house heating, and snowdrifting. Kansas Agricultural Experiment Station. Technical Bulletin, no. 77, December 1954. 27 p.
44. Wyllie, M. R. J. and M. B. Spangler. Application of electrical resistivity measurements to problems of fluid flow in porous media. *American Association of Petroleum Geologists. Bulletin*, 36(2): 359-403, February 1952.
45. Zingg, A. W., N. P. Woodruff, and C. L. Englehorn. Effect of wind-row orientation on erodibility of land in sorghum stubble. *Agronomy Journal*, 44: 227-230, May 1952.