A PROCEDURE FOR RAPIDLY DETERMINING TRANSPIRATION RATES AND EPIDERMAL PERMEABILITIES OF FRUITS

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JOE PERRY GENTRY

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This is to certify that the

thesis entitled

A PROCEDURE FOR RAPIDLY DETERMINING
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Joe Perry Gentry

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ABSTRACT

A PROCEDURE FOR RAPIDLY DETERMINING
TRANSPIRATION RATES AND
EPIDERMAL PERMEABILITIES OF FRUITS

By

Joe Perry Gentry

Transpiration rates of grapes and cherries as measured by mass-transfer coefficients were evaluated from experimental measurements and a lumped capacity unsteady-state mass-transfer analysis. Parameters to be used in mass-transfer equations to describe the flow of moisture through the epidermis were determined. Effects of mechanical polishing and chemically disturbing the cuticle on the mass-transfer coefficient of grapes were found.

Fruits were placed in a small container of dry air, and the dew-point of the air was observed by circulating the air through a hygrometer. The dew points were converted to vapor pressure and the mass-transfer coefficient and an apparent equilibrium relative humidity were determined by iteratively fitting the vapor pressure ratio to an exponential regression.

Permeabilities of the epidermis were determined from the thickness of the tissue, apparent and true convective mass-transfer coefficients.

The true convective mass-transfer coefficient was considered to be the mass-transfer coefficient of the peeled fruit, while the apparent mass-transfer coefficient was the mass-transfer coefficient from the unpeeled fruit.

Values of the mass-transfer coefficients were of the order of 0.4×10^{-8} to 2.0×10^{-8} grams of H_2O per (minute) (square mm) (mm of mercury). The pedicel with its small surface area in relation to the surface area of the fruit was a significant factor in the total mass transfer.

Air flows over a rnage of from one to ten air changes per minute had no significant effect on the convective mass-transfer coefficients.

For purposes of predicting epidermal mass transfer, fruits were modeled after a slab. The relationship between vapor pressure and time in a lumped capacity unsteady-state mass-transfer system as predicted by these equations was in close agreement with experimental values.

The procedure developed in this study is expected to be quite valuable in developing systems in which the moisture loss of fresh fruits will be reduced.

Approved B A Stout
Major Professor

Approved B A Stout
Department Chairman

A PROCEDURE FOR RAPIDLY DETERMINING TRANSPIRATION RATES AND EPIDERMAL PERMEABILITIES OF FRUITS

By

Joe Perry Gentry

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1970

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For the cooperative effort that made this study possible, the author is indebted to many people in both the Department of Agricultural Engineering, University of California, Davis California, and the Department of Agricultural Engineering, Michigan State University.

Recognition must be given to my wife, daughter, and son, without whose devotion and patience this work would not have been completed.

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A	=	area
A_W	=	water activity
C	=	concentration
C_m	=	specific moisture coefficient
D	=	diffusivity
E	=	rate of transpiration
F	=	leaf dimension in direction of air flow
G	=	air flow rate
J	=	transpiration constant
K	=	rate constant
L	=	empirical constant
N	=	empirical constant
M	=	moisture content
$\dot{M}$	=	mass flow rate
P	=	vapor pressure in the air
P_a	=	partial pressure of the air
P_E	=	vapor pressure at equilibrium
P_S	=	vapor pressure at the surface of fruit
P_T	=	total pressure
P_1	=	vapor pressure inside the fruit

R	=	ideal-gas constant
T	=	temperature
U	=	chemical potential
V	=	volume
$\overline{V}$	=	partial molar volume
W	=	leaf dimension perpendicular to air flow
W_s	=	humidity ratio
X	=	linear distance
a	=	intercept of regression equation
b	=	slope of regression equation
e	=	2.71828
h	=	apparent mass-transfer coefficient
h_g	=	mass-transfer coefficient
h_g'	=	true mass-transfer coefficient (i.e., from a fruit with epidermis removed or a water source)
h_q	=	heat-transfer coefficient
r	=	radial distance
r_i	=	resistance of component i
r.h.	=	relative humidity, decimal
t	=	time
v	=	velocity
Ψ	=	water potential
λ	=	epidermal permeability
ρ	=	density

$\frac{dW}{dt}$	=	drying rate
$\frac{dQ}{dt}$	=	heat-transfer rate
Δt	=	time increment
Δx	=	distance increment
exp	=	exponential

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INTRODUCTION

1.1 The Problem

Desiccation (moisture loss) from fresh fruit is an important market quality factor, for the resulting shrivel or shrinkage not only affects appearance, texture, and flavor but also reduces salable tonnage. The so-called "tired" or "dead" look of fruits in the market is due largely to desiccation. As fruits shrivel, they take on a dull lifeless appearance which contrasts seriously with the bright fresh condition of high-quality fruit. Desiccation can also drastically affect the stem condition of fruit. The pedicels (stems) of cherries and table grapes show signs of shrinkage before the fruits exhibit signs of water loss. Nelson (1964) stated that the appearance of stems is often used accurately by experienced fruit buyers as a measure of fruit condition and a determination as to whether it has been abused in post-harvest handling. The ASHRAE Guide and Data Book 1964 Applications (1964) states that with grapes the first noticeable effect of moisture loss is drying and browning of stems and pedicels, and this effect becomes apparent with a loss of only 1 to 2 percent of the weight of the fruit. The fruit also loses its turgidity and softens when the loss reaches 3 to 5 percent.

As pointed out by Gentry et al.(1964), Lentz et al.(1964), and Lentz (1966) the rate that fruit loses moisture is directly related to the difference in the vapor pressure of the fruit and the vapor pressure of the surrounding air.

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Moisture loss causes the crisp, turgid texture of fruit to become soft or rubbery and unpleasant to the touch or taste. Moisture loss also causes packed fruit to settle in the container, which makes the container appear slack or only partly full. This presents an unfavorable appearance to fruit buyers, who are essentially concerned with the amount of salable fruit in the container. Mitchel et al.(1968) report that loose fruits in a container are more subject to injury than are firmly held fruits, because vibrations may cause the loose fruits to move about, which may result in surface scarring.

Moisture loss of fruit is an intricate phenomenon in the total handling system. In discussing transitions in produce handling, Roark (1964) made the following statement:

> "To me, perishable handling is the art or science of bringing the fully matured fresh fruit or vegetable -- at the peak of appearance, flavor, and taste on tree, vine or plant -- right to the dining table. Or coming as close to that objective as conditions, including time, geography, and economic realities permit."

The textural properties of fresh fruits, commonly referred to as crispness, firmness, and succulence, are all related to the moisture content of the frut. Any loss of moisture from fresh fruit has an undesirable effect on these properties. A better understanding of the desiccation process should help in developing systems in which the moisture loss of fresh fruits will be reduced. In order to improve

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systems, such as these described by Gentry et al.(1968) for reducing the moisture loss of grapes, a procedure for rapidly determining transpiration rates of fruits is essential.

Improvements in the appearance and quality of fresh fruits offered the consumer is a worthy goal for such a study. These improvements depend upon a clear understanding of the desiccation process and the behavior of fruit under the influence of physical factors which may aggravate this process.

1.2 Objectives

The overall goal of this study was to develop a method for rapid and accurate prediction of the transpiration rates of intact fruit organs and fruit components. Quantitative measures have been made of the moisture loss of some fruits under steady-state mass-transfer conditions. The objectives of this study were: 1) to determine mass-transfer coefficients and epidermal permeabilities for the berry and pedicel of cherries and grapes under specific unsteady-state conditions; and 2) to explain the physical movement of moisture through the epidermal tissue and to the surrounding air during an unsteady-state desiccation process.

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II. LITERATURE REVIEW

Desiccation or transpiration of fresh fruit is a mass-transfer process in which water vapor moves from the surface of the fruit to the surrounding air. Water, the most abundant compound in fresh fruit, forms a continuous liquid phase through the fruit and pedicel*. Analysis of the transpiration of fresh fruits requires a thorough understanding of the structure and properties of the fruit.

2.1 Water as a Fruit Component

Fresh fruits are intact plant organs which, as noted by Esau (1967), generally have structural-type fruit walls, classified as the parenchymatic fleshy type. The structural unit of the fruit wall is the cell. The cells, grouped together, form tissues, which in fruits may be classified as fundamental or ground tissue and protective tissue.

Each cell in the fruit wall is enclosed by its own cell wall. According to Robbins et al. (1967), adjacent cells are cemented together by means of the middle lamella, which is composed primarily of a pectic compound. The characteristic softening of fruits during the ripening process is caused by this pectic compound becoming more soluble in the cell-wall water and losing its binding properties. Slatyer (1967) stated that, in turgid cells, most cell-wall water is probably held by surface tension

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*See Glossary (p.73) for definition of botanical terms such as this.

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The ground tissues in fruit are primarily parenchyma cells, which are large, thin-walled, and approximately 14-sided polyhedrons (Figure 2.1). Parenchyma cells are often separated by intercellular spaces which, according to Reeve (1953), may constitute as much as 25 percent of the total volume of the fruit tissue. These intercellular spaces may be filled with air or water.

The protoplast in the fully grown parenchyma cell constitutes about 5 percent of the total cell volume and may have a water content of 95 percent. The protoplast contains proteins, which have a strong affinity for water.

The vacuole, as noted by Van Arsdel and Copley (1964), is important in desiccation because it may hold 90 percent of the water in the fruit. Slatyer (1967) states that the vacuole frequently has water-content levels of 98 percent. Water is retained in the vacuole primarily by osmotic forces. The vacuole is also important in fresh fruit because of its role in creating the textural attributes of crispness, firmness, succulence, and turgidity. Turgor is the result of osmotic pressure developed within the vacuole and the pressure exerted by the relatively rigid cell wall.

In fruits, the protective tissues, which include the epidermis and periderm tissues, protect the organ from mechanical injury, insects, and microorganisms, and play an important role in desiccation or moisture loss. Part of the epidermal surface of most fresh fruits is made up of

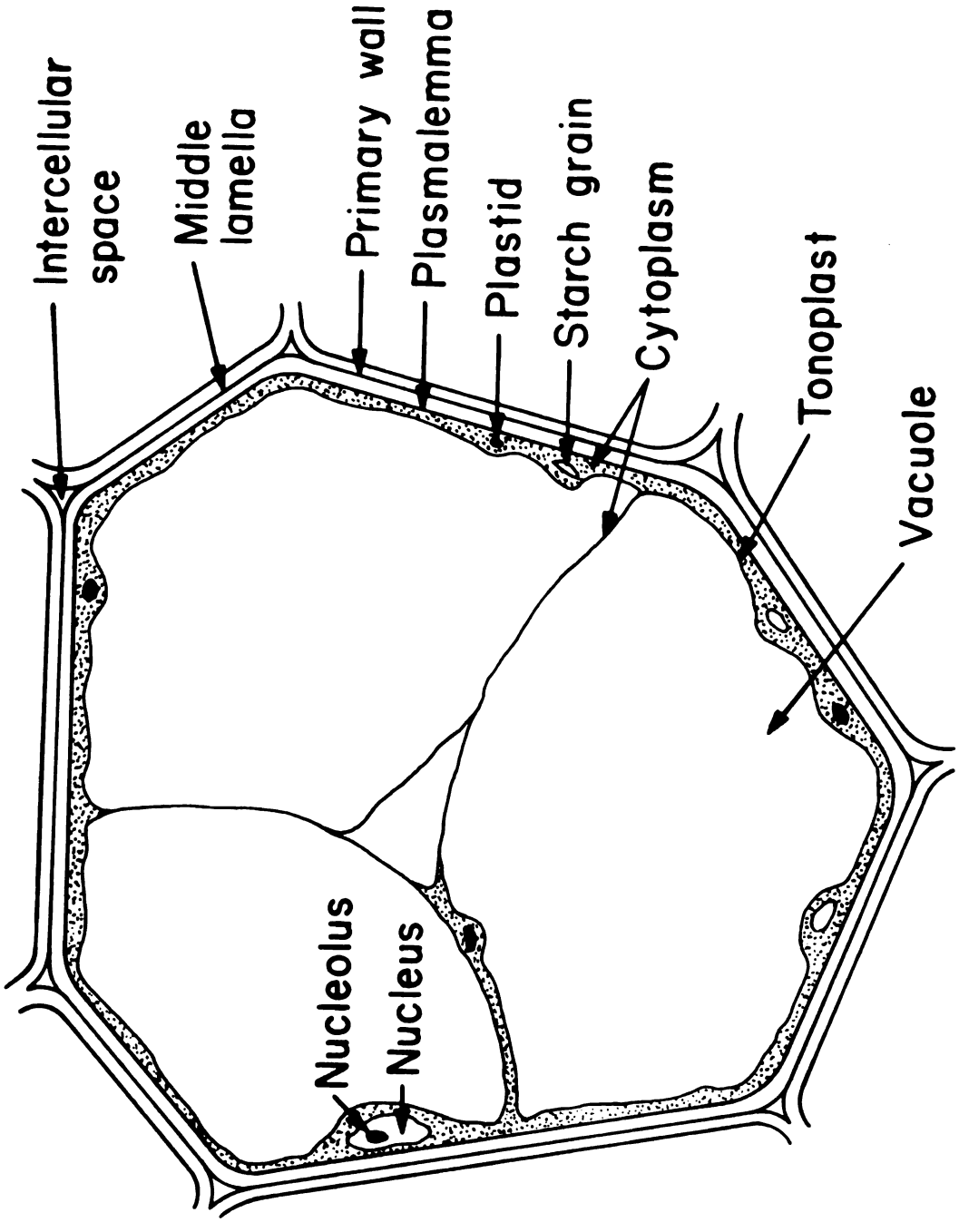

Figure 2.1 Diagram of a Mature Parenchyma Cell (Van Arsdale and Copley, 1964).

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microscopic pores or valves, called stomata. There may also be lenticels, which consist mostly of patches of suberized cells. The epidermis is covered with a cuticle, which is a waxlike layer of cutin.

2.2 Water as a Pedicel Component

The pedicel contains xylem and phloem conducting tissues. Xylem tissues contain mainly water and mineral salts absorbed from the soil, while phloem tissues contain mainly metabolites produced in leaves.

Slatyer (1967) noted that water in these tissues may be subjected to tensions in excess of 100 bars during transpiration.

Esau (1967) pointed out that tyloses, which are formed in injured pedicel tissue, may effectively block moisture movement through this tissue.

2.3 Types of Transpiration

Devlin (1966) classified transpiration of plants as: 1) stomatal; 2) cuticular; and 3) lenticular. He stated that water loss through cuticular and lenticular transpiration is insignificant compared with water lost through stomatal transpiration. Some fruits (e.g. grapes) have no stomata on the fruit surfaces but numerous stomata on the pedicels.

2.4 Transpiration Models

Raschke (1960) and Gates (1968) have used electrical-circuit models to describe transpiration by leaves. Gates (1968) presented the following

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equation to describe the rate of transpiration per unit leaf area:

$$E = \Delta P/r = [P_l\ (T_l) - P_a\ (T_a)]\ /\ (r_l + r_a), \qquad (1)$$

where

E = Rate of transpiration per square cm leaf area

$P_l\ (T_l)$ = Concentration of water vapor considered at leaf temperature, T_l

$P_a\ (T_a)$ = Concentration of water vapor in the free air at temperature, T_a

r_l = Internal resistance to flow

r_a = External resistance in the adhering air layer

Gates (1968) also developed the following empirical relationships from wind-tunnel studies:

$$E = [P_l\ (T_l) - r.h\ P_{as}\ (T_a)]\ /\ [r_l + K(F^{0.35}\ W^{0.20})\ /v^{0.35}] \qquad (2)$$

where

r.h. = Relative humidity of the free air

P_{as} = Saturated vapor concentration

K = Coefficient dependent on D and W

F = Leaf dimension in direction of air flow

W = Leaf dimension perpendicular to air flow

v = Velocity of air flow

Internal leaf diffusive resistances of several plants, summarized by Gates,(1968) are presented here in Table 2.1. The leaf resistance is determined by the stomatal resistance, r_s, in parallel with a cuticular resistance, r_c. The use of circuit theory for modeling plant transpiration

Table 2.

Plant
Poplar
Birch
Oak
Maple
Sunflower
Cotton
Turnip, sugar
Barley
Tomato and bea
Wheat

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Table 2.1 -- Resistances to the Diffusive Transfer of Water Vapor Through the Stomates, r_s, the Cuticle, r_c, and the Boundary Layer, r_a (Gates, 1968).*

Plant	r_s	r_c	r_l	r_a	r
Poplar	2.3		2.3	0.6	2.9
Birch	1.2	70	1.2	0.8	2.0
Oak	7.1	265	6.9	0.8	7.7
	16.2	315	15.4	0.9	16.3
Maple	5.0	82	5.3	0.8	6.2
Sunflower	0.4		0.4	0.5	1.0
Cotton	1.0	32.3	1.0	2.1	3.1
Turnip, sugar beet			1.5-1.7		
Barley			1.0-2.0		
Tomato and bean			2.3-3.3		
Wheat			0.2-2.4		

* The total leaf resistance is given by $r_l = \frac{r_s r_c}{(r_s + r_c)}$

and the total resistance of the diffusion pathway is given by $r = r_l + r_a$. Resistance units are in sec cm^{-1}.

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has been critized by Cooke (1966), who has suggested a field-theory approach. When analyzing the flow from individual stoma, the field theory would permit a concentration gradient along the leaf whereas the circuit theory approach does not.

Wells (1962), Gentry et al. (1963), and others have reported on the weight loss of various fruits as related to temperature, humidity, and air velocity in storage. These studies have all been gravimetric studies under "constant" conditions.

2.5 Water Potential and Water Activity

Fresh fruits, like plants, most food products, and other biological materials, are hygroscopic. When placed in a confined environment, hygroscopic materials come to an equilibrium moisture content which is a function of the temperature and humidity of the ambient air and of whether they are gaining or losing moisture.

Slatyer (1967) defines the energy of water in plant systems on the basis of thermodynamic free energy and uses the term "water potential." This relationship may be written as

$$\Psi = \left(\frac{U_w - U_w^\circ}{\overline{V}_w}\right) = \frac{RT}{\overline{V}_w} \ln P/P_o \qquad (3)$$

where

Ψ = Water potential

$(U_w - U_w^\circ)$ = The difference between the chemical potential of water in the system and that of pure free water at the same temperature.

$\overline{V}_w$ = Partial molar volume of water

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R = Gas constant

T = Absolute temperature

P = Vapor pressure of water in the system

P_o = Vapor pressure of pure free water at the same temperature

Water potential is normally determined under equilibrium conditions by means of a thermocouple psychrometer which, as noted by Hoffman and Splinter (1968), for accuracy of $\pm$ 0.1 bar, requires the control and measurement of system temperature to 0.001° C.

Rockland (1969) defines "water activity" as the relative chemical activity of water, and presents the following thermodynamic equation:

$$U - U^\circ = RT \ln A_w$$

where

U = Chemical potential of water in a food

U° = Chemical potential of pure water

A_w = Water activity term = P/P_o

Both water potential and water activity as defined above are derived from the free-energy relationship, which is given by Perry (1963) as

$$U = F(P, V, T, C, \text{etc.})$$

and

$$dU = \left(\frac{\partial U}{\partial P}\right)_{T, V, C, \text{etc.}} dP + \left(\frac{\partial U}{\partial T}\right)_{P, V, C. \text{etc.}} dT + \left(\frac{\partial U}{\partial C}\right)_{T, V, P, \text{etc.}} dC + \text{etc.} \quad (4)$$

In the water-activity and water-potential equations given above, it is assumed that all the independent properties other than pressure are held constant.

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2.6 Theory of Mass Transfer During Drying

Desiccation, moisture loss, or transpiration of fresh fruit is basically a mass flow process, and theories of moisture distribution during drying should be applicable in analysis of this process. The simplest approach to moisture distribution during drying is by the use of differential equations developed by Newman (1931) for various configurations. These equations are based on

$$\frac{\dot{M}}{A} = -D \frac{\partial C}{\partial X} \tag{5}$$

where

$\dot{M}$ = Mass flow rate, mass/time

A = Area

D = Diffusivity, area/time

C = Concentration, mass/volume

X = Linear distance

Newman (1931) noted the analogy of this equation to Fourier's Law of condition for heat, and modified the heat-transfer equations to obtain mass-diffusion equations in usable forms. In spherical coordinates assuming symmetry with respect to the origin, the equation is

$$\frac{\partial C}{\partial t} = D \left[\frac{\partial^2 C}{\partial r^2} + \frac{2}{r} \frac{\partial C}{\partial r} \right] \tag{6}$$

where

t = Time

r = Radial distance

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In cylindrical coordinates, with no angular dependence, the equation is

$$\frac{\partial C}{\partial t} = D \left[\frac{\partial^2 C}{\partial r^2} + \frac{1}{r} \frac{\partial C}{\partial r} + \frac{\partial^2 C}{\partial Z^2} \right] \tag{7}$$

where

Z = Axial distance

In one-dimensional cartesian coordinates the equation is

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial X^2} \tag{8}$$

Van Arsdel (1947) noted that several characteristics of moist bodies, besides concentration differences, might be pictures in the role of diffusion-producing potentials. An obvious one is the activity of the moisture at any given point, which may be measured by its equilibrium vapor pressure. In diffusion studies it is customary for the conductance variable to be called 'permeability' when the potential is vapor pressure, and 'diffusivity' when the potential is concentration. Tuwiner (1962) defines permeability as a numerical measure of the rate at which transfer of a stated component occurs under specific conditions.

Sherwood (1929a, 1929b, 1930) describes three states in the drying of porous solids, which he refers to as the 'constant-rate period', the 'first falling-rate period,' and the 'second falling-rate period.' The constant-rate period is that in which evaporation takes place at the solid surface, with liquid diffusion from within the solid being sufficient to maintain saturation at the surface. The principal resistance to mass transfer during this period is in the removal of vapor from the surface,

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and the rate of mass transfer is the same as from a free liquid surface. Agricultural products, as noted by Hall (1957) and Henderson and Perry (1955), seldom exhibit a constant-rate drying period of any significance. If a constant rate exists it would be exhibited in the transpiration of fresh fruit.

Sherwood (1929a) describes the first falling-rate period as one in which evaporation takes place at the surface but with the rate of moisture removal restricted by resistance to diffusion of liquid to the surface. Hall (1957) gives the following equation, which during the first falling-rate period relates moisture content of a drying solid to time.

$$\frac{M_t - M_E}{M_0 - M_E} = e^{-Kt}$$

where

M_t = Moisture content at time t

M_0 = Initial moisture content, dry basis

M_E = Equilibrium moisture content, dry basis

t = Time

K = Drying constant, a property of the material and drying conditions, time^{-1}

Hall (1957) states, for hay drying

$K = L - NG$

where

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N = Function of temperature and relative humidity

G = Mass flow rate of air, (air mass/dry matter mass)

The second falling-rate period is one in which evaporation takes place within the solid and in which heat and vapor diffusion are the controlling factors. This period would not be applicable in the area of this study.

Fresh fruits, like other biological materials, may be hygroscopic. The equilibrium moisture content of hygroscopic materials is a function of the temperature and humidity of the ambient air and of whether they are gaining or losing moisture (hysteresis). The equilibrium moisture is usually determined from an isothermal curve, but for a computational approximation Henderson (1952) has derived the equation

$$1 - \text{r.h.} = e^{-LTM_E^N} \tag{10}$$

where

r.h. = Relative humidity

M_E = Equilibrium moisture content

T = Temperature, °F

L, N = Constants, properties of the material

During the constant-rate drying period, moisture movement within the solid is rapid enough to maintain a saturated condition at the surface, and the rate of moisture transfer is controlled by the rate of heat transfer to the evaporating surface. The rate of mass transfer balances the rate of heat transfer, and the temperature of the surface remains constant. Perry (1963) stated thatthe rate of evaporation of water from the surface is governed by the external conditions and is essentially independent of the nature of the solids.

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Jason (1958) noted that during the constant-rate drying period the mass transfer could be defined by the following:

$$\frac{dW}{dt} = h_g A (P_s - P) \tag{11}$$

where

W = Weight of mass transferred (gm)

t = Time (min)

$\frac{dW}{dt}$ = Drying rates (gm/min)

h_g = Mass transfer coefficient (gm/min - cm^2 - mm Hg)

A = Surface area (cm^2)

P_s = Partial pressure of the vapor at the surface (mm Hg)

P = Partial pressure of the vapor in the air (mm Hg)

The rate of heat loss, dQ/dt, is given by the equation

$$-\frac{dQ}{dt} = H \left(\frac{dW}{dt}\right) \tag{12}$$

where H, the latent heat of vaporization at a surface temperature, T_s, is given by Clapeyron's equation

$$\frac{dP_s}{dt} = \frac{H}{T_s (V_1 - V_2)} \tag{13}$$

where

H = Latent heat of vaporization (cal/mole)

T_s = Surface temperature (°K)

V_1 = Volume of moisture in vapor phase (cc)

V_2 = Volume of moisture in liquid phase (cc)

The rate of heat transfer is

$$\frac{dQ}{dt} = -h_q A (T_a - T_s) \tag{14}$$

where

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h_q = Effective heat transfer coefficient

T_a = Air temperature (°C)

T_s = Surface temperature (°C)

When heat is supplied by the air, dynamic equilibrium is established between the rate of heat transfer to the material and the rate of vapor removal from the surface. Then the following equation gives the moisture transfer rate:

$$\frac{dW}{dt} = \frac{h_q A (T_a - T_s)}{H} = -h_g A (P - P_s) \qquad (15)$$

Perry (1963) stated that when heat transfer is by convection only, then the surface temperature, T_s, under equilibrium conditions is the wet-bulb temperature of the air, and P_s is the vapor pressure at this temperature. Gorling (1958) noted that this analysis holds only when evaporation effectively takes place at the highly moist surface.

Perry (1963) also pointed out that the magnitude of the constant rate from this equation depends upon the following: 1) the heat or mass-transfer coefficient; 2) the area exposed to the drying medium; and 3) the temperature or humidity difference between the air and the wet surface of the solid. These factors are all external variables and do not depend on the internal mechanism of moisture flow.

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2.7 Methods for Measuring Permeability

Osmometers such as those described by Dumbroff (1968) are often used to measure permeabilities of plant tissue. Osmometers produce a steady-state potential across the tissue by placing the tissue between two solutions with different osmotic pressures.

Many biological materials are somewhat soluble in the solutions used in osmometers and physical changes in the tissue, such as leaching of solids (e.g. the color will leach out of grapes epidermal tissue when placed in water), may take place when the tissue is placed in the osmometer.

ASTM Book of Standards Part 27 (1968) describes tests used for measuring the rate that moisture vapor will permeate plastic membranes. These tests provide a moisture vapor potential across the membrane by sealing the membrane to a container which has either water or a desiccant inside. The weight loss or weight gain per unit of time of the continer, which is placed in a steady-state environment, is a measure of permeability. In this method only water vapor is in contact with the membrane.

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III. DEVELOPMENT OF MOISTURE-TRANSFER EQUATIONS

The mass transfer from a simple pan humidifier can be expressed by the following equation:

$$\frac{\dot{M}_s}{A} = h_g (P_S - P) \tag{16}$$

where

$\dot{M}_s$ = Mass transfer rate, grams per minute.

A = Mass transfer surface area, square mm.

h_g = Mass transfer coefficient, grams per (minute) (square mm) (mm of mercury)

P_S = Partial pressure of the vapor at the surface, mm of Hg

P = Partial pressure of the vapor in the air, mm of Hg

The mass transfer from a fruit to a small volume of air can be analyzed as a lumped-mass-capacity system. Such systems are idealized since a vapor-pressure gradient must exist in a material if mass is to be conducted into or out of the material. In general, the smaller the body the more realistic the assumption of a uniform vapor pressure; in the limit a differential volume could be employed. When a fruit is placed in a small container of dry air, the lumped-mass-capacity method of analysis might be used if we could justify an assumption of uniform fruit moisture content during the mass-transfer process. Clearly, the moisture distribution in the fruit would depend on the moisture conductivity of the fruit and the mass-transfer conditions from the surface of the fruit to the surrounding air, i.e., the surface-convection mass-transfer coefficient. We should obtain a reasonably uniform mass distribution

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$$\frac{P - P}{P_0 - P}$$

in the fruit if the resistance to mass transfer inside the fruit were small compared with the convection resistance at the surface, so that the major mass-transfer gradient would occur through the boundary layer at the surface. The lumped-mass-capacity analysis is one which assumes that the internal resistance is negligible in comparison with the external resistance.

Assuming the process is isothermal, the convective mass loss from the fruit is given by the following equation:

$$\dot{M} = h_g A (P - P_E) = - C_m \rho V \frac{dP}{dt} \qquad (17)$$

where

P = Partial pressure of the vapor in the air, mm of Hg

P_E = Partial pressure at equilibrium

C_m = Specific moisture coefficient, gram of moisture/gram of dry air per (mm of mercury)

ρ = Density of air, gram of dry air per cm^3

V = Volume of air, cm^3

t = Time, minutes

$\frac{dP}{dt}$ = Rate of vapor pressure change, mm of mercury per minute

with initial conditions

$$P = P_0$$

$$t = 0$$

The solution to equation (17) is

$$\frac{P - P_E}{P_0 - P_E} = \exp \left(- \frac{h_g A}{\rho C_m V} t\right) \qquad (18)$$

The assumption of an isothermal process insures that P_E is constant. This assumption can be justified provided the volume of air is sufficiently small to insure that the evaporation of moisture from the surface of the fruit does not cause a temperature drop at the surface of the fruit. In this study 0.006 gram of moisture would raise the dew-point temperature of the volume of air used from 0 to 70° F. If all the latent heat necessary to evaporate this moisture was provided by the fruit, it would result in a temperature drop of approximately 1/2° F for a grape weighing 9 grams. Because of the time interval during which this evaporation takes place and because of the high air-flow rates most of the heat necessary for this evaporation can be expected to be furnished by conduction from the walls of the system. Heat of respiration, although small, and heat from the air pump would also contribute to furnishing the heat for evaporation.

3.1 Specific-Moisture Coefficient

If dry air and water vapor are mixed, according to Dalton's Rule each gas occupies the whole volume of the container at the temperature of the mixture and the pressure of the mixture is the sum of the individual pressures. Assuming that both behave like perfect gases:

$$V_T = \frac{N_a RT}{P_a} = \frac{N_w RT}{P} = \frac{(N_a + N_w)\, RT}{P_T} \qquad (19)$$

where

V_T = Total volume

N_a = Mols of dry air

N_w = Mols of water vapor

P_a = Pressure of dry air

P = Pressure of water vapor

P_T = Total pressure

The partial pressure of each constituent is its mol-fraction multiplied by the total pressure of the mixture. Thus

$$P = \frac{N_w}{N_a + N_w} \quad P_T \tag{20}$$

$$P_a = \frac{N_a}{N_a + N_w} \quad P_T \tag{21}$$

The humidity ratio, W_s, is determined by multiplying the mol-ratio N_w/N_a by the ratio of molecular weights (18.016/28.966 = 0.622). Thus

$$W_s = 0.622 \frac{P}{P_T - P} \tag{22}$$

The specific-moisture coefficient from equation (17) is the rate of change of the humidity ratio with vapor pressure. From equation (22) it can be seen that this rate is not linear. However, over the range from 0 to 70° F, with humidity ratios and vapor pressures determined for 5° intervals, the linear regression equation of humidity ratio and

vapor pressure is given by

$$W_s = -0.000037 + 0.000841\ P \tag{23}$$

where

W_s = Humidity ratio, grams of water vapor per gram of dry air

P = Vapor pressure, mm of mercury

The correlation coefficient was 0.999954.

The specific moisture coefficient, C_m, is thus

C_m = 0.000841 gram of water vapor/gram of dry air per mm of mercury

3.2 Epidermal Permeability

Because the epidermis of a fruit is a thin layer relative to the radius, it can be approximated as a flat layer for purposes of determining epidermal permeability from mass-transfer coefficients (Figure 3.1). Assuming that the resistance to moisture movement can be described by one apparent mass-transfer coefficient,

$$\frac{\dot{M}}{A} = h\ (P_1 - P) \tag{24}$$

where

$\frac{\dot{M}}{A}$ = Mass flow rate per unit area

h = Apparent mass-transfer coefficient

P_1 = Vapor pressure inside fruit

P = Vapor pressure in air

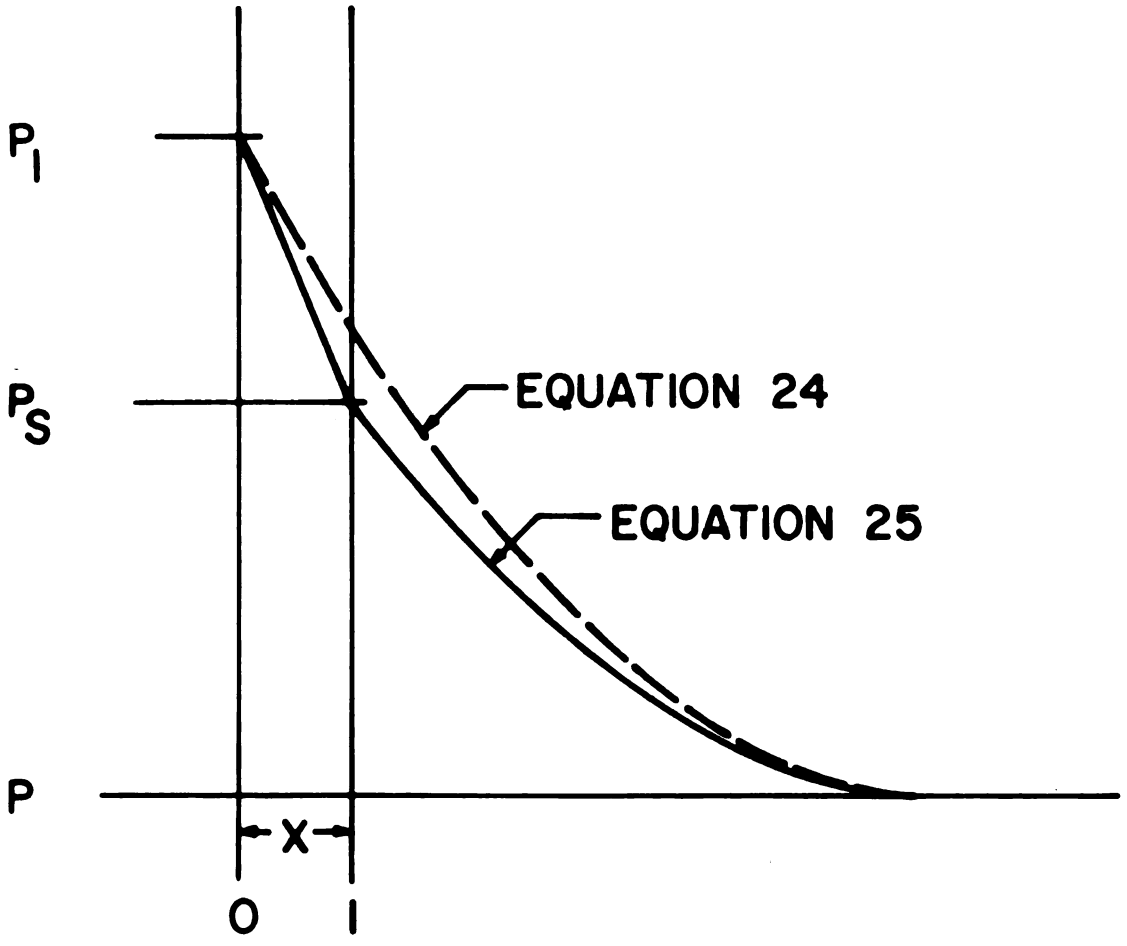


Figure 3.1 Locations of Surfaces for Determination of Epidermal Permeability.

If the resistance is assumed to be diffusive and convective in series, and the epidermis is assumed to be sufficiently thin that $\frac{dP}{dX}$ can be replaced by $\frac{P_1 - P_S}{X}$, then

$$\frac{\dot{M}}{A} = h_g' (P_S - P) = \frac{\lambda}{X} (P_1 - P_S) \tag{25}$$

where

h_g' = True convection coefficient

λ = Epidermal permeability

P_S = Vapor pressure at surface

X = Thickness of epidermis

Solving for P in equation (24)

$$P = \frac{h P_1 - \frac{\dot{M}}{A}}{h} \tag{26}$$

From equation (25)

$$\frac{\dot{M}}{A} = \frac{\lambda}{X} (P_1 - P_S) \tag{27}$$

Which is used in equation (26) to give:

$$P = \frac{h P_1 - \frac{\lambda}{X} (P_1 - P_S)}{h} \tag{28}$$

Using this value to eliminate P in the first part of equation (25), and multiplying both parts of the equation by h, gives:

$$h\ h_g'\ P_S - h_g'\ h\ P_1 + \frac{h_g'\ \lambda}{X} (P_1 - P_S) = \frac{\lambda h}{X} (P_1 - P_S) \tag{29}$$

Dividing both sides by $(P_1 - P_S)$ the equation becomes

$$-h \quad h_g' + \frac{h_g' \lambda}{X} = \frac{\lambda h}{X} \tag{30}$$

Solving equation (30) for λ, gives:

$$\lambda = \frac{X h_g' \quad h}{h_g' - h} \tag{31}$$

from which the epidermal permeability can be determined given an apparent mass-transfer coefficient and a known true-convection coefficient.

From equation (25), the vapor pressure at the surface, P_S, is:

$$P_S = \frac{\frac{\lambda}{X} P_1 + h_g' P}{h_g' + \frac{\lambda}{X}} \tag{32}$$

The mass-flow rate through the epidermis from equation (25) is

$$\dot{M} = \frac{\lambda A}{X} (P_1 - P_S) \tag{33}$$

Assuming the fruit is placed in a small volume of air, the vapor pressure of the air will be increased by this mass-flow rate in a time interval, Δt, by

$$\Delta P = \frac{\dot{M} \Delta t}{\rho C_m V} \tag{34}$$

or

$$\Delta P = \frac{\lambda}{X} (P_1 - P_S) \left(\frac{A \Delta t}{\rho C_m V} \right) \tag{35}$$

Using time notations as a second subscript, the resulting solutions for a one-dimensional slab with a constant vapor pressure on one side and with convective mass transfer to an unsteady-state medium on the other are:

$$P_{1,\,t} = K \text{ for all } t \tag{36}$$

at convecting surface

$$P_{S,\,t+1} = \frac{\frac{\lambda}{X} P_{1,\,y+1} + h_g' P_{,\,t+1}}{h_g' + \frac{\lambda}{X}} \tag{37}$$

in the unsteady-state medium

$$P_{,t+1} = P_t + \frac{\lambda A \Delta t}{X C_m V \rho} \left[P_{1,\,t} - P_{S,\,t} \right] \tag{38}$$

IV. EXPERIMENTAL STUDIES

4.1 Objectives

Moisture loss from fruit is not only of interest in preserving fresh fruit but is an important factor in fruit dehydration. The interest is on limiting moisture flow in one application and on increasing moisture flow in the other. Both are concerned with mass transfer and have many common physical parameters. In raisin making, grapes are often treated to speed moisture flow from the berry.

The experimental studies were done to determine: a) the magnitudes of convective mass-transfer coefficients of the intact grape and cherry fruits, with and without pedicels under specific unsteady-state conditions; b) the magnitudes of the convective mass-transfer coefficient of the grape berry with epidermis removed; c) the relative magnitudes of the epidermal permeability of the grape and cherry; d) the effect of a cold-water-emulsified oil dip, used in raisin making on the mass-transfer coefficient of Thompson Seedless grapes, and e) the effect on the mass-transfer coefficient of mechanically polishing the surface of Thompson Seedless grapes.

4.2 Equipment

The equipment used consisted of treatment equipment and instrumentation. Much of the equipment was designed and built especially for these studies.

The equipment (Figures 4.1, 4.2) consisted of an air pump, control valves, sample cylinder for fruit, desiccant bed, dew point instrument, and recording potentiometer.

The air pump was a diaphragm-actuated Neptune Dyna-Pump, model number 54904-006, with a rated capacity of 225 cubic inches per minute at a pressure of two pounds per square inch. In the system, the pump output was normally 3600 cc/min.

The control valves were stainless-steel needle valves. Stainless-steel tubing was used for connecting practically all of the components together.

The dew point was measured by an industrial dew point hygrometer, Model 992-C1 (Figures 4.1, 4.2, 4.3), a product of Cambridge Systems Inc., which utilized the well-known thermoelectric or "Peltier" cooling effects to cool a stainless-steel mirror to the dew point. A scattering type of optical system sensed the dew point of the air sample and tracked it continuously. The basic sensing unit of this instrument (Figure 4.3) contained the thermoelectric dew-point sensor, its associated amplifier and power-supply circuitry, and a gas sampling system. This unit could measure dew points between the ambient temperature of the installation down to 100° F lower. The accuracy of this instrument was specified to be plus or minus 1.0° F, with a response time of 2-3° F/second.

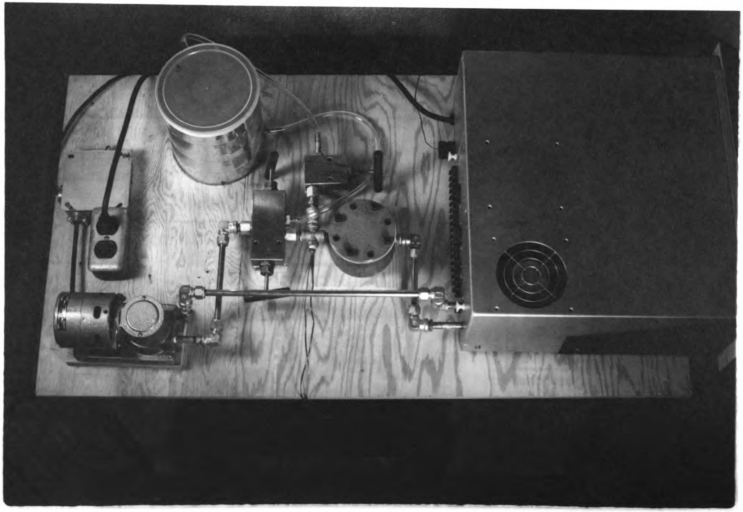


Figure 4.1 Apparatus for Determining Mass Transfer Coefficients. Lower left, air pump; Upper left, desiccant container, center left and center top, control valves; Right, dew-point instrument, center right, sample cylinder.

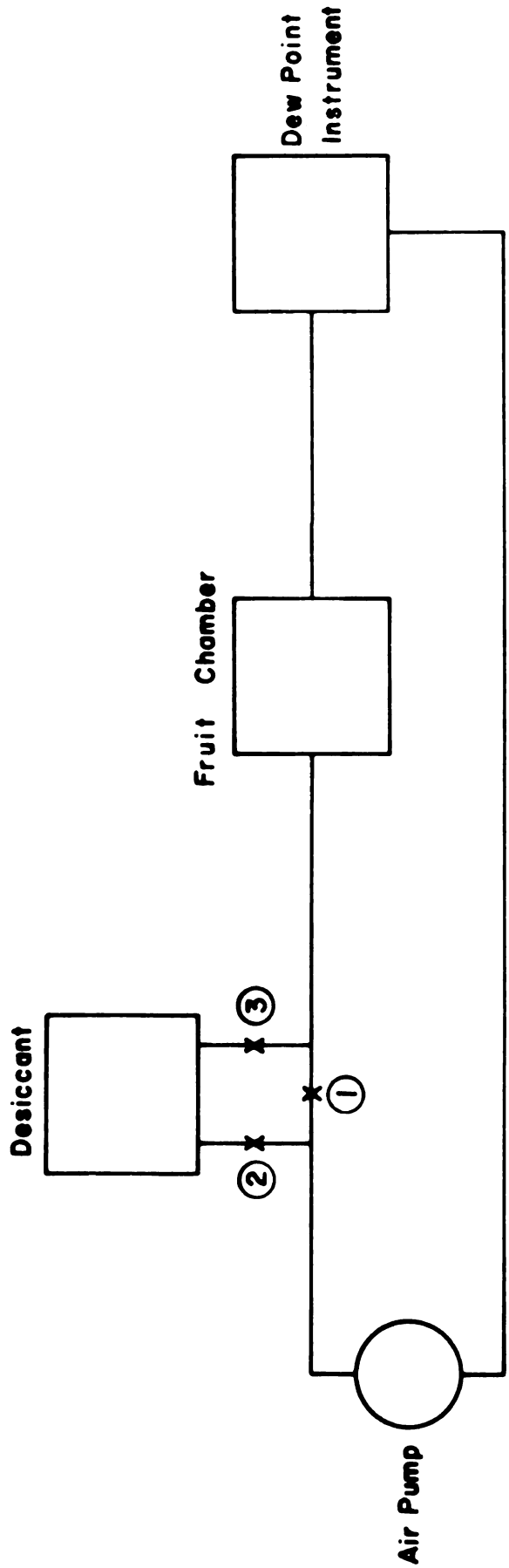
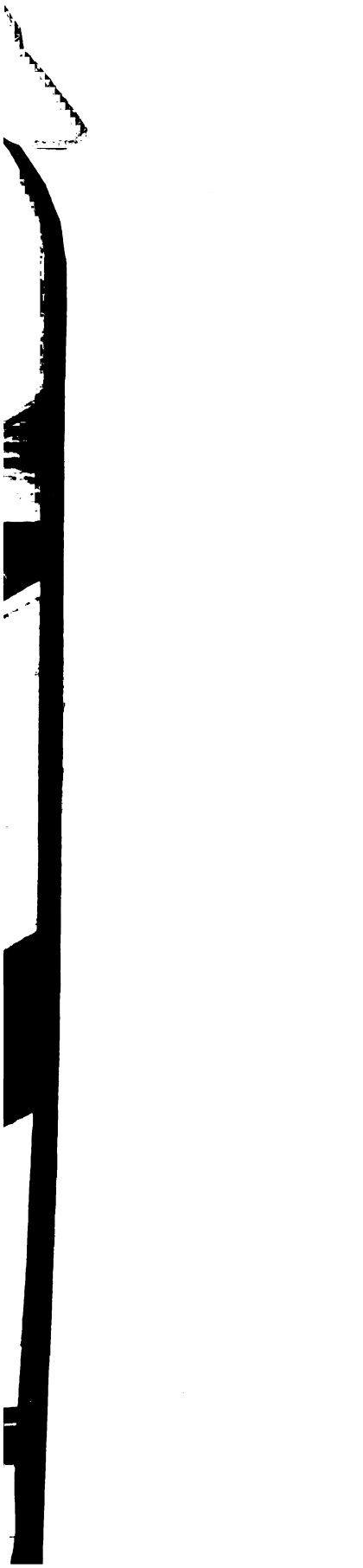


Figure 4.2 Schematic of Apparatus for Determining Mass-Transfer Coefficients.



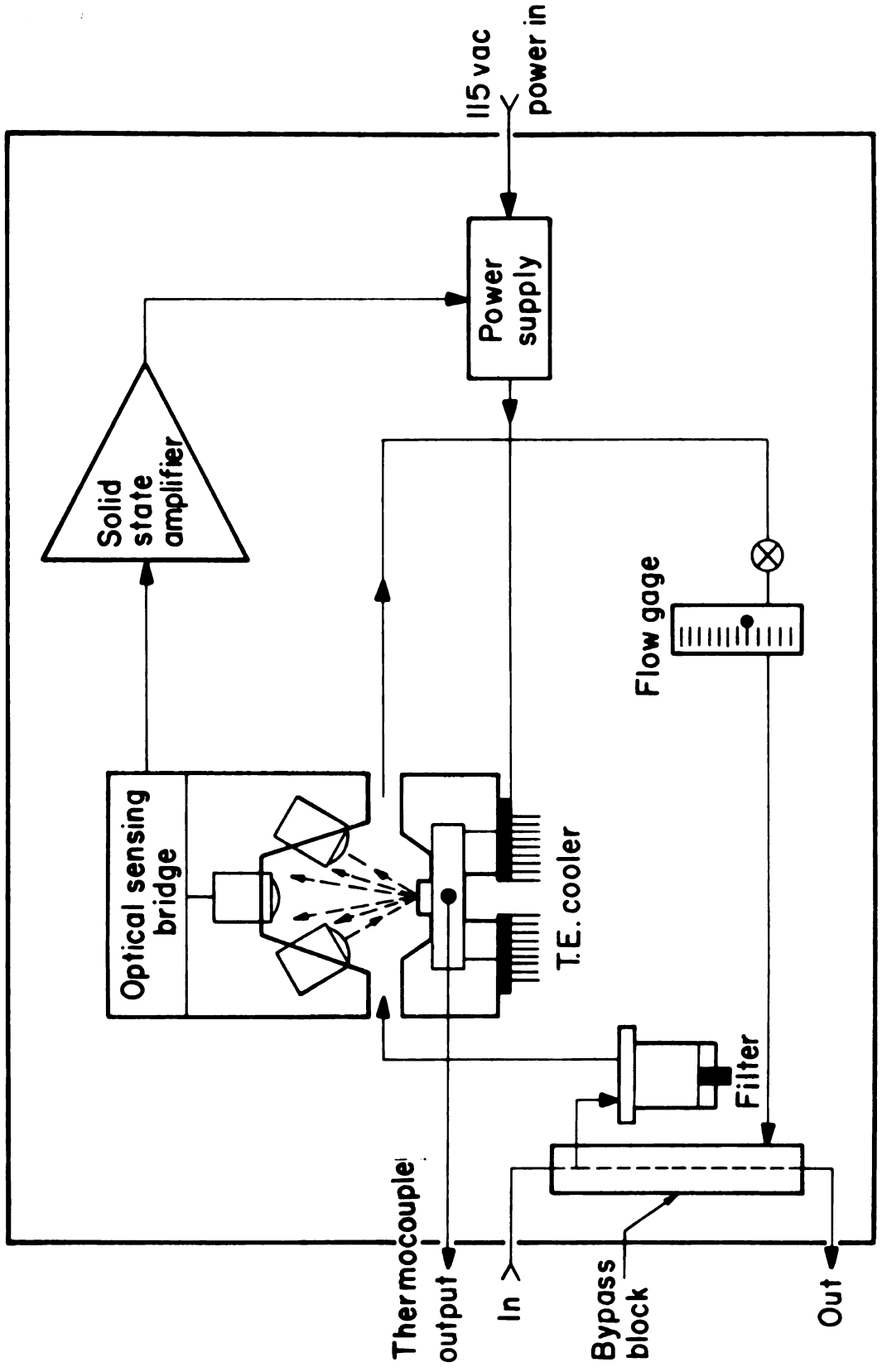


Figure 4.3 Principle of Operation of the Model 992-C1 Cambridge Systems Dew-Point Hygrometer (Redrawn from Cambridge Systems Technical Data Sheet 992B3A).

The sample cylinder was constructed from a stainless-steel bar 4 inches in diameter by 2-1/2 inches long (Figures 4.1, 4.4, 4.5). Machined into this cylinder was a hole 2-1/2 inches in diameter by 2 inches deep. The surfaces were ground smooth. Eight holes were drilled and tapped around the circumference of this cylinder to allow the cover to be fastened to the cylinder. Two holes were drilled into the sides of the cylinder for attaching the cylinder to the air-circulating-and-measuring system.

Two covers (Figures 4.4, 4.6) were made for the sample cylinder from 5/16 - inch stainless-steel. One cover was solid, the other had an access hole for exposing only parts of the berries to the system. A Teflon seal was constructed to go between the ground surfaces of the cover and the sample cylinder.

To prevent variations in readings taken at different locations within the sample cylinder, a baffle (Figure 4.5) was constructed from 20 gage sheet metal and inserted in the sample cylinder.

The temperature inside the sample cylinder was determined by copper-constantan thermocouples which entered the system through a hole drilled through a pipe plug. The thermocouple wires were sealed to the pipe plug with epoxy.

A twleve-point copper-constantan compensated Brown recorder was used to provide a record of both the dew point and the system temperature, The recorder used normally had 1/2° F divisions and a print speed of one point each 15 seconds. The recorded used on peeled fruit had a print speed of one point each 5 seconds. Temperatures appeared to be accurate

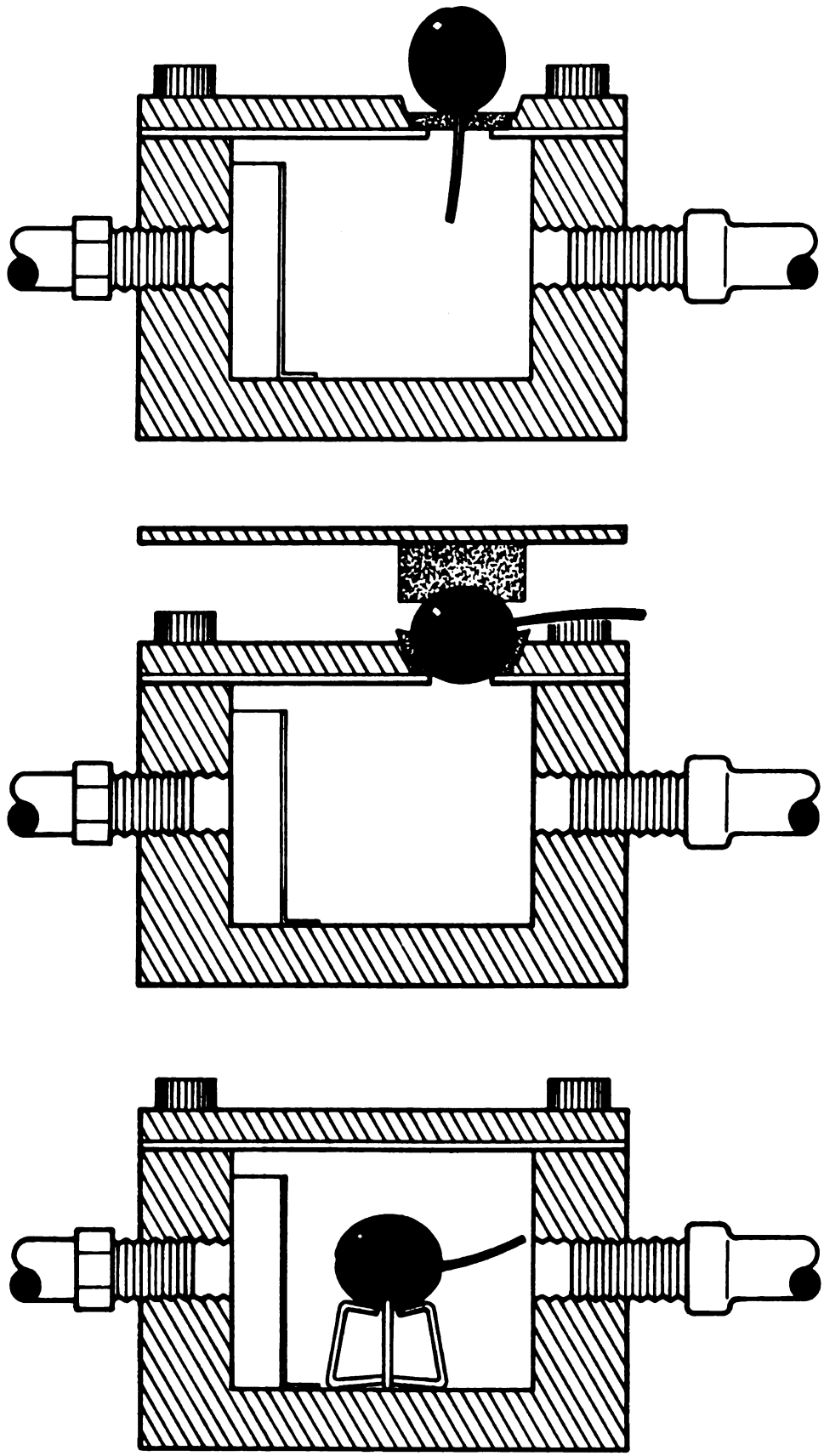


Figure 4.4 Cutaway Drawings of Fruit Arrangements in Sample Cylinder.
A) Top, arrangement for testing pedicel.
B) Middle, arrangement for testing cheek of fruit.
C) Bottom, arrangement for testing entire fruit.

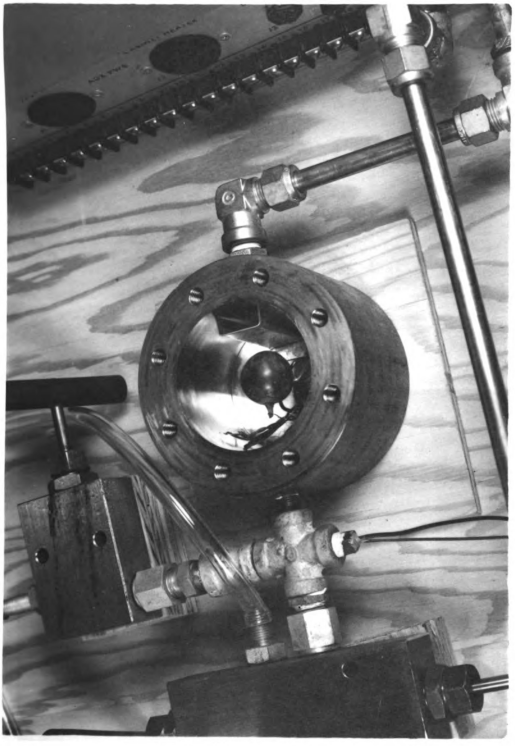
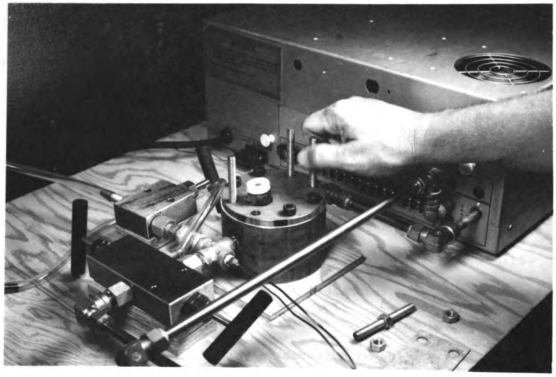


Figure 4.5 Sample Cylinder with Cover Removed and Grape in Position for Test on Entire Fruit.



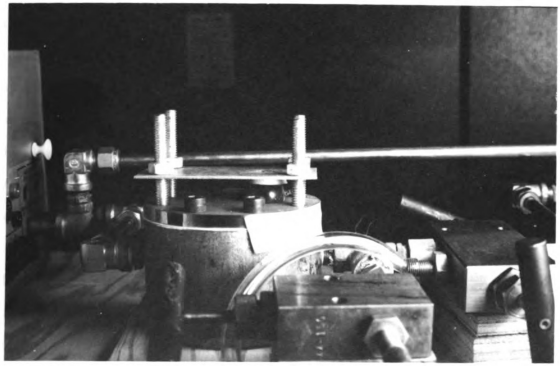


Figure 4.6 Apparatus for Determining Mass-Transfer Coefficient from Cheek of Fruit. Top, grape being placed in position; bottom, grape during test.

to at most $\pm$ 0.5 degree.

Air flow rates were measured with Fisher and Porter Tri-Flat Variable Area Flowmeters. Air flow rates were adjusted by means of a stainless-steel needle valve (Number 1, Figure 4.2).

To measure epidermal permeability of excised epidermal tissue, a cylindrical aluminum container was made from 1-inch by 1/2-inch round stock by drilling and reaming to 0.250 inch by 3/4 inch deep. A 3/16-inch-deep cylindrical cap with a 0.250-inch-diameter hole in the center was made for this container from the same material. The container and cap were sealed together during epidermal permeability tests by means of a 1/2-inch-inside-diameter neoprene tube (Figure 4.7).

The desiccant used was Sovabead (a product of Socony-Vacuum Oil Company), which is a chemically inert solid siliceous material in the form of beads (4-to-8 mesh). The desiccant was frequently reactivated by placing it in an open container in an oven at 300° F. The reactivated desiccant was placed in a Number 10 steel can which had fittings attached near the botton and top (Figure 4.1). The air entered the bottom of the desiccant bed by means of a plenum chamber formed from woven wire. The top of the container was covered with a plastic cap. Plastic tubing connected the desiccant container to the diverting valves.

In the laboratory the equipment was operated in a chamber in which air temperature was controlled to $\pm$ 1° F. Early in the grape-growing season the equipment was taken to Southern California, where it was operated in an air-conditioned motel room. Here the equipment was maintained at a relatively constant temperature by air cooled with an ice chamber, fan and duct arrangement.

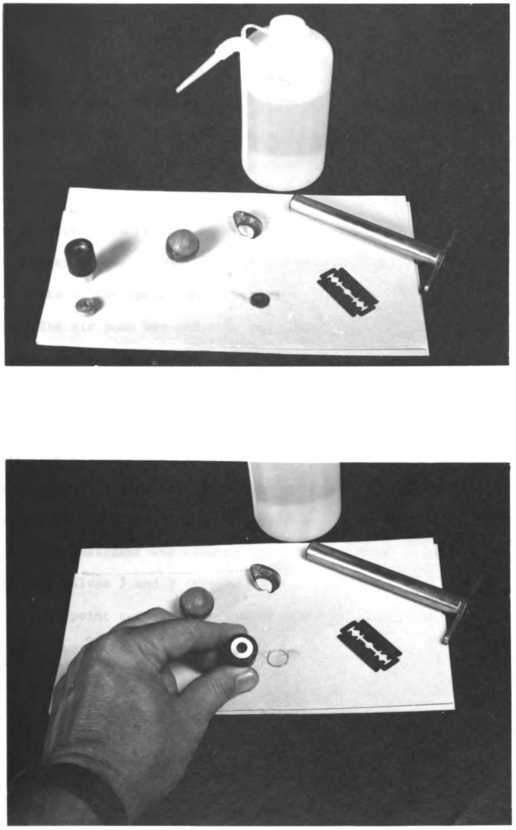


Figure 4.7 Preparation of Excised Epidermal Tissue for Permeability Test. Top, sample prepared ready to insert in holder; bottom, sample inserted in holder.

4.3a General Operational Procedures

All tests were conducted according to the following procedure:

1) The dew-point instrument and air pump were turned on.

2) Valves 2 and 3 (Figure 4.2) were opened and valve 1 was closed. This caused the air in the system to flow through the desiccant, removing moisture from the air. The air was circulated through the desiccant for thirty minutes to insure that all moisture was removed from all internal parts of the apparatus.

3) The air pump was stopped, and the fruit or fruit component was put into the sample chamber. In tests where the chamber top was removed, this procedure was done very rapidly (2 to 3 seconds) to keep excessive moisture from entering the system from the ambient air.

4) The air pump and the recording potentiometer were turned on, and the air in the system was circulated through the desiccant for three additional minutes. This permitted the dew-point instrument to stablize.

5) The desiccant was removed from the system by opening valve 1 and closing valves 2 and 3 (Figure 4.2).

6) Dew-point temperature, system temperature and time were recorded by a potentiometer.

4.3b Operational Procedures for Cherries

Bing and Burlat varieties of fresh cherries were harvested daily from selected trees in the orchard of the Pomology Department, University

of California, Davis, California. The harvested fruits were transported in polyethylene bags to the temperature-controlled test chamber, where they were stored for approximately 18 hours before tests were conducted. This procedure provided uniform fruit temperature.

Tests on both varieties were conducted on the intact fruit and pedicel, which were placed in the test chamber as illustrated in Figure 4.4 (bottom).

The surface areas of the cherries were determined by assuming that the fruit had the same surface area as a sphere of diameter equal to the average of the three axial diameters of the fruit.

The surface areas of the pedicels were assumed to equal the surface of a cylinder of equal length and a diameter the average of three measurements of the diameter of the pedicel. The area of the pedicel tip was assumed to be negligible.

4.3c Operational Procedures for Grapes

Early-season Cardinal variety grapes were studied by setting up the apparatus in a motel room in Indio, California. Cardinal grapes were obtained fresh daily from the vineyeards of the Harlan Kettle Ranch and placed in polyethylene bags immediately upon harvest. Tests on the intact fruit and pedicel and on the pedicel end of the fruit were conducted with the early-season Cardinal grapes. Some of the early grapes were packed in lug boxes, shipped in a refrigerated truck to Davis, California and stored two weeks before tests were conducted. This was to determine the effects of storage on transpiration.

Later-season Cardinal and Thompson Seedless varieties of table grapes were obtained from vineyards of the Department of Viticulture and Enology, University of California, Davis, California. The grapes were harvested daily from a selected area of the vineyard, placed in polyethylene bags, and transported to the controlled-temperature test chamber, where samples were prepared and held for approximately eighteen hours before tests were conducted. This permitted the cut on the pedicel to callus over, effectively blocking moisture transfer from the end of the pedicel.

For determination of epidermal permeabilities, selected grapes were prepared by cutting the pedicel close to the berry, allowing the cut to callus over, testing the berry, and then peeling the epidermis from the berry and testing it again without the epidermis.

Excised epidermal tissue was tested by peeling large areas of the grape epidermis, cutting circular segments of this tissue with a cork bore, and sealing the tissue segment to a container filled with water (Figure 4.7). This provided a reservoir of water with a steady vapor pressure on one side of the epidermal tissue.

The effect of an oil emulsion dip on the transpiration of Thompson Seedless grapes was determined by selecting grapes, cutting the pedicel close to the berry, allowing the cut to callous over, testing the berry, and then dipping the grape in the oil emulsion for 3 minutes and testing the berry again. The dipping emulsion consisted of 2.5 percent potassium carbonate in water and 2 percent dipping oil (Shelltana, a product of Shell Oil Company).

The surface areas of the nearly spherical Cardinal grapes were assumed to be the same as a sphere with the diameter equal to the average of three perpendicular diameter measurements. The surface areas of the Thompson Seedless grapes were assumed to be the same as that of a cylinder whose diameter was the average of two perpendicular measurements across the sides of the grape and whose length was the length of the berry. The surface area of the pedicel was assumed to be the same as the surface area of a tapered cylinder as long as the pedicel and with end diameters the same as those at the ends of the pedicel. The end area of the pedicel was assumed to be effectively sealed, and hence not contributing to moisture transfer.

4.4 Analysis Procedures

Data from the tests were analyzed using equation (18), and on the basis of a transpiration constant, J, defined by

$$-J = \frac{1}{t} \quad \ln \frac{P - P_E}{P_0 - P_E} \tag{39}$$

where

$$J = \frac{h_g A}{V \rho C_m} \tag{40}$$

Equation (39), somewhat similar to the drying equation given by Hall (1957), is, according to Draper and Smith (1966), a non-linear model that is intrinsically linear. The transpiration constant, J, was found as the regression coefficient of an exponential curve. An apparent equilibrium vapor pressure was determined iteratively to give the least error. All of these functions were performed by a computer program.

The computer program, designated TRANSP, was used to analyze all data. At the start of the program an array was read into the computer to convert dew-point readings to vapor pressures (mm of mercury) for each half degree from 0.5 to 90° F. For each test, the data were read into the computer from three cards.

The first card of a test set had the number of data points, the vapor pressure that corresponded to the ambient temperature, the test number, and surface area of the sample. After the first card was read, the number of data points was checked. It was programmed to terminate when given a card with the number of data points listed as minus one. So that each test would be summarized on a single output page, the test number and number of data points were printed at the top of an output page.

The second card in a set had the times of the dew-point readings that were on the third card. Dew points were read to the nearest half degree. Dew-point readings were converted to vapor pressures and printed out along with corresponding time values.

Starting with P_E equal to the vapor pressure for the ambient temperature values for $\frac{P - P_E}{P_O - P_E}$ were calculated for all vapor pressures. Natural logarithms of these values were summed and squared, and the squares summed. The time values were summed and the products of each time value and its corresponding vapor pressure were summed. The time values were also squared and summed.

The parameters of the curves were found from the equation

$$J = \frac{n\Sigma t \ln\left(\frac{P - P_E}{P_0 - P_E}\right) - \Sigma t \Sigma \ln\left(\frac{P - P_E}{P_0 - P_E}\right)}{n\Sigma t^2 - (\Sigma t)^2} \tag{41}$$

A correlation coefficient was determined by

$$r = \frac{n\Sigma t \ln\left(\frac{P - P_E}{P_0 - P_E}\right) - \Sigma t \Sigma \ln\left(\frac{P - P_E}{P_0 - P_E}\right)}{\sqrt{\left[n\Sigma t^2 - (\Sigma t)^2\right]\left[n\Sigma \left(\ln \frac{P - P_E}{P_0 - P_E}\right)^2 - \left(\Sigma \ln \frac{P - P_E}{P_0 - P_E}\right)^2\right]}} \tag{42}$$

The values of J and r were stored, P_E was reduced by 0.1, and new values of J and r were calculated. The new value of r was compared with the old value, and as long as r was approaching - 1.0 this iterative process was repeated. When the correlation coefficient stopped approaching -1.0, the values of r, j, P_E, Intercept, and Mass-transfer Coefficient were printed. The next set of data was then processed. An illustration of this iterative procedure is presented in Appendix I.

4.5 Variability With Locations in Sample Container

To determine the variability of results with the location in the sample chamber, mass-transfer coefficients were made for a cylinder filled with water placed at three locations on an axis of the chamber which was perpendicular to the axis of the air openings. The tests were made with water-filled cylinders positioned at each end and at the center of the axis. An analysis of variance of three tests at each location gave an observed F value of 1.17, with a required F(0.10) of 3.46 (Appendix II).

This indicated that there was no real difference in mass-transfer coefficients between the different locations in the sample chamber.

V. RESULTS OF EXPERIMENTAL STUDIES

5.1 Mass-Transfer Coefficients for Grapes

Figure 5.1 presents the results of a typical test run on Thompson Seedless grapes. This shows the dew-point temperatures which were normally read from the strip chart for each three-minute interval. The computer converted these dew-point temperatures to vapor pressures, which are shown as the experimental values in Figure 5.2. The computer iteratively determined the equilibrium vapor pressure and correlation coefficient, and the results of analysis of this typical test run are illustrated in Figure 5.3.

The results with Cardinal grapes are summarized in Table 5.1, and the results with Thompson Seedless grapes are summarized in Table 5.2 and Figure 5.4. A test on the means of the mass-transfer coefficients for the whole grapes with pedicel indicated a significant difference (0.001 level) in mass-transfer coefficients between the Cardinal and Thompson Seedless grapes, confirming observations that Cardinal grapes do not store as well as Thompson Seedless grapes.

With Cardinal grapes there was a significant difference in mass-transfer coefficients between the whole grape plus pedicel and the pedicel end of the grape plus pedicel. With both Cardinal and Thompson Seedless grapes there was no significant difference in mass-transfer coefficients between fresh and stored grapes.

Figure 5.5 illustrates mass-transfer coefficients determined at different air flows for Cardinal and Thompson Seedless grapes.

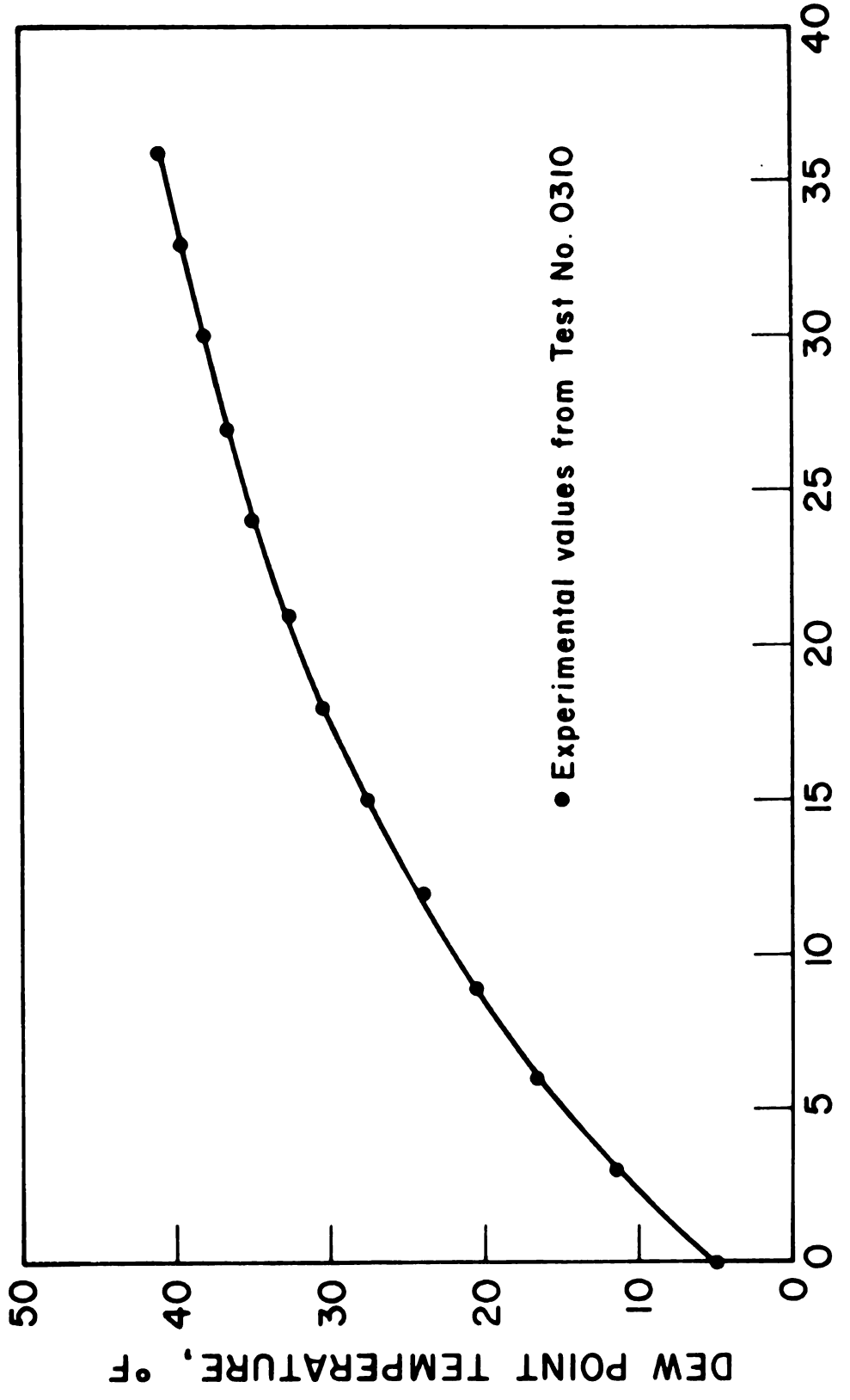


Figure 5.1 Typical Dew-Point Values From a Test on a Thompson Seedless Grape.

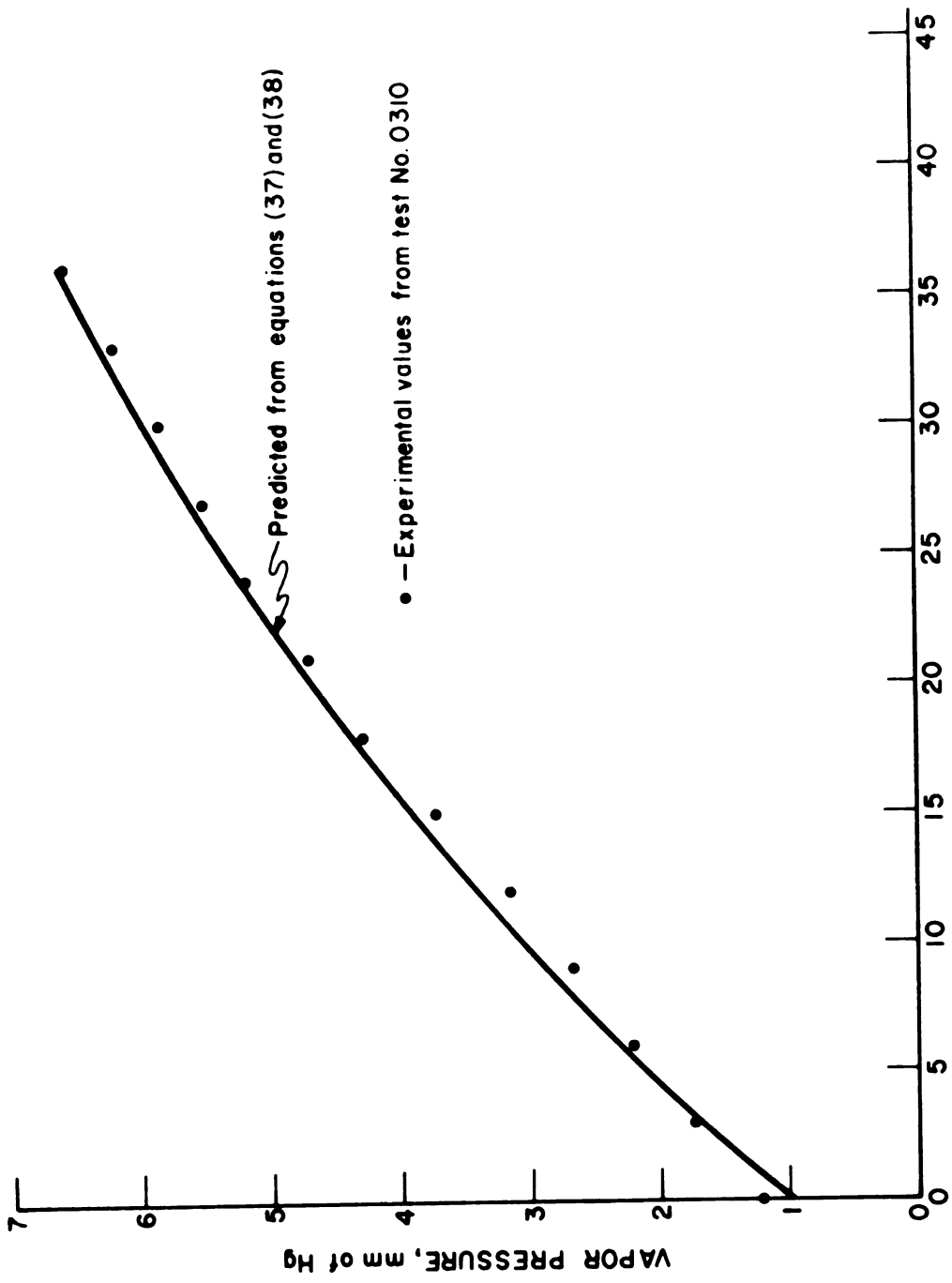


Figure 5.2 Predicted and Experimental Vapor Pressures for a Thompson Seedless Grape.

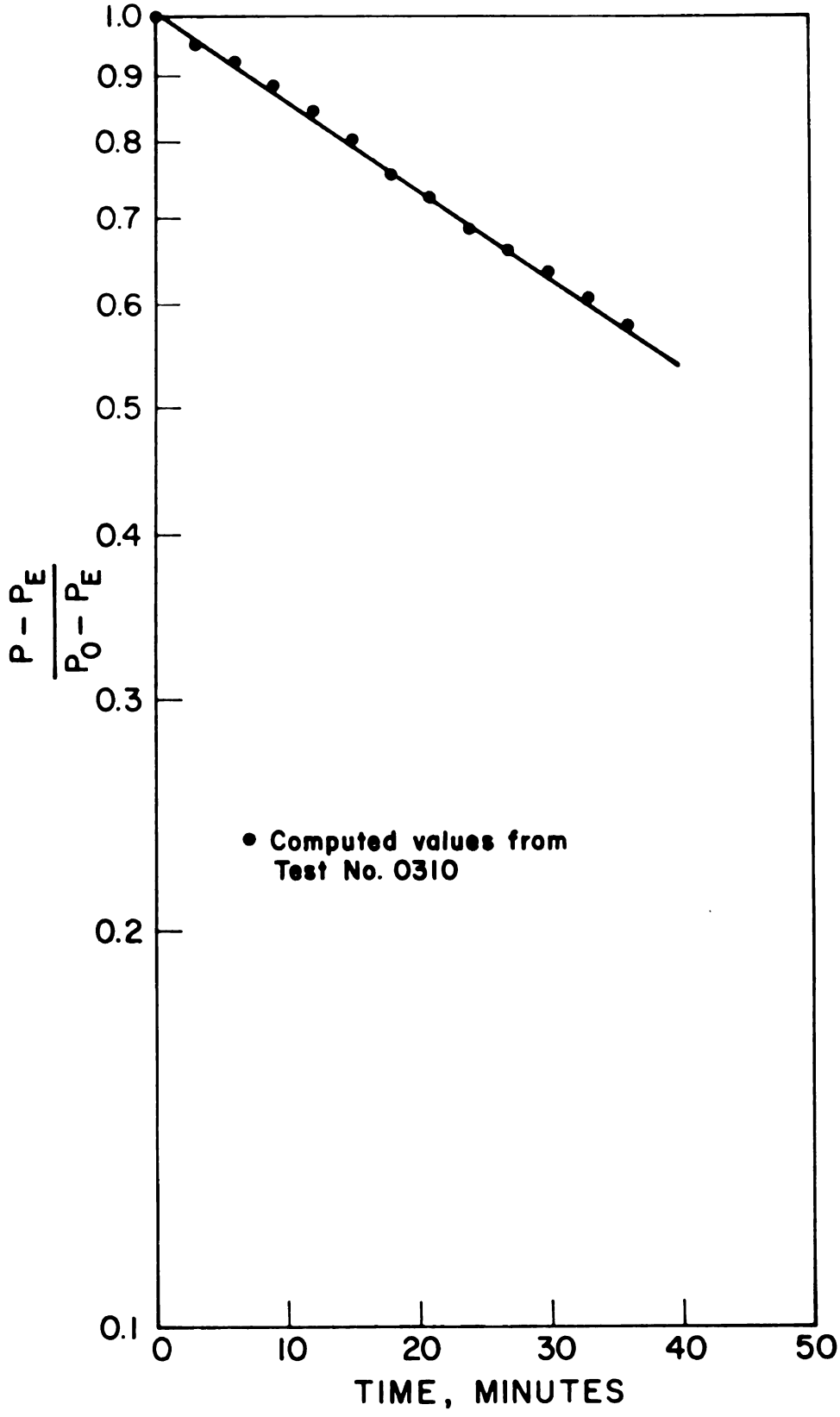


Figure 5.3 Typical Relation Between Vapor Pressure Ratio and Time for a Thompson Seedless Grape.

Table 5.1 Mass-Transfer Coefficients for Cardinal Grapes*

Test condition	No. of tests	Average ($h_g \times 10^8$)**	Standard Deviation $\times 10^8$
Whole grapes with pedicel	11	0.874	0.185
Pedicel and pedicel end of grape	9	1.94	1.13
Whole grapes (Air flow 350 cc/min)	4	0.889	
Grapes (stored 2 weeks)			
No pedicel (unpeeled)	5	0.987	0.036
No pedicel (peeled)	5	20.5	3.3
Excised epidermal tissue (68°)	2	4.78	
Excised epidermal tissue (45°)	2	6.17	

* All air flows were 3600 cc/min unless otherwise stated,

** Units of h_g are grams of H_2O per (minute) (square mm) (mm of mercury).

Table 5.2 Mass-Transfer Coefficients for Thompson Seedless Grapes*

Test condition	No. of tests	Average $(h_g \times 10^8)$**	Standard Deviation $\times 10^8$
Whole grapes with pedicel	4	0.415	0.143
Whole grapes with pedicel Air flow (350 cc/min)	4	0.637	0.111
Whole grapes with pedicel (polished)	4	0.813	0.139
Grape (stored 2 weeks)			
No pedicel	9	0.583	0.179
Dipped (no pedicel)	5	0.847	0.307
Peeled (no pedicel)	5	23.9	0.95
Excised epidermal tissue	4	15.94	14.77

* All air flows were 3600 cc/min unless otherwise stated.

** Units of h_g are grams of H_2O per (minute) (square mm) (mm of mercury)

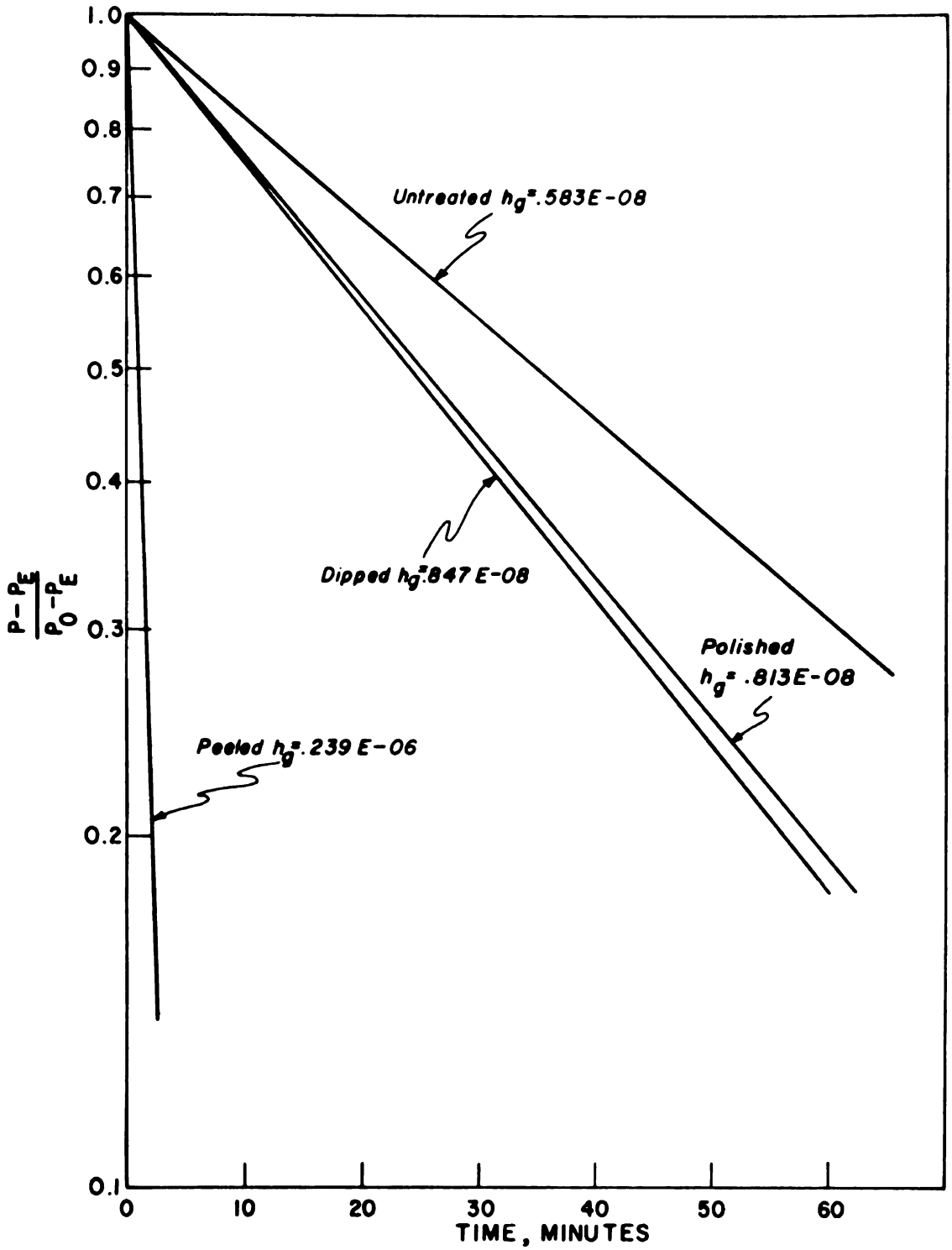


Figure 5.4 Computed Relation Between Vapor-Pressure Ratio and Mass-Transfer Coefficients for Thompson Seedless Grapes. A surface area of 1200 square mm and a value for $\rho C_m V$ of 0.0003532 were used. E-08 = 10^{-8}.

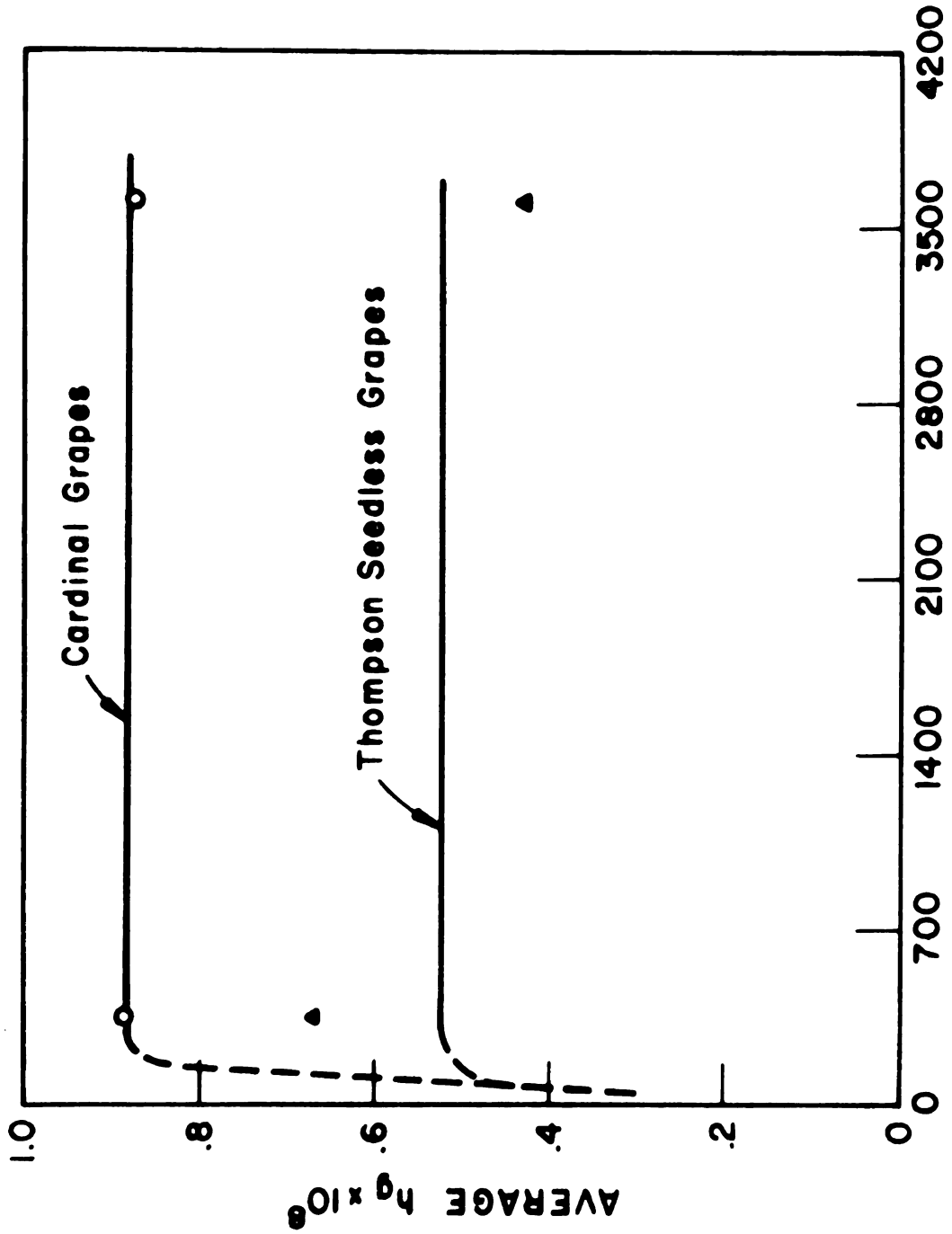


Figure 5.5 Relation of Mass-Transfer Coefficients to Air Flow.

Although the mass-transfer coefficient should decrease with reduced air flow a t-test on the results of this study indicated that evidence was insufficient to say that the mass-transfer coefficients with air flow of 3600 cc per minute were different from those with air flow of 350 cc per minute. Air flows below 350 cc per minute could not be used since the dew-point instrument required enough air to function.

Polishing Thompson Seedless grapes for three minutes with burlap fragments on a rotary vibrator increased the mass-transfer coefficient significantly (0.001 level). (Table 5.2 and Figure 5.4). Thus, rough handling or vibratory damage of loosely packed grapes can reduce resistance to moisture transfer through the epidermis, thereby damaging the quality of fresh fruit.

For raisin making, mechanical polishing of grapes may be an alternative to dipping. Thompson Seedless grapes dipped in an oil emulsion dip (made of 2.5% potassium carbonate and 2% "dipping oil"), used in Australia to increase moisture transfer through the epidermis in raisin making, gave a mass-transfer coefficient significantly higher than that for untreated grapes, though not significantly higher than that for polished grapes.

5.2 Mass-Transfer Coefficients for Cherries

Table 5.3 and Figure 5.6 present results of studies on cherries. A t-test on the means of the mass-transfer coefficients for the whole fruit indicated a significant difference (0.001 level) in the mass-transfer

Table 5.3 Mass-Transfer Coefficients for Bing and Burlat Cherries

Variety	Fruit component	No. of tests	Average ($h_g \times 10^8$)*
Bing	Whole	11	0.879 (0.215)**
	Pedicel	9	4.783 (1.504)
Burlat	Whole	8	1.995 (0.360)
	Pedicel	7	15.671 (2.985)

* Units of h_g are gram of H_2O per (minute) (square mm) (mm of mercury).

** Standard deviations are in parentheses.

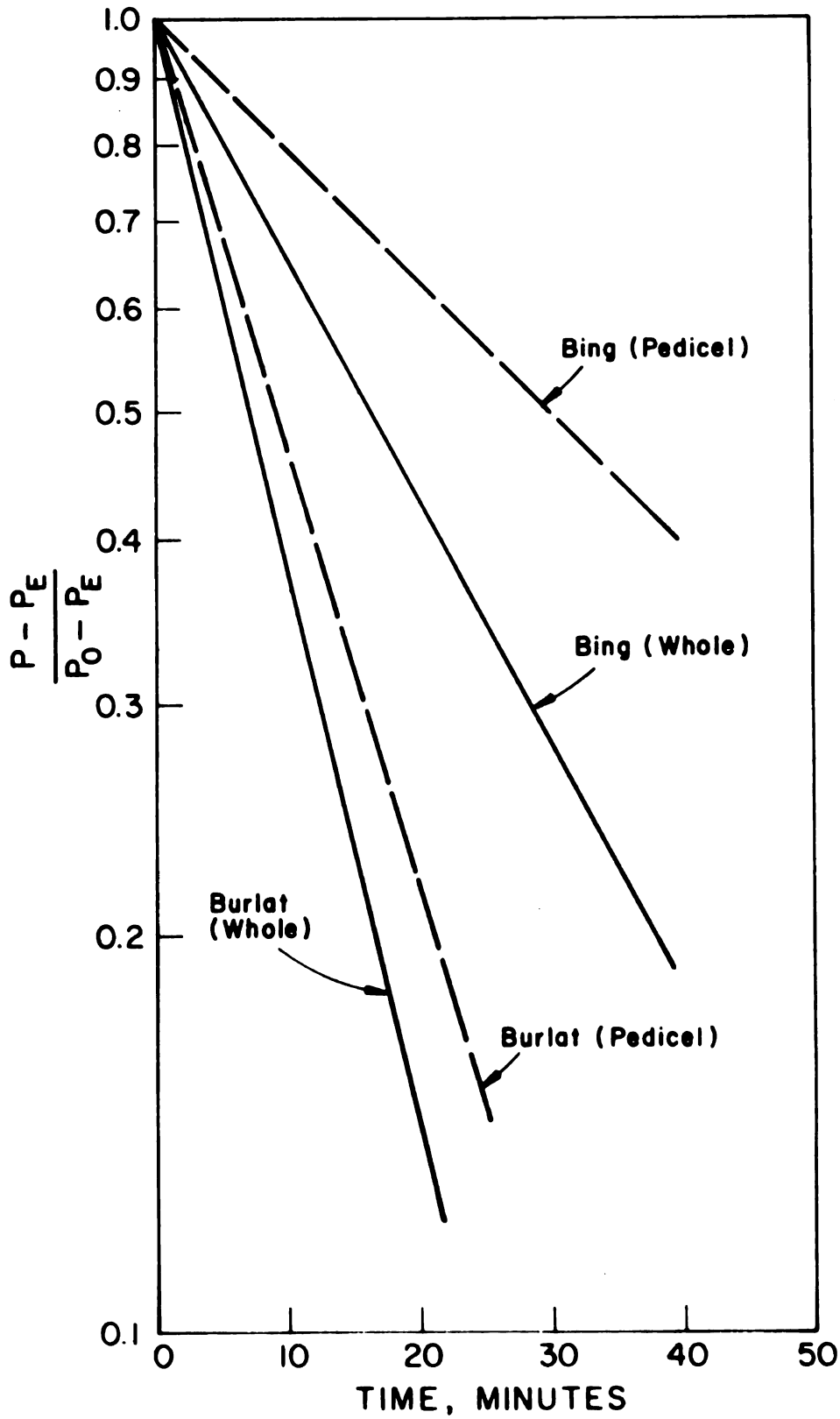


Figure 5.6 Computer Relation Between Vapor Pressure Ratio and Mass-Transfer Coefficients for Cherries. A surface area of 1700 square mm was used for the whole cherries, and a surface area of 170 square mm was used for the pedicels.

coefficients between Bing and Burlat cherries. This confirmed observations that the Burlat variety loses moisture and deteriorates faster in storage than does the Bing variety.

In both cases the pedicels lost moisture significantly (0.001 level) faster than the whole fruit. The pedicel of the Burlat variety, which was a very important factor in moisture loss from this variety, had a significantly (0.001 level) larger mass-transfer coefficient than the pedicel of the Bing variety.

Assuming that the pedicel has a surface area one-tenth the surface area of the whole fruit, as in Figure 5.6, the convective mass-transfer coefficient for the epidermis of the fruit for the Bing cherry was calculated to be 0.446×10^{-8} grams of H_2O per (minute) (square mm) (mm of mercury); and the convective mass-transfer coefficient for the epidermis of the Burlat cherry was calculated to be 0.476×10^{-8} grams of H_2O per (minute) (square mm) (mm of mercury).

5.3 Equilibrium Vapor Pressures

The average equilibrium vapor pressure for 14 tests on Thompson Seedless grapes was 13.693 mm of mercury, with a standard deviation of 2.475 mm. Using the saturated vapor pressure for the ambient temperature, an average equilibrium relative humidity of 75.5% was calculated. This equilibrium relative humidity is significantly lower than the static equilibrium relative humidity normally expected for grapes.

Measurements with a 40-gage thermocouple placed just below the surface of a container filled with water showed a temperature drop of three degrees below ambient early in the test. Since there must be a temperature gradient at the epidermis of the fruit, use of the saturated vapor pressure at the ambient temperature is questionable. The equilibrium vapor pressure determined by the procedure used in this study should probably be designated as an apparent equilibrium vapor pressure.

5.4a Epidermal Permeabilities of Whole Grapes

Equation (31) gives the epidermal permeability as

$$\lambda = \frac{X h_g' h}{h_g' - h}$$

The average thickness of ten excised epidermal tissue samples of both Cardinal and Thompson Seedless grapes was determined by a micrometer to be 0.305 mm. The value of the mass-transfer coefficient of the peeled grapes was considered to be the true convective mass-transfer coefficient. Using the values for the apparent mass-transfer coefficients as those for grapes without pedicels (Tables 5.1 and 5.2), the epidermal permeability for Thompson Seedless grapes was 1.82×10^{-9} gram H_2O per (minute) (square mm) (mm of mercury) per mm of thickness, and the epidermal permeability of Cardinal grapes was 3.16×10^{-9} gram H_2O per (minute) (square mm) (mm of mercury) per mm of thickness.

5.4b Permeabilities of Excised Grape Epidermal Tissue

Tests of the excised epidermal tissue were made with water contained below the tissue in the cylindrical holder (Figure 4.7). To obtain a true convective mass-transfer coefficient for this study, test runs were made with water in the test cylinder and no epidermal tissue in the cylinder. The average mass-transfer coefficient for three tests was 0.213×10^{-6}, and the value therefore, used as the true convective mass-transfer coefficient for this study. This value compared favorably with the values for peeled Cardinal grapes (0.205×10^{-6}) and peeled Thompson Seedless grapes (0.239×10^{-6}). Using the mass-transfer coefficient values from Table 5.1, the epidermal permeability for excised epidermal Cardinal grape tissue was 2.24×10^{-8} gram H_2O (minute) (square mm) (mm of mercury) per mm of thickness. The epidermal permeability of excised epidermal Thompson Seedless tissue was 1.93×10^{-7} gram H_2O per (minute) (square mm) (mm of mercury) per mm of thickness.

With both varieties, permeability was greater for the excised tissue than for the whole fruit. Because of the large standard deviation in the mass-transfer coefficients of the excised tissue, this procedure appears to be excessively injurious to the epidermal tissue.

5.4c Epidermal Permeabilities of Cherries

Cherries being difficult to peel were not tested without skins. The average thickness of both Bing and Burlat epidermal tissues was approximately 0.305 mm. Using a value of 0.210×10^{-6} for a true

convective coefficient, the epidermal permeability was calculated to be 1.37×10^{-9} gram of H_2O per (minute) (square mm) (mm of mercury) per mm of thickness for Bing cherries and 1.49×10^{-9} gram H_2O per (minute) (square mm) (mm of mercury) per mm of thickness for Burlat cherries.

5.5 Predicted and Experimental Vapor Pressures

Assuming that the vapor pressure inside the fruit was equal to P_E equations (37) and (38) were used to predict the system vapor pressure during a typical run with Thompson Seedless grapes. Values for the variables, chosen to correspond with those for the Thompson Seedless grape used in test number 0310, were as follows:

P_E = 13.843

h_g = 0.394×10^{-8}

h'_g = 0.239×10^{-6}

A = 1385 square mm

Δt = 3 minutes

ρ = 0.0012 grams of dry air per cubic centimeter

C_m = 0.000841 grams of H_2O per gram of dry air per mm of mercury

V = 350 cubic centimeters

P_a = 1.000 at t = 0

Since

$$\lambda = \frac{Xh \; h'_g}{h'_g - h}$$

then $$\frac{\lambda}{X} = \frac{h\ h'_g}{h'_g - h}$$

and equation (37) becomes

$$P_{i,t} = \frac{\frac{h\ h'_g}{h'_g - h} P_E + h'_g P_{,t}}{h'_g + \frac{h\ h'_g}{h'_g - h}}$$

and equation (38) becomes

$$P_{,\ t+1} = P_{,t} + \frac{h\ h'_g}{h'_g - h} \frac{A\Delta t}{\rho C_m V} (P_E - P_{S,t})$$

Figure 5.2 shows the value predicted from these equations along with the corresponding experimental values. From the above equations it can be noted that epidermis thickness need not be known if both a true and an effective mass-transfer coefficient is known.

The good agreement between predicted and experimental values indicates that use of the slab equations was justified on the basis that the epidermis is a thin layer relative to the radius, and that there is little if any vapor pressure gradient in the flesh of the fruit.

CONCLUSIONS

The following conclusion can be drawn from this study:

1) Transpiration rates as measured by the mass-transfer coefficient can be determined from experimental measurements and an unsteady-state mass-transfer analysis.

2) The mass-transfer coefficient and an apparent equilibrium vapor pressure can be determined by iterative least-squares fitting of the data to an exponential equation.

3) The permeability of the epidermis can be determined from the thickness of the tissue and apparent and true convective mass-transfer coefficients.

4) Air flow changes over a range of one to ten air changes per minute in the system had no significant effect on mass-transfer coefficients.

5) Values of the mass-transfer coefficients are of the order of 0.4×10^{-8} gram H_2O per (minute) (square mm) (mm of mercury) for Thompson Seedless grapes 0.9×10^{-8} gram H_2O per (minute) (square mm) (mm of mercury) for both Cardinal grapes and Bing cherries and 2.0×10^{-8} gram of H_2O per (minute) (square mm) (mm of mercury) for Burlat cherries.

6) The pedicel, with its small surface area, contributed over one-half of the total mass transfer for Bing cherries, and over three-fourths of the total mass transfer for Burlat cherries.

7) The effects of different surface treatments on transpiration rates can be rapidly determined. Transpiration rates of individual fruits can be determined, the fruits treated so as to either increase or

decrease transpiration, and the transpiration rate on the same fruit determined again.

8) Prediction equations for a fruit with known apparent and true mass-transfer coefficients and equilibrium vapor pressure can accurately determine what the vapor pressure in relation to time will be for a lumped capacity unsteady-state mass-transfer system.

SUGGESTIONS FOR FURTHER STUDY

Further studies should be made in the following areas:

1) The effects of treatments for increasing or decreasing moisture transfer through the epidermis should be evaluated. This should include the effect of different types and amounts of waxes on both the fruit and pedicel.

2) The relation of the convective mass-transfer coefficient to the moisture content of grapes during the raisin-making process should be determined.

3) The effect of including a temperature gradient in the epidermis, and a variable permeability in the vapor-pressure distribution equations, should be examined.

4) Further study should be undertaken to develop this procedure so that equilibrium relative humidities can be predicted rapidly and accurately.

5) A more precise non-destructive method is needed for determining the surface areas of fruits and pedicels.

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APPENDIX I

ILLUSTRATION OF HOW THE EQUILIBRIUM VAPOR PRESSURE WAS ITERATIVELY DETERMINED BY THE BEST-FIT METHOD

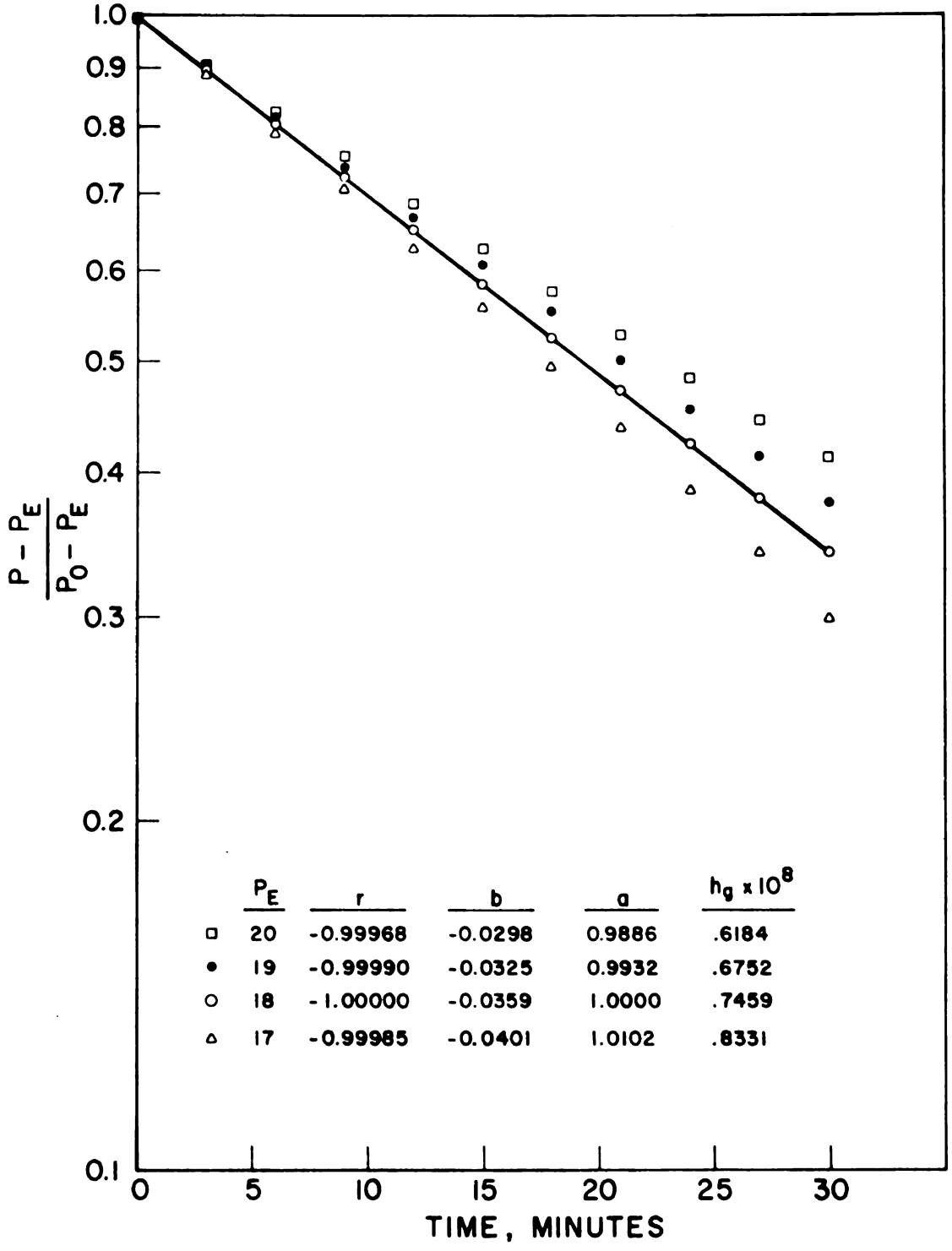

Figure A1.1 Illustration of How the Equilibrium Vapor Pressure was Iteratively Determined by the Best Fit Method. The surface area was 1700 square mm and the value used for $\rho C_m V$ was 0.0003532.

APPENDIX II

ANALYSIS OF VARIABILITY IN LOCATIONS IN SAMPLE CONTAINER

APPENDIX II

ANALYSIS OF VARIABILITY IN LOCATIONS IN SAMPLE CONTAINER

Table A2.1 Mass-Transfer Coefficients at Different Locations in Sample Cylinder

Location	$h_g \times 10^6$		
Center	.879	.687	.730
Top	.674	.754	.742
Bottom	.640	.665	.731

Table A2.2 Analysis of Variance of Mass-Transfer Coefficient at Different Locations

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	Observed F	Required F (0.10)
Total	8	.0398			
Locations	2	.0112	.0056	1.167	3.46
Error	6	.0286	.0048		

APPENDIX III

GLOSSARY

berry	a simple, fleshy fruit in which the ovary wall remains succulent
cuticle	a waxy layer formed on the outer layer of epidermal cells
cytoplasm	the protoplasm of a cell exclusive of the nucleus and membranes
epidermis	the outermost cell layer of the plant body
lenticel	a pore consisting of cells covered with a waxy material
middle lamella	the cementing substance between adjoining cells
nucleolus	a spherical body found in the nucleus
nucleus	a protoplasmic body found in the cytoplasm and thought to be the metabolic center of the cell
osmosis	diffusion of solvent molecules through a differentially permeable membrane
parenchyma	a tissue made up of living thin-walled cells
pedicel	the stalk (stem) of an individual flower or fruit
phloem	the conducting tissue concerned primarily with the movement of food materials in the plant
plasmalemma	outer protoplast membrane
plastid	a specialized body found in the cytoplasm
protoplasm	the generalized living substance in a cell
stoma (pl. stomata)	an opening between two guard cells
tonoplast	inner protoplast membrane
turgor	the result of osmotic pressure developed within the vacuole and the pressure exerted by the cell wall

tylos

vacuc

xylem

tyloses	callus like protrusions from parenchyma cells into adjacent passageways often numerous enough to fill passageway completely
vacuole	a cavity in the protoplasm filled with a watery fluid
xylem	the conducting tissue, concerned primarily with the movement of water in the plant