SINGLE PARTICLE CONVECTIVE MOISTURE LOSSES FROM HORTICULTURAL PRODUCTS IN STORAGE

Dissertation for the Degree of Ph. D.

MICHIGAN STATE UNIVERSITY

LUIS G. VILLA

1973

This is to certify that the

thesis entitled

SINGLE PARTICLE CONVECTIVE
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presented by

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has been accepted towards fulfillment
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ABSTRACT

SINGLE PARTICLE CONVECTIVE MOISTURE
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Many horticultural products are stored for extended periods of time. Moisture losses during the storage life of these products is a major cause of deterioration. Moisture losses not only cause wilting and shriveling but also reduce salable tonnage.

A good understanding of the mechanism governing the moisture loss process in individual particles will certainly help in developing systems for minimizing the losses. Besides, the prediction of the expected losses at different storage conditions can be useful in the design of storage facilities.

A semi-theoretical mathematical model was developed for predicting moisture losses from horticultural products in storage. The model is based on the distinctive behavior of different regions of the skin of a product with regard to the movement of the water vapor from the product to the

environment. Free water, porous membrane and impervious regions were identified as the components of the skin of a horticultural product.

For using the model, it is necessary to determine the surface area of the commodity, the convective heat and mass transfer coefficients and the vapor pressure deficit of the environment-product system. Besides, three so-called "skin parameters" have to be known. These parameters represent the fraction of the surface behaving as a free water surface, γ_1, the fraction of the surface behaving as a porous membrane, γ_2, and the resistance to water vapor movement through membrane like regions, $r\delta$.

The model was used for studying the behavior of apples (Jonathan), potatoes (Manona), and sugar beets (US H20). From moisture loss data of individual particles the skin parameters of these products were determined. Values of $\gamma_1 = 0$, and $\gamma_2 = .01286$ were obtained for the free water and porous membrane fraction parameters of Jonathan apples. In the case of Manona potatoes, values of $\gamma_1 = 0$ and $\gamma_2 = .00890$ were obtained. It was found that the diffusional resistance parameter, $r\delta$, is a linear function of the vapor pressure deficit in apples and potatoes. On the other hand, the behavior of sugar beets can be explained by assuming that the skin of the sugar beet is a combination of free water and impervious regions. It was found that about 43.6% ($\gamma_1 = .436$) of the surface area of US H20 sugar beet is of a free water nature. Good agreement between predicted and experimental values were observed. The model can be applied for studying other horticultural crops.

Graphs for predicting moisture losses and storage times for apples, potatoes and sugar beets at various storage conditions were developed. The graphs can be effectively used in studying the individual effect of each variable in the moisture loss process from these products.

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SINGLE PARTICLE CONVECTIVE MOISTURE

LOSSES FROM HORTICULTURAL

PRODUCTS IN STORAGE

By

Luis G. Villa

Gabriel

A DISSERTATION

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to my wife Gloria

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LIST OF SYMBOLS

A = Area, surface area, ft^2

A_s = Surface area of a sphere having a diameter equal to the height $\underline{H}$ of an apple, ft^2.

B = Mass transfer driving force, defined by eqn. (2.53), dimensionless.

b_0, b_1 = Estimation of parameters β_0 and β_1, respectively

C = Water vapor concentration, lbm/ft^3

c_p = Air specific heat at constant pressure, BTU/lbm °F

C_{ws} = Water vapor concentration at the surface of the body, lbm/ft^3.

$C_{w\infty}$ = Environmental water vapor concentration, lbm/ft^3

c_1, c_2, c_3, c'_1, c'_2, c'_3 = Coefficients of equations for calculating the convective heat and mass transfer coefficients.

d = Specific gravity of apples, eqn(2.29), dimensionless.

D_e = Equivalent diameter of a product ($= \sqrt{A/\pi}$), ft.

D_{wa} = Molecular diffusivity, ft^2/hr.

F = Force units.

f = Fraction of the surface area through which gaseous exchange occurs, eqn. (2.62), decimal.

g = Convective mass transfer coefficient, defined by eqn. (2.52), $lbm/hr\text{-}ft^2$.

H = Height of an individual apple (Cooke's model), ft.

h = Overall convective heat transfer coefficient, $BTU/hr\text{-}ft^2\text{-}°F$.

h_d = Overall convective mass transfer coefficient, ft/hr.

h'_d = Overall convective mass transfer coefficient, lbm/ft^2-hr-lbf/ft^2.

$h'_{d\ app}$ = Overall apparent convective mass transfer coefficient for an unpeeled product, lbm/ft^2-hr-lbf/ft^2.

h_{fg} = Heat of vaporization, BTU/lbm.

h_x = Local convective heat transfer coefficient at some point x, BTU/hr-ft^2-°F.

K = Thermal conductivity, BTU/hr-ft-°F.

L = Units of length.

L = Slant height of a sugar beet, ft.

M = Units of mass.

M = Molecular weight of water (= 18.01), eqn.(2.48).

$\dot{M}_w$ = Total mass flow rate, lbm/hr.

$\dot{M}_{w1}$ = Fraction of the total mass rate occuring through free water surface regions, eqn. (4.1), lbm/hr.

$\dot{M}_{w2}$ = Fraction of the total mass rate occuring through "membrane like" regions, eqn.(4.2), lbm/hr.

$\dot{M}_{w3}$ = Mass rate through impervious regions (=0).

$m_{w\infty}$ = Environmental mass concentration defined by eqn.(2.54), dimensionless.

m_{ws} = Mass concentration at the surface defined by eqn.(2.54), dimensionless.

n = Number of data points.

Nu = Nusselt number $(=\frac{hx}{K})$, dimensionless.

Nu_x = Local Nusselt number at some point x, dimensionless.

PL = Percentage of moisture loss, eqns.(2.64) and (2.65), percentage.

P_o = Vapor pressure at the outside of a "membrane like" surface, lbf/ft^2.

Pr = Prandlt number $(=\frac{\nu}{\alpha})$, dimensionless.

P_s = Vapor pressure at the inside of a "membrane like" surface, lbf/ft^2.

P_{sat} = Saturated vapor pressure, eqn.(2.55), lbf/ft^2.

P_v = Vapor pressure, lbf/ft^2.

P_{ws} = Vapor pressure at the body surface, lbf/ft^2.

$P_{w\infty}$ = Environmental vapor pressure, lbf/ft^2.

r = "Resistivity" of a membrane to water vapor movement, dimensionless.

$r\delta$ = Skin parameter (=resistivity r times membrane thickness δ), ft.

Re = Reynolds number $(=\frac{V_\infty x}{\nu})$, dimensionless.

Re_x Reynolds number based on a x characteristic dimension, dimensionless.

RML = Rate of moisture loss, lbm/hr.

R_o = Universal gas constant (=1544 ft-lb per (mole) (°R).

R_x = Local radius of a body of revolution at some point x, ft.

R^2 = Regression coefficient for comparing two linear or nonlinear models, defined by eqn.(4.18), dimensionless.

$R_1{}^2$ = Regression coefficient for comparing eqn.(4.21) with eqn.(4.22), dimensionless.

Sh = Overall Sherwood number $(=\frac{hd\ x}{D_{wa}})$ dimensionless.

St = Overall Stanton number $(=\frac{h}{\rho c_p\ V\infty})$, dimensionless.

St_x = Local Stanton number at some point x, dimensionless.

s.d.(I) = Standard deviation of (I).

T = Absolute temperature, °R.

T_s = Surface temperature, °F or °R.

$\tilde{T}_s$ = Surface temperature calculated by eqn.(4.5),°R.

T = Environmental temperature, °F or °R.

u = Velocity component in the x direction, eqns. (2.3) (2.4) and (2.5), ft/hr.

v = Velocity component in the y direction, eqns.(2.3), (2.4) and (2.5), ft/hr.

Var(I) = Variance of I.

VPD = Vapor pressure deficit, lbf/ft^2.

V_w = Vapor pressure deficit (mm of Hg) x weeks of storage, eqn.(2.64) and (2.65).

V∞ = Environmental air velocity, ft/hr.

W = Width of an individual apple (Cooke's model), ft.

W_o = Weight of the individual particle, lbm.

x = Characteristic dimension of a body, ft.

x = Cartesian coordinate.

X_i = Independent variable of a given model.

y = Cartesian coordinate.

Y_i = Dependent variable of a given model.

α = Thermal diffusivity, ft^2/hr.

$\beta_o, \beta_o', \beta_1, \beta_1'$ = Parameters of a given model.

γ_1 = Fraction of the surface area that behaves as a free water surface, decimal.

γ_2 = Fraction of the surface area that behaves as a porous membrane, decimal.

δ = Membrane thickness, ft.

$\varepsilon_i, \varepsilon_i'$ = Error in measurement i.

μ = Air dynamic viscocity, lbm/hr-ft.

ρ = Air density, lbm/ft^3.

θ = Time units.

ω = Absolute humidty, lbm water/lbm dry air.

ψ = Dummy variable, eqn. (2.40).

η = Dummy variable, eqn. (2.40).

ν = Kinematic viscocity of air, ft^2/hr.

I. INTRODUCTION

Loss of water from harvested horticultural crops is a major cause of deterioration in storage. Moisture losses not only cause wilting and shriveling but also reduces salable tonnage.

Wilting and shriveling caused by water losses seriously damages the appearance of produce and thus affects consumer appeal. Many fruits and vegetables will appear shriveled or wilted after water loss of only a small percentage of their original weight (3 to 5%). Besides, the loss in produce weight as a result of water loss becomes a direct economical loss.

Although the different variables affecting moisture loss from horticultural products has been recognized for quite some time, insufficient use had been made of the physical transport phenomena theory in investigating the problem. The effect of variables such as the airflow of the environmental air on moisture losses has been insufficiently studied. Lack of information was found with regard to the behavior of the skin of agricultural products under different environmental conditions. A better understanding of the mechanism of the moisture loss process will certainly help in developing systems for minimizing moisture losses.

The main objective of this research was to integrate the different variables affecting the moisture loss process into a mathematical model. This approach allows a systematic study of the individual effect of each variable.

The developed model will be used in studying the behavior of individual Jonathan apples, Manona potatoes and US H20 sugar beets with regard to moisture losses. Graphs for the prediction of moisture losses and allowable storage times at different storage conditions will also be developed.

II. REVIEW OF LITERATURE

The investigation of the process of moisture transfer from a moist body can be divided for purposes of analysis into two parts: (i) the transfer process occurring within the product, and (ii) the interaction of the product surface with the environment. The first of these processes occurs as a result of capillary flow and diffusion caused by a difference in concentration. On the other hand, the factors controlling the rate of transfer of water vapor from the moist body to its surroundings are associated with convection of the vaporized water away from the body. Van Arsdel (1963) stated that the factors that determine the rate of movement of water within the body can be regarded as independent of the external conditions.

The phenomenon of moisture losses from perishable agricultural products can be analyzed at a macroscopic level as a process controlled by the rate at which moisture moves through the skin of the product and is carried away from the surface by convection.

The following review of literature examines the theory behind the evaporation from a free water surface, the diffusion through membranes, and the effect of the skin of the product on the loss of moisture.

2.1. Convection Heat and Mass Transfer from Free Water Surfaces

In the study of evaporation of water from free water surfaces, macroscopic energy and mass balances lead to the following governing equations:

$$\dot{M}_w h_{fg} = hA \ (T_\infty - T_s) \tag{2.1}$$

and

$$\dot{M}_w = h_d \ A \ (C_{ws} - C_{w\infty}) \tag{2.2}$$

The convective heat and mass transfer coefficients, h and h_d, are essentially aerodynamic properties of the system whereas the temperature and mass driving forces are thermodynamic properties.

A study of the variables defined in equations (2.1) and (2.2) follows. Relationships for calculating the convective heat and mass transfer coefficients for flow over different geometrical shapes (to which agricultural products can be approximated) are analyzed first. The prediction of surface areas is studied specifically for those products studied in this research. An analysis of the different unit systems used for expressing the driving force is given next. Finally, a tabulation is made of some properties of air and air-vapor mixtures in the range of temperatures used in this study.

2.1.1. Convection Heat and Mass Transfer Coefficients

A considerable amount of research has been carried out on the prediction of the convective heat and mass transfer coefficients for flow over single bodies of various geometrical shapes. From principles of the boundary layer theory analytical solutions have been obtained for a limited number of situations. Regrettably, it has not always been possible to obtain analytical solutions, especially for situations where separation of flow occurs. Experimental methods have been used in such cases.

Analytical solutions of the boundary layer for flow over external surfaces include assumptions such as: thermal and velocity boundary layers which develop along the surface of the body are not influenced by the development of boundary layers on any adjacent surface; all body forces are negligible so that the fluid is forced over the body by some external means unrelated to the temperature field in the fluid. The solutions are also based on an idealization of constant fluid properties, unaffected by temperature.

Under the preceding assumptions the applicable differential equations of the boundary layer for a two dimensional situation are (Kays, 1966):

$$\text{Continuity} \qquad \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2.3}$$

$$\text{Momentum} \qquad u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} \tag{2.4}$$

$$\text{Energy} \qquad u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 u}{\partial y^2} \tag{2.5}$$

Adding the proper boundary conditions, equations (2.4), and (2.5) have been solved for a limited number of situations.

In cases where analytical solutions have not been obtained, dimensional analysis has been effectively used. Relationships in terms of dimensionless numbers have been developed for predicting the convective heat and mass transfer coefficients from experimental data.

In general, the following relationships relate the different variables that affect the convective heat and mass transfer coefficients:

$$Nu = c_1 Re^{c_2} Pr^{c_3} \tag{2.6}$$

$$Sh = c'_1 Re^{c'_2} Pr^{c'_3} \tag{2.7}$$

Agricultural products can be approximated by shapes such as flat surfaces, spheres, cylinder, axisymmetrical bodies, cones or prolate spheroids. A discussion of the working formulas for the convective heat and mass transfer coefficients of flow over those geometrical shapes follows.

a. Flow Over Flat Surfaces.--An analytical solution can be obtained if the following assumptions are made: laminar flow, incompressible and steady flow, no pressure variations in the direction perpendicular to the plate, constant properties of fluid, and negligible viscous shear in the direction perpendicular to the plate. The solution leads to the relationship (Holman, 1972):

$$Nu_x = .332\ Pr^{1/3} Re_x^{1/2} \tag{2.8}$$

for the local convective heat transfer coefficient.

An overall value for h can be written by integrating over the length of the plate:

$$h = \frac{\int_0^L h_x\, dx}{\int_0^L dx} = 2h_{x=L} \tag{2.9}$$

or

$$Nu = .664\ Pr^{1/3} Re_{x=L}^{1/2} \tag{2.10}$$

$$Re < 5 \times 10^5$$

Holman (1972) presents a semi-empirical formula for calculating the convective heat transfer coefficient over a length L of a plate when both the laminar and the turbulent layers are present. A value of 5×10^5 for the

Reynolds number is assumed for transition from laminar to turbulent flow. The resulting relationship is:

$$Nu = Pr^{1/3} \left(.036\ Re_{x=L}^{.8} - 836\right) \qquad (2.11)$$

$$Re > 5 \times 10^5$$

Powell and Griffith (1935) and Powell (1940) obtained experimental data on evaporation rates of water from saturated surfaces into air for various geometrically shaped bodies. They expressed the evaporation data in terms of the quantities (ul) and $el/(P_w - P_a)$, where

u = Air velocity

l = Characteristic dimension

e = Rate of evaporation per unit area

P_w = Vapor pressure at saturated surface

P_a = Vapor pressure in the air stream.

If Powell's data are rearranged in terms of dimensionless numbers, the following relationships hold for a flat plate:

$$Sh = .091\ Re^{.69} \qquad (2.12)$$

$1000 < Re < 20,000$ streamlined edge

$$Sh = .046\ Re^{.76} \qquad (2.13)$$

$20,000 < Re < 400,000$ streamlined edge

$$Sh = .56\ Re^{.50} \qquad (2.14)$$

$2000 < Re < 20,000$ non-streamlined edge

Powell's data are valid for only a Schmidt number of .6. The mass and heat transfer equations for flow over flat plates without streamlined leading edges, agree well with each other in both the laminar and turbulent regions. The mass transfer data for flow over flat plates with streamlined leading edges fall approximately 30 percent below the mass transfer data for flow over non-streamlined flat plates in the laminar region, and fall approximately 5 percent below the mass transfer data for flow over non-streamlined flat plates in the turbulent region (Boelter *et al*., 1965).

b. Flow Over Spherical Surfaces.--Flow over spheres typified the problem of separation of flow over external surfaces. Heat and mass transfer coefficients diminish from the forward stagnation point to the point of separation of the laminar boundary layer and then increase. When the transition to a turbulent boundary layer is followed by separation, the two points are indicated by sudden trends of increasing h_x in the region 90 to 120 degrees from stagnation (Bennett and Myers, 1962).

Extensive data have been taken to determine the convective heat and mass transfer coefficient for flow over spheres. McAdams (1954), on the basis of the results of a number of investigators, recommends the use of the following equation for calculating the convective heat transfer coefficient:

$$Nu = 0.33\ Re^{.6} \qquad (2.15)$$

$$1000 < Re < 50{,}000$$

An analytical solution for Reynolds number approaching zero gives,

$$Nu = 2 \qquad (2.16)$$

$$Re \rightarrow 0$$

One of the earliest analyses of mass transport from spheres is contained in the work of Frossling (1938). In addition to a rather complete theoretical analysis, as well as some experimental work involving macroscopic transport to an air stream from drops of different hydrocarbons, a relationship for calculating the overall mass transfer coefficient was obtained:

$$Sh = 2.0 + .6\ Sc^{1/3} Re^{1/2} \qquad (2.17)$$

The constant 2.0 in this equation corresponds to the analytical value for Sherwood number when Reynolds number tends to zero:

$$Sh = 2.0 \qquad (2.18)$$

$$Re \rightarrow 0$$

Powell's evaporation data for airflow over spherical surface results in the following equation:

$$Sh = .29\ Re^{.59} \qquad (2.19)$$

$$600 < Re < 46{,}000$$

Figure 1 shows a comparison between equations (2.17) and (2.19) in the Reynolds number range from 600 to 10,000. The formulas agree to within ± 18%

<u>c. Flow Over Cylindrical Surfaces</u>.--The most extensive data for flow over cylinders are those of Hilpert (1933). He considered flow of air normal to cylinders at various diameters. The results presented in terms of the Nusselt and Reynolds numbers based on the cylinder diameter are:

$$Nu = c_1\ Re^{c_2} \qquad (2.20)$$

The coefficients c_1 and c_2 from Hilpert's data are given in Table 1.

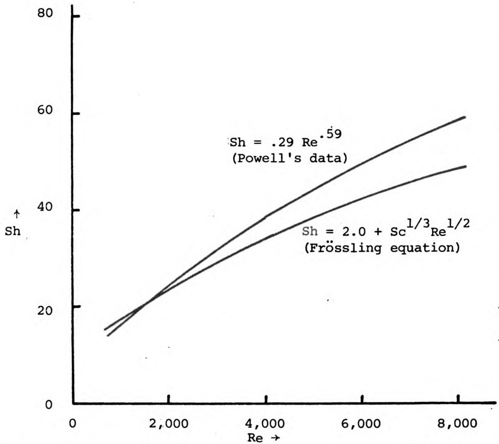
For evaporation from cylinders normal to the airstream, Powell's data lead to the relationships:

$$Sh = .24\ Re^{.59} \qquad (2.21)$$

$$100 < Re < 2000$$

$$Sh = .17\ Re^{.64} \qquad (2.22)$$

$$2000 < Re < 40{,}000$$



Re	Sh Eqn. (2.19)	Sh Eqn. (2.17)	Diff. %
600	12.8	14.4	-12.5
1,000	17.1	18.1	- 5.8
2,000	25.5	24.6	3.5
3,000	32.5	29.7	8.3
4,000	38.2	34.1	10.7
5,000	44.4	37.8	14.7
6,000	49.3	41.8	15.2
7,000	54.0	44.7	17.2
8,000	58.0	47.9	17.4
9,000	62.3	51.4	17.5
10,000	65.2	53.0	18.7

$Sc \simeq .60$

Figure 1.--Comparison between convective mass transfer relationships for flow over spheres. Powell's data versus Frössling equation.

TABLE 1.--Coefficients in equation (2.20) for various Reynolds numbers. Flow normal to a circular Cylinder (Kays, 1966).

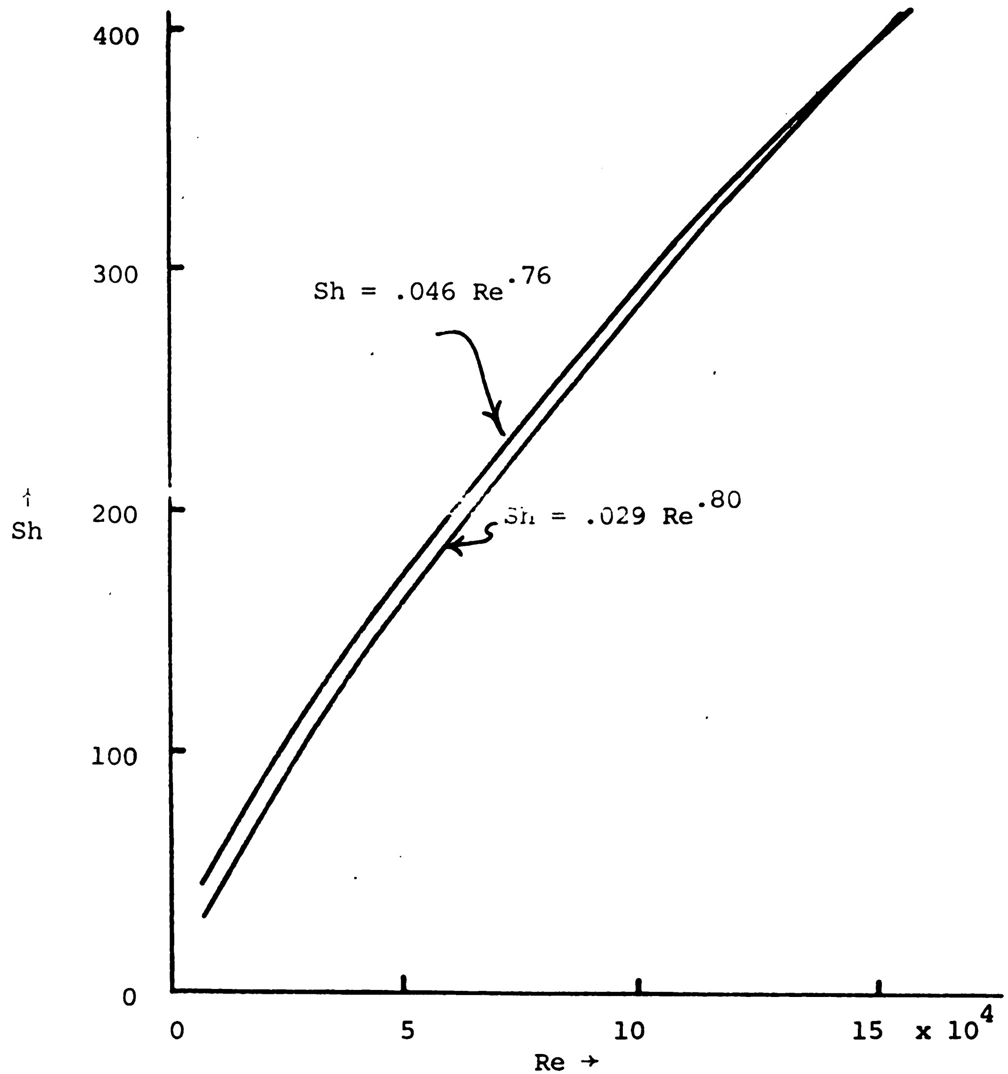
Re	c_1	c_2
1-4	.891	.330
4-40	.821	.385
40-4,000	.615	.466
4,000-40,000	.174	.618
40,000-250,000	.0239	.805

In the case of cylinders parallel to the air-stream, the following relationship developed from Powell data holds:

$$Sh = .029\ Re^{.8} \tag{2.23}$$

The order of agreement over an extended range of Reynolds number (5,000 to 200,000) of equations (2.13) and (2.23) is shown in Figure 2. Differences of less than 10 percent were observed.

d. Flow Over Axisymmetrical Bodies.--Smith and Spalding (1958) proposed an approximate solution for the case of flow over axisymmetric bodies. The solution is restricted to the laminar constant-surface temperature problem and to situations where separation of flow does not occur. The solution leads to the relationship:



Re	Sh Eqn. (2.13)	Sh Eqn. (2.23)	Diff. %
5,000	29.9	26.5	10.70
10,000	50.6	46.4	8.30
30,000	115.4	110.2	4.50
50,000	171.3	166.8	2.60
70,000	222.9	217.5	2.40
90,000	266.6	264.6	.08
120,000	332.1	333.5	- .04
140,000	375.8	377.0	-0.30
160,000	415.2	420.5	-1.20
180,000	454.5	464.0	-1.90
200,000	498.2	507.5	-2.00

$Sc \simeq .6$

Figure 2.--Comparison between convective mass transfer relationships for flat plates (equation 2.13) and for cylinders parallel to the air stream (equation 2.23). Powell's data.

$$St_x = \frac{c_1\ \mu^{1/2}\ R_x (V_\infty \rho)^{c_2}}{[\int_0^x (V_\infty \rho)^{c_3}\ R_x^{\ 2}\ dx]^{1/2}} \qquad (2.24)$$

The coefficients c_1, c_2 and c_3, are given in Table 2, for various Prandtl numbers. In order to find the average convective heat transfer coefficient equation (2.9) can be used.

TABLE 2.--Coefficients in equation (2.24) for various Prandtl numbers. Heat transfer to the laminar-constant property boundary layer (Kays, 1966).*

Pr	c_1	c_2	c_3
.7	.418	.435	1.87
.8	.384	.450	1.90
1.0	.332	.475	1.95
5.0	.117	.595	2.19
10.0	.073	.685	2.37

*$T_\infty = T_s$ = constant

By analogy, the local convective mass transfer coefficient $\underline{g_x}$, defined in equation (2.52) can be computed by

$$g_x = V_\infty \rho \frac{c_1\ \mu^{1/2}\ R_x (V_\infty \rho)^{c_2}}{[\int_0^x (V_\infty \rho)^{c_3}\ R_x^{\ 2}\ dx]^{1/2}} \qquad (2.25)$$

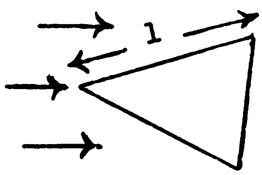
The coefficients c_1, c_2 and c_3, as computed by Spalding and Chi (1963) are functions of the Schmidt number, Sc, and the driving force, B, and are given in Table 3. As before, equation (2.9) is used to calculate the overall mass transfer coefficient.

TABLE 3.--Coefficients for equation (2.25) for various values of Schmidt number, Sc. Laminar constant-property boundary layer (Kays, 1966).

Sc	B	c_1	c_2	c_3
.7	-.9	1.850	.050	1.10
	-.6	.812	.150	1.30
	0.0	.418	.435	1.87
	1.0	.244	.650	2.30
	3.0	.136	1.150	3.30
	9.0	.060	1.900	4.80
1.0	-.9	1.430	.150	1.30
	-.6	.633	.250	1.50
	0.0	.332	.475	1.95
	1.0	.200	.650	2.30
	3.0	.113	1.000	3.00
	9.0	.052	1.450	3.90
5.0	-.9	.431	.450	1.90
	-.6	.205	.500	2.00
	0.0	.117	.595	2.19
	1.9	.073	.650	2.30
	3.0	.045	.750	2.50
	9.0	.023	.900	2.80
5.0	-.9	$1.037(Sc)^{-2/3}$	.90	2.8
	-.6	$.568(Sc)^{-2/3}$	.90	2.8
	0.0	$.339(Sc)^{-2/3}$	.90	2.8
	1.0	$.230(Sc)^{-2/3}$	.90	2.8
	3.0	$.145(Sc)^{-2/3}$	.90	2.8
	9.0	$.077(Sc)^{-2/3}$	.90	2.8

e. Flow Over Conical Surfaces.--Luikov (1965) obtained experimental relationships for calculating the convective heat transfer coefficient of flow over bodies of a conical shape. Miranov (1962) reported relationships of convective mass transfer coefficients over cones during porous cooling. Table 4 presents the reported equations for each tested condition.

TABLE 4.--Convective heat and mass transfer coefficients for flow over conical surfaces.

Orientation to Airflow	Characteristic Dimension	Relationship	Reference
	1	$Nu=.128Re^{.65}$ (2.26) (Metal body)	Luikov (1965)
		$Sh=.161Re^{.67}$ (2.27) (Porous Cooling)	Miranov (1962)

f. Flow Over Prolate Spheroids.--Lochiel and Caderbank (1964) developed relationships for calculating the convective mass transfer coefficient of flow over prolate spheroids by using results of flow over spheres:

$$\frac{Sh_{ps}}{Sh_s} = [\frac{2}{3}\ (1+J)]^{1/2}\ \ [\frac{2E^{1/3}(1-E^2)^{1/2}}{E(1-E^2)^{1/2} + \sin^{-1}(1-E^2)^{1/2}} \qquad (2.28)$$

where

Sh_{ps} = Sherwood number for prolate spheroids

Sh_s = Sherwood number for spheres [Equation (2.17) or (2.19)]

$$J = -\left\{\frac{\mathrm{Ln}[(1+e)/(1-e)] - 2e}{\mathrm{Ln}[(1+e)/(1-e)] - 2e/(1-e^2)}\right\}$$

$e = (1-E^2)^{1/2}$

E = "Eccentricity" or width to height ratio.

2.1.2 Surface Area of Single Particles of Agricultural Products

Formulas for the prediction of surface area of individual product are empirical in nature. A number of researchers have determined the surface area of the product by peeling the commodity in narrow strips and taking the planimeter sum of the tracings as the surface area. Others have used a method consisting of coating the product surface with spherical beads and then correlate the weight of those beads with the surface area. In each case the value obtained was assumed to be the actual area of the commodity and it was used to obtain relationships between the surface area and product parameters such as the area of traverse cross section, traverse diameter, axial or longitudinal diameter, correlation with the geometric volume and correlation with the geometric volume and correlation with the weight. A review of the literature on prediction of surface area of individual apples, potatoes and sugar beets follows.

a. Apples.--Some researchers have calculated the surface area of an apple on the assumption it is a sphere. Magness *et al*. (1926) used measurements of the circumference, while Hamilton (1929) used caliper measurements of the diameter of tagged apples. Gunther (1948), Baten and Marshall (1943), Chapman *et al*. (1934) and Smith (1926) measured the traverse and vertical axis and used the average of these diameters to calculate the area. Chapman *et al*. (1934) measured the volume displaced by an apple to calculate the diameter of a sphere of that volume and then used the diameter to compute the surface area.

Barnes (1929) considered an apple as a cardioid and used the formula:

$$A = .3095 \sqrt[3]{(W_o d)^2} \qquad (2.29)$$

Barnes (1929) reported that the surface areas computed by equation (2.29) did not differ over 5% from his best "unstated" mechanical measurement.

Baten and Marshall (1943) compared several methods to predict surface areas of apples and other fruits. They found that the traverse diameter, i.e., perpendicular to the core, gave the best predictions for unpicked fruits, while the relation of surface area to weight gave the best predictions of surface area for picked apples. The following weight-surface area relationships were reported:

For Delicious apples

$$A = .045993 + .40635W_o \qquad (2.30)$$

For Jonathan apples

$$A = .044701 + .42840W_o \qquad (2.31)$$

For McIntosh apples

$$A = .049458 + .40635W_o \qquad (2.32)$$

For Stayman Winesap apples

$$A = .058472 + .35280W_o \qquad (2.33)$$

Frechette and Zahradnik (1965) compared a linear and a second degree polynomial weight-surface area relationship for McIntosh apples. The following two regression equations were compared:

$$A = .054306 + .34650W_o \qquad (2.34)$$

and

$$A = .155764 + .71820(W_o - .28983) - .6044(W_o^2 - .08675) \qquad (2.35)$$

Although the second degree polynomial gave the best fit curve for the data, the two regression equations differ insignificantly. The researchers pointed out that the linear equation can be used with confidence because it gave a correlation coefficient of .975 and a maximum error of 2.9% from the mean.

Frechette and Zahradnik (1965) also developed an empirical equation for the surface area of equivalent spheres based on the average density of the McIntosh apples tested:

$$A = .36069(W_o)^{.667} \tag{2.36}$$

The values of this curve differ a maximum of 3.86% from the best fit curve for the 84 McIntosh apples that were tested for the relationship of surface area based on weight.

Recent studies have idealized several fruits as bodies of revolution having some characteristic parameters. Moustafa (1971) idealized the apple fruit as an ellipse whose coordinate axes were translated and rotated to create a shape similar to one half of an apple cross section. The elliptical shape was then rotated 360 degrees about its new major axis.

The surface area resulting from the rotation of the upper part of the ellipse through an angle of 2π around the x-axis will be

$$A = 2\pi \int_{o}^{\pi} R^2 \operatorname{Sin} \theta \, d\theta \tag{2.37}$$

where

$$R = a^2 c \operatorname{Sin} (\theta - z) + \sqrt{\frac{a^4 c^2 \operatorname{Sin}^2(\theta - z) - [b^2 + (a^2 - b^2)\operatorname{Sin}^2(\theta - z)][c^2 a^2 - a^2 b^2]}{b^2 + (a^2 - b^2)\operatorname{Sin}^2(\theta - z)}} \tag{2.38}$$

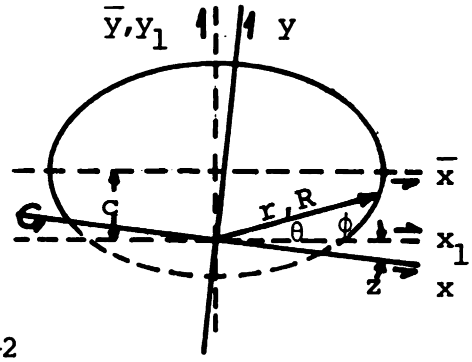
a, b, c and z are the characteristic parameters. Their definition is given in Figure 3.

Using numerical approximations, equation (2.37) takes the form:

$$A = 2\pi \sum_{i=1}^{n} R_i^{\,2} \operatorname{Sin} \theta_i \, (\Delta\theta) \tag{2.39}$$

a, b, c and z are measured from a longitudinal section through the longitudinal axis of symmetry of the fruit. Figure 4 shows the method of measuring model parameters.

Moustafa's results show close agreement between experimental and predicted surface areas for apples with differences of less than 10 percent. No information of the variety used for testing the model is given. Moustafa pointed out that small errors in measuring the model parameters can result in a large error in the theoretical



$$\frac{\bar{x}^2}{a^2} + \frac{\bar{y}^2}{b^2} = 1$$ Ellipse in Cartesian Coordinates

if

$$\bar{x} = x_1$$

$$\bar{y} = y_1 - c$$

$$b^2 x_1{}^2 + a^2 (y_1 - c)^2 = a^2 b^2$$

or in polar coordinates

$$b^2 r^2 \mathrm{Cos}^2 \phi + a^2 r^2 \mathrm{Sin}^2 \phi - 2a^2 cr\mathrm{Sin}\phi = a^2 (b^2 - c^2)$$

where

$$x_1 = r\mathrm{Cos}\phi$$

$$y_1 = r\mathrm{Sin}\phi$$

rotating througn an angle z,

$$b^2 R^2 \mathrm{Cos}^2 (\theta - z) - 2a^2 cR\mathrm{Sin}(\theta - z) = a^2 (b^2 - c^2)$$

Figure 3.--Diagram of an Ellipse used as the Basic Curve for Generating a Model to Represent an Apple. Axis x and y were Translated to x_1, y_1, and then Rotated to x, y. The Major Portion of the Ellipse was Then Rotated 360 Degrees about the x-axis, Generating the Model. Moustafa (1971).

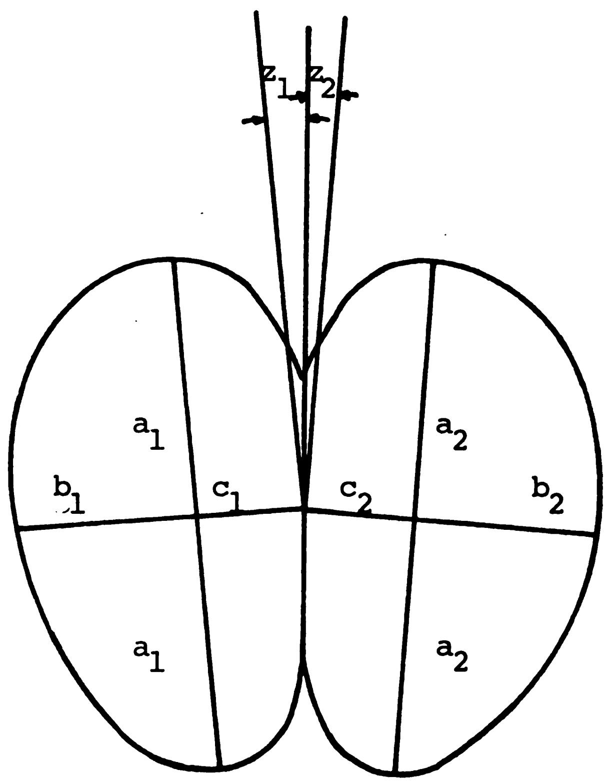


Figure 4.--Method of Measuring Model Parameters for Each Side of the Longitudinal Section of an Apple. Moustafa Model.

predicted area due to the high power to which the parameter is computed.

A mathematical model of the apple using bi-sphercal coordinates was developed by Cooke and Rand (1969). The width W and height H are the descriptive parameters. The surface area A of the apple can be computed from:

$$A = 2a^2 \int_{\eta=o}^{\infty} \int_{\psi=o}^{2\pi} \frac{\text{Sin}\,\theta\, d\psi\, d\eta}{(\text{Cosh}\ \ \eta - \text{Cos}\ \theta)^2} \qquad (2.40)$$

where

$$\theta = \cos^{-1} \left(\frac{W}{H} - 1\right) \qquad (2.41)$$

$$a = \frac{H\ \text{Sin}\ \theta}{2} \qquad (2.42)$$

Equation (2.40) may be normalized by dividing by the surface area (A_s) of a sphere having a diameter equal to the height H of the apple:

$$\frac{A}{4\pi\ (H/2)^2} = [\text{Sin}\,\theta + (\pi - \theta)\ \cos\,\theta] = \sigma \qquad (2.43)$$

or

$$A = \sigma\ A_s \qquad (2.44)$$

The function σ defined in equation (2.44) increases monotonically with W/H and is equal to unity for W/H=1. A plot of W/H versus σ is presented in Figure 5.

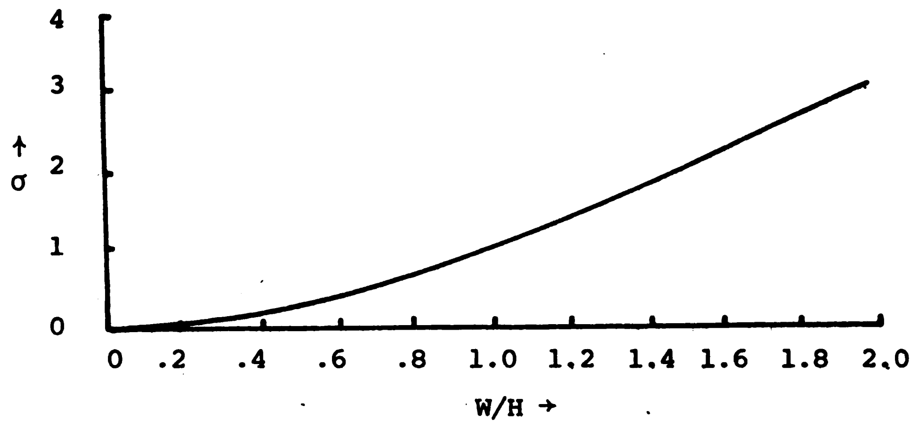


Figure 5.--Weight:Height Ratio (W/H) Versus the Normalized Surface Area Parameter, σ. Equation (2.44).

b. Potatoes.--Maurer and Eaton (1971) described a method for predicting surface areas of potatoes by measuring the major and minor axis of potato tubers. It was assumed that the shape of the potato is closer to the geometric form of a prolate spheroid than to other geometrical forms. The equation for a surface area of a prolate spheroid is:

$$A = \frac{\pi b^2}{2} + \frac{\pi db\ \mathrm{Sin}^{-1}\ Ec}{2Ec} \tag{2.45}$$

where d is the major axis, b the minor axis and

$Ec = \sqrt{\frac{d^2-b^2}{b}}$ is the eccentricity.

Because of differences in the traverse sections of individual tubers, the minor axis was estimated by adding the value of the width (b_1) and thickness (b_2) and dividing by 2 to obtain the minor axis. In terms of a potato tuber, equation (2.45) becomes:

$$A = \frac{\pi (b_1 + b_2)\ [(b_1 + b_2)\ Ecc + 2d\ \mathrm{Sin}^{-1} Ecc]}{8Ecc} \tag{2.46}$$

where

$$Ecc = \frac{\sqrt{d^2 - (\frac{b_1 + b_2}{2})^2}}{d}$$

Maurer and Eaton (1971) applied equation (2.46) to tubers of several varieties including Red Pontiac, Kennebec and Warba. Although there was close agreement between experimental and predicted results some varieties did not correlate as well as others. The errors resulted mostly from tubers with a flat side.

c. Sugar Beets.--Sandera and Suecova (1954) suggested the following weight-surface area relationship for sugar beets

$$A = C_o W_o^{2/3} \tag{2.47}$$

The constant C_o is a function of the $\frac{\text{height}}{\text{diameter}}$ $(\frac{H}{D})$ ratio. For the variety for which equation (2.47) was developed the value of $(\frac{H}{D})$ ranged between 4 to 6 and C_o between 6.83 and 7.17.

2.1.3 Driving Force for Evaporation

Units of the energy driving force defined in equation (2.1) are temperature. Three different sets of units are used to express the mass driving force:

a. In terms of concentration units. C in equation (2.2) can be expressed in $[ML^{-3}]$ units. In this case h_d will be given in $[L\theta^{-1}]$ units.

b. In terms of vapor pressure units. Assuming water vapor as an ideal gas:

$$(C_{ws} - C_{w\infty}) = \frac{M}{R_o} \left(\frac{P_{ws}}{T_s} - \frac{P_{v\infty}}{T_\infty}\right) \tag{2.48}$$

Substituting (2.43) into (2.2)

$$\dot{M}_w = h_d \, A \, \frac{M}{R_o} \left(\frac{P_{ws}}{T_s} - \frac{P_{w\infty}}{T_\infty} \right) \tag{2.49}$$

Since T_s and T_∞ are absolute temperatures and close in value, equation (2.49) can be approximated by:

$$\dot{M}_w = h'_d \, A \, (P_{ws} - P_{w\infty}) \tag{2.50}$$

where

$$h'_d = h_d \frac{M}{R_o T} \tag{2.51}$$

Units of the mass transfer coefficient h'd, defined in equation (2.51), are $[M\theta^{-1} \, F^{-1}]$.

c. In terms of dimensionless units. Equation (2.2) can also be written as (Kays, 1966):

$$\dot{M}_w = gAB \tag{2.52}$$

where

$$B = \frac{m_{w\infty} - m_{ws}}{m_{ws} - 1} \text{, dimensionless} \tag{2.53}$$

and

$$m_{wi} = 1 - \frac{1}{1 + \omega_i} \tag{2.54}$$

where

$$\omega_i = \text{Absolute humidity } \left(\frac{\text{Mass of water}}{\text{Mass dry air}}\right)$$

Units of the mass transfer coefficient $\underline{g}$, defined in equation (2.52), are $[M\theta^{-1} L^{-2}]$.

Although dimensionless units are more convenient from an engineering stand point, pressure units have most often been used to present data on moisture losses from agricultural products. The term "vapor pressure deficit" (VPD) is employed to describe the driving force for the moisture losses phenomenon.

2.1.4 Some Properties of Air-Vapor Mixtures in the Range 32-100°F

For completeness purposes, tabulation of those properties of air and air-vapor mixture important in the evaporation process is presented in this section. The listing of such properties is limited to the 32-100°F temperature range. Equations describing properties were preferred whenever they were available in the literature. Linear interpolation was used in some cases.

a. Saturation Pressure Line of Air-Vapor Mixtures.-- From Brooker (1970):

$$\mathrm{Ln}(P_{sat}/144\ A_o) = \frac{A_1 + A_2 + A_3T^2 + A_4T^3 + A_5T^4}{A_6T - A_7T^2} \qquad (2.55)$$

$$491.69 \leq T(°R) \leq 959.69$$

where,

A_o = 0.3206182232000000 D 04	A_4 = 0.2153211916363544 D -04
A_1 = -0.2740552583614256 D 05	A_5 = -0.4620266568199822 D -08
A_2 = 0.5418960763289505 D 02	A_6 = 0.2416127209874000 D 01
A_3 = -0.4513703841126545 D-01	A_7 = 0.1215465167060546 D -02

b. Latent Heat of Vaporization, h_{fg}.--Brooker (1967), using Keenan and Keyes data, developed the following linear regression curve for the latent heat of vaporization:

$$h_{fg} = 1075.8965 - 0.56983\ (T - 459.69) \qquad (2.56)$$

$$491.69 \leq T\ (°R) \leq 609.69$$

c. Absolute Humidity.--Assuming that the air and water vapor are ideal gases the well known psychrometric expression for the absolute humidity can be derived:

$$\omega = \frac{.6219\ P_v}{P_{atm} - P_v} \qquad (2.57)$$

$$459.69 \leq T\ (°R) \leq 959.69$$

d. Air Density.--

$$\rho = \frac{(P_{atm} - P_v)}{53.35\ T} \qquad (2.58)$$

Equation (2.58) is the ideal gas law and needs no explanation.

e. Additional Aerodynamic and Thermodynamic Properties of Air in the Range 32-100°F.--Table 5 shows a tabulation of additional aerodynamic and thermodynamic air properties which affect the evaporation process. Holman (1972) and Perry (1963) were used as the source of information. Linear interpolation was used whenever the exact value at a given temperature was not found.

Throughout the present research the units are expressed in the British system. In Appendix A a conversion table from British units to SI units is presented.

2.2 Diffusion of Gases Through Membranes

Fick's law of diffusion may be applied to describe the movement of water vapor through porous membranes. In terms of molecular flux such an equation is:

$$\dot{M}_w = -D_{wa}\ A\ \frac{\partial C}{\partial x} \qquad (2.59)$$

When equation (2.59) is used to describe the movement of water vapor through a membrane, a parameter

TABLE 5.--Properties of air at atmospheric pressure in the range 32-100°F.

Temp.	Dynamic Viscosity $\frac{lbm}{hr\text{-}ft}$	Density $\frac{lbm}{ft^3}$	Kinematic Viscosity $\frac{ft^2}{hr}$	Specific Heat $\frac{BTU}{lbm\ °F}$	Thermal Conduc. $\frac{BTU}{hr\text{-}ft°F}$	Thermal Diffus. $\frac{ft^2}{hr}$	Prandt Number	Molecular Diffus. $\frac{ft^2}{hr}$	Schmidt Number
32	.0415	.0805	.516	.240	.0137	.709	.728	.854	.602
35	.0417	.0800	.521	.240	.0138	.719	.724	.864	.602
40	.0420	.0792	.530	.240	.0140	.736	.720	.880	.603
45	.0423	.0784	.539	.240	.0141	.739	.718	.895	.604
50	.0427	.0776	.550	.240	.0143	.768	.716	.910	.605
55	.0430	.0769	.559	.240	.0144	.780	.717	.925	.606
60	.0434	.0761	.570	.240	.0146	.799	.714	.939	.607
65	.0437	.0754	.479	.240	.0147	.812	.713	.953	.608
70	.0440	.0747	.589	.240	.0149	.831	.710	.967	.609
75	.0443	.0740	.598	.240	.0150	.845	.707	.981	.610
80	.0446	.0733	.608	.240	.0152	.864	.705	.995	.611
85	.0449	.0726	.618	.240	.0153	.878	.704	1.009	.612
90	.0453	.0720	.629	.240	.0155	.897	.702	1.022	.615
95	.0456	.0713	.639	.240	.0156	.912	.701	1.035	.617
100	.0459	.0707	.649	.240	.0157	.925	.701	1.048	.619

which characterizes the behavior of the specific membrane must be included. This parameter (r) is a measure of "resistivity" to the flow of water vapor through the membrane. Equation (2.59) can be transformed in:

$$\dot{M}_w = -\frac{D_{wa}}{r} A \frac{\partial C}{\partial x} \tag{2.60}$$

If a constant gradient concentration and isothermal diffusion are assumed, equation (2.60) becomes:

$$\dot{M}_w = -\frac{D_{wa}}{r\delta} A \frac{M}{R_o T} (P_o - P_s) \tag{2.61}$$

Equation (2.61) may be used to describe the mechanism of water vapor movement through a porous membrane.

2.3 Skin Nature of Horticultural Products

The nature of the skin of a commodity as a barrier to the evaporation process limits the independent use of equation (2.1) and (2.2) or equation (2.61) for describing the phenomenon of moisture loss from horticultural products.

The thickness and nature of the protective coating is highly variable. Mushrooms behave as free water surfaces (Fockens, 1967). Carrots and sugar beets have less protective coating than apples or pears and consequently loose water faster. Tomatoes have a relative impermeable skin and lose almost no water at all. Differences have also been observed in varieties of the same commodity (Lutz, et al., 1968).

In order to predict the behavior of a specific commodity with respect to moisture losses the nature of its skin must be known. Due to the individuality in skin composition, only the three products covered in the present study will be considered in this section.

Information on the characteristics of the skin of specific products with regard to moisture losses is scarce. Most of the available literature on this topic is related to fruits.

2.3.1 Apples

There have been several conflicting reports concerning the avenue of gas exchange in fruits. In general, three different routes have been proposed (1) pedical opening of floral end (Brooks, 1937); (2) lenticels or stomata (Haberlandt, 1971); and (3) the cuticle (Smith, 1954).

Burg and Burg (1965) found that diffusion of gases through the pedicel opening or floral end was important in some commodities. When this pathway was sealed off the rate of gas evoluted declined in tomatoes and green peppers but no measurable response was observed in apples.

Clement (1935) studied the morphology and physiology of lenticels in apples. Conclusions of his work are the following:

1. Lenticels may be open or closed depending on the character of the hypodermal cells. The cells may be cutinized or suberized and then rendered closed to the free movement of gases or liquids. Lenticels may also be closed when the stomata, associated with the lenticel, is closed over by means of the epidermal cuticle. Lenticels may be open when the hypodermal cells are unmodified or when the modified cells have been torn apart.

2. The total number of lenticels per apple is characteristic of the apple variety. The number may range from 450 to 800 in the case of Winesap apples and from 1500 to 2500 in the case of Spitzenburger apples.

3. The number of lenticels per apple varies depending on the amount of water available to the plant during the early development of the apples. This reaction is varietal rather than general. The Winesap apple when given more water produced more lenticels per apple than when grown with less water. The Delicious apples when given more water actually produced fewer lenticels even though the apples were larger.

4. Lenticels are closed by processes which favor dehydration of the outer tissues of the apple. While the

apples are still unmature, they respond more completely to such treatment than do mature apples. After apples have been in storage for 6-8 weeks, they respond only after prolonged treatments.

5. Carbon dioxide gas within the apple escapes with equal speed whether the apple has many or few open lenticels.

Some studies have shown that about 99.5% of the surface of the apples is impervious to water vapor (Fockens, 1967). The presence of wax in the skin of the apple is probably the cause of this behavior. Smock (1950) observed that if an apple cuticle is separated from its adjacent tissues and is them immersed in warm ether, the ether solution fraction, referred as "wax," amounts to some 50 percent of the total cuticle matter. Horrocks (1964) compared the permeability to water vapor of a disk of apple skin with and without wax. Results showed a very dramatic increase in permeability whenever the wax was removed from the skin by soaking in two successive solutions of hot chloroform.

Burg and Burg (1965) suggested that regardless of the nature of the pathways for gas exchange in apples (unless it directly or indirectly involves one or more enzymatic steps) it is highly likely that the process will be governed by Fick's law of diffusion:

$$\dot{M}_w = \frac{D_{wa}}{r} fA \frac{\partial C}{\partial x} \qquad (2.62)$$

Fockens (1967) proposed a model to predict moisture losses from agricultural products:

$$\dot{M}_w = A\{\gamma_1 \frac{hd}{R_o T} + \gamma_2 [(\frac{1}{R_o T})(\frac{1}{\frac{1}{h_d} + \frac{r\delta}{D_{wa}}})]\} (P_{ws} - P_{w\infty}) \qquad (2.63)$$

Fockens tested his model on beds of apples. The vapor pressure deficit was calculated assuming a vapor pressure at the apple surface equal to the saturated vapor pressure at the environmental dry bulb temperature. Values of $\gamma_1 = 0$ and $\gamma_2 = 1/250$ for apples were reported. Fockens also found that the so called "coefficient of diffusional resistance," $r\delta$, is an inverse function of the relative humidity of the surrounding air. Wilkinson (1965) noticed a similar increase in permeability to water vapor of the apple skin when the relative humidity of the surrounding air was increased.

Lentz and Rooke (1964) observed a non-linear response to vapor pressure deficit changes in eight different variety of apples. When the vapor pressure deficit was decreased, i.e., increasing the relative humidity, the moisture loss per unit of vapor pressure deficit increased. Although the trend was the same for all varieties, the quantitative response was varietal dependent.

A considerable amount of data was found in the literature for the moisture loss from apples. Most of the reported experiments were conducted in beds of products. The information is generally presented in terms of mass loss per unit time per unit weight per unit of vapor pressure deficit. Vapor pressure deficit is always calculated at the environmental dry bulb temperature.

Table 6 summarized the published moisture loss data for several varieties of apples.

2.3.2 Potatoes

Smith (1968) described the skin of the potato as a layer of corky periderm 6 to 10 cells deep acting as a protective area over the surface of the tuber. Small lenticels-like structures occur over the surface of the tuber. These develop in the tissue under the stomata and are initiated in the young tuber when it still has an epidermis. Periderm thickness varies considerably among varieties. Cultural conditions also influence periderm thickness.

Burton (1966) stated that "water is lost from the tubers by evaporation, there being no regulation mechanism, and the rate of loss of any particular sample of potatoes being proportional to the water vapor pressure deficit between the tuber and the surrounding air."

TABLE 6.--Published data on rate of moisture loss from apples.

Variety	Temp. °F	VPD lb/ft^2	Duration of Test	Rate of Moisture Loss $\frac{\text{lb water}}{\text{lb apple-hr-}\frac{\text{lbf}}{\text{ft}^2}}$	References	Remarks
Bramley's	32	1.278 2.556 3.830	4 days	6.455×10^{-6} 6.671×10^{-6} 6.346×10^{-6}	Smith (1932)	First 24 hr. of test ignored in calculating results to reduce initial effect of change in relative humidity.
	33.8	2.418	3 months	8.654×10^{-6}	Kidd and West (1931)	
	37.4	.806	6 months	10.313×10^{-6}	Smith (1933)	25% decrease in rate of loss during first 50 days.
Calville Blanc	39.2 50.0	4.363 5.113	5 months	5.553×10^{-6} 8.185×10^{-6}	Gac (1956)	High loss first 5-10 days, then constant.
Cortland	32.0	.472 .639 1.223 1.523 2.390	24-72 hrs	7.392×10^{-6} 8.149×10^{-6} 6.552×10^{-6} 7.212×10^{-6} 5.445×10^{-6}	Lentz (1964)	Average velocity of 100 ft/min. Sample held at test condition for 1 or 2 days.
Cox Orange Pippen	37.4	.306 4.030	6 months	17.381×10^{-6} 13.450×10^{-6}	Smith (1933)	

TABLE 6.--Continued.

Variety	Temp. °F	VPD lb/ft^2	Duration of Test	Rate of Moisture Loss $\frac{\text{lb water}}{\text{lb apple-hr-}\frac{\text{lbf}}{\text{ft}^2}}$	References	Remarks
Golden Delicious	34.7	1.390	6-8 days	24.520×10^{-6}	Wells (1962)	
		2.779		17.669×10^{-6}		
	54.5	4.530	6 hours	10.565×10^{-6}	Pianiazek (1942a)	Samples held 77°F and 50% RH for 48 hrs before test.
	77.0	6.614		11.395×10^{-6}		
Grimes	34.7	1.390	6-8 days	21.636×10^{-6}	Wells (1962)	
		2.779		16.227×10^{-6}		
Jonathan	34.7	1.390	6-8 days	10.818×10^{-6}	Wells (1962)	
		2.779		8.654×10^{-6}		
McIntosh	32	.667	24-72 hrs	5.265×10^{-6}	Lentz (1964)	Air velocity from 32 to 100 ft/min did not affect considerably the rate of loss.
		1.251		6.265×10^{-6}		
		2.140		6.094×10^{-6}		
		3.196		5.611×10^{-6}		
	54.5	4.530	8-12 hrs	5.625×10^{-6}	Pianiazek (1942a)	Samples held at 77°F and 98% RH for 24 hrs before test.
	77.0	6.614	6 hrs	6.779×10^{-6}		
Northern Spy	32.0	.611	24-72 hrs	9.015×10^{-6}	Lentz (1964)	Air velocity from 32 to 100 ft/min did not affect the rate of moisture loss
		1.251		6.022×10^{-6}		
		1.445		6.923×10^{-6}		
		2.390		6.274×10^{-6}		
		3.168		5.373×10^{-6}		

TABLE 6.--Continued.

Variety	Temp. °F	VPD lb/ft^2	Duration of Test	Rate of Moisture Loss $\frac{\text{lb water}}{\text{lb apple-hr-}\frac{\text{lbf}}{\text{ft}^2}}$	References	Remarks
Red Delicious	32	.361	24-72 hrs	13.883×10^{-6}	Lentz (1964)	
		.639		14.099×10^{-6}		
		1.278		11.359×10^{-6}		
		1.890		8.474×10^{-6}		
		2.501		8.222×10^{-6}		
Rhode Island Greening	32	.556		14.243×10^{-6}	Lentz (1964)	
		.695		15.145×10^{-6}		
		1.445		10.024×10^{-6}		
		2.501		8.619×10^{-6}		
	54.5	4.530	26 hrs	4.796×10^{-6}	Pianiazek (1942a, b)	Samples held at 77°F and 50% RH for 48 hrs before test.
	77.0	6.614	21 hrs	4.976×10^{-6}		
Sandow	32	.639	24-72 hrs	14.099×10^{-6}	Lentz (1964)	
		1.362		11.612×10^{-6}		
		2.779		8.582×10^{-6}		
Yellow Bellflower	32-33.8	.667	18 weeks	7.428×10^{-6}	Allen and Pentzer (1935)	
		1.973		5.373×10^{-6}		

Butchbaker (1970) suggested that equation (2.61) expressing Fick's law of diffusion could be used to predict moisture losses in potatoes. The difficulty in measuring the thickness of the potato tuber skin was considered as the limitation for using Fick's law for calculating the moisture losses.

Schippers (1971) reported two different moisture loss relationships obtained for the same variety of potatoes (Katahdin) in two consecutive years:

$$1968: \quad PL = .676V_w + 1.40 \tag{2.64}$$

$$1969: \quad PL = .874V_w + .61 \tag{2.65}$$

Limited data were found in the literature for moisture losses from potatoes. Table 7 summarizes the reported data for several varieties of potatoes.

2.3.3 Sugar Beets

Very little useful information about the behavior of the sugar beet skin in regard to moisture losses was found in the literature.

Khelemski and Zhadan (1964) found empirical relationships between the velocity of the surrounding air and the mass transfer coefficient for individual beets. The relationships are given in terms of an apparent convective mass transfer coefficient for sugar beets, $h'_{d\ app}$ When such relationships were expressed in terms of British units the following equations were obtained:

TABLE 7.--Published data on rate of moisture loss from potatoes.

Variety	Sample Charact.	Temp. °F	RH %	Rate of Moisture Loss $\frac{\text{lb water}}{\text{lb pot.-hr-}\frac{\text{lbf}}{\text{ft}^2}}$	References	Remarks
Kennebec	uncured	38-40	98-100	29.569×10^{-6}	Lentz (1971)	An air flow of 10 fpm was used in all tests. Potatoes were cured by holding them at 50°F and 90-100% RH for 10-14 days (weight loss 1-1 1/2%) before storage. Test samples consisted of 6 to 9 potatoes.
	cured			10.457×10^{-6}		
Katahdin	uncured			7.212×10^{-6}		
	cured			4.327×10^{-6}		
Sebago	uncured			27.405×10^{-6}		
	cured			6.491×10^{-6}		
Warba	uncured			9.736×10^{-6}		
	cured			5.409×10^{-6}		
Netted Gem	cured			5.770×10^{-6}		

Schippers (1971) reported an average rate loss of 2.682×10^{-6} pound of water/pound of potato-hr-lbf/ft^2 for Katahdin and Russet varieties.

Burton (1966) gives an average rate loss for potatoes of $.736 \times 10^{-5}$ to 1.104×10^{-5} lb of water/hr-ft^2 - lbf/ft^2.

$$h'_{d\ app} = .000528 \left(\frac{V_\infty}{11,808}\right)^{.6} \tag{2.66}$$

$$h'_{d\ app} = .000294 \quad \text{still air} \tag{2.67}$$

III. OBJECTIVES

The objectives of this study were:

1. Development of a model for predicting moisture losses from horticultural products in storage.
2. Comparison and development of relationships for predicting surface areas of individual Jonathan apples, Manona potatoes and US H20 sugar beets.
3. Study of the effect of the shape of the individual particles on moisture losses from apples, potatoes and sugar beets.
4. Determination of the skin parameters that affect the rate of moisture losses in Jonathan apples, Manona potatoes and US H20 sugar beets.
5. Preparation of prediction graphs of moisture losses from Jonathan apples, Manona potatoes and US H20 sugar beets.

IV. THEORY

4.1 Model for Predicting Moisture Losses from Horticultural Products

Weight losses of horticultural products result as the combination of the respiration and evaporation (moisture losses) processes. Weight losses due to respiration are of negligible nature in comparison with losses due to evaporation. For that reason the contribution of respiration to the weight loss process will be neglected in this study.

Moisture losses from horticultural products is basically a mass transfer process, and the theory of physical transport phenomena may thus be used to study the problem.

The agricultural products studied in this investigation contain between 80 to 95 percent of water by weight. Some of this water is lost during storage by evaporation. The moisture movement within the product is rapid enough to maintain during normal storage conditions a saturated condition just below the skin. Therefore, no concentration gradient exists within such products. This "lumped concentration capacity" assumption is transient in nature, but considering that the maximum allowable moisture loss from the product is relatively small (from 3 to 10 percent in a 6 to 9 month period), a constant rate of moisture loss during the storage time can be expected as long as the storage conditions do not change. The steady state condition has been observed by most of the researchers after the first few days of storage time.

The problem of moisture losses from horticultural products can be analysed as a process controlled by the rate at which water vapor moves through the skin of the product and is carried away from the surface by convection.

In general, the skin of a commodity may be considered as a combination of zones that present a distinctive "resistance" to the movement of water vapor (Figure 6). Certain areas of the surface may behave as free water surfaces; equation (2.1) describes their contribution in the moisture transfer process. Other regions of the surface may behave as porous membranes and their contribution to the loss of moisture can be predicted by Fick's equation of diffusion. Finally, zones of the skin may be impervious to water vapor. The overall behavior of a product with regard to moisture losses is given by the relative magnitude of these areas and by the value of the parameters affecting the governing equations.

In the following analysis, an electrical analogy is used to model the skin of an agricultural product. Figure 7 shows the equivalent electric circuit that represents the different paths water vapor may follow in

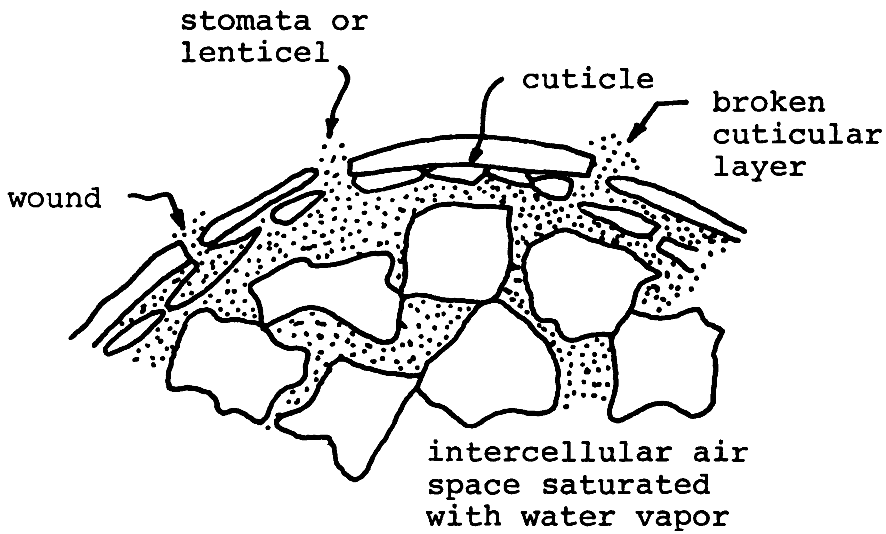
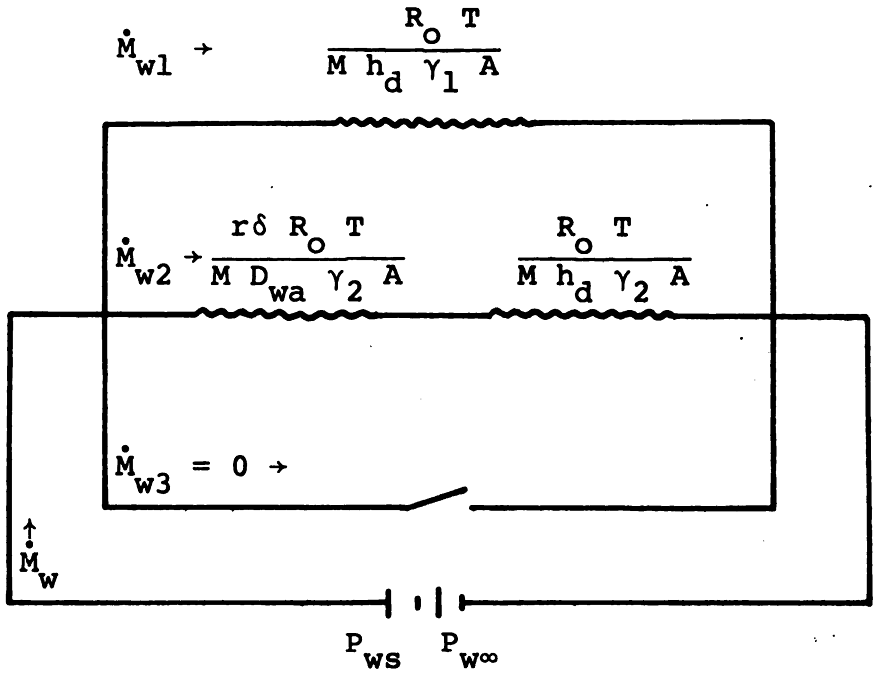


Figure 6.--Schematic Diagram of the Skin of a Horticultural Product. Common Routes of Water Vapor are Shown. The Cuticle is a Natural Waxy Covering Found in Some Fruits and Vegetables. Adopted from Mitchell et al. (1972).



Governing Equations:

$$\dot{M}_{w1} = \left(\frac{M\ h_d\ \gamma_1\ A}{R_o\ T}\right)(P_{ws} - P_{w\infty}) \tag{4.1}$$

$$\dot{M}_{w2} = \left(\frac{1}{\dfrac{r\delta\ R_o\ T}{M\ D_{wa}\ \gamma_2\ A} + \dfrac{R_o\ T}{M\ h_d\ \gamma_2\ A}}\right)(P_{ws} - P_{w\infty}) \tag{4.2}$$

$$\dot{M}_{w3} = 0 \tag{4.3}$$

$$\dot{M}_w = \dot{M}_{w1} + \dot{M}_{w2} + \dot{M}_{w3} \tag{4.4}$$

$$\tilde{T}_s = \frac{hAT - 1337.8416\ \dot{M}_w}{hA - .56983\ \dot{M}_w} \tag{4.5}$$

Figure 7.--Electrical Analogy to Represent the Behavior of the Skin of a Product with Regard to Moisture Losses.

leaving the product. The governing equations are also given.

The first path corresponds to that region of the skin that behaves as a free water surface. The governing equation [see equation (2.50) and (2.51)] is them:

$$\dot{M}_{w1} = \left(\frac{M\ h_d\ \gamma_1\ A}{R_o\ T}\right)\ (P_{ws} - P_{w\infty}) \tag{4.1}$$

The second path corresponds to the portion of the total area behaving as a porous membrane. Two resistances in series, the one for the diffusion through the membrane and the one for the convection process, characterize this path. The describing equation for moisture losses through this path is then:

$$\dot{M}_{w2} = \left(\frac{1}{\dfrac{r\delta\ R_o\ T}{M\ D_{wa}\ \gamma_2\ A} + \dfrac{R_o\ T}{M\ h_d\ \gamma_2\ A}}\right)\ (P_{ws} - P_{w\infty}) \tag{4.2}$$

Finally, the third path is an open circuit corresponding to impermeable regions of the skin:

$$\dot{M}_{w3} = 0 \tag{4.3}$$

The overall mass losses from a product can be obtained by adding these partial losses:

$$\dot{M}_w = \dot{M}_{w1} + \dot{M}_{w2} + \dot{M}_{w3} \tag{4.4}$$

An analysis of the variables and parameters of the skin model described by equations (4.1), (4.2), (4.3), and (4.4) follows.

The convective mass transfer coefficient, h_d, is not a constant but is a function of position on the surface. Regrettably, the variation of h_d with position is known for only those cases where separation of flow does not occur. An overall value for the convective mass transfer coefficient has to be used.

Relationships for calculating the mass transfer coefficient of flow over different geometrical shapes were discussed previously. Agricultural products can only be approximated by the following shapes: apples by spheres, potatoes by prolate spheroids and sugar beets by cones. Due to the variability in shape of individual samples of the same commodity, a study of accuracy of such approximation with regard to the prediction of h_d seems appropriate.

The effect of shape of the product on moisture losses can be isolated by studying the behavior of peeled samples. If the skin of the different products under investigation is removed, the behavior of the individual samples with regard to moisture losses is governed by the shape of the product under similar environmental conditions. This is true if the study is performed during an appropriate short period of time, where an approximately constant rate of moisture loss is observed, and a steady state assumption is justified.

The study of moisture losses from peeled samples will also give comparison values to measure the effectiveness of the product as a barrier for the migration of moisture from the product.

Study of moisture loss from peeled samples of those products under investigation is one objective of the present research.

The surface area determination is empirical in nature. Equations for prediction of the surface area apply to the variety of the commodity they were developed for. This is particularly true in the case of weight-surface area relationships. More general formulas are needed. However, the goodness of the prediction may be more important than its generality at least for certain type of studies. On the other hand, due to the fact that products are stored in beds, weight-surface area relationships could be more useful when knowledge of the behavior of individual bodies is going to be applied to practical situations.

Weight-surface area relationships for Jonathan apples, Manona potatoes, and US H20 sugar beets will be developed in the present research. Comparative studies of different formulas will be conducted whenever it seems appropriate.

The driving force (voltage in the electrical analogy) needs especial consideration. In general, regardless of the nature of the product, the assumption of a vapor pressure at the surface equal to the saturated vapor pressure at the environmental dry bulb temperature has been used in the literature for calculating the driving force for the mass loss process. Although this approximation could be good enough for products with highly impervious skins, i.e., apples, it is misleading for products that behave as free water surfaces.

To determine the driving force affecting the evaporation process, the temperature at the surface, T_s, must be known. Equation (2.1) can be used to obtain an estimate of an average value of the temperature at the surface. If the formula for h_{fg} given by equation (2.56) is substituted into equation (2.1) the following relationship is obtained:

$$\tilde{T}_s = \frac{h\ AT - 1337.8414\ \dot{M}_w}{h\ A - .56983\ \dot{M}_w} \quad (^{\circ}R) \tag{4.5}$$

In calculating the driving force for evaporation the vapor pressure at the surface can be assumed to be equal to the saturated vapor pressure at $\tilde{T}_s$.

Parameters γ_1, γ_2, $\underline{r}$ and $\underline{\delta}$ characterize in general the behavior of the skin with regard to moisture losses. From these four parameters only three are independent; r and δ cannot be simultaneously determined by using the described model. The product $\underline{r\delta}$ will be considered as one parameter from now on.

The individual behavior of a product may allow simplifications into the model. For some products the fraction of the total area that behaves as a free water surface might be negligible in comparison with the "membrane like" path. In such case $\gamma_1 = 0$ and the effect of the environmental air velocity will be a minor variable in the moisture loss process. On the other hand, in some products the porous membrane path might be considered negligible in comparison with the free water path. In the latter case the parameter γ_1 represents an "effective area" of moisture loss. Finally the skin of some products may be considered approximately impervious to moisture migration.

Two different problems may be considered with regard to the model: the "inverse" problem of estimating the parameters from mass loss data and the "classical" one of calculating moisture losses when the parameters are known. Both problems will be studied.

Techniques for predicting the parameters of the models discussed above are outlined in the next section. The statistics associated with the prediction is also discussed.

4.2 Estimation of Parameters

The models discussed in the previous section fall into two categories: linear or nonlinear with respect to the parameters.

Weight-surface area relationship may be expressed by models which are linear, or by models that can be linearized. Dimensionless relationships for calculating the convective mass transfer coefficients are also equations that can be linearized. On the other hand, the model for predicting the moisture loss from horticultural products (equation 4.4) is a nonlinear model with respect to the parameters, γ_1, γ_2 and $\underline{r\delta}$.

In analysing the problem of estimating the parameters of those models described above, the concepts and notation presented by Beck (1973) are used.

4.2.1 Linear Models

Three models will be considered in determining weight-surface area relationships for individual products. A linear model,

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i \tag{4.6}$$

and the "intrinsically" nonlinear models,

$$Y_i = \beta_0 \, X_i^{\beta_1} + \varepsilon_i \tag{4.7}$$

and

$$Y_i = \beta_0(\beta_1)^{X_i} + \varepsilon_i \tag{4.8}$$

Equation (4.7) is also the basic model for determining the convective mass transfer coefficient, h_d.

Equations (4.7) and (4.8) can be linearized by taking logarithms:

$$\text{Ln } Y_i = \text{Ln}(\beta_0) + \beta_1 \text{ Ln}(X_i) + \varepsilon'_i \tag{4.9}$$

$$\text{Ln } Y_i = \text{Ln}(\beta_0) + \text{Ln } \beta_1 \, X_i + \varepsilon'_i \tag{4.10}$$

Equations (4.6), (4.9) and (4.10) may be similarly analyzed with regard to the determination of parameters β_0 and β_1.

If the criteria of minimization of the sum of squares is used, the following set of equations allows the determination of estimates for β_0 and β_1:

$$b_1 = \frac{\sum_{i=1}^{n} (X_i-\overline{X})(Y_i-\overline{Y})}{\sum_{i=1}^{n} (X_i-\overline{X})^2} \tag{4.11}$$

and

$$b_0 = \overline{Y} - b_1\overline{X} \tag{4.12}$$

where,

b_0 and b_1 = estimates of parameters β_0 and β_1, respectively

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i \qquad (4.13)$$

$$\bar{Y} = \frac{1}{n} \sum_{i=1}^{n} Y_i \qquad (4.14)$$

n = number of data points.

The predicted regression value of Y_i is denoted by $\tilde{Y}_i$:

$$\tilde{Y}_i = b_0 + b_1 X_i \qquad (4.15)$$

The residual $\underline{e_i}$ is the measured value of Y_i minus the predicted value or,

$$e_i = Y_i - \tilde{Y}_i \quad (e_i \neq \varepsilon_i) \qquad (4.16)$$

Equations for estimating the variance and standard deviations for Y_i, b_0 and b_1 are summarized in Table 8.

Parameter confidence intervals can be calculated from:

$$b_i - \text{s.d.}(b_i)\, t_{1-\alpha/2}\,(n-p) < \beta_i < b_i + \text{s.d.}(b_i)\, t_{1-\alpha/2}\,(n-p)$$

(4.17)

TABLE 8.--Formulas for estimating variances and standard deviations of Y_i, b_0 and b_1 in the model $Y_i = b_0 + b_1 X_i$.

I	Estimated Variances Var (I)	Estimated standard deviations s.d. (I)
Y_i	$\frac{1}{n-2} \sum_{i=1}^{n} (Y_i - \tilde{Y}_i)^2$	$\sqrt{Var(Y_i)}$
b_0	$\frac{Var(Y_i) \sum_{i=1}^{n} (X_i)^2}{n \sum_{i=1}^{n} (X_i - \bar{X})^2}$	$\sqrt{Var(b_0)}$
b_1	$\frac{Var(Y_i)}{\sum_{i=1}^{n} (X_i - \bar{X})^2}$	$\sqrt{Var(b_1)}$

where

n = number of data points

p = number of parameters

$t_{1-\alpha/2}(n-p)$ = value from a t-distribution table for $(n-p)$ degrees of freedom and $(1-\alpha/2)$ probability.

4.2.2 Nonlinear Models

The dependent variable, $\dot{M}_w$, of the model for predicting moisture losses (equation 4.4) is linear with respect to γ_1 and γ_2 but is nonlinear with respect to $\underline{r\dot{\delta}}$. The problem of predicting these parameters is then of a nonlinear nature. Iterative techniques must be used for predicting the parameters.

Meeter and Woolfe (1968) developed a computer routine called GAUSHAUS which estimates parameters entering nonlinearly into a mathematical model.

In GAUSHAUS the estimates of each iteration are obtained by a method developed by Marquardt (1963) which combines the Gauss (Taylor series) method and the method of steepest descent. The user must provide a main program to read input data from cards or tape and to initialize certain constants. A subroutine that determines values of the model for a choice of parameter values transmitted to it by GAUSHAUS must also be provided by the user. Output from GAUSHAUS is a printed report which includes a description of the problem, a summary of each iteration relating to the precision of the estimates and possible to the adequacy of the mathematical model.

The skin parameters of horticultural products can be estimated by applying the GAUSHAUS routine to the moisture loss data.

4.2.3 Comparison of Models

In general, if two or more linear or nonlinear models apply to the same data, a coefficient, R^2, can be used to compare the effectiveness of the models in reproducing the experimental data. This coefficient is defined as:

$$R^2 = 1 - \frac{\Sigma_B \, e_i^{\,2}}{\Sigma_A \, e_i^{\,2}} \tag{4.18}$$

where

$\Sigma_B \, e_i^{\,2}$ = sum of square residuals for model B

$\Sigma_A \, e_i^{\,2}$ = sum of square residuals for model A,

assuming that

$$\Sigma_A \, e_i^{\,2} > \Sigma_B \, e_i^{\,2} \tag{4.19}$$

Because of condition (4.19), an examination of (4.18) leads to $0 \leq R^2 \leq 1$, where $R^2 = 0$ corresponds to the models being nearly equally effective, and $R^2 = 1$ corresponds to model B being much better than model A.

For simple linear models such as (4.6), (4.9) and (4.10) the following expression for $R_1^{\,2}$ is frequently used:

$$R_1^{\,2} = \frac{b_1^{\,2} \, \Sigma \, (X_i - \overline{X})^2}{\Sigma \, (Y_i - \overline{Y})^2} \tag{4.20}$$

The value of $R_1^{\,2}$ defined by equation (4.20) implies the comparison of

$$\text{model A} \qquad {}_AY_i = \beta_0 + \varepsilon_{i,A}\;\; {}_A\tilde{Y}_i = \overline{Y} = b_0 \qquad (4.21)$$

$$\text{with} \quad \text{model B} \qquad {}_BY_i = \beta_0 + \beta_1 X_i + \varepsilon_{i,B}\;\; {}_B\tilde{Y}_i = b_0 + b_1 X_i \qquad (4.22).$$

As before, a value of $R_1^{\,2} \to 0$ corresponds to model A (equation 4.21) being equally effective as model B (equation 4.22). If $R_1^{\,2} \to 1$, model B is much better than model A.

With regard to model A (equation 4.21) and model B (equation 4.22), an F-test can be used to obtain a measure of how much the additional term (β_1) has improved the prediction. If F is small, then the two parameter model does not significantly improve the fit compared to the one parameter model.

Finally, the computed F value can be statistically bounded by comparing the value with a tabulated $F_{1-\alpha}$ (1, n-2) value. If the calculated value F exceeds the tabulated value, the probability that the hypothesis H_o: $B_1 = 0$ is false is α. If the calculated F value is less than the tabulated one, the null hypothesis is rejected; that is, it may be that $\beta_1 = 0$.

V. EXPERIMENTAL PROCEDURES

To achieve the objectives, a group of experiments were conducted during Fall, Winter and Spring seasons of 1972-1973 at the Agricultural Engineering Processing Laboratory of Michigan State University. A description of how the products were handled and the apparatus and procedures used is given below.

Before any weight loss test was performed, the products were handled in a somewhat different manner.

Mature Jonathan apples from the MSU Horticultural Farm at Grand Rapids were hand picked from four different trees. They were packed in plastic bags, placed on carton boxes, and immediately stored at 36°F.

Potatoes of Manona variety were picked at Stanton, Michigan after they were machine harvested. They were placed in mesh bags and stored at 65°F, 90-100% relative humidity, for two weeks. Immediately after the suberization process they were stored at 36°F.

Sugar beets of US H20 variety were hand dug from a MSU field in East Lansing. They were topped at the base, placed in plastic bags and stored at 36°F.

In general, the moisture loss tests consisted of measuring the weight loss history of individual peeled or unpeeled samples placed in a test chamber in which the temperature, relative humidity and airflow of the air were controlled. Specifics about the procedure and apparatus used during each set of experiments follows.

5.1 Comparison and Development of Formulas for Predicting Surface Areas of Individual Apples, Potatoes and Sugar Beets

Experimental surface areas of apples, potatoes, and sugar beets were obtained by peeling each individual sample in narrow strips and calculating the planimeter sum of the tracings.

Shape parameters were measured in each sample to allow comparison of the different methods for predicting the surface area of individual particles. The weight of the unpeeled sample was taken for the development of surface area-weight relationships of each product.

In the case of apples, before each sample was peeled a longitudinal section was made through the longitudinal axis of symmetry of the fruit. The section was then drawn on paper, and the parameters for predicting surface areas were measured. Parameters a, b, c, and z for the Moustafa model were measured according to the method described in Figure 4. Width and height of each sample were measured for the prediction of surface areas using Cooke's bispherical model. Weights of the unpeeled samples were taken to the nearest .001 gram.

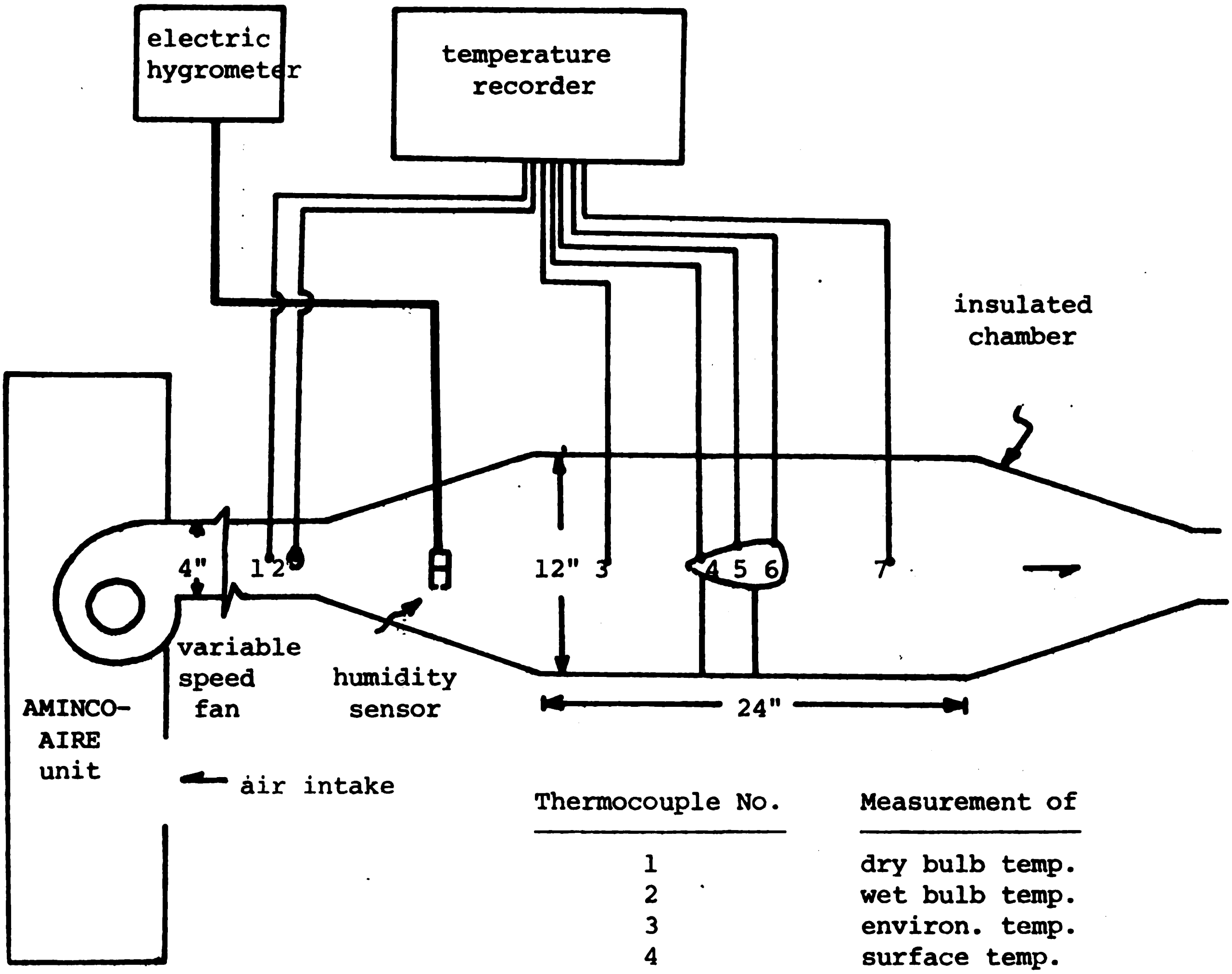
Comparison of a weight-surface area relationship with Maurer's prolate spheroid model for potatoes was performed. In order to predict the surface area of each potato sample by Maurer's model, sections were made through the major and minor axis of each sample. These sections were drawn on paper, and parameters b_1, b_2 and d (equation 2.46) were measured. Weights of the unpeeled samples were obtained to the nearest .001 gram.

In the case of sugar beets, three weight-surface area relationships were compared with each other. Weights of the unpeeled samples were obtained to the nearest .01 gram.

5.2 Study of the Effect of the Shape of the Body on Moisture Losses from Apples, Potatoes and Sugar Beets

A set of experiments was conducted to study the effect of the product shape on moisture losses from peeled samples. Tests consisted of measuring the weight loss from individual peeled samples placed in a test chamber during a one hour period. Temperature, relative humidity and airflow of the environmental air were kept constant during each experiment.

Figure 8 shows the experimental set-up for this study. The test chamber consisted of a box of two feet in length and one foot square cross sectional area. The box was insulated with one inch expanded polystyrene.



Thermocouple No.	Measurement of
1	dry bulb temp.
2	wet bulb temp.
3	environ. temp.
4	surface temp.
5	surface temp.
6	surface temp.
7	environ. temp.

Figure 8.--Schematic Diagram of the Experimental Set-up Used in Moisture Losses Studies from Peeled Samples.

Temperatures were measured with 20 gage copper-constantan thermocouples placed at the locations shown in Figure 8. A texas Instrument* potentiometer was used for continuous monitoring of the temperature. Temperatures were recorded to the nearest .5°F.

Relative humidity was measured with a series of Hygrodynamics** humidity sensing elements. An electric hygrometer was used to monitor the sensor readings. The sensor's accuracy was checked continuously with a dry-wet thermocouple set (thermocouples 1 and 2).

Air velocity was measured with a calibrated hot-wire anemometer.

Thermocouples were placed on the surface of the sample at three different locations.

In order to condition the environmental air, an Aminco-Aire*** unit was used. This unit is able to control the dry bulb temperature and relative humidity of the air to within ± .75°F and .5 R.H., respectively.

A variable speed fan controlled the airflow in the environmental chamber.

The procedure described below was followed during each test:

---

*Texas Instruments Incorporated, Houston, Texas.

**Hygrodynamics, Inc., Silver Springs, Maryland.

***American Instrument Company, Silver Springs, Maryland.

a. The sample was removed from storage (36°F) and placed in the chamber for a 18-24 hrs period under test conditions.

b. The sample was peeled and the resulting narrow strips of skin were recorded on paper to determine the surface area.

c. Holes were drilled through the samples in order to place thermocouples for measuring the temperature at the surface.

d. Initial weight of the sample was obtained. The scale was located immediately adjacent to the test chamber to reduce difficulty with handling during the weighing procedure. Weights were obtained to the nearest .001 gram in the case of apples and potatoes and .01 gram in the case of sugar beets.

e. The sample was placed in the test chamber and after one hour of exposure to the conditions, a final weight was obtained.

f. Characteristic shape parameters of the sample were recorded.

5.3 Estimation of Skin Parameters of Jonathan Apples, Manona Potatoes and US H20 Sugar Beets

A set of tests was conducted to determine the parameters which characterize the behavior of Jonathan apples, Manona potatoes and US H20 sugar beets with regard to moisture losses.

The tests consisted of measuring the weight loss history of individual samples placed in a test box during a certain period of time. The duration of each experiment and the frequency of weight measurements varied with the product being tested. In the case of apples and potatoes a 110-120 hrs period was used, with periodical weight measurements every 24 hrs. In the case of sugar beets, a 12-18 hrs period was used, with periodical weight measurements every two hrs.

The test chamber consisted of an 8 foot long and one foot square cross sectional area insulated box.

The temperature, relative humidity and airflow of the environmental air were measured with the same type of instruments described previously for the weight loss tests of the peeled samples.

Aminco-Aire units were also used for conditioning the environmental air. In this set of experiments, however, the test chamber was arranged in a closed circuit with the conditioning Aminco unit.

Because variation in the behavior of individual samples was expected, several samples were placed in the test chamber during each individual test. In the case of sugar beets, four samples evenly distributed in the chamber were studied simultaneously. In the case of apples and potatoes, eight samples were studied simultaneously.

The following steps were followed during each individual test:

a. Samples were removed from storage (36°F) and placed in the chamber for a 18-24 hrs period under test conditions.

b. The initial weight of each sample was recorded. Weights were obtained to the nearest .001 gram in the case of apples and potatoes, and to the nearest .01 gram in the case of sugar beets.

c. Periodic weights of each individual sample were obtained.

d. Samples were peeled and the resultant narrow strips of skin were drawn on paper to determine the surface area.

e. Peeled samples were replaced in the chamber and periodic weights of the peeled samples were taken.

f. Characteristic shape parameters of the samples were recorded.

VI. RESULTS AND DISCUSSION

6.1 Prediction of Surface Areas of Single Particles

Weight-surface area relationships were developed for each one of the products being researched. A computer routine, ALEASQ, was written to estimate the parameters β_0 and β_1 of the linear model $A = \beta_0 + \beta_1 W_o$. ALEASQ also linearizes models $A = \beta'_0 (W_o)^{\beta'_1}$ and $A = \beta'_0 (\beta'_1)^{W_o}$ and gives an estimation of parameters β'_0 and β'_1. The routine finally gives a statistical analysis of the estimated parameters. A listed of ALEASQ is given in Appendix B.

Comparison of the developed relationships was made with some of the models described in the literature.

In the case of Jonathan apples, Baten's weight-surface area relationship, Cooke's two-parameters, and Moustafa's four parameters model were compared with the linear relationship developed from planimeter data.

For Manona potatoes, the prolate spheroid Maurer's model was compared with the developed weight-surface area relationship.

Sandera's formula for predicting surface area of sugar beets was developed for a different variety than the one used in this study. For this reason no attempt was made to compare the experimental weight-surface area relationship with Sandera's equation. Instead, the weight-planimeter area data were applied to those models described by equations (4.6), (4.7) and (4.8). A comparison of the prediction of surface area by these models was made.

Results and discussion on the developed relationships and model comparisons for each individual product are presented below.

6.1.1 Jonathan Apples

The linear least square analysis on the planimeter data of Jonathan apples gave the following weight-surface area relationship for individual apples:

$$A = .04164 + .4359\ W_o \qquad (6.1)$$

A plot of the planimeter surface area data and of the linear relationship (equation 6.1) is presented in Figure 9. The statistical analysis associated with equation (6.1) is given in Tables 9 and 10.

A high regression coefficient, $R_1^2 = .98811$, and a calculated F value ($F = 4655.42$) much larger than the tabulated F value ($F_{.01} = 7.10$) characterizes statistically the prediction of equation (6.1). The 95% intervals of confidence for b_0 and b_1 are: $.03780 < b_0 < .04548$ and $.4231 < b_1 < .4487$.

Predicted surface areas by equation (6.1) and by the relationships developed by Baten, Cooke and Moustafa are summarized in Appendix C.

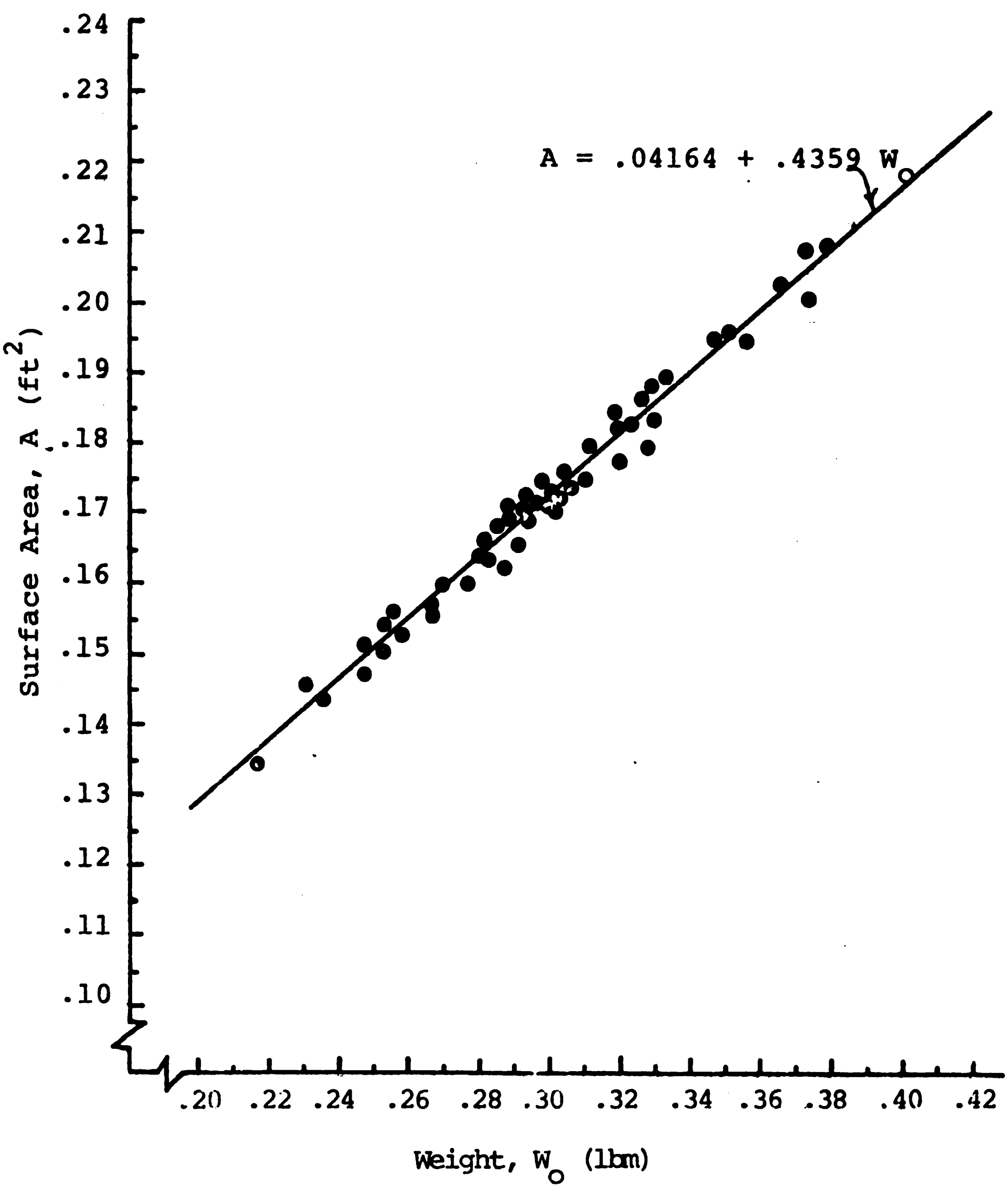


Figure 9.--Weight-Surface Area Relationship for Individual Jonathan Apples. Equation (6.1).

TABLE 9.--Estimated variances and standard deviations of the dependent variable and parameters of equation (6.1).

I	Estimated Variance of I Var (I)	Estimated Standard Deviation of I s.d. (I)
A	.0000038	.00195
b_0	.0000037	.00192
b_1	.0000408	.00639

Coefficient $R_1^2 = .98811$

95% interval of confidence for $b_0 = .03780 < b_0 < .04548$

95% interval of confidence for $b_1 = .4231 < b_1 < .4487$

TABLE 10.--Table for partition about the mean. Equation (6.1).

Source of Variation	Sum of Squares	D. of F	Mean Squares	F
Residuals	.0002	56	.000003	$F_{calculated}$ 4655.42
Deviation Between Line and Mean	.0178	1	.0178	$F_{.01\ table}$ 7.10
TOTAL	.0180	57		

Table 11 presents a comparison of the models. The linear relationship developed by Baten gives comparative results to those of equation (6.1) (coefficient $R^2 = .17$). On the other hand, equation (6.1) gives better prediction than Cooke's or Moustafa's models ($R^2 = .83$ and $R^2 = .99$, respectively).

It is interesting to notice, however, that the predicted surface areas by Cooke's model are within ± 6% of the experimental ones. This model could be useful for studies where the weighing procedure is difficult or not possible, i.e., in preharvesting studies.

TABLE 11.--Comparison of four models for prediction of surface areas of individual Jonathan apples.

Model	Residuals	Square Residuals	R^2
Linear experimental Equation (6.1)	.0000	.0002	.00
Baten	.0479	.0003	.17
Cooke	-.1696	.0013	.83
Moustafa	1.3364	.0648	.99

Moustafa's model showed poor prediction of surface areas of Jonathan apples. It was observed that the residuals increase as the size of the sample increases, Figure 10. It may indicate that the deviation from the

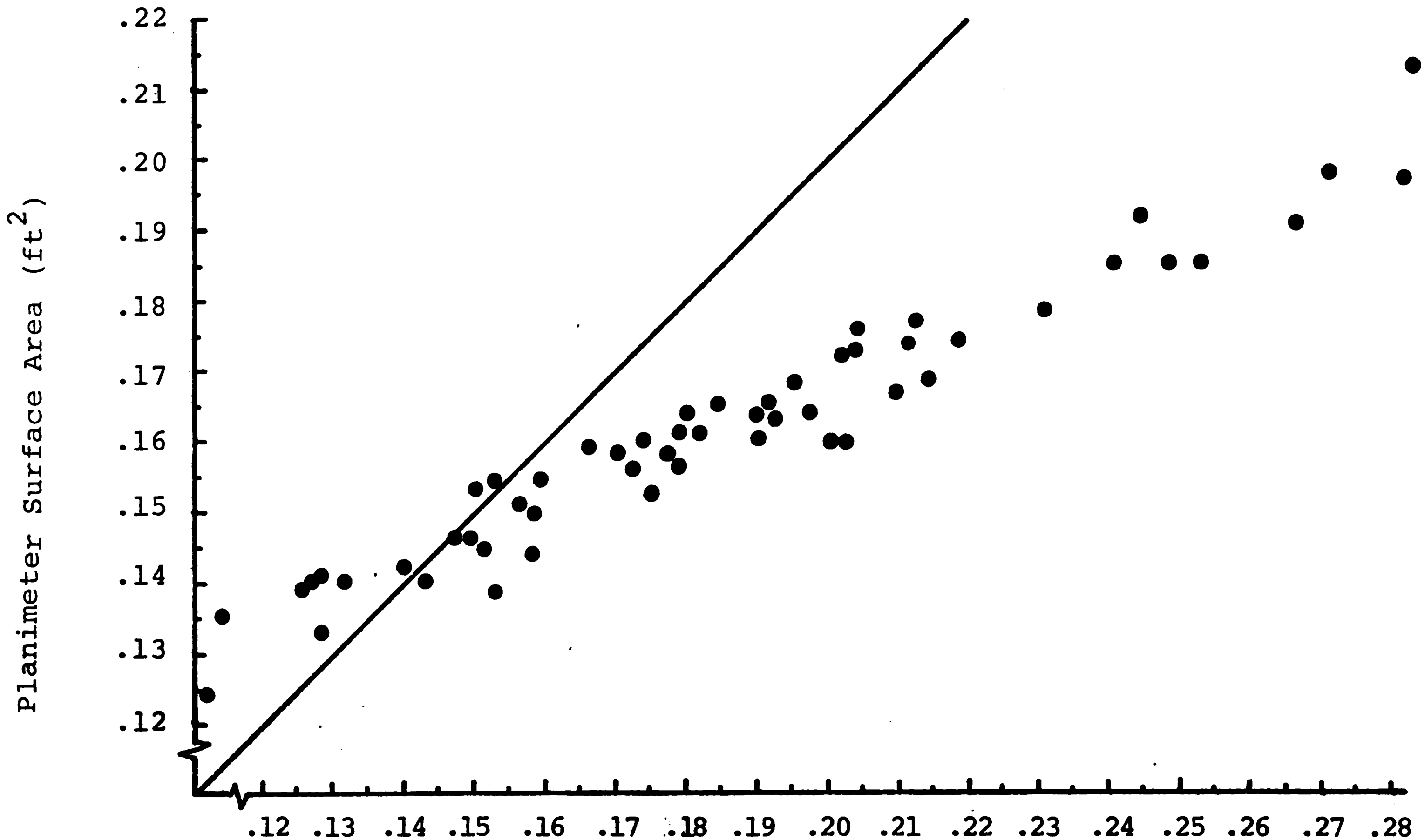


Figure 10.--Area Predicted by Moustafa's Model Versus the Experimental Planimeter Area.

assumed elliptical shape is larger for big than for small samples.

6.1.2 Manona Potatoes

The least square analysis on the planimeter data of 120 Manona potatoes gave the following weight-surface area relationship for individual potatoes:

$$A = .3018\ W_o^{.6638} \qquad (6.2)$$

Figure 11 shows a plot of the planimeter surface area and of the relationship expressed by equation (6.2). The statistical analysis on equation (6.2) is given in Tables 12 and 13.

A high R_1^2 coefficient ($R_1^2 = .97888$) was obtained. The calculated F value is much higher than the tabulated one at 99% confidence limit. The 95% intervals of confidence for b_0 and b_1 are: $.2967 < b_0 < .3069$ and $.6461 < b_1 < .6816$.

Predicted surface areas by Maurer's model and by equation (6.2) are presented in Appendix D. Maurer's model showed poor prediction of the surface area of Manona potatoes in comparison with equation (6.2). A R^2 coefficient of .97 was obtained (see Table 14).

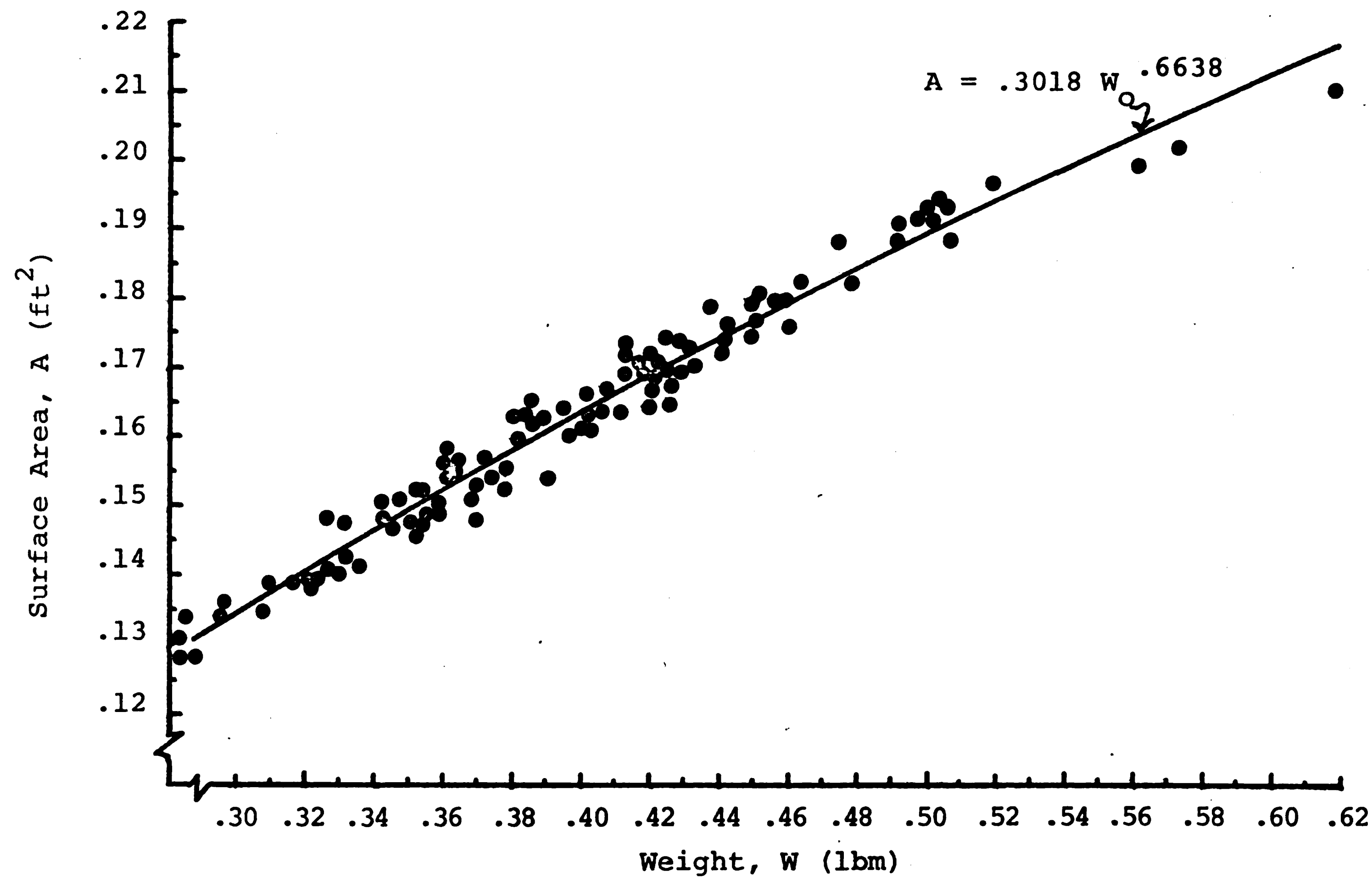


Figure 11.--Weight-Surface Area Relationship for Individual Manona Potatoes. Equation (6.2).

TABLE 12.--Estimated variances and standard deviations of the dependent variable and parameters of the linear representation of equation (6.2).

I	Estimated Variance of I Var (I)	Estimated Standard Deviation of I s.d. (I)
Ln(A)	.00025	.01575
Ln(b_0)	.00007	.00858
b_1	.00008	.00898

Coefficient $R_1^2 = .97888$.

95% interval of confidence for b_0: $.2967 < b_0 < .3069$.

95% interval of confidence for b_1: $.6461 < b_1 < .6816$.

TABLE 13.--Table for partition about the mean for the linear representation of equation (6.2).

Source of Variation	Sum of Squares	D. of F	Mean Squares	F
Residuals	.0239	118	.0002	$F_{calculated}$ 5469.15
Deviation Between Line and Mean	1.3564	1	1.3564	$F_{.01 \text{ table}}$ 7.02
TOTAL	1.3857	119		

TABLE 14.--Comparison of models for predicting surface areas of individual manona potatoes.

Model	Residuals	Square Residuals	R^2
Experimental Equation (6.2)	-.0022	.0008	.00
Maurer	1.1388	.0283	.97

6.1.3 US H20 Sugar Beets

When surface area planimeter data of 68 beets were applied to equations (4.6), (4.7) and (4.8) the following relationships were obtained:

$$A = .1088 + .2227\ W_o \tag{6.3}$$

$$A = .3247\ W_o^{.7744} \tag{6.4}$$

$$A = .2474\ (1.487)^{W_o} \tag{6.5}$$

A plot of the planimeter surface area data and of the relationships expressed by equations (6.3), (6.4) and (6.5) is presented in Figure 12. Tables 15 and 16 summarized the statistics of the equations. High regression coefficients and F values higher than the tabulated F values are obtained for each relationship. The 95% confidence intervals of the parameters for each equation are presented in Table 15.

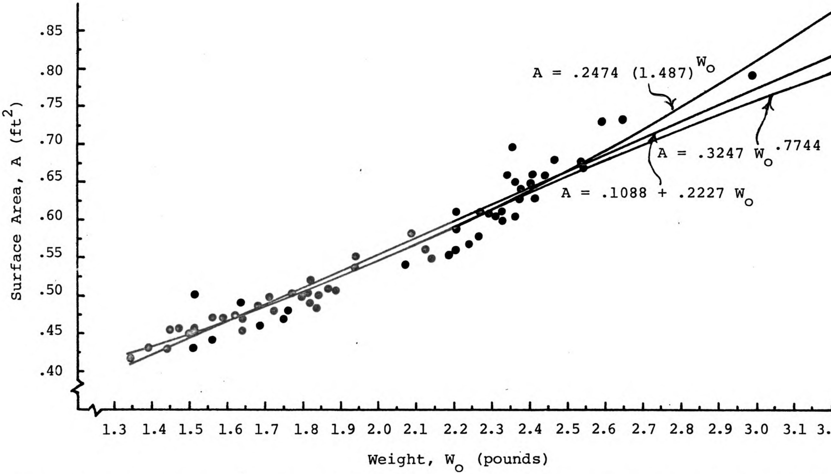


Figure 12.--Weight-Surface Area Relationships for US H20 Sugar Beets. Equations (6.3), (6.4) and (6.5).

TABLE 15.--Estimated variances and standard deviations of the dependent variable and parameters of the linear representation of equations (6.3), (6.4) and (6.5).

	Equation (6.3)	Equation (6.4)	Equation (6.5)
Estimated Variance of A or Ln (A)	.00050	.00169	.00128
Estimated Variance of b_0 or $Ln(b_0)$	.00021	.00033	.00053
Estimated Variance of b_1 or $Ln(b_1)$	.00005	.00066	.00013
Estimated Standard Deviation of A or Ln(A)	.02242	.04106	.03571
Estimated Standard Deviation of b_0 or $Ln(b_0)$	.01452	.01803	.02312
Estimated Standard Deviation of b_1 or $Ln(b_1)$	.00713	.02571	.01136
Coefficient R_1^2	.93658	.93219	.94872
95% Confidence Interval for b_0	$.07979 < b_0 < .13737$	$.31319 < b_0 < .33661$	$.23627 < b_0 < .25916$
95% Confidence Interval for b_1	$.20842 < b_1 < .23694$	$.72237 < b_1 < .82581$	$1.4540 < b_1 < 1.5216$

TABLE 16.--Table for partition about the mean for the linear representation of Equations (6.3), (6.4) and (6.5).

Source Variation	Equation	Sum of Squares	D. of F.	Mean Square	F	
					$F_{cal.}$	$F_{.01}$
Residuals	6.3	.0332		.0005	974.60	
	6.4	.1113	66	.0017	907.30	7.05
	6.5	.0842		.0013	1,221.09	
Deviation Between Line and Mean	6.3	.4897		.7897		
	6.4	1.5298	1	1.5298		
	6.5	1.5570		1.5570		
TOTAL	6.3	.5229				
	6.4	1.6411	67			
	6.5	1.6411				

Results of the prediction of the surface area by equations (6.3), (6.4) and (6.5) are summarized in Appendix E. Equation (6.5) shows to be more accurate in predicting the surface area of individual sugar beets (see Table 17). However, the comparison in accuracy between equation (6.4) and (6.5) gives a relative small R^2 value (R^2 = .25). The simple linear relationship expressed by equation (6.3) gives the poorest prediction of the three compared models.

TABLE 17.--Comparison of weight-surface area relationships for predicting surface areas of individual US H20 sugar beets.

Model	Residuals	Square Residuals	R^2
Equation 6.3	.0000	.83858	.96
Equation 6.4	-37.6695	.03635	.25
Equation 6.5	-.0266	.02715	.00

6.2 Study of the Effect of the Single Particle Shape on Moisture Losses

The study of the effect of the shape of the individual particle on moisture losses was performed by measuring the mass loss of individual peeled particles at different environmental conditions. The results are expressed in terms of dimensionless numbers.

The vapor pressure deficit was calculated as the difference between the saturated pressure at the surface (at the recorded temperature) and the environmental air vapor pressure.

Surface areas of the individual particles were obtained by the planimeter technique.

The diameter of a sphere with a surface area equal to the planimeter area was used as the characteristic dimension of apples and potatoes. In the case of the individual sugar beet, the slanted height of the beet was used as its characteristic dimension.

The ALEASQ routine was used to calculate the coefficients β_0 and β_1 of the following model:

$$Sh = \beta_0 \; Re^{\beta_1} \tag{6.6}$$

Comparison of the experimental relationships for peeled apples, potatoes and sugar beets was made with those relationships described in the literature for spheres, prolate spheroids and cones, respectively.

Results and discussion on the developed relationships and comparisons for each individual product are presented below.

6.2.1 Jonathan Apples

Appendix F summarizes the results of experimental data for peeled Jonathan apples in the 2,000-10,000

Reynolds number range. Analysis of such data leads to the following relationship:

$$Sh = .539\ Re^{.504} \tag{6.7}$$

Tables 18 and 19 summarize the statistical analysis of equation (6.7). A high regression coefficient ($R_1^2 = .91369$) and a calculated F value larger than the tabulated F value at a 99% confidence limit are obtained. The 95% confidence intervals for b_0 and b_1 are: $.2110 < b_0 < 1.376$ and $.395 < b_1 < .613$.

TABLE 18.--Estimated variances and standard deviations of the dependent variable and parameters of the linear representation of equation (6.7).

I	Estimated Variance of I Var (I)	Estimated Standard Deviation of I s.d. (I)
Ln(Sh)	.00925	.09620
$Ln(b_0)$	.17719	.42094
b_1	.00240	.04903

Coefficient $R_1^2 = .91369$

95% interval of confidence for b_0: $.2110 < b_0 < 1.376$.

95% interval of confidence for b_1: $.395 < b_1 < .613$.

TABLE 19.--Table for partition about the mean for the linear representation of equation (6.7).

Source of Variation	Sum of Squares	D. of F	Mean Squares	F
Residuals	.0925	10	.0093	$F_{calculated}$ 105.86
Deviation Between Line and Mean	.9797	1	.9797	$F_{.01\ table}$ 10.04
TOTAL	1.0723	11		

Equation (6.7) was compared with the Frössling and Powell relationships for flow over spheres [equations (2.17) and (2.19), respectively]. The experimental data fall closer to the Frössling equation than to the Powell equation (see Figure 13). When a residual comparison of equation (6.7) with equations (2.17) and (2.19) was made (Table 20), R^2 values of .34 and .75 were obtained, respectively.

TABLE 20.--Comparison of equation (2.17) and (2.19) with equation (6.7).

Model	Residuals	Square Residuals	R^2
Equation 6.7	- 2.1989	142.19498	.00
Equation 2.17	-24.82239	217.11945	.34
Equation 2.19	65.23221	585.71629	.75

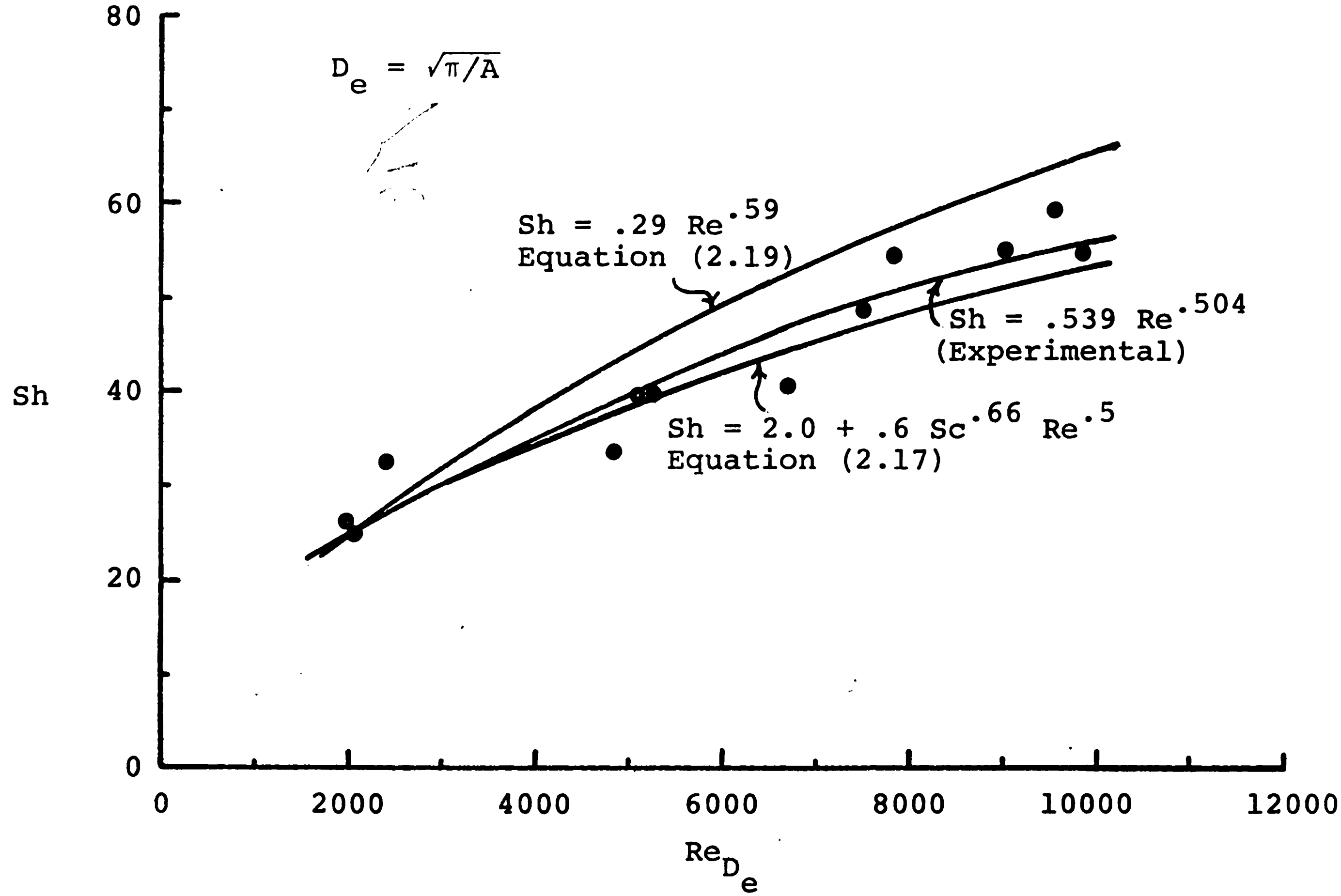


Figure 13.--Reynolds Versus Sherwood Numbers for Individual Jonathan Apples

6.2.2 Manona Potatoes

Appendix G summarizes the results of experimental data for peeled Manona potatoes in the 2000 to 10,000 Reynolds number range. Analysis of such a data led to the following relationship:

$$Sh = .344\ Re^{.539} \tag{6.8}$$

In Tables 21 and 22 the statistical analysis of equation (6.8) is presented. A regression coefficient of .91421, and a calculated F value larger than the tabulated F value at the 99% confidence limit are obtained. The 95% confidence intervals for b_0 and b_1 are: $.126 < b_0 < .933$, and $.423 < b_1 < .655$.

TABLE 21.--Estimated variances and standard deviations of the dependent variable and parameters of the linear representation of equation (6.8).

I	Estimated Variance of I Var (I)	Estimated Standard Deviation of I s.d. (I)
Ln(Sh)	.01084	.10412
Ln(b_0)	.20058	.44786
b_1	.00273	.05220

Coefficient R_1^2 = .91421

95% interval of confidence for b_0: $.126 < b_0 < .933$.

95% interval of confidence for b_1: $.423 < b_1 < .655$.

TABLE 22.--Table for partition about the mean for the linear representation of equation (6.8).

Source of Variation	Sum of Squares	D. of F.	Mean Square	F
Residuals	.1084	10	.0108	$F_{calculated}$ 106.56
Deviation Between Line and Mean	1.1551	1	1.1551	$F_{.01\ table}$ 10.04
TOTAL	1.2635	11		

Equation (6.8) was compared with the Frossling equation for flow over spheres (equation 2.17) and with the Lochiel relationship of flow over prolate spheroids [equations (2.28) and (2.17)]. All the experimental data fall below the curve expressed by equation (2.17) (see Figure 14). Improvement of the prediction was obtained when the Lochiel relationship [equation (2.28)] was added to equation (2.17).

Table 23 shows a comparison of residuals of equation (6.8) with equations (2.17) and (2.28). Equation (2.28) showed to be equally effective as equation (6.8) in predicting the experimental data (R^2 = .100).

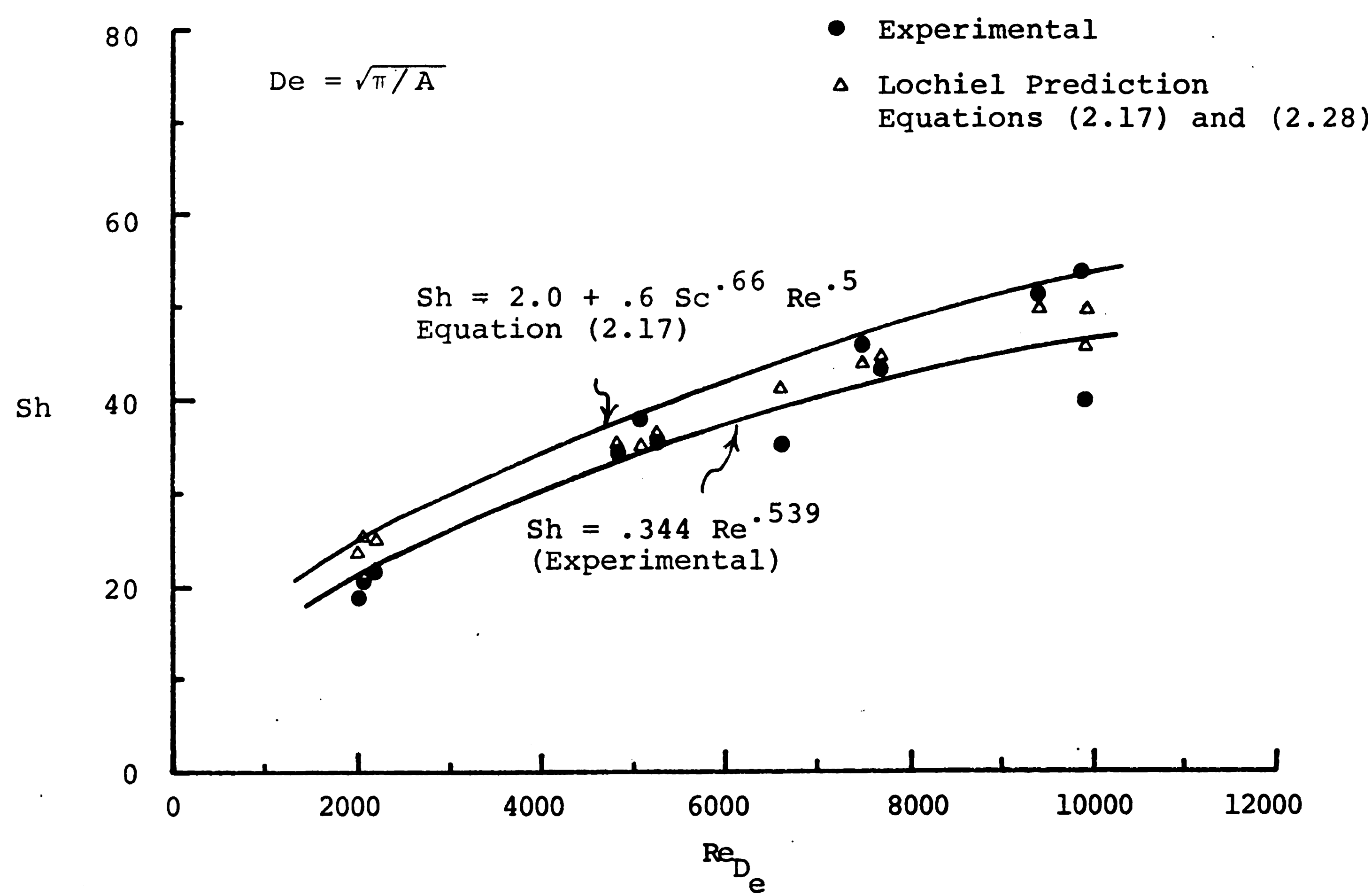


Figure 14.--Reynolds Versus Sherwood Number for Individual Manona Potatoes.

TABLE 23.--Comparison of equations (2.17) and (2.28) with equation (6.8).

Model	Residuals	Square Residuals	R
Equation 6.8	- 1.75610	157.94197	0.00
Equation 2.17	46.49266	336.62772	0.53
Equation 2.28	18.58314	175.17557	0.10

6.2.3 US H20 Sugar Beets

Results of experimental data on moisture losses from peeled US H20 sugar beets in the 6,000-35,000 Reynolds number range is presented in Appendix H. The analysis of such data led to the relationship:

$$Sh = .199\ Re^{.634} \tag{6.9}$$

The statistical analysis of equation (6.9) is summarized in Tables 24 and 25. A regression coefficient, $R_1^{\ 2}$, of .94017, and a calculated F value larger than the tabulated F value at a 99% confidence limit are obtained. The 95% confidence intervals for b_0 and b_1 are $.0662 < b_0 < .597$, and $.521 < b_1 < .746$.

Figure 15 shows a plot of the experimental data and of equation (6.9). The Miranov relationship for flow over cones [equation (2.27)] is also plotted in Figure 15. When the residuals of equation (6.9) were compared with residuals of equation (2.27) a R^2 value of .74 was obtained (see Table 26).

TABLE 24.--Estimated variances and standard deviations of the dependent variable and parameters of the linear representation of equation (6.9).

I	Estimated Variance of I Var (I)	Estimated Standard Deviation of I s.d. (I)
Ln (Sh)	.00861	.09281
Ln (b_0)	.24362	.49358
b_1	.00256	.05057

Coefficient $R_1^2 = .94017$

95% interval of confidence for b_0: $.0662 < b_0 < .597$

95% interval of confidence for b_1: $.521 < b_1 < .746$.

TABLE 25.--Table for partition about the mean for the linear representation of equation (6.9).

Source of Variation	Sum of Squares	D. of F.	Mean Square	F
Residuals	.0861	10	.0086	$F_{calculated}$ 157.14
Deviation Between Line and Mean	1.3535	1	1.3535	$F_{.01}$ table 10.04
TOTAL	1.4396	11		

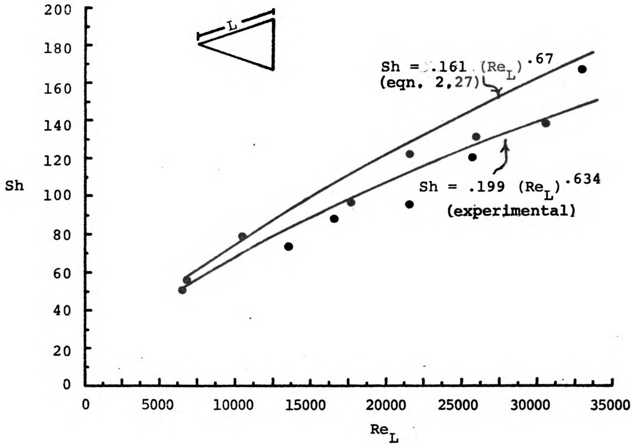


Figure 15.--Reynolds Versus Sherwood Number for Individual Peeled US H20 Sugar Beets.

TABLE 26.--Comparison of equation (2.9) with equation (2.27).

Model	Residuals	Square Residuald	R^2
Equation (6.9)	-6.43599	1035.7098	0.00
Equation (2.27)	182.2309	4007.2051	0.74

6.3 Determination of Skin Parameters

Moisture losses data of individual Jonathan apples, Manona potatoes and US H20 sugar beets were applied to the model described by equations (4.1), (4.2), (4.3), (4.4) and (4.5) for determining the skin parameters of each one of these products.

The GAUSHAUS computer routine was used to determine the parameters in the case of apples and potatoes. In the case of sugar beets a simplification of the model was used. Sugar beet results are expressed in terms of an "effective surface area" for moisture migration.

Results and discussion on the skin parameter values for each individual product are presented below.

6.3.1 Jonathan Apples

Moisture losses data on 72 Jonathan apples were used for determining the skin parameters of this commodity. Tests were performed at an environmental temperature of 70°F. Three different airflows (3000, 6000 and 9000 ft/hr), and three different relative humidities (50, 62.5 and 75%)

were tested. Eight samples were used at each storage condition. Tabulation of the experimental data is presented in Appendix I.

A computer program was written for applying the experimental data and the model described by equations (4.1), (4.2), (4.3), (4.4) and (4.5) to the GAUSHAUS routine. The mass transfer coefficient, h_d, was calculated by using equation (6.7). Equation (6.1) was used for calculating the surface area of the individual samples. In order to calculate the vapor pressure deficit equations (4.5) and (2.56) were used.

The results gave a comparatively small value for the free water surface area fraction, γ_1 (of a 10^{-6}-10^{-11} order of magnitude). Because of such a small effect of the parameter γ_1 on the mass losses process and because a decreasing tendency of the γ_1 parameters was observed during the iterative procedure, the model was simplified by making $\gamma_1 = 0$. It was observed that a decrease in the sum of squares resulted when the simplified model was used.

Table 27 shows the results of the skin parameter values when the experimental data and the simplified model ($\gamma_1 = 0$) were fed to the GAUSHAUS routine. Average values of $\gamma_1 = 0$, $\gamma_2 = .01286$, and $\underline{r\delta} = .01943$ feet, were obtained.

TABLE 27.--Skin parameters of Jonathan apples at 70°F.

Relative Humidity (Decimal)	γ_1 (Dimensionless)	γ_2 (Dimensionless)	$r\delta$ (ft)
.500	0	.01150	.02282
.625	0	.01385	.01920
.750	0	.01322	.01628
AVERAGES	0	.01286	.01943

The results show negligible free water regions in the apple skin. As a result the air velocity of the environmental air has little effect on moisture losses from this commodity. The results also show that approximately 98.7% of the Jonathan apple skin is impervious to water vapor.

Besides, it was found that the parameter $\underline{r\delta}$ does depend on the relative humidity of the environmental air. Figure 16 shows the experimentally determined relationship between $\underline{r\delta}$ and the relative humidity of the environmental air. It can be seen that $\underline{r\delta}$ has a higher value when the relative humidity is low and vice versa. So the diffusional resistance against moisture loss is higher when the relative humidity is low. This phenomenon has also been observed by Wilkinson (1965) and Fockens (1967). Fockens (1967) suggests that the cells of the skin change in shape at different environmental relative humidities.

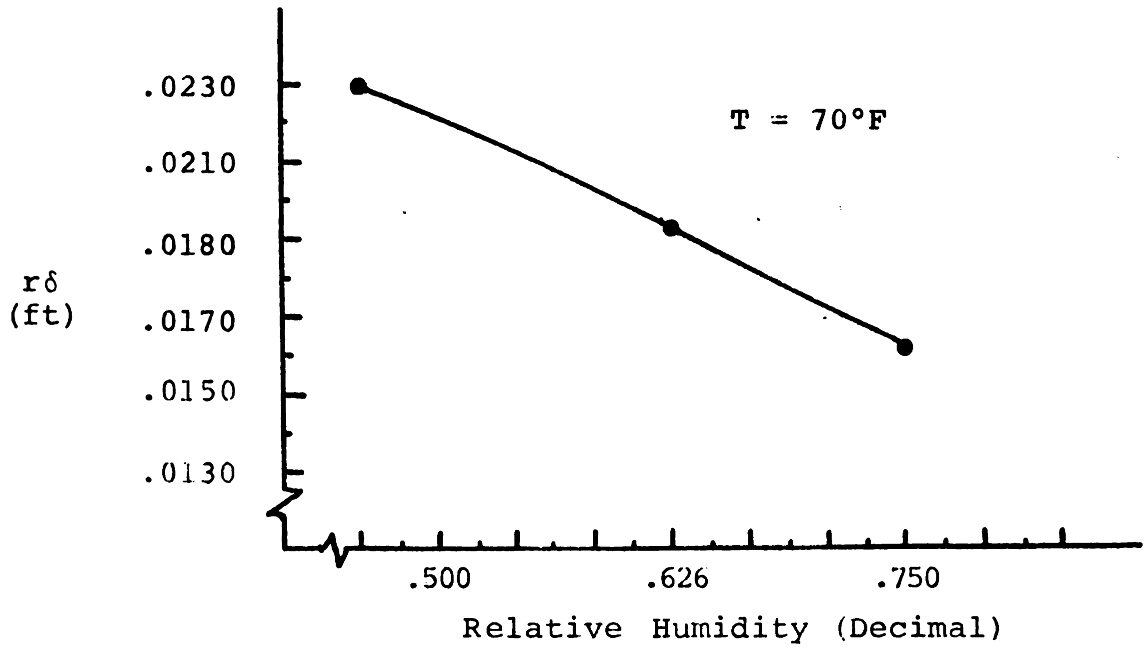


Figure 16.--Environmental Relative Humidity Versus the $r\delta$ Parameter for Jonathan Apples at 70°F.

The cells become flatter at lower relative humidities reducing the amount of intercellular spaces through which the water vapor moves from the product to the environmental air. This reduction in intercellular spaces originates an increase in the resistance to the movement of the water vapor through the "membrane like" skin. On the other hand, high environmental relative humidities result in round cells which originate a larger amount of intercellular spaces and a decrease in resistance to the movement of water vapor through the porous membrane skin.

A study of the effect of vapor pressure deficit on the $\underline{r\delta}$ parameter was performed. A 6-26 lb/ft^2 VPD range was investigated by placing 56 individual samples in air atmospheres at different combinations of temperatures and relative humidities. Temperatures ranged from 50 to 80°F and relative humidities from 50 to 75%. The air velocity was kept at 6000 ft/hr. Eight samples were tested at each storage condition. In Appendix J the experimental data is presented.

Equations (4.1), (4.2), (4.3), (4.4) and (4.5) were used for calculating the $\underline{r\delta}$ parameter for each sample, at each VPD condition. Values of $\gamma_1 = 0$ and $\gamma_2 = .0186$ were used as the other two skin parameters.

When VPD was plotted against $\underline{r\delta}$, a decrease in $\underline{r\delta}$ was observed whenever the VPD was increased and vice versa. The following linear relationship was obtained when the VPD-$r\delta$ data was applied to the ALEASQ routine:

$$r\delta = .00770 + .00064(\text{VPD}) \qquad (6.10)$$

Tables 28 and 29 summarize the statistics analysis of equation (6.10). A coefficient $R_1^2 = .70047$ was obtained. The 95% intervals of confidence for the parameters b_0 and b_1 are: $.00584 < b_0 < .00956$ and $.00052 < b_1 < .00076$. The calculated F value is larger than the tabulated $F_{.01}$ value.

Figure 17 shows the experimental data and the relationship expressed by equation (6.10). Each data point in the graph represents an average value of eight samples.

TABLE 28.--Estimated variances and standard deviations of the dependent variable and parameters of equation (6.10).

I	Estimated Variance of I Var (I)	Estimated Standard Deviation of I s.d. (I)
$r\delta$	.000007	.00262
b_0	.000001	.00093
b_1	.000000	.00006

Coefficient $R_1^2 = .70047$

95% interval of confidence for b_0: $.00584 < b_0 < .00956$.

95% interval of confidence for b_1: $.00052 < b_1 < .00076$

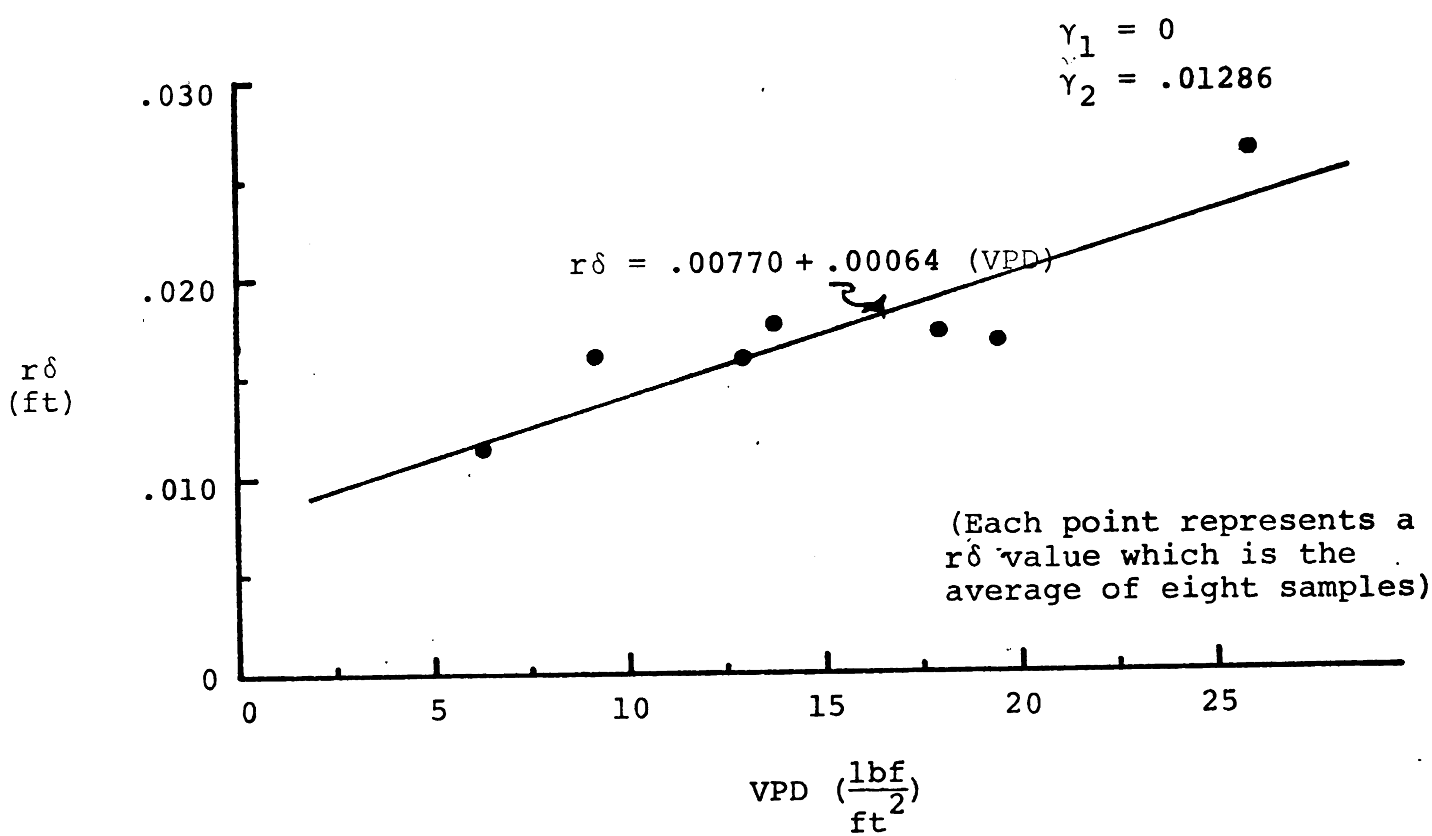


Figure 17.--VPD-rδ Relationship for Jonathan Apples.

TABLE 29.--Table for partition about the mean. Equation (6.10).

Source of Variation	Sum of Squares	D. of F.	Mean Square	F
Residuals	.0004	54	.0000	$F_{calculated}$ 126.28
Deviation Between Line and Mean	.0009	1	.0009	$F_{.01\ table}$ 7.12
TOTAL	.0013	55		

The prediction of moisture losses was compared with the experimental data. An apparent mass transfer coefficient for apples, $h'_{d\ app}$, was used as the comparison criterion. Table 30 summarizes the results of the comparison. It was observed that the predicted $h'_{d\ app}$ values were within ± 10% of the experimental eight sample average values.

The quantitative effect of the environmental air velocity on moisture losses can be observed in Table 30. Doubling the airflow resulted in an increase of the mass transfer coefficient for Jonathan apples of only 10 percent. This increase in the mass transfer coefficient is small compared with the effect of air velocity on moisture losses from free water surfaces. For free water

TABLE 30.--Comparison of experimental versus predicted moisture losses from Jonathan apples.*

T °F	RH Decimal	VPD $\frac{lbf}{ft^2}$	V_∞ $\frac{ft}{hr}$	$h'_{d\ app}$ Predicted $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	$h'_{d\ app}$ Experimental $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	Differential %
50	.750	6.37	6000	1.324×10^{-5}	1.376×10^{-5}	-3.79
60	.750	9.15	6000	1.227×10^{-5}	1.145×10^{-5}	7.16
70	.750	12.95	9000	1.189×10^{-5}	1.215×10^{-5}	-2.14
70	.750	12.95	6000	1.111×10^{-5}	1.128×10^{-5}	-1.50
70	.750	12.95	3000	$.973 \times 10^{-5}$	$.988 \times 10^{-5}$	-1.52
60	.625	13.75	6000	1.080×10^{-5}	1.040×10^{-5}	3.85
80	.750	18.04	6000	$.983 \times 10^{-5}$	1.059×10^{-5}	-7.17
70	.625	19.45	9000	1.006×10^{-5}	1.119×10^{-5}	-10.09
70	.625	19.44	6000	$.948 \times 10^{-5}$	1.058×10^{-5}	-10.40
70	.625	19.45	3000	$.847 \times 10^{-5}$	$.931 \times 10^{-5}$	-9.02
70	.500	25.95	9000	$.873 \times 10^{-5}$	$.820 \times 10^{-5}$	6.46
70	.500	25.95	6000	$.829 \times 10^{-5}$	$.777 \times 10^{-5}$	6.69
70	.500	25.95	3000	$.741 \times 10^{-5}$	$.689 \times 10^{-5}$	7.55

*Each value is the average of eight samples.

surfaces the mass transfer coefficient is approximately proportional to the square root of the air velocity.

6.3.2 Manona Potatoes

A behavior somewhat similar to the Jonathan apples was observed in Manona potatoes. An identical set of experiments was performed with 72 individual Manona potatoes for determining the skin parameters. Tabulation of the experimental data is presented in Appendix K.

As in the case of apples, the model was simplified because a comparatively small value for γ_1 was obtained.

Table 31 shows the results of the skin parameter values when the experimental data and the simplified model (γ_1 = 0) were applied to the GAUSHAUS routine. The convective mass transfer coefficient, h_d, was calculated by using equation (6.8). The surface area of the samples was obtained experimentally by the planimeter technique. Equations (4.5) and (2.56) were used for calculating the vapor pressure deficit. Average values of γ_1 = 0. γ_2 = .00890 and $\underline{r\delta}$ = .01143 feet were obtained.

The results show negligible free water regions in the skin of Manona potatoes. As a results, the air velocity of the environmental air has little effect on moisture losses from this commodity. The results also

TABLE 31.--Skin parameters of Manona potatoes at 70°F.

Relative Humidity (Decimal)	γ_1 (Dimensionless)	γ_2 (Dimensionless)	$r\delta$ (ft)
.50	0	.008935	.01515
.625	0	.008867	.01086
.75	0	.008908	.00827
AVERAGES	0	.008900	.01143

show that approximately 99.1% of the Manona potato is impervious to water vapor.

It was found that, as in the apples case, the value $\underline{r\delta}$ for Manona potatoes ia a function of the relative humidity of the environmental air. Figure 18 shows the experimental relationship between $\underline{r\delta}$ and the relative humidity of the environmental air. Decreasing of the environmental relative humidity resulted in an increase of the resistance of the skin to water vapor migration.

The effect of vapor pressure deficit on the $\underline{r\delta}$ parameter was also studied for Manona potatoes. Fifty-six individual samples were placed at different storage conditions, covering a 6-26 VPD range. Temperatures ranged from 50 to 80°F and relative humidities from 50 to 75°F. The air velocity was kept at 6000 ft/hr. Eight

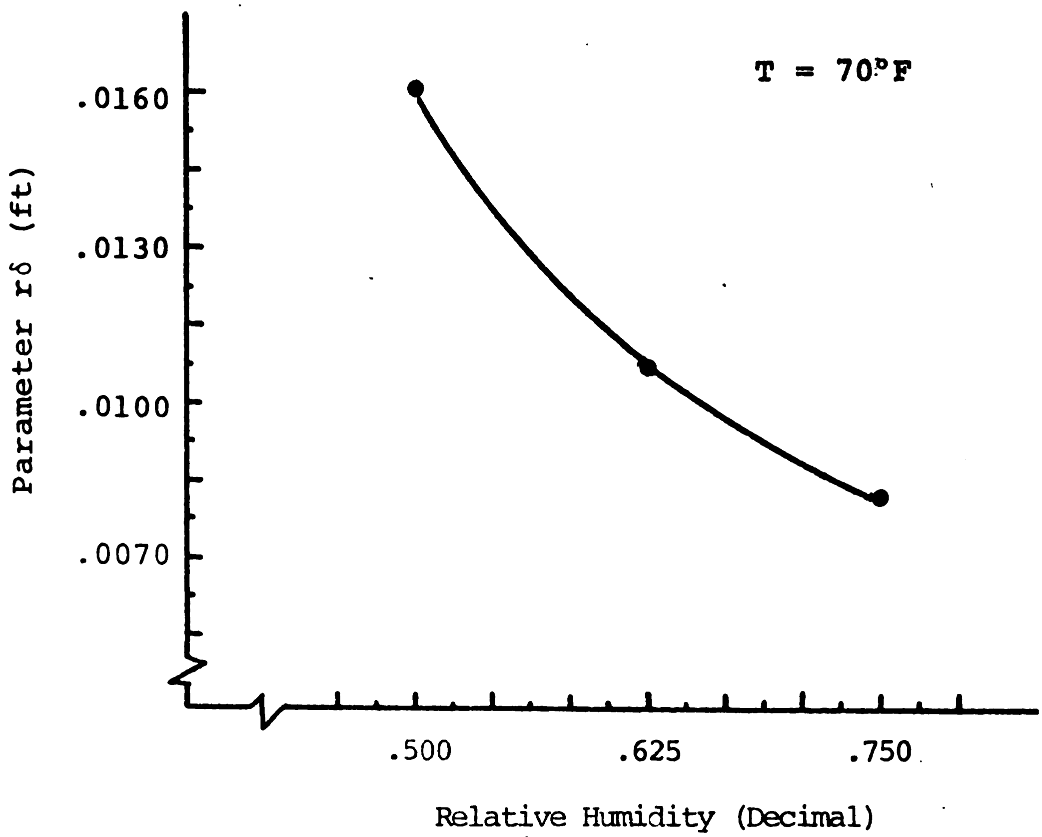


Figure 18.--Relative Humidity of the Environmental Air Versus the rδ Parameter for Manona Potatoes.

samples were tested at each storage condition. In Appendix J the experimental data is presented.

Equations (4.1), (4.2), (4.3), (4.4) and (4.5) were used for calculating the <u>rδ</u> parameter for each sample at each VPD condition. Values of $\gamma_1 = 0$ and $\gamma_2 = .00890$ were used as the other two skin parameters.

When VPD was plotted against <u>rδ</u>, a decrease in <u>rδ</u> was observed whenever the VPD was increased and vice versa. The following linear relationship was obtained when the VPD-rδ data was analysed with the ALEASQ routine.

$$r\delta = .00162 + .00052\ (\text{VPD}) \qquad (6.11)$$

Tables 32 and 33 summarize the statistic of equation (6.11). A coefficient $R_1^2 = .80595$ was obtained. The 95% intervals of confidence for the parameters b_0 and b_1 are: $.00050 < b_0 < .00274$ and $.00046 < b_1 < .00058$. The calculated F value is larger than the tabulated $F_{.01}$ value.

Figure 19 shows the experimental data and the relationship expressed by equation (6.11). Each data point in the graph represents an average value of eight samples.

The prediction of moisture losses from Manona potatoes was compared with the experimental data by using the apparent mass transfer coefficient as the

TABLE 32.--Estimated variances and standard deviations of the dependent variable and parameters of equation (6.11).

I	Estimated Variance of I Var (I)	Estimated Standard Deviation of I s.d. (I)
$r\delta$	.000002	.00158
b_0	.000000	.00056
b_1	.000000	.00003

Coefficient $R_1^2 = .80595$

95% interval of confidence for b_0: $.00050 < b_0 < .00274$.

95% interval of confidence for b_1: $.00046 < b_1 < .00058$

TABLE 33.--Table for partition about the mean. Equation (6.11).

Source of Variation	Sum of Squares	D. of F.	Mean Square	F
Residuals	.0001	54	.0000	$F_{calculated}$ 224.27
Deviation Between Line and Mean	.0006	1	.0006	$F_{.01}$ table 7.12
TOTAL	.0007	55		

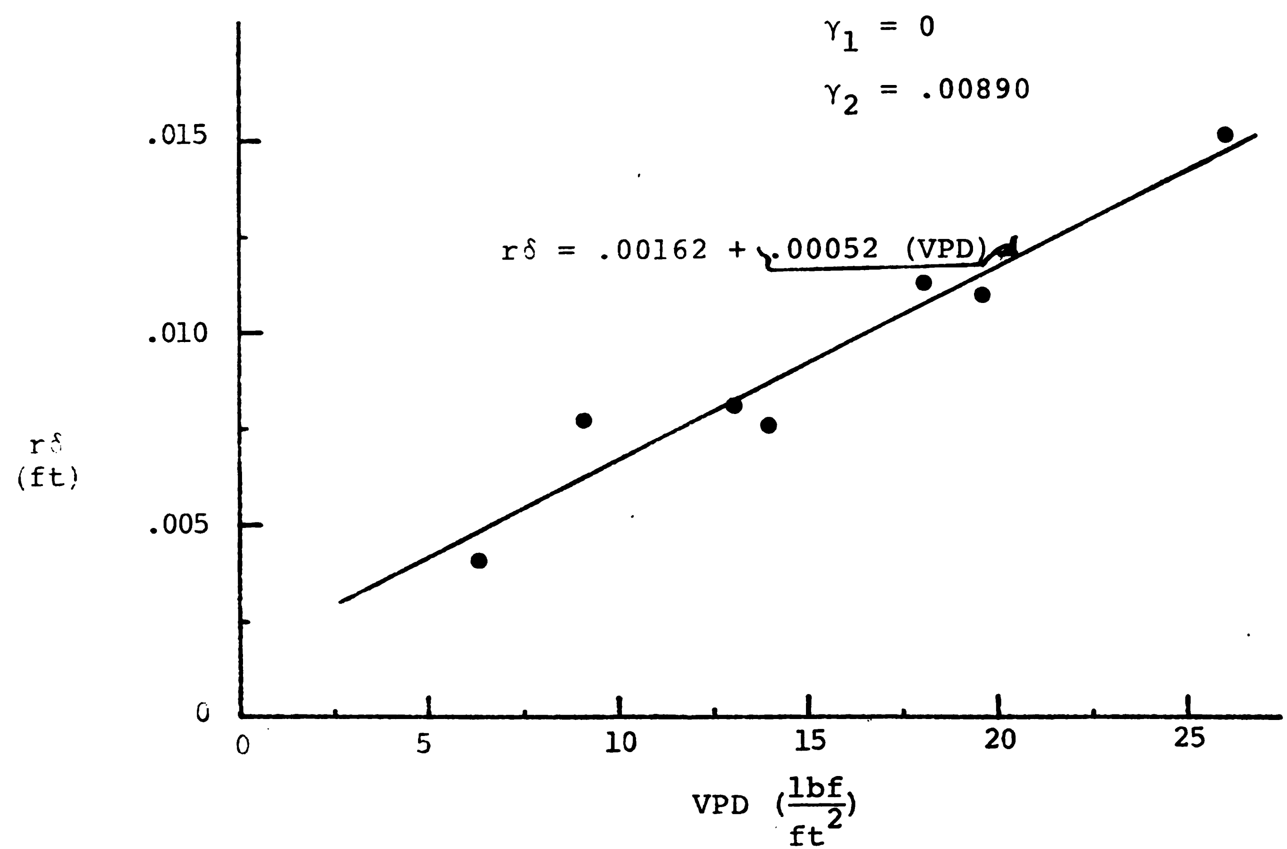


Figure 19.--VPD-$r\delta$ relationship for Manona potatoes.

comparison criterion. Table 34 summarizes the results of the comparison. It was observed that the predicted $h'_{d\ app}$ values were within $\pm$ 9% of the experimental eight sample average values.

The quantitative effect of the environmental air velocity can be observed in Table 34. Doubling the airflow resulted in an increase of about 15 percent in the apparent mass transfer coefficient for Manona potatoes.

6.3.3 US H20 Sugar Beets

Data on moisture losses from 68 individual samples of US H20 sugar beets were used for determining the skin of this commodity.

A simplification of the model described by equations (4.1), (4.2), (4.30), (4.4) and (4.5) was performed. From preliminary research results and some evidences from the literature it was found that the skin of a sugar beet can be represented by free water and impervious regions only. As a result the parameter γ_1 represents an "effective area" of moisture migration.

In analysing the data the effective area was defined as:

$$\text{Effective Area} = \frac{\text{Mass transfer coefficient of the sample unpeeled}}{\text{Mass transfer coefficient of the sample peeled}}$$

TABLE 34.--Comparison of experimental versus predicted moisture losses from Manona potatoes.*

T °F	RH Decimal	VPD $\frac{lbf}{ft^2}$	V_∞ $\frac{ft}{hr}$	$h'_{d\ app}$ Predicted $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	$h'_{d\ app}$ Experimental $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	Differential %
50	.750	6.37	6000	1.26619×10^{-5}	1.38485×10^{-5}	-8.5
60	.750	9.17	6000	1.16979×10^{-5}	1.09161×10^{-5}	7.2
70	.750	12.97	9000	1.15690×10^{-5}	1.16501×10^{-5}	-0.7
70	.750	12.96	6000	1.03866×10^{-5}	1.04736×10^{-5}	-0.8
70	.750	12.94	3000	$.82689 \times 10^{-5}$	$.84507 \times 10^{-5}$	-2.2
60	.625	13.75	6000	1.01817×10^{-5}	1.09930×10^{-5}	-7.3
80	.750	18.07	6000	$.91054 \times 10^{-5}$	$.87646 \times 10^{-5}$	3.9
70	.625	19.47	9000	$.94897 \times 10^{-5}$	$.98999 \times 10^{-5}$	-4.1
70	.625	19.46	6000	$.86194 \times 10^{-5}$	$.89372 \times 10^{-5}$	-3.5
70	.625	19.42	3000	$.73792 \times 10^{-5}$	$.76774 \times 10^{-5}$	3.9
70	.500	26.00	9000	$.81854 \times 10^{-5}$	$.81998 \times 10^{-5}$	-0.2
70	.500	25.98	6000	$.76260 \times 10^{-5}$	$.76994 \times 10^{-5}$	-1.0
70	.500	25.95	3000	$.64983 \times 10^{-5}$	$.64353 \times 10^{-5}$	1.0

*Each point is the average of eight samples.

In order to determine the effective area parameter, γ_1, a set of weight loss experiments were conducted. The 1.8 - 9.6 lbf/ft^2 VPD range was studied by placing 68 samples in air atmospheres at different combinations of temperatures and relative humidities. Temperatures ranged from 50 to 80°F and relative humidities from 50.0 to 87.5%. Airflows of 6000 and 9000 ft/hr were used. The experimental data is presented in Appendix M.

Figure 20 shows a histogram prepared with the calculated effective area values. A Chi square test was used for checking the hypothesis of a Gaussian behavior of the effective area parameter. The test proved that the normal hypothesis can be accepted.

An average value of γ_1 = .436 was obtained for the effective area parameter. This value is bounded by a .4181 - .4539 interval at a 95% probability confidence.

A comparison of predicted versus experimental moisture losses was made. Table 35 shows that predicted values are within $\pm$ 15% of the experimental four sample average values.

6.4 Prediction of Moisture Losses

The experimentally determined parameters were applied to the developed model for obtaining prediction graphs of moisture losses at various storage conditions.

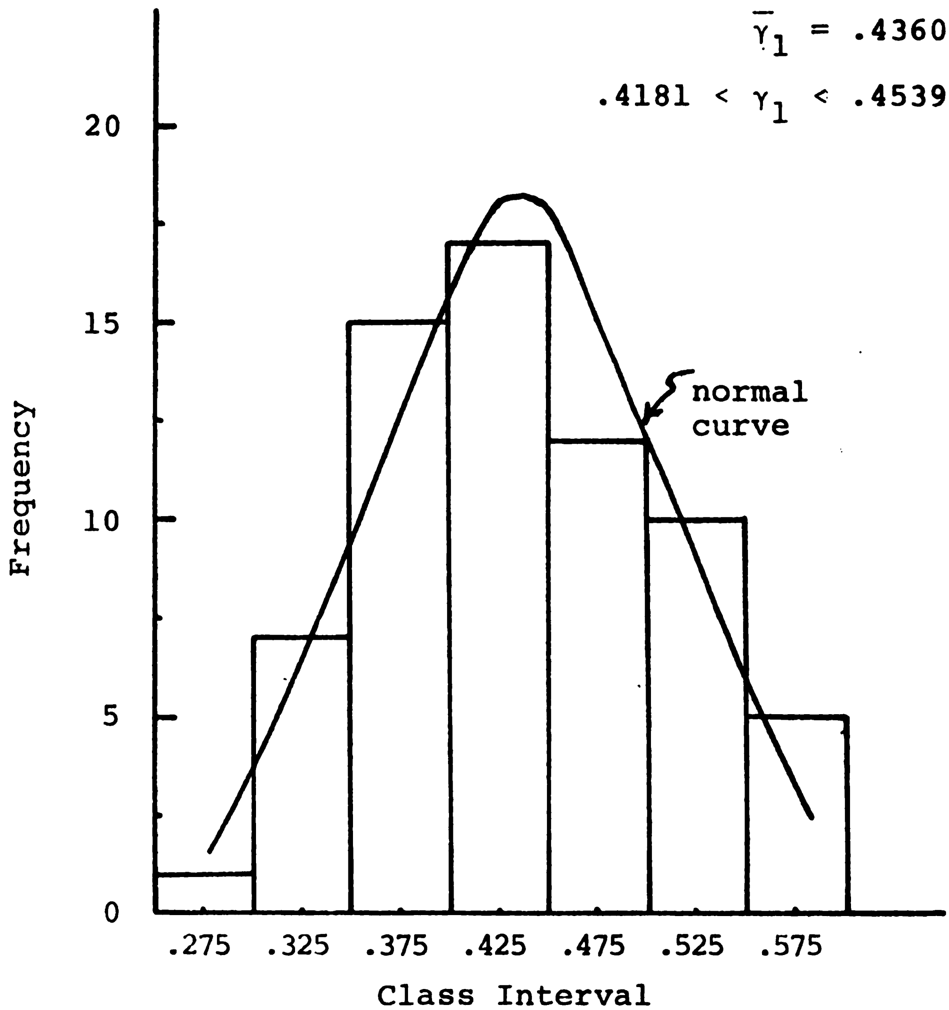


Figure 20.--Frequency histogram and normal curve for the effective area parameter, γ_1, in US H20 sugar beets.

TABLE 35.--Comparison of predicted versus experimental results of moisture losses from US H20 sugar beets.*

T °F	RH Decimal	V_∞ $\frac{ft}{hr}$	$h'_{d\ app}$ Predicted $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	$h'_{d\ app}$ Experimental $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	Differential %
70	.500	9000	.0013501	.0015416	14.2
70	.500	6000	.0011653	.0010700	-8.1
70	.625	9000	.0012422	.0012793	3.0
70	.625	6000	.0010214	.0010208	-0.1
80	.750	9000	.0017360	.0016867	-2.8
80	.750	6000	.0015715	.0014255	-9.3
70	.750	9000	.0020011	.0020265	1.2
70	.750	6000	.0015002	.0012920	13.9
60	.750	9000	.0014515	.0016578	14.1
60	.750	6000	.0011457	.0011568	1.0
70	.875	9000	.0016515	.0016476	-0.2
50	.750	9000	.0014227	.0015965	12.2
50	.750	6000	.0011780	.0013184	11.2
60	.875	9000	.0017346	.0015666	-9.7

*Each point is the average of four samples.

Two different types of graphs are presented. The first type can be used for determining the rate of moisture loss per unit area (or per unit weight) at different storage conditions. The second type can be used for predicting the allowable storage time at different storage conditions and at various percentages of moisture losses.

A discussion follows on the development and significance of these prediction graphs for each product studied in this investigation.

6.4.1 Jonathan Apples

A graph for predicting moisture losses from Jonathan apples at various storage conditions is presented in Figure 21.

In Figure 21 the vapor pressure deficit is plotted against the rate of moisture loss per unit area (or per unit weight). A second abscissa scale represents the equivalent relative humidity of the environmental air at 35°F. A third abscissa scale represents the equivalent environmental temperature at 90% relative humidity. The assumption of a surface saturated condition at a temperature equal to the dry bulb temperature was used in drawing the relative humidity and temperature scales. A .33 pound (150 grams) apple was used for developing the graph.

The nonlinear relationship between vapor pressure deficit and the rate of moisture losses can be observed

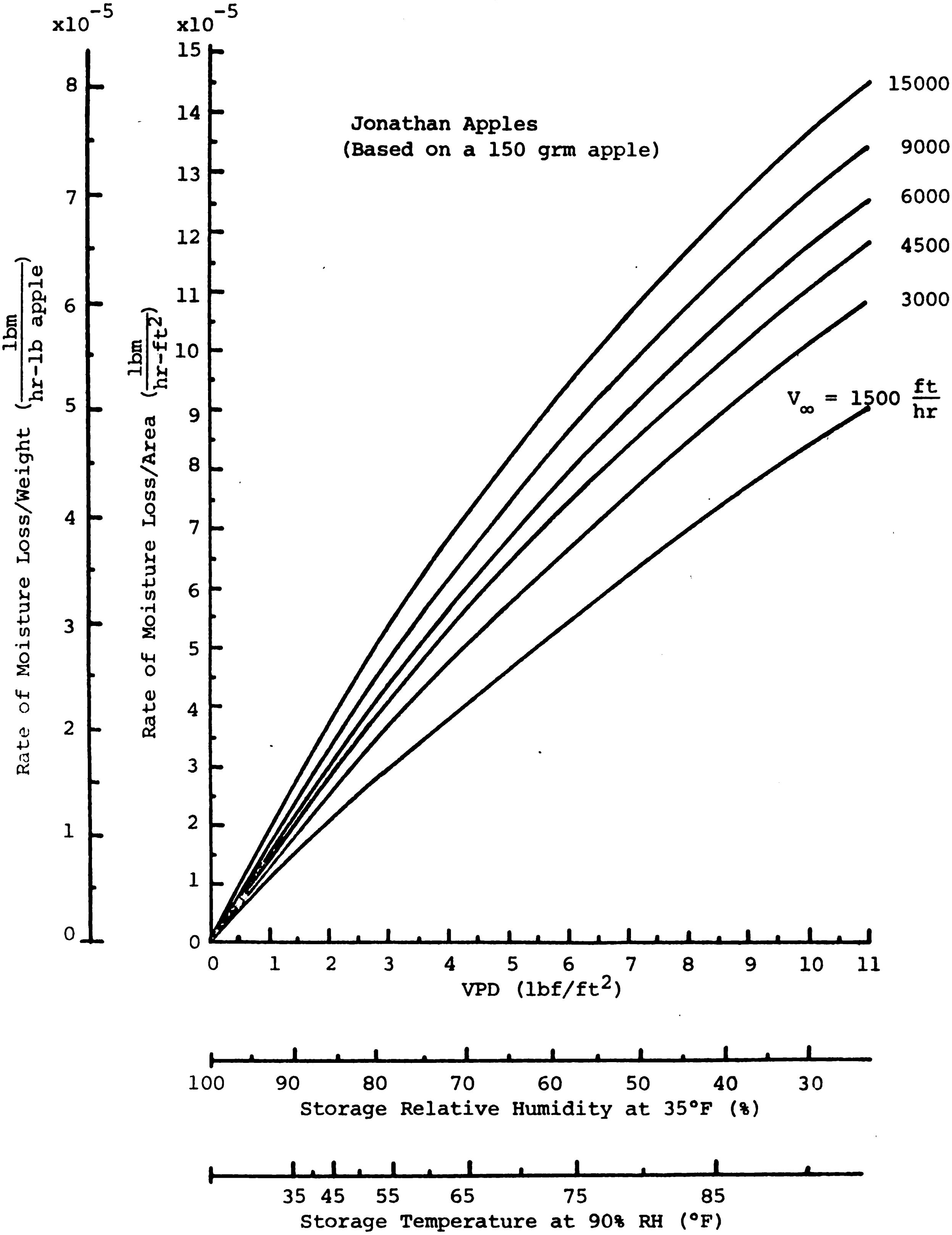


Figure 21.--Predicted moisture losses from Jonathan apples.

in Figure 21. The increase in skin resistance to water movement at higher vapor pressure deficits is responsible for such a behavior.

The comparative effect of the different variables affecting the moisture loss process in Jonathan apples can be studied in Figure 21.

Relative humidity is the most critical variable affecting moisture losses of Jonathan apples. A small decrease of the environmental relative humidity results in an important increase in the rate of moisture losses. For example, a reduction of 6% (from 93 to 87%) in the environmental relative humidity results in a doubling of the rate of moisture losses at 35°F. A similar doubling of the rate of moisture losses only occurs after an environmental temperature increase of about 20°F, i.e., from 35°F to 55°F, at 90%. On the other hand, doubling of moisture losses at 35°F and 90% only occurs after a ten times larger airflow (from 1500 to 15000 ft/hr) is used.

Allowable storage time predictions for Jonathan apples at various percentages of moisture losses are presented in Figures 22 and 23. In Figure 22 an environmental air velocity of 1500 ft/hr (25 ft/min) was used. In Figure 23 a 3000 ft/hr air velocity was used. Relative humidity and temperature scales were also drawn

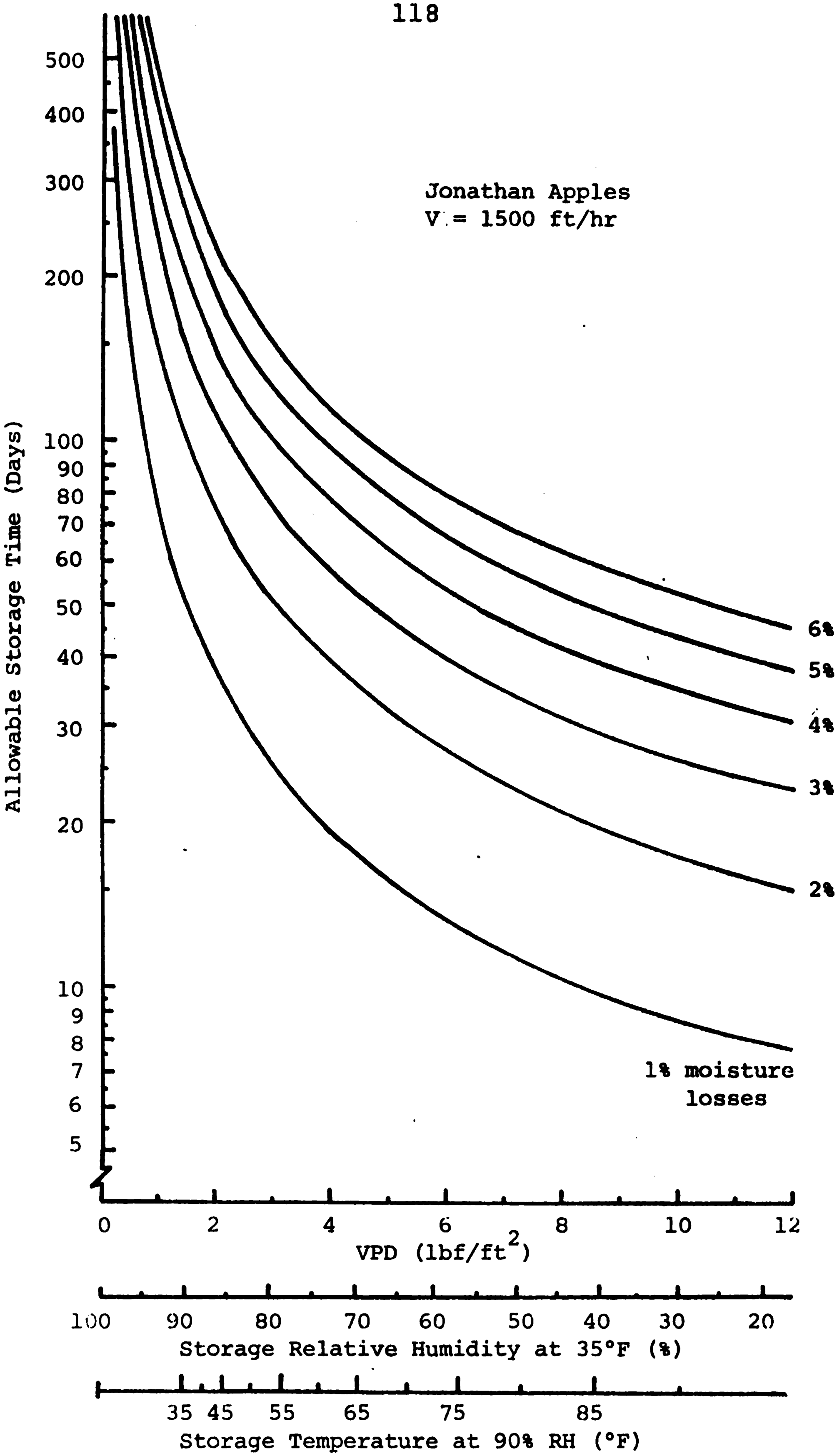


Figure 22.--Predicted allowable storage time for Jonathan apples. V = 1500 ft/hr.

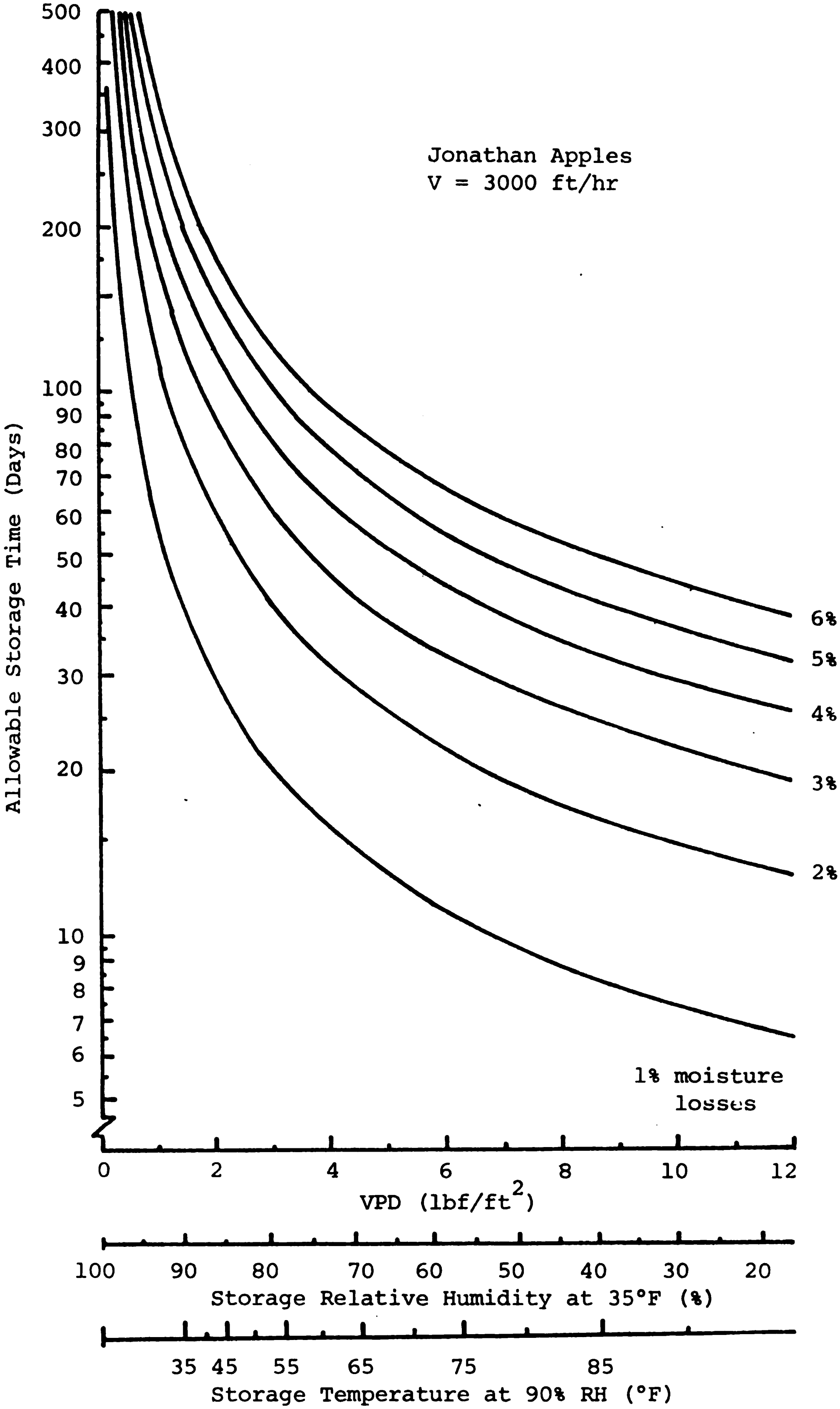


Figure 23.--Predicted allowable storage time for Jonathan apples. V = 3000 ft/hr.

in both figures. A .33 pound apple was used in calculating the predictions.

The effect of the different variables on the storage time can be studied in Figure 22 and 23. It can be observed for example, that a storage relative humidity between 90 to 95% has to be maintained for keeping Jonathan apples for a six month period with a 3% maximum of moisture loss, using a 1500 ft/hr air velocity. If twice this velocity is used (3000 ft/hr), the storage time, under the same conditions, will be reduced in only 20 days.

Changes in the storage relative humidity will dramatically affect the storage time. A 3% of moisture loss, for example, will occur in five months at a 90% relative humidity, 35°F of temperature, and 1500 ft/hr. If a 5% decrease in relative humidity takes place (from 90 to 85) the same amount of loss will occur in only 3 1/2 months at the same storage temperature and air velocity.

On the other hand, a change of 5°F (from 35 to 40°F) during the storage of Jonathan apples (at 90% relative humidity and 1500 ft/hr of air velocity) will result in a reduction of only 25 days in the storage time.

6.4.2 Manona Potatoes

Figures 24, 25 and 26 present the graphs for predicting moisture losses and allowable storage times of Manona potatoes at various storage conditions.

In Figure 24 the vapor pressure deficit is plotted against the rate of moisture loss per unit area (or per unit weight). A second abscissa scale represents the equivalent relative humidity of the environmental air at 40°F. A third abscissa scale represents the equivalent environmental temperature at 90% relative humidity. The assumption of a saturated surface at a temperature equal to the dry bulb temperature was used in drawing the relative humidity and temperature scales. A .397 of a pound (180 grams) potato was used for developing the graph.

A similar analysis to the one for Jonathan apples can be performed on Figure 24. The nonlinear relationship between the vapor pressure deficit and the rate of moisture losses from Manona potatoes can be observed in this figure. Besides, as in the case of Jonathan apples, relative humidity is the most critical variable affecting the moisture loss process from this commodity. On the other hand, the environmental air velocity has comparatively little effect on moisture losses.

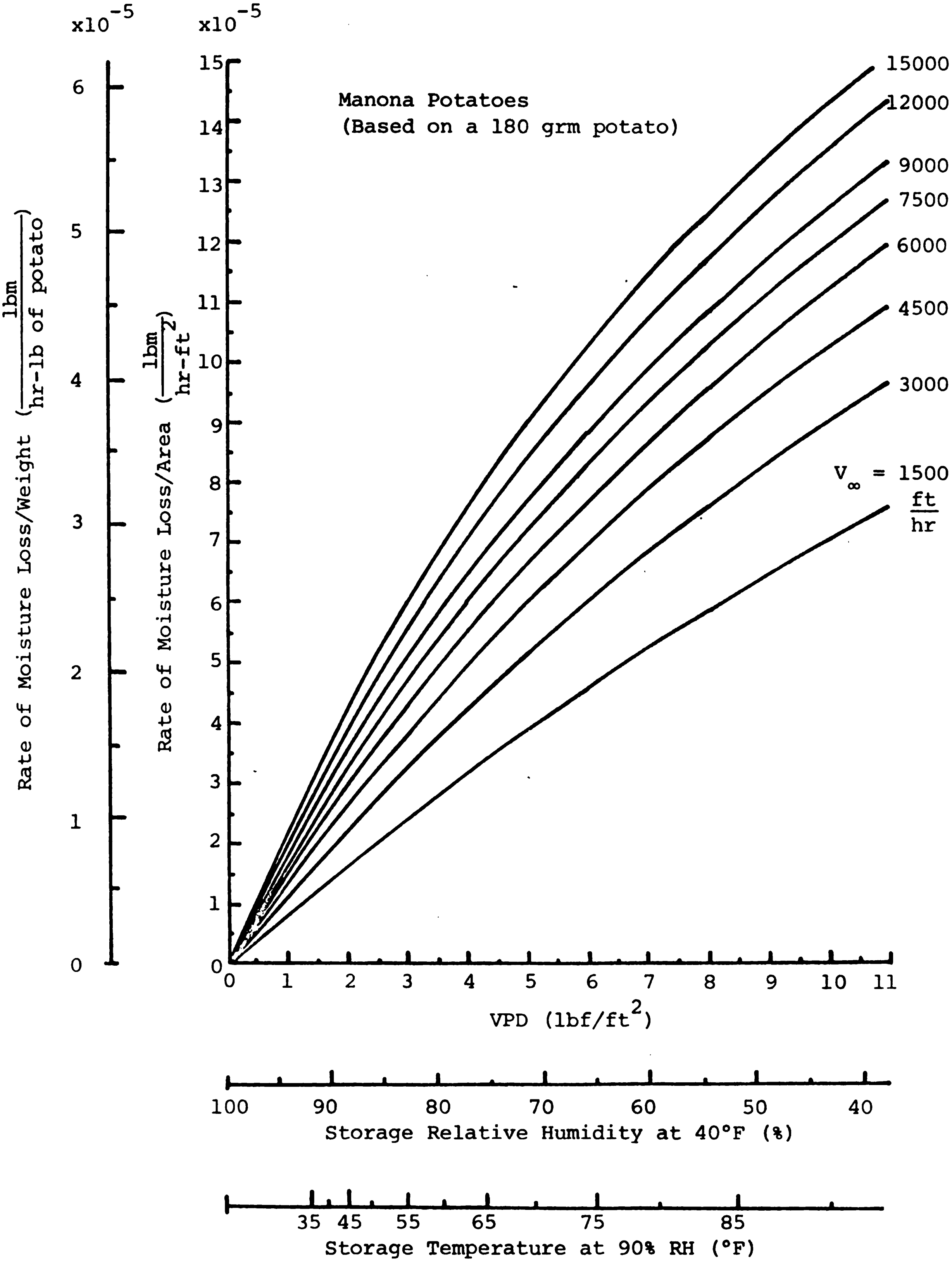


Figure 24.--Predicted moisture losses from Manona potatoes.

Allowable storage time predictions for Manona potatoes at various percentages of moisture loss are presented in Figures 25 and 26. An air velocity of 1500 ft/hr was used in Figure 25. In Figure 26 a 3000 ft/hr air velocity was used. Relative humidity and temperature scales were drawn in both figures. A .394 pound potato was used in developing the graphs.

The effect of the different variables on the storage time of Manona potatoes can be studied in Figures 25 and 26. It can be observed that, if an environmental relative humidity between 90 to 95% is maintained, Manona potatoes can be kept for eight months with a maximum of 3% in moisture losses, using a 1500 ft/hr air velocity. If twice this velocity is used (3000 ft/hr) the storage time, under the same conditions, will be reduced in 40 days.

Changes in relative humidity will affect the storage time considerably. A 3% of moisture losses for example, will occur in seven months at a 90% relative humidity, 40°F of temperature and 1500 ft/hr. If a 5% decrease in relative humidity takes place (from 90 to 85%) the same amount of losses will occur in only 4 1/2 months.

On the other hand, changes of 5°F (from 40 to 45°F) during the storage of Manona potatoes (at 90% relative humidity and 1500 ft/hr of air velocity) will result in a reduction of 45 days in the storage time.

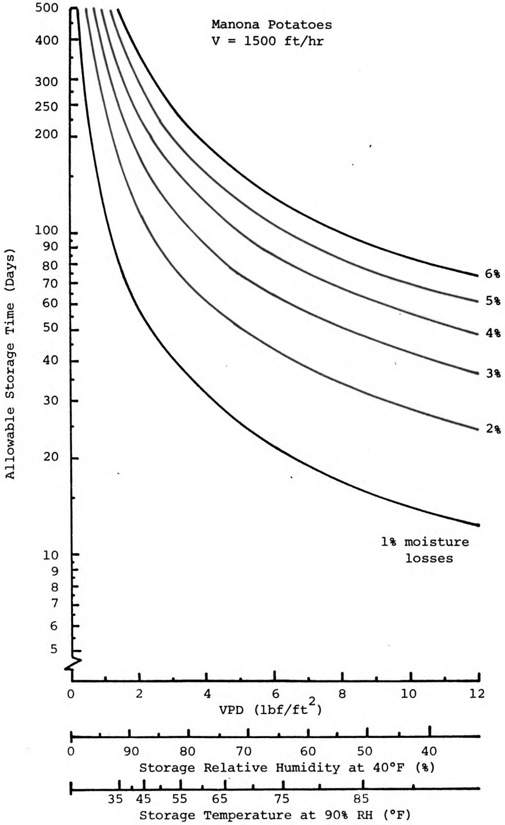


Figure 25.--Predicted allowable storage time for Manona potatoes. V = 1500 ft/hr.

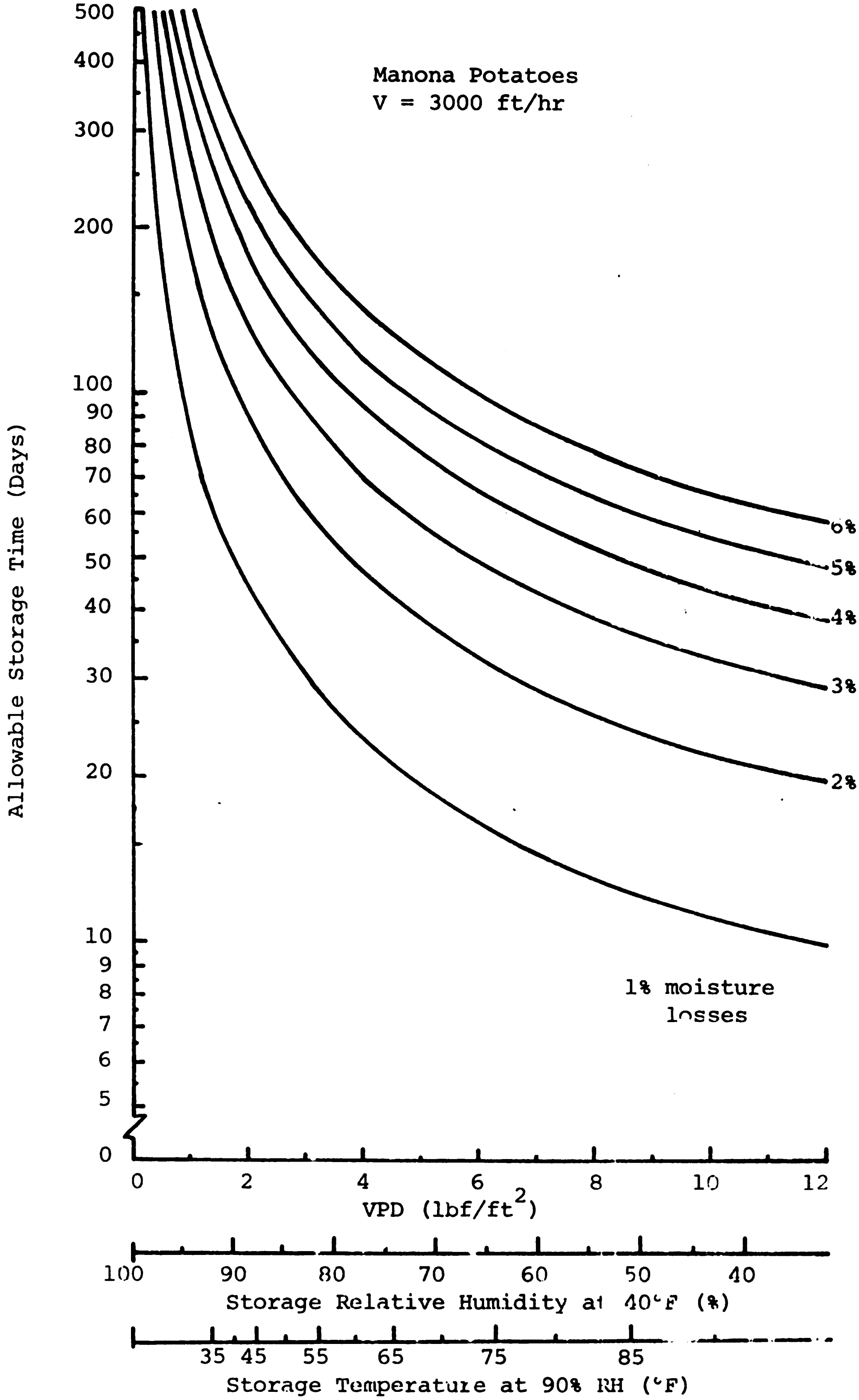


Figure 26.--Predicted allowable storage time for Manona potatoes.
V = 3000 ft/hr.

6.4.3 US H20 Sugar Beets

In Figures 27, 28 and 29 the graphs for predicting moisture losses and allowable storage times of US H20 sugar beets at various storage conditions are presented.

In Figure 27 the vapor pressure deficit is plotted against the rate of moisture loss per unit area (or per unit weight). A second abscissa scale represents the equivalent relative humidity of the environmental air at 35°F. A third abscissa scale represents the equivalent environmental temperature at 90% relative humidity. The assumption of a saturated surface at a temperature equal to the wet bulb temperature was used in drawing the relative humidity and temperature scales. A 2.645 pounds (1200 grams) beet was used for developing the graph.

The effect of the different variables affecting the moisture loss process in US H20 sugar beets can be studied in Figure 27.

Relative humidity is the most critical variable affecting moisture losses from US H20 sugar beets. A reduction of 5% (from 90 to 85%) in the environmental relative humidity at 35°F is equivalent, in terms of the increase in the rate of moisture losses, to a temperature increase of 20°F (from 35°F to 55°F), at 90% relative humidity.

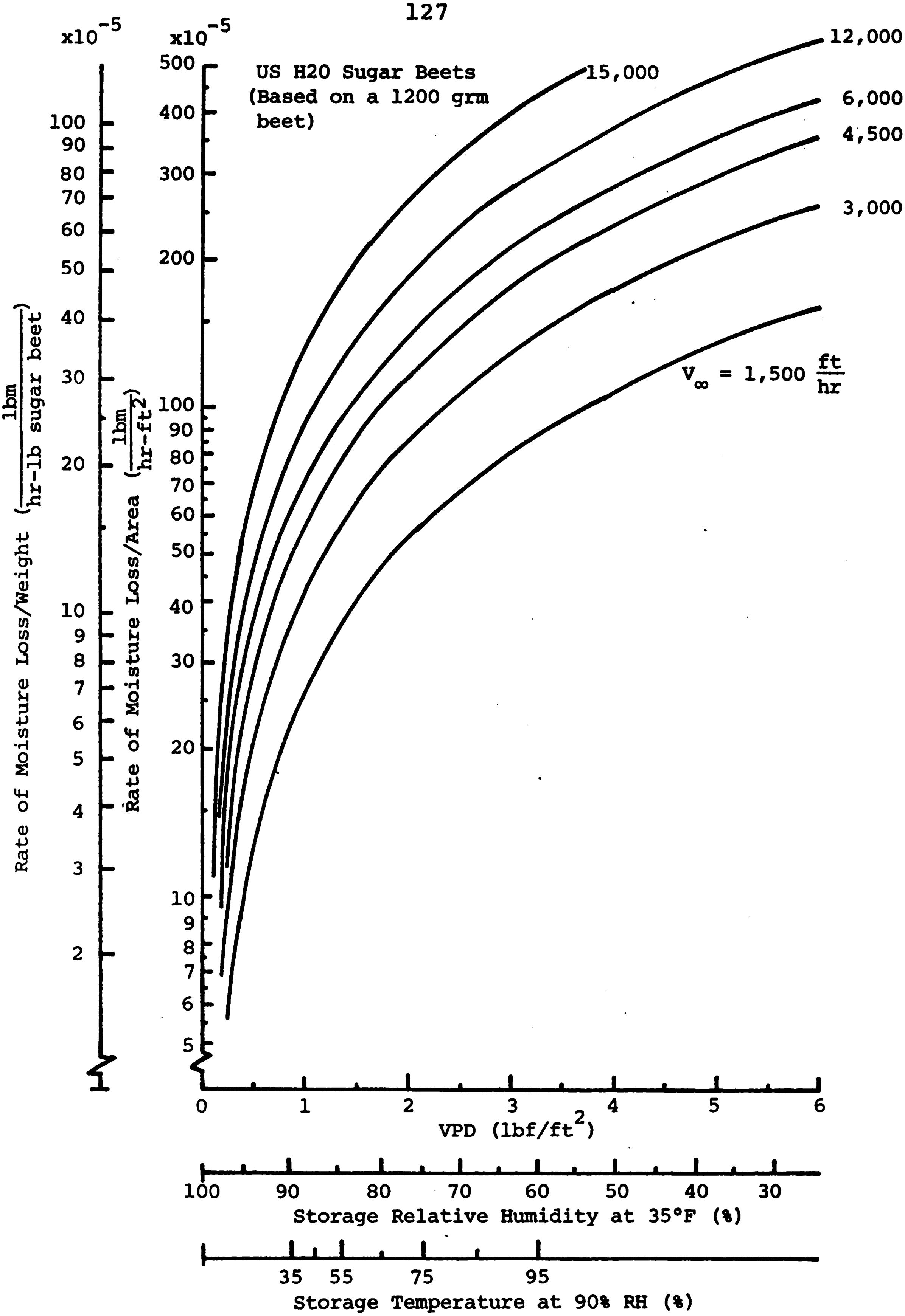


Figure 27.--Predicted moisture losses from US H20 sugar beets.

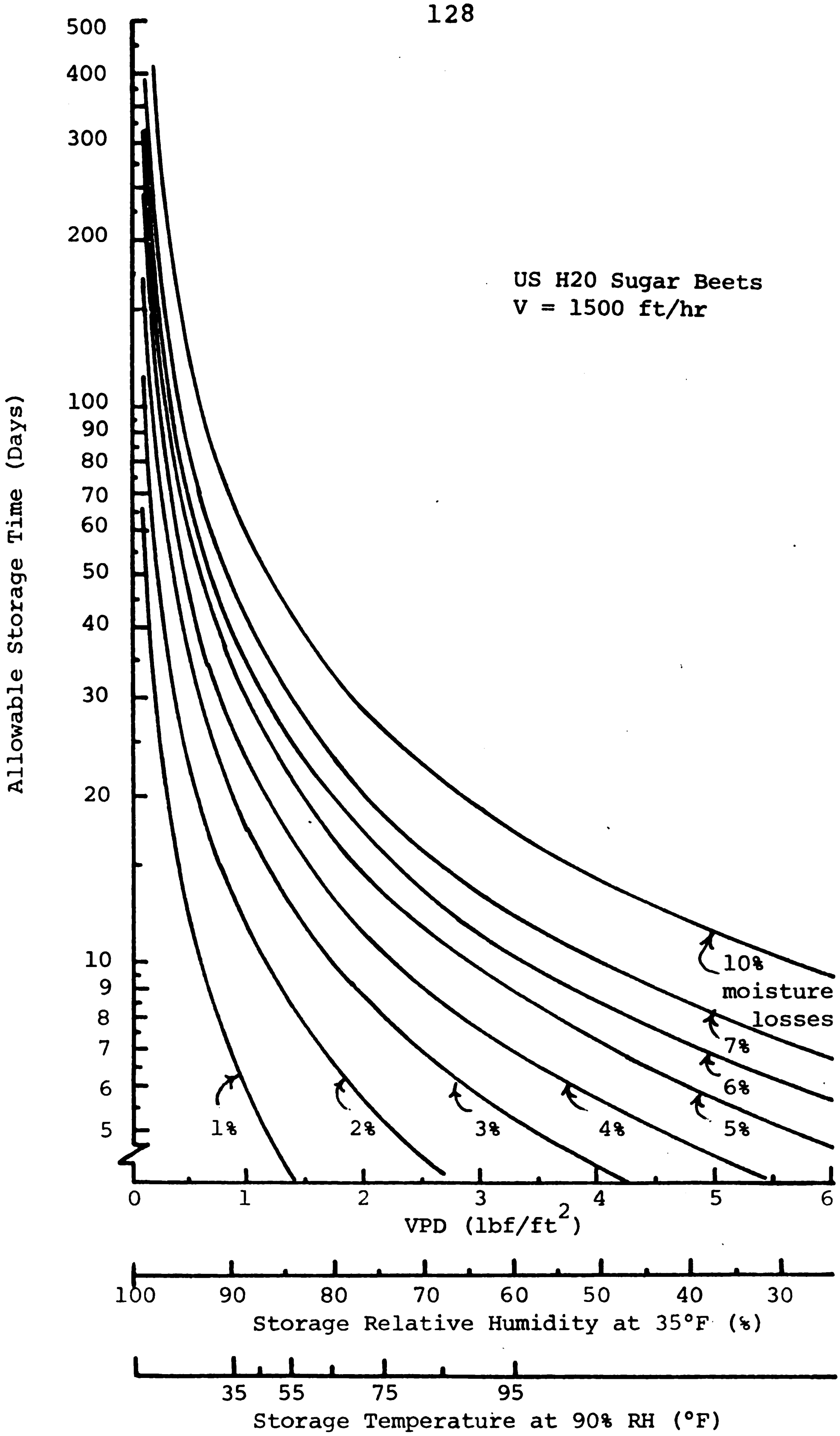


Figure 28.--Predicted allowable storage time for US H20 sugar beets. V = 1500 ft/hr.

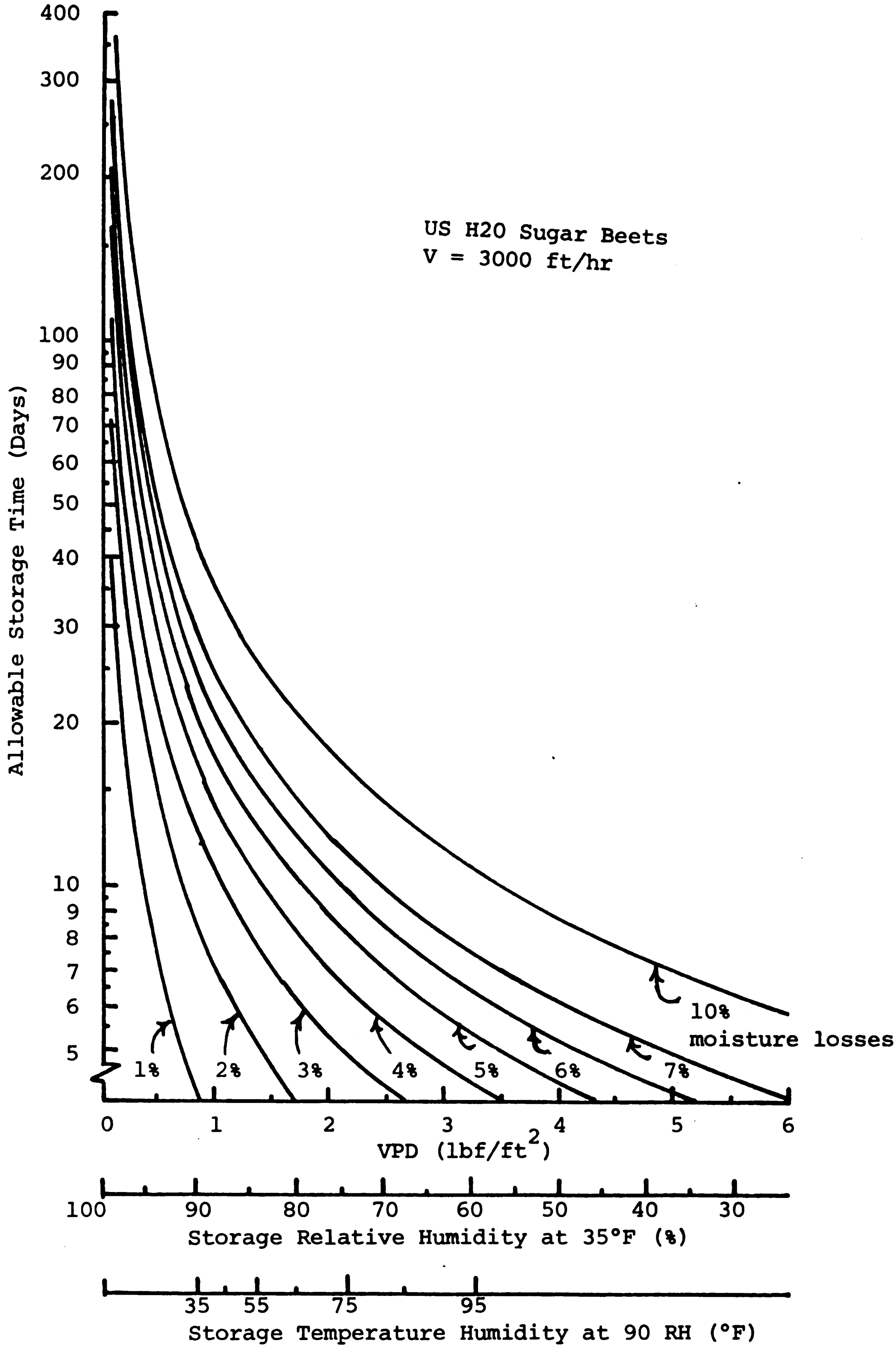


Figure 29.--Predicted allowable storage time for US H20 sugar beets. V = 3000 ft/hr.

On the other hand, the air velocity has a more important effect on moisture losses from US H20 sugar beets than its effect on moisture losses from Jonathan apples or Manona potatoes. When the air velocity is doubled (from 1500 to 3000 ft/hr for example) at 35°F and 90% relative humidity the rate of moisture losses is increased in 45%.

Allowable storage time predictions for US H20 sugar beets at various percentages of moisture losses are presented in Figures 28 and 29. In Figure 28 an environmental air velocity of 1500 ft/hr was used. A 3000 ft/hr air velocity was used in Figure 29. Relative humidity and temperature scales were also drawn in both figures. A 2.645 pound beet was used for developing the graphs.

The effect of the different variables on the storage time of US H20 sugar beets can be studied in Figures 28 and 29. It can be observed that, unless a very high relative humidity (from 95 to 100%) will be kept in the storage of this product, important moisture losses will occur during the storage time. For example, losses as high as 10% will occur in a two month period when the product is stored at 35°F, 90% relative humidity and a 1500 ft/hr air velocity is used. If the air velocity is doubled (300 ft/hr) at the given storage conditions (35°F and 90% relative humidity) the 10% moisture losses will occur in only 40 days. Therefore in the storage of sugar beets it is very important to maintain a very high relative humidity and keep the airflow to a minimum.

VII. SUMMARY AND CONCLUSIONS

A semi-theoretical methematical model for predicting moisture losses from horticultural products in storage was developed.

The model is based on the distinctive behavior of different regions of the skin of a product with regard to moisture losses. Free water, porous membrane, and impervious regions were identified as the components of the skin of a horticultural product. An electric analogy was used to present the model. Equations (4.1), (4.2), (4.3), (4.4) and (4.5) describe the model mathematically.

For using the model, it is necessary to determine the surface area of the commodity, the convective heat and mass transfer coefficients, and the vapor pressure deficit of the environment-product system. Besides, the values of three so called "skin parameters" have to be known. These parameters represent the fraction of the surface behaving as a free water surface, the fraction of the surface behaving as a porous membrane and the resistance to water vapor movement through membrane like regions (parameters γ_1, γ_2 and $r\delta$, respectively).

The model was used for studying the behavior of Jonathan apples, Manona potatoes and US H20 sugar beets with regard to moisture losses.

Weight-surface area relationships were developed for predicting surface areas in single Jonathan apples, Manona potatoes and US H20 sugar beets. Good correlations were found in all cases.

The developed weight-surface area relationships for apples and potatoes were compared with some models from the literature.

In the case of Jonathan apples, Baten's weight-surface area relationship, Cooke's two parameter model, and Moustafa's four parameter models were compared with the linear relationship developed from planimeter data.

Baten's weight-surface area relationship gave comparative results to those of the developed relationship.

Although the developed relationship gave better prediction of the surface area than Cooke's model, predictions by Cooke's model were within $\pm$ 6% of the experimental ones. Cooke's model can be useful for studies where the weighting procedure is difficult or not possible, i.e., in preharvesting studies.

Moustafa's model showed poor prediction of surface areas of Jonathan apples. It was observed that the deviation from the assumed elliptical shape is larger for big than for small samples.

For Manona potatoes, Maurer's prolate spheroid model was compared with the developed weight-surface area relationship. Maurer's model showed poor prediction of the surface area of Manona potatoes in comparison with the developed weight-surface area relationship.

Dimensionless relationships were developed for calculating the convective mass transfer coefficients of individual peeled Jonathan apples, Manona potatoes and US H20 sugar beets. Good agreement was found when these relationships were compared with equations described in the literature for flow over spheres, prolate spheroids and cones, respectively.

Moisture loss data of individual Jonathan apples, Manona potatoes and US H20 sugar beets were applied to the model described by equations (4.1), (4.2), (4.3), (4.4) and (4.5) for determining the skin parameters of each one of these products.

A nonlinear routine (GAUSHAUS) was used for predicting the skin parameters of Jonathan apples and Manona potatoes. In the case of US H20 sugar beets a simplification of the model was used. Sugar beet results were expressed in terms of an "effective surface area" for moisture migration.

The results show negligible free water regions in the Jonathan apple skin. It was also found that approximately 98.7% of the Jonathan apple skin is impervious to water vapor. Average values of $\gamma_1 = 0$, $\gamma_2 = .1286$ and $r\delta = .01943$ ft, at 70°F, were obtained for the skin parameters of Jonathan apples.

It was found that the parameter $r\delta$ is a function of the vapor pressure deficit. Equation (6.10) describes the $r\delta$ - VPD relationship for Jonathan apples.

Due to the fact that free water regions are of negligible nature in the Jonathan apple skin, the velocity of the environmental air has comparatively little effect on moisture losses from this commodity. It was observed that doubling the airflow resulted in only a 10% increase in moisture loss. This in comparison with free water surfaces where the mass transfer coefficient is approximately proportional to the square root of the air velocity.

A somewhat similar behavior to the Jonathan apples behavior was observed in Manona potatoes. As in the case of apples, negligible free water regions in the skin of the Manona potato were observed.

It was found that approximately 99.1% of the Manona potato is impervious to water vapor. Average values of $\gamma_1 = 0$, $\gamma_2 = .00890$ and $r\delta = .01143$ feet were obtained for the skin parameters of this commodity.

As in the case of apples, a linear relationship between the VPD and the parameter $r\delta$ was obtained for Manona potatoes. Equation (6.11) describes this relationship.

The environmental air velocity has little effect on moisture losses from Manona potatoes. Doubling the airflow resulted in a 15% increase in the loss of moisture from this commodity.

The behavior of sugar beets with regard to moisture losses can be explained by assuming that the skin of the sugar beet is a combination of free water and impervious regions. It was found that about 43.6% (γ_1 = .436) of the surface area of US H20 sugar beets if of a free water nature.

Finally, graphs for predicting moisture losses and storage times were developed for Jonathan apples, Manona potatoes and US H20 sugar beets. The effect of each variable on the moisture loss process can be analysed by using the graphs. It is expected that the prediction graphs will be useful in designing storage facilities for these products.

VIII. SUGGESTIONS FOR FUTURE RESEARCH

Further studies should be made in the following areas:

1. Of practical importance is the study of the effect of low ranges of vapor pressure deficits (1 to 5 lbf/ft^2) on the $\underline{r\delta}$ parameter.

2. Treatments for decreasing moisture losses should be evaluated. This may include studies of the effect of covering the skin with different types and amount of waxes.

3. Models for predicting moisture losses during the cooling process should be developed. Results from the present research may be useful for that purpose.

4. The developed model may be particularly useful in studying the suberization process. The effect of temperature on the skin resistance to moisture losses may be effectively studied through the analysis of the effect of the temperature on the skin parameters.

APPENDICES

APPENDIX A

APPENDIX A

Convertion Table from British Units to SI Units

Quantity	British Unit	SI Unit	Multiply British by Obtain SI
Length	foot	metre	3.048×10^{-1}
Area	square foot	square metre	9.290×10^{-2}
Volume	cubic foot	cubic metre	2.832×10^{-2}
Time	hour	second	3.600×10^{3}
Velocity	foot/ hour	metre/ second	8.467×10^{-5}
Mass	pound mass	kilo- gramme	4.536×10^{-1}
Force	pound force	Newton	4.448
Energy (heat)	BTU	Joule	1.055×10^{3}
Pressure	pound force/ ft^2	Newton/ $metre^2$	4.788×10
Temperature	^oF	^oC	$^oC=5/9(^oF-32)$

APPENDIX B

APPENDIX B
ALEASQ Computer Routine

```
      SUBROUTINE ALEASQ(M,ND,X,Y,B0,B1)
      DIMENSION X(120),Y(120),YH(120),RES(120),RSQ(120)
      GO TO (500,600,700)M
  700 DO 705 I=1,ND
      Y(I)=ALOG(Y(I))
  705 CONTINUE
      GO TO 500
  600 DO 605 I=1,ND
      X(I)=ALOG(X(I))
      Y(I)=ALOG(Y(I))
  605 CONTINUE
  500 AN=ND
      SX=0.0
      SY=0.0
      DO 505 I=1,ND
      SX=SX+X(I)
      SY=SY+Y(I)
  505 CONTINUE
      XM=SX/AN
      YM=SY/AN
      SUMXSQ=0.0
      SUMYSQ=0.0
      SUMXY=0.0
      DO 510 J=1,ND
      SUMXSQ=SUMXSQ+(X(J)-XM)**2
      SUMYSQ=SUMYSQ+(Y(J)-YM)**2
      SUMXY=SUMXY+(X(J)-XM)*(Y(J)-YM)
      B1=SUMXY/SUMXSQ
      B0=YM-B1*XM
  510 CONTINUE
      SSE=0.0
      SSR=0.0
      SST=0.0
      SSX=0.0
      REX=0.0
      DO 520 K=1,ND
      YH(K)=B0+B1*X(K)
      RES(K)=Y(K)-YH(K)
      RSQ(K)=RES(K)**2
      SSE=SSE+RSQ(K)
      SSR=SSR+((YH(K)-YM)**2)
      SST=SST+((Y(K)-YM)**2)
      SSX=SSX+(X(K)**2)
  520 CONTINUE
      VYI=SSE/(AN-2.)
      VB0=VYI*SSX/(AN*SUMXSQ)
      VB1=VYI/SUMXSQ
      SDYI=SQRT(VYI)
      SDB0=SQRT(VB0)
      SDB1=SQRT(VB1)
      RR=(B1**2)*SUMXSQ/SUMYSQ
      F=SSR/VYI
      GO TO(522,523,710)M
  710 B0=EXP(B0)
      B1=EXP(B1)
```

APPENDIX B

ALEASQ Computer Routine

```
    DO 715 L=1,ND
    Y(L)=EXP(Y(L))
    YH(L)=EXP(YH(L))
    RES(L)=Y(L)-YH(L)
    RSQ(L)=RES(L)**2
715 CONTINUE
    WRITE(61,720)B0,B1
720 FORMAT(*1*,15X,*MODEL YH(J)=B0( B1 TO X(J))*,//,23X,*B0= *,F10.5,
   1/,23X,*B1= *,F10.5,//)
    GO TO 528
523 B0=EXP(B0)
    DO 524 L=1,ND
    X(L)=EXP(X(L))
    Y(L)=EXP(Y(L))
    YH(L)=EXP(YH(L))
    RES(L)=Y(L)-YH(L)
    RSQ(L)=RES(L)**2
524 CONTINUE
    WRITE(61,526)B0,B1
526 FORMAT(*1*,15X,*MODEL YH(J)=B0(X(J) TO B1)*,//,23X,*B0= *,F10.5,
   1/,23X,*B1= *,F10.5,//)
    GO TO 528
522 WRITE(61,525)B0,B1
525 FORMAT(*1*,15X,*MODEL  YH(J)=B0+B1(X(J))*,//,23X,*B0= *,F10.5,
   1/,23X,*B1= *,F10.5,//)
528 WRITE(61,530)
530 FORMAT(5X,*  (J)    *,5X,*X(J)*,7X,*Y(J)*,5X,*YH(J)*,4X,
   1*RES(J)*,3X,*SQ RES(J)*,/)
    DO 540 J=1,ND
    WRITE(61,550)J,X(J),Y(J),YH(J),RES(J),RSQ(J)
550 FORMAT(5X,I3,6X,F11.5,4F10.5)
540 CONTINUE
    WRITE(61,570)VYI,VB0,VB1,SDYI,SDB0,SDB1,RR
570 FORMAT(5X,//,5X,*VYI= *,F10.5,/,5X,*VB0= *,F10.5,/,5X,
   1*VB1= *,F10.5,/,5X,*SDYI= *,F10.5,/,5X,*SDB0= *,F10.5,/,5X,
   2*SDB1= *,F10.5,/,5X,*RR= *,F10.5,//)
    NFR=ND-2
    NFLM=1
    AVSR=SSE/NFR
    AVSLM=SSR/NFLM
    NFT=ND-1
    WRITE(61,585)
585 FORMAT(15X,*TABLE FOR PARTITION ABOUT THE MEAN*,//,5X,
   1*SOURCE*,9X,*SUM OF SQUARES*,4X,*D.OF.F.*,6X,
   2*MEAN SQ*,7X,*F*,//)
    WRITE(61,590)SSE,NFR,AVSR,SSR,NFLM,AVSLM,F,SST,NFT
590 FORMAT(5X,*RESIDUALS*,8X,F10.4,7X,I2,9X,F10.4,/,
   15X,*LINE AND MEAN*,4X,F10.4,7X,I2,9X,F10.4,F10.4,/,
   25X,*TOTAL*,12X,F10.4,7X,I2)
    RETURN
    END
```

APPENDIX C

APPENDIX C

Comparative Results of Four Models for Predicting Surface Areas of Individual Jonathan Apples.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Linear Regres. Area (ft^2)	Baten Model Area (ft^2)	Cooke Model W (in)	Cooke Model H (in)	Cooke Model Area (ft^2)	Moustafa Model a (in)	Moustafa Model b (in)	Moustafa Model c (in)	Moustafa Model z (Deg.)	Moustafa Model Area each side (ft^2)	Average Area (ft^2)
1	.29198	.16993	.16892	.16978	2.85	2.47	.16684	1.20	.87	.55	6.3	.19354	.20078
								1.25	.88	.53	0.0	.20803	
2	.29722	.17396	.17120	.17230	2.92	2.48	.17369	1.20	.86	.54	8.0	.18764	.20669
								1.26	.96	.53	8.0	.22573	
3	.27672	.16076	.16227	.16325	2.74	2.38	.15436	1.09	.77	.50	1.8	.12958	.16641
								1.24	.93	.50	2.2	.20270	
4	.29145	.16618	.16869	.16956	2.76	2.46	.15830	1.18	.83	.51	5.0	.16737	.18899
								1.25	.86	.55	3.5	.21061	
5	.24669	.15049	.14918	.15038	2.69	2.27	.14702	1.13	.90	.46	0.0	.14839	.14110
								1.08	.79	.52	6.0	.13380	
6	.30088	.17333	.17280	.17360	2.87	2.48	.16899	1.18	.81	.51	5.8	.16368	.20234
								1.27	.93	.57	3.9	.24101	
7	.29929	.17083	.17211	.17058	2.89	2.47	.17058	1.28	.93	.57	0.0	.24583	.21102
								1.17	.80	.57	3.7	.17621	
8	.30258	.17174	.17354	.17433	2.85	2.43	.16573	1.17	.80	.55	3.0	.17080	.18927
								1.20	.83	.62	2.0	.20775	

APPENDIX C

Comparative Results of Four Models for Predicting Surface Areas of Individual Jonathan Apples.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Linear Regres Area (ft^2)	Baten Model Area (ft^2)	Cooke Model W (in)	Cooke Model H (in)	Cooke Model Area (ft^2)	Moustafa Model a (in)	Moustafa Model b (in)	Moustafa Model c (in)	Moustafa Model z (Deg.)	Moustafa Model Area each side (ft^2)	Average Area (ft^2)
9	.37930	.20812	.20698	.20719	3.10	2.70	.19780	1.35	.96	.54	6.0	.26894	.27993
								1.36	.97	.57	4.0	.29091	
10	.29052	.16840	.16828	.16916	2.92	2.32	.16908	1.22	1.01	.51	1.0	.21337	.18002
								1.09	.78	.57	5.6	.14668	
11	.35470	.19472	.19626	.19665	3.07	2.62	.19238	1.27	.92	.54	2.6	.22749	.25764
								1.33	.98	.59	5.2	.28779	
12	.31971	.17729	.18101	.18166	2.94	2.47	.17530	1.27	.92	.59	1.0	.24695	.21918
								1.19	.80	.60	4.0	.19140	
13	.24735	.14764	.14947	.15067	2.67	2.39	.14841	1.21	.85	.50	5.3	.17726	.16265
								1.16	.75	.51	2.0	.14804	
14	.28787	.16306	.16713	.16803	2.81	2.43	.16205	1.25	.92	.50	3.0	.20435	.18470
								1.14	.78	.58	4.0	.16505	
15	.26561	.15521	.15742	.15849	2.73	2.35	.15266	1.15	.82	.50	2.0	.15410	.16096
								1.16	.78	.57	7.8	.16783	
16	.32727	.17910	.18430	.18490	2.90	2.56	.17407	1.30	.88	.56	8.6	.23604	.22389
								1.26	.88	.53	0.0	.21174	

APPENDIX C

Comparative Results of Four Models for Predicting Surface Areas of Individual Jonathan Apples.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Linear Regres Area (ft^2)	Baten Model Area (ft^2)	Cooke Model W (in)	Cooke Model H (in)	Cooke Model Area (ft^2)	Moustafa Model a (in)	Moustafa Model b (in)	Moustafa Model c (in)	Moustafa Model z (Deg.)	Moustafa Model Area each side (ft^2)	Average Area (ft^2)
17	.25600	.15243	.15323	.15437	2.74	2.26	.15113	1.14	.89	.47	5.5	.15229	.15003
								1.13	.80	.51	1.6	.14777	
18	.25247	.14951	.15170	.15286	2.66	2.33	.14598	1.15	.75	.49	5.0	.13959	.15347
								1.16	.80	.55	4.2	.16734	
19	.30223	.17056	.17339	.17418	2.82	2.51	.16516	1.34	.93	.58	3.8	.27597	.21165
								1.17	.73	.51	2.0	.14733	
20	.29187	.16875	.16887	.16974	2.84	2.33	.16201	1.20	.87	.54	2.8	.19114	.17685
								1.13	.77	.59	3.0	.16255	
21	.32870	.18361	.18493	.18552	2.96	2.50	.17808	1.20	.83	.58	5.0	.19524	.22135
								1.28	.92	.58	0.0	.24747	
22	.34795	.19493	.19332	.19376	3.09	2.63	.19468	1.39	.97	.55	2.0	.27281	.26234
								1.29	.91	.59	6.2	.25186	
23	.28062	.16379	.16397	.16492	2.75	2.33	.15391	1.22	.93	.49	3.8	.19154	.16337
								1.09	.71	.57	3.8	.13520	

APPENDIX C

Comparative Results of Four Models for Predicting Surface Areas of Individual Jonathan Apples.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Linear Regres Area (ft^2)	Baten Model Area (ft^2)	Cooke Model W (in)	Cooke Model H (in)	Cooke Model Area (ft^2)	Moustafa Model a (in)	Moustafa Model b (in)	Moustafa Model c (in)	Moustafa Model z (Deg.)	Moustafa Model Area each side (ft^2)	Average Area (ft^2)
24	.31122	.17799	.17731	.17803	2.94	2.46	.17501	1.26	.91	.51	6.3	.20896	.20503
								1.20	.84	.59	0.0	.20110	
25	.30260	.17375	.17355	.17434	2.85	2.46	.16657	1.10	.78	.50	8.6	.13229	.19007
								1.31	.98	.52	4.0	.24785	
26	.37324	.20111	.20434	.20460	3.11	2.72	.19942	1.35	.98	.58	5.0	.29296	.27614
								1.31	.90	.59	3.0	.25932	
27	.41590	.22251	.22294	.22287	3.25	2.68	.21260	1.39	.97	.63	2.3	.30900	.29249
								1.28	.98	.62	6.1	.27598	
28	.30225	.17514	.17339	.17418	2.92	2.42	.17197	1.19	.86	.52	4.4	.17913	.20126
								1.21	.83	.66	1.9	.22340	
29	.23552	.14326	.14430	.14560	2.68	2.21	.14457	1.11	.76	.53	0.0	.14067	.13833
								1.06	.74	.59	1.9	.13599	
30	.25734	.15583	.15382	.15495	2.75	2.35	.15444	1.16	.85	.48	4.5	.15558	.15700
								1.14	.80	.54	3.8	.15842	

APPENDIX C

Comparative Results of Four Models for Predicting Surface Areas of Individual Jonathan Apples.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Linear Regres Area (ft^2)	Baten Model Area (ft^2)	Cooke Model W (in)	Cooke Model H (in)	Cooke Model Area (ft^2)	Moustafa Model a (in)	Moustafa Model b (in)	Moustafa Model c (in)	Moustafa Model z (Deg.)	Moustafa Model Area each side (ft^2)	Average Area (ft^2)
31	.30970	.17458	.17664	.17738	2.85	2.55	.16906	1.24	.81	.56	4.5	.19935	.19397
								1.23	.82	.53	3.0	.18859	
32	.28799	.16875	.16718	.16807	2.80	2.38	.15976	1.23	.88	.52	1.3	.19715	.17568
								1.13	.78	.55	5.0	.15421	
33	.32610	.18576	.18376	.18440	3.04	2.47	.18491	1.24	.93	.52	2.0	.21028	.21387
								1.20	.88	.62	6.5	.21746	
34	.25304	.15437	.15194	.15310	2.74	2.38	.15436	1.18	.82	.50	4.2	.16283	.16842
								1.18	.83	.53	1.0	.17401	
35	.28177	.16562	.16447	.16541	2.36	2.42	.16637	1.21	.92	.51	1.5	.19383	.18203
								1.16	.75	.60	5.5	.17023	
36	.28036	.16306	.16385	.16481	2.79	2.32	.15721	1.11	.73	.53	0.0	.13576	.16049
								1.15	.87	.58	3.8	.18522	
37	.36748	.20229	.20183	.20213	3.05	2.65	.19128	1.31	.95	.54	2.1	.25055	.25377
								1.30	.88	.61	5.0	.25699	

APPENDIX C

Comparative Results of Four Models for Predicting Surface Areas of Individual Jonthan Apples.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Linear Regres Area (ft^2)	Baten Model Area (ft^2)	Cooke Model W (in)	Cooke Model H (in)	Cooke Model Area (ft^2)	Moustafa Model a (in)	Moustafa Model b (in)	Moustafa Model c (in)	Moustafa Model z (Deg.)	Moustafa Model Area each side (ft^2)	Average Area (ft^2)
38	.26955	.15993	.15914	.16018	2.74	2.41	.15516	1.15	.77	.43	4.6	.12660	.16834
								1.23	.88	.56	5.6	.21008	
39	.21614	.13403	.13586	.13729	2.54	2.25	.13373	1.06	.73	.45	7.0	.10489	.12220
								1.14	.80	.47	4.0	.13951	
40	.29735	.17118	.17126	.17209	2.85	2.49	.16740	1.22	.88	.51	4.0	.18974	.19122
								1.21	.83	.56	5.1	.19269	
41	.35004	.19493	.19423	.19466	3.06	2.65	.19228	1.31	.95	.55	2.4	.25481	.25007
								1.25	.89	.63	3.0	.24533	
42	.33216	.18819	.18644	.18700	2.95	2.66	.18172	1.31	.88	.52	4.2	.22616	.24008
								1.30	.88	.60	2.0	.25401	
43	.23000	.14500	.14190	.14324	2.72	2.12	.14560	.99	.73	.55	5.0	.10813	.12355
								1.08	.81	.53	6.4	.13898	
44	.29295	.17132	.16934	.17020	2.89	2.47	.17058	1.18	.81	.45	3.8	.14617	.18906
								1.21	.88	.65	3.6	.23196	

APPENDIX C

Comparative Results of Four Models for Predicting Surface Areas of Individual Jonathan Apples.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Linear Regres Area (ft^2)	Baten Model Area (ft^2)	Cooke Model W (in)	Cooke Model H (in)	Cooke Model Area (ft^2)	Moustafa Model a (in)	Moustafa Model b (in)	Moustafa Model c (in)	Moustafa Model z (Deg.)	Moustafa Model Area each side (ft^2)	Average Area (ft^2)
45	.24145	.14736	.14689	.14814	2.60	2.30	.14004	1.09	.73	.48	3.9	.11899	.13501
								1.14	.73	.56	3.0	.15102	
46	.24998	.15104	.15061	.15179	2.69	2.29	.14755	1.12	.83	.48	3.9	.14113	.13781
								1.09	.72	.56	5.6	.13450	
47	.29603	.17104	.17068	.17152	2.85	2.52	.16823	1.26	.88	.52	3.0	.20776	.19109
								1.19	.77	.56	1.8	.17442	
48	.27884	.16368	.16319	.16415	2.75	2.42	.15632	1.18	.79	.54	7.0	.16830	.16879
								1.18	.76	.56	0.5	.16927	
49	.28721	.16958	.16684	.16774	2.91	2.43	.17132	1.16	.85	.57	5.0	.18194	.18414
								1.18	.85	.56	5.0	.18634	
50	.37438	.20708	.20484	.20509	3.21	2.71	.20939	1.33	.97	.60	4.0	.29021	.29088
								1.33	.94	.62	2.0	.29155	
51	.24885	.15028	.15012	.15131	2.74	2.26	.15113	1.10	.80	.53	2.1	.14406	.13699
								1.08	.76	.52	3.0	.12992	

APPENDIX C

Comparative Results of Four Models for Predicting Surface Areas of Individual Jonathan Apples.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Linear Regres Area (ft^2)	Baten Model Area (ft^2)	Cooke Model W (in)	Cooke Model H (in)	Cooke Model Area (ft^2)	Moustafa Model a (in)	Moustafa Model b (in)	Moustafa Model c (in)	Moustafa Model z (Deg.)	Moustafa Model Area each side (ft^2)	Average Area (ft^2)
52	.26667	.15625	.15788	.15894	2.76	2.35	.15534	1.15	.82	.50	2.7	.15402	.15884
								1.15	.80	.55	6.1	.16365	
53	.32881	.18715	.18498	.18557	3.05	2.51	.18709	1.25	.90	.57	3.0	.22640	.22187
								1.22	.87	.60	5.7	.21733	
54	.31830	.18382	.18039	.18106	3.01	2.60	.18585	1.25	.88	.55	4.4	.21460	.22799
								1.29	.88	.58	5.0	.24138	
55	.28466	.16826	.16573	.16665	2.92	2.48	.17369	1.21	.92	.50	2.0	.19023	.18669
								1.20	.87	.52	7.8	.18314	
56	.31993	.18278	.18110	.18176	2.99	2.54	.18214	1.23	.90	.55	4.2	.21111	.21342
								1.24	.87	.57	4.0	.21574	
57	.32286	.18201	.18238	.18302	2.99	2.54	.18214	1.24	.91	.51	3.0	.20261	.21223
								1.25	.90	.56	6.0	.22185	
58	.30604	.17382	.17505	.17581	2.92	2.53	.17512	1.24	.88	.51	4.2	.19667	.20033
								1.24	.90	.52	4.6	.20400	

APPENDIX D

APPENDIX D

Comparative Results of Two Methods for Predicting Surface Areas of Individual Manona Potatoes.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Regression Area Eqn.(6.2) (ft^2)	Maurer Model Long Axis L (in)	Trans Axis b_1 (in)	Trans Axis b_2 (in)	Area (ft^2)
1	.50309	.19535	.19125	3.03	3.11	2.15	.18683
2	.49877	.19306	.19015	3.15	2.79	2.20	.17962
3	.47399	.18854	.18383	3.15	2.94	2.16	.18463
4	.43660	.17868	.17407	2.75	2.78	1.97	.15317
5	.38409	.16069	.15988	2.65	2.65	1.99	.14484
6	.32558	.14785	.14327	2.63	2.23	1.70	.11680
7	.40178	.16618	.16473	2.55	2.55	2.25	.14738
8	.50450	.19424	.19160	2.80	2.75	2.21	.16397
9	.61662	.21250	.21891	3.08	3.01	2.15	.18441
10	.49985	.19222	.19043	2.83	2.65	2.05	.15421
11	.47729	.14250	.18468	2.91	2.74	2.03	.16028
12	.57167	.20278	.20818	2.98	2.71	2.22	.16999

APPENDIX D

Comparative Results of Two Methods for Predicting Surface Areas of Individual Manona Potatoes.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Regression Area Eqn.(6.2) (ft^2)	Maurer Model Long Axis L (in)	Maurer Model Trans Axis b_1 (in)	Maurer Model Trans Axis b_2 (in)	Maurer Model Area (ft^2)
13	.41934	.17222	.16947	2.80	2.36	2.03	.14040
14	.44053	.17465	.17511	2.80	2.55	2.03	.14810
15	.56038	.19972	.20544	3.15	2.66	2.30	.17826
16	.44846	.17535	.17720	2.82	2.55	2.10	.15174
17	.40178	.16181	.16473	2.72	2.71	1.95	.14832
18	.36864	.14931	.15558	2.51	2.41	2.01	.13103
19	.42372	.16979	.17065	2.75	2.47	2.26	.15234
20	.39629	.16146	.16323	2.68	2.63	2.06	.14800
21	.42870	.16979	.17197	2.81	2.64	2.10	.15510
22	.35344	.14722	.15129	2.55	2.60	2.01	.13985
23	.38927	.15486	.16131	2.92	2.39	1.97	.14354
24	.42457	.16528	.17087	2.83	2.82	2.02	.16008

APPENDIX D

Comparative Results of Two Methods for Predicting Surface Areas of Individual Manona Potatoes.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Regression Area Eqn.(6.2) (ft^2)	Maurer Model Long Axis L (in)	Trans Axis b_1 (in)	Trans Axis b_2 (in)	Area (ft^2)
25	.33540	.14271	.14612	2.68	2.35	1.91	.13097
26	.34249	.15069	.14816	2.78	2.60	1.78	.13927
27	.41934	.16528	.16947	3.12	2.64	2.05	.16504
28	.35841	.15104	.15270	2.86	2.66	1.80	.14543
29	.37767	.15326	.15810	2.80	2.52	2.04	.14728
30	.42278	.16722	.17039	2.80	2.73	2.07	.15721
31	.35261	.14806	.15105	2.82	2.64	1.78	.14233
32	.32579	.14208	.14333	2.53	2.43	1.86	.12682
33	.42210	.17160	.17021	3.15	2.77	2.01	.16719
34	.35317	.15264	.15121	2.72	2.52	2.03	.14112
35	.37185	.15576	.15648	2.72	2.68	2.20	.15450
36	.38504	.16236	.16014	3.02	2.80	2.05	.16512

APPENDIX D

Comparative Results of Two Methods for Predicting Surface Areas of Individual Manona Potatoes.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Regression Area Eqn.(6.2) (ft^2)	Maurer Model Long Axis L (in)	Trans Axis b_1 (in)	Trans Axis b_2 (in)	Area (ft^2)
37	.38504	.16979	.16994	3.02	2.75	2.32	.17477
38	.32194	.14028	.14220	2.82	2.55	2.07	.14769
39	.41520	.17097	.16836	3.03	2.91	2.18	.17608
40	.38532	.16090	.16022	2.91	2.78	2.30	.17067
41	.40452	.16417	.16547	2.78	2.62	2.15	.15232
42	.38858	.16347	.16111	2.78	2.22	2.70	.15855
43	.36351	.15618	.15414	3.22	2.68	1.80	.15674
44	.45542	.18014	.17902	3.11	2.70	2.28	.17446
45	.49647	.19201	.18957	3.28	2.71	2.12	.17456
46	.31164	.13938	.13916	2.67	2.43	2.11	.13887
47	.34183	.14861	.14797	2.66	2.43	2.08	.13733
48	.41169	.16451	.16741	2.93	2.81	2.28	.17193

APPENDIX D

Comparative Results of Two Methods for Predicting Surface Areas of Individual Manona Potatoes.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Regression Area Eqn.(6.2) (ft^2)	Maurer Model Long Axis L (in)	Trans Axis b_1 (in)	Trans Axis b2 (in)	Area (ft^2)
49	.51903	.19736	.19525	3.12	3.03	2.55	.20621
50	.41198	.17160	.16749	2.68	2.89	2.14	.16286
51	.38376	.16493	.15978	3.38	2.42	1.72	.15059
52	.38297	.16354	.15957	3.06	2.52	1.98	.15454
53	.41180	.17222	.16744	3.06	2.85	1.98	.16882
54	.38040	.16333	.15886	2.72	2.72	2.05	.15282
55	.41071	.16889	.16715	2.76	2.72	2.14	.15813
56	.44936	.17937	.17743	3.02	2.68	2.02	.16159
57	.37125	.15590	.15631	2.80	2.73	2.03	.15554
58	.41713	.16882	.16888	3.10	2.79	1.97	.16733
59	.30921	.13771	.13844	2.83	2.53	1.83	.14028
60	.36015	.15590	.15319	2.83	2.43	1.93	.14028

APPENDIX D

Comparative Results of Two Methods for Predicting Surface Areas of Individual Manona Potatoes.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Regression Area Eqn.(6.2) (ft^2)	Maurer Model Long Axis L (in)	Maurer Model Trans Axis b_1 (in)	Maurer Model Trans Axis b_2 (in)	Maurer Model Area (ft^2)
61	.42433	.17431	.17081	2.94	2.87	2.04	.16749
62	.35976	.15361	.15308	2.86	2.54	1.94	.14625
63	.42105	.17118	.16993	2.93	2.67	2.21	.16579
64	.34044	.14806	.14757	2.85	2.57	2.02	.15040
65	.37112	.15597	.15627	2.75	2.47	2.03	.14024
66	.33761	.14667	.14676	2.79	2.62	1.68	.13376
67	.32974	.14757	.14448	2.58	2.58	1.89	.13285
68	.28476	.13424	.13107	2.45	2.40	1.73	.11563
69	.35425	.14931	.16876	2.53	2.50	2.00	.13218
70	.41670	.16910	.15667	2.63	2.45	2.18	.14093
71	.37255	.15486	.15667	2.69	2.40	2.03	.13529
72	.42049	.16757	.16978	2.72	2.70	1.95	.14513

APPENDIX D

Comparative Results of Two Methods for Predicting Surface Areas of Individual Manona Potatoes.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Regression Area Eqn.(6.2) (ft^2)	Maurer Model Long Axis L (in)	Maurer Model Trans Axis b_1 (in)	Maurer Model Trans Axis b_2 (in)	Maurer Model Area (ft^2)
73	.33963	.16153	.16414	2.88	2.63	1.98	.14954
74	.35162	.15257	.15077	2.80	2.60	1.98	.14531
75	.48955	.18819	.18781	3.09	3.02	2.35	.19132
76	.29573	.13604	.13440	2.46	2.42	1.77	.11814
77	.40132	.16312	.16460	2.89	2.54	2.02	.14786
78	.35348	.15271	.15130	2.73	2.61	1.97	.14269
79	.36849	.15299	.15554	2.89	2.57	1.93	.14539
80	.38602	.16104	.16041	2.85	2.45	1.99	.14149
81	.37086	.15646	.15620	2.80	2.50	1.98	.4531
82	.38110	.15979	.15905	2.88	2.83	2.02	.15958
83	.34376	.14792	.14853	2.81	2.50	1.90	.13843
84	.39995	.16243	.16423	2.86	2.70	2.22	.16175

APPENDIX D

Comparative Results of Two Methods for Predicitng Surface Areas of Individual Manona Potatoes.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Regression Area Eqn.(6.2) (ft^2)	Maurer Model Long Axis L (in)	Maurer Model Trans Axis b_1 (in)	Maurer Model Trans Axis b_2 (in)	Maurer Model Area (ft^2)
85	.37734	.15625	.15801	3.01	2.80	2.13	.16821
86	.45681	.18035	.17938	3.22	2.93	2.13	.18260
87	.40425	.16576	.16540	2.93	2.84	2.26	.17237
88	.36957	.15375	.15584	3.08	2.54	2.06	.15668
89	.39405	.16403	.16262	2.86	2.69	2.21	.16090
90	.42709	.17354	.17155	3.01	2.93	2.13	.17392
91	.35139	.14882	.15071	2.81	2.50	1.91	.13883
92	.44861	.17861	.17724	3.12	2.92	2.20	.18117
93	.49125	.19069	.18825	2.83	2.65	2.05	.15136
94	.32541	.14257	.14322	2.51	2.41	2.01	.12841
95	.31743	.13958	.14087	2.48	2.40	2.02	.12734
96	.42987	.17340	.17229	3.02	2.95	2.03	.17080

APPENDIX D

Comparative Results of Two Methods for Predicting Surface Areas of Individual Manona Potatoes.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Regression Area Eqn.(6.2) (ft^2)	Maurer Model Long Axis L (in)	Maurer Model Trans Axis b_1 (in)	Maurer Model Trans Axis b_2 (in)	Maurer Model Area (ft^2)
97	.28669	.12965	.13166	2.61	2.42	1.99	.13163
98	.28443	.12910	.13097	2.44	2.59	1.93	.12964
99	.34702	.15132	.14946	2.91	2.53	1.90	.14327
100	.32880	.14340	.14420	2.79	2.58	1.92	.14171
101	.32714	.14146	.14372	2.78	2.63	1.94	.14416
102	.27540	.12674	.12820	2.34	2.44	1.96	.12160
103	.44224	.17611	.17556	3.11	2.82	2.15	.17443
104	.28366	.13181	.13074	2.70	2.43	1.97	.13447
105	.34633	.15160	.14926	2.83	2.44	2.13	.14602
106	.35826	.15056	.15265	2.92	2.72	1.92	.15230
107	.41276	.16875	.16770	3.13	2.74	2.11	.16949
108	.29534	.13444	.13429	2.71	2.54	2.85	.17568

APPENDIX D

Comparative Results of Two Methods for Predicting Surface Areas of Individual Manona Potatoes.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Regression Area Eqn.(6.2) (ft^2)	Maurer Model			
				Long Axis L (in)	Trans Axis b_1 (in)	Trans Axis b_2 (in)	Area (ft^2)
109	.45474	.18000	.17884	3.19	2.81	2.02	.17099
110	.36468	.15722	.15447	2.71	2.68	2.01	.14636
111	.45970	.17778	.18013	2.93	2.85	2.32	.17544
112	.50337	.19299	.19132	3.56	2.96	2.18	.20063
113	.33165	.14326	.14503	2.51	2.41	2.00	.11029
114	.44098	.17361	.17523	2.82	2.65	2.10	.15304
115	.26546	.12799	.12511	2.61	2.42	2.00	.13201
116	.46362	.18312	.18115	2.92	2.74	2.05	.15861
117	.43229	.17153	.17293	2.80	2.38	2.03	.13847
118	.45419	.17715	.17870	2.81	2.63	2.02	.14854
119	.30708	.13653	.13781	2.67	2.35	1.92	.12838
120	.40690	.16660	.16612	2.79	2.35	2.02	.13652

APPENDIX E

APPENDIX E

Comparative Results of Three Models for Predicting Surface Areas of US H20 Sugar Beets.

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Model 1* Area (ft^2)	Model 2** Area (ft^2)	Model 3*** Area (ft^2)
1	1.34352	.41722	.40801	.40811	.42185
2	1.88386	.50653	.52833	.53023	.52279
3	1.63514	.48889	.47294	.47517	.47363
4	2.99162	.79639	.77500	.75859	.81161
5	2.52784	.67549	.67173	.66582	.67511
6	2.35743	.60569	.63378	.63079	.63094
7	2.32315	.60201	.62615	.62367	.62241
8	2.63889	.73319	.69646	.68836	.70555
9	2.46168	.67986	.65700	.65229	.65761
10	2.40157	.66431	.64361	.63991	.64210
11	2.31647	.61375	.62466	.62228	.62077
12	2.29171	.63993	.61915	.61713	.61469
13	1.93739	.53868	.54025	.54186	.53402
14	2.35769	.65097	.63384	.63084	.63101
15	1.67765	.48771	.48241	.48470	.48169

* Model 1: $A = .10883 + .22268 W_o$

** Model 2: $A = .32469\, W_o^{.77439}$

*** Model 3: $A = .24745\, (1.48743)^{W_o}$

APPENDIX E

Comparative Results of Three Models for Predicting Surface Areas of

US H20 Sugar Beets

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Model 1* Area (ft^2)	Model 2** Area (ft^2)	Model 3*** Area (ft^2)
16	2.06592	.53944	.56887	.56950	.56198
17	1.94264	.55090	.54142	.54300	.53514
18	2.24482	.56875	.60871	.60733	.60335
19	2.19184	.55799	.59691	.59620	.59080
20	2.09149	.57521	.57456	.57495	.56772
21	2.39599	.65000	.64237	.63876	.64068
22	2.20269	.61201	.59932	.59848	.59335
23	2.34364	.66431	.63049	.62772	.62725
24	2.20331	.58847	.59946	.59861	.59349
25	2.43541	.65993	.65115	.64689	.65078
26	2.25617	.57708	.61123	.60970	.60608
27	1.86590	.51542	.52433	.52631	.51908
28	2.20254	.56562	.59929	.59845	.59331
29	2.23902	.57049	.60741	.60611	.60197
30	1.82119	.49007	.51437	.51652	.50994
31	1.64308	.47187	.47471	.47695	.47513
32	1.75860	.48056	.50043	.50272	.49743
33	1.75313	.47222	.49922	.50151	.49635

APPENDIX E

Comparative Results of Three Models for Predicting Surface Areas of US H20 Sugar Beets

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Model 1* Area (ft^2)	Model 2** Area (ft^2)	Model 3*** Area (ft^2)
34	1.84039	.50000	.51865	.52073	.51385
35	2.14350	.55049	.58614	.58599	.57956
36	1.72405	.47938	.49274	.49505	.49065
37	1.63622	.45569	.47318	.47541	.47384
38	1.69034	.46076	.48524	.48754	.48413
39	1.50545	.45097	.44406	.44571	.44986
40	1.39464	.43090	.41939	.42009	.43050
41	1.55930	.46965	.45606	.45801	.45958
42	1.51658	.50278	.44654	.44826	.45185
43	1.62496	.47556	.47068	.47287	.47172
44	1.51318	.43299	.44579	.44748	.45124
45	2.58891	.72931	.58533	.67824	.69168
46	2.35388	.69986	.63299	.63005	.63006
47	1.80545	.50646	.51087	.51306	.50677
48	2.31349	.61444	.62400	.62167	.62003
49	1.71345	.49604	.49038	.49270	.48859
50	1.51587	.47028	.44638	.44810	.45173
51	1.80245	.50403	.51020	.51240	.50616

APPENDIX E

Comparative Results of Three Models for Predicting Surface Areas of

US H20 Sugar Beets

Sample Nº	Weight W_o (lbm)	Planimeter Area (ft^2)	Model 1* Area (ft^2)	Model 2** Area (ft^2)	Model 3*** Area (ft^2)
52	1.55842	.44424	.45586	.45781	.45942
53	2.12191	.56229	.58134	.58141	.57462
54	1.77288	.50896	.50362	.50588	.50026
55	2.31966	.62174	.62537	.62295	.62155
56	2.54444	.67750	.67543	.66920	.67958
57	1.81993	.52437	.51409	.51624	.50969
58	1.46953	.46194	.43607	.43745	.44349
59	1.51074	.45188	.44524	.44692	.45081
60	1.58706	.46701	.46224	.46431	.46468
61	1.45448	.46424	.43271	.43398	.44085
62	2.40946	.63847	.64573	.64154	.64411
63	2.37454	.63174	.63759	.63433	.63524
64	2.27798	.61437	.61609	.61426	.61135
65	1.58933	.47479	.46274	.46482	.46510
66	1.44365	.43632	.43030	.43148	.43896
67	2.26221	.60972	.61258	.61097	.60754
68	2.37059	.63938	.63671	.63351	.63425

APPENDIX F

APPENDIX F

Experimental Data of Moisture Losses from Individual Peeled Jonathan Apples.

Sample Nº	Environmental Conditions: T °F	RH Dec.	VPD $\frac{lbf}{ft^2}$	Air Vel. $\frac{ft}{hr}$	Product Parameters: $D_e=\sqrt{A/\pi}$ (ft^2)	Planimeter Area A (ft^2)	Aver. Surf. Temp. °F	RML lbm/hr	h'_d $\frac{lbm}{hr\text{-}ft^2 \frac{lbf}{ft^2}}$	Re_{D_e}	Sh
1	70	.750	7.15	23,400	.247	.19201	66.5	.0063955	.00466	9821	53.98
2	70	.625	9.08	23,400	.229	.16451	63.5	.0076940	.00515	9091	55.05
3	70	.500	12.10	23,400	.241	.18264	61.0	.0116798	.00529	9579	59.42
4	70	.750	7.15	18,000	.219	.15104	66.5	.0043269	.00400	6701	41.18
5	70	.625	9.82	18,000	.248	.19340	64.0	.0082363	.00434	7582	50.29
6	70	.500	13.47	18,000	.254	.20229	62.0	.0126293	.00463	7755	54.87
7	70	.750	7.15	12,600	.248	.19292	66.5	.0047244	.00343	5301	39.78
8	70	.625	9.82	12,600	.244	.18646	64.0	.0064043	.00350	5211	39.83
9	70	.500	13.47	12,600	.229	.16493	62.0	.0069728	.00314	4901	33.55
10	70	.750	7.95	5,400	.222	.15514	67.0	.0027777	.00225	2037	23.44
11	70	.625	11.33	5,400	.256	.20507	65.0	.0062598	.00269	2342	32.21
12	70	.500	15.62	5,400	.222	.15521	63.5	.0059016	.00243	2038	25.28

APPENDIX G

APPENDIX G

Experimental Data of Moisture Losses from Individual Peeled Manona Potatoes.

Sample Nº	Environmental Conditions T °F	RH Dec.	VPD $\frac{lbf}{ft^2}$	Air Vel. $\frac{ft}{hr}$	Product Parameters $D_e = \sqrt{A/\pi}$ (ft²)	Planimeter Area A (ft²)	Aver. Surf. Temp. °F	RML lbm/hr	h'd $\frac{lbm}{hr\text{-}ft^2 \frac{lbf}{ft^2}}$	Re_{De}	Sh
1	70	.750	7.15	23,400	.236	.17472	66.5	.0057099	.00457	9369	50.52
2	70	.625	9.08	23,400	.246	.19056	63.5	.0080129	.00461	9784	53.27
3	70	.500	13.47	23,400	.247	.19167	62.0	.0088624	.00343	9813	39.55
4	70	.750	7.15	18,000	.245	.18819	66.5	.0053571	.00398	7479	45.67
5	70	.625	9.82	18,000	.251	.19757	64.0	.0070988	.00366	7663	42.89
6	70	.500	14.18	18,000	.218	.14986	62.5	.0074956	.00353	6674	35.97
7	70	.750	7.15	12,600	.242	.18403	66.5	.0041005	.00316	5177	35.35
8	70	.625	10.57	12,600	.225	.15882	64.5	.0054453	.00324	4810	34.10
9	70	.500	14.18	12,600	.241	.18208	62.5	.0082672	.00320	5148	35.99
10	70	.750	7.96	5,400	.227	.16167	67.0	.0028219	.00219	2080	23.33
11	70	.625	11.33	5,400	.234	.17132	65.0	.0038801	.00200	2141	21.84
12	70	.500	15.62	5,400	.226	.15993	63.5	.0042659	.00170	2068	18.00

APPENDIX H

APPENDIX H

Experimental Data of Moisture Losses from Individual Peeled US H20 Sugar Beets.

Sample Nº	Environmental Conditions				Product Parameters		Aver. Surf. Temp. °F	RML lbm/hr	h'_d $\frac{lbm}{hr\text{-}ft^2 \frac{lbf}{ft^2}}$	Re_L	Sh
	T °F	RH Dec.	VPD $\frac{lbf}{ft^2}$	Air Vel. $\frac{ft}{hr}$	L (ft^2)	Planimeter Area A (ft^2)					
1	70	.750	7.15	23,400	.843	64.40	66.5	.013492	.00422	33501	166.77
2	70	.625	9.82	23,400	.672	79.78	64.0	.022707	.00417	26707	131.15
3	70	.500	13.47	23,400	.767	88.07	62.0	.031996	.00388	30486	139.04
4	70	.750	7.15	18,000	.705	68.15	66.5	.012500	.00369	21560	122.16
5	70	.625	9.82	18,000	.706	89.90	64.0	.017454	.00285	21580	94.00
6	70	.500	14.18	18,000	.868	79.33	62.5	.023207	.00297	26528	120.44
7	70	.750	7.15	12,600	.824	71.30	66.5	.008907	.00252	17620	97.13
8	70	.625	10.57	12,600	.769	98.96	64.5	.017791	.00245	16449	88.08
9	70	.500	14.18	12,600	.633	70.90	62.5	.017681	.00253	13555	74.93
10	70	.750	7.15	5,400	.705	79.70	66.5	.006129	.00155	6470	51.22
11	70	.625	10.57	5,400	1,138	111.31	64.5	.012103	.00148	10438	78.88
12	70	.500	15.62	5,400	.747	101.93	63.5	.017769	.00161	6851	56.12

APPENDIX I

APPENDIX I

Experimental Data on Moisture Losses for Determining the Skin Parameters of Jonathan Apples.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 75%
Air Velocity = 9000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RML (lbm/hr)	$h'_{d\,app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$
1	.298115	.17159	12.97	2.61675×10^{-5}	1.17563×10^{-5}
2	.328404	.18480	12.96	3.00791×10^{-5}	1.25556×10^{-5}
3	.279610	.16353	12.97	2.57323×10^{-5}	1.21326×10^{-5}
4	.325890	.18370	12.98	2.53637×10^{-5}	1.06373×10^{-5}
5	.248353	.14990	12.96	2.58343×10^{-5}	1.32962×10^{-5}
6	.264510	.15695	12.96	2.60625×10^{-5}	1.28081×10^{-5}
7	.350979	.19464	12.97	2.85030×10^{-5}	1.12878×10^{-5}
8	.276850	.16232	12.96	2.68024×10^{-5}	1.27361×10^{-5}
Averages	.296588	.17093	12.97	2.69431×10^{-5}	1.21513×10^{-5}

APPENDIX I

Experimental Data on Moisture Losses for Determining the Skin Parameters of Jonathan Apples.

Environmental Conditions: Temperature = 70 ^oF
Relative Humidity = 75%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RML (lbm/hr)	h'_d app $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$
1	.247901	.14971	12.97	1.92734×10^{-5}	$.99281 \times 10^{-5}$
2	.261168	.15549	12.93	2.70236×10^{-5}	1.34415×10^{-5}
3	.311190	.17729	12.94	2.68425×10^{-5}	1.16963×10^{-5}
4	.288935	.16759	12.94	2.57327×10^{-5}	1.18620×10^{-5}
5	.306042	.17505	12.96	2.36739×10^{-5}	1.04365×10^{-5}
6	.248735	.15007	12.95	2.33175×10^{-5}	1.20023×10^{-5}
7	.320635	.18141	12.95	2.51437×10^{-5}	1.06989×10^{-5}
8	.286400	.16649	12.96	2.21005×10^{-5}	1.02413×10^{-5}
Averages	.283882	.16539	12.95	2.41385×10^{-5}	1.12884×10^{-5}

APPENDIX I

Experimental Data on Moisture Losses for Determining the Skin Parameters of Jonathan Apples.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 75%
Air Velocity = 3000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RML (lbm/hr)	h'_d app $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.364559	.20056	12.93	2.25127×10^{-5}	$.86843 \times 10^{-5}$
2	.295558	.17048	12.90	2.26336×10^{-5}	1.02881×10^{-5}
3	.343779	.19150	12.91	2.47198×10^{-5}	1.00024×10^{-5}
4	.266770	.15793	12.90	2.12625×10^{-5}	2.12625×10^{-5}
5	.327116	.18424	12.92	2.19143×10^{-5}	$.92065 \times 10^{-5}$
6	.320031	.18115	12.92	2.17673×10^{-5}	$.93015 \times 10^{-5}$
7	.274310	.16122	12.91	2.15135×10^{-5}	1.03398×10^{-5}
8	.292213	.16902	12.90	2.34625×10^{-5}	1.07630×10^{-5}
Averages	.310541	.17702	12.92	2.24733×10^{-5}	$.98773 \times 10^{-5}$

APPENDIX I

Experimental Data on Moisture Losses for determining the Skin Parameters of Jonathan Apples.

Environmental Conditions: Temperature 70 ^{o}F
Relative Humidity = 62.5%
Air Velocity = 9000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD. (lbf/ft^2)	RML (lbm/hr)	h'd app $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.316049	.17941	19.45	$4.24489x10^{-5}$	$1.21639x10^{-5}$
2	.281393	.16430	19.46	$3.67765x10^{-5}$	$1.15012x10^{-5}$
3	.332981	.18679	19.46	$4.12458x10^{-5}$	$1.13468x10^{-5}$
4	.306415	.17521	19.47	$3.59306x10^{-5}$	$1.05314x10^{-5}$
5	.284810	.16579	19.47	$3.40308x10^{-5}$	$1.05405x10^{-5}$
6	.279039	.16328	19.47	$3.44316x10^{-5}$	$1.08304x10^{-5}$
7	.317154	.17989	19.47	$3.81393x10^{-5}$	$1.08908x10^{-5}$
8	.311074	.17724	19.46	$4.04683x10^{-5}$	$1.17348x10^{-5}$
Averages	.303614	.17399	19.46	$3.79340x10^{-5}$	$1.11925x10^{-5}$

APPENDIX I

Experimental Data Moisture Losses for Determining the Skin Parameters of Jonathan Apples.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 62.5%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RML (lbm/hr)	h'_d app $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.296517	.17090	19.43	3.58345×10^{-5}	1.07900×10^{-5}
2	.297619	.17138	19.44	3.38103×10^{-5}	1.01467×10^{-5}
3	.312346	.17780	19.45	3.24233×10^{-5}	$.93737 \times 10^{-5}$
4	.338228	.18908	19.42	4.24324×10^{-5}	1.15577×10^{-5}
5	.267592	.15829	19.45	3.09844×10^{-5}	1.00657×10^{-5}
6	.325617	.18358	19.42	4.02838×10^{-5}	1.12981×10^{-5}
7	.292019	.16894	19.44	3.35698×10^{-5}	1.02204×10^{-5}
8	.277601	.16265	19.43	3.53936×10^{-5}	1.12006×10^{-5}
Averages	.300942	.17288	19.44	3.55915×10^{-5}	1.05816×10^{-5}

APPENDIX I

Experimental Data Moisture Losses for Determining the Skin Parameters of Jonathan Apples.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 62.5%
Air Velocity = 3000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RML (lbm/hr)	h'd app $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.229832	.14183	19.39	2.48538×10^{-5}	$.90352 \times 10^{-5}$
2	.300340	.17256	19.37	3.26004×10^{-5}	$.97537 \times 10^{-5}$
3	.218364	.13683	19.39	2.45521×10^{-5}	$.92534 \times 10^{-5}$
4	.266735	.15792	19.37	3.08410×10^{-5}	1.00846×10^{-5}
5	.257125	.15373	19.38	2.80098×10^{-5}	$.94001 \times 10^{-5}$
6	.256116	.15329	19.42	2.35585×10^{-5}	$.79147 \times 10^{-5}$
7	.239751	.14615	19.39	2.64318×10^{-5}	$.93287 \times 10^{-5}$
8	.267465	.15823	19.37	2.98663×10^{-5}	$.97428 \times 10^{-5}$
Averages	.254466	.15257	19.39	2.75892×10^{-5}	$.93141 \times 10^{-5}$

APPENDIX I

Experimental Data Moisture Losses for Determining the Skin Parameters of Jonathan Apples.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 50%
Air Velocity = 9000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RML (lbm/hr)	$h'_{d\ app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.279610	.16353	26.00	3.49643×10^{-5}	$.82222 \times 10^{-5}$
2	.321221	.18167	26.01	3.63287×10^{-5}	$.76882 \times 10^{-5}$
3	.292546	.16917	26.01	3.41727×10^{-5}	$.77661 \times 10^{-5}$
4	.294526	.17004	25.99	3.85324×10^{-5}	$.87175 \times 10^{-5}$
5	.302372	.17345	25.99	3.81296×10^{-5}	$.84555 \times 10^{-5}$
6	.287405	.16693	26.00	3.47321×10^{-5}	$.80003 \times 10^{-5}$
7	.283316	.16514	25.99	3.75437×10^{-5}	$.87457 \times 10^{-5}$
8	.295481	.17045	26.00	3.54727×10^{-5}	$.80023 \times 10^{-5}$
Averages	.294560	.17005	26.00	3.62345×10^{-5}	$.81997 \times 10^{-5}$

APPENDIX I

Experimental Data Moisture Losses for Determining the Skin Parameters of Jonathan Apples.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 50%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RML (lbm/hr)	$h'_{d\ app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.336832	.18847	25.96	3.95436×10^{-5}	$.80808\times10^{-5}$
2	.283948	.16542	25.97	3.44273×10^{-5}	$.80137\times10^{-5}$
3	.303347	.17388	25.97	3.48373×10^{-5}	$.77132\times10^{-5}$
4	.274894	.16147	25.98	3.13995×10^{-5}	$.74843\times10^{-5}$
5	.278331	.16297	25.96	3.49225×10^{-5}	$.82526\times10^{-5}$
6	.299880	.17236	25.98	3.25737×10^{-5}	$.72729\times10^{-5}$
7	.310990	.17721	25.97	3.53296×10^{-5}	$.76752\times10^{-5}$
8	.310830	.17714	25.97	3.54842×10^{-5}	$.77120\times10^{-5}$
Averages	.299882	.17237	25.98	3.48147×10^{-5}	$.77756\times10^{-5}$

APPENDIX I

Experimental Data Moisture Losses for Determining the Skin Parameters of Jonathan Apples.

Environmental Conditions: Temperature = 70 ^{o}F
Relative Humidity = 50%
Air Velocity = 3000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RML (lbm/hr)	h'_d app $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.303993	.17416	25.89	$3.41002x10^{-5}$	$.75611x10^{-5}$
2	.351770	.19498	25.90	$3.63922x10^{-5}$	$.72060x10^{-5}$
3	.312317	.17779	25.93	$2.95323x10^{-5}$	$.64056x10^{-5}$
4	.308851	.17627	25.91	$3.15627x10^{-5}$	$.69092x10^{-5}$
5	.295093	.17028	25.91	$3.05274x10^{-5}$	$.69173x10^{-5}$
6	.313064	.17811	25.92	$3.01743x10^{-5}$	$.65341x10^{-5}$
7	.331140	.18599	25.92	$3.17342x10^{-5}$	$.65816x10^{-5}$
8	.324129	.18293	25.91	$3.33328x10^{-5}$	$.70326x10^{-5}$
Averages	.317545	.18006	25.92	$3.21695x10^{-5}$	$.68934x10^{-5}$

APPENDIX J

APPENDIX J

Experimental Data on Moisture Losses for Determining a $r\delta$ -VPD Relationship for Jonathan Apples.

Environmental Conditions: Temperature = 50 °F
Relative Humidity = 75%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	$h'_{d\ app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.33207	.18640	6.37	.01114	1.61443×10^{-5}	1.35894×10^{-5}
2	.29007	.16809	6.37	.00830	1.72032×10^{-5}	1.60738×10^{-5}
3	.25849	.15432	6.37	.01101	1.37179×10^{-5}	1.39464×10^{-5}
4	.29412	.16985	6.37	.01340	1.33209×10^{-5}	1.22970×10^{-5}
5	.31490	.17891	6.37	.01225	1.47335×10^{-5}	1.29166×10^{-5}
6	.34683	.19283	6.37	.01162	1.62453×10^{-5}	1.32168×10^{-5}
7	.31498	.17895	6.37	.01031	1.62437×10^{-5}	1.42458×10^{-5}
8	.32181	.18193	6.37	.01094	1.59537×10^{-5}	1.37596×10^{-5}
Averages	.30916	.17641	6.37	.01112	1.54453×10^{-5}	1.37556×10^{-5}

APPENDIX J

Experimental Data on Moisture Losses for Determining a $r\delta$ -VPD Relationship for Jonathan Apples.

Environmental Conditions: Temperature = 60 °F
Relative Humidity = 75%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	h'_d app $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.29210	.16897	9.15	.01347	1.90634×10^{-5}	1.23204×10^{-5}
2	.29246	.16913	9.16	.01488	1.79372×10^{-5}	1.15764×10^{-5}
3	.33691	.18851	9.15	.01458	2.00546×10^{-5}	1.16144×10^{-5}
4	.30234	.17344	9.17	.01893	1.56681×10^{-5}	$.98506 \times 10^{-5}$
5	.29168	.16879	9.16	.01607	1.70427×10^{-5}	1.10175×10^{-5}
6	.27750	.16261	9.15	.01410	1.79000×10^{-5}	1.20181×10^{-5}
7	.28726	.16686	9.16	.01838	1.54213×10^{-5}	1.00787×10^{-5}
8	.27120	.15986	9.15	.01216	1.92702×10^{-5}	1.31694×10^{-5}
Averages	.29383	.16977	9.15	.01532	1.76697×10^{-5}	1.14557×10^{-5}

APPENDIX J

Experimental Data on Moisture Losses for Determining a $r\delta$ -VPD Relationship for Jonathan Apples.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 75%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	$h'_{d\ app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.24790	.14971	12.97	.01915	1.92734×10^{-5}	$.99281 \times 10^{-5}$
2	.26116	.15549	12.93	.01187	2.70236×10^{-5}	1.34415×10^{-5}
3	.31119	.17729	12.94	.01464	2.68425×10^{-5}	1.16963×10^{-5}
4	.28893	.16759	12.94	.01443	2.57327×10^{-5}	1.18620×10^{-5}
5	.30604	.17505	12.96	.01749	2.36739×10^{-5}	1.04363×10^{-5}
6	.24873	.15007	12.95	.01438	2.33175×10^{-5}	1.20023×10^{-5}
7	.32063	.18141	12.95	.01677	2.51437×10^{-5}	1.06989×10^{-5}
8	.28640	.16649	12.96	.01809	2.21005×10^{-5}	1.02413×10^{-5}
Averages	.28388	.16539	12.95	.01585	2.41385×10^{-5}	1.12883×10^{-5}

APPENDIX J

Experimental Data or Moisture Losses for Determining a $r\delta$ -VPD Relationship for Jonathan Apples.

Environmental Conditions: Temperature = 60 °F
Relative Humidity = 62.5%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	h'_d app $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.32519	.18340	13.75	.01646	2.71650×10^{-5}	1.07744×10^{-5}
2	.29163	.16877	13.76	.02061	2.16025×10^{-5}	$.93016\times10^{-5}$
3	.29185	.16886	13.75	.01796	2.37636×10^{-5}	1.02324×10^{-5}
4	.32406	.18290	13.75	.01898	2.46374×10^{-5}	$.97926\times10^{-5}$
5	.34076	.19018	13.74	.01522	2.95163×10^{-5}	1.12938×10^{-5}
6	.28660	.16658	13.76	.01899	2.25897×10^{-5}	$.98577\times10^{-5}$
7	.27915	.16332	13.74	.01429	2.67379×10^{-5}	1.19152×10^{-5}
8	.28125	.16424	13.75	.01863	2.25907×10^{-5}	$.99992\times10^{-5}$
Averages	.30256	.17353	13.75	.01764	2.48254×10^{-5}	1.03959×10^{-5}

APPENDIX J

Experimental Data on Moisture Losses for Determining a $r\delta$-VPD Relationship for Jonathan Apples.

Environmental Conditions: Temperature = 80 ^{o}F
Relative Humidity = 75%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	$h'_{d\ app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.30730	.17560	18.03	.01656	3.43924×10^{-5}	1.08608×10^{-5}
2	.29857	.17179	18.04	.01761	3.23882×10^{-5}	1.04495×10^{-5}
3	.34006	.18988	18.04	.01798	3.50144×10^{-5}	1.02203×10^{-5}
4	.31058	.17703	18.03	.01624	3.50856×10^{-5}	1.09920×10^{-5}
5	.27755	.13739	18.02	.01442	3.00001×10^{-5}	1.21174×10^{-5}
6	.35026	.19433	18.05	.02026	3.30246×10^{-5}	$.94108 \times 10^{-5}$
7	.31628	.17951	18.06	.02048	3.04637×10^{-5}	$.93960 \times 10^{-5}$
8	.31508	.17899	18.02	.01550	3.64972×10^{-5}	1.13133×10^{-5}
Averages	.01738	.31446	18.04	.01738	3.33582×10^{-5}	1.05950×10^{-5}

APPENDIX J

Experimental Data on Moisture Losses for Determining a $r\delta$-VPD Relationship for Jonathan Apples.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 62.5%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	h'_d app $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.29652	.17090	19.43	.01668	3.58345×10^{-5}	1.07900×10^{-5}
2	.29762	.17138	19.44	.01828	3.38103×10^{-5}	1.01467×10^{-5}
3	.31235	.17780	19.45	.02043	3.24233×10^{-5}	$.93737 \times 10^{-5}$
4	.33823	.18908	19.42	.01478	4.24324×10^{-5}	1.15577×10^{-5}
5	.26759	.15829	19.45	.01866	3.09844×10^{-5}	1.00657×10^{-5}
6	.32562	.18358	19.42	.01539	4.02838×10^{-5}	1.12981×10^{-5}
7	.29202	.16894	19.44	.01872	3.35698×10^{-5}	1.02204×10^{-5}
8	.27760	.16295	19.43	.01585	3.53936×10^{-5}	1.12006×10^{-5}
Averages	.30094	.17288	19.44	.01727	3.55915×10^{-5}	1.05816×10^{-5}

APPENDIX J

Experimental Data on Moisture Losses for Determining a $r\delta$ -VPD Relationship for Jonathan Apples.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 50%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	$h'_{d\,app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.336832	.18847	25.97	.02498	3.95436×10^{-5}	$.80808\times10^{-5}$
2	.283948	.16542	25.97	.02553	3.44283×10^{-5}	$.80137\times10^{-5}$
3	.303347	.17388	25.97	.02676	3.48373×10^{-5}	$.77132\times10^{-5}$
4	.274894	.16297	25.98	.02800	3.13995×10^{-5}	$.74843\times10^{-5}$
5	.278331	.16297	25.96	.02458	3.49225×10^{-5}	$.82526\times10^{-5}$
6	.299880	.17236	25.98	.02893	3.25737×10^{-5}	$.72729\times10^{-5}$
7	.310990	.17721	25.97	.02690	3.53296×10^{-5}	$.76752\times10^{-5}$
8	.310830	.17714	25.97	.02673	3.54842×10^{-5}	$.77120\times10^{-5}$
Averages	.299881	.17237	25.97	.02655	3.48147×10^{-5}	$.77756\times10^{-5}$

APPENDIX K

APPENDIX K

Experimental Data on Moisture Losses for Determining Skin Parameters of Manona Potatoes.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 75%
Air Velocity = 9000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RML (lbm/hr)	$h'_{d\ app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.42210	.17160	12.96	2.69350×10^{-5}	1.21031×10^{-5}
2	.35317	.15264	12.97	2.26289×10^{-5}	1.14243×10^{-5}
3	.37185	.15576	12.97	2.41635×10^{-5}	1.19591×10^{-5}
4	.38504	.16236	12.97	2.40500×10^{-5}	1.14158×10^{-5}
5	.42108	.16979	12.96	2.79360×10^{-5}	1.26936×10^{-5}
6	.32361	.14028	12.97	2.24467×10^{-5}	1.23363×10^{-5}
7	.41520	.17097	12.97	2.47059×10^{-5}	1.11354×10^{-5}
8	.38532	.16090	12.98	2.21734×10^{-5}	1.01332×10^{-5}
Averages	.38467	.16054	12.97	2.43799×10^{-5}	1.16501×10^{-5}

APPENDIX K

Experimental Data on Moisture Losses for Determining Skin Parameters of Manona Potatoes.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 75%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2	VPD (lbf/ft^2)	RML (lbm/hr)	$h'_{d\ app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.40452	.16417	12.97	2.09344×10^{-5}	$.98346 \times 10^{-5}$
2	.38858	.16347	12.95	2.38678×10^{-5}	1.12737×10^{-5}
3	.36351	.15618	12.96	2.12321×10^{-5}	1.04894×10^{-5}
4	.45542	.18014	12.96	2.27788×10^{-5}	$.97532 \times 10^{-5}$
5	.49647	.19201	12.96	2.63543×10^{-5}	1.05951×10^{-5}
6	.31164	.13938	12.95	2.05336×10^{-5}	1.13728×10^{-5}
7	.34183	.14861	12.96	1.90430×10^{-5}	$.98815 \times 10^{-5}$
8	.41169	.16451	12.96	2.25723×10^{-5}	1.05886×10^{-5}
Averages	.39671	.16356	12.96	2.21645×10^{-5}	1.04736×10^{-5}

APPENDIX K

Experimental Data on Moisture Losses for Determining Skin Parameters of Manona Potatoes.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 75%
Air Velocity = 3000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RML (lbm/hr)	$h'_{d\,app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.34633	.15160	12.94	1.67391×10^{-5}	$.85358 \times 10^{-5}$
2	.35826	.15056	12.92	1.88246×10^{-5}	$.96787 \times 10^{-5}$
3	.41276	.16875	12.92	2.01372×10^{-5}	$.92350 \times 10^{-5}$
4	.29534	.13444	12.95	1.31436×10^{-5}	$.75471 \times 10^{-5}$
5	.45474	.18000	12.95	1.75432×10^{-5}	$.75276 \times 10^{-5}$
6	.36468	.15722	12.94	1.65372×10^{-5}	$.81280 \times 10^{-5}$
7	.45970	.17778	12.94	1.80264×10^{-5}	$.78343 \times 10^{-5}$
8	.50337	.19299	12.92	2.27362×10^{-5}	$.91187 \times 10^{-5}$
Averages	.39939	.16417	12.94	1.79609×10^{-5}	$.84507 \times 10^{-5}$

APPENDIX K

Experimental Data on Moisture Losses for Determining Skin Parameters of Manona Potatoes.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 62.5%
Air Velocity = 9000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RLM (lbm/hr)	$h'_{d\ app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.50309	.19535	19.47	3.86742×10^{-5}	1.01659×10^{-5}
2	.49877	.19306	19.48	3.58436×10^{-5}	$.95295 \times 10^{-5}$
3	.47399	.18854	19.47	3.61473×10^{-5}	$.98424 \times 10^{-5}$
4	.43660	.17868	19.48	3.34237×10^{-5}	$.96008 \times 10^{-5}$
5	.38409	.16069	19.47	3.28725×10^{-5}	1.05042×10^{-5}
6	.32558	.14785	19.47	2.99328×10^{-5}	1.03937×10^{-5}
7	.40178	.16618	19.48	3.02726×10^{-5}	$.93474 \times 10^{-5}$
8	.50450	.19424	19.47	3.71373×10^{-5}	$.98154 \times 10^{-5}$
Averages	.44105	.17807	19.47	3.42880×10^{-5}	$.98999 \times 10^{-5}$

APPENDIX K

Experimental Data on Moisture Losses for Determining Skin Parameters of Manona Potatoes.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 62.5%
Air velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RML (lbm/hr)	$h'_{d\,app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.61662	.21250	19.45	3.80328×10^{-5}	$.92012 \times 10^{-5}$
2	.49985	.19222	19.45	3.44273×10^{-5}	$.92063 \times 10^{-5}$
3	.47729	.18250	19.47	2.94736×10^{-5}	$.82944 \times 10^{-5}$
4	.57167	.20278	19.46	3.37362×10^{-5}	$.85476 \times 10^{-5}$
5	.41934	.17222	19.45	3.12724×10^{-5}	$.93332 \times 10^{-5}$
6	.44053	.17465	19.45	3.27473×10^{-5}	$.96400 \times 10^{-5}$
7	.56038	.19972	19.46	3.41246×10^{-5}	$.87800 \times 10^{-5}$
8	.44846	.17535	19.46	2.90001×10^{-5}	$.84949 \times 10^{-5}$
Averages	.50426	.18899	19.46	3.28518×10^{-5}	$.89372 \times 10^{-5}$

APPENDIX K

Experimental Data on Moisture Losses for Determining Skin Parameters of Manona Potatoes.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 62.5%
Air Velocity = 3000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RML (lbm/hr)	$h'_{d\ app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.33165	.14326	19.41	2.25796×10^{-5}	$.81178\times10^{-5}$
2	.44098	.17361	19.44	2.39734×10^{-5}	$.71060\times10^{-5}$
3	.26546	.12799	19.43	1.95518×10^{-5}	$.78639\times10^{-5}$
4	.46362	.18312	19.44	2.45543×10^{-5}	$.68990\times10^{-5}$
5	.43229	.17153	19.41	2.72208×10^{-5}	$.81770\times10^{-5}$
6	.45419	.17715	19.42	2.63665×10^{-5}	$.76648\times10^{-5}$
7	.30708	.13653	19.41	2.23497×10^{-5}	$.84336\times10^{-5}$
8	.40690	.16660	19.43	2.31724×10^{-5}	$.71575\times10^{-5}$
Averages	.38777	.15997	19.42	2.37210×10^{-5}	$.76774\times10^{-5}$

APPENDIX K

Experimental Data on Moisture Losses for Determining Skin Parameters of Manona Potatoes.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 50%
Air Velocity = 9000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RLM (lbm/hr	$h'_{d\ app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.40178	.16181	26.00	3.35715×10^{-5}	$.79773\times10^{-5}$
2	.36864	.14931	26.00	3.22725×10^{-5}	$.83117\times10^{-5}$
3	.42372	.16979	26.00	3.46775×10^{-5}	$.78525\times10^{-5}$
4	.39629	.16146	26.00	3.48372×10^{-5}	$.82976\times10^{-5}$
5	.42870	.16979	25.99	3.82477×10^{-5}	$.86655\times10^{-5}$
6	.35344	.14722	26.00	3.29737×10^{-5}	$.86143\times10^{-5}$
7	.38927	.15486	26.01	3.02773×10^{-5}	$.75148\times10^{-5}$
8	.42457	.16528	26.00	3.59486×10^{-5}	$.83650\times10^{-5}$
Averages	.39830	.15994	26.00	3.41008×10^{-5}	$.81998\times10^{-5}$

APPENDIX K

Experimental Data on Moisture Losses for Determining Skin Parameters of Manona Potatoes.

Environmental Conditions: Temperature = 70 ^{o}F
Relative Humidity = 50%
Air Velocity = 6000 ft/ht

Sample Nº	Weight W_6 (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RLM (lbm/hr)	$h'_{d\ app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.33540	.14271	25.96	3.21154×10^{-5}	$.86680 \times 10^{-5}$
2	.34249	.15069	25.98	2.99949×10^{-5}	$.76614 \times 10^{-5}$
3	.41934	.16528	25.97	3.25814×10^{-5}	$.75878 \times 10^{-5}$
4	.35841	.15104	25.98	3.00573×10^{-5}	$.76596 \times 10^{-5}$
5	.37767	.15326	25.99	2.77132×10^{-5}	$.69561 \times 10^{-5}$
6	.42278	.16722	25.97	3.49288×10^{-5}	$.80433 \times 10^{-5}$
7	.35261	.14806	25.99	2.66347×10^{-5}	$.69197 \times 10^{-5}$
8	.32579	.14208	25.97	2.98910×10^{-5}	$.80998 \times 10^{-5}$
Averages	.36681	.15254	25.98	3.04896×10^{-5}	$.76994 \times 10^{-5}$

APPENDIX K

Experimental Data on Moisture Losses for Determining Skin Parameters of Manona Potatoes.

Environmental Conditions: Temperature 70 ^oF
Relative Humidity = 50%
Air Velocity = 3000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	RML (lbm/hr)	$h'_{d\,app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.39405	.16403	25.92	2.93696×10^{-5}	$.69080 \times 10^{-5}$
2	.42709	.17354	25.93	2.94443×10^{-5}	$.65438 \times 10^{-5}$
3	.35139	.14882	25.92	2.74639×10^{-5}	$.71207 \times 10^{-5}$
4	.44861	.17861	25.93	3.06400×10^{-5}	$.66171 \times 10^{-5}$
5	.49125	.19069	25.92	3.36293×10^{-5}	$.68050 \times 10^{-5}$
6	.32541	.14257	25.96	2.16642×10^{-5}	$.58539 \times 10^{-5}$
7	.31743	.13958	25.97	2.04863×10^{-5}	$.56527 \times 10^{-5}$
8	.42987	.17340	25.96	2.69104×10^{-5}	$.59813 \times 10^{-5}$
Averages	.39814	.16391	25.95	2.74510×10^{-5}	$.64353 \times 10^{-5}$

APPENDIX L

APPENDIX L

Experimental Data on Moisture Losses for Determining a $r\delta$ -VPD Relationship for Manona Potatoes.

Environmental Conditions: Temperature = 50 °F
Relative Humidity = 75%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	h'_d app $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.37112	.15597	6.37	.00244	1.55024×10^{-5}	1.56054×10^{-5}
2	.33761	.14667	6.37	.00305	1.40232×10^{-5}	1.50063×10^{-5}
3	.32974	.14757	6.37	.00500	1.21893×10^{-5}	1.29529×10^{-5}
4	.28476	.13424	6.37	.00258	1.35736×10^{-5}	1.58742×10^{-5}
5	.35425	.14931	6.37	.00401	1.32168×10^{-5}	1.38869×10^{-5}
6	.41670	.16910	6.37	.00602	1.27736×10^{-5}	1.18416×10^{-5}
7	.37255	.15486	6.37	.00601	1.18637×10^{-5}	1.20092×10^{-5}
8	.42049	.16757	6.37	.00401	1.45390×10^{-5}	1.36118×10^{-5}
Averages	.36090	.15316	6.37	.00414	1.34602×10^{-5}	1.38485×10^{-5}

APPENDIX L

Experimental Data on Moisture Losses for Determining a $r\delta$ -VPD Relationship for Manona Potatoes.

Environmental Conditions: Temperature = 60 °F
Relative Humidity = 75%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	$h'_{d\ app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.37125	.15590	9.17	.00884	1.45324×10^{-5}	1.01652×10^{-5}
2	.41713	.16882	9.18	.01146	1.36649×10^{-5}	$.88205 \times 10^{-5}$
3	.30921	.13771	9.16	.00553	1.59273×10^{-5}	1.26287×10^{-5}
4	.36015	.15590	9.17	.00763	1.55453×10^{-5}	1.08783×10^{-5}
5	.42433	.17431	9.16	.00654	1.14260×10^{-5}	1.14260×10^{-5}
6	.35976	.15361	9.16	.00657	1.63482×10^{-5}	1.16156×10^{-5}
7	.42105	.17118	9.17	.00874	1.58492×10^{-5}	1.00974×10^{-5}
8	.34044	.14806	9.16	.00655	1.58686×10^{-5}	1.16974×10^{-5}
Averages	.37541	.15819	9.17	.00773	1.57479×10^{-5}	1.09161×10^{-5}

APPENDIX L

Experimental Data on Moisture Losses for Determining a $r\delta$ -VPD Relationship for Manona Potatoes.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 75%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	$h'_{d\,app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.40452	.16417	12.96	.00937	2.09344×10^{-5}	$.98346 \times 10^{-5}$
2	.38858	.16347	12.95	.00693	2.38678×10^{-5}	1.12737×10^{-5}
3	.36351	.15618	12.96	.00829	2.12321×10^{-5}	1.04984×10^{-5}
4	.45542	.18014	12.96	.00931	2.27788×10^{-5}	$.97532 \times 10^{-5}$
5	.49647	.19201	12.95	.00760	2.63543×10^{-5}	1.05951×10^{-5}
6	.31164	.13938	12.95	.00716	2.05336×10^{-5}	1.13728×10^{-5}
7	.34183	.14861	12.96	.00952	1.90430×10^{-5}	$.98815 \times 10^{-5}$
8	.41169	.16451	12.95	.00800	2.25723×10^{-5}	1.05886×10^{-5}
Averages	.44363	.16356	12.95	.00827	2.21645×10^{-5}	1.04736×10^{-5}

APPENDIX L

Experimental Data on Moisture Losses for Determining a $r\delta$ -VPD Relationship for Manona Potatoes.

Environmental Conditions: Temperature = 60 °F
Relative Humidity = 62.5%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	$h'_{d\,app}$ $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.39963	.16153	13.75	.00824	2.32258×10^{-5}	1.04555×10^{-5}
2	.35162	.15257	13.75	.00679	2.40640×10^{-5}	1.14751×10^{-5}
3	.48955	.18819	13.75	.00888	2.56255×10^{-5}	$.99001\times10^{-5}$
4	.29573	.13604	13.74	.00538	2.38920×10^{-5}	1.27852×10^{-5}
5	.40132	.16312	13.76	.00901	2.24726×10^{-5}	1.00153×10^{-5}
6	.35348	.15271	13.75	.00755	2.30082×10^{-5}	1.09582×10^{-5}
7	.36849	.15299	13.75	.00750	2.31187×10^{-5}	1.09910×10^{-5}
8	.38602	.16104	13.75	.00869	2.51626×10^{-5}	1.13637×10^{-5}
Averages	.38073	.15852	13.75	.00775	2.38153×10^{-5}	1.09930×10^{-5}

APPENDIX L

Experimental Data on Moisture Losses for Determining a $r\delta$ -VPD Relationship for Manona Potatoes.

Environmental Conditions: Temperature = 80 °F
Relative Humidity = 75%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	h'_d app $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.37086	.15646	18.07	.01056	2.63892×10^{-5}	$.93352 \times 10^{-5}$
2	.38110	.15979	18.07	.01210	2.50237×10^{-5}	$.86618 \times 10^{-5}$
3	.34376	.14792	18.06	.01037	2.53472×10^{-5}	$.94847 \times 10^{-5}$
4	.39995	.16243	18.08	.01308	2.43279×10^{-5}	$.82809 \times 10^{-5}$
5	.37734	.15625	18.08	.01281	2.37723×10^{-5}	$.84124 \times 10^{-5}$
6	.45681	.18035	18.08	.01269	2.71450×10^{-5}	$.83237 \times 10^{-5}$
7	.40425	.16576	18.07	.01181	2.61922×10^{-5}	$.87411 \times 10^{-5}$
8	.36957	.15375	18.07	.01166	2.46733×10^{-5}	$.88774 \times 10^{-5}$
Averages	.38795	.16034	18.07	.01189	2.53588×10^{-5}	$.87646 \times 10^{-5}$

APPENDIX L

Experimental Data on Moisture Losses for Determining a $r\delta$ -VPD Relationship for Manona Potatoes.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 62.5%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	h'_d app $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.61662	.21250	19.45	.01005	3.80328×10^{-5}	$.92012 \times 10^{-5}$
2	.49985	.19222	19.45	.01030	3.44273×10^{-5}	$.92063 \times 10^{-5}$
3	.47729	.18250	19.47	.01269	2.94736×10^{-5}	$.82944 \times 10^{-5}$
4	.57167	.20278	19.46	.01174	3.27362×10^{-5}	$.82922 \times 10^{-5}$
5	.41934	.17222	19.45	.01029	3.12724×10^{-5}	$.93332 \times 10^{-5}$
6	.44053	.17465	19.45	.00961	3.27473×10^{-5}	$.96400 \times 10^{-5}$
7	.56038	.19972	19.46	.01120	3.31246×10^{-5}	$.85209 \times 10^{-5}$
8	.44846	.17535	19.46	.01225	2.90001×10^{-5}	$.84949 \times 10^{-5}$
Averages	.50427	.18899	19.46	.01102	3.26018×10^{-5}	$.88729 \times 10^{-5}$

APPENDIX L

Experimental Data on Moisture Losses for Determining a $r\delta$ -VPD Realtionship for Manona Potatoes.

Environmental Conditions: Temperature = 70 °F
Relative Humidity = 50%
Air Velocity = 6000 ft/hr

Sample Nº	Weight W_o (lbm)	Area A (ft^2)	VPD (lbf/ft^2)	$r\delta$ (ft)	RML (lbm/hr)	h'_d app $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbm}{ft^2}}$
1	.33540	.14271	25.96	.01230	3.21154×10^{-5}	$.86680\times10^{-5}$
2	.34249	.15069	25.98	.01504	2.99949×10^{-5}	$.76614\times10^{-5}$
3	.41934	.16528	25.97	.01506	3.25814×10^{-5}	$.75878\times10^{-5}$
4	.35841	.15104	25.98	.01504	3.00573×10^{-5}	$.76596\times10^{-5}$
5	.37767	.15326	25.99	.01751	2.77132×10^{-5}	$.69561\times10^{-5}$
6	.42278	.16722	25.97	.01362	3.49288×10^{-5}	$.80433\times10^{-5}$
7	.35261	.14806	25.99	.01774	2.66347×10^{-5}	$.69197\times10^{-5}$
8	.32579	.14208	25.97	.01385	2.98910×10^{-5}	$.80998\times10^{-5}$
Averages	.36681	.15254	25.98	.01502	3.04896×10^{-5}	$.76994\times10^{-5}$

APPENDIX M

APPENDIX M

Experimental Data on Moisture Losses from Peeled and Unpeeled USH 20 Sugar Beets.

	Environmental Conditions			Product Characteristics					
Sample Nº	T °F	RH (decimal)	Air Vel. $(\frac{ft}{hr})$	L (ft)	Planimeter Area (ft^2)	Skin Nature	RML $\frac{lbm}{hr}$	h'_d $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	Effective Area γ_1 (Decimal)
1	70	.500	9,000	.771	.65993	unpeeled	.0075523	.0011905	.3066
						peeled	.0226521	.0038833	
2	70	.500	9,000	.848	.57708	unpeeled	.0070137	.0013750	.3424
						peeled	.0204850	.0040160	
3	70	.500	9,000	.846	.51542	unpeeled	.0058982	.0012503	.3600
						peeled	.0158245	.0034734	
4	70	.500	9,000	.808	.56562	unpeeled	.0079208	.0015843	.5716
						peeled	.0138580	.0027718	
5	70	.500	6,000	.811	.57049	unpeeled	.0060500	.0011998	.4448
						peeled	.0136013	.0026973	
6	70	.500	6,000	.725	.49007	unpeeled	.0055587	.0012832	.4742
						peeled	.0117218	.0027060	
7	70	.500	6,000	.722	.47187	unpeeled	.0044130	.0010319	.4473
						peeled	.0096230	.0023072	
8	70	.500	6,000	.644	.48056	unpeeled	.0048690	.0011463	.5441
						peeled	.0089490	.0021068	

APPENDIX M

Experimental Data on Moisture Losses from Peeled and Unpeeled US H20 Sugar Beets.

Sample Nº	Environmental Conditions T °F	RH Decimal	Air Vel. $\frac{ft}{hr}$	Product Characteristics L (ft)	Planimeter Area (ft^2)	Skin Nature	RML $\frac{lbm}{hr}$	h'_d $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	Effective Area η (Decimal)
9	70	.625	9,000	.640	.41722	unpeeled peeled	.0039359 .0087264	.0013596 .0030144	.4510
10	70	.625	9,000	.804	.50653	unpeeled peeled	.0056540 .0128269	.0016087 .0036496	.4408
11	70	.625	9,000	.804	.48889	unpeeled peeled	.0042122 .0099609	.0012417 .0029364	.4229
12	70	.625	9,000	.886	.79639	unpeeled peeled	.0053344 .0118065	.0007588 .0021366	.3551
13	70	.625	6,000	.809	.67549	unpeeled peeled	.0047325 .0112459	.0010097 .0023994	.4208
14	70	.625	6,000	.769	.60569	unpeeled peeled	.0047663 .0113561	.0011341 .0027021	.4197
15	70	.625	6,000	.849	.60201	unpeeled peeled	.0049831 .0095295	.0011930 .0022814	.5229
16	70	.625	6,000	.767	.73319	unpeeled peeled	.0038104 .0100831	.0007490 .0019820	.3779

APPENDIX M

Experimental Data on Moisture Losses from Peeled and Unpeeled USH 20 Sugar Beets.

Sample Nº	Environmental Conditions T °F	RH Decimal	Air Vel. $\left(\frac{ft}{hr}\right)$	Product Characteristics L (ft)	Planimeter Area (ft^2)	Skin Nature	RML $\frac{lbm}{hr}$	h'_d $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	Effective Area γ_1 (Decimal)
17	80	.750	9,000	.850	.56229	unpeeled	.0045194	.0015751	.3433
						peeled	.0131658	.0045887	
18	80	.750	9,000	1.010	.50896	unpeeled	.0046164	.0017775	.3660
						peeled	.0126124	.0048564	
19	80	.750	9,000	.730	.62174	unpeeled	.0051653	.0016281	.5676
						peeled	.0091005	.0028685	
20	80	.750	9,000	.868	.67750	unpeeled	.0040961	.0011632	.4757
						peeled	.0084524	.0024449	
21	80	.750	6,000	.887	.52437	unpeeled	.0047950	.0017920	.5065
						peeled	.0094665	.0035379	
22	80	.750	6,000	.804	.46194	unpeeled	.0029226	.0012398	.3628
						peeled	.0080556	.0034175	
23	80	.750	6,000	.771	.45188	unpeeled	.0038558	.0016722	.5026
						peeled	.0076720	.0033272	
24	80	.750	6,000	.644	.46701	unpeeled	.0037698	.0015820	.5659
						peeled	.0066623	.0027957	

APPENDIX M

Experimental Data on Moisture Losses from Peeled and Unpeeled USH 20 Sugar Beets.

Sample Nº	Environmental Conditions T °F	RH Decimal	Air Vel. $\frac{ft}{hr}$	Product Characteristics L (ft)	Planimeter Area (ft^2)	Skin Nature	RML $\frac{lbm}{hr}$	h'_d $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	Effective Area η_1 (Decimal)
25	60	.625	9,000	1.176	.67986	unpeeled	.0063331	.0016660	.3716
						peeled	.0170408	.0044829	
26	60	.625	9,000	1.260	.66431	unpeeled	.0042747	.0011509	.3066
						peeled	.0160362	.0043173	
27	60	.625	9,000	1.094	.61375	unpeeled	.0047540	.0013853	.3919
						peeled	.0121321	.0035353	
28	60	.625	9,000	1.176	.63993	unpeeled	.0043682	.0012208	.4280
						peeled	.0102066	.0028526	
29	60	.625	6,000	.890	.53868	unpeeled	.0038442	.0012763	.4577
						peeled	.0083982	.0027883	
30	60	.625	6,000	1.015	.65097	unpeeled	.0046410	.0012751	.4355
						peeled	.0106563	.0029277	
31	60	.625	6,000	.764	.48771	unpeeled	.0035591	.0013052	.4901
						peeled	.0072625	.0026633	
32	60	.625	6,000	.771	.53944	unpeeled	.0043440	.0014402	.5435
						peeled	.0079926	.0026498	

APPENDIX M

Experimental Data on Moisture Losses from Peeled and Unpeeled USH 20 Sugar Beets.

Sample Nº	Environmental Conditions T °F	RH Decimal	Air Vel. (ft/hr)	Product Characteristics L (ft)	Planimeter Area (ft^2)	Skin Nature	RML (lbm/hr)	h'_d $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	Effective Area η_1 (Decimal)
33	70	.750	9,000	.682	.47222	unpeeled	.0042360	.0022320	.3813
						peeled	.0111539	.0058528	
34	70	.750	9,000	.685	.50000	unpeeled	.0036350	.0018014	.3472
						peeled	.0104705	.0051880	
35	70	.750	9,000	.808	.55049	unpeeled	.0041038	.0018472	.4793
						peeled	.0085626	.0038542	
36	70	.750	9,000	.616	.47938	unpeeled	.0036732	.0018987	.5137
						peeled	.0071504	.0036961	
37	70	.750	6,000	.684	.45569	unpeeled	.0029943	.0016103	.5218
						peeled	.0057389	.0030862	
38	70	.750	6,000	.684	.46076	unpeeled	.0028789	.0015482	.4759
						peeled	.0060500	.0032536	
39	70	.750	6,000	.682	.45097	unpeeled	.0026008	.0014290	.4908
						peeled	.0052991	.0029115	
40	70	.750	6,000	.720	.43090	unpeeled	.0024751	.0014233	.5469
						peeled	.0045258	.0026025	

APPENDIX M

Experimental Data on Moisture Losses from Peeled and Unpeeled USH 20 Sugar Beets.

Sample Nº	Environmental Conditions: F °F	Environmental Conditions: RH Decimal	Environmental Conditions: Air Vel. $\frac{ft}{hr}$	Product Characteristics: L (ft)	Product Characteristics: Planimeter Area (ft^2)	Product Characteristics: Skin Nature	RML $\frac{lbm}{hr}$	h'_d $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	Effective Area η_1 (Decimal)
41	60	.750	9,000	.868	.55090	unpeeled	.0031015	.0015153	.2922
						peeled	.0106129	.0051850	
42	60	.750	9,000	.850	.56875	unpeeled	.0035198	.0016656	.3549
						peeled	.0099175	.0046932	
43	60	.750	9,000	.832	.55799	unpeeled	.0027532	.0013280	.3715
						peeled	.0074118	.0035751	
44	60	.750	9,000	.849	.57521	unpeeled	.0027721	.0012971	.4852
						peeled	.0057137	.0026735	
45	60	.750	6,000	1.054	.65000	unpeeled	.0030969	.0012823	.4325
						peeled	.0071605	.0029649	
46	60	.750	6,000	.930	.61201	unpeeled	.0024606	.0010821	.3536
						peeled	.0069589	.0030603	
47	60	.750	6,000	.808	.66431	unpeeled	.0028005	.0011346	.4817
						peeled	.0058132	.0023552	

APPENDIX M

Experimental Data on Moisture Losses from Peeled and Unpeeled USH 20 Sugar Beets.

Sample Nº	Environmental Conditions F °F	RH Decimal	Air Vel. (ft/hr)	Product Characteristics L (ft)	Planimeter Area (ft^2)	Skin Nature	RML (lbm/hr)	h'_d $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	Effective Area η_1 (Decimal)
48	60	.750	6,000	.771	.65993	unpeeled peeled	.0026575 .0054737	.0010838 .0022324	.4855
49	70	.875	9,000	.763	.46965	unpeeled peeled	.0020345 .0048148	.0019321 .0045723	.4226
50	70	.875	9,000	1.010	.50278	unpeeled peeled	.0016742 .0049361	.0014851 .0043786	.3392
51	70	.875	9,000	.909	.47556	unpeeled peeled	.0016900 .0034788	.0015849 .0032626	.4858
52	70	.875	9,000	.868	.43299	unpeeled peeled	.0015571 .0028172	.0016038 .0029017	.5527
53	50	.750	9,000	.772	.72931	unpeeled peeled	.0033455 .0103874	.0014841 .0046080	.3221
54	50	.750	9,000	.687	.69986	unpeeled peeled	.0030165 .0085500	.0013945 .0039526	.3528

APPENDIX M

Experimental Data on Moisture Losses from Peeled and Unpeeled USH 20 Sugar Beets.

	Environmental Conditions			Product Characteristics					
Sample Nº	F ^oF	RH Decimal	Air Vel. $\left(\frac{ft}{hr}\right)$	L (ft)	Planimeter Area (ft^2)	Skin Nature	RML $\frac{lbm}{hr}$	h'_d $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	Effective Area η_1 (Decimal)
55	50	.750	9,000	.566	.50646	unpeeled	.0026307	.0016806	.5062
						peeled	.0051972	.0033200	
56	50	.750	9,000	.786	.61444	unpeeled	.0022524	.0011314	.4090
						peeled	.0055071	.0027662	
57	50	.750	6,000	.683	.49604	unpeeled	.0024702	.0016112	.4326
						peeled	.0057099	.0037242	
58	50	.750	6,000	.723	.47028	unpeeled	.0021393	.0014718	.3934
						peeled	.0054387	.0037416	
59	50	.750	6,000	.852	.50403	unpeeled	.0022610	.0014513	.3768
						peeled	.0060009	.0038520	
60	50	.750	6,000	.804	.44424	unpeeled	.0019455	.0014169	.4013
						peeled	.0048479	.0035307	
61	60	.875	9,000	.927	.46424	unpeeled	.0017744	.0020988	.4482
						peeled	.0039588	.0046826	

APPENDIX M

Experimental Data on Moisture Losses from Peeled and Unpeeled USH 20 Sugar Beets.

Sample №	Environmental Conditions F °F	RH Decimal	Air Vel. $\left(\frac{ft}{hr}\right)$	Product Characteristics L (ft)	Planimeter Area (ft^2)	Skin Nature	RML $\frac{lbm}{hr}$	h'_d $\frac{lbm}{hr\text{-}ft^2\text{-}\frac{lbf}{ft^2}}$	Effective Area ϕ_1 (Decimal)
62	60	.875	9,000	.812	.63847	unpeeled. peeled	.0022288 .0049641	.0019169 .0042694	.4490
63	60	.875	9,000	.890	.63174	unpeeled peeled	.0016848 .0032678	.0014644 .0028404	.5156
64	60	.875	9,000	.649	.61437	unpeeled peeled	.0016316 .0029068	.0014583 .0025980	.5613
65	70	.625	9,000	1.170	.47479	unpeeled peeled	.0054187 .0134902	.0016448 .0040949	.4017
66	70	.625	9,000	.642	.43632	unpeeled peeled	.0040318 .0111243	.0013317 .0036745	.3624
67	70	.625	9,000	.862	.60972	unpeeled peeled	.0059692 .0130448	.0014110 .0030834	.4576
68	70	.625	9,000	.726	.63938	unpeeled peeled	.0050128 .0102973	.0009872 .0023211	.4253

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