To the Graduate Council:

I am submitting herewith a dissertation written by Linus Ross Walton, entitled "Moisture Diffusion in the Cured Burley Tobacco Leaf." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Agricultural Engineering.

Zachary A. Henry

Zachary A. Henry, Major Professor

We have read this dissertation
and recommend its acceptance:

John J. Madden

David L. Coffey

J. D. Thomison

Russell B. Stone

Accepted for the Council:

Hilton A. Smith

Vice Chancellor
Graduate Studies and Research

MOISTURE DIFFUSION IN THE CURED BURLEY TOBACCO LEAF

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee

Linus Ross Walton

December 1974

ACKNOWLEDGEMENTS

The author expresses his appreciation to the following people:

Dr. Z. A. Henry, Major Professor, Associate Professor, Department of Agricultural Engineering, whose guidance and encouragement were invaluable throughout the study.

Dr. W. H. Henson, Jr., Agricultural Engineer, ARS, USDA, Lexington, Kentucky, my supervisor, for his encouragement and guidance throughout my graduate program.

Dr. J. J. McDow, Dean of Admissions and Records, University of Tennessee, and Professor, Department of Agricultural Engineering; Dr. J. O. Thomson, Professor, Department of Physics; Dr. D. L. Coffey, Associate Professor, Department of Plant and Soil Science; and Mr. R. B. Stone, Jr., ARS, USDA, for serving on my faculty committee.

My wife, Sarah, for her encouragement throughout my graduate program and for helping to prepare specimens.

Dr. J. N. Walker, Professor and Head, Department of Agricultural Engineering, University of Kentucky, for his interest and suggestions throughout the course of my research.

Mr. T. C. Bridges, Mr. T. Collett, Mr. S. C. Key, and Mr. B. E. Plaster, whose efforts were beyond that necessary in the performance of their duties.

1175748

ABSTRACT

Mathematical models for the diffusion of moisture in the lamina and midrib portions of the cured burley tobacco leaf were developed and their applicability experimentally determined. The lamina and midrib were geometrically represented by the infinite thin sheet and the infinite circular cylinder, respectively. The models were based on the vapor diffusion equation and expressed the average lamina and midrib moisture content as a function of time in the form of an exponential series. Diffusion coefficients for application of the models were determined experimentally.

Sorption and desorption of the cured lamina and midrib were experimentally determined at temperatures of 55, 65, and 75°F to determine the applicability of the mathematical models. The exponential thin layer drying model was used as the standard of comparison. Specimens were conditioned at 44% relative humidity initially, then exposed to relative humidities of 75, 85, and 96% for sorption. After sorption, the specimens were exposed to the 44% relative humidity to obtain desorption data.

The results showed that the lamina and midrib models were substantially better than the exponential model in describing the experimental sorption curves while the exponential model was slightly superior to the lamina and midrib models in describing the experimental desorption curves. The lamina and midrib models were concluded to be superior to the exponential model in describing the nature of the diffusion process

by showing the effect of both moisture conductivity and physical dimensions of the leaf while the exponential model shows only the combined effect of the two.

Steady state experiments were conducted to determine independent diffusion coefficients for the lamina. Due to the physiology of the lamina, the steady state diffusion coefficients were considerably higher than the corresponding diffusion coefficients determined from sorption and desorption. Thus, the steady state diffusion coefficients were not applicable to sorption and desorption.

TABLE OF CONTENTS

CHAPTER		PAGE
I.	INTRODUCTION	1
II.	REVIEW OF LITERATURE	3
III.	MATHEMATICAL ANALYSIS	16
	Determination of Geometric Models	16
	Basic Assumptions	18
	General Mathematical Development	19
	Development of Mathematical Models	22
	Lamina model	22
	Midrib model	27
	Steady state analysis	31
IV.	METHODS AND PROCEDURE	34
	Investigation of Basic Assumptions	34
	Steady State Experiment	37
	Sorption and Desorption Experiments	41
	Methods and materials	41
	Equipment	43
	Procedure	48
V.	RESULTS AND DISCUSSION	53
	Verification of Basic Assumptions	53
	Steady State Results	57
	Sorption and Desorption Results	58
	Evaluation of lamina and midrib models	58

CHAPTER PAGE

Comparison of sorption, desorption, and steady state diffusion coefficients 65

VI. SUMMARY AND CONCLUSIONS. 69

BIBLIOGRAPHY 73

APPENDICES 78

A. THEORETICAL HEAT TRANSFER CALCULATIONS 79

B. THEORETICAL EFFECT OF FINITE CONVECTIVE MASS TRANSFER COEFFICIENT ON LAMINA SORPTION CURVE 85

C. TABLES AND GRAPHS OF RESULTS AND SAMPLE CALCULATIONS 93

D. MATHEMATICAL FORMULA FOR CALCULATING THE MOISTURE RATIO OF THE MIDRIB. 108

VITA 112

LIST OF TABLES

TABLE PAGE

1. Heat Transfer Lag Coefficient (sec) for the Burley Lamina as a Function of Stalk Position, Temperature, and Direction of Flow. 54

2. Heat Transfer Lag Coefficient (sec) for the Burley Midrib as a Function of Stalk Position, Temperature, and Direction of Flow. 54

3. Moisture Content (Dry Basis) of Midrib Sections at 0 and 5 Hours When Exposed to 96% RH and Room Temperature (Approximately 75°F) 56

4. Mass Diffusion Coefficient (Average of Four Replications) as a Function of Temperature and Relative Humidity 60

5. Average Standard Error in Percent Moisture Content of Lamina and Midrib Models (Equations 34 and 46, Respectively) at Various Temperatures and Relative Humidities 60

6. Average Value of Parameter k in Exponential Equation (Equation 2) as a Function of Temperature and Relative Humidity 61

7. Average Standard Error in Percent Moisture Content of Exponential Equation (Equation 2) at Various Temperatures and Relative Humidities. 61

TABLE PAGE

B-1. First Ten Solutions for $\lambda_n L$ from Equations 61a and 61b . . . 90

B-2. First Ten Coefficients of Equation 33. 91

B-3. Values of Dimensionless Moisture Ratio, $\Theta(t)$ or $(M - M_e)/(M_o - M_e)$ at t = 5, 10, 20 Hours from Equation 33 92

C-1. Analysis of Variance of Steady State Diffusion Coefficient . 93

C-2. Mass Diffusion Coefficient for the Sorption of the Cured Burley Lamina as a Function of Temperature and Relative Humidity 94

C-3. Mass Diffusion Coefficient for the Sorption of the Cured Burley Midrib as a Function of Temperature and Relative Humidity 94

C-4. Mass Diffusion Coefficient for the Desorption of the Cured Burley Lamina as a Function of Temperature and Relative Humidity 95

C-5. Mass Diffusion Coefficient for the Desorption of the Cured Burley Midrib as a Function of Temperature and Relative Humidity 95

C-6. Value of Parameter k in Exponential Equation (Equation 2) for the Burley Lamina During Sorption as a Function of Temperature and Relative Humidity. 96

C-7. Value of Parameter k in Exponential Equation (Equation 2) for the Burley Midrib During Sorption as a Function of Temperature and Relative Humidity. 96

TABLE PAGE

C-8. Value of Parameter k in Exponential Equation (Equation 2) for the Burley Lamina During Deosorption as a Function of Temperature and Relative Humidity. 97

C-9. Value of Parameter k in Exponential Equation (Equation 2) for the Burley Midrib During Desorption as a Function of Temperature and Relative Humidity. 97

C-10. Standard Error of Mathematical Model (Equation 34) for Lamina When Applied to Sorption Data at Various Temperatures and Relative Humidities. 98

C-11. Standard Error of Mathematical Model (Equation 46) for Midrib When Applied to Sorption Data at Various Temperatures and Relative Humidities. 98

C-12. Standard Error of Mathematical Model (Equation 34) for Lamina When Applied to Desorption Data at Various Temperatures and Relative Humidities. 99

C-13. Standard Error of Mathematical Model (Equation 46) for Midrib When Applied to Desorption Data at Various Temperatures and Relative Humidities. 99

C-14. Standard Error of Exponential Equation (Equation 2) When Applied to Sorption Data of the Burley Lamina at Various Temperatures and Relative Humidities. 100

C-15. Standard Error of Exponential Equation (Equation 2) When Applied to Sorption Data of the Burley Midrib at Various Temperatures and Relative Humidities. 100

TABLE PAGE

C-16. Standard Error of Exponential Equation (Equation 2) When Applied to Desorption Data of the Burley Lamina at Various Temperatures and Relative Humidities. 101

C-17. Standard Error of Exponential Equation (Equation 2) When Applied to Desorption Data of the Burley Midrib at Various Temperatures and Relative Humidities. 101

C-18. Weight Gain of the Whole Leaves of Plant 5 at Air Velocities of 10, 15, and 30 Feet Per Minute as a Function of Time at 75°F, 75% rh. 103

C-19. Weight Gain, Observed and Predicted Moisture Content (Percent) as a Function of Time for the Lamina of Plant 2 (Replication 2) at 65°F, 95% rh 105

C-20. Weight Loss, Observed and Predicted Moisture Content (Percent) as a Function of Time for the Lamina of Plant 2 (Replication 2) at 65°F, 43% rh After Removal From 65°F, 95% rh 106

D-1. Observed and Predicted Moisture Content (Percent) as a Function of Time for the Sorption of the Midrib of Plant 2 (Replication 2) at 65°F, 95% rh 110

D-2. Observed and Predicted Moisture Content (Percent) as a Function of Time for the Desorption of the Midrib of Plant 2 (Replication 2) at 65°F, 43% rh After Removal From 65°F, 95% rh 111

LIST OF FIGURES

FIGURE		PAGE
1.	Equilibrium Moisture Content as a Function of Temperature and Relative Humidity from Combined Data of Jeffrey (1941) and Locklair, et al. (1957).	4
2.	Cross Section of Proposed Geometric Models for Lamina and Midrib.	17
3.	A Paraffin Mold was Used to Hold Lamina Disks Firmly in Place During Steady State Experiment.	38
4.	The Paraffin Molds were Placed on Top of Test Tubes Containing Saturated Salts.	40
5.	Schematic of the Sorption Chamber	44
6.	The Sorption Chamber was Housed in a Small Environmentally Controlled Room	45
7.	The Test Section of the Sorption Chamber.	46
8.	The Specimens in the Desorption Chamber were Suspended from the Load Cell for Weighing	49
9.	The Desorption Chamber.	50
10.	Observed Moisture Content and that Predicted by Lamina Model (Equation 34) for Sorption of the Lamina of Plant 2 at 65°F, 95% rh	62
11.	Observed Moisture Content and that Predicted by Lamina Model (Equation 34) for Desorption of the Lamina of Plant 2 at 65°F, 44% rh After Removal from 65°F, 95% rh . .	63

FIGURE PAGE

A-1. Dimensionless Temperature Ratio given by Equation 52 for the Center of the Lamina as a Function of Time 81

A-2. Dimensionless Temperature Ratio Given by Equation 55 for the Center of the Midrib as a Function of Time 84

C-1. Weight Gain of the Whole Leaves of Plant 5 at Air Velocities of 10, 15, and 30 Feet Per Minute as a Function of Time at 75°F, 75% rh 102

CHAPTER I

INTRODUCTION

Processing, handling, and storage of biological materials usually involves one major basic problem; controlling the exchange of moisture between the material and its ambient environment. The moisture within the material exerts a vapor pressure which varies with the moisture content and nature of the material. When the vapor pressure of the material and that of the surrounding air are unequal, moisture diffuses in the direction of the lower vapor pressure. Thus, the moisture exchange may be either a drying or a wetting process or a combination of alternate drying and wetting.

Historically, interest has been in drying due to the necessity of moisture removal to prevent spoilage of many agricultural crops. Moisture relationships have been studied for many biological materials such as corn, wood, peanuts, wheat, cotton, and tobacco. However, many problems do arise after drying, especially in such hygroscopic materials as tobacco, wheat and cotton. Physical properties such as elastic moduli are generally functions of moisture content and must often be closely controlled during processing, both on and off the farm. Specific moisture levels are often required for a given phase of processing, thus, requiring knowledge of wetting as well as drying phenomena.

Moisture relationships are important in burley tobacco since different moisture levels are required for handling, storage and

manufacturing. To be handled, the tobacco must be in order; i.e., a moisture level high enough for the tobacco to be soft and pliable. Storage moisture level is lower than that needed for handling and the required moisture levels for manufacturing are critical and, therefore, must be closely controlled.

Tobacco readily absorbs moisture from the atmopshere and tobacco producers depend upon nature to order the tobacco on the farm. Efforts in the area of curing indicate a trend toward more environmental control or modification. A natural extension of controlled curing facilities would be to control the ordering of burley leaf for better scheduling of labor during the tobacco stripping season. Mechanization of stripping and grading will probably require more stringent requirements on a specific moisture content. Before the environment can be controlled to provide a specific moisture level in the cured leaf, the response of the tobacco to a given environment must be known.

The purpose of this investigation was to develop a means for predicting the moisture transfer response of burley tobacco to environmental changes. The following objectives were designed to accomplish this:

1. To develop mathematical models for moisture content of the cured burley tobacco leaf during sorption and desorption.
2. To experimentally determine the applicability of the mathematical models to actual sorption and desorption of the cured burley leaf.
3. To determine the value of physical parameters defined by the mathematical models which are required to describe the sorption and desorption of the cured burley leaf.

CHAPTER II

REVIEW OF LITERATURE

Moisture uptake of burley tobacco has been studied by several investigators. Jeffrey (1940) studied the equilibrium moisture content of burley tobacco and the safe-storage of tobacco in order. Locklair, et al. (1957) studied the equilibrium moisture content as a function of both temperature and relative humidity. Jeffrey's and Locklair's data are used to give equilibrium moisture content of burley tobacco as a function of temperature and relative humidity (Figure 1).

Walton, et al. (1970) and Young, et al. (1964) studied the moisture uptake of whole burley leaves detached from the stalk. Young used dimensional analysis to develop the following mathematical model:

$$\frac{M - M_e}{M_o - M_e} = \left(\frac{a}{a + t}\right)^b , \qquad (1)$$

where M_e = equilibrium moisture content of the tobacco in the new environment, dry basis,

M = moisture content at time t,

M_o = moisture content at t = 0,

t = time, and

a, b = constants.

Equation 1 represented the data for single leaves very well, however, the constants a and b varied considerably with stalk position.

Walton and Henson (1970) used the following thin layer drying equation as a model for detached leaves:

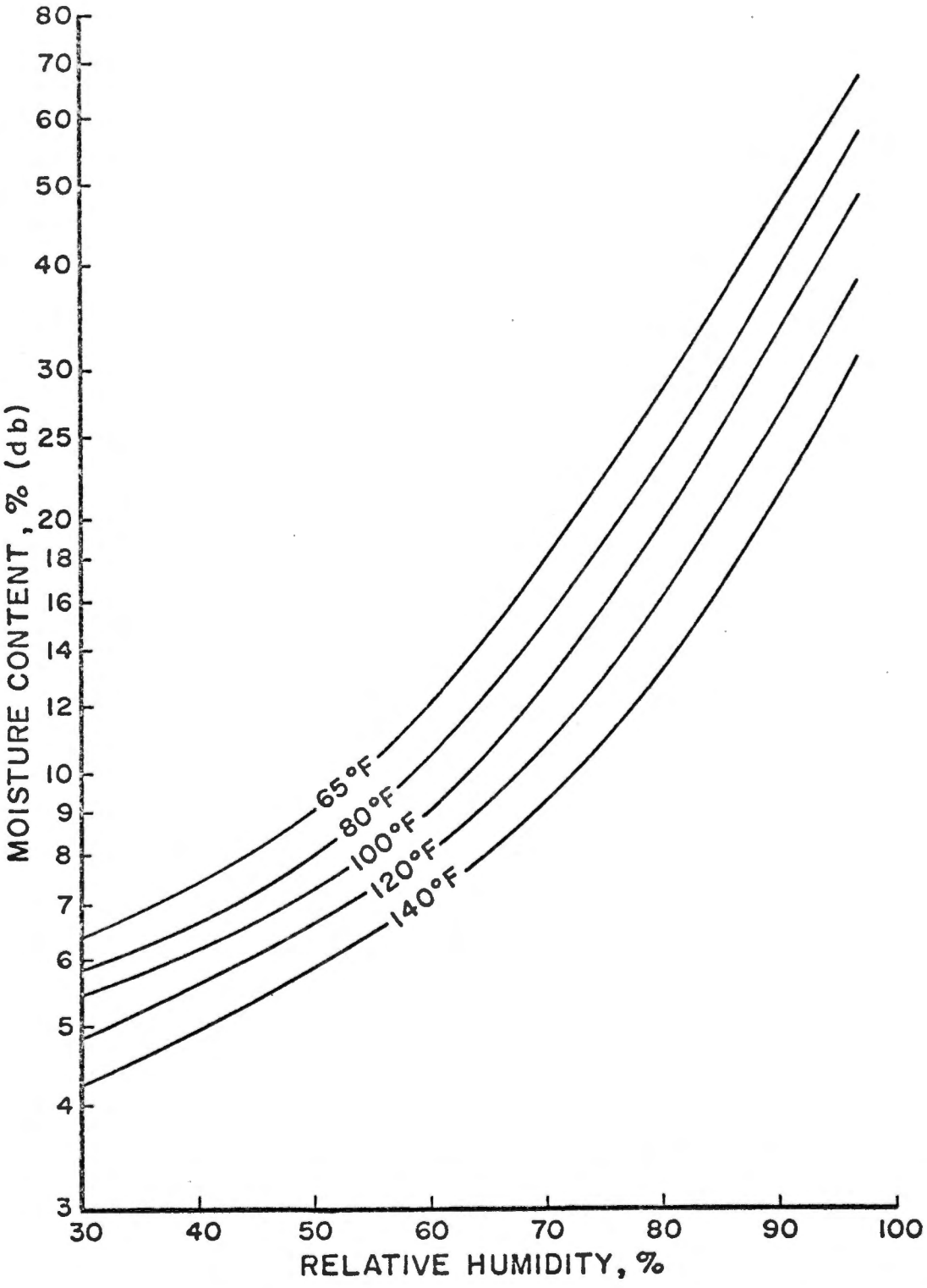


Figure 1. Equilibrium moisture content as a function of temperature and relative humidity from combined data of Jeffrey (1941) and Locklair, et al. (1957).

$$\frac{M - M_e}{M_o - M_e} = e^{-kt} \quad , \tag{2}$$

where k = an absorption constant, hr^{-1}.

The exponential equation underestimated the data in the initial portion of the curve.

The theory of drying is tied closely to simultaneous heat and mass transfer theory. Grober, et al. (1961) and Eckert and Gross (1963) give the basic equation for diffusion of heat and mass transfer as

$$\frac{\partial \Phi}{\partial t} = K \frac{\partial^2 \Phi}{\partial x^2} \quad , \tag{3a}$$

where Φ = temperature for heat transfer and concentration gradient for mass transfer,

K = thermal diffusivity for heat transfer and diffusion coefficient for mass transfer, and

x = coordinate.

The rate of heat or mass flow in the material is

$$q = - K \frac{\partial \Phi}{\partial x} \quad , \tag{3b}$$

where q = rate of heat or mass flow per unit area.

The moisture and temperature distribution within a material is always affected by the transfer of moisture and heat between the surface of the material and the air stream. This transfer between the surface and air stream is called transfer by convection and is given by the following equation:

$$q_s = h \, (\phi_s - \phi_\infty) \quad , \tag{3c}$$

where q_s = rate of heat or mass flow per unit area between surface of a material and air stream,

h = convective heat or mass transfer coefficient,

ϕ_s = temperature or vapor concentration at surface, and

ϕ_∞ = temperature or vapor concentration of the air stream at a point well removed from the surface.

For mass transfer, equation 3b is commonly called Fick's first law and equation 3a is Fick's second law. For heat transfer, equation 3c is commonly referred to as Newton's law of cooling.

Newman (1931, 1931) outlined the theory of three possible distinct stages in the drying process.

1. A constant drying rate period, during which the surface remains completely wet, the rate of evaporation being the same as that from a free liquid surface.
2. A falling rate period during which there is a falling off of wetted surface, the rate being directly propoertional to the fraction of surface which is wet. This rate has been shown to decrease linearly with the average liquid concentration until the liquid concentration at the surface has reached equilibrium with that of the air.
3. A second falling rate period, during which the liquid evaporates from the surface as fast as it can get there by diffusion from the interior of the solid. During this period, the liquid concentration of the surface layer remains constant.

Newman's first two stages apply only to certain very moist

materials. Only the third stage would apply to cured tobacco since the moisture content is generally less than 35%, dry basis. No literature could be found that described the response of cured tobacco when exposed to a drying environment. There are, however, studies on the response of cotton to alternate drying and wetting environment.

Henry (1939, 1948) treated the problem of diffusion in absorbing media. The problem as stated by Henry was

> . . . that of diffusion of one substance through another in the pores of a solid body which may absorb and immobilize some of the diffusing substance. Heat will be evolved by the absorption process, and will affect the extent to which the solid can absorb the diffusing substance.

Henry, who was interested in the uptake of moisture by cotton bales, envisaged a continuous network of spaces included in the solid, containing the medium (air) through which the diffusion takes place. The solid itself was considered to be either discontinuous, as is a bale of cotton fibers, or continuous, like a sponge.

The governing equations were determined by Henry to be the equation for vaporous diffusion and the equation for thermal diffusion.

$$\frac{\partial C}{\partial t} = D'' \nabla^2 C - \frac{1 - \alpha}{\alpha} \rho_s \frac{\partial M}{\partial t} , \text{ and} \tag{4}$$

$$c\rho' \frac{\partial T}{\partial t} = \kappa \nabla^2 T + \kappa \rho' \frac{\partial M}{\partial t} , \tag{5}$$

where M = mass of diffusing absorbed by unit mass of the solid,

C = concentration,

D'' = diffusion coefficient,

$\alpha = (\rho_s - \rho) / (\rho_s - \rho_r)$,

ρ = overall density of material,

ρ_s = density of solid,

ρ_r = density of material filling pores,

t = time,

c = specific heat,

ρ' = mass of solid per unit volume of whole,

k = heat given out of 1 g of vapor is absorbed by the solid,

κ = thermal conductivity, and

T = temperature of material.

The vapor in the pores was assumed to be in equilbrium with the absorbed vapors on the walls and a third equation involving M, C and T expressed the relationship between the concentrations of the quantities as follows:

$$M = \sigma + \beta C - \omega T \tag{6}$$

where σ, β, ω are constants.

Henry stated that in the case of water vapor and cotton, there is a considerable range of conditions over which equation 6 is a reasonable approximation, though it is not so in the general case.

Henry's (1939) solution to equations 4 and 5, using equation 6 are

$$\Delta C - \frac{1 - \mu_2^2 D}{\lambda} \Delta T = \Psi_1 (x, y, z, t), \text{ and} \tag{7}$$

$$\Delta T - \frac{1 - \mu_1^2 D}{\lambda} \Delta C = \Psi_2 (x, y, z, t) , \tag{8}$$

where Δ C = deviation of C from initial value,

Δ T = deviation of T from initial value,

D = thermal diffusivity = $\frac{\kappa}{\rho' c}$, and

Ψ = solution of ordinary diffusion equations with diffusion coefficients equal to $1/\mu_1^2$ and $1/\mu_2^2$, respectively, and subject to appropriate initial and boundary conditions.

Equation 6 can be used to solve for ΔM. Henry solved for Ψ_1 and Ψ_2 for an infinite plane sheet and rectangular parallelepiped.

Whitney (1966) solved equations 4 and 5 for application to the drying of peanuts. His main interest was in determining the effect of a temperature gradient on the rate of moisture movement in a porous hydroscopic solid. He determined that relative to the case of no temperature gradient, drying rate is greater when a temperature gradient exists in the same direction as the moisture gradient. The greater drying rate was concluded to be a result of temperature gradient increasing the vapor pressure gradient. He also concluded that after a given amount of water has been removed, the moisture gradients are similar whether or not a temperature gradient exists in the same direction as the moisture gradient.

In a series of articles, Young and Whitaker (1968, 1969, 1970, 1971) treated the subject of thin layer drying of peanuts. Young (1969) simultaneously solved the equations for heat and mass transfer in a spherical body by using a numerical technique. Variable mass diffusivities and thermal conductivities were considered as well as internal heating. In addition, criteria were developed for determining to what extent the heat transfer affects the drying of the body. These criteria were based on the modified Lewis number,

$$Le_m = \frac{\kappa\,[f + (1 - f)\,\rho_s\,\beta]}{D''\,(1 - f)\rho_s(C_s + C_w + L\omega)} \tag{9}$$

where f = void ratio,

C_s = specific heat of solid,

C_w = specific heat of water, and

L = latent heat of vaporization.

If $Le_m > 60$, then instantaneous heat transfer can be assumed.

Young and Whitaker (1971) analytically solved the diffusion equation for several regular geometric shapes. The initial and boundary conditions used were

a) The drying body is initially at a uniform moisture content, and

b) The surface instantaneously reaches equilibrium with the drying environment for time $t \geq 0$.

The simplifying assumptions were

a) The drying body has a constant mass diffusivity, and

b) The drying body is homogeneous.

The solutions investigated were

a) For a plane sheet,

$$\frac{M - M_e}{M_o - M_e} = \frac{8}{\Pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n + 1)^2}\; e^{-(2n + 1)^2 Kt}\,, \tag{10}$$

where M = average moisture content of the body, dry basis,

M_e = equilibrium moisture content of body, dry basis,

M_o = initial moisture content of body, dry basis,

D = mass diffusivity of moisture in body, ft^2 per hr,

t = elapsed time, hr,

L = half-thickness of sheet, and

$$K = \text{computational parameter} = \frac{D\pi^2}{L^2}, \ hr^{-1}.$$

b) For an infinite cylinder,

$$\frac{M - M_e}{M_o - M_e} = \sum_{n=1}^{\infty} \frac{4}{a^2 \alpha_n^2} e^{-a^2 \alpha_n^2 \kappa t/\Pi^2} , \tag{11}$$

where a = radius of cylinder, ft,

$\alpha_n = n^{th}$ positive root of $J_o(a\ \alpha_n) = 0$,

$J_o(x)$ = Bessell function of order zero, and

$$\kappa = \text{computational parameter} = \frac{D\pi^2}{a^2}, \ hr^{-1}.$$

c) For a sphere

$$\frac{M - M_e}{M_o - M_e} = \frac{6}{\Pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-n^2 Kt} , \tag{12}$$

where a = radius of sphere, ft, and

$$K = \text{computational parameter} = \frac{D\pi^2}{a^2}, \ hr^{-1}.$$

d) The moisture ratio for a finite cylinder is the product of the solution for an infinite cylinder of the same radius and that for a plane sheet with a half-thickness equal to one-half the length of the finite cylinder,

$$\frac{M - M_e}{M_o - M_e} = \frac{8}{\Pi^2} \left\{ \sum_{n=0}^{\infty} \frac{4}{a^2 \alpha_n^2} e^{\frac{-Ka^2 \alpha_n^2 t}{\Pi^2}} \right\} \left\{ \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} e^{-K(2n+1)^2 t \left(\frac{a}{L}\right)^2} \right\} , \tag{13}$$

where a = radius of finite cylinder, ft,

L = one-half the length of the cylinder, ft, and

K = computational parameter = $\frac{D\pi^2}{a^2}$, hr^{-1}.

The equation for the finite cylinder fit the data best with the sphere second best when equations 10, 11, 12 and 13 were compared to the experimental data on the drying of peanuts. However, the a/L ratio which gave the best fit was greatly different than the true a/L ratio of peanuts. The theoretical drying rates were too slow initially and too rapid in the later stages of drying. The effect of temperature on the computational parameter, K, was determined to be the same as given by the Arrhenius equation, Williams and Williams (1967).

Whitaker and Young (1968) later applied equations 10, 11, 12 and 13 to the drying of the peanut kernel and not the whole peanut pod. The experiment showed that in most cases the cylindrical model (finite or infinite) predicted the experimental drying curve best. The theoretical curves fit the experimental curves accurately over the entire range and with considerably more accuracy than with the whole pod data. The increased accuracy was due to the peanut kernels representing a much more homogeneous body than pods. In addition, the computational parameter, K, was shown to vary independently of the dewpoint temperature.

Young and Whitaker (1970) then made a numerical analysis of the vapor diffusion equation (equation 4) in a porous compisite sphere with concentric shells. They concluded that a spherical composite body best represented the drying peanut product. This model was shown by Whitaker and Young (1970) to accurately predict drying rates of the peanut

product over the entire drying period. Improvement was noted in all cases for the composite model as compared to the homogeneous model already discussed. The improved accuracy was contributed to the account taken of the different diffusional properties of the kernel and hull.

Chen and Johnson (1969) studied the kinetics of moisture movement in hygroscopic materials. The following rate law was postulated:

$$\frac{d\,\bar{M}}{d\,t} = -\,K\,(\bar{M} - M_e)^n\,, \tag{14}$$

where $\bar{M}$ = average moisture content at time t,

K = empirical constant,

n = empirical constant, and

M_e = moisture content at the end of the period under consideration. Equation 14 was solved for n = 1, but a nomograph was used to predict $\bar{M}$ for $n \neq 1$. The value of n was found to vary from 0.64 to 0.76 for flue-cured tobacco. The results showed that equation 14 described the data closely.

Chang and Johnson (1971) solved, numerically, two models which were developed to describe the temperature of a tobacco leaf during high temperature, high moisture, convective drying during the curve. The two models used were

$$\frac{\partial\,(cpT)}{\partial\,t} = k\,\frac{\partial^2 T}{\partial x^2} \quad \text{(Model 1)} \tag{15}$$

$$\frac{d(cWT)}{dt} = 2\,h\,A\,(T_a - T) - LD \quad \text{(Model 2)} \tag{16}$$

where c = specific heat of leaf,

p = leaf density,

T = leaf temperature,

W = weight of leaf,

h = convective heat transfer coefficient,

L = latent heat of vaporization,

D = drying rate,

k = thermal conductivity,

A = leaf area, one side, and

t = time.

Close agreement was found between theoretical and experimental values of leaf temperature for the high moisture range during the initial 60% loss of total moisture; however, at lower moisture contents, the values were not in agreement.

Becker and Sallans (1955) used the following model of the equation for diffusion out of homogeneous spheres to describe the drying of wheat kernels:

$$\frac{\overline{M} - M_s}{M_o - M_s} = \frac{6}{\Pi^2} \sum_{n=1}^{\infty} e^{-n^2\Pi^2 D_c t/r_o^2}, \qquad (17)$$

where M_s = surface moisture conte,t

r_o = kernel radius, and

D_c = diffusion coefficient.

Becker concluded that in the range of practical drying, moisture migration at a given temperature is accurately portrayed by the diffusion equation (equation 17) with constant values of the diffusion coefficient and surface moisture content.

Several studies on the theory of sorption and desorption isotherms have been made. Henderson and Perry (1955) proposed the following empirical equation:

$$1 - rh = e^{-\mu T M^{n}} , \tag{18}$$

where rh = equilibrium relative humidity,

M = equilibrium moisture content,

T = absolute Fahrenheit temperature, and

μ, n = constants.

Young and Nelson (1967) studied the hysteresis between sorption and desorption isotherms of wheat. Theoretical equations were developed and verified that predicted that equilibrium moisture contents would be higher for desorption than sorption. Ngoddy and Bakker-Arkema (1970) developed an alternate theoretical isotherm equation.

Humphries (1963) performed a structural analysis of leaf material revealing two primary sources of resistance to moisture movement between individual cells and the drying atmosphere. These resistance sources were associated with the cytoplasm of individual cells and the epidermal surfaces. A model of lamina tissue was developed which incorporated these resistance sources in series. The rate of transport across these structural barriers was described by

$$\frac{1}{A}\frac{dw}{dt} = \frac{P\,(p_1 - p_2)}{L} , \tag{19}$$

where $\frac{1}{A}\frac{dw}{dt}$ = rate of transfer per unit area,

$p_1 - p_2$ = vapor pressure difference,

P = a factor of proportionality, and,

L = thickness of the barrier.

CHAPTER III

MATHEMATICAL ANALYSIS

Mathematical models of the lamina and midrib which define the transient moisture (sorption and desorption) of the cured burley tobacco leaf due to a sudden change in the ambient environment have been developed. The stalk was not included in the model; however, its effect on the leaf was considered. The problem was approached from basic mass transfer theory.

The following steps were followed in development of the model:

1. Determine an appropriate geometric model to represent the shape of the material.
2. Make necessary assumptions.
3. Apply appropriate partial differential equations.
4. Determine applicable boundary conditions.
5. Solve the partial differential equations subject to geometry and boundary conditions of the problem.

I. DETERMINATION OF GEOMETRIC MODELS

The leaf has two primary components, lamina and midrib. The lamina is the thin broad portion of the leaf with a very small thickness to surface area ratio. Therefore, the geometric model chosen to represent the lamina was the infinite thin sheet.

The midrib is the central vein of the leaf with a diameter in the range of 1/8 to 3/16 inches near the stalk. The cross section of the

midrib is actually irregular with a V-shaped notch in the top. The midrib is tapered from its point of attachment to the stalk to the tip of the leaf with a very large length to base diameter ratio (> 200).

The moisture of the midrib near the stalk can be expected to be affected by the moisture in the stalk. The stalk, which takes up and gives off moisture very slowly compared to the leaf, acts as a constant moisture source which, in general, transfers moisture to the midrib. The cross-sectional area through which moisture is transferred from the stalk to the midrib is much smaller than the surface area through which moisture is exchanged with the atmosphere. While the diffusion coefficient in the radial and axial direction would be a factor, the limiting factor should be the ratio of cross-sectional area to surface area ratio. Thus, the effect of the stalk on the average moisture content of the midrib was assumed to be negligible.

The infinite circular cylinder was chosen as the geometric model to represent the midrib. This approximation should allow an adequate mathematical solution to the problem. A cross section of the proposed geometric models is shown in Figure 2.

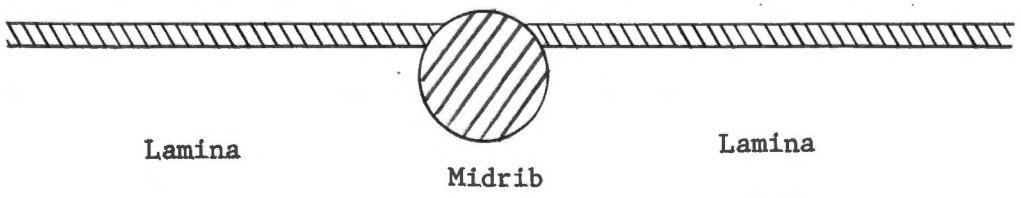


Figure 2. Cross section of proposed geometric models for lamina and midrib.

II. BASIC ASSUMPTIONS

The mathematical models were based on the following simplifying assumptions:

1. Effect of the stalk on the average moisture content of the midrib was assumed to be negligible.
2. Each component was assumed to be a homogeneous body.
3. Transfer of moisture directly between midrib and lamina during sorption and desorption was assumed to be negligible.
4. The transient thermal period of the lamina and midrib was assumed to be negligible compared to the transient moisture period.
5. The moisture content of the tobacco (between 8 and 32%) was assumed to be a linear function of vapor concentration and temperature.
6. The external resistance to moisture movement was assumed to be negligible (the convective mass transfer coefficient was thereby assumed infinite) compared to the internal resistance as a result of theoretical calculations made during the mathematical development.
7. The diffusion coefficient was assumed to be a constant for a given environmental condition.

The assumption of homogeniety allowed a solution which gave average moisture properties of the leaf.

The average thickness of the lamina was determined to be 0.0002 ft. The average diameter of the midrib taken at 4 to 5 inches from

stalk was 0.012 ft. The surface area of the midrib and lamina was so large compared to the interface area between midrib and lamina that assumption 3 was considered to be a reasonable assumption.

The transient moisture period has been shown by Walton and Henson (1970), and Young (1964) to involve at least several hours and sometimes, days. Theoretical calculations shown in Appendix A predict that the midrib at an initial temperature T_o when suddenly plunged into a new thermal environment at temperature T_∞, equilibrates to within 1% of the temperature difference $T_o - T_\infty$ in 5 minutes. Similar calculations predict the lamina would equilibrate to within 1% of the temperature difference $T_o - T_\infty$ in 90 seconds. Thus, the transient temperature period for burley tobacco was assumed to be very short compared to the transient moisture period.

The variance of assumptions 5 and 7 from the actual case was acknowledged to cause an inherent error in the mathematical models. This disadvantage was mitigated by allowing the developing of an analytical solution that describes the physics of the process better than the mathematical models in prior use.

Assumptions 3, 4 and 6 were verified in preliminary experiments.

III. GENERAL MATHEMATICAL DEVELOPMENT

The time rate of change of concentration in the pore space of a differential element $\Delta X\ \Delta Y\ \Delta Z$ in a porous hygroscopic solid is equal to the difference of the net moisture entering or leaving the element and the time rate of change of the moisture being absorbed or given off by

the solid. The rate at which the moisture diffuses into and from the small volume element proceeds according to Fick's first law. The net moisture entering or leaving the element is, therefore, given by $D \nabla^2 C \Delta X \Delta Y \Delta Z$ where ∇^2 is the Laplacian operator. The rate at which water vapor is being absorbed or given off by the solid is $\rho \frac{\partial M}{\partial t}$ where ρ is the bulk density (mass per unit of overall volume) and M is the mass of vapor absorbed or given off by unit mass of solid. Thus, the vapor diffusion equation is

$$f \frac{\partial C}{\partial t} = D \nabla^2 C - \rho \frac{\partial M}{\partial t} \text{ , or}$$

$$D \nabla^2 C = f \frac{\partial C}{\partial t} + \rho \frac{\partial M}{\partial t} , \tag{20}$$

where D = diffusion coefficient,

f = void ratio,

ρ = weight of dry matter per unit of overall volume,

C = vapor concentration,

M = moisture content of solid, and

t = time.

Henry (1939, 1948), Whitney (1966), and Young (1971) have indicated that within a limited moisture range the relationship between moisture content, concentration and temperature could be assumed to be linear as in equation 6

$$M = \sigma + \beta C - \omega T. \tag{6}$$

The moisture content range of interest in ordering burley was considered to be 10 to 25%, dry basis, a narrow range compared to drying problems such as that considered by Whitney and Young. Application of equation 6

Lamina boundary conditions. At time t = 0, M = M_o, thus, the initial condition is Θ (x,0) = 1. The assumed condition of symmetry from each leaf surface to the center gave the same moisture distribution in the upper half of the leav as in the lower half of the leaf, thus, $\frac{\partial \Theta (0,t)}{\partial x} = 0$. As t approaches infinity, M approaches M_e, thus $\lim_{t\to\infty} \Theta(x,t) = 0$. The third boundary condition was found by equating equations 3b and 3c for the moisture transfer at the surface of the solid and the moisture transfer between the surface and the air stream

$$- D \frac{\partial \Theta (L,t)}{\partial x} = h_m \Theta (L,t) ,$$

where h_m = convective mass transfer coefficient and D' = $D\rho\beta$. Thus, the initial and boundary conditions were determined to be

$$\Theta (x,0) = 1,$$

$$\frac{\partial \Theta}{\partial x} (0,t) = 0, \text{ and}$$

$$-D \frac{\partial \Theta (L,t)}{\partial x} = h_m \Theta (L,t) . \qquad (27)$$

Lamina solution. A product solution of equation 26 was assumed as follows:

$$\Theta (x,t) = X (s) \tau(t).$$

Substitution in equation 26 gave

$$\frac{1}{X} \frac{d^2 X}{d x^2} = \frac{1}{D'} \frac{1}{\tau} \frac{d \tau}{dt} = - \lambda^2 . \qquad (28)$$

This gave rise to two equations with boundary conditions

$$\frac{d \tau}{dt} + D' \lambda^2 \tau = 0 : \lim_{t\to\infty} \tau (t) = 0, \text{ and} \qquad (29)$$

$$\frac{d^2X}{dX^2} + \lambda^2 X = 0 \quad : \quad \frac{d\,X(0)}{dx} = 0, \; - D\frac{dX(L)}{dx} = h_m X(L) \; . \qquad (30)$$

Equation 29 may be solved to obtain

$$\tau(t) = A\, e^{D'\lambda^2 t} + B\, e^{-D'\lambda^2 t} \; .$$

The term $e^{D'\lambda^2 t}$ goes to ∞ as $t \to \infty$, therefore A = 0 and

$$\tau(t) = B\, e^{-D'\lambda^2 t} \; .$$

Equation 30 may be solved to obtain

$$X(x) = C \sin \lambda X + E \cos \lambda x.$$

The boundary conditions were applied to give the following:

$$\frac{d\,X\,(0)}{dx} = C\,\lambda \cancel{\cos}^{\,1}\,\lambda\, x - E\,\lambda \cancel{\sin}^{\,0}\,\lambda\, x = 0,$$

$\therefore C = 0$, and

$$-D\,\frac{d\,X(L)}{dx} = +D\,\lambda \sin \lambda\, L = h_m \cos \lambda\, L = h_m\, X(L) \; .$$

There are an infinite number of λ which satisfy this equation. Each solution is denoted by λ_n where n = 0, 1, 2, . . . and the λ_n are given by

$$\tan \lambda_n L = \frac{h_m}{D\lambda_n} \; .$$

The solution to this point was

$$\Theta(x, t) = \sum_{n=0}^{\infty} B_n\, e^{-D'\lambda_n^2 t} \cos \lambda_n x \; .$$

The constant B_n was given by

$$B_n = \frac{\int_{-L}^{L} \cos \lambda_n x \, d y}{\int_{-L}^{L} \cos^2 \lambda_n x \, d y} \text{ , and ,}$$

$$B_n = \frac{2 \sin \lambda_n L}{\lambda_n L + \sin \lambda_n L \cos \lambda_n L}$$

The solution for the lamina in terms of time and distance was

$$\Theta(x,t) = 2 \sum_{n=0}^{\infty} \frac{\sin \lambda_n L}{\lambda_n L + \sin \lambda_n L \cos \lambda_n L} e^{-D'\lambda_n^2 t} \cos \lambda_n x \text{ ,} \qquad (31)$$

where λ_n satisfies

$$\tan \lambda_n L = \frac{Bi}{\lambda_n L} \text{ ,} \qquad (32)$$

where Bi = Biot number for mass transfer = $\frac{h_m L}{D}$.

The primary interest was in variation of the average moisture content as a function of time. To find the average moisture content, equation 31 was integrated as follows:

$$\Theta(t) = \frac{1}{2L} \int_{-L}^{L} \Theta(x, t) \, dx$$

$$= \frac{1}{L} \sum_{n=0}^{\infty} \frac{\sin \lambda_n L}{\lambda_n L + \sin \lambda_n L \cos \lambda_n L} e^{-D'\lambda_n^2 t} \int_{-L}^{L} \cos \lambda_n x \, d x.$$

The last integral was evaluated to obtain

$$\frac{1}{L} \int_{-L}^{L} \cos \lambda_n x \, d x = \frac{1}{L\lambda_n} \sin \lambda_n x \Big]_{-L}^{L}$$

$$= \frac{1}{L\lambda_n} (\sin \lambda_n L - \sin (-\lambda_n L))$$

$$= \frac{2}{L\lambda_n} \sin \lambda_n L.$$

$\Theta(t)$ for the lamina was therefore

$$\Theta(t) = 2 \sum_{n=0}^{\infty} \frac{\sin^2 \lambda_n L}{(\lambda_n L)^2 + \lambda_n L \sin \lambda_n L \cos \lambda_n L} e^{-D'\lambda_n^2 t} . \qquad (33)$$

The relationship between the resistance to moisture transfer internally and the surface resistance to moisture transfer to the leaf surface from the surroundings to the leaf surface was considered at this point. The internal diffusion coefficient, D', provides an indication of the internal resistance. The external convective mass transfer coefficient, h_m, is an indication of surface resistance. Therefore, the external resistance and internal resistance to moisture transfer were present as separate quantities.

Equation 33 reduces to a much simpler form as h_m approaches infinity. It can be seen by equation 32 that as h_m approaches infinity, tan $\lambda_n L$ approaches infinity, also. Therefore, as h_m approaches infinity $\lambda_n L$ approaches $\frac{(2n + 1)\pi}{2}$. Practically, h_m, the surface conductance to moisture transfer, would never be infinite. However, it is possible that the ratio of internal resistance to external resistance was so large that the error caused by considering h_m to be infinite would be negligible. This possibility has been pursued through theoretical calculations in Appendix B. It appears that the error would be small by considering h_m to be infinite. From the calculations in Appendix B and the resulting values of $\Theta(t)$ shown in Table B-3, the error introduced by considering h_m to be infinite was computed to be on the order of 0.2%. The convective mass transfer coefficient was, therefore, assumed infinite as previously stated. This was analogous to

assuming the external resistance to moisture transfer was negligible compared to internal resistance to moisture transfer. Thus equation 33 became

$$\Theta(t) = \sum_{n=0}^{\infty} \frac{2}{(\lambda_n L)^2} e^{-D'\lambda_n^2 t} , \qquad (34)$$

where $\lambda_n L = \frac{(2n + 1)\pi}{2}$ $\quad n = 0, 1, 2, \ldots .$

Equation 34 is the mathematical model for moisture content of the burley lamina as a function of time.

Midrib Model

The governing equation was the one dimensional form of equation 22 in cylindrical coordinates

$$D' \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \Theta}{\partial r}\right) = \frac{\partial \Theta}{\partial t} , \qquad (35)$$

where $\Theta(r, t) = \frac{M(r,t) - M_e}{M_o - M_e}$

M_o = Moisture content of midrib at t = 0,

$M(r,t)$ = Moisture content at any position and time, and

M_e = Equilibrium Moisture Content of midrib at conditions that prevail for t > 0.

Midrib boundary conditions. At time t = 0, M = M_o, thus the initial condition was $\Theta(x,0) = 1$. Geometrical symmetry showed that since moisture flow was uniform in the radial direction toward the center of the midrib, $\frac{\partial \Theta(0,t)}{\partial r} = 0$. The boundary condition at the surface of the midrib was found by equating equations 3b and 3c

$$- D \frac{\partial \Theta (R,t)}{\partial r} = h_m \Theta (R,t) ,$$

where h_m = convective mass transfer coefficient, and $D = \rho\beta D'$. It was noted that equation 36 involved D which was related to D' by $D = \rho\beta D'$. The initial and boundary conditions were

$$\frac{\partial \Theta(0,t)}{\partial r} = 0 ,$$

$$\Theta(r,0) = 1, \text{ and} \qquad (36)$$

$$-D \frac{\partial \Theta (R,t)}{\partial r} = h_m \Theta (R,t).$$

Midrib solution. The solution of equation 35 was assumed to be a product solution

$$\Theta(r,t) = R (r) \tau(t) , \qquad (37)$$

which, when substituted into equation 35, gave rise to two characteristic equations

$$\frac{d\tau}{dt} + D'\lambda^2 \tau = 0 \qquad \tau(0) = 1, \text{ and} \qquad (38)$$

$$\frac{d}{dr} (r \frac{dR}{dr}) + \lambda^2 rR = 0, \quad \frac{dR(0)}{dr} = 0, \quad -D \frac{\partial R(R)}{\partial r} = h_m R(R) . \qquad (39)$$

The solution to equation 38 is

$$\tau(t) = e^{-D'\lambda^2 t} .$$

Equation 39 was recognized to be Bessel's equation and was solved through the use of Table 3-1 in Arpaci (1966). The general solution to equation 39 is

$$R(r) = A J_o (\lambda r) + B Y_o (\lambda r), \qquad (40)$$

where $J_o (\lambda r)$ = Bessel's function of the first kind, and

$Y_o (\lambda r)$ = Bessel's function of the second kind.

The concentration $\Theta(r,t)$ must be finite at $r = 0$ where the Bessel function $Y_o(\lambda r)$ is infite. Therefore $Y_o(\lambda r)$ cannot be allowed as a solution, and equation 40 reduces to

$$R(r) = A\, J_o(\lambda r).$$

Application of the second boundary condition defined the values of the parameter λ as follows:

$$-D \frac{dR(R)}{dr} = + D \lambda R J_1(\lambda R) = h_m J_o(\lambda R) . \tag{41}$$

The parameter λ_n is, therefore, the solution to

$$J_o(\lambda_n R) - \frac{D}{h_m} (\lambda_n R) J_1(\lambda_n R) = 0 . \tag{42}$$

The convective mass transfer coefficient, h_m, for the midrib was assumed to be about the same order of magnitude as that calculated for the lamina in Appendix B. The estimated value of diffusion coefficient for the lamina in Appendix B indicated that the experimental diffusion coefficients, yet to be determined for both midrib and lamina, could be expected to be very small numbers. It seemed reasonable to expect that $\frac{D}{h_m} < 10^{-4}$. Thus the second term in equation 42 would be so small compared to the first that it could be neglected. The resulting equation was

$$J_o(\lambda_n R) = 0. \tag{43}$$

The general solution to equation 35 was, therefore,

$$\Theta(r,t) = \sum_{n=1}^{\infty} A_n J_o(\lambda_n r)\, e^{-D'\lambda_n^2 t} . \tag{44}$$

The A_n can be evaluated using the initial condition as follows:

$$A_n = \frac{\int_0^R r\, J_o\,(\lambda_n r)\, dr}{\int_0^R r\, J_o^{\,2}(\lambda_n r)\, dr}$$

$$= \frac{2}{(\lambda_n R)\, J_1(\lambda_n R)}$$

Thus, the solution was

$$\Theta(r,t) = 2 \sum_{n=1}^{\infty} \frac{J_o\,(\lambda_n r)}{(\lambda_n R)\, J_1(\lambda_n R)}\; e^{-D'\lambda_n^{\,2} t} \,. \tag{45}$$

To obtain the average moisture content, equation 45 was integrated with respect to r:

$$\Theta(t) = \frac{\int_0^R r\Theta(r,t)\, dr}{\int_0^R r dr} = \frac{2}{R^2} \int_0^R \Theta(r,t) dr$$

$$= \sum_{n=1}^{\infty} \frac{1}{(\lambda_n R)}\; e^{-D'\lambda_n t} \left[\frac{4}{R^2 J_1\,(\lambda_n R)} \int_0^R r J_o(\lambda_n r) dr \right]$$

$$\left[\frac{4}{R^2 J_1(\lambda_n R)} \int_0^r r J_o(\lambda_n r) dr \right] = \frac{4}{R^2\, J_1(\lambda_n R)} \left[\frac{r}{\lambda_n} - J_1(\lambda_n r) \right]_0^R$$

$$= \frac{4}{R^2\, J_1(\lambda_n R)} \left[\frac{R J_1(\lambda_n R)}{n} \right]$$

$$= \frac{4}{\lambda_n R} \,.$$

Thus, the solution for the average moisture content of the midrib was

$$\Theta(t) = \sum_{n=1}^{\infty} \frac{4}{(\lambda_n R)^2} e^{-D'\lambda_n^2 t} , \qquad (46)$$

where λ_n were the zeros of

$$J_o (\lambda_n R) = 0.$$

The mathematical models were originally derived to be applied to moisture sorption only. Even though it was of great importance to study the moisture sorption of burley tobacco, it was also of interest to know the rate of drying. It was considered important to know just how long tobacco could be expected to remain in order when exposed to a drying environment. Thus, the models were applied to both sorption and desorption of cured burley leaves.

Steady State Analysis

The evaluation of equations 34 and 46 was to be by comparison to experimental sorption and desorption data. It was considered that an independent means of evaluating the diffusion coefficient, D', would strengthen the study. Comstock (1963) reported diffusion coefficients for wood based on steady state, sorption, and desorption data. The steady state condition was accomplished by maintaining different levels of constant relative humidity on each side of a thin slab of wood and measuring the transfer of moisture across the specimen. It was, thus, concluded that a steady state determination of diffusion coefficient for the burley lamina would be made.

The rate of moisture flow across a section of lamina has been given by equation 3b,

$$\frac{m}{A} = -D \frac{\partial C}{\partial x} ,$$

where m = rate of moisture transfer through lamina, lb/hr, and

A = lamina area, ft^2.

Under the assumption that surface resistance to moisture flow was negligible compared to internal resistance, the steady state form of equation 3b became

$$\frac{m}{A} = -D^* \frac{\Delta C}{\delta} .$$

where ΔC = difference in vapor concentration across the lamina, lb/ft^3,

δ = lamina thickness, ft, and

D^* = steady state diffusion coefficient based on concentration, ft^2/hr.

The vapor concentration difference was converted to moisture content difference by using equation 6

$$\frac{m}{A} = - \frac{D^*}{\beta} \frac{\Delta M}{\delta} ,$$

where ΔM = difference in equilibrium moisture contents between upper and lower surfaces of leaf. After dividing through by ρ, the resulting equation was

$$D' = - \frac{m \delta}{A \Delta M \rho} \qquad (47)$$

where $d' = \frac{D^*}{\rho\beta}$ = steady state diffusion coefficient based on lbs of water per lb of dry material, ft, and

ρ = average density of lamina.

Equation 47 relates steady state diffusion coefficient to the rate of moisture transfer.

CHAPTER IV

METHODS AND PROCEDURE

I. INVESTIGATION OF BASIC ASSUMPTIONS

A basic assumption in the mathematical development was that heat transfer period was negligible compared to mass transfer. Theoretical calculations were made in Appendix A to show that the transient heat transfer period is, at most, a few minutes long. The calculations were made using the thermal properties of Duncan, et al. (1966). It was assumed that these thermal properties, which were determined for the whole leaf, could be applied equally to the lamina and midrib. Young (1964) showed that the transient moisture period for burley tobacco takes at least several hours and, in some cases, days. Thus, the assumption appears valid; however, this conclusions should be experimentally validated by determining the length of the transient temperature period.

A thirty-six gage wire thermocouple was imbedded directly into the leaf midrib. The mass of the thermocouple was small compared to the mass of the midrib and also small enough to obtain a reasonable value of center temperature. In addition, the error due to conduction of heat along the thermocouple was minimized.

An exponential lag coefficient from an assumed exponential rate of decay curve was determined which was defined as the time for the temperature to move 63.2% of the total range between initial and final

temperature. No reference to the use of a lag coefficient in heat transfer was found in the literature; however, it was considered to be an appropriate means of comparing the rate of change in the transient phenomenon. As an example, the theoretical lag coefficients taken from Figures A-1 and A-2, are 16.5 and 68.3 seconds for the lamina and midrib, respectively.

Temperature monitoring of leaf lamina was difficult due to the thickness (an average of 0.0002 ft) of the lamina. Thermocouples were placed between six layers of lamina (three layers on each side of thermocouple) and the transient temperature measured. Layers were removed, two at a time, so that the lag coefficient for six, four, and two layers thick was determined. The plot of lag coefficient versus thickness was extrapolated to one layer thickness.

The levels of variables tested were

Temperature range . . . 35 to 75, 55 to 75, 75 to 95, 95 to 75, 75 to 55, 75 to 35.

Components. . . . . midrib, lamina

A second basid assumption which required verification was that the moisture transfer between midrib and lamina was negligible. Six leaves were dried to a moisture content of seven percent. Three strips one inch in width were cut perpendicular to the midrib across the breadth of the leaves. The lamina and midrib were left intact on one strip while the lamina was removed from the midrib of the two remaining strips of each leaf. The strips were then exposed to 96% relative humidity environment. The moisture content of the midrib sections were

determined after five hours of moisture adsorption. The moisture contents were then compared to ascertain whether the presence of lamina enhanced moisture sorption by the midrib.

To further substantiate the magnitude of transfer between lamina and midrib, two sections from different leaves at 7% moisture content were coated with paraffin. The lamina was then shaved off as close to the midrib as possible. This left the cross section of the lamina exposed to the atmosphere on each side of the midrib. Thus, the only pathway for moisture was through the lamina to the midrib. Both sections were then exposed to 96% relative humidity and room temperature for 20 hours. Weights were recorded before and after to determine moisture gain.

It was shown through theoretical calculations in Chapter III that, for all practical purposes, the convective mass transfer coefficient could be assumed infinite. To test this assumption sorption tests of whole leaves were run at air velocities of 10, 15, and 30 feet per minute at temperatures of 55, 65, and 75°F and 75% relative humidity. The premise was that a finite convective mass transfer coefficient, which is a function of boundary layer thickness and thereby a function of velocity, would vary drying rates as a function of velocity at each temperature humidity condition. Should the difference in drying rates be undetectable, then the assumption could be considered valid and air velocity would not be included as an experimental variable in the sorption and desorption tests.

II. STEADY STATE EXPERIMENT

G. L. Comstock (1963) developed steady state diffusion by placing a thin slab of wood over the top of a dish containing a saturated salt solution. The wooden slab was sealed over the dish with paraffin. The dish was then placed in a chamber maintained at a relative munidity well removed from that of the saturated salt. After some period of time, the moisture transfer through the slab of wood reached steady state.

In a similar manner, several disks of tobacco leaf lamina were placed in layers to form test tube sized specimens for a steady state determination of the diffusion coefficient. An average value for the steady state diffusion coefficient for the plant was obtained. Three leaves representing the top, mid-stalk, and bottom portions of the plant were selected for sampling from each of four plants from the same population as used in subsequent experiments. Disks were cut to form three specimens per plant of six disks thick (two from each leaf) for a total of 24 disk specimens. One specimen of each thickness from each plant was tested at each of three relative humidity differences (44 to 75%, 44 to 85%, and 44 to 95%). The tests were run at 55, 65, and 75°F.

Paraffin was used to create a mold to hold the lamina disks firmly in place. The form used for molding the paraffin molds is shown in Figure 3. It consisted of two rubber stoppers with their small surfaces facing. The lamina disks were placed between the stoppers. Pressure was applied to the stoppers to product intimate contact between the layers of lamina. Several coatings of paraffin were applied to the tobacco and to the curved surfaces of the stoppers, until, when hardened,

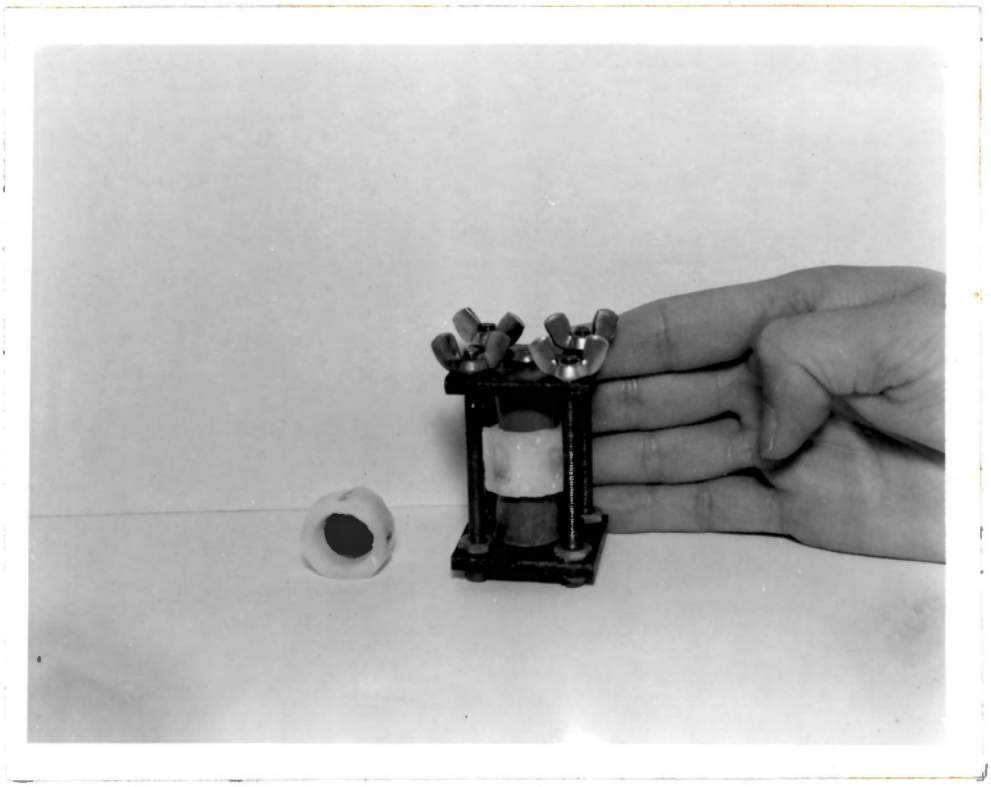


Figure 3. A paraffin mold was used to hold lamina disks firmly in place during steady state experiment.

the paraffin provided a rigid mold for holding the lamina disks as shown in Figure 4. Size of the stoppers was such that the mold could be placed on top of a test tube containing a saturated salt solution as shown in Figure 4 and sealed to the test tube with paraffin.

Twenty-four (three sets of eight) test tubes were partially filled with saturated salt solution of NaCl, KCl, and K_2SO_4 to provide relative humidities as shown in this chapter. Disk specimens were sealed over the top of the test tubes which were then placed in two desiccator jars which contained a saturated solution of K_2CO_3 to maintain a 44% relative humidity.

The jars were placed in a small environmental control chamber to maintain temperature. The specimens were allowed to equilibrate for 72 hours to reach steady state. The test tubes were then weighed every 12 hours on an electrical balance which weighed to the nearest 0.0001 gm. Each test was run for at least 60 hours for five weight recordings.

At the end of the tests, a slight deposit of salt was detected on a few of the samples. As a precaution against possible error, the tests were completely rerun using sulfuric acid solutions to provide the desired relative humidity in the test tubes. The new specimens were made from four other plants taken from the same population.

After completion of the steady state experiment using sulfuric acid solutions, eight additional specimens were made up to be run at one relative humidity difference (44 to 95%). Saturated salt was used in the test tubes, however, a loose ball of cotton was placed above the salt to prevent build up of salt on the specimens.

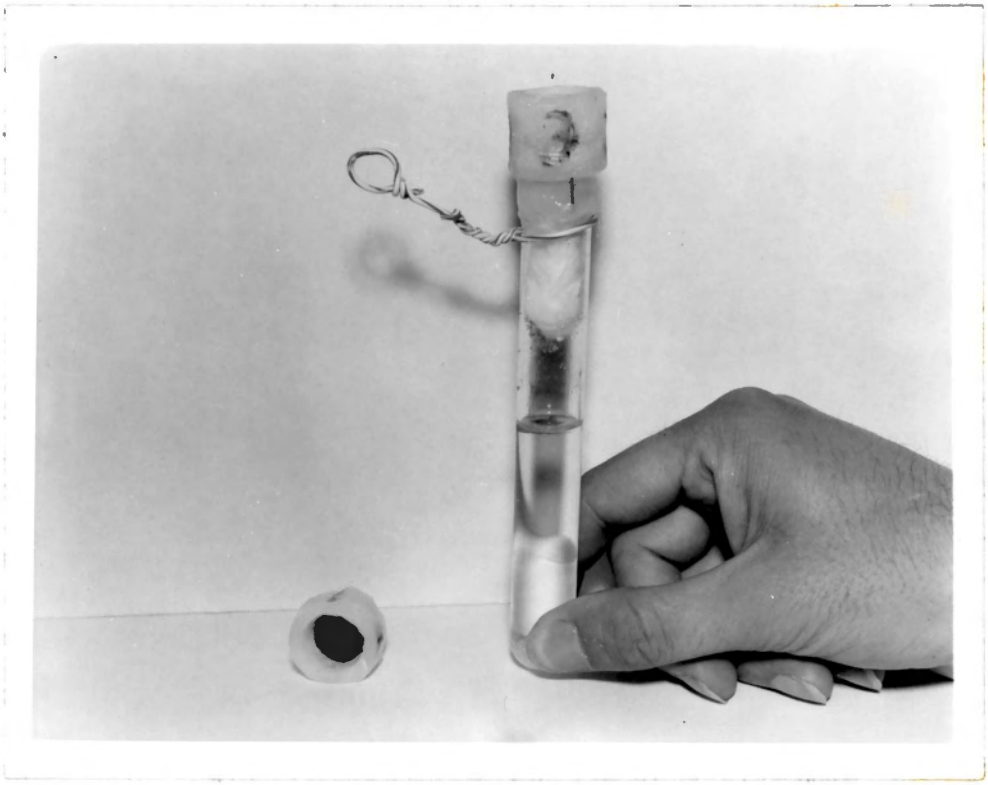


Figure 4. The paraffin molds were placed on top of test tubes containing saturated salts.

The best fit of the weight as a function of time was determined using linear regression. The slope of the regression line was the rate of mass transfer, m, needed in equation 47. The steady state diffusion coefficients were then calculated from this equation.

III. SORPTION AND DESORPTION EXPERIMENTS

Methods and Materials

The steps in the sorption and desorption experiments were as follows:

1. Sorption and desorption data for whole burley leaves were determined.
2. Sorption and desorption data for the lamina only of these same leaves were determined.
3. Lamina data were subtracted from whole leaf data to obtain sorption and desorption data for the midrib.
4. The mathematical models (equations 34 and 46) were then "fitted" to the data by computing the value of the diffusion coefficient, D', that minimized the difference between predicted and observed values of $\Theta(t)$.

The following levels of variables were chosen for these tests

Temperature (sorption and desorption)	55, 65, 75°F
Sorption Relative Humidities	75, 85, 95%
Components	Lamina, midrib
Direction of moisture flow	Sorption, Desorption
Replications	4

Desorption relative humidity was maintained at 44% throughout all tests.

The test units were single tobacco plants of Burley variety 21. A total of 12 plants were used in the tests. Three sets of four plants (replications) were prepared for testing at 55, 65, and 75°F. Two sets of plants were being conditioned at 44% relative humidity while the other set was being tested.

The tests on whole leaves were made with the leaves on the stalk. To accomplish this, the stalk was coated with paraffin. The split in the base of stalk (made at harvest in placing the stalks on a stick for handling and curing) caused difficulty especially in proper coating of the split section. Thus, the split was covered completely with masking tape and the tape covered with paraffin. A coated stalk less leaves was tested to determine the effectiveness of the masking tape and paraffin coating. The stalk showed a 0.2% moisture content gain over a 23 hour sorption test. Thus, the combination proved to be a very good moisture barrier for the stalk.

After the whole leaf tests were completed, the leaves were removed from the stalk, the midribs coated with paraffin, and the leaves repositioned on a wire for the lamina tests with approximately the same spacing as on the plant. Removal from the stalk was required, since the coating process necessitated moving and bending the leaves, which caused cracks in the paraffin. This effect was minimized when the leaves were removed from the stalk and easy access was afforded to both sides of the midrib. A heavy coating was applied to both sides, not only to provide a moisture barrier, but also to provide structural rigidity to prevent the paraffin from cracking.

Paraffin was proven to be a good vapor barrier for the midrib. Five midribs, stripped of lamina and conditioned at 44% relative humidity, were coated with paraffin which was allowed to harden overnight in the same 44% environment. The midribs were weighed the next morning, placed in a 75% relative humidity environment and reweighed after 24 hours. Three specimens showed no weight gain and two specimens showed gains of approximately 0.03% moisture content.

The moisture change of the whole leaves and lamina during sorption and desorption was determined by monitoring weight change as a function of time using small load cells.

Figure 1, page 4, has illustrated the high correspondence between relative humidity and moisture content for sorption tests. At least three days are required to reach equilibrium in sorption (Artho, 1955) with a much shorter period for desorption. On the basis of the data from Walton and Henson (1970) the sorption tests were run for 24 hours and the desorption tests were run to equilibrium. Also, the tobacco was not allowed to exceed 35% moisture content (dry basis) to prevent mold.

Equipment

A general sketch of the chamber built for the sorption tests is shown in Figure 5. A small room (Figure 6), with 50 square feet of floor area and atmospheric control ($\pm$1°F dry bulb and dew point temperature), was built to house the dorption chamber shown in Figure 7. The well insulated chamber was placed inside the room which provided the temperature control for the sorption chamber through control of the

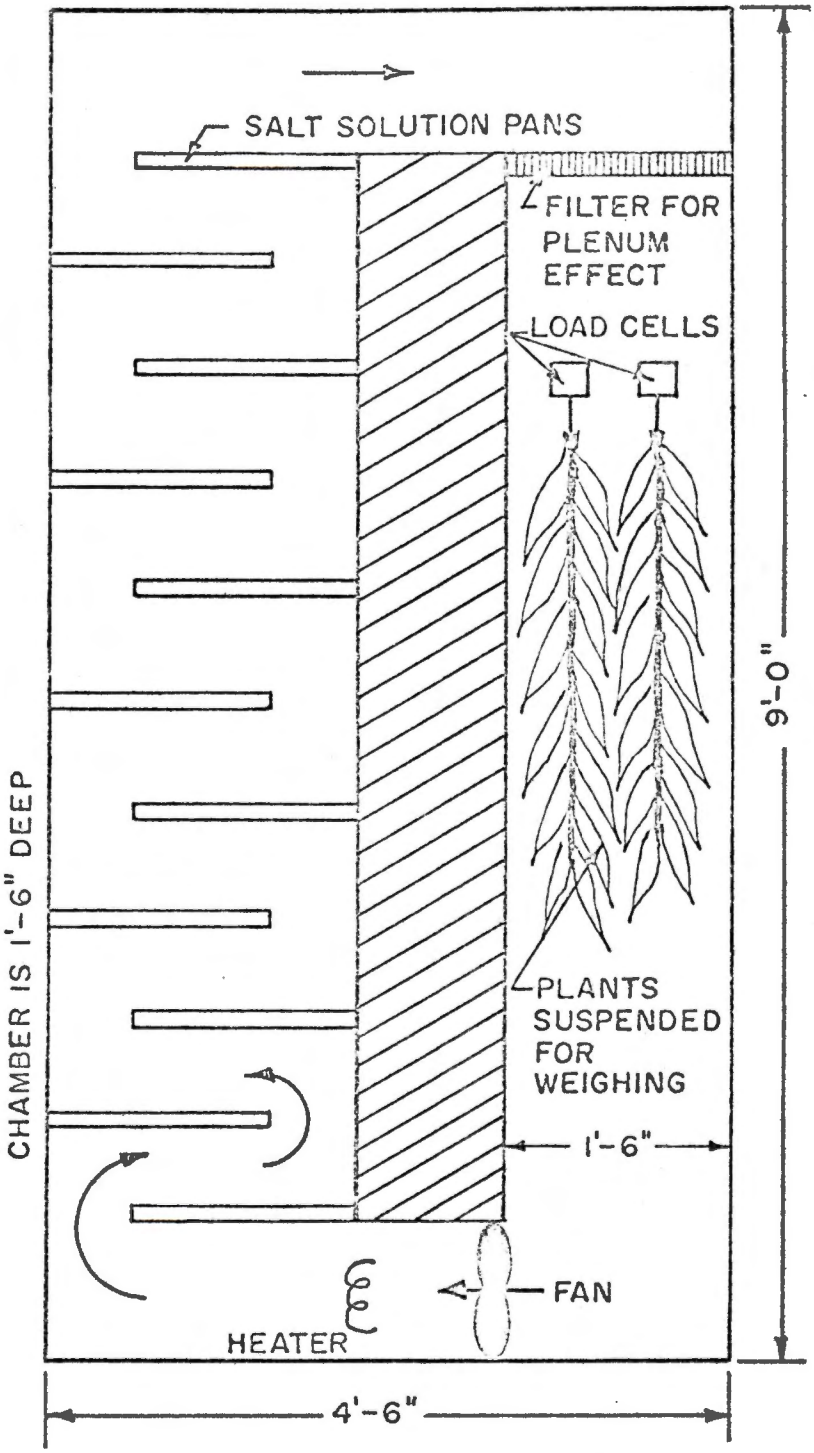


Figure 5. Schematic of the sorption chamber.



Figure 6. The sorption chamber was housed in a small environmentally controlled room.

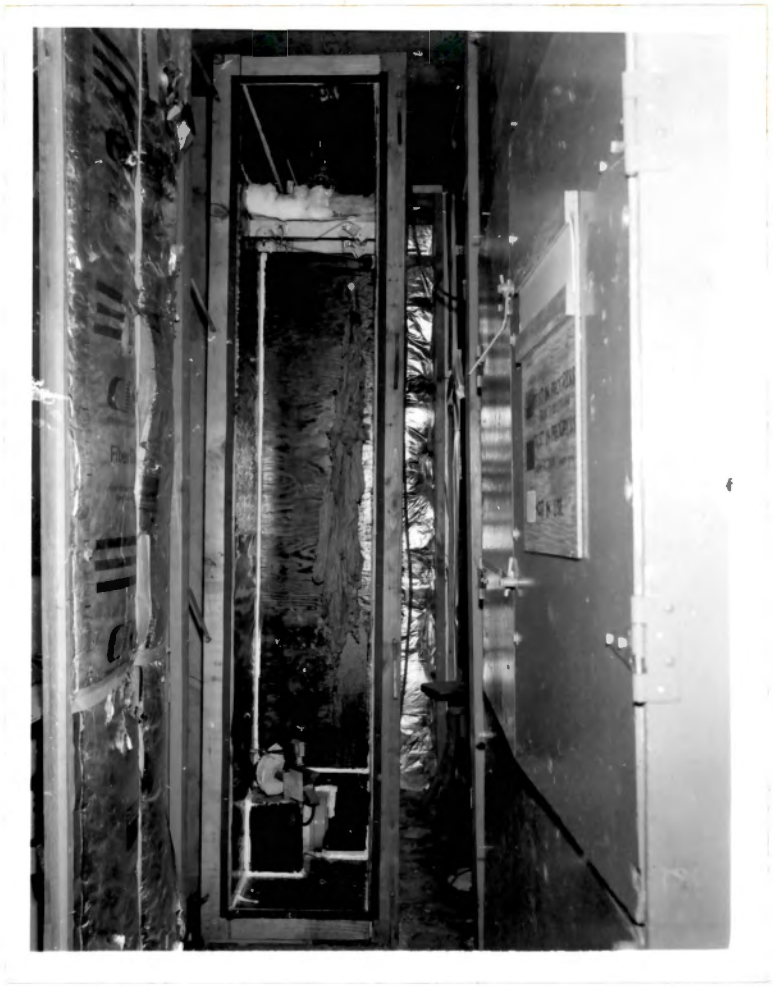


Figure 7. The test section of the sorption chamber.

ambient temperature. Saturated salts as discussed below provided the desired relative humidities within the sorption chamber. Air flow from a squirrel cage fan was varied by a damper over the suction opening. The fan motor was insulated from the chamber; however, friction of the fan and sidewall caused the temperature within the chamber to rise 5 - 7°F above ambient. This proved to be no problem; however, as temperature within the chamber was very uniform as sensed by thermocouples placed above and below the test section. Wet bulb thermocouples were installed above and below the test section to monitor relative humidity. The heater shown in Figure 5 was used to provide rapid temperature increases between tests.

Appeoximately five gallons of saturated salt solution was placed in the eleven pans shown in Figure 5 to provide 24.75 square feet of liquid surface exposed to the circulating air. The surface area was in all cases adequate to replace sorbed moisture as monitored by wet bulb thermocouples above and below the test section. The salts used were NaCl, KCl, and K_2SO_4. Relative humidities produced by these salts have been given by Artho (1955) and Hall (1957) as

Temperature	NaCl	KCl	K_2SO_4
55°	75.5	88	98
65°	75.5	86	97.5
75°	75.5	84	97

These salts did not give the precise relative humidities of 75, 85, and 95% but did cover the desired range.

Four 16-oz load cells were used to monitor specimen weight in the

sorption chamber (Figure 5). The sensitivity of the load cells was 244.38 microvolts (open circuit) per volt per ounce. The load cells were connected to a multi-channel digital strain indicator having a sensitivity of 0.5 microvolts per volt per count. The combined sensitivity of the system was 482 counts per ounce.

The desorption chamber is shown in Figure 8 and Figure 9. A small fan was placed in the chamber to provide air circulation to facilitate moisture transfer to the surface of the salt solution. Potassium carbonate (K_2CO_3) was used to maintain a relative humidity of 44% over the desired temperature range. This chamber was placed in another controlled atmosphere room where the temperature of the desorption chamber was maintained by controlling the ambient temperature. The specimens were suspended from the load cell in Figure 8 for weight recording.

Procedure

The test plants were always stored in a dry environment (40-45% relative humidity) when not being tested or prepared for a test. Twenty-hour hours before a test was to begin, the four test plants were removed to the desorption chamber for conditioning to a uniform initial moisture content at the test temperature. Immediately before a test, the plants were removed from the conditioning chamber, weighed, and transported to the sorption chamber. The fan was turned off in the sorption chamber which was already at the specified conditions. The chamber was opened and the tobacco placed in as quickly as possible. The fan was turned on and the initial weight readings were taken. Weight readings were taken at 10 minute intervals during the first hour, 15 minute intervals for

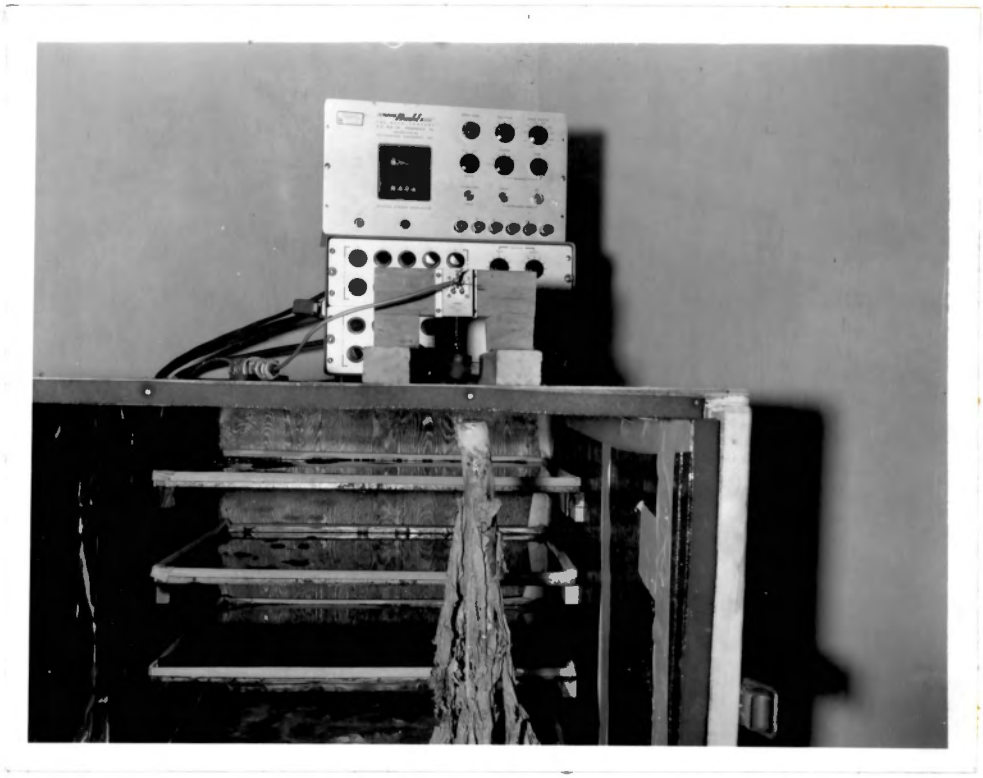


Figure 8. The specimens in the desorption chamber were suspended from the load cell for weighing.



Figure 9. The desorption chamber.

approximately eight hours, and at irregular intervals for the next four to six hours with a final reading at approximately 24 hours from the initiation of the test. The tobacco was then removed from the sorption chamber and transferred as quickly as possible to the desorption chamber which was maintained at the same temperature as the sorption chamber. Data were recorded for desorption at 10 minute intervals the first hour, 15 minute intervals the second hour and 30 minute intervals thereafter until weight loss was so small that longer irregular intervals were used.

Equilibrium moisture contents for the burley lamina and midrib were needed corresponding to the relative humidities given for the saturated salts used in the experiment in order to apply the mathematical models for the lamina and midrib (equations 34 and 46, respectively) to the sorption and desorption data. The equilibrium moisture contents of the lamina and midrib were assumed to be the same. Equilibrium moisture contents used in making calculations for the sorption and desorption tests were taken from Figure 1, page 4, as follows:

Temperature	44% RH	75.5% RH	84-88% RH	97-98% RH
55°F	8.6%(db)	24.9	46.8	79.0
65°F	8.0	22.8	38.5	70.0
75°F	7.4	20.7	30.2	62.0

Equations 34 and 46 were fitted to the sorption and desorption data using the method of Marquardt (1966) of minimizing the sum of squares of the differences between observed and predicted values of moisture ratio, $\Theta(t)$, through an iterative process. The computed

parameter was the mass diffusion coefficient giving the best fit of equations 34 and 46 to the experimental data.

The exponential equation (equation 2) was used as the standard of comparison in evaluating the success or failure of equations 34 and 46. The exponential equation was chosen because it is the most widely used model for describing moisture transfer in burley tobacco.

A standard error of regression (hereafter referred to as standard error) was calculated from the sum of squares of the difference between observed and predicted values of moisture ratio. It was used as the criterion for describing the goodness of fit of the mathematical models to the data. The mathematical definition of the standard error as applied here is

$$S.\ E. = (M_o - M_e)\sqrt{\frac{\sum_{i=1}^{n} (\Theta_o - \Theta_p)_i^2}{n - 1}}\ , \qquad (48)$$

where S. E. = standard error, % moisture content,

Θ_o = experimentally observed value of moisture ratio,

Θ_p = predicted value of moisture ratio,

n = number of observations, and

$(M_o - M_e)$ = factor for converting standard error in terms of moisture ratio to standard error in moisture content, %.

CHAPTER V

RESULTS AND DISCUSSION

I. VERIFICATION OF BASIC ASSUMPTIONS

In Appendix A, the transient heat transfer curves were predicted for both lamina and midrib using the thermal properties of Duncan, et al. (1966). The predicted lag coefficients were 16.5 seconds for the lamina and 68.3 seconds for the midrib. The experimentally determined lag coefficients for the lamina and midrib are shown in Tables 1 and 2, respectively. Comparison of the heat gain data to heat loss data show that the lag coefficient for heat gain was consistently less than that for heat loss for both lamina and midrib. In contrast, the theoretical calculations predicted no difference between heat loss and heat gain lag coefficients. Tables 1 and 2 show no consistent trends with stalk position or temperature range. However, the 83° - 96°F and 96° - 83°F tests showed a much lower lamina lag coefficient than did the other tests. Comparison of the predicted lag coefficient, 16.5 seconds, and the average of all experimental lag coefficients for the lamina shown in Table 1, 15.5 seconds, showed that the predicted lag coefficient and consequently, the predicted curve to be reasonable. Therefore, the data would substantiate the thermal properties given by Duncan, et al (1966) for the lamina. The predicted lag coefficient for the midrib, 68.3 seconds, was considerably higher than that from the experimental data, an average of 23.0 seconds for Table 2. The difference was attributed

Table 1. Heat Transfer Lag Coefficient (sec) for the Burley Lamina as a Function of Stalk Position, Temperature, and Direction of Flow

Stalk Position	Initial Temperature (°F) 38-83	61-84	93-96	Mean[a]	Final Temperature (°F) 83-38	84-61	96-83	Mean[b]
Bottom	15.0	12.5	5.2	10.9	21.8	19.2	14.8	18.6
Middle	9.0	17.0	3.8	9.9	26.0	22.3	6.9	18.4
Top	18.0	18.0	7.2	14.4	25.0	25.8	11.8	20.9
Mean	14.0	15.8	5.4	11.7	24.3	22.4	11.2	19.3

[a]Mean of columns 1, 2, and 3.

[b]Mean of columns 4, 5, and 6.

Table 2. Heat Transfer Lag Coefficient (sec) for the Burley Midrib as a Function of Stalk Position, Temperature, and Direction of Flow

Stalk Position	Initial Temperature (°F) 35-80	59-79	79-100	Mean[a]	Final Temperature (°F) 80-35	79-59	100-79	Mean[b]
Bottom	21.8[c]	19.3	20.8	20.6	27.9	21.4	20.8	23.4
Middle	18.1	24.0	24.0	22.0	27.5	24.4	27.6	26.5
Top	19.6	17.9	19.6	19.0	28.7	19.7	30.3	26.3
Mean	19.8	20.4	21.5	20.5	28.0	21.2	26.2	25.4

[a]Mean of columns 1, 2, and 3.

[b]Mean of columns 4, 5, and 6.

[c]Average for three midribs.

to the assumption that the thermal conductivity of the midrib is the same as that of the lamina. The thermal conductivity of the midrib is apparently two to two and a half times greater than that of the lamina and comparable to that of wood. This might be expected since some other properties of the midrib, such as modulus of elasticity, have been shown by Walton (1974) to approach that of wood. These results validate the assumption that the very small transient heat transfer period for both the lamina and midrib could be neglected compared to the relatively long moisture transfer period.

Moisture content of the midrib taken at 0 and 5 hours for three one-inch wide strips of leaf cut perpendicular to the midrib (B with lamina, A and C without) taken from each of six leaves are shown in Table 3. Test conditions were 96% relative humidity and room temperature (approximately 75°F) with a corresponding equilibrium moisture content of 62%. If transfer between lamina and midrib was substantial, the difference should be apparent after five hours exposure to an equilibrium moisture content of such magnitude. The midribs gained 8.9 to 10.7% moisture content during the five-hour period. By comparing the moisture content of the A, B, and C specimens after five hours, it was apparent that the effect of the lamina on midrib moisture content was not large enough to be seen over the variation in moisture content between midrib sections of the same leaf. Maximum moisture gain of the lamina specimen over stripped specimens was 0.6%. Transfer of moisture between lamina and midrib must be at the most, a few tenths of one percent.

Table 3. Moisture Content (Dry Basis) of Midrib Sections at 0 and 5 Hours When Exposed to 96% RH and Room Temperature (Approximately 75°F)

Sample No.	M. C. at 0 hrs.	M. C. at 5 hrs.
1 A[a]	6.3	16.4
1 B[b]	-	16.6
1 C	6.5	16.2
2 A	7.1	17.0
2 B	-	17.4
2 C	6.8	16.8
3 A	5.8	14.9
3 B	-	14.6
3 C	5.9	14.8
4 A	6.4	16.6
4 B	-	16.5
4 C	6.2	16.9
5 A	6.9	16.5
5 B	-	16.7
5 C	7.0	16.3
6 A	6.3	16.0
6 B	-	16.1
6 C	6.3	16.4

[a]Three sections (A, B, C) taken from each of 6 leaves. A, C--stripped of lamina, B--lamina intact.

[b]The B specimens had lamina intact and the midrib could not be weighed separately.

The two coated midrib lamina sections with the exposed cross section of the lamina were exposed to the 96% relative humidity and room temperature (approximately 75°F) for 20 hours. The initial moisture content of the specimens was 7% while equilibrium moisture content was 62%. Thus, the potential for moisture transfer was great. The moisture content gain of the two coated specimens was 0.6 and 0.7%, respectively. Again, the indication was that the transfer of moisture between lamina and midrib during sorption and desorption is negligible when compared to the moisture exchange between each leaf component and the atmosphere.

The effect of air velocity on the moisture transfer was determined by plotting and comparing the moisture gain curves of whole leaves where the only difference between the curves was the air velocities of 10, 15, and 30 feet per minute. A typical example of these curves are shown in Figure C-1 of Appendix C. The difference between the curves was generally less than four counts (482 counts = 1 ounce) with no consistent trends. The moisture gain was independent of velocity. Thus, it was concluded that the convective mass transfer coefficient could be considered infinite and air velocity need not be included as a variable.

II. STEADY STATE RESULTS

The analysis of variance of the diffusion coefficients as calculated from the steady state disk data is shown in Table C-1 of Appendix C. The two sets of data (called tests in Table C-1) were considered as a treatment. The effect of temperature and relative humidity on the

diffusion coefficients were significant at the 1% level. The temperature test interaction was significant at the 5% level. Thickness as well as all other interactions were not significant. The diffusion coefficients averaged across test; thickness, and plant (replication) were as follows:

	75% RH	85% RH	95% RH
55°F	1.022×10^{-8} ft^2/hr	0.872	0.686
65°F	2.190	1.623	1.299
75°F	3.172	2.823	2.330

The eight specimens using the loose cotton to prevent build up of salt on the specimens produced comparable data to that shown above indicating that any consequent error was negligible.

The steady state diffusion coefficients varied directly with temperature and indirectly with relative humidity. The diffusion coefficients were very small numbers due primarily to the half thickness of the lamina used in the calculations.

The analysis of variance showed that there was no significant difference in diffusion coefficients between the three and six layer thick specimens. This was interpreted as another indication that the surface resistance is negligible compared to internal resistance.

III. SORPTION AND DESORPTION RESULTS

Evaluation of Lamina and Midrib Models

The mass diffusion coefficients, D', computed from fitting equations 34 and 46 to the sorption and desorption data are shown in

Table 4. The values are averaged over replications (plants). The corresponding standard errors of regression as defined by equation 48 of Chapter IV and averaged over replications are shown in Table 5. A sample calculation is made in Appendix C.

The corresponding average k-values computed in fitting the exponential equation (equation 2) to the sorption and desorption data are shown in Table 6. The average standard error for the exponential equation is shown in Table 7. The mass diffusion coefficients, k-values, and standard errors for each individual data curve are shown in Tables C-2 through C-17.

From comparison of Tables 5 and 7, the mathematical models for the lamina and midrib proved to be far superior to the exponential equation as mathematical predictors of burley sorption. The superiority extended to all environmental conditions for both lamina and midrib sorption. The standard error of equations 34 and 46 were approximately one third that of the exponential equation. Thus, it was concluded that the lamina and midrib models describe the nature of sorption of burley tobacco better than previously developed models.

Typical examples of the lamina sorption and desorption data with the prediction curves from the lamina model are shown in Figures 10 and 11, respectively. The model generally over estimated moisture content change during the initial portion of the curve and under estimated during the latter portion of the curve for both sorption and desorption. In contrast, the exponential equation typically under estimated during the initial portion of the curve and over estimated in the latter

Table 4. Mass Diffusion Coefficient (Average of Four Replications) as a Function of Temperature and Relative Humidity

Environmental Conditions	Mass Diffusion Coefficient (ft^2/hr) x 10^{10}			
	Lamina Sorption	Midrib Sorption	Lamina Desorption	Midrib Desorption
55°F, 75%	0.949	529.0	7.655	3296
65°F, 75%	1.383	891.0	18.250	4962
75°F, 75%	2.558	1157.0	19.875	8311
55°F, 75%	0.298	144.1	5.383	3270
65°F, 85%	0.776	313.3	10.923	5518
75°F, 85%	1.519	1114.0	14.373	8260
55°F, 95%	0.278	117.4	3.970	3189
65°F, 95%	0.426	196.3	7.865	7942
75°F, 95%	0.657	402.3	11.698	7077

Table 5. Average Standard Error in Percent Moisture Content of Lamina and Midrib Models (Equations 34 and 46, Respectively) at Various Temperatures and Relative Humidities

Environmental Conditions	Standard Error (Percent Moisture Content)			
	Lamina Sorption	Midrib Sorption	Lamina Desorption	Midrib Desorption
55°F, 75°	0.30	0.25	0.17	0.22
65°F, 75%	0.32	0.47	0.16	0.18
75°F, 75°	0.35	0.24	0.14	0.21
55°F, 85%	0.39	0.45	0.39	0.31
65°F, 85%	0.51	0.27	0.35	0.49
75°F, 85%	0.49	0.74	0.52	0.73
55°F, 95%	0.56	1.07	0.65	0.58
65°F, 95%	0.51	0.69	0.87	1.28
75°F, 95%	0.86	0.49	0.76	1.24

Table 6. Average Value of Parameter k in Exponential Equation (Equation 2) as a Function of Temperature and Relative Humidity

Environmental Conditions	k-Value (hr^{-1})			
	Lamina Sorption	Midrib Sorption	Lamina Desorption	Midrib Desorption
55°F, 75%	0.0487	0.0372	0.2652	0.1368
65°F, 75%	0.0647	0.0478	0.5348	0.1704
75°F, 75°	0.1141	0.0656	0.6555	0.2174
55°F, 85%	0.0259	0.0177	0.1873	0.1225
65°F, 85%	0.0464	0.0276	0.3580	0.1802
75°F, 85%	0.0691	0.0543	0.4686	0.2310
55°F, 95%	0.0240	0.0166	0.1566	0.1470
65°F, 95%	0.0317	0.0244	0.2646	0.2480
75°F, 95%	0.0400	0.0291	0.3462	0.2440

Table 7. Average Standard Error in Percent Moisture Content of Exponential Equation (Equation 2) at Various Temperatures and Relative Humidities

Environmental Conditions	Standard Error (Percent Moisture Content)			
	Lamina Sorption	Midrib Sorption	Lamina Desorption	Midrib Desorption
55°F, 75%	1.00	0.77	0.28	0.22
65°F, 75%	0.92	1.01	0.32	0.32
75°F, 75%	0.40	0.49	0.28	0.46
55°F, 85%	1.35	1.21	0.28	0.32
65°F, 85%	1.67	1.19	0.31	0.40
75°F, 85%	1.58	1.13	0.15	0.44
55°F, 95%	2.37	1.67	0.57	0.49
65°F, 95%	2.47	2.00	0.51	0.67
75°F, 95%	3.02	2.47	0.39	0.53

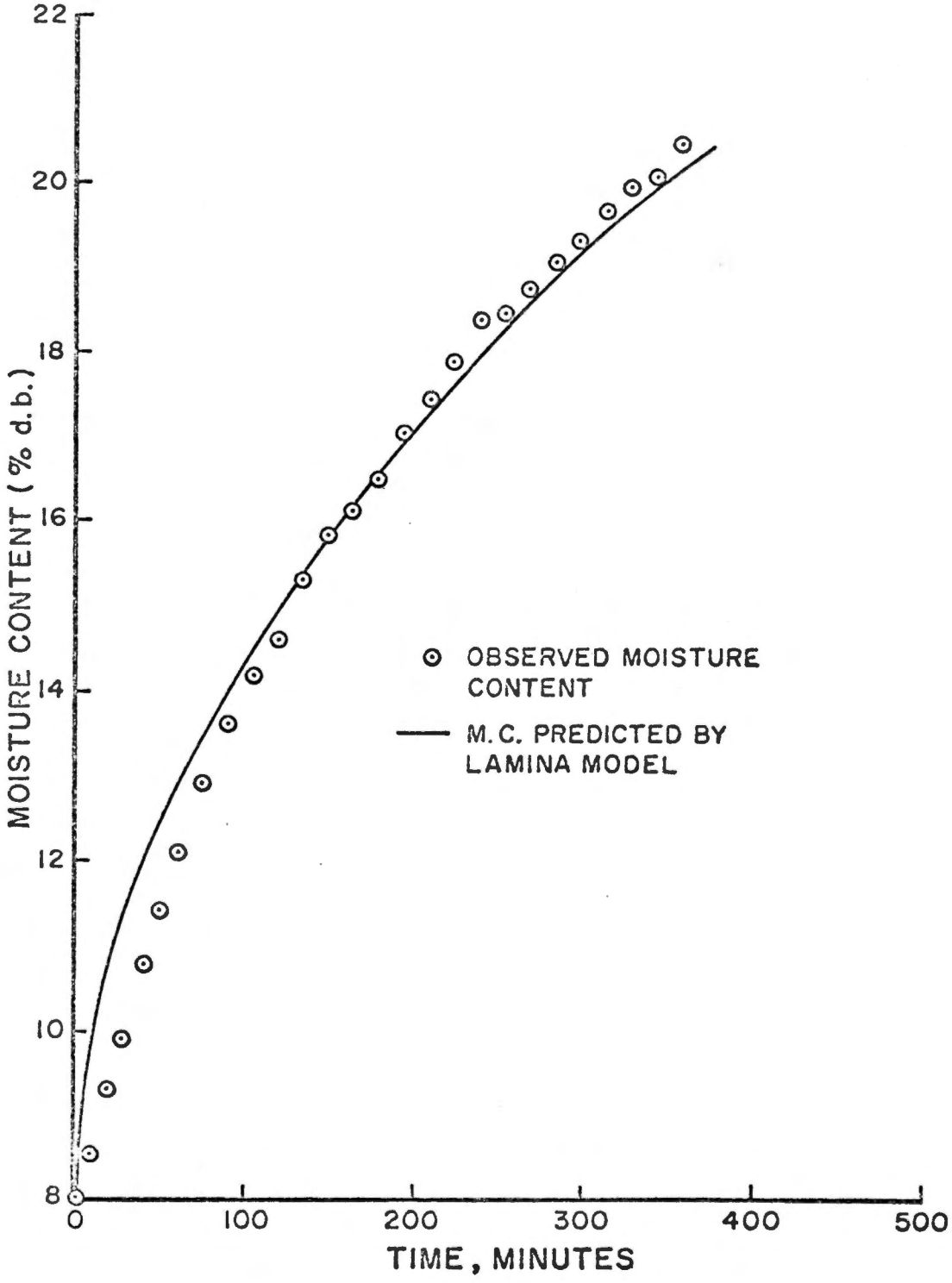


Figure 10. Observed moisture content and that predicted by lamina model (equation 34) for sorption of the lamina of plant 2 at 65°F, 95% rh.

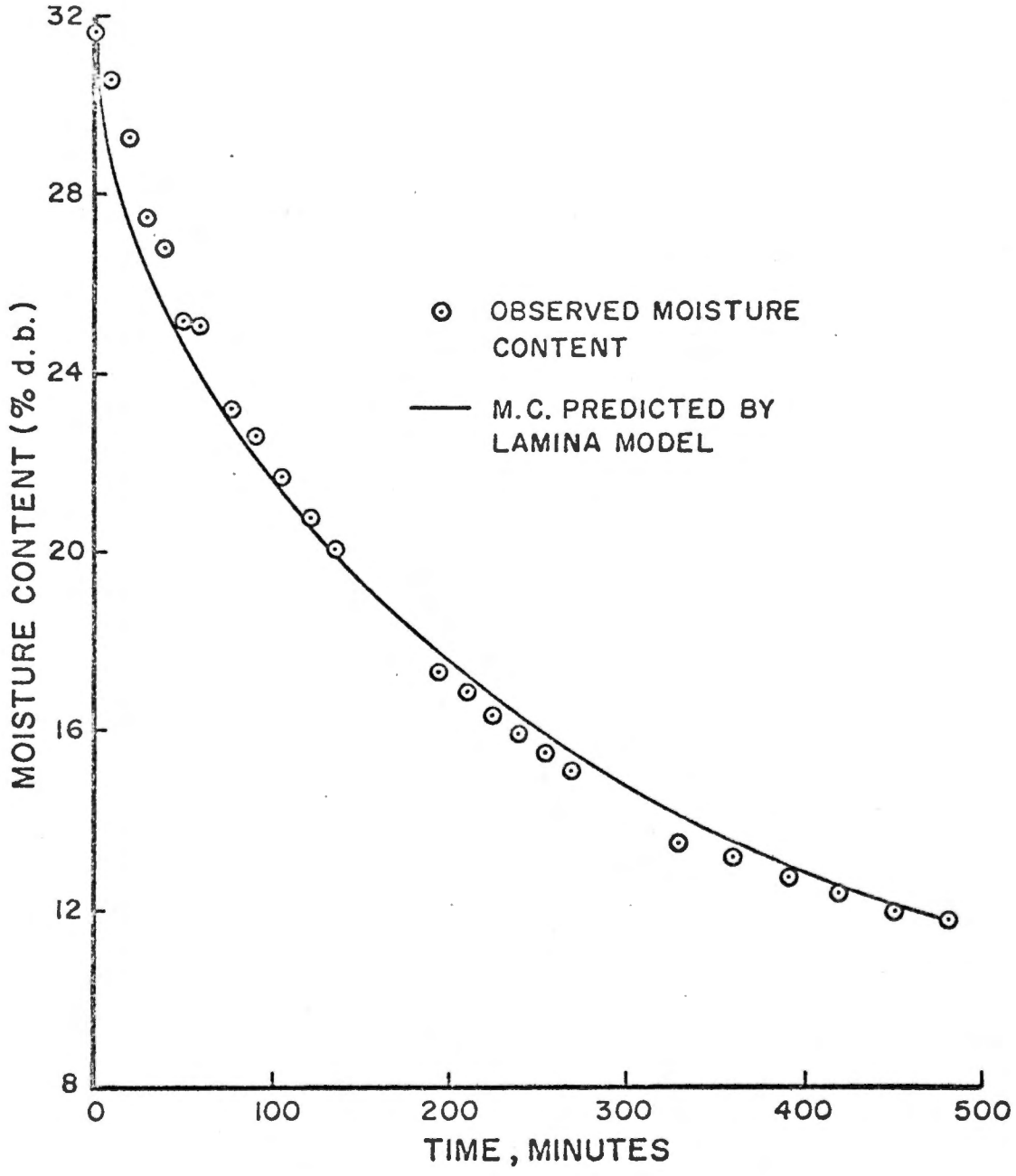


Figure 11. Observed moisture content and that predicted by lamina model (equation 34) for desorption of the lamina of plant 2 at 65°F, 44% rh after removal from 65°F, 95% rh.

portion of the curve for both sorption and desorption. Midrib moisture content typically lagged the lamina moisture content which was expected due to the thickness. For example, the lag corresponding to the sorption curve of Figure 10 was 1.4% moisture content after four hours.

The mathematical models for lamina and midrib were consistent in standard error over lamina and midrib sorption and desorption as shown in Table 5. The exponential equation showed a great variation in standard error between sorption and desorption. The standard error was much less for desorption than for sorption. The difference was so great that the exponential equation had less error for desorption than the developed models for a majority of the nine environmental conditions. Thus, the results showed that the exponential equation was slightly superior to the mathematical models for the lamina and midrib as far as accuracy in fitting the experimental data was concerned.

Comparison of the standard errors for desorption in Tables 5 and 7 showed the exponential equation to be superior to the lamina and midrib models for high humidity while the reverse was true at low humidity. The different humidities represented the sorption humidities from which the tobacco came prior to being placed in the desorption chamber which contained a 44% relative humidity salt. The results indicated that possibly the relative humidity was raised a few percent upon introduction of moist tobacco from the high relative humidity sorption tests. No relative humidity measurements were taken in the desorption chamber during the tests; therefore, to test this hypothesis, the 75°F, 95% desorption test was recreated with a continuous recording of relative

humidity. The relative humidity within the chamber increased 5% upon introduction of the moist tobacco into the chamber. The relative humidity then decreased to 44% over a three hour period. Desorption during the early portions of the high humidity desorption tests would be reduced due to the higher relative humidity in the desorption chamber. A reduction in moisture transfer aided the exponential equation at the expense of the lamina and midrib models since the exponential equation typically lags the observed data while the lamina and midrib models lead the data during the early portion of the curves.

Comparison of Sorption, Desorption, and Steady State Diffusion Coefficients

The steady state diffusion coefficients for the lamina were considerably larger than either the lamina sorption or desorption diffusion coefficients. The reason for this lies in the physiology of the leaf and sheds considerable light on the pathway of moisture movement within the leaf.

The tobacco leaf is made up of three types of cells; eipdermal, palisade, and mesophyll. The epidermal cells form the upper and lower surfaces of the leaf. The palisade cells are long columnar cells located perpendicular to the surface of the leaf and just below the upper epidermal cells. Several layers of mesophyll cells, often called the spongy mesophyll, are located between the palisade cells and the lower epidermis. Avery (1933) observed that, during plant growth, the epidermal cells continue enlarging after the mesophyll cells have ceased to enlarge. As a consequence, the mesophyll cells are pulled apart

creating large air spaces. As the epidermal cells continue to enlarge the palisade cells are pulled apart to some extent. Thus, a continuous network of pore space is present between the epidermal cells. It was apparent that during the steady state tests moisture moved through the epidermal cells, then through the continuous network of pore space and out of the other epidermal layer. The resistance of entering the interior cells was never encountered in the steady state. Since the resistance to moisture transfer was less in the steady state as compared to sorption and desorption, the corresponding diffusion coefficients were higher. It was concluded that the resistance to moisture movement during sorption and desorption stems from two sources. The overall resistance is a summation of the resistances encountered in moving through the epidermal cells and into and out of the interior cells respectively.

Comparison of the mass diffusion coefficients of the lamina and midrib during sorption and desorption show that both components dry considerably faster than they sorb moisture. This phenomena was expected since it is true of biological materials in general. The difference between drying and wetting of burley was much greater than that of wood as given by Comstock (1963). This difference was attributed to swelling of the tobacco during sorption and shrinking during desorption. Swelling required an adsorption of energy while shrinkage involved a release of energy. The effect was to retard moisture sorption and enhance desorption.

During sorption, leaf surfaces were exposed to high relative humidities, causing the leaf surfaces to swell. The internal cells

resisted this swelling causing a compressive stress at the surface. Comstock (1963) stated that if wood is absorbing while under compression, its equilibrium moisture content will be lower than the stress free value by an amount dependent on the magnitude of the stress. It is possible that the same phenomena applies to tobacco, thus, lowering the rate of sorption. During desorption, the leaf surface is under tensile stress causing an increase in equilibrium moisture content. This would also reduce the rate of desorption. However, Comstock (1963) indicated the effect on the desorption curves would be minimal as compared to the sorption curves since wood shrinks faster than it swells. This would indicate that dimensional change and moisture change are interrelated with the rate of one affecting the other.

Comparison of the mass diffusion coefficients for lamina and midrib showed the mass diffusion coefficient for the midrib to be much greater than that of the lamina. This was intuitively expected since the models for lamina and midrib showed that if the diffusion coefficients of the lamina and midrib were equal, the moisture of the midrib would drastically lag the lamina. Although the midrib moisture does in practice lag the lamina moisture, it is not anything like that expected if the diffusion coefficients of the lamina and midrib were equal. Future research is needed on the mechanism of the diffusion process to determine whether this huge difference in diffusion coefficient of the midrib and lamina can be attributed to a greater cell surface area in the midrib, a greater cell permeability in the midrib, a combination of the two, or some other factor altogether.

The superiority of the lamina and midrib models to the exponential equation in describing the physics of the moisture transfer can now be shown. Conductivity of moisture in the midrib was greater than that of the lamina, yet, the characteristic length of path for moisture movement was the midrib radius as compared to the half-thickness of the lamina. The combined effect of these factors was that rate of moisture change was greater in the lamina than in the midrib. While the lamina and midrib models show the effect of both conductivity and path length, the exponential equation shows only the bulk effect of the combination of the two. Therefore, the mathematical models developed for the lamina and midrib better describe the physics of moisture transfer than does the exponential equation.

The mass diffusion coefficients for the desorption and sorption data vary directly with temperature and indirectly with relative humidity as did the steady state diffusion coefficients. The exponential k-value also varied directly with temperature and indirectly with relative humidity. However, the mass diffusion coefficient was larger in the midrib than in the lamina, while the reverse was true for the k-value. The midrib mass diffusion coefficient, while not as high as wood, proved to be closer to that of wood than to that of lamina.

CHAPTER VI

SUMMARY AND CONCLUSIONS

A mathematical analysis of the sorption and desorption of the burley tobacco leaf showed that the lamina and midrib should be modeled separately. The lamina and midrib were geometrically represented by the infinite thin sheet and the infinite circular cylinder, respectively. The mathematical models were based on the vapor diffusion equation and expressed the average lamina and midrib moisture content as a function of time in the form of an exponential series. Both models involved three parameters: equilibrium moisture content, a finite convective mass transfer coefficient, and diffusion coefficient. Equilibrium moisture contents were taken from the literature. Theoretical calculations, later substantiated by experimental results, showed that for all practical purposes, the convective mass transfer coefficient could be considered infinite, i.e., surface resistance is negligible compared to the internal resistance of the lamina and midrib to moisture transfer. Diffusion coefficients were determined experimentally.

Experiments were designed to determine the applicability of the mathematical models to the sorption and desorption of the cured burley lamina and midrib. The exponential thin layer drying model was used as the standard of comparison. The procedure was first to determine the sorption and desorption of whole leaves. The midrib of these same leaves were next coated with paraffin to prevent moisture transfer to or from the midrib. The sorption and desorption of the lamina was

determined. The lamina data were then subtracted from the whole leaf data to determine the midrib data.

Environmental control chambers were designed and built for the experiments to allow control of temperature, relative humidity (using saturated salt), and air flow. Load cells were used to determine weight gain and loss (which could easily be converted to moisture gain or loss) during sorption and desorption, respectively. Tests were conducted at temperatures of 55, 65, and 75°F. Specimens were conditioned at 44% relative humidity initially, then exposed to relative humidities of 75, 85 and 96% for sorption. After sorption, the specimens were exposed to the 44% relative humidity to determine the desorption curves.

The results showed that the lamina and midrib models were substantially better than the exponential equation in describing the experimental sorption curves. In contrast, the exponential model was slightly superior to the lamina and midrib models in describing the experimental desorption curves. However, the lamina and midrib models were judged superior to the exponential model in describing the nature of the mass transfer process by showing the effect of both moisture conductivity and physical dimensions of the leaf while the exponential model shows only the combined effect of the two. Therefore, the midrib and lamina models have a more general application than the exponential model since the exponential k-value varies with midrib diameter and lamina thickness.

Steady state experiments were conducted to determine independent diffusion coefficients for the lamina. Results showed the steady state diffusion coefficients to be considerably higher than the corresponding

diffusion coefficients determined from sorption and desorption data. The difference was attributed to the physiology of the lamina. There is a continuous network of pore space between the epidermal layers of the lamina that allows moisture in the steady state to move between epidermal layers without encountering the resistance of moving into and from interior cells. Thus, the lower resistance to moisture movement in the steady state resulted in higher diffusion coefficients.

From considerations made during the mathematical analysis and from results of experimental tests, the following conclusions were formulated:

1. The lamina and midrib models developed in this dissertation describe the nature of the moisture transfer process better than the exponential model in that they include both moisture conductivity and physical dimensions of the leaf while the exponential equation shows only the combined effect of the two.
2. The lamina and midrib models are more accurate than the exponential model in describing sorption of cured burley tobacco.
3. The convective mass transfer coefficient can be considered infinite for velocities of more than 10 feet per minute over the cured burley leaf.
4. Heat transfer need not be considered simultaneously with the mass transfer of burley tobacco since the transient heat transfer period is very short compared to the transient moisture transfer period.

5. Both lamina and midrib dry much faster than they sorb moisture.
6. The diffusion coefficients of the midrib are greater than the corresponding diffusion coefficients of the lamina.
7. The mass diffusion coefficients of both lamina and midrib vary directly with temperature and indirectly with relative humidity.
8. Lamina diffusion coefficients cannot be determined by steady state since the lamina contains a continuous network of pores which allows moisture to flow, in steady state, from one epidermal layer through the network of pores to the other epidermal layer without passing through the interior cells.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Anderson, P. J. 1937. Studies on the anatomy of the tobacco leaf. Bulletin 39, Connecticut Experiment Station.

2. Arpaci, V. S. 1966. Conduction heat transfer. Addison-Wesley Publishing Company, Reading, Massachusetts.

3. Artho, A. J. 1955. Physical properties of cured tobacco leaves. Vierteljahrsschrift 100:87-113.

4. Avery, G. S. 1933. Structure and development of the tobacco leaf. American Journal of Botany 20:565-592.

5. Becker, H. A. and H. R. Sallans. 1955. A study of internal moisture movement in the drying of the wheat kernel. Cereal Chemistry 32:212-226.

6. Carslaw, H. S. and J. C. Jaeger. 1959. Conduction of heat in solids. Clarendon Press, Oxford.

7. Chang, C. S. and W. H. Johnson. 1971. Transport phenomena in high temperature convective drying of foliar materials. Transactions of the American Society of Agricultural Engineers 14:590-595.

8. Chen, C. S. and W. H. Johnson. 1969. Kinetics of moisture movement in hygroscopic materials (theoretical considerations of drying phenomena). Transactions of the American Society of Agricultural Engineers 12:109-113.

9. Chen, C. S. and W. H. Johnson. 1969. Kinetics of moisture movement in hygroscopic materials II (an application of foliar materials). Transactions of the American Society of Agricultural Engineers 12:478-481.

10. Comstock, G. L. 1963. Moisture diffusion coefficients in wood as calculated from adsorption, desorption, and steady state data. Forest Products Journal 13:97-103.

11. Crank, J. 1964. The mathematics of diffusion. London: Oxford University Press.

12. Duncan, G. A., J. M. Bunn, and W. H. Henson, Jr. 1966. Thermal conductivity of burley tobacco during the cure. Transactions of the American Society of Agricultural Engineers 9:36-38.

13. Duncan, G. A., J. M. Bunn, and W. H. Henson, Jr. 1968. Specific heat of burley tobacco during the cure. Transactions of the American Society of Agricultural Engineers, 11:480-483.

14. Eckert, E. R. G. and J. R. Gross. 1963. Introduction to heat and mass transfer. McGraw-Hill Book Company, Inc., New York.

15. Esau, Katherine. 1953. Plant anatomy. John Wiley and Sons, Inc., New York.

16. Grober, H., F. Erk, and U. Grigull. 1961. Fundamentals of heat transfer. McGraw-Hill Book Company, Inc., New York.

17. Garner, W. W. 1951. The production of tobacco. McGraw-Hill Book Company, Inc., New York.

18. Hall, C. W. 1957. Drying farm crops. Agricultural Consulting Associates, Inc., Reynoldsburg, Ohio.

19. Henderson, S. M. and R. L. Perry. 1955. Agricultural process engineering. John Wiley and Sons, Inc., New York.

20. Henry, P. S. H. 1939. Diffusion in absorbing media. Proceedings of the Royal Society. Series A, 171:215-241.

21. Henry, P. S. H. 1948. The diffusion of moisture and heat through textiles. Discussions of the Faraday Society, No. 3:243-257.

22. Humphries, E. G. 1963. Mechanisms controlling the drying rate of tobacco during curing. Unpublished Ph.D. Dissertation, North Carolina State University.

23. Jeffrey, R. N. 1940. The effect of temperature and relative humidity during and after curing upon the quality of white burley tobacco. Bulletin No. 407, Kentucky Agricultural Experiment Station, Lexington, Kentucky.

24. Krieth, F. 1964. Principles of heat transfer. International Textbook Company, Scranton, Pennsylvania.

25. Levitt, J. 1969. Introduction to Plant Physiology. The C. V. Mosby Company, St. Louis.

26. Locklair, E. E., L. G. Veasey, and M. Samfield. 1957. Equilibrium desorption of water vapor on tobacco. Agricultural and Food Chemistry 5:294-298.

27. Lykov, A. V. and Y. A. Mikhailev. 1965. Theory of heat and mass transfer. Davey and Company, Inc., New York.

28. Marquardt, D. W. 1966. Least squares estimate of nonlinear parameters. Engineering Department, E. I. DuPont de Nemours and Company, Inc., Wilmington, Delaware.

29. Newman, A. B. 1931. The drying of porous solids: diffusion and surface emission equations. Transactions of the American Institute of Chemical Engineers 27:203-220.

30. Newman, A. B. 1931. The drying of porous solids: diffusion calculations. Transactions of the American Institute of Chemical Engineers 27:310-333.

31. Ngoddy, P. O. and F. W. Bakker-Arkema. 1970. A generalized theory of sorption phenomena in biological materials. (Part I. The isotherm equation). Transactions of the American Society of Agricultural Engineers 13:612-617.

32. Ngoddy, P. O. and F. W. Bakker-Arkema. 1970. A generalized theory of sorption phenomena in biological materials. II. Adsorption compressions on sorbing biological materials--a density function for sorbed water. Transactions of the Americal Society of Agricultural Engineers 15:1153-1159.

33. Ngoddy, P. O. and F. W. Bakker-Arkema. 1970. A generalized theory of sorption phenomena in biological materials. III. A pore size distribution function of the power law type for biological material. Transactions of the American Society of Agricultural Engineers 15:1160-1164.

34. Siau, J. F. 1971. Flow in wood. Syracuse University Press, Syracuse, New York.

35. Snedecor, G. W. 1956. Statistical methods. Iowa State University, Press, Ames, Iowa.

36. Stamm, A. J. 1959. Bound-water diffusion into wood in the fiber direction. Forest Products Journal, 9(1):27-32.

37. Stamm, A. J. 1960. Bound-water diffusion into wood in across-the-fiber directions. Forest Products Journal, 10:524-528.

38. Walton, L. R. and W. H. Henson, Jr. 1970. Moisture sorption of burley tobacco. Transactions American Society of Agricultural Engineers 13:466-468.

39. Walton, L. R. 1974. Elasticity of the cured burley tobacco midrib. An unpublished report, USDA, ARS, Lexington, Kentucky.

40. Whitaker, T. B. and J. H. Young. 1972. Simulation of moisture movement in peanut kernels: evaluation of the diffusion equation. Transactions of the American Society of Agricultural Engineers 15:163-166.

41. Whitaker, T. B. and J. H. Young. 1972. Application of the vapor-diffusion equation for concentric spheres in describing moisture movement in peanut pods. Transactions of the American Society of Agricultural Engineers 15:167-171.

42. Whitney, J. D. 1966. Moisture transfer in a porous, hygroscopic solid. Unpublished Ph.D. Thesis, Oklahoma State University, Stillwater, Oklahoma.

43. Whitney, J. D. and J. G. Porterfield. 1968. Moisture movement in a porous hygroscopic solid. Transactions of the American Society of Agricultural Engineers 11:716-719.

44. Williams, V. R. and H. B. Williams. 1967. Basic physical chemistry for the life sciences. W. H. Freeman and Company, San Francisco, California.

45. Young, J. H. 1964. Development of a relationship between moisture content and time for burley tobacco in a controlled environment. Unpublished M.S. Thesis, University of Kentucky, Lexington, Kentucky.

46. Young, J. H. and G. L. Nelson. 1967. Theory of hysteresis between sorption and desorption isotherms in biological materials. Transactions of American Society of Agricultural Engineers 10:260-263.

47. Young, J. H. and G. L. Nelson. 1967. Research of hysteresis between sorption and desorption isotherms of wheat. Transactions of American Society of Agricultural Engineers 10:756-761.

48. Young, J. H. 1969. Simultaneous heat and mass transfer in a porous, hygroscopic solid. Transactions of the American Society of Agricultural Engineers 12(5):720-725.

49. Young, J. H. and T. B. Whitaker. 1971. Evaluation of the diffusion equation for describing thin-layer drying of peanuts in the hull. Transactions of the American Society of Agricultural Engineers 14(2):309-312.

50. Young, J. H. and T. B. Whitaker. 1970. Numerical analysis of vapor diffusion in a porous composite sphere with concentric sheels. Transactions of the American Society of Agricultural Engineers 14:1051-1057.

APPENDICES

APPENDIX A

THEORETICAL HEAT TRANSFER CALCULATIONS

The problem was to define the theoretical transient temperature period of the lamina and midrib. A finite convective heat transfer coefficient was assumed.

Lamina

An equation for the convective heat transfer coefficient over a flat plate in free convection is

$$\overline{Nu} = 0.555\ (Gr_L Pr)^{1/4}\ , \tag{49}$$

where $\overline{Nu}$ = Nusselt Number = $h\ L'/k$,

Gr_L = Groshoff Number,

Pr = Prantl Number,

$\overline{h}$ = convective heat transfer coefficient, Btu/hr ft^2F,

k = thermal conductivity of air, Btu/hr ft^2F, and

L' = length of lamina, ft.

The values for the parameters taken from Krieth (1964) were

$Gr_L = 460 \times 10^6$ (calculated),

$Pr = 0.72$,

$k = 0.0147$ Btu/hr ft ^oF, and

$L = 2$ ft (measured).

The result of $\overline{h} = 0.55$ Btu/hr ft^2F.

The equation for the transient temperature period is the equation for the center temperature of the infinite thin sheet,

$$\frac{T - T_\infty}{T_o - T_\infty} = 2 \sum_{n=1}^{\infty} \left(\frac{\sin \lambda_n L}{\lambda_n L + \sin \lambda_n L \cos \lambda_n L} \right) e^{-a\lambda_n^2 t} , \qquad (50)$$

where T = center temperature of lamina at time t, F,

T_o = initial uniform temperature of lamina, F,

T_∞ = ambient temperature, F

L = 0.0001 ft, half thickness of lamina (measured), and

a = 0.00167 ft^2/hr, thermal diffusivity of lamina, Duncan, et al. (1966).

The λ_n's are zeros of the following equation:

$$\text{Tan } \lambda_n L = \frac{h}{k_s L} ,$$

where k_s = 0.04167 Btu/hr ft F, thermal conductivity of lamina, Duncan, et al. (1966).

Thus the equation for λ_n reduces to

$$\text{Tan } 0.0001 \lambda_n = \frac{13.20}{\lambda_n} . \qquad (51)$$

The first two solutions of this equation are

λ_1 = 363, and

λ_2 = 31,430.

Using the first two terms of the Fourier series as an approximation gives,

$$\frac{T - T_\infty}{T_o - T_\infty} = 1.002196 \, e^{-0.0611262t} - 0.0008952 \, e^{-458.25t} , \qquad (52)$$

where t is in seconds.

Several calculations from this equation are shown below and plotted in Figure A-1.

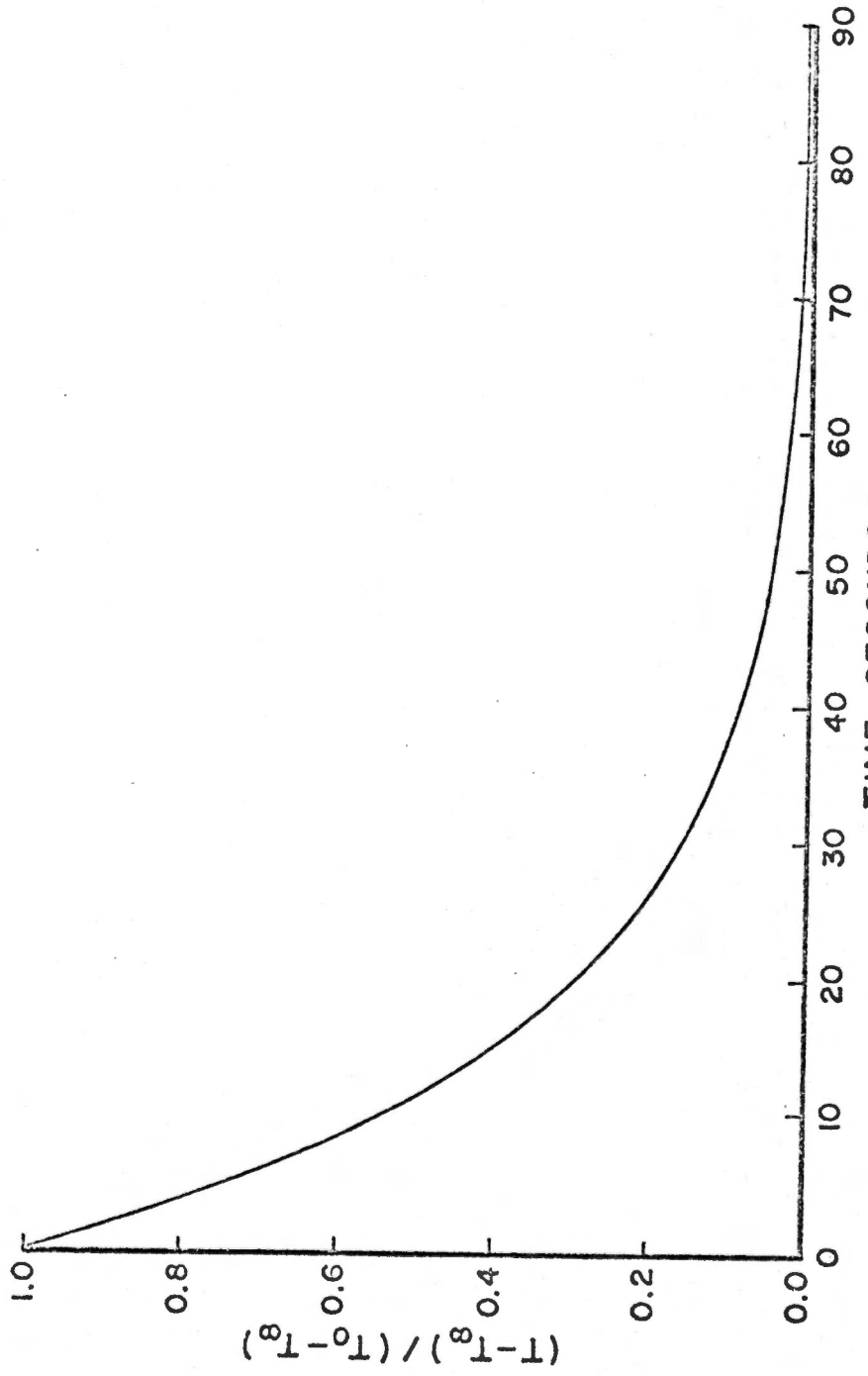


Figure A-1. Dimensionless temperature ratio given by equation 52 for the center of the lamina as a function of time.

t	0	10	20	30	40	50	60	90
$\frac{T-T_\infty}{T_o-T_\infty}$	0.99930	0.54278	0.29455	0.15984	0.08674	0.04707	0.02550	0.0408

Midrib

The convective heat transfer coefficient was calculated as $\bar{h}$ = 2.82 Btu/hr ft^2 °F from Figure 7-3 of Krieth (1964). The model used for the center temperature of the tobacco midrib was that of the infinite circulat cylinder with finite convective heat transfer coefficient

$$\frac{T - T_\infty}{T_o - T_\infty} = 2\ Bi \sum_{n=1}^{\infty} \frac{e^{-a\lambda_n^2 t}\ J_o(\lambda_n r)}{[(\lambda_n R)^2 + Bi^2]\ J_o(\lambda_n R)}\ , \qquad (53)$$

where T = center temperature of midrib, °F,

R = 0.00521 ft, radius of midrib (measured),

Bi = Biot number = $\frac{hR}{k_s}$ = 0.54466, and

k_s = thermal conductivity of midrib = 0.0417 $\frac{Btu}{ft\ hr\ F}$ (assumed to be the same as that of the lamina).

The values of λ_n are the zeros of the following equation:

$$(\lambda_n R)\ J_1(\lambda_n R) - 0.54466\ J_o(\lambda R) = 0\ , \qquad (54)$$

where $J_o(\lambda_n R)$ = Bessel's function of the first kind of order 0 with argument λ_n R, and

$J_1(\lambda_n R)$ = Bessel's function of the first kind of order 1 with argument λ_n R.

The first four solutions are:

$\lambda_1 R = 0.98$ $\qquad$ $\lambda_1 = 188.10$

$\lambda_2 R = 3.97$ $\qquad$ $\lambda_2 = 761.99$

$\lambda_3 R = 7.10$ $\qquad$ $\lambda_3 = 1362.77$

$\lambda_4 R = 10.23$ $\qquad$ $\lambda_4 = 1963.55$

Substituting these values into equation 53 tives:

$$\frac{T - T_\infty}{T_o - T_\infty} = 1.12008\ e^{-0.16410t} - 0.17023\ e^{-0.26935t} + 0.07182\ e^{-0.86151t} - 0.04162\ e^{-1.78854t}, \tag{55}$$

where t is in seconds.

The curve generated by calculations from equation 55 are shown below and plotted in Figure A-2.

t	0	10	20	30	40	50	60
$\frac{T-T_\infty}{T_o-T_\infty}$	0.98010	0.93906	0.80592	0.68456	0.58100	0.49307	0.41845

90	120	150	180	240	200
0.25576	0.15623	0.0955	0.05840	0.02182	0.00815

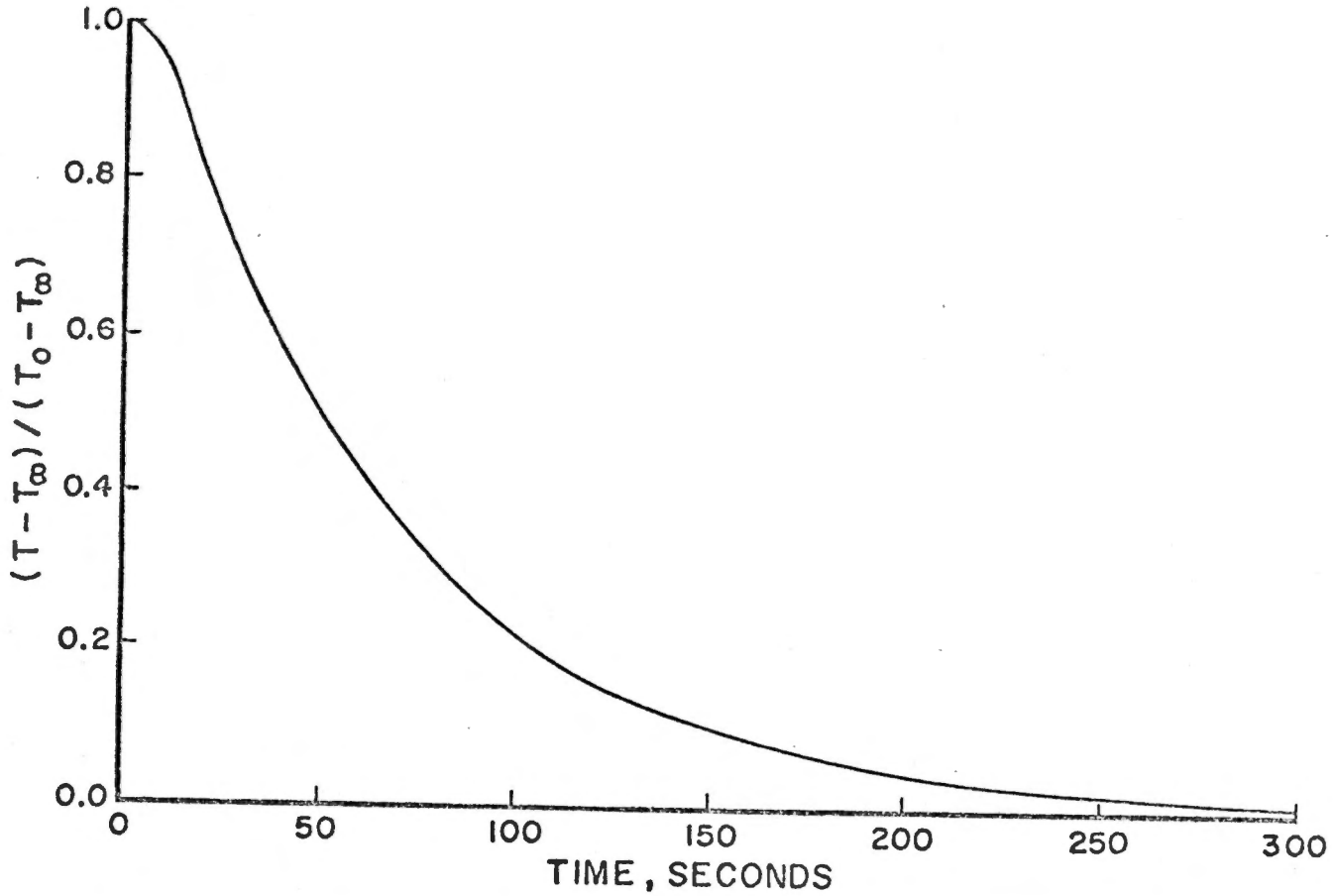


Figure A-2. Dimensionless temperature ratio given by equation 55 for the center of the midrib as a function of time.

APPENDIX B

THEORETICAL EFFECT OF FINITE CONVECTIVE MASS TRANSFER COEFFICIENT ON LAMINA SORPTION CURVE

The Lewis number is an important dimensionless ratio in an analogy between heat and mass transfer:

$$N_{Le} = \frac{\alpha}{D} , \tag{56}$$

where N_{Le} = Lewis number,

α = thermal diffusivity, ft^2/hr, and

D = mass diffusion coefficient based on concentration gradient, ft^2/hr.

Eckert and Gross (1963), Gröber, et al. (1961), and Kays (1966) indicate that for a Lewis number approximately equal to unity, a simple relationship exists between the convective mass transfer coefficient and the convective heat transfer coefficient:

$$h_m = \frac{h}{c_p \rho} , \tag{57}$$

where h_m = convective mass transfer coefficient, ft/hr,

h = convective heat transfer coefficient, Btu/hr ft^2 F,

c_p = specific heat of carrying gas, Btu/lb F, and

ρ = density of carrying gas, lb/ft^3.

Eckert and Gross (1963), Gröber, et al. (1961), and Kays (1966) indicate that for the air water vapor mixture the Lewis number is close enough to unity that the last equation can be considered valid for the air water vapor problem.

The flow of air over the tobacco leaf is analogous to flow over a flat plate. The velocity range is 10 to 30 feet per minute. The flow over a flat plate is laminar for Reynold's number less than 10^5, therefore, the flow should be laminar in this velocity range. Krieth (1964) gives the following expression for laminar flow over a flat plate:

$$Nu = 0.664\ Re^{1/2}\ Pr^{1/3}\ , \text{ or} \tag{58}$$

$$\frac{hL_1}{k} = 0.664 \left(\frac{VL_1}{\nu}\right)^{1/2} \left[Pr\right]^{1/3} \tag{59}$$

where h = convective heat transfer coefficient Btu/hr ft^2 F,

L_1 = leaf length, ft,

k = thermal conductivity, Btu/hr ft F,

V = velocity, ft/sec,

ν = kinematic viscosity, ft^2/sec,

Nu = Nusselt Number,

Re = Reynold's Number, and

Pr = Prandl Number.

For the calculation of h, the value of parameters will be taken at 65°F. The length of the leaf will be taken as two feet. At 65°F, Krieth (1964) gives

$k = 0.0147$ Btu/hr ft F

$\nu = 0.162 \times 10^{-3}$ ft^2/sec

$Pr = 0.72$

The Reynold's number at 10 and 30 ft/min are:

$$Re_{10} = \frac{VL_1}{\nu} = \frac{10\ (2)}{60(0.162 \times 10^{-3})} = 2058$$

$$Re_{30} = \frac{30\ (2)}{60(0.162 \times 10^{-3})} = 6174$$

The respective heat transfer coefficients are

$$h_{10} = 0.664 \frac{k}{L_1} (Re_{10})^{1/2} (Pr)^{1/3} = 0.198, \text{ and}$$

$$h_{30} = 0.344.$$

Using the value of $c_p = 0.24$ Btu/lb °F and $\rho = 0.076$ lb/ft^3 for air, the convective mass transfer coefficient can now be calculated:

$$(h_m)_{10} = \frac{h_{10}}{C_p \rho} = \frac{0.198}{0.24(0.76)} = 10.9 \text{ ft/hr}$$

$$(h_m)_{30} = \frac{h_{30}}{C_p \rho} = \frac{0.344}{0.24(0.076)} = 18.9 \text{ ft/hr.}$$

Before equation 32 can be solved, an estimate of the diffusion coefficient is needed. Comstock (1963) uses the following formula to determine diffusion coefficient from the initial stages of adsorption or desorption:

$$D' = \frac{\pi}{16} \frac{L^2}{t} \frac{(M_t)}{(M_\infty)} \tag{60}$$

where L = half thickness of the leaf, ft,

M_t = amount of moisture absorbed or desorbed at time, t,

M_∞ = total amount adsorbed or desorbed at equilibrium,

t = time, hr, and

D' = mass diffusion coefficient based on moisture gradient, ft^2/hr.

Walton and Henson (1970) give the following data for their whole leav adsorption curve shown in Figure 1 of their paper:

M_o = 7.9% (dry basis),

M_e = 24.9%, and

M_t = 2.6% at 1 hr.

This M_t is the moisture gain of the whole leaf. Since the thickness of the lamina is small compared to the diameter of the midrib, it is expected that the lamina will adsorb moisture much faster than the midrib. It will be assumed that the moisture content gain of the midrib is negligible compared to that of the lamina. Since the lamina makes up approximately two-thirds of the weight of the leaf, it will be assumed that M_t for the lamina is 1.5 M_t for the whole leaf. In addition, it is assumed that M_o and M_e are the same for both lamina and midrib. Thus, the data for the lamina are

M_t = 3.9% at t = 1 hr, and

M_∞ = 17%.

Taking the average half thickness of the leaf as L = 0.0001 ft, an approximate diffusion coefficient can be obtained:

$$D' = \frac{\pi}{16} \frac{(0.0001)^2}{1} \left(\frac{3.9}{17}\right)^2$$

$$D' = 1.03 \times 10^{-10} \text{ ft}^2/\text{hr}$$

To solve equation 32, the Biot number is needed which requires a value of D, which is the diffusion coefficient based on concentration gradient as opposed to D', which is the diffusion coefficient based on moisture content gradient. The relationship between the two is

$$D = \rho \beta D'$$

where ρ = bulk density of the lamina, lb/ft^3, and

β = slope of desorption isotherms shown in Figure 1, page 4, ft^3/lb.

The average value of β over the moisture content range 7.9% to 24.9% is $\beta = 500$. The value of density is approximately $\rho = 40$ lb/ft^3. Thus:

$$D = \rho \beta D' = 40(500\ 1.03 \times 10^{-10}$$

$$= 2.06 \times 10^{-6} \text{ ft}^2/\text{sec}.$$

The Biot number is as follows:

$$Bi_{10} = \frac{h_m L}{D} = \frac{10.9\ (0.0001)}{2.06 \times 10^{-6}}$$

$$= 529, \text{ and}$$

$$Bi_{30} = \frac{18.9\ (0.001)}{2.06 \times 10^{-6}}$$

$$= 917.$$

Substituting the Biot number into equation 32 gives:

$$\text{Tan } \lambda_n L = \frac{529}{\lambda_n L} \quad \text{for V = 10 ft/min, and} \tag{61a}$$

$$\text{Tan } \lambda_n L = \frac{917}{\lambda_n L} \quad \text{for V = 30 ft/min.} \tag{61b}$$

The solution for the first 10 solutions for $\lambda_n L$ from the above equations are shown in Table B-1. The corresponding coefficients

$$C_n = \frac{\sin^2 \lambda_n L}{(\lambda_n L)^2 + \lambda_n L \sin \lambda_n L \cos \lambda_n L}$$

for equation 33 are shown in Table B-2. The value of $\Theta(t)$ at times of 5, 10, and 20 hours for $D' = 1.03 \times 10^{-10}$ ft^2/hr is shown in Table B-3.

Table B-1. First Ten Solutions for $\lambda_n L$ from Equations 61a and 61b

Biot No.	$\lambda_1 L$	$\lambda_2 L$	$\lambda_3 L$	$\lambda_4 L$	$\lambda_5 L$	$\lambda_6 L$	$\lambda_7 L$	$\lambda_8 L$	$\lambda_9 L$	$\lambda_{10} L$
∞	1.5708	4.7124	7.8540	10.9956	14.1372	17.2788	20.4204	23.5619	26.7035	29.8451
917	1.5691	4.7073	7.8454	10.9835	14.1218	17.2600	20.3981	23.5303	26.5645	29.8126
529	1.5678	4.7035	7.8392	10.9748	14.1105	17.2452	20.3818	23.5175	26.6532	29.7889

Table B-2. First Ten Coefficients of Equation 33

Biot No.	C_1	C_2	C_3	C_4	C_5	$C_6 \times 10^3$	$C_7 \times 10^3$	$C_8 \times 10^3$	$C_9 \times 10^3$	$C_{10} \times 10^3$
∞	0.81057	0.090063	0.032423	0.016542	0.010007	6.6989	4.7963	3.6025	2.8047	2.2453
917	0.81145	0.090159	0.032456	0.016558	0.010016	6.7039	4.7991	3.6041	2.8054	2.2454
529	0.81209	0.090226	0.032477	0.016566	0.010019	6.7045	4.7982	3.6022	2.8029	2.2424

Table B-3. Values of Dimensionless Moisture Ratio, $\Theta(t)$ or $(M - M_e)/(M_o - M_e)$ at t = 5, 10, 20 Hours from Equation 33

Biot Number	Time (hr) 0	5	10	20
∞	1.00000	0.74393	0.63786	0.48851
917	1.00000	0.74501	0.63895	0.48959
529	1.00000	0.74581	0.63975	0.49038

APPENDIX C

TABLES AND GRAPHS OF RESULTS AND SAMPLE CALCULATIONS

Table C-1. Analysis of Variance of Steady State Diffusion Coefficient

Source	Degrees of Freedom	Mean Square x 10^{15}
Temp (A)	2	4.421981**
Rel. Hum. (B)	2	0.571251**
Thickness (C)	1	0.157452
Test (D)	1	0.016821
A x B	4	0.042951
A x C	2	0.024481
A x D	2	0.201313*
B x C	2	0.022844
B x D	2	0.145006
C x D	1	0.029604
Error	124	0.048646
Total	143	0.120150

**99% level.

*95% level.

Table C-2. Mass Diffusion Coefficient for the Sorption of the Cured Burley Lamina as a Function of Temperature and Relative Humidity

Encironmental Condition	Mass Diffusion Coefficient ($ft^2/hr) \times 10^{10}$ Replications			
	1	2	3	4
55°F, 75%	1.037	0.951	0.854	0.952
65°F, 75%	1.591	1.709	1.098	1.135
75°F, 75%	2.499	2.687	2.395	2.650
55°F, 85%	0.324	0.345	0.228	0.296
65°F, 85%	0.853	0.916	0.708	0.626
75°F, 85%	1.910	1.910	1.010	1.246
55°F, 95%	0.314	0.313	0.201	0.284
65°F, 95%	0.437	0.502	0.401	0.365
75°F, 95%	0.623	0.814	0.586	0.604

Table C-3. Mass Diffusion Coefficient for the Sorption of the Cured Burley Midrib as a Function of Temperature and Relative Humidity

Environ-mental Condition	Mass Diffusion Coefficient ($ft^2/hr) \times 10^8$ Replications			
	1	2	3	4
55°F, 75%	6.105 (1.794)[a]	4.677 (1.523)	5.369 (1.321)	5.008 (1.938)
65°F, 75%	5.568 (1.684)	10.792 (3.514)	8.148 (1.624)	11.129 (3.415)
75°F, 75°	9.278 (2.168)	15.301 (3.971)	12.422 (2.795)	9.278 (3.021)
55°F, 85%	1.504 (0.442)	1.327 (0.432)	1.768 (0.435)	1.165 (0.451)
65°F, 85%	3.177 (0.961)	3.117 (1.015)	2.895 (0.577)	3.343 (1.011)
75°F, 85%	11.096 (2.593)	12.751 (3.308)	12.302 (2.768)	8.411 (2.739)
55°F, 95%	1.276 (0.375)	1.017 (0.331)	1.422 (0.350)	0.982 (0.380)
65°F, 95%	3.280 (0.992)	1.158 (0.377)	1.550 (0.309)	1.858 (0.562)
75°F, 95%	4.309 (1.007)	4.170 (1.082)	4.009 (0.902)	3.605 (1.174)

[a]Value in parenthesis is $D'/R^2 \times 10^3$.

Table C-4. Mass Diffusion Coefficient for the Desorption of the Cured Burley Lamina as a Function of Temperature and Relative Humidity

Environmental Condition	Mass Diffusion Coefficient ($ft^2/hr \times 10^9$) Replications 1	2	3	4
55°F, 75%	0.905	0.797	0.633	0.727
65°F, 75%	1.822	1.996	1.577	1.905
75°F, 75%	2.280	1.993	2.218	1.459
55°F, 85%	0.512	0.577	0.556	0.508
65°F, 85%	0.986	1.131	1.040	1.212
75°F, 85%	1.729	1.380	1.388	1.252
55°F, 95%	0.275	0.563	0.318	0.432
65°F, 95%	0.872	0.850	0.722	0.702
75°F, 95%	1.402	1.111	1.149	1.017

Table C-5. Mass Diffusion Coefficient for the Desorption of the Cured Burley Midrib as a Function of Temperature and Relative Humidity

Environmental Condition	Mass Diffusion Coefficient (ft^2/hr) $\times 10^7$ Replications 1	2	3	4
55°F, 75%	3.961 (1.164)[a]	2.976 (0.969)	4.158 (1.023)	2.090 (0.809)
65°F, 75%	5.508 (1.666)	5.018 (1.634)	6.377 (1.271)	2.943 (0.890)
75°F, 75%	9.119 (2.131)	8.980 (2.101)	9.031 (2.032)	6.114 (1.991)
55°F, 85%	3.045 (0.895)	3.019 (0.983)	4.934 (1.214)	2.080 (0.805)
65°F, 85%	5.065 (1.532)	4.330 (1.410)	7.476 (1.490)	5.201 (1.573)
75°F, 85%	9.021 (2.108)	6.286 (1.631)	9.862 (2.219)	7.871 (2.503)
55°F, 95%	2.661 (0.782)	3.206 (1.044)	4.828 (1.188)	2.062 (1.030)
65°F, 95%	9.224 (2.790)	6.474 (2.108)	8.956 (1.785)	7.115 (2.152)
75°F, 95%	7.810 (1.825)	6.337 (1.644)	9.000 (2.025)	5.162 (1.681)

[a]Value in parenthesis is $D'/R^2 \times 10^2$.

Table C-6. Value of Parameter k in Exponential Equation (Equation 2) for the Burley Lamina During Sorption as a Function of Temperature and Relative Humidity

Environmental Condition	k-Value (hr^{-1}) Replications			
	1	2	3	4
55°F, 75%	0.0522	0.0489	0.0452	0.0485
65°F, 75%	0.0718	0.0755	0.0551	0.0562
75°F, 75%	0.1122	0.1180	0.1094	0.1168
55°F, 85%	0.0274	0.0282	0.0225	0.0255
65°F, 85%	0.0494	0.0419	0.0438	0.0403
75°F, 85%	0.0813	0.0814	0.0542	0.0594
55°F, 95%	0.0261	0.0258	0.0202	0.0240
65°F, 95%	0.0321	0.0353	0.0306	0.0287
75°F, 95%	0.0383	0.0462	0.0372	0.0381

Table C-7. Value of Parameter k in Exponential Equation (Equation 2) for the Burley Midrib During Sorption as a Function of Temperature and Relative Humidity

Environmental Condition	k-Value (hr^{-1}) Replications			
	1	2	3	4
55°F, 75%	0.0394	0.0359	0.0324	0.0412
65°F, 75%	0.0379	0.0594	0.0372	0.0588
75°F, 75%	0.0557	0.0771	0.0633	0.662
55°F, 85%	0.0177	0.0177	0.0178	0.0175
65°F, 85%	0.0291	0.0296	0.0218	0.0297
75°F, 85%	0.0516	0.0596	0.0534	0.0525
55°F, 95%	0.0166	0.0167	0.0165	0.0164
65°F, 95%	0.0291	0.0312	0.0155	0.0217
75°F, 95%	0.0277	0.0318	0.0260	0.0308

Table C-8. Value of Parameter k in Exponential Equation (Equation 2) for the Burley Lamina During Desorption as a Function of Temperature and Relative Humidity

Environmental Condition	k-Value (hr^{-1}) Replications			
	1	2	3	4
55°F, 75%	0.3074	0.2729	0.2262	0.2542
65°F, 75%	0.6076	0.6592	0.5218	0.3506
75°F, 75%	0.7572	0.6547	0.7234	0.4866
55°F, 85%	0.1793	0.1987	0.1931	0.1780
65°F, 85%	0.3261	0.3696	0.3405	0.3958
75"F, 85%	0.5591	0.4507	0.4531	0.4115
55°F, 95%	0.1177	0.2086	0.1304	0.1698
65°F, 95%	0.2899	0.2844	0.2449	0.2390
75°F, 95%	0.4698	0.3814	0.1801	0.3534

Table C-9. Value of Parameter k in Exponential Equation (Equation 2) for the Burley Midrib During Desorption as a Function of Temperature and Relative Humidity

Environmental Condition	k-Value (hr^{-1}) Replications			
	1	2	3	4
55°F, 75%	0.1518	0.1348	0.1399	0.1208
65°F, 75%	0.1957	0.1918	0.1639	0.1301
75°F, 75%	0.2232	0.2193	0.2146	0.2125
55°F, 85%	0.1158	0.1229	0.1443	0.1071
65°F, 85%	0.1826	0.1724	0.1798	0.1859
75°F, 85%	0.2283	0.1905	0.2373	0.2680
55°F, 95%	0.1265	0.1499	0.1621	0.1494
65°F, 95%	0.3015	0.2395	0.2071	0.2439
75°F, 95%	0.2469	0.2293	0.2656	0.2342

Table C-10. Standard Error of Mathematical Model (Equation 34) for Lamina When Applied to Sorption Data at Various Temperatures and Relative Humidities

Environmental Condition	Standard Error (Percent Moisture Content) Replications			
	1	2	3	4
55°F, 75%	0.36	0.33	0.21	0.31
65°F, 75%	0.41	0.33	0.25	0.28
75°F, 75%	0.33	0.39	0.34	0.32
55°F, 85%	0.40	0.45	0.38	0.33
65°F, 85%	0.52	0.61	0.44	0.45
75°F, 85%	0.43	0.52	0.51	0.48
55°F, 95%	0.61	0.57	0.58	0.49
65°F, 95%	0.51	0.67	0.51	0.34
75°F, 95%	1.09	0.97	0.71	0.67

Table C-11. Standard Error of Mathematical Model (Equation 46) for Midrib When Applied to Sorption Data at Various Temperatures and Relative Humidities

Environmental Conditions	Standard Error (Percent Moisture Content) Replications			
	1	2	3	4
55°F, 75%	0.28	0.28	0.20	0.22
65°F, 75%	0.39	0.51	0.41	0.57
75°F, 75%	0.20	0.26	0.28	0.23
55°F, 85%	0.31	0.49	0.59	0.39
65°F, 85%	0.19	0.36	0.27	0.26
75°F, 85%	0.88	0.65	0.77	0.67
55°F, 95%	0.58	1.99	1.30	0.39
65°F, 95%	0.62	0.55	0.63	0.94
75°F, 95%	0.48	0.60	0.41	0.46

Table C-12. Standard Error of Mathematical Model (Equation 34) for Lamina When Applied to Desorption Data at Various Temperatures and Relative Humidities

Environmental Condition	Standard Error (Percent Moisture Content) Replications			
	1	2	3	4
55°F, 75%	0.16	0.22	0.13	0.18
65°F, 75%	0.11	0.20	0.14	0.18
75°F, 75%	0.14	0.13	0.13	0.17
55°F, 85%	0.53	0.29	0.34	0.40
65°F, 85%	0.26	0.38	0.45	0.31
75°F, 85%	0.63	0.60	0.50	0.35
55°F, 95%	0.86	0.73	0.66	0.33
65°F, 95%	0.90	0.81	0.86	0.91
75°F, 95%	0.76	0.89	0.65	0.72

Table C-13. Standard Error of Mathematical Model (Equation 46) for Midrib When Applied to Desorption Data at Various Temperatures and Relative Humidities

Environmental Condition	Standard Error (Percent Moisture Content) Replications			
	1	2	3	4
55°F, 75%	0.20	0.19	0.21	0.26
65°F, 75%	0.14	0.14	0.21	0.24
75°F, 75%	0.20	0.24	0.14	0.26
55°F, 85%	0.38	0.25	0.24	0.38
65°F, 85%	0.55	0.54	0.44	0.43
75°F, 85%	1.02	0.73	0.62	0.56
55°F, 95%	0.73	0.54	0.42	0.61
65°F, 95%	0.92	1.77	0.94	1.47
75°F, 95%	1.12	1.28	1.26	1.31

Table C-14. Standard Error of Exponential Equation (Equation 2) When Applied to Sorption Data of the Burley Lamina at Various Temperatures and Relative Humidities

Environmental Condition	Standard Error (Percent Moisture Content) Replications			
	1	2	3	4
55°F, 75%	0.99	1.05	0.81	1.15
65°F, 75%	1.04	0.86	0.82	0.94
75°F, 75%	0.55	0.32	0.35	0.38
55°F, 85%	1.30	1.57	0.97	1.55
65°F, 85%	1.74	1.80	1.56	1.59
75°F, 85%	1.52	1.62	1.62	1.55
55°F, 95%	2.25	2.66	1.71	2.86
65°F, 95%	2.57	2.54	2.36	2.41
75°F, 95%	3.42	3.20	2.84	2.60

Table C-15. Standard Error of Exponential Equation (Equation 2) When Applied to Sorption Data of the Burley Midrib at Various Temperatures and Relative Humidities

Environmental Condition	Standard Error (Percent Moisture Content) Replications			
	1	2	3	4
55°F, 75%	0.89	0.77	0.84	0.59
65°F, 75%	0.70	1.32	0.67	1.33
75°F, 75%	0.30	0.66	0.58	0.40
55°F, 85%	1.16	1.14	1.15	1.40
65°F, 85%	1.12	1.35	0.95	1.35
75°F, 85%	0.81	1.15	1.22	1.34
55°F, 95%	1.68	1.64	1.41	1.94
65°F, 95%	2.77	2.31	1.22	1.71
75°F, 95%	2.58	2.56	2.42	2.30

Table C-16. Standard Error of Exponential Equation (Equation 2) When Applied to Desorption Data of the Burley Lamina at Various Temperatures and Relative Humidities

Environmental Condition	Standard Error (Percent Moisture Content) Replications			
	1	2	3	4
55°F, 75%	0.32	0.21	0.33	0.25
65°F, 75%	0.40	0.35	0.30	0.23
75°F, 75%	0.30	0.27	0.19	0.36
55°F, 85%	0.19	0.42	0.33	0.19
65°F, 85%	0.41	0.34	0.22	0.26
75°F, 85%	0.12	0.12	0.08	0.28
55°F, 95%	0.47	0.47	0.43	0.90
65°F, 95%	0.47	0.80	0.43	0.32
75°F, 95%	0.28	0.26	0.70	0.33

Table C-17. Standard Error of Exponential Equation (Equation 2) When Applied to Desorption Data of the Burley Midrib at Various Temperatures and Relative Humidities

Environmental Condition	Standard Error (Percent Moisture Content) Replications			
	1	2	3	4
55°F, 75%	0.27	0.25	0.17	0.19
65°F, 75%	0.33	0.47	0.21	0.24
75°F, 75%	0.44	0.60	0.42	0.36
55°F, 85%	0.30	0.38	0.40	0.20
65°F, 85%	0.24	0.45	0.48	0.44
75°F, 85%	0.37	0.42	0.35	0.61
55°F, 95%	0.35	0.62	0.60	0.38
65°F, 95%	1.32	0.64	0.28	0.43
75°F, 95%	0.44	0.59	0.63	0.47

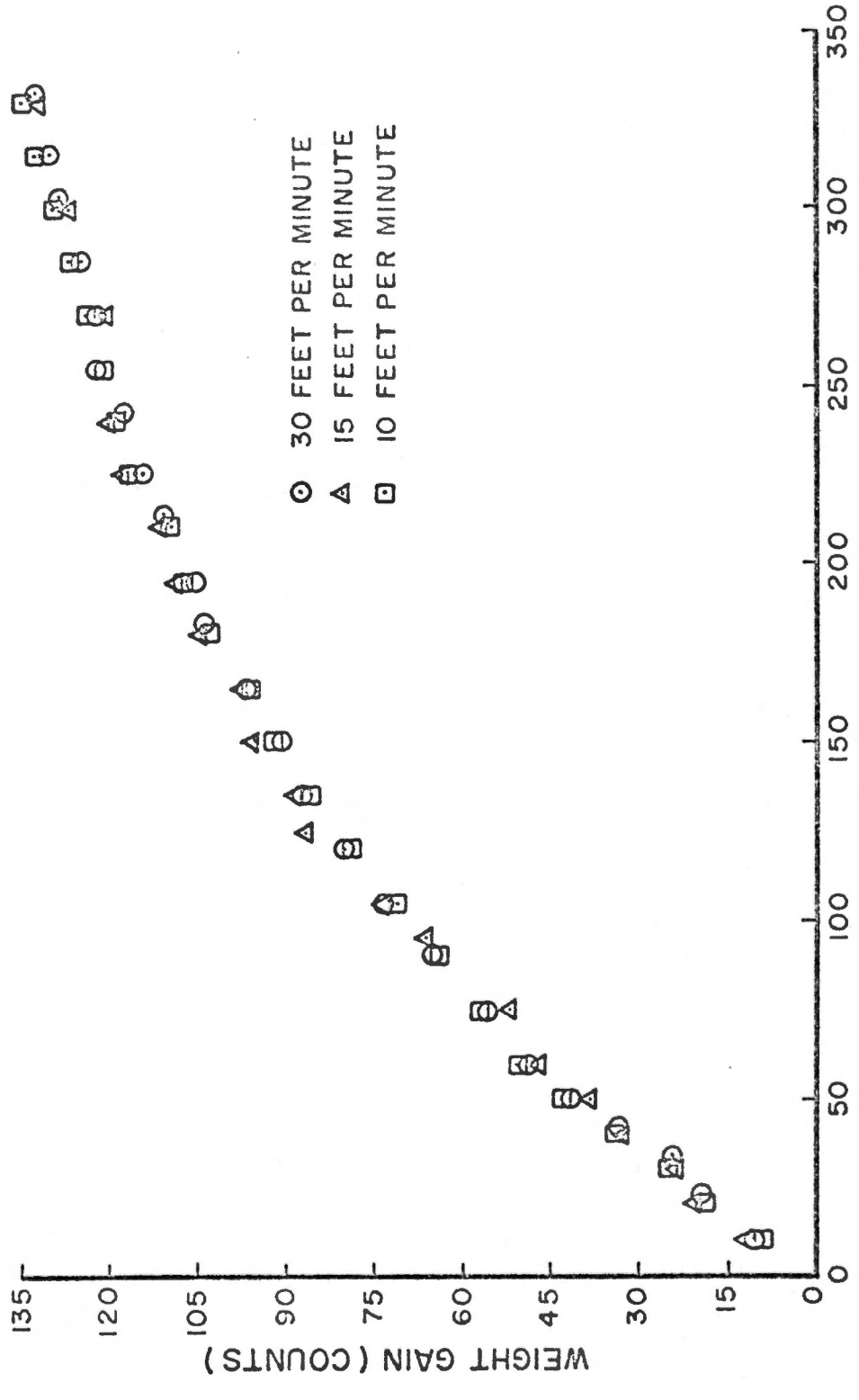


Figure C-1. Weight gain of the whole leaves of plant 5 at air velocities of 10, 15, and 30 feet per minute as a function of time at 75°F, 75% rh.

Table C-18. Weight Gain of the Whole Leaves of Plant 5 at Air Velocities of 10, 15, and 30 Feet Per Minute as a Function of Time at 75°F, 75% rh

Time (Minutes)	Weight Gain (counts)		
	10 ft/min	15 ft/min	30 ft/min
0	0	0	0
10	9	13	9
20	18	20	18
30	25	23	24
40	34	33	34
50	43	38	41
60	50	47	48
75	57	51	56
90	65	66	65
105	71	73	73
120	79	87	80
135	86	89	86
150	92	96	91
165	96	98	97
180	103	105	103
195	107	109	106
210	110	111	111
225	116	117	114
240	118	120	118
255	121	-	121
270	124	120	123
285	127	-	126
300	129	126	129
315	132	-	131
330	135	132	133
345	137	-	-
480	-	156	154
520	161	158	-
1260	-	215	-
1440	221	-	222

I. SAMPLE CALCULATION

The weight gain in counts of the lamina of plant 2 at 65°F, 95% rh are shown in column 2 of Tables C-19 and C-20. The data needed for calculation of the observed moisture ratio (Θ_o) in column 3 were

dry weight of lamina = 66.85 grams

M_o = 8.0% (db)

M_e = 70.0%

W_o = 501 (initial weight in counts)

Sensitivity = 17 counts/gram

The calculation of equilibrium weight in counts was

$$W_e = W_o + \text{dry wt. } (M_e - M_o) \text{ (Sensitivity)}$$

$$= 501 + 66.85\ (0.70 - 0.08)\ (17)$$

$$= 1206$$

As an example, the moisture ratio was then calculated at 60 minutes as

$$\Theta = \frac{M - M_e}{M_o - M_e} = \frac{W - W_e}{W_o - W_e} = \frac{548 - 1206}{501 - 1206} = 0.93333$$

The weight readings in counts were entered into the computer along with the initial count W_o, the equilibrium count W_e, and the time t of each reading. The computer then calculated the moisture ratio as a function of time and determined the value of the diffusion coefficient, D', in equation 34 that gave the minimum standard error. The computed value of the diffusion coefficient was

$$D' = 0.502 \times 10^{-10}\ ft^2/hr.$$

The predicted values as given in column 4 were calculated by the computer

Table C-19. Weight Gain, Observed and Predicted Moisture Content (Percent) as a Function of Time for the Lamina of Plant 2 (Replication 2) at 65°F, 95% rh

Time (Minutes)	Weight (Counts)	Observed Moisture Ratio	Observed Moisture Content	Predicted Moisture Ratio	Predicted Moisture Content
0	501	1.000	8.00	0.993	8.43
10	507	0.991	8.56	0.967	10.05
20	516	0.979	9.30	0.954	10.85
30	523	0.969	9.92	0.943	11.53
40	533	0.955	10.79	0.935	12.03
50	540	0.945	11.41	0.927	12.53
60	548	0.933	12.15	0.920	12.96
75	557	0.921	12.90	0.911	13.52
90	565	0.909	13.64	0.902	14.08
105	571	0.901	14.14	0.894	14.57
120	576	0.894	14.57	0.887	15.00
135	584	0.882	15.32	0.880	15.44
150	590	0.874	15.82	0.874	15.81
165	593	0.870	16.06	0.867	16.25
180	598	0.862	16.56	0.862	16.56
195	604	0.854	17.05	0.856	16.93
210	608	0.848	17.42	0.850	17.30
225	614	0.840	17.92	0.845	17.61
240	619	0.833	18.35	0.840	17.42
255	619	0.833	18.34	0.835	18.23
270	623	0.827	18.73	0.830	18.54
285	627	0.821	19.10	0.826	18.79
300	630	0.817	19.35	0.821	19.10
315	633	0.813	19.59	0.817	19.35
330	636	0.809	19.84	0.813	19.59
345	638	0.806	20.03	0.808	19.90
360	642	0.800	20.40	0.804	20.15
610	684	0.740	24.12	0.745	23.81
1230	759	0.634	30.69	0.738	30.44

Table C-20. Weight Loss, Observed and Predicted Moisture Content (Percent) as a Function of Time for the Lamina of Plant 2 (Replication 2) at 65°F, 43% rh After Removal From 65°F, 95% rh

Time (Minutes)	Weight (Counts)	Observed Moisture Ratio	Observed Moisture Content	Predicted Moisture Ratio	Predicted Moisture Content
0	657	1.00000	31.67	0.99324	31.51
10	644	0.95167	30.53	0.86572	28.49
20	630	0.89963	29.29	0.81010	27.18
30	608	0.81784	27.36	0.76742	26.16
40	602	0.79554	26.83	0.73144	25.31
50	583	0.72491	25.16	0.69974	24.56
60	581	0.71747	24.98	0.67108	23.88
75	560	0.63941	23.13	0.63227	22.97
90	554	0.61710	22.61	0.59718	22.14
105	543	0.57621	21.64	0.56495	21.37
120	532	0.53532	20.67	0.53502	20.66
135	524	0.50558	19.97	0.50703	20.00
195	494	0.39405	17.33	0.41029	17.71
210	488	0.37175	16.80	0.38927	17.21
225	482	0.34944	16.27	0.36936	16.74
240	478	0.33457	15.92	0.35047	16.30
255	472	0.31227	15.39	0.33256	15.87
270	468	0.29740	15.04	0.31557	15.47
330	450	0.23048	13.46	0.25588	14.06
360	446	0.21561	13.10	0.23041	13.45
390	441	0.19703	12.66	0.20748	12.91
420	437	0.18216	12.31	0.18683	12.42
450	532	0.16357	11.87	0.16824	11.98
480	430	0.15613	11.69	0.15150	11.59
4200	388	0.00000	8.00	0.00000	8.00

by substituting this value of D' into equation 34. The standard error as given by the computer was 0.0108 in terms of moisture ratio. To convert the standard error in terms of moisture ratio to a standard error in terms of moisture content, the standard error in terms of moisture ratio was multiplied by $M_e - M_o$.

$$\text{S. E. (Percent Moisture Content)} = 0.0108\ (70.0 - 8.0)$$

$$= 0.67$$

APPENDIX D

MATHEMATICAL FORMULA FOR CALCULATING THE MOISTURE RATIO OF THE MIDRIB

In the sample calculation in Appendix C, it was shown that weight could be used to calculate moisture ratio. The purpose of the following derivation was to find a mathematical formula for calculating the moisture ratio of the midrib (stem) from the moisture ratios of the whole leaf and lamina. In this derivation, moisture ratio was abbreviated to MR and W was used to indicate weight. The subscripts used were

w--whole leaf,

l--lamina,

s--stem or midrib,

o--initial weight, and

e--equilibrium weight.

The derivation was made by setting the weight of the whole leaf equal to the sum of its parts, lamina and midrib (stem).

$$\frac{(W - W_e)_w}{(W_o - W_e)_w} = \frac{(W - W_e)_l + (W - W_e)_s}{(W_o - W_e)_l + (W_o - W_e)_s}$$

$$MR_w = \frac{(W - W_e)_l}{(W_o - W_e)_l + (W_o - W_e)_s} + \frac{(W - W_e)_s}{(W_o - W_e)_l + (W_o - W_e)_s}$$

By noting that $(W - W_e)_l$ is $(W_o - W_e)_l \, MR_l$ and $(W - W_e)_s$ is $(W_o - W_e)_s \, MR_s$, the equation becomes

$$MR_w = \frac{(W_o - W_e)_1}{(W_o - W_e)_1 + (W_o - W_e)_s} MR_1 + \frac{(W_o - W_e)_s}{(W_o - W_e)_1 + (W_o - W_e)_s} MR_s$$

$$MR_s = \frac{(W_o - W_e)_1 + (W_o - W_e)_s}{(W_o - W_e)_s} MR_w - \frac{(W_o - W_e)_1}{(W_o - W_e)_s} MR_1$$

By noting that $(W_o - W_e) = (W_o - W_e)_w - (W_o - W_e)_1$, the equation became

$$MR_s = \frac{(W_o - W_e)_w}{(W_o - W_e)_w - (W_o - W_e)_1} MR_w - \frac{(W_o - W_e)_1}{(W_o - W_e)_w - (W_o - W_e)_1} MR_1$$

All of the values in the above equation were either known or could be obtained from the data, Tables D-1 and D-2.

Table D-1. Observed and Predicted Moisture Content (Percent) as a Function of Time for the Sorption of the Midrib of Plant 2 (Replication 2) at 65°F, 95% rh

Time (Minutes)	Observed Moisture Ratio	Observed Moisture Content	Predicted Moisture Ratio	Predicted Moisture Content
0	1.00000	8.00	0.98662	8.83
10	0.97701	9.43	0.96941	9.89
20	0.96839	9.96	0.95746	10.64
30	0.96264	10.32	0.94803	11.22
40	0.95115	11.03	0.94010	11.72
50	0.94540	11.39	0.93313	12.15
60	0.94540	11.39	0.92684	12.53
75	0.93678	11.92	0.91836	13.06
90	0.92816	12.45	0.91071	13.54
105	0.91379	13.35	0.90370	13.97
120	0.90804	13.70	0.89719	14.37
135	0.90230	14.06	0.89109	14.75
150	0.89368	14.60	0.88535	15.11
165	0.88506	15.13	0.87990	15.45
180	0.88218	15.30	0.87470	15.77
195	0.87931	15.48	0.86972	16.08
210	0.86782	16.20	0.86495	16.37
225	0.85632	16.91	0.86035	16.66
240	0.85345	17.09	0.85591	16.93
255	0.83908	17.98	0.85162	17.20
270	0.84195	17.80	0.84746	17.46
285	0.83333	18.33	0.84341	17.71
300	0.82471	18.87	0.83949	17.95
330	0.82759	18.69	0.83194	18.42
345	0.81897	19.22	0.82831	18.64
360	0.81609	19.40	0.82475	18.87
540	0.78736	21.18	0.78722	21.19
1150	0.68391	27.60	0.69635	26.83

Table D-2. Observed and Predicted Moisture Content (Percent) as a Function of Time for the Desorption of the Midrib of Plant 2 (Replication 2) at 65°F, 43% rh After Removal From 65°F, 95% rh

Time (Minutes)	Observed Moisture Ratio	Observed Moisture Content	Predicted Moisture Ratio	Predicted Moisture Content
0	1.00000	28.20	0.98662	27.93
10	0.94766	27.14	0.86979	25.57
20	0.91470	26.48	0.81798	24.52
30	0.95825	27.36	0.77909	23.74
40	0.86840	25.54	0.74688	23.09
50	0.82437	24.65	0.71895	22.52
60	0.76498	23.45	0.69408	22.02
75	0.75971	23.35	0.66094	21.35
90	0.61097	20.34	0.63156	20.76
105	0.68673	21.87	0.60499	20.22
120	0.61526	20.43	0.58071	19.73
135	0.60344	20.19	0.55827	19.28
225	0.41621	16.41	0.44985	17.09
240	0.38576	15.79	0.43490	16.78
270	0.32436	14.55	0.40697	16.22
330	0.29040	13.87	0.35761	15.22
360	0.20105	12.06	0.33563	14.78
390	0.22924	12.63	0.31519	14.37

VITA

Linus Ross Walton was born April 28, 1941 at Mt. Olivet, Kentucky to Edith P. Walton and the late Lee R. Walton. He attended Milford Elementary School and Deming High School, where he graduated in 1959. He entered the University of Kentucky in 1959 and served as a cooperative student with the Tennessee Valley Authority from 1961 to 1964. He received a Bachelor of Science in Agricultural Engineering in 1965. He then received an appointment as Research Specialist in the Agricultural Engineering Department at the University of Kentucky where he received the degree of Master of Science in Agricultural Engineering in 1967.

He has been employed with the Agricultural Research Service, United States Department of Agriculture, from 1967 to present. He was located in Lexington, Kentucky from 1967 to 1970, Knoxville, Tennessee, 1970 to 1971 and returned to Lexington in 1971. He expects to receive a Doctor of Philosophy with a major in Agricultural Engineering in December 1974.

He is married to the former Sarah Culp of Mt. Olivet, Kentucky. They have two children, Lona, 12, and Susan, 4.

He is a registered Professional Engineer in Kentucky and is a member of the American Society of Agricultural Engineers, Phi Kappa Phi, Sigma Xi, and Gamma Sigma Delta.