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MATHEMATICAL SIMULATION OF DRYING FULLY
EXPOSED EAR AND SHELLED CORN.

THE OHIO STATE UNIVERSITY, PH.D., 1979

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MATHEMATICAL SIMULATION OF DRYING FULLY EXPOSED
EAR AND SHELLED CORN

DISSERTATION

Presented in Partial Fulfillment of the Requirement for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By
Yahya Ibrahim Sharaf-Eldeen, B.Sc., M.Sc.

**********

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NOMENCLATURE

A Constant in equation [32]

A_c Constant in equation [7]

A_i Constant in equation [20]; i = 0, 1, 2, ....

a Constant in equation [3]

a_0, a_1, a_2 Constants in equation [41]

a_3, a_4, a_5 Constants in equation [42]

B Constant in equation [32]

B_c Constant in equation [7]

B_i Constant in equation [21]; i = 1, 2, 3, ....

b Constant in equation [3]

C_i Constant in equation [20]; i = 0, 1, 2, ....

C_q Specific heat (Kcal/Kg °C)

D Diffusion coefficient (m^2/hr)

D_0, D_1 Constants in equation [10]

g Constant in equation [4]

K_c, K_d Drying parameter (hr^{-1})

K_{ii} Phenomenological coefficients; i = 1, 2, 3

K_{ij} Coupling coefficients; i = 1, 2, 3; α = 1, 2, 3; i ≠ j

x Thickness of a slab (m)

M Moisture content, percent (d.b.)

M_e Equilibrium moisture content, percent (d.b.)
\( M_0 \)
Initial moisture content, percent (d.b.)

\( \bar{M} \)
Average moisture content, percent (d.b.)

\( \bar{M}_x \)
Average moisture content observed during the last falling-rate period of drying, percent (d.b.)

\( m, m_1, m_2 \)
Constants in equation [6]

MR
Moisture ratio

\( \bar{MR} \)
Average moisture ratio

\( \bar{MR}_{exp} \)
Experimental average moisture ratio

\( N_1, N_2 \)
Constants in equation [31]

\( n \)
Constant in equation [5]

\( P \)
Vapor pressure (Kg/cm²)

\( P_s \)
Saturation vapor pressure (Kg/cm²)

\( R \)
Radius of a sphere (m)

\( r \)
Radial position (m)

\( r.h. \)
Relative humidity (decimal)

\( T \)
Material temperature (°C)

\( T_d \)
Air temperature (°C)

\( T_i \)
Initial temperature of the drying object (°C)

\( T_{abs} \)
Absolute temperature of drying air (°K)

TR
Temperature ratio

\( t \)
Drying time (hr)

\( t_{x} \)
Drying time at the start of the last falling-rate period (hr)

\( V \)
Air velocity (m/s)

\( x, y, z, \)
Thickness, width, and length of a brick (m)

\( \alpha \)
Constant in equation [34]

\( \alpha_0, \alpha_1 \)
Constants in equation [35]
\( \bar{\alpha} \)  
Thermal diffusivity \((m^2/hr)\)

\( P_0, P_1 \)  
Constants in equation [36]

\( \varepsilon \)  
Evaporation coefficient

\( \lambda \)  
Latent heat of vaporization \((\text{Kcal/Kg})\)
CHAPTER I. INTRODUCTION

Cereal grains have been and continue to be a major source of food for humans and for animals throughout the world. Corn is raised on more acres and has a larger production than other cereal grains, particularly in the United States. The production of corn per acre has been increasing rapidly, and has at least doubled in the past 30 years, largely as a result of new varieties, fertilizers, and weed and insect control measures. The increase in yield necessitates continued emphasis on harvesting, handling, and drying to economically preserve the crop produced.

Corn matures in the fall and is usually harvested at a moisture content that is higher than is safe for storage. In some corn producing areas, the moisture content of shelled corn at harvest time may average from 30 to 42 percent, w.b. High-moisture corn stored at moderately high temperatures is vulnerable to damage due to deterioration, molds, and insects during the period of storage. On the other hand, weather conditions cannot be depended upon to allow harvesting for maximum return after the grain is naturally dried in the field. Losses in both corn yield and quality may result from extended periods of inclement weather during field drying. For these reasons, mechanical drying of corn each year becomes an essential operation in modern processing practice.
Corn harvesting methods have undergone a major transition since the 1950's, evolving from ear-corn harvesting systems to high-moisture, field-shelling systems. Foster (36)* reported that field shelling of corn in the central U.S. corn belt (Indiana, Illinois, and Iowa) increased from 2% of the total crop in 1956 to 85% by 1975. The adaptation of large combines for field-shelling has resulted in harvesting rates up to three times as high as with the commonly available two-row pickers. Furthermore, field-shelling greatly facilitates large-scale handling and storing of corn. Shelled corn occupies about half the volume of that required by ear corn.

Artificial drying of corn is an energy intensive agricultural operation that will be increasingly affected by the growing fossil fuel shortage. The energy required for drying shelled corn often exceeds the total amount required for preparing the seedbed, planting, cultivating, and harvesting the crop (23). The present increased use of field-shelling equipment demands that a sufficient capacity be provided to dry the corn harvested each day within 24 hours. This capacity must be obtained with a minimum capital investment while keeping fuel and power costs to a practical minimum. As a result, the load on conventional drying and handling equipment is often excessive at the peak of harvest.

Present-day methods of field-shelling and artificial drying are believed to be responsible for the marked increase in broken kernels in subsequent commercial handling with a corresponding decrease in

*Numbers in parentheses refer to the appended references.
resultant corn quality at delivery (43).

Interest is being revived in ear-corn harvesting systems to obtain a better quality final product. Improvement in corn quality was reported by Hamdy et al. (43) and Richey and Peart (86) due to harvesting, handling, drying, and shelling sequences of ear corn. Several additional advantages of ear-corn systems have long been recognized. Johnson and Lamp (62) reported reduced field losses in early harvesting due to reduced lodging, which favors corn picking over field-shelling since the former can be performed earlier (at up to 33% moisture) than the latter (less than 26 to 28% moisture). Ear corn can be safely stored at moisture contents of up to 24 percent, making it amenable to energy-efficient drying methods such as low temperature drying, solar heat drying, or natural air drying because it could be dried at a leisurely rate over an extended period while held in storage. Ear-corn harvesting retains the cob which may be utilized for feed, bedding, or industrial uses. Moreover, ear-corn harvesting is used exclusively for producing seed corn with high germination potential (13).

Ear corn drying is not as widely practiced as shelled corn drying. Bulk drying of ear corn is based on experimental data collected under specific conditions of both the product and the drying medium (13,81). Ear corn driers have been designed on an empirical basis (13,81). Current techniques involve high operating costs in comparison to those used in removing moisture from other agricultural products (13,82). The use of prediction equations which have the capability of describing the drying rate of ear corn under different conditions would permit a more systematic and innovative design.
To accurately describe the deep bed drying of biological products such as cereal grains, fruits, and vegetables, and to explain the effects of various drying conditions on the quality of these products, the drying behavior of the individual particles making up the bed must be known, preferably accurately represented by a mathematical model developed from a conceptual perspective (10,11,16,17,18,21,22,40,49,78, 79,99). In the most general case, heat and moisture transfer in the particles must be considered simultaneously to develop an accurate description of the transport processes within the bed.

Several different mathematical models have been proposed by investigators to describe fully exposed drying characteristics of agricultural products. The diffusion equation and the logarithmic model have been used in the drying analysis of most cereal grains and other food products (4,17,18,26,39,40,47,83,97). The form of the diffusion equation used depends upon the assumptions made regarding the shape of the drying object and its moisture diffusion coefficient (1,28,41,42, 60,83,110,116). Exact solutions are difficult, if not impossible, to obtain, especially for irregularly-shaped nonhomogeneous objects such as ear corn. On the other hand, the logarithmic drying model, because of its simplicity, has been used for describing drying behavior of many farm products, even though it underestimates the drying rate in the early stages and overestimates it in the later stages of drying (73,78,84,87,93,100). Although considerable drying data and analyses are available for cereal grains and other agricultural products, no work has been traced on the drying characteristics of fully exposed corn ears and their component parts, excepting shelled corn.
The purpose of this work was to study the drying characteristics of fully exposed ear corn and its component parts under different conditions of both the product and the drying medium and to evaluate the principal factors which influence their rate of drying. Major consideration would be directed toward establishing a reasonably accurate mathematical model that does not require expensive solution techniques and which would describe the drying behavior at any time over the entire drying period. Such a model should be valuable in the design of efficient high capacity ear corn drying systems.
CHAPTER II. REVIEW OF LITERATURE

The science of drying is thought to date back to 1904 when a Russian scientist, Kossivich, published his thesis on the molecular mechanism of moisture movement in capillary porous bodies (9,55). Since the publication of the series of articles on drying rates of porous solids by Sherwood (94,95,96), considerable research, both theoretical and experimental, has been conducted by a large number of investigators. The literature concerning heat and/or mass transfer in porous hygroscopic solids is so extensive that no attempt will be made to present a complete review. However, the most pertinent information will be reviewed.

Physical Mechanism of Drying:

Drying is a complex thermophysical and physiochemical process involving the thermodynamics of moist gases and moist solids (37) and may be described as follows:

a) Heat and mass exchange between the surface of the substance and the surrounding medium, and

b) Transfer of heat and matter within the substance.

This definition includes two fundamental and simultaneous processes which occur during drying (55):

i) Mass transfer as liquid and/or vapor within the solid, and
ii) Heat transferred to evaporate the surface moisture.
Several mechanisms have been advanced for describing moisture movement in capillary porous products such as cereal grains (4,22,38,63,69,71): (a) Liquid movement due to surface forces (capillary flow); (b) liquid movement due to moisture concentration differences (liquid diffusion); (c) liquid movement due to diffusion of moisture on the pore surfaces (surface diffusion); (d) vapor movement due to moisture concentration differences (vapor diffusion); (e) vapor movement due to temperature differences (thermal diffusion); and (f) water and vapor movement due to total pressure differences (hydrodynamic flow). The relative importance of these mechanisms is dependent on the nature of the material, type of moisture bonding, moisture content, temperature and pressure in the pores, etc. (34). Therefore, the assumption of some overriding kinetic mechanism may be unduly restrictive, particularly for food systems which are complex structures (51,63,89).

Investigations of the drying of a number of biological products under constant external conditions revealed that drying usually can be divided into two periods (4,22,63,67,77,95): (i) A constant-rate period during which the drying rate is determined by external conditions (temperature, humidity, air flow, etc.); and (ii) a falling-rate period during which the drying rate is governed by internal flow of liquid and/or vapor in response to external conditions. The concepts of a constant-rate period followed by one or more falling-rate periods with sharp discontinuities in rate at critical moisture contents are firmly entrenched in the literature, and may be regarded as constituting the classical theory of drying (24,39,57,61,73).
Luikov (70) and Krischer and Kroll (65) investigated the basic mechanisms of moisture transfer in capillary porous bodies and showed that osmosis plays an important role for moisture content above the maximum hygroscopic moisture and capillary forces dominate constant-rate drying period. Since most biological materials do not exhibit a constant-rate drying period, diffusion must be the most likely physical mechanism governing the moisture movement in biological materials (20, 22, 42, 77, 96, 101, 110, 111).

Hall and Rodrigues-Arias (39), Hamdy and Barre (40, 41) and Henderson and Perry (48) suggested that moisture moves through cereal grains by the mechanism of diffusion during the falling-rate period. Baughman et al. (17, 18), Chittenden and Hustrulid (26), and Husain et al. (56) also assumed that diffusion is the rate controlling mechanism during drying of biological products. They applied the diffusion equation to describe the drying of corn and rice kernels. Hougen et al. (51) and Keey (63) postulated that other mechanisms such as capillarity, gravity, external pressure (shrinkage), etc. may exist. They, therefore, suggested that caution should be exercised when characterizing moisture movement by the diffusion equation.

Although diffusion is very well accepted to be the basic mechanism, there is no general agreement as to the exact nature of the driving potential for drying. Gorling (38) distinguished between the liquid diffusion due to concentration gradient and vapor diffusion due to vapor pressure gradient. Krischer and Hall (65) stated that, in general, liquid diffusion occurs in the moisture content range corresponding to about 85-100% relative humidity and vapor diffusion dominates at lower
moisture contents. Chhinnan and Young (25) suggested that both liquid and vapor diffusions may occur simultaneously due to moisture and vapor concentration gradients. Babbitt (5,6,7) and Barre (14) hypothesized that drying is in response to vapor pressure gradient rather than moisture concentration gradient.

Mathematical Models for Drying Phenomena:

Convection drying of biological products at moderate temperatures during the falling-rate period has always been of great importance and has been the subject of many studies. Several attempts have been made, with varying degrees of success, to develop mathematical models that describe the drying characteristics of fully exposed objects. Basically, there are three methods of describing the moisture transfer (22,93):

1. Diffusion equations using the moisture concentration gradient and/or the vapor concentration gradient as the driving force,

2. Semitheoretical models developed by analogy to Newton's law of cooling, chemical kinetics, etc., and

3. Purely empirical models.

Due largely to the complexity of the process and the simplicity of their computation routines, semitheoretical, as well as purely empirical approaches were more successful in earlier studies and proved useful to drier designers.

The most commonly used relationship is a semitheoretical equation analogous to Newton's law of cooling. Lewis (67) suggested that the rate of drying is directly proportional to the difference between the
moisture content of the material being dried and the moisture content which it would have at equilibrium with the surrounding air; that is,

\[
\frac{d\bar{M}}{dt} = -K_c(\bar{M} - M_e)
\]  

[1]

where:

- \( \bar{M} \) = average moisture content at any time, \( t \) (d.b.)
- \( t \) = drying time (hr)
- \( K_c \) = drying parameter or constant (hr\(^{-1}\))
- \( M_e \) = equilibrium moisture content (d.b.).

This model assumes that all the resistance to moisture flow is concentrated in a layer at the surface of the material. Thus, the moisture gradients within the material are considered negligible. This equation may be integrated to:

\[
\bar{M} = \exp(-K_c t)
\]  

[2]

where:

- \( \bar{M} = (\bar{M} - M_e)/M_o - M_e) \) = average moisture ratio (dimensionless)
- \( M_o \) = initial moisture content (d.b.).

The equilibrium moisture content used in this model is an asymptotic value of the drying curve. This has been called by McEwen and O'Callaghan (75) the dynamic equilibrium moisture content and by Becker and Sallans (20) the effective surface moisture content. Chu and Hustrulid (29) described it as "probably a time average of the instantaneous surface moisture content." Allen (4) concluded "that for the purposes of prediction and description of grain drying processes, the
dynamic equilibrium moisture content is the logical choice...." Although this term is still a subject of discussion regarding its physical significance, it appears to yield good results and has been used by several researchers (39,47,83,102).

Henderson and Pabis (47) gave a theoretical justification for using an Arrhenius-type equation to relate the drying parameter, $K_c$, to drying air temperature. This proposed equation is:

$$K_c = a \exp(-b/T_{abs})$$  \[3\]

where:

- $a, b$ = material constants
- $T_{abs}$ = absolute temperature (°K).

They indicated that $K_c$, being concerned with the internal moisture movement, is dependent on grain rather than air temperature. In most drying applications, however, both become nearly the same after a short period from the start of drying.

Several investigators (4,16,18,47,52,83,97,102,103,104) applied equation [2], commonly known as the exponential or logarithmic model, to describe the drying of some agricultural materials. Many researchers (39,47,73,83,87,93,100), however, tried, without good success, to describe the complete drying curve with such a relationship. Experimental evidence showed that a single temperature-dependent drying parameter underestimates the drying speed in the initial stages and overestimates it in the final stages of drying.

Hall and Rodrigues-Arias (39) suggested describing the drying curve by a set of straight lines with different values of $K_c$, each
appropriate to a short range of moisture content. The basis for their suggestion was that their drying curves, when plotted on semilog paper, showed definite breaks and each portion of the curve could be represented by a straight line. Menzies and O'Callaghan (73) observed that the falling-rate drying period of grass is divisible into three distinct phases. They used equation [2] with different values of $K_c$ and $M_e$ to describe each of these three periods.

Page (84) added an empirical exponent to time in equation [2],

$$MR = \exp(-K_c t^g)$$  \[4\]

where:

$g =$ empirical drying exponent.

Page's model (also known as the modified exponential model) gave somewhat better results, in describing the fully exposed drying of shelled corn and soybeans, than the exponential model (35,74,80,84,91,112).

Babbitt (5,6,7) and Barre (14) hypothesized that vapor pressure is the driving force causing movement of moisture. Using this assumption, Hukill and Schmidt (53) developed a complex empirical model using two phases with the final phase having a drying parameter indicating a greater resistance to moisture flow, and used it to describe the drying curve of fully exposed grain sorghum. Their work is fairly accurate but too complicated or too time-consuming in practical applications.

By analogy to chemical kinetics, Chen and Johnson (24) proposed the following model:

$$\frac{dM}{dt} = -K_c (\bar{M} - M_e)^n,$$  \[5\]
where $K_c$ and $n$ are empirical constants which vary for different drying periods, and $M_e$ is the moisture content at the end of each period under consideration. Troeger and Hukill (100) used a three-equation model of the above form to describe the drying curve of fully exposed corn kernels over the entire drying period. The above equation reduces to equation [2] when $n$ is equal to 1.

Equations [4] and [5] represent just some of the modifications that have been made in the basic Lewis equation (Equation [1] or [2]).

Many grain drying researchers (4,39,47,87,90) assumed that the drying air temperature is the only factor that significantly affects the drying parameter, $K_c$. This assumption appears to be a simplification. Chittenden and Hustrulid (26), Chu and Hustrulid (28), and Van Rest and Isaacs (103) found that the mean value of $K_c$ of shelled corn and other grains is dependent on the moisture content as well as the drying air temperature. The effect of moisture content, however, seems to be less than that of drying air temperature.

The relative humidity and velocity of the drying air are not considered significant in grain drying under fully exposed conditions during the falling-rate period. White et al. (112) reported that, "From a theoretical standpoint relative humidity should have little, if any, effect on the fully exposed drying parameter, $K_c$, in the logarithmic model." Henderson and Pabis (47) suggested that the influence of relative humidity on the rate of drying is primarily due to its effect on the equilibrium moisture content. Chu (27) found that the adoption of dynamic equilibrium moisture content eliminates the dependence of drying parameters on relative humidity of the drying air. A comparison
of the conclusions of various researchers (4,5,26,47,59,75,77,97,99, 100,108) concerning the effect of relative humidity on drying indicates that the relative humidity, in the range of up to 30 percent, has negligible effect on the drying rate of fully exposed shelled corn and other grains during the falling-rate period.

Barre et al. (16) and Henderson and Perry (48) considered the effect of air velocity on the drying parameter in equation [2], $K_c$, and suggested the following modification,

$$K_c = m P_s m_1 V^{m_2}$$

[6]

where:

$m, m_1, m_2 = \text{constants}$

$P_s = \text{saturation vapor pressure (Kg/cm}^2\text{)}$

$V = \text{air velocity (m/s)}$.

According to Henderson and Henderson (49) and Henderson and Pabis (47), the effect of air velocity on the drying constant is trivial and, hence, the value of $m_2$ becomes zero. Simmonds et al. (97), in drying wheat grain, concluded that the drying rate is independent of air velocity in the range above 0.1524 m/s (30 fpm); a four-fold change of velocity produced insignificant effects. The conclusions of a number of investigations (47,52,78,85,88,99) indicated that the air velocity in the range over 0.254 m/s (50 fpm) has negligible effect on the drying rate of fully exposed grains and other farm crops during the falling-rate period.

Thompson et al. (99) developed an empirical model for the drying time, $t$, based on a second order exponential function to describe
thin-layer drying of shelled corn over temperatures ranging from 60 to 150°C:

\[ t = A_c \ln(MR) + B_c [\ln(MR)]^2, \]  

[7]

where \( A_c \) and \( B_c \) are empirical coefficients that are functions of drying temperature.

Thin-layer drying equations for other cereal grains have been proposed by O'Callaghan et al. (79) for barley, Sabbah et al. (92) for soybeans, Agrawal and Singh (2) for rice, and by Watson and Bhargava (107) for wheat.

The diffusion-based modeling approach has in recent years become most popular and indeed it provides a conceptual basis for physically understanding the drying process. The fundamental differential equation of diffusion assumes that the resistance to moisture flow is uniformly distributed throughout the interior of the material (31), that is,

\[ \frac{\partial M}{\partial t} = \nabla \cdot [D \cdot \nabla M] \]  

[8]

where:

- \( D \) = diffusion coefficient (m²/hr).
- \( M \) = moisture concentration at any point within the material (d.b.).

The use of diffusion equations to correlate drying data of fully exposed porous media was first suggested by Newman (77) and Sherwood (94,95,96). They assumed that the diffusion coefficient was constant and that the potential causing the flow was the difference in moisture
concentration. Babbitt (5) was among the first to apply the diffusion equation to describe moisture movement in an agricultural crop. His work centered around describing the rate of moisture desorption in wheat.

Van Arsdel (101) suggested that the potential could be either concentration or vapor pressure difference, and both methods of expressing the diffusion equation appear valid. The appropriate choice is determined by the experimental procedure. If vapor pressure were the potential, temperature effects would be reflected in the vapor pressure, while if concentration were used, temperature effects would be reflected in the diffusion coefficient.

Becker and Sallans (19), Hamdy and Barre (41), and Hustrulid and Flikke (59) used the diffusion equation in spherical coordinates assuming only radial flow and constant diffusivity to describe moisture movement in grain kernels. Young and Whitaker (116) evaluated the diffusion equation for a homogeneous body assuming constant diffusivity, as a model for describing the movement of moisture in individual peanut pods. Pabis and Henderson (83) treated the corn kernel as a homogeneous, isotropic brick and used the diffusion equation in rectangular coordinates with a constant diffusivity to describe moisture movement. Although the three-dimensional diffusion equation as applied was quite satisfactory, they recommended the solution for the kernel shaped as a sphere because of its simplicity.

The solution to equation [8] with a constant diffusion coefficient, uniform initial concentration, a step change in surface concentration, no surface resistance, and a homogeneous and isotropic body
was derived by Crank (31) for a slab of thickness $\xi$,

$$\bar{MR} = \frac{8}{\pi^2} \left[ \exp\left(-\frac{Dt\pi^2}{4\xi^2}\right) + \frac{1}{9} \exp\left(-9Dt\pi^2/4\xi^2\right) + \frac{1}{25} \exp\left(-25Dt\pi^2/4\xi^2\right) + \ldots \right].$$ \[9\]

If the object is a sphere, $8/\pi^2$ becomes $6/\pi^2$ and $4\xi^2$ is replaced by $R^2$, where $R$ is the radius of the sphere; and if a brick shape, $8/\pi^2$ becomes $(8/\pi^2)^3$ and $4\xi^2$ is replaced by $1/(1/x^2 + 1/y^2 + 1/z^2)$, where $x$ is the thickness, $y$ is the width, and $z$ is the length of the brick.

Equation [9] was proposed by Newman (77) and Sherwood (96) to represent thin-layer drying of biological materials in the falling-rate period. Many subsequent investigations relative to agricultural materials (22,45,47,83) revealed that the equation is only generally appropriate. Experimentally derived modifying coefficients for equation [9] may be used to account for the fact that agricultural particles are not perfect spheres, or cylinders, or combinations of these.

This equation is based on several assumptions:

1. Moisture moves through the individual particles by diffusion,

2. Air flow has no effect on the drying rate if flow is turbulent (47,97).

3. Isothermal conditions are assumed (77), but heat energy is required to remove the moisture from the particles. Consequently, a temperature gradient must exist between the passing air and each individual particle (83).

4. The equilibrium relative humidity to be used shall be computed from a drying study although this is lower than the value ob-
tained in published data at the same moisture ratio, presumably because a moisture gradient is present in the particles during drying (4,47).

5. An Arrhenius-type equation (Equation [10]) relates the rate of drying to the temperature of the drying air by modifying the diffusivity,

\[
D = D_0 \exp \left( -D_1/T_{abs} \right), \tag{10}
\]

Although the moisture independent diffusivity solution has been used by several researchers because of the simplicity, it does not seem to predict drying behavior of biological materials accurately in the entire range of drying as pointed out by Sherwood (95), Van Arsdel (101), and Bakker-Arkema et al. (11). In most cases, the predicted drying rates were too slow in the early stages and too rapid in the later stages of drying. Numerous researchers (4,22,26,28,39,47,53,104) have recognized that the diffusion coefficient is affected by moisture concentration as well as the temperature of the material being dried.

Hustrulid and Flikke (59) used equation [9] in spherical coordinates to describe the drying rate of individual corn kernels. In a later study, Chittenden and Hustrulid (26) found that the diffusion coefficient varied with the initial moisture content of the corn kernel and concluded that it must apply at every point within the kernel. They also found that the surface moisture content giving the best fit was slightly higher than the moisture content in equilibrium with the environment and that its value increased with higher initial moisture content.
Hamdy and Barre (41) suggested the presence of a thin stagnant film layer of air around the kernel, which would account for a surface moisture higher than the equilibrium moisture content. They developed a method for evaluating the film coefficient and moisture diffusion coefficient and obtained a better fit to the drying data of Chittenden and Hustrulid (26) using the diffusion equation with a constant diffusion coefficient.

For a moisture-dependent diffusion coefficient, the fundamental diffusion equation (Equation [8]) becomes a nonlinear partial differential equation, and only a few analytical solutions are known for which the functional form of the diffusion coefficient satisfies a special type (31,69,70,71). Chittenden and Hustrulid (26) stated that, "no solution has been obtained for an arbitrary moisture-dependent diffusion coefficient in diffusion from sphere." Numerical methods can be utilized, however, for solving for a more general variation of diffusion coefficient with moisture content.

Crank and Henry (32) obtained numerical solutions for equation [8] in rectangular coordinates for a number of cases where the diffusion coefficient varies in particular ways with the moisture concentration. They also published a method to determine empirically the variation of \( D \) with concentration by observing the curve of average moisture ratio as a function of time.

Hamdy and Johnson (42) used finite differences to solve the unidirectional diffusion equation in rectangular coordinates on an analog computer for a coefficient that was an arbitrary function of both position and concentration.
Whitaker et al. (111) on the other hand solved the nonlinear diffusion equation in spherical coordinates on an analog computer for radial diffusion assuming an arbitrary concentration-dependent diffusivity. They applied the solution to the drying of a porous sphere of an inorganic material. Least squares fitting yielded a diffusivity function of the form,

\[ D = 0.0135 - 0.00042 M. \]  \[11\]

Chu and Hustrulid (28) assumed that diffusivity was an exponential function of temperature and concentration and used numerical methods to solve the diffusion equation. They applied the method to the drying of corn kernels successfully and obtained the following relationship:

\[ D = 1.5134 \exp \left[ (0.00045 T_{abs} - 0.05485)M - \frac{2513}{T_{abs}} \right]. \]  \[12\]

The relationship between diffusivity and moisture content in wet solids is complex and depends upon not only the diffusing material but also the medium through which the solute is redistributing itself (63). Luikov, as reported by Keey (63), suggested that the relationship may be explained by the way in which moisture is bound to the solid skelton. He postulated four regions as depicted in Figure 1.

Region I, AB. Monomolecular adsorption takes place, and moisture moves by vapor-phase diffusion \((0 < \text{r.h.} < 0.2)\).

Region II, BC. Moisture is adsorbed in multimolecular layers; moisture begins to travel in the liquid-phase and there is a corresponding decline in diffusivity with moisture content \((0.2 < \text{r.h.} < 0.8)\).
FIGURE 1. VARIATION OF MOISTURE DIFFUSIVITY WITH MOISTURE CONTENT (63).

FIGURE 2. VARIATIONS OF VAPOR, LIQUID, AND TOTAL DIFFUSIVITIES WITH MOISTURE CONTENT (63).
Region III, CD. Moisture is held in the microcapillaries, and migration of moisture becomes easier as the finest pores are filled ($0.8 < \text{r.h.} < 1.0$).

Region IV, DE. Moisture exerts its full vapor pressure, and the migration of moisture is determined primarily by capillarity, and thus is independent of moisture content up to saturation ($\text{r.h.} > 1.0$).

Results of experiments by several investigators, as reported by Keey (63), suggested that the vapor-phase diffusivity passes through a maximum at low moisture contents, and the liquid-phase diffusivity continuously rises with moisture content, eventually becoming the larger conductance. The apparent or effective moisture diffusivity, then, varies in a way that is superficially similar to the curve of Figure 1 as sketched in Figure 2 (63). In many circumstances, particularly when only a limited range of moisture content is of interest, a monotonic description of diffusivity-moisture content relationship may be satisfactory.

Most of the early work in thin-layer studies was concerned with only the mass transfer in the drying process. Little attention was given to the heat transfer involved. However, some studies were made for simultaneous heat and moisture transfer during drying. Wang and Hall (105) assumed vapor diffusion to be the governing mechanism for internal moisture migration inside porous hygroscopic solids. They solved the simultaneous vapor and heat diffusion equations for a homogeneous, isotropic, and symmetrical sphere assuming uniform initial conditions, constant thermal and mass diffusivities, and constant boundary conditions. They applied the solution to shelled corn and concluded
that the effect of temperature changes due to the loss of moisture at points inside a kernel has profound effects on the rate of moisture diffusion.

Young (115) used a modified version of Henry's (50) model for the uptake of moisture by cotton bales to include the cases where mass and thermal diffusivities are not constant. To describe the simultaneous heat and mass diffusion in a porous solid, linear dependence of mass and thermal diffusivities were assumed. He solved the simultaneous equations numerically, but no experimental data were reported to confirm the validity of the model.

King (64) considered mass diffusion along with heat transfer and derived a model for rates of sorption from a porous foodstuff dried in the hygroscopic range. The model involved many transport coefficients which might pose difficulties if used to describe moisture movement in foodstuffs. Also, no experimental work was reported to confirm the applicability of the model.

Harmathy (44) derived a set of partial differential equations for the simultaneous transfer of moisture and heat in a porous organic material using evaporation-condensation theory. The theory, however, does not seem to be applicable to food products (55).

In 1934 Luikov and Mikhailov (71) discovered the phenomena of moisture thermal diffusion and established a new factor causing moisture transfer in solids, the temperature gradient. They derived a system of coupled partial differential equations (Equation [13]) based on the principles of irreversible thermodynamics, thus not only avoiding the need to hypothesize a particular governing kinetic mechanism or
mechanisms for moisture flux but also providing a rigorous means of coupling the fluxes due to thermal, pressure, and moisture gradients. Further, in order to unify heat and mass transfer problems, Luikov introduced the concept of moistness as the moisture transfer analogue of temperature.

\[
\begin{align*}
\frac{\partial M}{\partial t} &= \nabla^2 K_{11} M + \nabla^2 K_{12} T + \nabla^2 K_{13} P \\
\frac{\partial T}{\partial t} &= \nabla^2 K_{21} M + \nabla^2 K_{22} T + \nabla^2 K_{23} P \\
\frac{\partial P}{\partial t} &= \nabla^2 K_{31} M + \nabla^2 K_{32} T + \nabla^2 K_{33} P
\end{align*}
\]\[13\]

where:

\[K_{ij} = \text{phenomenological coefficients}; \ i = 1, 2, 3\]

\[K_{ij} = \text{coupling coefficients}; \ j = 1, 2, 3; \ i \neq j.\]

Moisture flow due to a pressure gradient is significant only in drying at product temperatures well above the temperature range employed in cereal-grain drying \((22, 24, 57)\). This means that the pressure \((P)\) terms can be dropped in equations \[13\] and the simplified system of equations becomes:

\[
\begin{align*}
\frac{\partial M}{\partial t} &= \nabla^2 K_{11} M + \nabla^2 K_{12} T \\
\frac{\partial T}{\partial t} &= \nabla^2 K_{21} M + \nabla^2 K_{22} T.
\end{align*}
\]\[14\]

Chen and Johnson \((24)\) and Husain et al. \((57)\) modified equations \[14\] to represent simultaneous heat and moisture transfer during forced drying of biological materials in the hygroscopic range of moisture content. They developed a mathematical model for moisture and heat transfer
in a piece of foodstuff during drying as follows:

\[
\frac{\partial M}{\partial t} = D \nabla^2 M + \frac{\partial}{\partial M} (\sigma M)^2 \\
\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{\lambda \varepsilon}{c_q} \frac{\partial M}{\partial t}
\]

where:

- $\alpha$ = thermal diffusivity ($m^2/hr$)
- $\lambda$ = latent heat of vaporization (Kcal/Kg)
- $\varepsilon$ = evaporation coefficient
- $c_q$ = specific heat (Kcal/Kg°C).

Because of difficulties in solving these equations, Chen and Johnson (24), instead, devised empirical moisture flux equations and used them to analyze the falling-rate periods of drying. On the other hand, Husain (55) provided numerical solutions to equations [15] using finite difference approximation technique. He studied the drying behavior of potato and rice and reported that the diffusivity for the first falling-rate period was constant, but varied exponentially with moisture content during the second falling-rate period.

Brooker et al. (22) and Husain et al. (56,57) concluded that the coupling effects of temperature and moisture, in the analysis of cereal-grain drying, could be neglected and the majority of cases could be described by the following simplified version of equations [14]:

\[
\frac{\partial M}{\partial t} = \nabla^2 K_{11} M \\
\frac{\partial T}{\partial t} = \nabla^2 K_{22} T.
\]
Young (114) solved the simultaneous partial differential equations describing heat and vapor transfer in porous spheres. Assuming that the mass diffusivity is linearly dependent on moisture content and temperature, and that thermal conductivity is a linear function of moisture, he obtained a solution to these equations on a digital computer for uniform initial conditions and constant boundary conditions. He examined the effect of mass and heat diffusivities and combined them in a modified Lewis number (essentially the same as the reciprocal of the Luikov number (70)), which could be used to determine the significance of the heat transfer equation in drying problems. He proposed that the temperature gradient becomes insignificant for a modified Lewis number greater than 60, thereby allowing the heat transfer equation to be dropped without any serious error.

Neglecting the temperature gradients in an object during drying simplifies Luikov's equations (Equations [16]) to:

\[
\frac{aM}{at} = v^2K_{11}M. \tag{17}
\]

Since the moisture flow within a porous product takes place by liquid and/or vapor diffusion, the transfer coefficient \(K_{11}\) is called an effective diffusion coefficient, \(D\), and equation [17] reduces to equation [8], the fundamental differential equation of diffusion.

**Drying of Ear Corn:**

Although considerable drying data and analysis are available for cereal grains and other agricultural products, relatively little research has been reported with regard to the drying characteristics of
ear corn. Furthermore, a mathematical model has not been established which would predict the drying behavior of ear corn for different drying conditions.

Equilibrium moisture contents of ear corn exposed to different atmospheres of relative humidity and temperature were determined by Alberts (3), Bailey (8), Coleman and Fellows (30), and Ward (106). More recently, Kumar et al. (66) investigated the moisture equilibrium isotherms of intact ears of corn and their component parts. They concluded that the equilibrium moisture isotherms of ear corn and shelled corn do not differ significantly. They added that the experimental values for ear corn were slightly lower than those of shelled corn.

Pabis and Hall (82) studied the temperature and moisture profiles while drying an ear of corn placed parallel to the direction of air flow. Empirical equations were given to determine the thickness of the boundary layer as a function of air velocity, and to determine the temperature distribution inside the ear with moisture content ranging from 0 to 90 percent, d.b. They indicated that the air velocity has no effect on the drying rate in the range over 0.254 m/s (50 fpm).

Barre and Swanson (15) observed the drying curve of an ear corn fully exposed to an atmosphere of constant temperature and humidity and using air velocities in the range up to 0.254 m/s. They found that the rate of drying was increased slowly as the rate of air movement was increased. Barre et al. (16) used a modified form of Hukill's equation (52) to analyze and design cross-flow deep-bed drying systems for ear corn as well as shelled corn and small grains. They reported
that the departures between the calculated and observed moisture ratios of ear corn in the first and last parts of the drying period reflect the variation of the drying constant, being greater during the first and decreasing during the latter part of the drying period.

Pabis (81) dealt with moisture distribution in ear corn as a function of the drying time, layer position, air flow rate, air humidity and temperature, and presented some empirical equations.

Hamdy et al. (43) indicated that shelled corn exhibits a greater susceptibility to mechanical damage when artificially dried than corn dried on the ear, even if it were hand-shelled. This susceptibility was found to increase with drying temperature at a greater rate than that of corn dried on the ear. They reported that ear corn dries more slowly than shelled corn and has less tendency to develop stress cracks.
CHAPTER III. RESEARCH OBJECTIVES

The overall objective of this research was to establish a mathematical model (or models) developed from a sound theoretical basis for describing the fully exposed drying characteristics of homogeneous as well as nonhomogeneous biological materials of different geometrical shapes with the required accuracy and the computational ease desired for efficient drying simulations.

The following specific objectives were considered:

1. To determine and compare the drying characteristics of fully exposed corn ears, shelled corn, and corn cobs under different conditions of both the product and the drying medium.

2. To establish mathematical model (or models) based on the general form of the diffusion equation solution for predicting the fully exposed drying behavior of each product at any time during the drying process.

3. To evaluate the closeness of fit between the predicted and the experimental drying data.

4. To compare the developed model (or models) with existing drying models, particularly the frequently used logarithmic drying equation and diffusion model, with regard to precision of predicting drying behavior.
Theoretical Considerations

Considerable work has been done in past decades to describe the drying characteristics of fully exposed porous hygroscopic materials during the falling-rate period. Several different mathematical models have been proposed and compared with experimental drying data. The simultaneous heat and moisture transfer models seem to have a distinct advantage over other drying models in accurately predicting the drying behavior of biological materials over the entire drying period (56, 57, 98). These models, although they represent the actual process of drying, involve many transport coefficients which often pose difficulties when used to predict the drying characteristics of agricultural products. In most grain drying situations, however, thermal diffusivity is large compared to moisture diffusivity. Young (114) concluded that for a modified Lewis number greater than 60, the temperature gradient within the object becomes insignificant compared to the moisture gradient. Pabis and Henderson (83) calculated the drying and heating time constants for shelled corn as 252 and 1.74 min., respectively, which yields a Lewis number of 145. Consequently, the moisture diffusion equation alone is sufficient for characterizing moisture movement in fully exposed drying of cereal grains. Because the diffusion models are complex and often time-consuming to solve, many semitheoretical and purely...
empirical relations have been used to describe fully exposed drying data.

The following sections present and discuss the development and validity of two mathematical models that are frequently used for describing the fully exposed drying characteristics of most agricultural products including corn. These models are the logarithmic drying equation and the isothermal diffusion model. Moreover, major consideration would be directed toward developing a reasonably accurate mathematical model, whose basis is the diffusion equation and is nearly as simple in application as the logarithmic drying model.

**Logarithmic Drying Model**

A moisture relationship analogous to Newton's law of cooling in heat transfer is often used in grain drying analyses. Assuming that the rate of moisture loss from a moist object is proportional to the difference between the object moisture and its equilibrium moisture content corresponding to the temperature and humidity of the surrounding medium (67, 95),

\[
\frac{d\bar{M}}{dt} = -K_c(\bar{M} - M_e).
\]  

This relationship is frequently accepted as a hypothesis for the assignment of coefficients describing the rate of drying of many agricultural products (4, 47, 52, 87, 97).

Equation [1] assumes that all the resistance to moisture flow is concentrated in a layer at the surface of the material. Thus, the moisture gradients within the material are considered negligible. This equation may be integrated to:
\[ \frac{\bar{M} - M_e}{M_0 - M_e} = \exp(-K_C t). \]  \[ \text{[2]} \]

\( K_C \) has been referred to as a "moisture availability factor"; it is, in fact, a "rate constant" as this term is understood in the classical theory of rate processes. Sometimes \((\bar{M} - M_e)\) is referred to as the "free water" (59), but this term has no particular physical significance apart from its application to the conditions of the experiment (53).

Henderson and Pabis (47) developed an expression from fundamental considerations relating the drying parameter, \( K_C \), and the air temperature, \( T_{abs} \),

\[ K_C = a \exp\left(-\frac{b}{T_{abs}}\right) \]  \[ \text{[3]} \]

where:

\( a, b \) = material constants.

Chittenden and Hustrulid (26), Chu and Hustrulid (28), and Van Rest and Isaacs (103) found that the mean value of \( K_C \) for shelled corn and other grains is dependent on the moisture content as well as the drying air temperature. The effect of moisture content, however, seems to be less than that of drying air temperature.

A plot of \( \log(\bar{M} - M_e) \) against \( t \) according to equation [2] is a straight line with slope \(-K_C\) and a vertical intercept (at \( t = 0 \)) of \( \log(M_0 - M_e) \). Simmonds et al. (97), in drying wheat grain, found that it was necessary to use a "dynamic" value of \( M_e \) to obtain a straight line. It is probable that, with the type of curve obtained, one can always find by trial and error a value of \( M_e \), independent of the actual equilibrium moisture, which will give an approximate straight line in this plot.
Henderson and Perry (48) stated that "the equilibrium moisture content that must be postulated to secure a linear plot of MR against t on semi-logarithmic coordinates is often found to be considerably above the equilibrium values obtained from hygroscopic measurements at constant weight."

A modified form of the logarithmic equation is often used to describe fully exposed drying characteristics of cereal grains and other farm products. Page (84) added an empirical exponent to time in equation [2],

\[ MR = \exp(-K_c t^q). \] [4]

Flood et al. (35), Overhaults et al. (80), Sabbah (91) and White et al. (112) found that Page's equation gave better predictions of the drying behavior for shelled corn and soybeans over a long drying period than the logarithmic equation.

**Diffusion Model:**

It has been generally accepted that convection drying of biological products at moderate temperatures during the falling-rate period is controlled by the mechanism of diffusion (1,20,40,41,42,60,77,96, 110,111). The fundamental differential equation of diffusion assumes that the resistance to moisture flow is distributed throughout the interior of the material (31), that is,

\[ \frac{\partial M}{\partial t} = \nabla \cdot (D \cdot \nabla M). \] [8]
The analysis of moisture diffusion on porous media is simplified if the material is of a simple geometric shape such as a cylinder or a sphere. The assumption does not seriously limit the scope of the analysis and seems reasonable since, in general, moisture moves outwardly in all directions \((111)\). Becker and Sallans \((20)\), Chittenden and Hustrulid \((26)\), Hamdy and Barre \((41)\), and Hustrulid and Flikke \((50)\) described moisture flow in grain kernels using the unidirectional diffusion equation in spherical coordinates. Agrawal \((1)\), Igbeka et al. \((60)\), and Husain \((55)\), on the other hand, used the diffusion equation in cylindrical and cartesian coordinates to describe moisture movement in bologna and potato slices, respectively.

**Diffusion in a Sphere (Kernel Model):** Crank \((31)\) derived the mathematical model characterizing radial diffusion in spherical conditions,

\[
\frac{\partial M}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( D r^2 \frac{\partial M}{\partial r} \right)
\]

where:

- \(r\) = radial position \((m)\).

Becker and Sallans \((20)\), Chittenden and Hustrulid \((26)\), Hamdy and Barre \((40,41)\), Hustrulid and Flikke \((59)\), and others used equation \([18]\) to describe moisture diffusion in corn kernels. The following assumptions are made to justify using the equation:

i. Diffusion is assumed to be the rate controlling mechanism \((20,40,41,59)\).

ii. The kernel is assumed to be a homogeneous isotropic solid sphere and its moisture distribution is symmetrical...
with respect to its center (40).

iii. Air velocity is sufficiently high so that surface resistance to moisture transfer is negligible compared to internal resistance (47,111).

iv. With a Lewis number for shelled corn of 145 (83,114), resistance to heat transfer is mainly at the kernel surfaces and, consequently, the temperature gradient within the kernel is negligible.

v. Shrinkage in cereal grains is negligible (28).

The boundary conditions utilized with equation [18] in accordance with the underlying assumptions are:

1. The initial moisture content is uniform throughout the kernel.

2. The surface moisture content falls to the value in equilibrium with the environment immediately at the start of drying.

3. The moisture gradient at the center of the kernel would vanish because of the symmetry.

Mathematically, these conditions can be expressed as follows:

\[
\begin{align*}
M(r,0) &= M_0 \\
M(R,t) &= M_e, \quad t > 0 \\
\frac{\partial M}{\partial r} \bigg|_{r=0} &= 0, \quad t > 0.
\end{align*}
\]

[19]

The drying behavior predicted by the diffusion model fits experimental data over a long drying period more accurately than that predicted by the logarithmic equation and other empirical models (20,26,41,83).
The good agreement indicates that moisture is transferred to the kernel surface by a process of diffusion.

Foster (36) stated that "the diffusion model, as applied to grain drying in thin layers, relates the drying constant to a moisture, temperature, and particle size dependent diffusion coefficient. This overcomes some of the shortcomings of the logarithmic model (Equation [2]), but introduces other problems and increases the complexity of the model such that computer methods are required for solution. The exponential relationship in equation [2], because of its simplicity, will probably continue to be used until a more acceptable theoretical approach is found."

Diffusion-Based Drying Model:

In spite of the large body of literature in the area of drying, there has still been no clear consensus drying model that has the desired accuracy and the computational ease required for efficient drying simulations. The purpose of this analysis was to develop a fully exposed drying model from a sound theoretical basis that is easier to apply than the diffusion model yet allows accurate prediction of drying behavior for a longer time than is possible with the logarithmic drying equation.

The diffusion-based modeling approach has in recent years become most popular because it is reasonably accurate and it provides a conceptual basis for physically understanding the drying process. The predominant factor causing moisture movement in most biological materials has been assumed to be molecular diffusion (19,77,96,111). Therefore,
the kinetics of sorption and desorption may be represented by Fick's second law of diffusion (31), that is,

\[ \frac{\partial M}{\partial t} = \nabla \cdot (D \cdot \nabla M). \]  

[8]

Exact solutions are difficult, if not impossible, to obtain, especially for irregularly-shaped nonhomogeneous objects such as ear corn. The general form of the solution is still very useful, however, because it gives the expected pattern of the average moisture content of the drying object and points out the trend of variation as affected by various parameters.

The solution to the diffusion equation with a constant diffusivity is a series of negative exponential terms, regardless of the geometry of the particles or the boundary conditions surrounding them (77),

\[ \frac{M - M_e}{M_0 - M_e} = A_0 e^{-C_0 D t} + A_1 e^{-C_1 D t} + A_2 e^{-C_2 D t} + \ldots. \]  

[20]

where:

\[ A_i = \text{constant, characteristic of the geometry of the object being dried (dimensionless); } i = 0, 1, 2, \ldots \]

\[ C_i = \text{constant, characteristic of the geometry of the object being dried (m}^{-2}; i = 0, 1, 2, \ldots \]

Numerous researchers (26, 28, 42, 47) recognized that the diffusion coefficient is not constant but, in general, is affected by material temperature and moisture concentration. In most grain drying situations, however, thermal diffusivity is sufficiently large compared to moisture diffusivity and the effect of temperature gradient on moisture movement within the material can be neglected (83, 114). Crank (31), Pabis and
Henderson (83), and Rowe and Gunkel (90), however, included the effect of the temperature change within the material on the drying rate in their analyses by making substitution of variables that allowed the series solution for constant $D$ to be used even though $D$ changed during drying. Chu and Hustrulid (29), on the other hand, showed that the average moisture ratio obtained from the solution of the diffusion equation with initial concentration-dependent diffusivity in a desorption process is the sum of converging series of negative exponential terms regardless of the size or shape of the drying solid.

For large values of time, $t$, equation [20] converges very rapidly and only the first term needs to be used. The constant part, $C_0D$, of the first term exponent is commonly referred to as the drying parameter, $K_d$. Equation [20] may now be written in the following form:

$$\overline{MR} = A_0 e^{-K_d t} + A_1 e^{-B_1 K_d t} + A_2 e^{-B_2 K_d t} + \ldots$$  \[21\]

where:

$$K_d = C_0 D$$

= drying parameter (hr$^{-1}$)

$$B_i = C_i / C_0, \ i = 1, 2, 3, \ldots$$

= constant, characteristic of the geometry of the object being dried (dimensionless).

Although the general form of the series follows that from Newman's work (77), the particular constants and parameters must be chosen to fit the experimental data. Furthermore, the number of terms used is determined by the accuracy and the computational ease required. When two or more terms of equation [21] are used and the coefficients and
parameters are determined from a least squares fit of the experimental data, the resulting prediction equation can be considered an approximation to the solution of the diffusion equation for the material for which the data was taken. It is important to note that this approach is not restricted to any specific boundary conditions or geometry. If a drying curve represents a diffusion process, it can be represented as the sum of a converging series of negative exponential terms (29, 59, 77, 90).

The drying rate may be found by differentiating equation [21],

\[ \frac{d\bar{M}}{dt} = -K_d (\bar{M} - M_e) \left( \frac{A_0 e^{-K_d t} + A_1 B_1 e^{-B_1 K_d t} + \ldots}{A_0 e^{-K_d t} + A_1 e^{-B_1 K_d t} + \ldots} \right) \]  \[ [22] \]

where \( K_d \) is determined from an empirical relationship between the drying parameter and the conditions of both the product and the drying medium.

Glenn* (1979) independently developed a similar model for grain drying. He assumed that the kernel is represented by discrete lumps. Each lump was assumed to have a centrally located moisture storage element and a resistive element to moisture transfer between consecutive lumps. He related the storage and resistive elements of each lump to

the geometry and diffusivity of the kernel. All lumps were assumed to have the same equilibrium moisture content. Moisture transfer in two and three-lump models was described analytically to obtain a drying model similar to equation [21].

Glenn derived the transfer functions of the model and evaluated their parameters for shelled corn using step input and frequency response analysis of previously published data (100). He utilized these transfer functions in conducting a dynamic analysis of continuous flow deep-bed drying systems. He used a perturbation analysis to linearize his dynamic model. His linearized model lends itself readily to analysis of deep-bed drying models for automatic control.

Computer Solution and Analyses

Various mathematical models were examined to describe the fully exposed drying data of this study. The mathematical models represented by equations [2], [4], [18] and [19], and [21], may predict the drying behavior if the correct values of parameters and coefficients are used. The following sections outline the computer methods and procedures of analyses used to obtain numerical solution and to evaluate parameters and/or coefficients for these mathematical models.
Determination of Equilibrium Moisture:

A knowledge of the equilibrium moisture content associated with certain air temperature and relative humidity is essential for using most drying models. Several investigators (3,8,30,46,66,106) presented data on static equilibrium moisture contents for corn ears and their components, but little of the data cover the range of air temperatures and relative humidities used in this study. In the absence of appropriate experimental data, an alternative method was developed to evaluate the equilibrium moisture content using the characteristic drying curve.

A number of research workers (29,45,59,77) indicated that the second and subsequent terms in equation [21] become negligible (the average moisture ratio approaches a negative exponential function) after extended drying regardless of the size or shape of the drying solid,

\[
\lim_{t \to t_e} \frac{M - M_e}{M_0 - M_e} = A_0 e^{-K_d t},
\]

where \( t_e \) is the drying time at the start of the last falling-rate period. Therefore, the value of \( M_e \) which gives a straight line plot of the average moisture ratio, calculated from the experimental data, on a semilogarithmic paper versus drying time at later stages of drying is the appropriate value. In general, the following relationship can be obtained:

\[
\frac{M_e - M_e}{M_0 - M_e} = A_0 e^{-K_d t}
\]
where:
\[ \bar{M}_\ell = \text{average moisture content observed during the last falling-rate period (d.b.).} \]

The equilibrium moisture content was predicted by nonlinear regression techniques using the above exponential relationship (Equation [24]) in conjunction with the experimental observations taken during the last falling-rate period of drying. The parameters \( M_e, A_0, \) and \( K_d \) were all treated as unknown parameters and were determined by computing a least squares solution of an approximate linearization of the nonlinear model using truncated Taylor's series and initial estimates of these parameters (26,54). Marquardt (72) developed the computer techniques for the calculations.

**Evaluation of Logarithmic Model Parameters:**

Two approaches may be taken to estimate the drying parameter \( K_c \) of the logarithmic drying equation (Equation [2]): (a) The logarithmic least squares, and (b) the direct least squares. In the first approach, the equation is linearized,

\[ \ln(\bar{M}) = -K_c t, \quad [25] \]

and a regression procedure is applied to the linearized model to evaluate the drying parameter \( K_c \).

In the direct least squares approach, the value of \( K_c \) is determined from a nonlinear procedure applied directly to the original model. Three iterative techniques may be used, namely: (i) The Marquardt method (72), (ii) the gradient method (12), and (iii) the Gauss-Newton method (12).
Because of the logarithmic weighing, the logarithmic least squares gave a better fit to the final portion of the drying curve while the direct or nonlinear least squares approach gave a better overall fit. Although the Gauss-Newton method was found to be the least expensive, the Marquardt method was preferred since it was found to be the most accurate.

The applicability of Equation [4] for describing the drying behavior over the entire period of drying was examined. The unknown parameters of the model were selected to minimize the least squares of the deviation of the data from the fitted curve. Initial estimates of the parameters, \( K_c \) and \( g \), were determined from a regression procedure applied to the linearized form of the model (Equation [26]).

\[
\ln[-\ln(MR)] = \ln(K_c) + g \ln(t). \tag{26}
\]

Direct least squares method using Marquardt technique was then applied to Equation [4].

**Computer Solution of Kernel Model:**

Equations [18] and [19] were written in a dimensionless form:

\[
\begin{align*}
\frac{\partial MR}{\partial t} &= \frac{1}{r^2} \frac{\partial}{\partial r} \left( Dr^2 \frac{\partial MR}{\partial r} \right) \\
MR (r, 0) &= 1 \\
MR (R, t) &= 0, \ t > 0 \\
\frac{\partial MR}{\partial r} \bigg|_{r=0} &= 0, \ t > 0
\end{align*}
\tag{27}
\]

The solution to equations [27] was obtained numerically on an IBM 370
digital computer utilizing the statement oriented CSMP-370 (Continuous System Modeling Program).

Equations [27] has two independent variables, the space coordinate and time, and cannot be directly simulated by the CSMP which has only one independent variable, time. The method of Hamdy and Barre (41) was used to eliminate the space coordinate, r, by dividing the sphere into 10 spherical shells of equal thickness with a node at the mean radius of each shell, and an unknown moisture concentration ratio associated with each node (Figure 3). The moisture ratio profile within each shell was assumed to be a parabola. The three coefficients of each parabola were calculated such that the parabola was consistent with the moisture concentration ratios associated with the shell node and the adjacent nodes on each side. Since the innermost and the outermost parabolas lacked one adjacent node each, the boundary conditions were used to provide an additional equation for each. The innermost parabola was calculated such that its gradient vanished at the sphere center, and the outermost parabola was calculated such that it gave a moisture concentration equal to $M_e$ at the surface. The kernel moisture diffusion equation (Equations [27]) was transformed into the following set of equations:
FIGURE 3. SPHERE DIVIDED INTO 10 SHELLS.
Innermost shell \((i = 0)\):

\[
M_{R_0} = 1 + \frac{100 \, D}{R^2} \int_0^t (3 \, M_{R_1} - 3 \, M_{R_0}) \, dt
\]

Intermediate shells \((i = 1, 2, \ldots, 8)\):

\[
M_{R_i} = 1 + \frac{100 \, D}{R^2} \int_0^t \left( \frac{2i+3}{2i+1} \, M_{R_{i+1}} - 2 \, M_{R_i} + \frac{2i-1}{2i+1} \, M_{R_{i-1}} \right) \, dt
\]  \hspace{1cm} \text{[28]}

Outermost shell \((i = 9)\):

\[
M_{R_9} = 1 + \frac{100 \, D}{R^2} \int_0^t \left( -\frac{80}{19} \, M_{R_9} + \frac{24}{19} \, M_{R_8} \right) \, dt.
\]

The average moisture ratio was calculated by dividing the sum of the volume integral of each parabola over its respective shell by the sphere volume \((41)\). The average moisture ratio of the kernel was obtained as follows:

\[
\bar{M_R} = \frac{1}{1000} \left( 0.75 \, M_{R_0} + 6.75 \, M_{R_1} + 18.75 \, M_{R_2} + 36.75 \, M_{R_3} + 60.75 \, M_{R_4} + 90.75 \, M_{R_5} + 126.75 \, M_{R_6} + 168.75 \, M_{R_7} + 207.825 \, M_{R_8} + 282.175 \, M_{R_9} \right).
\]  \hspace{1cm} \text{[29]}

Evaluation of Diffusion Coefficient: The value of the diffusion coefficient \(D\) was determined by matching the computer solution to the observed drying data. The normalized standard deviation between observed and computed (based on an assumed \(D\)) average moisture ratios was determined as follows:

\[
\sigma = \left[ \frac{1}{t} \int_0^t (M_{R_{\text{exp}}} - \bar{M_R})^2 \, dt \right]^{1/2}
\]  \hspace{1cm} \text{[30]}
where:
\[ \sigma = \text{normalized standard deviations (dimensionless)} \]
\[ \overline{\text{MR}}_{\exp} = \text{observed average moisture ratio at any time, } t. \]

The observed average moisture ratio over the entire drying period was generated by a nonlinear function generator. A second slightly higher value of D was assumed and the associated \( \sigma \) was computed and compared with the previous \( \sigma \). The diffusivity was changed in the direction of lower \( \sigma \) and the process was repeated until \( \sigma \) could not be reduced. The value of D which gave the minimum \( \sigma \), i.e., the best fit, was taken as that of the object. The CSMP-370 computer program is shown in the Appendix.

**Evaluation of Diffusion-Based Model Parameters:**

Determination of the drying parameter and coefficients for a finite number of exponential terms in equation [21] was done using a computerized technique of curve fitting. The model parameter and coefficients, \( K_d \), \( A_i \)'s, and \( B_i \)'s, were all treated as unknowns and were selected to minimize the deviation of the observed data from the computed curve using Marquardt's technique. Initial estimates of \( A_0 \) and \( K_d \) were determined by fitting the first term of equation [21] to the experimental observations taken during the last falling-rate period of drying. A new set of data was then obtained when the predicted moisture ratios using the first term with the estimated values of \( A_0 \) and \( K_d \) were subtracted from the corresponding moisture ratios of the observed data. The same procedure was used to obtain initial estimates of \( A_1 \) and \( B_1 \) of the second exponential term of the model (Equation [21]).
The method was repeated for as many terms as were necessary to fit the experimental data.

The computation of regression coefficients was accomplished by direct least squares method using statistical analysis on an IBM 370 digital computer. The computer programs shown in the Appendix were written in the procedure-oriented language SAS, the Statistical Analysis System (12).
CHAPTER V. EXPERIMENTAL INVESTIGATIONS

This investigation was carried out to study the drying characteristics of fully exposed corn ears, shelled corn, and corn cobs under different conditions of both the product and the drying medium. The experimental phase of this work involved observing the moisture and temperature histories for each product under controlled temperature, humidity, and velocity of the drying air. A detailed description of the apparatus and the experimental procedure follows.

Equipment and Instrumentations

Drying Apparatus:

The laboratory dryer shown schematically in Figure 4 was equipped with temperature, relative humidity, and air velocity controls. It was fully instrumented for measurement of air flow, temperature and relative humidity, and temperature and weight loss of the drying samples.

An electrically driven centrifugal blower, capable of delivering 33 m$^3$ of air per minute against a pressure of 0.023 Kg/cm$^2$, was used to force room air through the system consisting of a conditioning tower, plenum, and four drying or exposure chambers. The total air into the system was controlled by two sliding gates built into the duct connecting the fan to the conditioning tower.
FIGURE 4. SCHEMATIC DIAGRAM OF EXPERIMENTAL DRYING APPARATUS.
In the conditioning tower, the air can be passed through a sequence of humidifying, heating, and mixing operations. The air relative humidity could be controlled by a water conditioning unit including a water reservoir, a centrifugal water pump, eight immersion water heaters, and thirty-six spray nozzles mounted on six branches on the inside wall of the humidifying tower. The electric immersion heaters, which had sufficient capacity to boil the water in a tank at the bottom of the humidifying tower, could be used to control the water evaporation, hence, the air humidity. In addition, three 1250 watt finned electric preheaters installed in the duct between the fan and the humidifying tower were employed mainly for raising the air temperature a few degrees for greater moisture holding capacity. The relative humidity of the drying air could, therefore, be controlled by one or more of several means:

1) Adjusting the spray pressure with a by-pass valve.
2) Varying the number of active spray nozzles, selecting which branches to be active and/or the water pressure by using a hand operated valve located on each branch.
3) Manually controlling the number of active preheaters to control the water holding capacity of the air.
4) Manually controlling the number of active immersion heaters to control the temperature and evaporation of the water in the tank at the bottom of the humidifying tower.

The air temperature was raised to approximately the desired level by as many of the nine 2200 watt and two 1250 watt finned electric heaters located in the heating chambers as were required. Each heater was independently fused and controlled by an on-off toggle switch. A system
of baffle plates installed in the heating compartment of the tower en-
sured thorough mixing of the drying air. The drying air temperature
was maintained at the required level by three finned 1000 watt electric
heaters controlled by a Honeywell industrial thermostat placed at the
entrance to the plenum. The variation at any setting in the range of
35 to 100°C was normally less than ± 1.2°C.

Four test chambers, consisting of a cylindrical array of ten
10.2 cm diameter clothes dryer vent tubes each, were constructed to
dry as many as 40 samples at one time (Figure 5). The conditioned air
entered each drying chamber through a perforated metal plate located
below the chamber and was exhausted to the atmosphere. Perforated
metal plates with different hole sizes and pitches and plate areas were
used to obtain different air flow rates to the drying chamber, hence,
different air velocities in the drying tubes. Four different air
velocities could, therefore, be tested simultaneously with all drying
chambers providing air with the same temperature and humidity. Honey-
comb flow straighteners were installed at the entrance of the drying
tubes to assure equal air velocities in the tubes of each chamber.

Air Flow Measurement:

The air flow to each drying chamber was determined by measuring
the pressure drop across the perforated metal plate located below the
chamber. An inclined water gauge manometer, with least division of
0.0635 cm, was used to measure the pressure drop. The calibration data
for air flow through orifices by Shedd (1954) were used to convert
static pressures to air flow rates. A number of checks using a vane
WEIGHING BEAMS

10.2 CM

X-SECTION A-A

PERFORATED METAL PLATE

HONEYCOMB FLOW STRAIGHTENERS

PLAN

DRYING TUBES

30.5 CM

48.25 CM

FIGURE 5. DRYING CHAMBER.
anemometer and a thermocouple anemometer was made to verify the results obtained from Shedd's calibration curves and to ascertain that the air velocities were equal in the drying tubes of each exposure chamber.

**Air Temperature Measurement:**

The temperature of the drying air entering the exposure chamber was measured by ten Copper-Constantan thermocouples, each located at the entrance of a drying tube and connected in parallel to obtain an average air temperature. It was recorded using a Leads and Northrup Copper-Constantan 20-point temperature recorder, with least division of 10/9°C (2°F), which produces a record of each thermocouple reading at five minute intervals. A temperature traverse showed that air of the same quality entered all drying chambers.

**Relative Humidity Measurement:**

Copper-Constantan thermocouples, mounted as shown in Figure 6, were used to continuously measure the wet bulb and dry bulb temperatures of the drying air in each drying chamber. The wicks on the wet bulb thermocouples were kept wet continuously from a constant level distilled water reservoir. They were renewed before each drying test to prevent excessive contamination by dust which causes the indicated temperature to be higher than the actual wet bulb temperature. The air velocity (at least 4.6 m/s) was sufficient in all cases to fully ventilate the wet bulb thermocouples. The 20-point Leads and Northrup temperature recorder was used to produce records of the wet bulb as well as the dry bulb thermocouple readings. A psychrometric chart was used to determine the air relative humidity using the measured dry and wet
FIGURE 6. BOTTOM VIEW OF A DRYING CHAMBER SHOWING HONEYCOMB FLOW STRAIGHTENERS AND WET AND DRY BULB THERMOCOUPLES.
bulb temperatures.

The accuracy of the drying air relative humidity measurements was checked, several times during each drying test, by measuring the dry bulb and dew point temperatures with a calibrated YSI (Yellow Spring Inc.) dew point hygrometer. Referring to the psychrometric chart and superimposing the measured dry bulb and dew point temperatures, the relative humidity of the air passing through the drying tubes was read and compared with that determined from the dry bulb and wet bulb temperature readings.

**Measurement of Product Temperature:**

The temperature distribution inside samples of corn ears and cobs being dried was continuously measured at different radial positions (at the center, in the outer part of the cob, and in the kernel layer) using Copper-Constantan thermocouples. The conduction losses were minimized by inserting the probe through the longest path in the sample. In order to determine the exact locations of the probe points in the samples, each sample was carefully sliced upon completion of drying.

The temperature history of corn kernels being dried was measured using ultra-fine (40-gage) Copper-Constantan thermocouples. The thinness of the wires used allowed the assumption that no (conductive) heat was flowing into the kernels through the wires. The temperatures were measured in the center and at a point on the surface of a kernel. The difference was less than 0.5°C after the first 3 to 4 minutes of the drying period. Therefore, the temperature in the center of a kernel was assumed to be equal to the average temperature of the kernel. This
temperature was measured by ten thermocouples, each located at the center of a kernel and connected in parallel to obtain an average kernel temperature. An automatic data logger (KAYE Instruments System 800) was used to record the product temperatures.

Automatic Weighing System:

Drying characteristics of a particular product are normally determined by periodically removing the samples from the dryer for direct weighing. A major source of error in this procedure is the interruption of the drying process that occurs while the samples are removed. Not only the samples cease to dry during weighing but they also undergo cooling; thus drying is approximated by a discrete process involving a large number of steps. The solution to this problem is to develop a system that will weigh the samples continuously and automatically during drying without interrupting its progress. The air drag on the samples has to be essentially constant during drying. This restriction is not severe, though, since the change in the characteristic cross sectional area of most objects due to volume shrinkage during drying is negligible so that the change in drag is also negligible.

The automatic weighing system shown in Figures 7 and 8 was developed to determine the rate of moisture loss from the samples during drying without interrupting the progress of drying. It was designed to monitor continuously and automatically the weights of up to 20 samples simultaneously. Each sample was suspended from the free end of a cantilever beam made of a bandsaw blade with the cutting edges machined off the blade. Four polyimide-backed foil strain gages (M & M Type EA-13-250
SCHEMATIC OF WEIGHING BEAM.

SUPPLY 6.2 VOLT DC, 20 MA, MAX.

DATA LOGGER WHEATSTONE BRIDGE

STRAIN GAGE SCHEMATIC.

FIGURE 7. WEIGHING SYSTEM.
FIGURE 8. FRONT VIEW OF DRYING CHAMBERS SHOWING WEIGHING BEAMS AND DATA RECORDING EQUIPMENT.
BG-120) were mounted on top and bottom surfaces near the support end of the beam to sense strain variations within the beam due to moisture loss from the sample during drying. Epoxy cement (Type M-Bond 43-B Adhesive Kit) was used to attach the strain gages to the beam, enabling use at high temperatures. The gages were wired in a wheatstone bridge circuit providing a highly sensitive circuit compensated for temperature variations. Shielded cables were used for all d-c signals where exposure to stray noise was possible, and care was taken to ensure that all lead wires to a particular set of gages were of equal length.

Power was supplied to the wheatstone bridge circuits of the weighing system by a 6.2-V d-c power supply built into the data logger. This input voltage limited currents to less than the 20-milliampere (mA), maximum allowable for the strain gages to prevent heating effect. The output voltage of each bridge circuit was amplified and automatically recorded by the data logger using the 20-mV scale. By selecting the proper span resistor the output of a bridge could be scaled to have the desired full scale value.

Each cantilever beam was calibrated using a series of weights up to 500 gm, and the output voltages (mV) were recorded for one hour for each weight. The output voltage as recorded by the data logger was found to be linearly related to the load on the cantilever beam, Figure 9 and Table 1. The calibration results indicated a weighing sensitivity to be within 0.335 gm. Tests performed on the system indicated that the average error during a 6-day drying run of a 418-gm ear corn with initial moisture content of 47 percent, d.b., was approximately ± 0.5 gm and that the maximum error could be held to ±1.0 gm. These
FIGURE 9. TYPICAL CALIBRATION DATA FOR WEIGHING BEAM.
TABLE 1. CALIBRATION RESULTS OF AUTOMATIC WEIGHING BEAMS.*

<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Equation Slope (gm/mV)</th>
<th>Coefficient of Determination (R²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>335.062</td>
<td>0.99998</td>
</tr>
<tr>
<td>2</td>
<td>298.735</td>
<td>0.99994</td>
</tr>
<tr>
<td>3</td>
<td>305.680</td>
<td>0.99994</td>
</tr>
<tr>
<td>4</td>
<td>321.524</td>
<td>0.99993</td>
</tr>
<tr>
<td>5</td>
<td>337.413</td>
<td>0.99997</td>
</tr>
<tr>
<td>6</td>
<td>309.929</td>
<td>0.99995</td>
</tr>
<tr>
<td>7</td>
<td>317.163</td>
<td>0.99992</td>
</tr>
<tr>
<td>8</td>
<td>327.164</td>
<td>0.99995</td>
</tr>
<tr>
<td>9</td>
<td>330.460</td>
<td>0.99993</td>
</tr>
<tr>
<td>10</td>
<td>349.218</td>
<td>0.99994</td>
</tr>
<tr>
<td>11</td>
<td>241.966</td>
<td>0.99995</td>
</tr>
<tr>
<td>12</td>
<td>276.313</td>
<td>0.99991</td>
</tr>
<tr>
<td>13</td>
<td>290.527</td>
<td>0.99996</td>
</tr>
<tr>
<td>14</td>
<td>297.361</td>
<td>0.99997</td>
</tr>
<tr>
<td>15</td>
<td>323.007</td>
<td>0.99995</td>
</tr>
<tr>
<td>16</td>
<td>356.301</td>
<td>0.99995</td>
</tr>
<tr>
<td>17</td>
<td>315.628</td>
<td>0.99990</td>
</tr>
<tr>
<td>18</td>
<td>334.425</td>
<td>0.99993</td>
</tr>
<tr>
<td>19</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>20</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

*Results based on linear regression analysis.
correspond to average and maximum moisture content errors of approximately ± 0.175 and ± 0.35 percent, d.b., respectively.

Operation of the weighing system required only that the samples be weighed once on an analytical balance immediately before and again at the end of each drying test. This provided two reference points which could be used to convert the recorder readings to actual weights.

Data Recording Equipment:

A 30-channel data logger (KAYE Instruments System 800) was used to record the output voltages (mV) from the weighing beams and the temperatures (°C) of the drying samples. The system (Figure 10) may be operated in one of four scan modes, the choice depending on the number of active channels and the frequency with which readings are required. In the Continuous Scan mode the logger automatically advances to each active channel in the system, in order, recording one sample of the data on each channel. Scanning proceeds continuously until the Scan Mode switch is moved to a different mode. In the Single Scan mode the system automatically advances to each active channel in the system, as in the Continuous Scan mode, but scans the active channels at predetermined scan intervals. When the Single Step mode is used and the Start Scan switch is pressed, the system advances to the next active channel and monitors the data on that channel until the Start Scan switch is pressed again. The Random Access mode is used to continuously monitor the channel selected by the Random Channel switch when the Automatic Output mode is in the Random Channel position.

The rate of data sampling, and, therefore, the rate of printing in any mode and the rate of scanning in either the Single Scan or
FIGURE 10. DATA LOGGER.
Continuous Scan modes, is controlled by the Sample Interval switch. In each scan mode elapsed time is also recorded. Using a Teletype allows the output from the data logger to be recorded on punched paper tape for computer analysis.

Drying Conditions and Procedures

Preparation of Drying Samples:

In drying experiments with most farm crops, the availability of naturally moist samples at different initial moisture contents is limited to a short period of time. As a result, much of the literature on drying is based on remoistened as well as frozen and thawed materials. Findings by Hustrulid (58), Van Rest (102), and White et al. (112) indicated that there was no detectable difference between the drying characteristics of naturally moist and frozen and thawed shelled corn. Remoistened shelled corn was found to dry similarly to but slightly faster than naturally moist shelled corn by Hukill (52) and Hustrulid (58).

The drying characteristic tests conducted in this investigation were with frozen and thawed samples of corn ears, shelled corn, and corn cobs. Ears of Pioneer 3780 yellow dent corn were hand-picked from the crop grown at The Ohio State University Experimental Farm during the 1976 season while the ear moisture content was in the 20 to 60 percent, d.b., range. The ears were then wrapped individually in polyethylene bags and stored in a freezer at a temperature of about \(-15^\circ\text{C}\) until they were used in the experiments. Storage time varied between four to ten months.
Prior to each drying run, the samples were removed from the freezer and placed in a household refrigerator at an inside temperature of about 2 to 5°C and allowed to thaw at least 72 hours. The ears were then kept in their bags at room temperature for 12 hours, and then removed from the bags, husked, and held at room temperature for another 12 hours in order to remove any excess moisture or free water which had accumulated around the ears due to previous treatments. Ears of the same general size, about 23 cm length and 420 cm³ volume, and with sixteen kernel rows were selected to minimize the effect of size. The volume of the ears was determined by wrapping them individually in waterproof plastic bags and immersing each in water in a 1000-cm³ graduate.

Samples of shelled corn and corn cobs were obtained from corn ears treated as in the previous manner. The selected corn ears were flush cut at both ends leaving middle 14.90- to 17.85-cm uniform portions. Each ear portion was then hand-shelled giving kernels of approximately the same size and shape. Kernels with broken tips were discarded. Two shelled corn samples of the same size (70 to 80 kernels) and weight were selected from the kernels of any one ear. One sample was used to determine the average kernel size while the other was used for a drying test. The average volume of the corn kernel was determined by water displacement and was in the range of 0.3075 to 0.4125 cm³.

The drying characteristic tests for corn cobs were conducted using the middle cylindrical cobs obtained after shelling the 14.90- to 17.85-cm uniform portions of corn ears. The average diameter of the cob samples was in the 1.026 to 1.094 cm range.
Test Variables and Drying Conditions:

Fully exposed drying tests were conducted under constant controlled conditions using frozen and thawed samples of corn ears, shelled corn, and corn cobs at initial moisture contents ranging from 18 to 55, 29 to 50, and 52 to 148 percent, d.b., respectively. The experiments were performed at three different drying air temperatures, namely: 35, 55, and 75°C with ± 1.2°C. The corresponding air relative humidities were 13.4, 16.0, and 5.0 percent, respectively, for ear corn; and 13.4, 5.2, and 2 percent, respectively, for shelled corn and corn cobs. The average air velocity through the drying tubes was kept constant at approximately 2.65 m/s throughout this set of tests.

Freshly-harvested samples of corn ears at different initial moisture contents in the range of 33 to 54 percent, d.b., were used to duplicate the 55°C air temperature drying experiments. This was done to evaluate any influence of freezing and thawing on the drying characteristics of the test ear corn.

To evaluate the effect of air velocity in the drying tubes on the drying behavior of fully exposed ears of corn, four different air velocities were used, namely: 0.51, 1.02, 1.58, and 2.14 m/s. The drying air temperature and humidity were kept constant at approximately 54.4°C and 11.3 percent, respectively.

Experimental Procedures:

The drying apparatus was run for about two hours to stabilize its conditions before each drying test. Dummy samples were hung in the drying tubes to run up the dryer to operating conditions. The test was started when the thermocouples recorded an almost constant air
temperature. The drying samples were weighed on an analytical balance and immediately suspended, one in each drying tube, by plastic threads from the free ends of the weighing beams.

The corn ears as well as the corn cobs were hung in the drying tubes parallel to the direction of air flow. Wire baskets, made of 1/8-in wire mesh, were used to hold the shelled corn samples in air stream in the drying tubes. The sample size was such that the entire sample could be spread evenly over the bottom of the basket in a layer no more than one kernel deep.

The weights and temperatures of the drying samples, along with the dry and wet bulb temperatures of the drying air, were recorded as soon as the samples were suspended in the drying tubes. Outputs from the weighing system and the thermocouples were automatically and continuously printed at five-minute intervals using the data recording equipment. The samples were dried until their weights no longer decreased and their temperatures remained constant and were assumed to have reached their equilibrium moisture content. This usually required six to nine, four to six, and three to five days for corn ears, shelled corn, and corn cobs, respectively. The weight of each drying sample at the end of the test was determined by an analytical balance and used, along with the initial weight, to adjust and verify the recorder readings to correspond to actual weights.

The dry matter weight of the drying sample was determined at the end of each drying test by drying the samples in a vacuum oven at a temperature of 104 ± 1°C until no weight loss could be detected by weighing on an analytical balance. This usually required about 72
hours. All weight loss was considered to be moisture.

The original data of this investigation and the calculated parameters of the drying characteristic tests are included in the final report of project No. H-531/G-134, Ohio Agricultural Research and Development Center, Wooster, Ohio.
CHAPTER VI. RESULTS AND DISCUSSIONS

This work was carried out to establish a reasonably accurate mathematical model (or models) based on the general form of the diffusion equation solution for predicting the drying behavior of fully exposed agricultural products of different geometrical shapes and compositions. The experimental phase of this investigation included several drying tests for three agricultural materials, namely: Corn ears (typical, irregularly shaped, nonhomogeneous objects), shelled corn (may be considered homogeneous spheres or bricks), and corn cobs (composite cylindrical products).

The following sections present and discuss the results of the drying experiments of the three products. The experimental data are used in conjunction with equation [21] to establish mathematical models for describing the drying characteristics of each product at all stages of the drying process. Moreover, the developed mathematical models are compared with the existing drying models (which are frequently used for predicting fully exposed drying characteristics of most agricultural products) for prediction accuracy and the computational ease.

Drying Characteristics of Corn Ears:

Experimental data describing the fully exposed drying characteristics for ear corn were obtained under different drying conditions.
Typical moisture history plots given in non-dimensional moisture ratio versus time during the entire drying period are shown in Figure 11. No constant-rate period was observed in any of the experiments of ear corn drying carried out in this investigation although the initial moisture content of the ears was as high as 55.65 percent, d.b. This was ascertained by calculating the drying rate during the early stages of drying. The drying curves indicate that the ears dry rapidly initially and that the drying rate decreases as drying proceeds.

Inspection of the curves plotted in Figure 12 shows that the drying behavior of fully exposed ear corn may be approximated by two drying periods, both of the falling-rate character, with a transition period between them. The moisture content at the intersection of the two straight lines which approximate the two falling-rate periods on semi-log paper is a hypothetical moisture content that depends on the drying conditions. It was defined by Chen and Johnson (24) as the "tertiary moisture content" and by Husain (55) and Husain et al. (56, 57) as the "pseudo critical moisture content." The intersection was found to be at 11.05 ± 2.37, 7.90 ± 1.09, and 7.48 ± 1.16 at 35.21, 54.75, and 75.48°C, respectively. The intercept of the second term was 3.387 ± 0.335 $M_0$, 2.357 ± 0.233 $M_0$, and 1.893 ± 0.187 $M_0$ at 35.21, 54.75, and 75.48°C, respectively. The average values (16.4, 11.4, and 9.2) were below the tertiary moisture content interpolated from the paper of Kumar et al. (66) of 18, 17, and 15, respectively.

Similar observations were reported by other researchers for fully exposed thin layers of cereal grains and other agricultural products (39, 73, 93, 100). Barre and Swanson (15), in drying fully exposed corn
**Figure 11. Drying Curves for Fully Exposed Ear Corn.**

- Initial Moisture Content (% D.B.): 39.14, 37.10, 41.38
- Air Temperature (°C): 74.48, 54.75, 35.21
- Relative Humidity (%): 5.0, 16.0, 13.4

The graph shows the drying curves for ear corn under different initial moisture contents, air temperatures, and relative humidities.
**Figure 12. Drying Curves for Fully Exposed Ear Corn.**
ears, proposed that the first falling-rate period represented unsaturated surface drying and the second falling-rate period was controlled by internal diffusion. Henderson and Pabis (47) reported that "When drying is continued for longer times and lower moisture contents are reached, the curve may depart from a straight line due, it is believed, to an increase in the energy of desorption."

The mathematical models represented by equations [2], [4], and [21], were examined to describe the fully exposed drying characteristics of ear corn over the entire drying period. These models may predict the drying behavior if the correct values of parameters and coefficients are used.

The equilibrium moisture content satisfying the criteria developed in the previous chapter (page 40) was used to compute the average moisture ratio. The drying data presented in Figure 12 roughly approximates two straight lines. The dotted extension shows how a single straight line can be selected to fit the experimental data observed during the last falling-rate period of ear corn. This is also the part of the drying response curve that can be fitted to equation [24] to determine the equilibrium moisture content of ear corn associated with the conditions of the drying air.

The equilibrium moisture contents calculated by equation [24] were found slightly lower than the moisture content of the ears at the end of the drying tests, the difference being less than one percent, d.b. This indicates that the ears had almost reached equilibrium when they were removed from the dryer at the end of the drying tests. Henderson's equation (46), which has been applied to a wide range of materials and air conditions, was employed to relate the calculated equilibrium
moisture contents of ear corn to the temperature and relative humidity of the drying air. The following empirical equation was obtained from the fitting of the pooled data utilizing Marquardt's technique (72):

\[(1 - \text{r.h.}) = \exp(N_1 T_{\text{abs}} M_e^{N_2})\]  \[\text{[31]}\]

where:

- \text{r.h.} = relative humidity of the drying air (decimal)
- \(N_1 = -0.0061\)
- \(N_2 = -2.1198\)

The value of the coefficient of determination \((R^2)\) was found to be 0.99 indicating that 99 percent of the effect of the drying air temperature and relative humidity can be explained by regression. This equation cannot be compared to published data for ear corn due to its application to lower relative humidities than those of other investigators.

The applicability of using the logarithmic drying model to describe drying behavior of ear corn was next examined. The drying parameter, \(K_c\), was evaluated by fitting equations [2] and [25] to the experimental drying data of Figure 13. The values of \(K_c\) obtained were 0.073670 and 0.040228, respectively. The value obtained by the logarithmic least squares is not the best value because the least squares procedure minimizes the sum of the squares of deviations of \(\ln(MR)\) rather than the true variable \(MR\). A greater deviation between observed and predicted moisture ratios can be seen in Figure 13 when both equations [2] and [25] are used to describe the drying behavior of ear corn over the entire drying period. The logarithmic least squares approach gave a better fit to the final portion of the drying curve while the direct or non-linear least squares approach gave a better overall fit.
AIR TEMP., 54.75 °C
REL. HUMID., 16.0%
INIT. MOIST. CONT., 36.41% (D.B.)

The derivation of the logarithmic model is based on the assumption that the resistance to drying of agricultural materials is concentrated in a layer at the surface of the material (67). This assumption, however, does not seem to be valid for drying of many agricultural products (39,47,73,83,87,93,100). To overcome some of the shortcomings of the logarithmic drying model, Hall and Rodrigues-Arias (39) and Menzies and O'Callaghan (73) suggested describing the drying curve by a set of straight lines with different values of \( K_c \) and \( M_e \), each appropriate to a short range of moisture content. This introduces other problems and increases the computation routines required for drying simulations.

Page (84) modified the logarithmic drying model by adding an empirical exponent to time in equation [2]. Such modification was also examined in this work. The experimental data presented in Figure 14 were used in estimating the parameters, \( K_c \) and \( g \), of equation [4]. Direct least squares solution of the nonlinear model using Marquardt's computer technique (72) was obtained and the values of \( K_c \) and \( g \) were 0.094570 and 0.848292, respectively. Figure 14 shows that Page's equation also fails to predict the drying behavior of fully exposed ear corn during the entire drying period. The predicted moisture ratios were higher during the early stages and lower during the late stages of drying compared to the observed moisture ratios.

Although the logarithmic drying model fails to describe the fully exposed drying curve of ear corn during the entire drying period, it can be used to compare the relative influence of such parameters as air temperature, humidity, and air flow and ear moisture content on the drying rate (16).
FIGURE 14. COMPARISON OF MOISTURE RATIOS PREDICTED BY EQN. [4] WITH EXPERIMENTAL DRYING DATA FOR EAR CORN.
The diffusion-based model developed in the previous chapter and represented by equation [21] was employed to describe the drying behavior of ear corn over the entire drying period and at different conditions of both the product and the drying medium. In this analysis, two exponential terms of the general equation (Equation [21]) were found to be effective to describe analytically the experimental results in Figure 11 for the entire range. One term was sufficient, however, to adequately describe the region encountered in thin-layer or deep-bed drying of ear corn. Furthermore, the second term was small compared to the first during the early drying stages; however, it became significant when the drying entered the second falling-rate period. This is not incompatible with the hypothesis of assuming diffusion-controlled mechanisms and adapting the general form of the solution of the diffusion equation to describe the rate of drying nonhomogeneous objects of irregular shape such as ear corn. When additional terms were added the fit was not significantly improved (Figures 15 and 16). Therefore, equation [21] was reduced to:

\[ \overline{MR} = A e^{-K_d t} + (1 - A) e^{-B K_d t} \]  

[32]

where:

- \( A, B \) = constants, characteristics of the geometry of ear corn (dimensionless)
- \( K_d \) = drying parameter of ear corn (hr\(^{-1}\)).

The differential form of equation [32] is the drying rate equation for corn ears, and is:

\[ \frac{d\overline{M}}{dt} = -K_d (M - M_e) \left[ \frac{A e^{-K_d t} + (1 - A) e^{-B K_d t}}{A e^{-K_d t} + (1 - A) e^{-B K_d t}} \right] \]  

[33]
FIGURE 15. COMPARISON OF MOISTURE RATIOS PREDICTED BY TWO-TERM MODEL WITH EXPERIMENTAL DRYING DATA FOR EAR CORN.

AIR TEMP., 54.75 °C
REL. HUMID., 16.0%
INIT. MOIST. CONT., 36.78% (D.B.)
FIGURE 16. COMPARISON OF MOISTURE RATIOS PREDICTED BY THREE-TERM MODEL WITH EXPERIMENTAL DRYING DATA FOR EAR CORN.
where $K_d$ is determined from an empirical relationship between the drying parameter and the drying conditions.

Equation [32] was fitted individually to the data for each ear tested (Figure 15). The model parameter and coefficients, $K_d$, $A$ and $B$, were all treated as unknown parameters and were selected to minimize the least squares deviation of the data from the fitted curve. The values of $R^2$ were consistently greater than 0.98.

The estimated values of the coefficients $A$ and $B$ were found to be approximately the same for all the ears dried regardless of their different initial moisture contents or the surrounding conditions under which they were tested. This may be due in part to using ears of nearly the same size in all the experiments. The average values of $A$ and $B$ of equation [32] were 0.8459 and 0.1278, respectively. The maximum variations from the averages of $A$ and $B$ were normally less than 0.053 and 0.0085, respectively. These residual variations may be due to a number of reasons such as biological variation, different kernel or ear sizes, or that ears dried from different levels of initial moisture content will shrink differently during drying and would have different sizes and/or shapes at the end of drying, although they had the same size and shape at the start of the drying process.

The estimated values of the parameter, $K_d$, along with the corresponding temperatures and initial moisture contents are tabulated in Table 2 and plotted in Figure 17. The effect of the initial moisture content of the ears on the drying rate, for each of the three drying temperatures, was examined by fitting the following empirical relationship (28,56,93):

$$K_d = \alpha \exp(\beta M_0)$$  \[34\]
TABLE 2. DRYING PARAMETER FOR EQUATION [32]
DETERMINED BY LEAST SQUARES FIT OF
INDIVIDUAL DRYING TEST DATA.

<table>
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<th>Temp (°C)</th>
<th>M₀*</th>
<th>Kd**</th>
<th>Temp (°C)</th>
<th>M₀*</th>
<th>Kd**</th>
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*M₀ is the initial moisture content of ear corn, percent (d.b.).
**Kd is the drying parameter of ear corn (hr⁻¹).
Figure 17. Effect of drying conditions on drying parameter of ear corn.
The coefficients $\alpha$ and $\beta$ were related to the drying air temperature by fitting the following regression equations (28,47,55,93):

$$\alpha = \alpha_0 \exp(\alpha_1/T_{\text{abs}}) \quad [35]$$
$$\beta = \beta_0 + \beta_1 T_{\text{abs}} \quad [36]$$

Direct least squares fit of equation [34], which relates $K_d$ to drying air temperature and initial moisture content of ear corn, resulted in the following empirical regression equation:

$$K_d = \alpha_0 \exp[(\beta_0 + \beta_1 T_{\text{abs}}) M_0 + \alpha_1/T_{\text{abs}}] \quad [37]$$

where:

$$\alpha_0 = 902$$
$$\alpha_1 = -2619$$
$$\beta_0 = -97.5 (10)^{-3}$$
$$\beta_1 = 19.5 (10)^{-5}$$

The values of the drying parameter, $K_d$, derived from the fit of equation [32], were clearly a function of both the drying air temperature and the initial moisture content of the ears. Statistical analysis showed that the regression coefficients, $\alpha_0$, $\alpha_1$, $\beta_0$, and $\beta_1$, were significantly different from zero with an $R^2$ value of 0.67. The drying air temperature, however, has the greatest influence on the drying rate of ear corn (Figure 11). These findings are consistent with the results obtained by other researchers for fully exposed thin layers of grain and other products (28,42,47,56,60,93,111).

According to reaction rate analysis of $K_d$ as if it were proportional to a diffusivity, $\alpha_1$ corresponds to $\Delta H/R$ and $(\beta_0 + \beta_1 T_{\text{abs}}) M_0$ to $\Delta S/R$ in Cal/Mole and Cal °K/Mole, respectively; where $H$ is the heat
of vaporization, \( S \) is the entropy, and \( R \) is the perfect gas constant.

Note that the drying rate decreases with moisture with a modifying effect of a temperature moisture interaction (mobility increases with temperature). In the literature review it was pointed out that some researchers have suggested such a negative coefficient when vapor diffusion controls but a positive coefficient when liquid diffusion controls (63).

Air humidity enters into the prediction equation (Equation [32]) only in the value of the equilibrium moisture content, \( M_e \). The relative humidity, in the range of up to 30 percent, has negligible effects on the drying rate of fully exposed grains and other farm crops during the falling-rate period (4, 5, 26, 47, 59, 108) in this range of initial moisture; however, in this laboratory it has been found that higher moisture products such as potato and cassava, seemingly like porous media, appear to have an effective diffusivity which is rate sensitive and correspondingly sensitive to relative humidity or a condensed surface structure which is relative humidity sensitive (60).

The complete description of the diffusion-based drying model developed for describing the fully exposed drying behavior of ear corn is, therefore:

\[
\text{(Ear Corn Drying Model):} \quad \frac{\dot{M}_R}{M_0 - M_e} = A e^{-K_d t} + (1 - A) e^{-B K_d t} \quad [38]
\]

where:

\[
A = 0.8459
\]

\[
B = 0.1278
\]
The above mathematical model was used to predict the experimental data. Figure 18 is a typical plot of predicted drying curves along with the observed experimental data for different test conditions. The predicted curve and the experimental data show a good agreement over the whole drying period. The maximum difference in the moisture content was 1.77 percent, d.b., with only 9 out of 58 tests having more than 1% difference between the observed and predicted moisture contents.

The drying parameter of the diffusion-based drying model (Equation [38]) was related to the drying air temperature. It is, in fact, a function of the temperature of the material being dried, which for many products, such as cereal grains, may be close to the air temperature except for a short period after the start of drying (47,114). The temperature was measured and plotted at different radial positions in a corn ear: at the center, \( T_p \); in the outer part of the cob, \( T_c \); and in a kernel, \( T_k \) (Figure 19). Since the kernels constitute about 0.85 of the weight of a typical ear, Figure 19 indicates that the average ear temperature ratio approaches approximately 0.8 in two hours from the start of drying and continues to increase as the drying progresses.

\[
TR = \frac{T - T_i}{T_a - T_i} \quad [39]
\]

where:

- \( T \) = temperature at any time, \( t \) (°C)
- \( T_a \) = air temperature (°C)
- \( T_i \) = initial temperature of the ear (°C).
Figure 18. Comparison of moisture ratios predicted by Eqn. [38] with experimental drying data for ear corn.
FIGURE 19. TEMPERATURE RATIO WITHIN EAR OF CORN.
Similar results were reported by Pabis and Hall (82). The energy added by convection appears to be used primarily for vaporization rather than for warming the ear after the initial treatment period.

The drying parameter, $K_d$, can be thought of as an average effective drying parameter over the whole drying period. The deviation from the instantaneous value may not be significant shortly after the start of drying. Accordingly, the developed model may be used in bulk drying analysis of ear corn with the desired accuracy and computational ease required for efficient simulation. This is supported by the goodness of fit between the moisture ratios predicted by the model and the experimental moisture ratios. A method presented by Crank (31), Henderson and Pabis (47), and Rowe and Gunkel (90) may be used to eliminate the effect of temperature gradients within the drying object during drying.

The logarithmic drying model, although it fails to predict drying behavior of ear corn over the entire drying period, may be used in drying analysis with the desired accuracy in the moisture ratio range above 0.2 (Figure 13) usually encountered in deep-bed dryer design for ear corn. Consequently, it was decided to evaluate equation [2]. This required regression analysis and computational procedures similar to that used for the two terms exponential model discussed above. The experimental data were used in estimating the drying parameter, $K_c$, which yielded the least sum of squares of deviations between the predicted and the observed drying curves.

The evaluation of equation [2] resulted in the following model:

$$\frac{M - M_e}{M_0 - M_e} = \exp(-K_c t)$$  \[40\]

where:
The model was then employed to predict the experimental drying curve of ear corn. As shown in Figure 20, the agreement between observed and predicted values is good in the moisture ratio range above 0.2. The differences between the predicted and observed moisture ratios were great in the later stages of drying. The two term model of equation [38], however, has a distinct advantage over the one term model of equation [40] in accurately predicting drying behavior over the entire drying period (Figure 20). Hence, it could be concluded that the two term exponential model could effectively be used in describing drying behavior of corn ears at all stages of the drying process.

The drying tests to investigate the effect of air velocity on the rate of moisture loss from fully exposed corn ears were limited to air velocity in the range above 0.50 m/s. The effects of lower air velocities were investigated by Barre and Swanson (15) and Pabis and Hall (82). The values of drying parameter shown in Table 3 were obtained by fitting the logarithmic drying model (Equation [2]) to drying data of ear corn for different values of air velocity, namely: 0.509, 1.02, 1.58, and 2.14 m/s. The air temperature and relative humidity were kept constant at approximately 54.4°C and 11.3 percent, respectively.

The estimated values of the drying parameter, $K_c$, were related to the velocity of the drying air and the initial moisture content of the ears by fitting the following regression equations:

$$K_c = a_0 + a_1 M_0 + a_2 V$$  \[41\]

$$K_c = a_3 + M_0 a_4 V a_5$$  \[42\]
Figure 20. Observed and predicted drying curves for ear corn.

Air Temp., 54.48°C
Rel. Humidity, 16.0%
Init. Moist. Cont., 37.10% (d.b.)
### TABLE 3. EFFECT OF AIR VELOCITY ON DRYING PARAMETER OF EQUATION [2]*

<table>
<thead>
<tr>
<th>Drying Parameter ( K_c, \text{ hr}^{-1} )</th>
<th>Initial Moisture Content, ( M_o ) % D.B.</th>
</tr>
</thead>
<tbody>
<tr>
<td>.0608</td>
<td>47.87</td>
</tr>
<tr>
<td>.0608</td>
<td>42.14</td>
</tr>
<tr>
<td>.0536</td>
<td>35.23</td>
</tr>
<tr>
<td>.0587</td>
<td>41.23</td>
</tr>
<tr>
<td>.0568</td>
<td>37.74</td>
</tr>
<tr>
<td>.0582</td>
<td>33.02</td>
</tr>
<tr>
<td><strong>Air Velocity</strong>(^+) = 0.609 m/s</td>
<td></td>
</tr>
<tr>
<td>.0609</td>
<td>45.27</td>
</tr>
<tr>
<td>.0611</td>
<td>44.17</td>
</tr>
<tr>
<td>.0624</td>
<td>40.15</td>
</tr>
<tr>
<td>.0647</td>
<td>46.02</td>
</tr>
<tr>
<td>.0555</td>
<td>40.98</td>
</tr>
<tr>
<td>.0607</td>
<td>35.10</td>
</tr>
<tr>
<td><strong>Air Velocity</strong>(^+) = 1.02 m/s</td>
<td></td>
</tr>
<tr>
<td>.0640</td>
<td>48.20</td>
</tr>
<tr>
<td>.0670</td>
<td>50.24</td>
</tr>
<tr>
<td>.0627</td>
<td>39.85</td>
</tr>
<tr>
<td>.0643</td>
<td>46.56</td>
</tr>
<tr>
<td>.0588</td>
<td>36.72</td>
</tr>
<tr>
<td>.0615</td>
<td>37.38</td>
</tr>
<tr>
<td><strong>Air Velocity</strong>(^+) = 1.58 m/s</td>
<td></td>
</tr>
<tr>
<td>.0612</td>
<td>36.24</td>
</tr>
<tr>
<td>.0577</td>
<td>33.39</td>
</tr>
<tr>
<td>.0657</td>
<td>43.75</td>
</tr>
<tr>
<td>.0703</td>
<td>53.99</td>
</tr>
<tr>
<td>.0643</td>
<td>41.93</td>
</tr>
<tr>
<td>.0637</td>
<td>34.87</td>
</tr>
<tr>
<td><strong>Air Velocity</strong>(^+) = 2.14 m/s</td>
<td></td>
</tr>
</tbody>
</table>

*At air temp. and rel. humid. of 54.4°C and 11.3%, respectively.

+ Average air velocity in the drying tubes.
where:

\[ V = \text{air velocity (M/S)}. \]

Statistical analysis showed that the regression coefficients \( a_2 \) and \( a_5 \) were not different from zero. The value of the coefficient of determination \( (R^2) \) was found to be 0.36. This indicates that the air velocity, in the range above 0.50 m/s, has no appreciable effects on the drying characteristics of fully exposed corn ears. Variation in the air velocity is generally considered as not affecting the drying time if the flow is turbulent \((47, 52, 78, 82)\). This is believed to be due to the high internal resistance to moisture movement of the drying material compared to low resistance to surface moisture movement.

The effect of using frozen-and-thawed ears on their characteristic drying rate was considered in this work. Samples of frozen-and-thawed and freshly harvested ears were dried at constant temperature and humidity of approximately 54.75\(^\circ\)C and 16.0 percent, respectively. The drying data were fitted to the logarithmic drying model (Equation [2]). The estimated values of the drying parameter, \( K_c \), were plotted against moisture content for both frozen-and-thawed and freshly harvested corn ears (Figure 21). Regression analysis using linear relations between \( K_c \) and \( M_0 \), for freshly harvested and/or frozen-and-thawed samples, indicated that the regression coefficients, intercept and slope, were not different. Similar results were obtained by Hustrulid \((58)\) and Van Rest \((102)\), for shelled corn.

**Drying Characteristics of Shelled Corn:**

Drying data for fully exposed thin layers of shelled corn at different conditions of both the shelled corn and the drying air were
Figure 21. Drying parameter, $K_c$, for frozen-and-thawed and freshly-harvested corn ears.
observed in this study. Typical drying curves at three different air temperatures for the entire period of drying are presented in Figure 22. It appears from the curves that shelled corn dries entirely during the falling rate period. Moreover, the falling-rate is approximately divisible into two periods with a transition period between them (Figure 23). The intersection was found to occur at 17.7 ± 2.1, 11.8 ± 0.75, and 7.8 ± 0.44 with intercepts for the second segment at 4.98 ± 0.49 $M_0$, 2.79 ± 0.276 $M_0$, and 1.80 ± 0.179 $M_0$ at 35.21, 55.64, and 75.78°C, respectively. The average intercepts of 24.1, 13.5, and 8.7 did not correspond to the estimated tertiary moisture of 21.0, 18.6, and 16.4 extrapolated from the report of Kumar et al. (66).

The data in Figure 23 suggest that the drying of shelled corn may consist of one or more diffusional processes (26,40,41,83). The diffusion model describing moisture movement in an isotropic, homogeneous, symmetrical, solid sphere has been claimed to adequately describe the drying characteristics of shelled corn (40,41,59).

The center point temperature history shown in Figure 24 clearly indicates that the drying of fully exposed corn kernels may be considered as an isothermal process. Consequently, the moisture diffusion model, Equation [27], is sufficient for characterizing moisture movement in fully exposed shelled corn as the temperature ratio of 0.9 is reached in as little as 0.1 hour and climbs steadily thereafter. In addition to the diffusion model represented by Equation [27], the logarithmic drying model (Equation [2]) is also examined and compared with a diffusion-based model using a finite number of terms in Equation [21].

The equilibrium moisture contents of shelled corn associated with the temperatures and humidities used in this work was calculated using
FIGURE 22. DRYING CURVES FOR FULLY EXPOSED SHELLED CORN.
FIGURE 23. DRYING CURVES FOR FULLY EXPOSED SHELLED CORN.
FIGURE 24. TEMPERATURE RATIO WITHIN CORN KERNEL.
regression analysis and computational procedures similar to that used for the equilibrium moisture content of ear corn. The following empirical equation was obtained,

\[(1 - r.h.) = \exp[-1.12(10)^{-5} T_{abs}^{-1.9257}]. \tag{43}\]

Again, no data in this region are available for comparison. The moisture exponent is of the same order as for ear corn but the coefficient is much smaller than that of equation [34].

The logarithmic drying model was employed to fit the experimental data in Figure 25. The value of the drying parameter, \(K_c\), was evaluated using direct least squares solution of the model and was equal to 0.261921 hr\(^{-1}\). This value is much higher compared to that obtained for ear corn under similar drying conditions. This indicates that shelled corn dries at a faster rate compared to ear corn. Similar results are reported by Hamdy et al. (43). Comparison of the predicted moisture ratios using the logarithmic model and the experimental drying data is presented in Figure 25. A great deviation between the observed and predicted moisture contents can be seen in the figure. This is in contradiction with the results reported by Henderson and Perry (48) if the drying reduced the moisture ratio below about 0.2. They reported that the logarithmic model adequately describes the drying characteristics of fully exposed cereal grains including corn.

The diffusion-based model represented by Equation [21] was used to describe the drying behavior of shelled corn over the entire drying period. Three exponential terms of this equation were found to be effective in describing analytically the experimental drying curves (Figure 26). Additional terms did not significantly improve the accuracy of
FIGURE 25. COMPARISON OF MOISTURE RATIOS PREDICTED BY LOGARITHMIC MODEL WITH EXPERIMENTAL DRYING DATA FOR SHELLED CORN.
Air Temp., 53.64 °C
Rel. Humid., 5.2%
Init. Moist. Cont., 39.24% (D.B.)

Figure 26. Comparative fits of diffusion and three-term models to experimental drying data for shelled corn.
fitting the observed data.

The solution to the diffusion model of corn kernels (Equation [27]) was obtained numerically on an IBM 370 digital computer utilizing CSMP-370 (Figure 26). The diffusion coefficient D was determined by matching the computer solution to observed drying data. Good agreement is found over the whole drying period. The calculated value of D agreed with the literature (26).

Comparison between the diffusion model and the three exponential term model, as shown in Figure 26, indicates that both models predict drying data with great accuracy over the entire drying period. The good agreement obtained between the predicted drying behavior and the experimental data supports the hypothesis of assuming one or more diffusion-like mechanisms and adapting the general form of the solution of diffusion equation to describe the rate of drying nonhomogeneous as well as homogeneous objects regardless of the geometry of the particles or the boundary conditions surrounding them.

The exponential term model was also utilized to fit the experimental data in Figure 27. The improvement in fitting the observed drying data, using three terms instead of two terms of equation [21] was small (Figures 26 and 27). Therefore, it was decided to evaluate a two exponential term model for describing the drying behavior of fully exposed thin layers of shelled corn over the entire drying period. Regression analysis and computational procedures similar to those for the diffusion-based model of ear corn discussed above were used to fit the experimental data of shelled corn.

The complete description of the mathematical model developed for describing the fully exposed drying behavior of shelled corn is then:
FIGURE 27. COMPARISON OF MOISTURE RATIOS PREDICTED BY TWO-TERM MODEL WITH EXPERIMENTAL DRYING DATA FOR SHELLED CORN.
(Shelled Corn Drying Model):

\[
\frac{MR}{M_0 - M_e} = A e^{-K_d t} + (1 - A) e^{-K_d t}
\]

where:

\[
A = 0.8014 \\
B = 0.2090 \\
K_d = 76.7 \exp \left[ \{-0.05487 + 0.00081 T_{abs} \} M_0 - 2509/T_{abs} \right] \\
M_e = [-149.78 \ln(1 - r.h.)/T_{abs}]^{-0.3826}
\]

Shelled corn had \( K \) values many times larger than ear corn but with reduced moisture sensitivity (about 45%), a higher moisture-temperature interaction (about 4 fold) with the same order arrhenius temperature dependence.

Again, a negative moisture coefficient was observed again suggesting that a vapor transport mechanism be considered.

Drying Characteristics of Corn Cobs:

Typical drying curves of fully exposed corn cobs at three different drying conditions are presented in Figure 28. The total period of drying is divided into two phases, an initial phase of relatively high rate followed by a final phase of a very slow rate of drying.

A plot of the average moisture ratio versus time on a semilogarithmic paper, as shown in Figure 29, shows that the data approximates a straight line. This indicates that only the first term of the general solution of diffusion equation is sufficient to describe the drying data of fully exposed corn cobs over the entire drying period. Additional terms were found to be negligible and equation [21] was reduced to equation [2], the logarithmic drying model.
FIGURE 28. DRYING CURVES FOR FULLY EXPOSED CORN COBS.
FIGURE 29. DRYING CURVES FOR FULLY EXPOSED CORN COBS.
Corn cobs are composite cylindrical bodies of two different materials. The inner part of the cob has a very small storage capacity estimated to be less than 2 percent and such a small resistance to moisture movement compared to the wooden material of the outer part of the cob that we were not able to work with this material without unjustified experimental precision. The assumption that the resistance to moisture movement is concentrated in a layer at the surface of the cob seems to be valid. Therefore, the logarithmic drying equation developed by Lewis (67) based on this assumption may be used to accurately describe the drying characteristics of corn cobs over the entire drying period.

The drying parameter, $K_c$, was evaluated using equation [2] and was found to be higher than that obtained for ear corn and for shelled corn. The values of $K_c$ were 0.14626, 0.27806, and 0.46052 for cobs dried at air temperatures of 35.21, 55.64, and 75.78, respectively.

The temperature history within a corn cob is presented in Figure 30. The temperature ratio at the center of the cob approaches 0.8 after about four hours from the start of drying. Only for the cob did the temperature response curves break at or near the wet bulb as for an object loosely holding its moisture. The ear and the kernels reached much higher temperature ratios much earlier in the drying process.

Initially the intent had been to develop a multinode model for transfer in an ear utilizing rote data and equilibrium data for its components. This direction was terminated when it became apparent that much more information would be required for exchange between the kernels and the cob with the entrapped air space and between the kernel and the cob along the direction of its attachment to the ear.
TEMPERATURE RATIO

0.6
54.58 °C
16.0%
120.8% (D.B.)
22.26 °C

AIR TEMP.,
REL. HUMID.,
INIT. MOIST. CONT.,
INIT. TEMP.,
0.4
0.557 CM
1.103 CM
0.2
0.557 CM
1.103 CM

LOCATION OF TEMP. SENSING ELEMENT

TIME, HR.

FIGURE 30. TEMPERATURE RATIO WITHIN CORN COB.
CHAPTER VII. CONCLUSIONS

The following are conclusions resulting from this study:

1. The entire drying process of ear corn and shelled corn takes place in a falling-rate period of two or more distinct phases connected by transition phases; while the drying process of corn cobs takes place during one falling-rate period followed by a period of a very slow drying rate at the end of drying.

2. The general form of the solution of the diffusion equation could be used to establish mathematical models for describing the drying characteristics of agricultural products regardless of the geometry or the composition of the particles or the boundary conditions surrounding them appears valid for the ear, the kernel and the cob.

3. A two-term exponential model adequately describes the drying behavior of fully exposed ear corn as well as shelled corn over the entire drying period; while one-term model adequately describes the drying behavior of corn cobs for the entire period. One term, i.e., the logarithmic model is valid for design for ear corn, however.

4. A three-term exponential model describes the drying behavior of shelled corn as accurately as the diffusion model.

5. The frequently used logarithmic drying model and its modified form fail to adequately describe the drying characteristics of both ear corn and shelled corn over the entire drying period; the direct least
squares fit, however, gives better description of drying data compared to the logarithmic least squares fit.

6. The drying rate of corn ears and their component parts is a negative exponential function of the initial moisture content of the product as well as an arrhenius function of the temperature of the drying air.

7. The air velocity in the range over 0.609 m/s has negligible effect on the drying rate of fully exposed corn ears in this research.

8. There is no detectable difference between the drying characteristics of frozen-and-thawed and freshly-harvested corn ears.
CHAPTER VIII. SUGGESTIONS FOR FURTHER RESEARCH

Based on this investigation, the following potential areas are suggested for further work:

1. The effect of air velocity in the range below 0.50 m/s on the drying parameter of the two-term exponential model for ear corn and shelled corn.

2. The effect of air relative humidity on the drying rate of ear corn and shelled corn at elevated temperatures and humidities might be encountered in air recycle.

3. Studies of the kernel-cob; kernel-air space and cob-air space; and ear surface-environment mass transfer to assist in interpretation of the ear drying behavior.
CHAPTER IX. LIST OF REFERENCES


APPENDIX
TITLE MOISTURE DIFFUSION MODEL FOR SHELLED CORN

INIT

DIA=87.65
R=DIA/2.*100.
B1=10.*R/R
B0=1.+0.
TIME=76.22

PARAM DM=(1.0E-2,1.5E-2,2.0E-2,2.5E-2,3.0E-2,3.5E-2,4.0E-2,4.5E-2,...
5.0E-2)

FUNCTION EXPT=U1,58.761,13.641,72.55,2.471,46.355,37.537,5.510,...
-28.77,7.723,1.7,43.17,17.17,1D,15,20,77,13,32,38,10,...
41.68,87.34,9.7,0.71,66,55,0.459,70,22,0.458

INCON IC0=1.,11,12=1.,13=1.,14=1.,15=1.,16=1.,17=1.,18=1.,... IC9=1.

DYNA

XC=01*(3.C1-3.C0)*DM
X1=01*(1.6C1-2.0C2+0.6C1)*DM
X2=01*(1.2857C4-2.0C3+.7143C7)*DM
X4=01*(1.2222C5-2.0C4+.7778C31)*DM
X5=01*(1.1980C0-2.0C5+.9132C4)*DM
X6=01*(1.536C7-2.0C6+.8620C5)*DM
X7=01*(1.1323C6-2.0C7+.9667C5)*DM
X8=01*(1.1176C9-2.0C8+.824C7)*DM
X9=01*(1.1280C2105-2.0C9)*DM

CG=INTGRL1IC0,XC)
C1=INTGRL1IC1,X1)
C2=INTGRL1IC2,X2)
C3=INTGRL1IC3,X3)
C4=INTGRL1IC4,X4)
C5=INTGRL1IC5,X5)
C6=INTGRL1IC6,X6)
C7=INTGRL1IC7,X7)
C8=INTGRL1IC8,X8)
C9=INTGRL1IC9,X9)

CAVE=U1.75C0C1+18.75C2+36.75C3+90.75C4+90.75C5+120.75C6+168.75C7+207.825C8+282.175C91/1000.

B5=INTGRL1IC0,B4)
MIN=5.

MINT=MIN

TIMER DELT=U1,FINTIM=9B.5,OUTDEL=2

FINISH MINT=TIME

OUTPUT CAVE,EXPT,STD

END

STOP
TITLE 'Drying Data*

DATA NILE;

MAD=06.0;

Ht=MHR-HRO*(MIN-MIND)/60;

MLW_MAT=22.75;

MN=MT-MLW_MAT;

MTO=53.95;

HLW_T=MHR_MAT;

MOD=H1*100/MD;

MR1=(MT+HI)/(MD+HI);

LN_MRI=LOG(MR1);

LABEL Ti='Drying Time'

M1='Gruss Weight'

MRI='Moisture Content'

MR1='Moisture Ratio';

CARDS:

00 32.0 53.95
001 27.0 52.05
001 40.0 51.10
002 15.0 50.37
003 04.0 49.87
004 03.0 48.67
005 02.0 48.15
006 01.0 47.77
007 00.0 47.50
008 09.0 47.33
017 08.0 47.20
021 07.0 46.95
025 06.0 46.75
028 05.0 46.50
032 04.0 46.35
037 03.0 46.30
040 02.0 46.30

PROC PRINT;

VAR HK MIN MT TI WI MI MRI LN_MRI;
TITLE 'Drying Data*';

PROC SCATTER;

TITLE 'Drying Data*';

MODEL LN_MRI1 / NODFIT;

DUMMY OUT=NILE1 PREDICTED=LN_MRI1 RESIDUAL=RSD1;

TITLE 'One Term Linearized Model-1*';

PROC PRINT;

VAR TI LN_MRI LN_MRI1 RSD1;
TITLE 'Observed and Predicted Nat. Log. of MR and Residuals-1*';

PROC SCATTER;

PLOT TI*RSD1=***;

TITLE 'Residuals vs. Time-1*';
PARMS K1=0.15;
MODEL MRI=EXP(K1*T1);
ERR=K1*/T1*EXP(K1**T1);
OUTPUT OUT=RAMSES1 PREDICTED=MRI2 RESIDUAL=RSD21;
TITLE "ONE TERM NONLINEAR MODEL-2";
PROC PRINT;
VAR T1 MRI MR2 RSD21;
TITLE "OBSERVED AND PREDICTED MR'S AND RESIDUALS-2";
* EVALUATION OF NONLINEAR MODEL-2;
PROC SCATTER;
PLOT T1*RSD21="**";
TITLE "RESIDUALS VS. TIME-2";
PROC SCATTER;
PLOT MRI2*RSD21="**";
TITLE "RESIDUALS VS. PREDICTED MR-2";
DATA RAMSES2;
SET RAMSES1;
EK2=RSD21;
PROC KANK F OUT=RAMSES3;
VAR ER2;
DATA RAMSES4;
SET RAMSES3;
N=PRBIT(EK2-1/34); 
PROCL SCATTER;
PLOT RSD21*N2="**";
TITLE "NORMAL DISTRIBUTION PLOT-2";
PROCL SCATTER;
PLOT T1*MR12="**" T1*MR12="**" / OVERLAY;
TITLE "OBSERVED AND PREDICTED MR'S VS. TIME-2";
DATA RAMSES5;
SET RAMSES4;
N2=P(RBIT(I*N2));
N2=P(RBIT(I+N2/34));
RSQ=R2=RSQ=RSD22**2;
LABEL N2="PREDICTED MOISTURE CONTENT-2";
PROC PRINT;
VAR T1 N N2 RSD22 RSD22SQ;
TITLE "OBSERVED AND PREDICTED MOISTURE CONTENTS AND RESIDUALS-2";
PROC SCATTER;
PLOT T1*RSD22="**";
TITLE "RESIDUALS VS. TIME-2";
PROC SCATTER;
PLOT N2*RSD22="**";
TITLE "RESIDUALS VS. PREDICTED MOISTURE CONTENT-2";
PROC SCATTER;
PLOT T1*N2="**" / OVERLAY;
TITLE "OBSERVED AND PREDICTED M.C. VS. TIME-2";
PROC MEANS SUM;
VAR RSD22SQ;
OUTPUT OUT=RAMSES6 SUM=S22;
TITLE "ERRORS SUM OF SQUARES-2";
* FITTING TWO EXPONENTIAL TERMS MODEL IN NONLINEAR FORM- 3;
DATA AMONI;
SET NILE;
PROC NILE=BEST=10 IER=1000 METHOD=MARQUARDT;
PARMS A2=0.12;
K12=0.025
K22=0.372;
BOUNDS A2>0;
MODEL MRI=A2*EXP(K12*T1)+1-A2)*EXP(K22*T1);
DER\(A2=\exp(K12\cdot T1)\)-\(\exp(K22\cdot T1)\);
\(\text{DER}.K12=A2\cdot T1^{*}\exp(K12\cdot T1);
\(\text{DER}.K22=1-A2\cdot T1^{*}\exp(K22\cdot T1);
\text{OUTPUT OUT=A\textsc{mu}1 PREDICTED=MR13 RESIDUAL=RSD31;
\text{TITLE *TWO TERMS NONLINEAR MODEL-3*;
\text{PROC PRINT;\n\text{VAR TI MR1 MR13 RSD31;
\text{TITLE *OBSERVED AND PREDICTED MR1 AND RESIDUALS-3*;
\text{PROC SCATTER;\n\text{PLOT TIERSD31 in *-;\n\text{PROC SCATTER;}\n\text{PLOT MR13 RSD31 in *--;\n\text{TITLE *RESIDUALS VS. TIME-3*;\n\text{DATA A\textsc{mu}2;\n\text{SET AM\textsc{mu}3;\n\text{EN3=RSD31;\n\text{PROC RANK OUT=AM\textsc{mu}3;\n\text{VAR ER3;\n\text{DATA A\textsc{mu}3;\n\text{SET AM\textsc{mu}3;\n\text{N3=PROBIT(ER3-1/34));\n\text{PROC SCATTER;\n\text{PLOT RSD31 in *--;\n\text{TITLE *NORMAL DISTRIBUTION PLOT-3*;\n\text{PROC SCATTER;\n\text{PLOT TIMEK1 in *- TIMEMR1 in *-- / OVERLAY;\n\text{TITLE *OBSERVED AND PREDICTED MR1 VS. TIME-3*;\n\text{DATA A\textsc{mu}n;\n\text{SET AM\textsc{mu}n;\n\text{M13=MR13*(HI-ME)+ME;}\n\text{M13=HI-MID;}\n\text{RSD32=M1=M13;}\n\text{RSD32=RSD32<=2;}\n\text{LABEL M13* PREDICTED MOISTURE CONTENT-9*;\n\text{PROC PRINT;}\n\text{VAR TI MI M13 RSD32 RSD32Q;}\n\text{TITLE *OBSERVED AND PREDICTED MOISTURE CONTENTS AND RESIDUALS-3*;\n\text{PROC SCATTER;}\n\text{PLOT TIMEK1 in *-;\n\text{TITLE *RESIDUALS VS. TIME-3*;\n\text{PROC SCATTER;\n\text{PLOT M13K232 in *-;}\n\text{TITLE *RESIDUALS VS. PREDICTED MOISTURE CONTENT-3*;}\n\text{PROC SCATTER;}\n\text{PLOT TIMEK1 in *- TIMEM13 in *-- / OVERLAY;\n\text{TITLE *OBSERVED AND PREDICTED M*C* VS. TIME-3*;\n\text{PROC MEANS SUM;}\n\text{VAR RSD3250;}\n\text{OUTPUT OUT=A\textsc{mu}n SUM=532;}\n\text{TITLE *ERRORS SUM OF SQUARES-3*;\n\text{PROC MIN BEST=10 ITER=1000 METHOD=MARQUARDT;}\n\text{PARMS A3=-0.21 B3=0.10 K13=-0.025 K23=-0.110 K33=-0.520;}\n\text{BUDDS A3=0 B3>;\n\text{MODEL MR1=A3*EXP(K13*T1)+A3*EXP(K23*T1)+A3-B3*EXP(K33*T1);}\n\text{DER.A3=EXP(K13*T1)-EXP(K23*T1);}\n\text{DER.B3=EXP(K23*T1)-EXP(K33*T1);\n\text{PROC MIN BEST=10 ITER=1000 METHOD=MARQUARDT;}\n\text{PARMS A3=-0.21 B3=0.10 K13=-0.025 K23=-0.110 K33=-0.520;}\n\text{BUDDS A3=0 B3>;\n\text{MODEL MR1=A3*EXP(K13*T1)+A3*EXP(K23*T1)+A3-B3*EXP(K33*T1);}\n\text{DER.A3=EXP(K13*T1)-EXP(K23*T1);}\n\text{DER.B3=EXP(K23*T1)-EXP(K33*T1);}\n\text{PROC MIN BEST=10 ITER=1000 METHOD=MARQUARDT;}\n\text{PARMS A3=-0.21 B3=0.10 K13=-0.025 K23=-0.110 K33=-0.520;}\n\text{BUDDS A3=0 B3>;\n\text{MODEL MR1=A3*EXP(K13*T1)+A3*EXP(K23*T1)+A3-B3*EXP(K33*T1);}\n\text{DER.A3=EXP(K13*T1)-EXP(K23*T1);}\n\text{DER.B3=EXP(K23*T1)-EXP(K33*T1);\n\text{PROC MIN BEST=10 ITER=1000 METHOD=MARQUARDT;}\n\text{PARMS A3=-0.21 B3=0.10 K13=-0.025 K23=-0.110 K33=-0.520;}\n\text{BUDDS A3=0 B3>;\n\text{MODEL MR1=A3*EXP(K13*T1)+A3*EXP(K23*T1)+A3-B3*EXP(K33*T1);}\n\text{DER.A3=EXP(K13*T1)-EXP(K23*T1);}\n\text{DER.B3=EXP(K23*T1)-EXP(K33*T1);}\n\text{PROC MIN BEST=10 ITER=1000 METHOD=MARQUARDT;}\n\text{PARMS A3=-0.21 B3=0.10 K13=-0.025 K23=-0.110 K33=-0.520;}\n\text{BUDDS A3=0 B3>;\n\text{MODEL MR1=A3*EXP(K13*T1)+A3*EXP(K23*T1)+A3-B3*EXP(K33*T1);}\n\text{DER.A3=EXP(K13*T1)-EXP(K23*T1);}\n\text{DER.B3=EXP(K23*T1)-EXP(K33*T1);}\n\text{PROC MIN BEST=10 ITER=1000 METHOD=MARQUARDT;}\n\text{PARMS A3=-0.21 B3=0.10 K13=-0.025 K23=-0.110 K33=-0.520;}\n\text{BUDDS A3=0 B3>;\n\text{MODEL MR1=A3*EXP(K13*T1)+A3*EXP(K23*T1)+A3-B3*EXP(K33*T1);}\n\text{DER.A3=EXP(K13*T1)-EXP(K23*T1);}\n\text{DER.B3=EXP(K23*T1)-EXP(K33*T1);}\n\text{PROC MIN BEST=10 ITER=1000 METHOD=MARQUARDT;}\n\text{PARMS A3=-0.21 B3=0.10 K13=-0.025 K23=-0.110 K33=-0.520;}\n\text{BUDDS A3=0 B3>;\n\text{MODEL MR1=A3*EXP(K13*T1)+A3*EXP(K23*T1)+A3-B3*EXP(K33*T1);}\n\text{DER.A3=EXP(K13*T1)-EXP(K23*T1);}\n\text{DER.B3=EXP(K23*T1)-EXP(K33*T1);}\n\text{PROC MIN BEST=10 ITER=1000 METHOD=MARQUARDT;}\n\text{PARMS A3=-0.21 B3=0.10 K13=-0.025 K23=-0.110 K33=-0.520;}\n\text{BUDDS A3=0 B3>;\n\text{MODEL MR1=A3*EXP(K13*T1)+A3*EXP(K23*T1)+A3-B3*EXP(K33*T1);}\n\text{DER.A3=EXP(K13*T1)-EXP(K23*T1);}\n\text{DER.B3=EXP(K23*T1)-EXP(K33*T1);}\n\text{PROC MIN BEST=10 ITER=1000 METHOD=MARQUARDT;}\n\text{PARMS A3=-0.21 B3=0.10 K13=-0.025 K23=-0.110 K33=-0.520;}\n\text{BUDDS A3=0 B3>;\n\text{MODEL MR1=A3*EXP(K13*T1)+A3*EXP(K23*T1)+A3-B3*EXP(K33*T1);}\n\text{DER.A3=EXP(K13*T1)-EXP(K23*T1);}\n\text{DER.B3=EXP(K23*T1)-EXP(K33*T1);}\n\text{PROC MIN BEST=10 ITER=1000 METHOD=MARQUARDT;}\n\text{PARMS A3=-0.21 B3=0.10 K13=-0.025 K23=-0.110 K33=-0.520;}\n\text{BUDDS A3=0 B3>;\n\text{MODEL MR1=A3*EXP(K13*T1)+A3*EXP(K23*T1)+A3-B3*EXP(K33*T1);}\n\text{DER.A3=EXP(K13*T1)-EXP(K23*T1);}\n\text{DER.B3=EXP(K23*T1)-EXP(K33*T1);}
DER.K13=A3*TI*EXP(K13*TI);
DER.K23=B3*TI*EXP(K23*TI);
DER.K33=-A3-B3*TI*EXP(K33*TI);

OUTPUT OUT=NEFER1 PREDICTED=MR14 RESIDUAL=RSD41;
TITLE 'THREE TERMS NONLINEAR MODEL-4';
PROC PRINT;
VAR T1 M14 MR14 RSD41;
TITLE 'OBSERVED AND PREDICTED MRS. AND RESIDUALS-4';
* EVALUATION OF NONLINEAR MODEL-4;
PROC SCATTER;
PLOT T1*RSD41=*
TITLE 'RESIDUALS VS. TIME-4';
PROC SCATTER;
PLOT MR14*RSD41=*
TITLE 'RESIDUALS VS. PREDICTED MR-4';
DATA NEFER2;
SET NEFER1;
EK4=RSD41;
PROC RANK FOUT=NEFER3;
VAR ER4;
DATA NEFER4;
SET NEFER3;
RSD42=RSD41;
LABEL M14='PREDICTED MOISTURE CONTENT-4';
PROC PRINT;
VAR T1 M14 RSD42 RSD42;
TITLE 'OBSERVED AND PREDICTED MOISTURE CONTENTS AND RESIDUALS-4';
PROC SCATTER;
PLOT T1*RSD42=*
TITLE 'RESIDUALS VS. TIME-4';
PROC SCATTER;
PLOT M14*RSD42=*
TITLE 'RESIDUALS VS. PREDICTED MOISTURE CONTENT-4';
PROC SCATTER;
PLOT T1*M14=*
TITLE 'OBSERVED AND PREDICTED M.O. VS. TIME-4';
PROC MEANS SUM;
VAR RSD4250;
OUTPUT OUT=NEFER6 SUM=S42;
TITLE 'ERRORS SUM OF SQUARES-4';