NATURAL - AIR GRAIN DRYING: MODELING AND VALIDATION

1.05

by

SAMUEL GWINN MAURER

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Approved by:

L. E. Grosh
Major Professor

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CHAPTER 1

MATHEMATICAL MODEL EVALUATION

1.1 Introduction

Field shelling of corn has increased rapidly in the past two decades. To minimize field losses, corn is frequently harvested at or above 22% moisture content. This 'high moisture content' requires immediate action in order to preserve corn quality. Grain is frequently dried at local grain elevators to safe storage moisture levels.

This period of harvest drying is very short and vast quantities of grain must be handled within three to four weeks. High capacity grain dryers use large quantities of propane or L.P. gas to accomplish the fast corn drying. Alternate methods for grain drying should improve on the efficient use of portable fuels such as propane. There is a definite need for drying systems which will accept grain immediately upon harvest and minimize the use of fossil fuels.

'Natural Aeration' or 'Low-Temperature Aeration' grain drying units seem to fit these requirements perfectly, with one noteworthy drawback. This problem is how should this new system be designed and managed to insure successful drying? Successful drying is the reduction of grain moisture content to a safe storage level before excessive quality deterioration occurs. These drying systems, although simple in appearance (see Figure 1.1.1), are affected by several factors which can severely limit their performance. These factors can be controlled by accurate design and careful management.

Published research in the field of natural aeration has concluded that system performance is affected by five major factors. These system performance

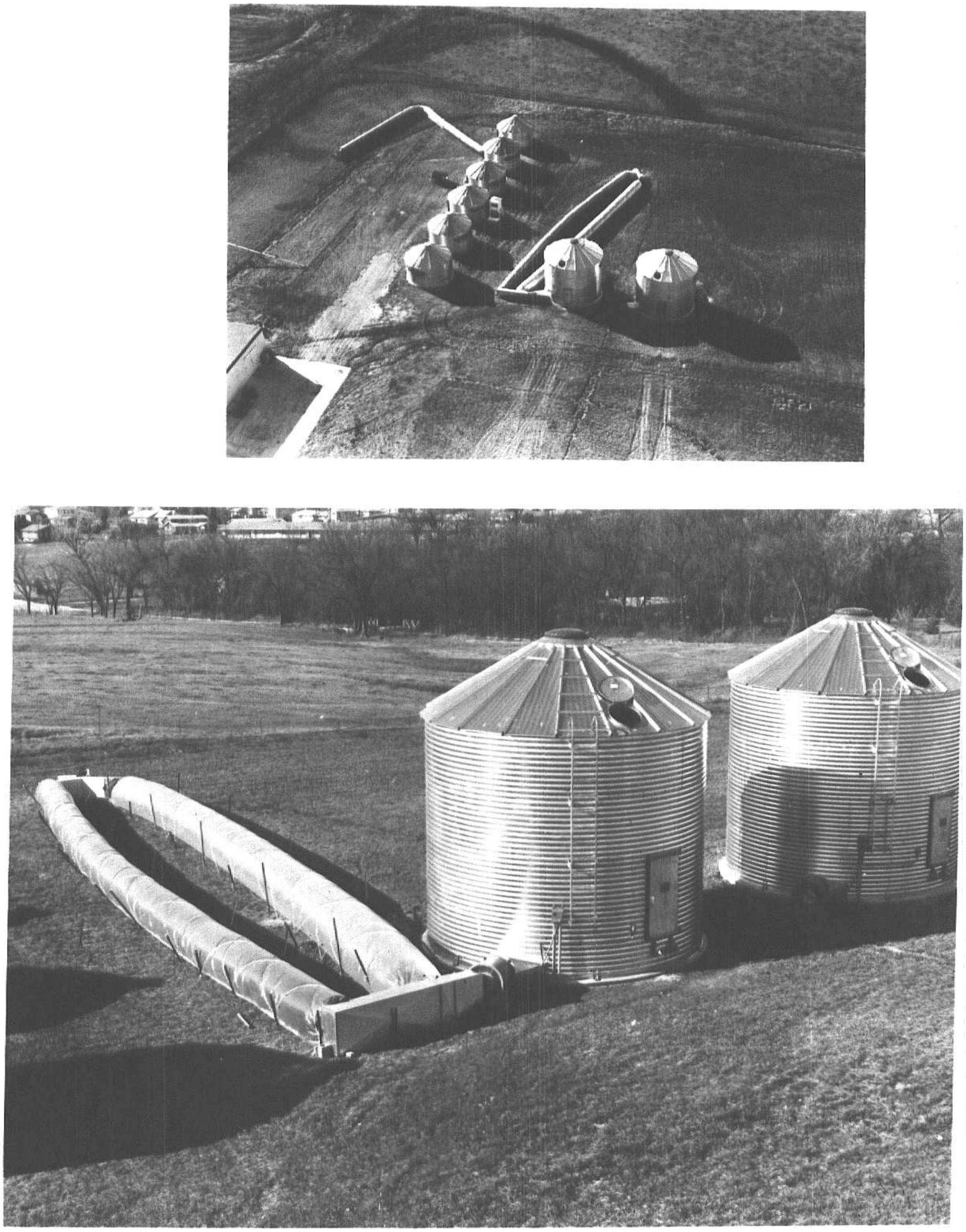


Figure 1.1.1 Natural Aeration Grain Drying Units
(photo courtesy Grain Marketing Research Center)

factors are:

1. Initial grain moisture content,
2. Ambient weather conditions during the drying period,
3. Airflow rate of the system,
4. Harvest date,
5. Amount of heat added to inlet air.

These factors as discussed in Thompson(72) and Bloome and Shove(71) were found to be the major contributing components of the natural aeration system studied.

Of the five factors listed only two, the airflow rate and the amount of added heat, can be effectively controlled by the research scientist. Since the experimental testing would be of a random fashion, efficient testing of system characteristics is rather hit or miss. This will cause the research costs to greatly increase. Mathematical modeling or a computer simulation model would give benefits of control of input variables, and allow testing of many proposed designs and management methods.

Fishman(73) gives eight benefits which are received from accurate modeling. The reasons for modeling are the following:

"1. Enables an investigator to organize his theoretical beliefs and empirical observations about a system and to deduce the logical implications of this organization,

2. Leads to improved system understanding,

3. Brings into perspective the need for detail and relevance,

4. Expedites the speed with which an analysis can be accomplished,

5. Provides a framework for testing the desirability of system modifications,

6. Is easier to manipulate than the system is,

7. Permits control over more sources of variation than direct study of a system would allow,

8. Is generally less costly."

In the recent published literature on drying of agricultural products, grain drying models have been referred to as 'mathematical models', Spencer(69), and as 'simulation models', Bakker-Arkema(74), Thompson(67), and Shove(71). In order to remain consistent with terms as they are defined in the modeling field of Operations Research, the following definitions are put forth by Gordon(69) and Fishman(73).

Mathematical models are deterministic models composed of numerical variables which can be either static or dynamic. The attributes of the mathematical model are entirely described by mathematical functions that inter-relate the variables. These models can be evaluated in either a continuous or discrete fashion. These models are sometimes referred to as symbolic models (Emshoff(70)).

Simulation models are stochastic models composed of numeric variables. These models are completely dynamic. Since at least part of the variation is random in nature, an investigator can at best obtain 'average' solutions by using these stochastic models to solve problems. These models may also be evaluated in a continuous or a discrete fashion. Stochastic models are sometimes referred to as procedural models (Emshoff(70)).

"A static model displays the relationships between the system variables when the system is in equilibrium. If the point of equilibrium is altered by changing one or more of the attributes, the model enables the new values for all of the variables to be derived but does not show the way in which they changed to their new values" (Gordon(69)).

"A dynamic model allows the changes of system variables to be derived as functions of time. The derivation may be analytical or require a numerical approximation" (Gordon (69)).

Grain drying models are a system of mathematical equations which comprise a deterministic model. This mathematical model is either static or dynamic depending upon modeling philosophy. These models are usually discrete approximations of continuous variables.

1.2 Review of Literature

Recent advancements in computer technology have made the use of sophisticated mathematical drying models economically feasible. These models have been developed to provide an experimental basis for testing proposed grain dryer designs and configurations. This model testing provides an economical alternative to full scale field experimentation. In this manner, hopefully, inefficient dryers need not be built or tested, thereby reducing the total cost of research and development of new energy efficient designs.

However, "... before an investigator claims that his model is a useful tool for studying behavior under new hypothetical conditions, he is well advised to check its consistency with the true system as it exists before any change is made. The success of this validation establishes a basis for confidence in the results that the model generates under new conditions. After all if a model cannot reproduce system behavior without change, we hardly expect it to produce truly representative results with change." (Fishman(73)).

"Validation of the operation of a mathematical model is as necessary as the validation of the operation of any other scientific experiment. While the basic problem of validation is no different for a simulation experiment, the complexity of the model is such that the processes by which its validity is established are quite different.

Therefore only conclusions from a valid model can be assumed to be valid conclusions for the actual system." (Bowersox (72)).

Given the idea that the nature of the validation process is a rigorous attempt to test a proposed model, the actual validation procedures used in some of the more recently published computer grain drying models are of value.

1.2.1 Review of Grain Drying Validation Method

Thompson(67) developed mathematical models for three high temperature convection dryers; crossflow, counterflow, and concurrent flow. Experimental tests were performed on a laboratory scale concurrent flow dryer. "This design was selected for the experimental tests since the method appeared to have the characteristics that result in higher quality corn. The experimental evaluations were made to determine the damage to quality, to experimentally evaluate the performance of this dryer design and to compare the experimental results with the simulation results to test the validity of the mathematical models." The drying experimental results and the model predictions were given in tabular form with the following statement. "The simulated results predicted 1 to 3 percentage points less moisture removed than was removed experimentally." A comparison of grain temperatures were also listed in the table. The predicted temperatures were between 2^oF above to 18^oF below the model. No conclusions as to model validity or verification were made for the concurrent flow model being tested. The crossflow and counterflow models were not specifically mentioned or tested. Recommendations for future research were further investigations for model validation purposes.

Bakker-Arkema, Evans, and Farmer(71) applied the Michigan State grain drying models to the analysis of an experimental multiple-zone grain dryer. The predicted results were used in a model validation study (compared with experimentally measured conditions). The moisture measurements were presented in graphical form for visual comparison. These moisture gradient plots appeared to coincide with one another. The following conclusion was made. "When these tests were simulated on the computer, the experimental and theoretical results agreed as well as the experiment analyzed in Figure 2 and 3. This fact prompted the decision to accept the simulation model presented in the analysis as an acceptable model for a parametric study of a fixed-bed, multiple-zone drier."

Bloome and Shove (71) proposed a 'near equilibrium' model for the natural aeration grain drying system. This model was tested with an experiment conducted in the fall and winter of 1968. Four moisture samples were taken during the drying test and presented as moisture gradients. Model deviations were summarized as "ranging from 1.2 percent wb less than the actual values to 0.8 percent wb greater." Moisture content of agricultural products is reported either in wet basis (wb) units or dry basis units (db). Moisture content wet basis (wb) is pounds of water per pound of wet grain. Dry basis is the pounds of water per pound of dry grain (no water). To convert from wet basis and dry basis, the following formulas are used:

$$M_{db} = \frac{M_{wb}}{1-M_{wb}} \quad (1.2.1) \qquad M_{wb} = \frac{M_{db}}{1+M_{db}} \quad (1.2.2)$$

M = Moisture content in decimal form.

The means of the errors through the bin were also compared. "Predicted values for the mean moisture content of the column ranged from 0.14 percent wb less than the actual values to 0.11 percent wb greater." The final conclusion as to model validity was not stated but the ability of the model was mentioned. "The model displays the ability to accurately predict both absorption and desorption in deep beds of shelled corn when aerated in the ambient condition range." Sensitivity of the proposed model was also noted, "The assumption that mass transfer is reversible without hysteresis responsible for this difference. However, the predicted mean moisture content was only 0.02 percent wb less than the actual mean."

Thompson, Villa, and Cross(71) proposed a model to be used for prediction on high moisture chilled grain studies. This model was compared to experimental results for verification. Predicted and actual grain temperatures were plotted for each of the tests conducted. "In general, the simulated temperatures agreed favorably with the experimental temperatures and similar temperature patterns were observed. However, the simulated grain temperatures were lower than those measured experimentally. Since grain drying was not the main objective of this study the moisture content was not measured continuously. However, a few 'spot check' determinations agreed favorably (within 1 percent wb) with the simulated results." No conclusion was made as to actual validity of the model, but favorable agreement was said to exist between the actual and the predicted.

Alam and Shove(73) developed an extension to the Bloome-Shove(71) model. This modified model was designed to predict soybean drying. A validation experiment was conducted in which the moisture contents were measured and reported by layers that correspond directly to the modeled layers. The results were presented in tabular form and plotted as moisture gradients. The range of the moisture errors of prediction ranged from 3.98 percent wb above to 1.92 percent wb below the observed moisture content. The average deviation reported per layer was in the range 0.13 percent wb above to 1.06 percent wb below. A modification to the proposed equilibrium model was given and also tested for accuracy improvement. "Comparison of the average deviation between the predicted moisture content and the experimental moisture content of each layer shows that Model$^+$ predicts moisture content more accurately than Model*. As drying progresses the deviation decreases for both cases; however, the deviation for Model$^+$ is always less (only 0.01 percent wb after 56 days)."

Paulsen and Thompson(73) modified the Thompson Model(68) for the analysis of grain sorghum drying. Three drying tests were performed for the verification of the drying model. The results were presented graphically for moisture and temperature. "In general, grain temperatures predicted were slightly higher than the experimental grain temperatures. Consequently, predicted moisture contents were slightly lower than the experimentally obtained moisture contents." No conclusions as to model validity were published but suggestions were given for future research. "Future research may be needed to verify the assumption that grain sorghum at slightly higher naturally wet initial moisture contents will dry in a manner consistent with the predicted thin layer drying equation."

1.2.2 Validation Method Conclusions

It has been the experience of the author that the validation studies of the past in the area of grain drying research have been verification studies. Once these models have been verified to behave as the experimenter has intended then the predicted results are accepted and the area of model application is begun with great enthusiasm.

The need for a concise, simple validation method of computer based models is apparent. This validation method would also be useful for model comparison. Because of the rapid evolution of new grain drying models, the need for analytical model comparison is imperative. There exists two distinct concepts of the natural aeration drying system in the Agricultural Engineering literature. These two viewpoints are static equilibrium, and dynamic diffusion models. Both models should be accurate for certain airflow ranges. Model comparison has not been performed because a simple standard for comparison has not been developed. A simple statistical evaluation method of grain drying models would be helpful.

1.3 Objectives of Study

1. Compare natural-air grain drying experimental results with mathematical model predictions.
2. Develop a plausible statistical method for natural aeration model validation.
3. Suggest useful tests and parameters to compare several models with each other.
4. Make reasonable modifications to model as indicated by the results of 1,2, & 3.

1.4 Literature Review of Simulation Model Validation

Bowersox et al (72) gave the following insight into the complexity of model validation. "The amount of time and effort needed to develop and make operational a computer simulation model is at present so great that the problem of its validation has generally been neglected. A common attitude seems to be that crude judgmental and graphic methods are preferable to completely ignoring validation." Three major positions on validation methods were summarized by Naylor and Finger(67) as "rationalism, empiricism, and positive economics."

> "Rationalism - A model or theory is a system of logical deductions from a series of synthetic premises of unquestionable truth. Validation is the search for the basic assumptions underlying the behavior of the system.
>
> Empiricism - The opposite view to rationalism is that empirical science is the ideal form of knowledge. The model should be constructed with facts, not assumptions. Then any postulates or assumptions which cannot be independently verified should not be considered.
>
> Positive Economics - This view championed by M. Friedman is that the validity of a model depends upon its ability to predict the behavior of the dependent variables and not on the validity of the assumptions on which the model rests."

In mathematical modeling,rationalism is the foundation of the basic equations, with empiricism used for improvement in accuracy. Validation will in general follow a positive economic approach toward accuracy improvement. Bowersox et al.(72) presented the combination in a multistage verification procedure:

1. Formulation of a set of postulates describing the behavior of the system,
2. An attempt to verify the assumptions of the model by statistical analysis,
3. Test the model's ability to predict the behavior of the system under study.

This verification procedure attempts to include all of the major ways in which to build confidence in a model.

Fishman and Kiviat(62) divided simulation model testing into three parts which are consistent with mathematical model validation.

1. Verification ensures that a simulation model behaves as an experimenter intends.

2. Validation tests the agreement between the behavior of the simulation model and a real system.
3. Problem analysis embraces statistical problems relating to the analysis of data generated by computer simulation.

These three steps will give an appropriate division to the validation method used for grain drying research.

1.4.1 Model Verification

Verification of model behavior is sometimes referred to as design validity. Design validity is a subjective verification that the model behaves in a fashion similar to the real system. Bowersox et al (72) quotes Amstutz(67) as giving the following tests for model verification.

1. Viability: Does the model generate behavior which persists over a significant time interval?
2. Stability: Variables and processes which are stable in the real system must also exhibit stability when modeled.
3. Consistency: The model must be internally consistent or have 'deductive veracity' i.e. does the model make sense?
4. Reliability: Tested by calculating 'interrun deviations' when changing the seed in the random number generator.
5. Performance evaluation: Possible by using the 'Turning Test'. If a person knowledgeable in the area to be modeled cannot distinguish the model response from the real system when provided with responses from both, then the model is realistic.

Viability is in general satisfied for all of the mathematical models under consideration in grain drying because the models are deterministic rather than stochastic.

Stability is an important test for dynamic models such as the solution of differential equations where the resulting variables will fluctuate drastically if proper calculational intervals are not adhered to. Static mathematical models enjoy somewhat of a privilege from having stability problems but are very sensitive to model assumptions.

Model consistency is judged according to accepted mathematical model forms and alteration of these models must be defined and tested for consistency. This is a subjective 'common sense' judgmental approach. Stochastic Reliability of the model is not applicable to a deterministic mathematical drying model because of the absence of random number generation.

Performance evaluation is widely used for model evaluation. This is sometimes called 'face validity'. The standard test is the 'Turing Test'. If a model is to fail this test for face validity the model is usually known to be in gross error and further testing in the validity section is not done until the source of this error is located.

These five methods and tests for model verification are useful for design validity. As the model is being built these tests can be performed to give some confidence in the model in its development phase. It is also important to note that while the verification phase is primarily an interaction phase between model builders and people familiar with the system, model validation phase will supply analytical information concerning the magnitude of nonconformity.

After a model has been verified to behave properly, its validity is questioned. Model validation or "output validity," (Bowersox(72) et al), is the measurement of model sensitivity to major assumptions.

1.4.2 Model Validation

"Many statistical and graphical techniques have been proposed and used in attempting to validate the output of computer models.", (Bowersox(72) et al.) In order to determine which of these techniques is most suitable for our validation of grain drying problems, the nature of the techniques should be examined and appropriate techniques chosen for our specific problem.

The following statistical tests were selected from a list presented by Bowersox(72) et al as being applicable to grain drying model validation. These are direct quotations from his book.

The Chi-Square Test

The chi-square statistic can be used to measure the discrepancy between observed and expected frequencies. The greater the value the larger the discrepancy. If the statistic is larger than a critical value the hypothetical frequency is rejected at a stated level of confidence.

Regression Analysis

It is often meaningful to be able to express the dependent variable (variable under study) and the other variables which affect it (independent variables). This is done by determining a line, curve, or plane which can be fitted to the data in such a manner which minimizes the squared vertical difference between the actual and predicted value. The resulting best fitting polynomial was determined by the method of least squares. This polynomial now shows the relationship of the dependent variable to the independent variable and can be used for the prediction of the dependent variable.

Correlation

Correlation can most easily be examined in terms of regression analysis. When all observations fall on the regression line developed from the data, perfect correlation is said to exist between the observed and predicted variables. If one increases as the other decreases or vice versa,inverse correlation exists. Direct correlation exists if one variable increases at the same time that the other increases.

Nonlinearity and multiple variables increase the complexity of calculation but the logic is not altered for this type of analysis.

Analysis of Variance (AOV)

Analysis of variance is used to test if two or more samples differ significantly from one another with respect to a specific (qualitative) property. If the observations are classified on the basis of a single property, the ratio of the average variance between groups to the average variance within groups (F ratio) is used to test if a significant difference does in fact exist between the groups with respect to the property of interest.

The F Distribution

To compare the variances of small samples, the F distribution is used. The F statistic (ratio) is equal to the ratio of the sample variances. Given a level of significance and the two sample sizes (degrees of freedom), the critical value of F can be found in a table of the F distribution. By comparing the calculated sample F statistic with the critical value from the table, the hypothesis that the variables are not significantly different from each other can be accepted or rejected.

Multiple Ranking

This procedure is a method of finding the best plan. It is used to answer the question: With what probability is the calculated ranking of the sample means equivalent to the actual ranking of the population means? The method used for this test is usually Least Significant Difference (LSD) (Snedecor and Cochran(71)).

Factor Analysis

Using the correlation matrix of the regression analysis technique the resolution of the set of variables linearly in terms of a small number of factors is possible. If this process is carried out satisfactorily, the factors will convey as much information about the system as did the original set of variables. A given matrix of correlations can be factored in an infinite number of ways. Therefore factor solutions are resolved to account for the maximum possible total variance, or according to the meaningfulness of the solution to the particular experimental context. It is emphasized that factor analysis does not produce an exhaustive set of fundamental factors which are in a complete description.

Graphical Methods

Aside from the methods of graphical analysis of the verification stage many graphing techniques are used for validation purposes. A graphical description of time series is easily developed and readily understood. Many graphical measures for comparing two time series are possible: number, timing and direction of turning points; amplitude of the fluctuations for corresponding time segments; average amplitude over the entire series; simultaneity of turning points for different variables; average values, probability distributions and variation about the mean (variance, skewness, kurtosis) of variables; and exact matching of variables.

Bartlett's Test for Homogeneity of Variance (Winer(62))

When several model validation experiments are performed each is known to contain error but each is assumed to have error variances which are equivalent. The analysis of variance tests have an underlying assumption that the populations are homogeneous, and are somewhat sensitive to departures from this assumption. The Bartlett test is a method for testing the hypothesis that all experimental error variances are statistically equivalent. Small departures in the homogeneity assumption are rather harmless because the F tests are robust and are not adversely affected by these departures. The Bartlett test is also applied to actual tests which yield conflicting decisions, when nonhomogeneity may be affecting model validation decisions.

Due to the number of possible tests and methods for analysis, the explanations were by necessity brief. However the interested reader is referred to the reference section at the end of the chapter for further explanation. From these techniques those suitable for grain drying validation procedures will be clarified and discussed in more detail. However each of the methods presented can be successfully applied to mathematical model validation studies.

Model Sensitivity to Basic Assumptions

Concurrent with the output validity testing, design validity should be observed continually. If the modeling assumptions are found to be limiting, alternate methods of modeling can drastically improve prediction accuracy. With the validation procedure the amount of improvement can be accurately weighed against the increased cost of assumption modification. This cost is composed of additional computing, programming alternation or complete model rebuilding. This analysis gives an indication of model robustness. If the model functions well under less than ideal conditions more faith is placed in the dryer designs which are to be built from the model.

1.4.3 Problem Analysis

This is of particular interest to the person directly involved with the application of mathematical models to grain drying. These are statistical problems of determining how the results of the models will be analyzed to determine an optimum design. Some of the questions which belong to this section are; What is an acceptable cost of failure for this drying system? How do I compare management methods for several modeled systems? What are the alternatives which I should furnish for a bad drying year? How should I compare the effect of solar energy input to the system with the natural or unheated aeration? Will these decisions be based upon mean moisture weight removed or amount of energy consumed?

1.5 Proposed Model Validation Procedure

To validate a proposed model analytically, a numerical attribute must be selected as an accurate measure of model performance. The specific reason for drying is to maintain grain quality and its market value.

Steele(67,69) began to predict corn quality using dry matter loss as a quantitative measure of corn deterioration. Actual dry matter loss is difficult to measure in a large scale natural aeration system. Grain grading is the marketing standard for determination of grain quality and market value. However grain grading is a subjective determination and not clearly definable as a numerical function of grain storage history.

Christensen(74) states that, "Fungi are a major cause of spoilage in stored grains and seeds, and probably rank second only to insects as a cause of deterioration and loss in all kinds of stored products throughout the world." Mold and insect invasion can be controlled by either moisture content or temperature being lowered to a safe storage level. In actual practice lowering the moisture content (drying) to prevent grain deterioration is more economical than temperature control (refrigeration).

Grain moisture content was chosen as the primary indication of natural aeration model accuracy for two reasons. Moisture content is an important factor in determining total deterioration rate (fungii, insects, rodents etc.), and it can be quantitatively measured.

*1.5.1 The Difference

Experimentally determined grain moisture observations can be seen to be composed of several error components. Once these error components have been properly identified, appropriate experimental methods can be incorporated to minimize their effect upon the test results. The observed moisture is seen to be:

$$M_o = M_a + E_o \tag{1.5.1}$$

M_o = Moisture content observed

M_a = Moisture content actual

E_o = Error of observation

"The accuracy of moisture determination is dependent upon many factors.", Pixton(74). Each of these factors contribute to a portion of the total error of observation, E_o.

*The error of observation is composed of two distinct groups, the (1) errors of measurement, and the errors due to (2) sampling. The errors of measurement are usually determined by the types of experimental equipment used. For control of this type of error the experimenter may purchase more accurate equipment or perform replications of his studies thereby reducing his average error. (2) The sampling error is caused by experimental factors which affect the data collection. The sampling error can be reduced by repeated sampling over the entire experiment. Then the average sample moisture content will approach the actual moisture content. These components are assumed to be additive and can be written symbolically as:

$$E_o = e_s + e_{sp} + e_{fm} + e_{vp} + e_m \qquad (1.5.2)$$

The problem of obtaining a representative sample yields the sampling error e_s. The error due to sample protection (e_{sp}) is the moisture loss between the time of sampling and the time the moisture content is determined. Sample protection should be achieved by using moisture proof containers and making the moisture determination as soon as possible.

The error of fine material distribution e_{fm} is a component whose magnitude is not clearly known. This distribution of fine material in the grain bed results in increased air pressures and decreased airflow rates. Decreased airflow reduces drying rates. Clean grain and/or multiple sampling locations within the bin will both reduce this effect and minimize its magnitude.

The velocity profile due to fan location and configuration e_{vp} is also an unknown magnitude. The velocity profile is the distribution of air velocity components in the plenum chamber in a direction normal to the grain bed. When the air exits from the fan, the flow and velocity are parallel to the plenum floor. Minimization of this effect can be made by adequate design of plenum chamber or preferably by repeated replication of moisture observations.

The error of measurement e_m is to be the error associated with the measurement method used to determine moisture content. The method by which the sample is weighed and prepared for the determination results in some losses according to Pixton(74). The method of measuring moisture content (oven, electric meter, nuclear magnetic resonance, etc.) contributes to the error of measurement. By selecting one particular method as being the most accurate (standard) and replication of samples, this error can be minimized.

All of these moisture errors can be minimized by replication of samples, or by utilization of more accurate measurement techniques. Because each of the components is additive and independent the Central Limit Theorem insures that our total error E_o will be distributed normally with mean $\bar{E}_o$ and variance σ^2.

* Model Error

The quantity of interest for model validation is the model error E_m, which can be described symbolically as:

$$\underline{E_m = M_a - M_m} \qquad (1.5.3)$$

The actual moisture M_a is an exact quantity which cannot be measured directly, the model moisture content M_m is a mathematically calculated quantity and the result of subtraction is the exact model error, E_m. Since M_a can not be measured directly, it must be estimated from observations. Therefore by substitution of the observed moisture content for actual yields;

$$\overset{\text{observ}}{M_o} - \overset{\text{total error}}{E_o} - \overset{\text{model}}{M_m} = E_m \qquad (1.5.4)$$

$$\underline{M_o - M_m = E_m + E_o} \qquad (1.5.5)$$

Since the experimental observation error, E_o, is assumed to be distributed $N(0, \sigma^2_{E_o})$, then taking expectations of both sides yields:

$$\boxed{\text{Expectation of } (M_o - M_m) = E_m} \qquad (1.5.6)$$

The expected value of the difference $M_o - M_m$ is the model error.

Imp. The model error as estimated will vary throughout the test but for an accurate model the mean should be equal to zero ($E_m = 0$), and the variance should be small (small $\sigma^2_{E_m}$). The difference X is the sample estimate of the model error. This difference is calculated according to the following formula:

$$X = M_o - M_m \qquad (1.5.7)$$

X = Sample moisture error decimal db.

M_o = Observed moisture content decimal db.

M_m = Model predicted moisture content, decimal db.

1.5.2 The Difference Table

The difference X has been shown as an effective measure of model error, but how can this difference be applied to grain drying model validation decisions? Grain moisture measurements have two characteristics which distinguish one from another. These independent variables are depth in the drying bed, and amount of drying time.

The observed grain moisture M_o varies according to an unknown function of four independent variables. This representation is defined as:

$$M_o = f(T, D, r, \theta) \qquad (1.5.8)$$

T = Drying time

D = Depth of grain above bin floor

r, θ = Polar coordinates describing sampling location within the drying bin.

However, the model moisture (M_m) content is dependent upon only the first two variables. This function is expressed as:

$$M_m = g(T,D) \qquad (1.5.9)$$

In calculating the difference of these two quantities, the effect of r and θ is assumed negligible. Experimentally this means that adequate sampling replication within layer moisture variation is mandatory. For model evaluation, the average layer moisture content could be used.

The experimental moisture content can then be represented as a table of moisture vs. time and depth. (Table 1.5.1) The model should also produce a table of predicted values which correspond to the actual values. (Table 1.5.1) The difference table is formed by taking the difference of the actual table minus the model predicted table. (Table 1.5.1) The expected value of the model error (E_m) can then be estimated by the mean of the difference table and the variance of the observation error can be approximated by the variance of the difference table. The following formulas are used to calculate the difference table statistics. The mean of the difference table:

$$\bar{X} = \sum^{i}\sum^{j} X_{ij}/N \qquad i = 1,2,\ \dots,\ nt \quad j = 1,2,\ \dots,\ nd \qquad (1.5.8)$$

nt = number of time observations nd = number of depth observations

N = nt x nd: total number of observations

The sample standard deviation of the observation error (E_o):

$$S = \sqrt{\frac{\sum\sum\left(X_{ij}^{2}\right) - \left[\frac{\sum\sum(X_{ij})}{N}\right]^{2}}{(N-1)}} \qquad \begin{matrix} i = 1,\ \dots,\ nt \\ j = 1,\ \dots,\ nd \end{matrix} \qquad (1.5.11)$$

Since we have assumed the distribution of observation errors E_o is normal, the mean of absolute deviations was calculated as a test of normality.

Table 1.5.1 Example: Actual, Predicted and Difference Tables

Actual Moisture Content for Example Only

Drying Time (Hours)	Grain Depth Measured From Bin Floor (Inches) 7.9"	16.5"	25.8"	35.0"	44.3"
44	21.53	22.56	22.11	21.73	21.67
92	16.75	22.49	22.20	22.10	21.90
161	12.65	16.95	24.60	21.65	21.38
213	12.20	14.68	18.68	21.33	21.20
260	12.93	14.30	16.38	20.35	21.68
332	13.60	13.62	15.58	15.87	16.94
382	14.08	14.05	14.45	15.84	16.57
480	14.66	14.06	14.11	14.47	14.23

Grain Drying Model Predictions for Example Only

Drying Time (Hours)	Grain Depth Inches From Floor Simulated Layer # 2	4	6	9	11
45	19.67	22.13	22.18	22.15	22.13
93	13.52	19.77	22.28	22.38	22.32
162	9.06	11.44	17.63	20.63	21.77
213	10.48	10.07	10.88	13.16	20.65
261	12.99	11.90	11.22	11.07	12.74
333	14.56	13.91	12.95	12.56	11.94
381	14.82	14.28	14.04	13.76	13.17
480	15.32	13.81	13.22	13.24	13.65

Difference Table (Observed-Expected) Example Only

	7.7	18.0	28.2	33.4	43.6
45	1.86	.43	-.07	-.42	-.46
93	3.23	2.72	-.08	-.28	-.42
162	3.59	5.51	3.97	1.00	-.39
213	1.72	4.61	7.80	8.17	.55
261	-.06	2.40	5.16	9.28	8.94
333	-.96	-.29	2.63	3.31	5.00
381	-.74	-.23	.41	2.08	3.40
480	-.66	.25	.90	1.23	.58

Absolute Mean = 2.3948 = $|\bar{X}|$

Mean = 2.1418 = $\bar{X}$

Standard Deviation = 2.8331 = S

$$\text{Absolute mean: } |\bar{X}| = \sum_i \sum_j \frac{|X|_{ij}}{N} \qquad \begin{array}{l} i = 1, \ldots, nt \\ j = 1, \ldots, nd \end{array} \qquad (1.5.12)$$

These parametric statistics are also given for the example difference table in Table 1.5.1. Brown (62) listed appropriate values of the ratio of absolute mean to standard deviation ($\frac{|X|}{s}$) for several distributions (Table 1.5.2). This ratio can be upheld statistically as indicating if model errors are normally distributed.

1.5.3 Graphical Analysis

Comparisons of the two moisture tables can be shown graphically as moisture gradients within the bin, or as time series of one layer. Figures 1.5.1 and 1.5.2 show a moisture gradient and a time series taken from the data of Table 1.5.1. These are helpful in visualization of model discrepancy from the actual observed drying front. But the difference table contains at a glance all of the information on model prediction accuracy. If all of the data for this experiment were plotted 5 moisture gradient and 8 time series graphs would have to be drawn. For several tests and several models the graphical analysis is a technique which should be used sparingly for display of interesting data, rather than as an exploratory comparison method. Graphical analysis can best be used after investigation of the difference tables.

These two-dimensional representations (Figure 1.5.1, 1.5.2) of the two moisture tables show a slice of the actual experimental response. However, Figure 1.5.3 shows a three-dimensional view of the actual and predicted moisture surfaces with respect to time and depth of grain. These surfaces

Table 1.5.2 Accepted Ratios of Sampling from the Following Distributions Brown(62)

Distribution	Ratio $\frac{\overline{\|X\|}}{S}$
Normal	.79788
Exponential	.73576
Uniform	.86603
Triangular	.83805

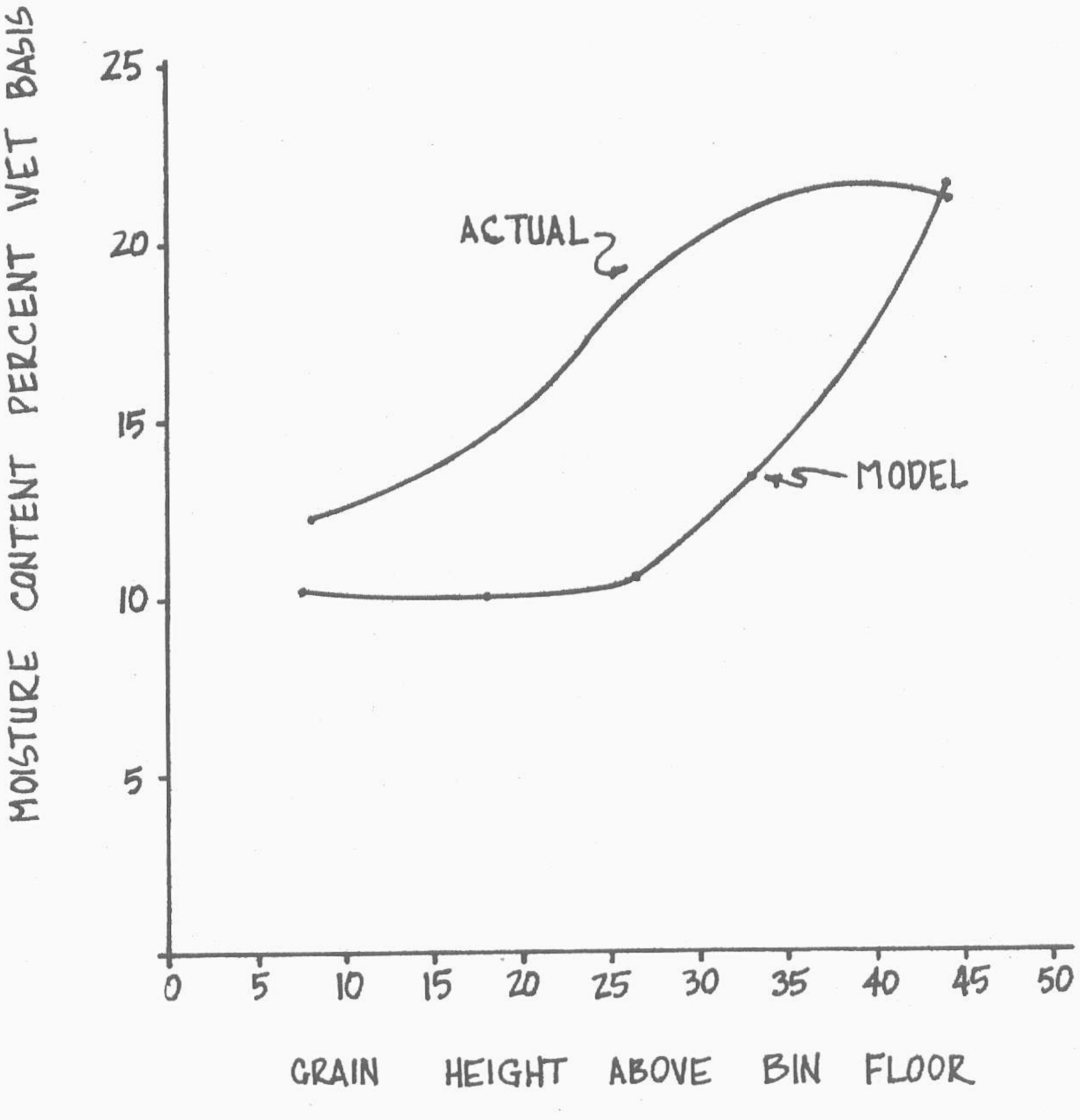


Figure 1.5.1 Moisture Content Gradients

Actual and Predicted

After 213 Hours of Drying

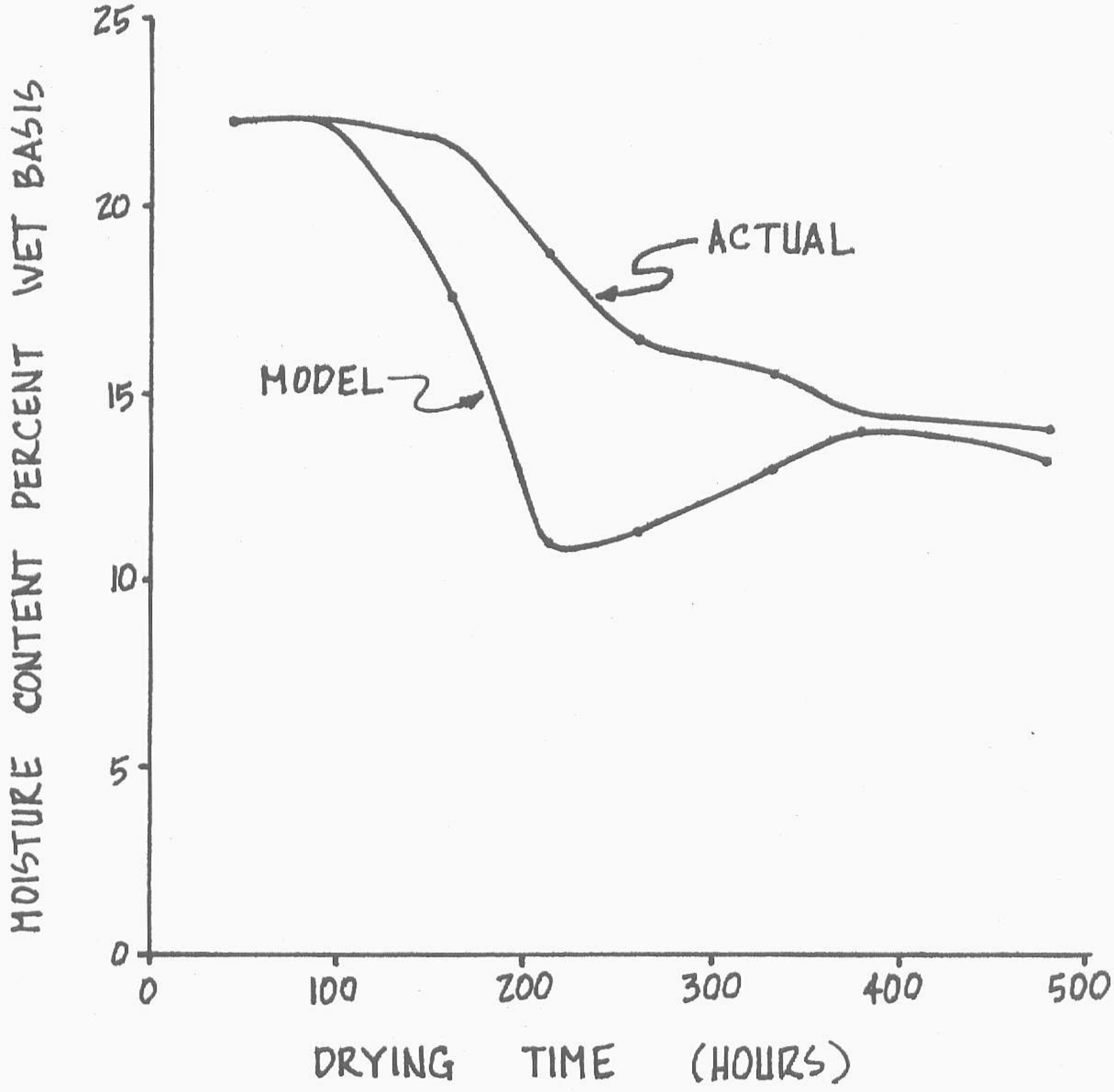


Figure 1.5.2 Moisture Content Time Series

Actual and Predicted

For Grain Depth of 28 Inches

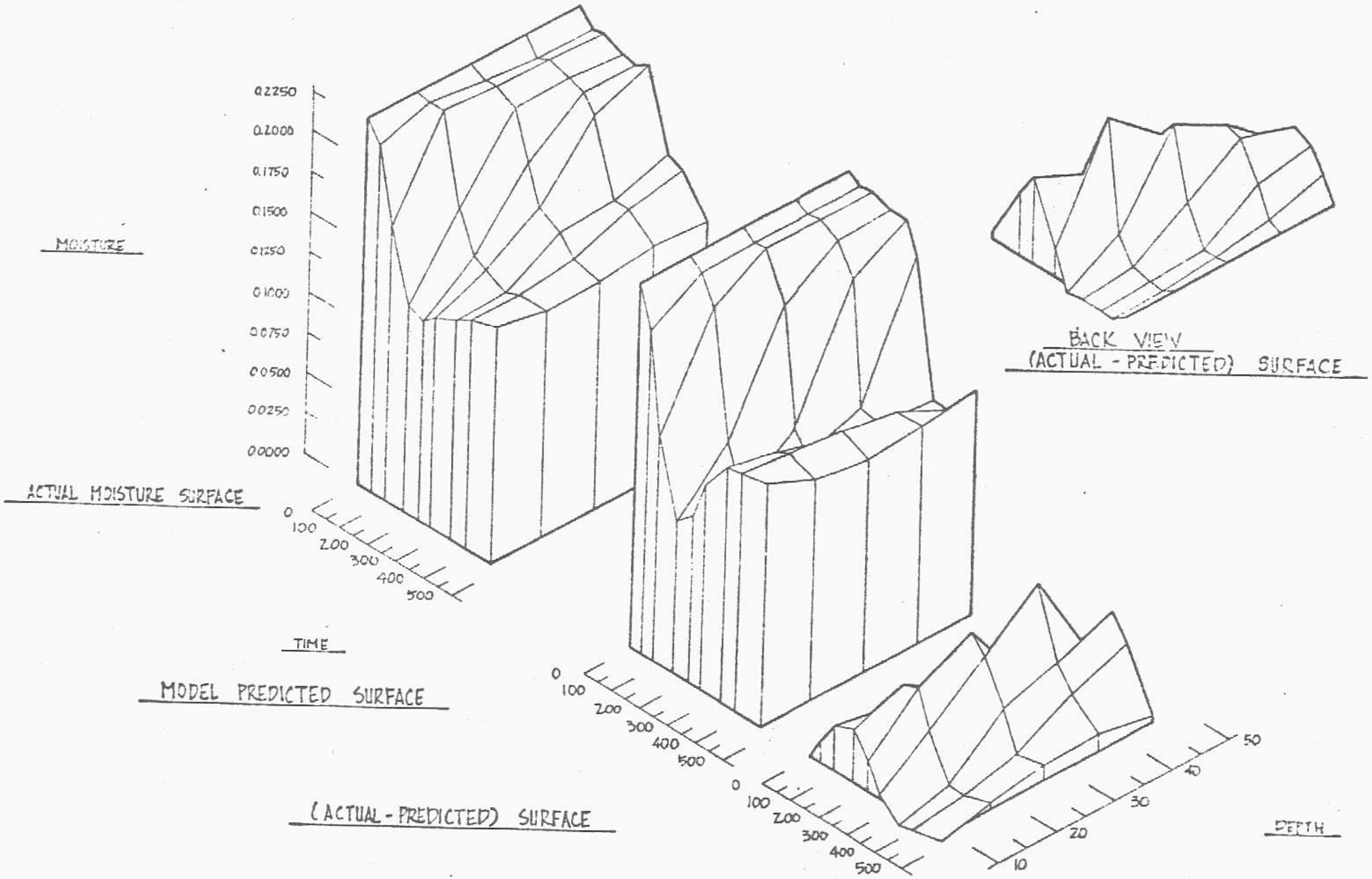


Figure 1.5.3 Example of the Experimental, Equilibrium Model and Differenced Drying Surfaces for Test 1-N

are very similar in shape and contour and give good support to the verification of model behavior as intended by the experimenter. Neither surface can be readily distinguished by persons familiar with grain drying. (Turning Test) Figure 1.5.3 also shows a surface plot of the difference table. Note the large ridge down the diagonal and the two flat areas of good prediction.

✓⊛ 1.5.4 An Adequate Model (Students t Test)

Our search is for a model whose sample estimate of the error mean ($\bar{X}$) is not significantly different from zero. If the model can satisfy this requirement, it is considered to be an adequate model of the experimental results. The criterion to be tested is stated as a null hypothesis, that the population error mean E_m is equal to zero.

$$* \quad H_o: \; E_m = 0.0 \qquad (1.5.13)$$

To test this hypothesis a confidence interval is formed about the true population mean. A confidence interval about a sample mean $\bar{X}$ has a known probability of containing the true population mean E_m. If the constructed interval contains zero then the hypothesis (1.5.13) is accepted. The probability that the true mean does lie within the confidence interval is known as the confidence level.

The following test statistic t_c is calculated to determine directly if zero lies within the confidence interval.

$$\text{imp.} \quad t_c = \frac{(\bar{X} - E_m)}{s/\sqrt{N}} \qquad (1.5.14)$$

t_c = calculated t test statistic

$\bar{X}$ = sample mean of difference table

E_m = true population mean for testing

s = standard deviation of difference table

N = total number of observations in the difference table, nt x nd.

Note: $E_m = 0.0$ for an adequate model.

The numeric example of the difference table Table 1.5.1 is used to calculate an example t test for model adequacy and is given in Table 1.5.3.

If the null hypothesis (1.5.13) is accepted as true, the model is stated as being an adequate model. Rejection of the null hypothesis indicates that the model is inadequate and model refinement is recommended.

The calculated t statistic (t_c) is compared with a tabled Student t statistic with $(N - 1)$ degrees of freedom. The confidence interval can then be visualized as:

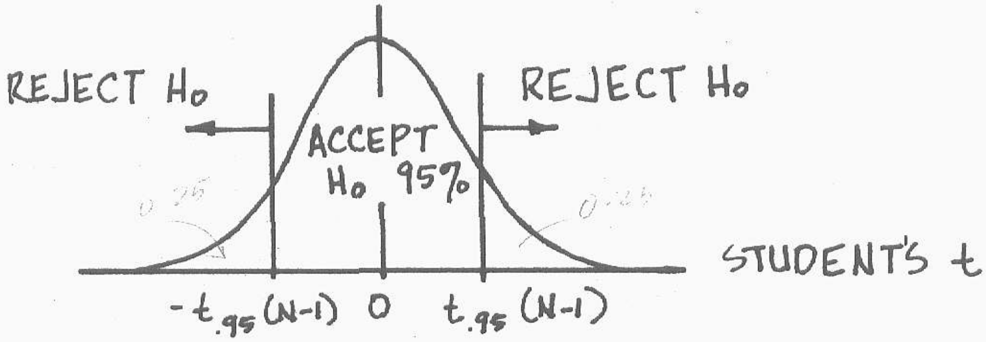


Figure 1.5.4 A Student's t distribution with N-1 df.

Table 1.5.3 A t Test of Difference Table Mean

H_o: $\bar{E}_m = 0.0$

$$t_c = \frac{\bar{X} - \bar{E}_m}{S/\sqrt{N}} \qquad E_m = 0.0 \text{ for an adequate model}$$

$$t_c = \frac{2.1418 - 0.0}{\dfrac{2.8331}{\sqrt{40}}} = \frac{2.1418}{.4480} = 4.78$$

$$\frac{0.015 - 0}{0.065/\sqrt{26}} = \underline{\underline{1.15}} \rightarrow \text{do not reject}$$

$t_{.95}(39) = 2.02$

$t_{.95}(25) = 2.06$

Decision:

Since $t_c(39) >> t_{.95}(39)$; Reject H_o

Therefore the example model is inadequate. →

A 95 % confidence interval was chosen because model accuracy is desired and a 95 % interval is much more narrow than a 99 % interval. This narrow interval can be stated as an acceptance interval. With a narrow acceptance interval we are assured that our accepted model is an adequate model.

The decision rules for this test can now be finalized to the following:

1. reject H_0 (1.5.13) if $|t_c| \geq t_{.95}(N-1)$,
2. otherwise accept H_0.

1.5.5 An Accurate Model (AOV Model I) *

A mathematical model whose errors X_{ij} are:

a) small in magnitude,

b) with mean $\bar{X}$ equal to zero, and

c) distributed in a random fashion,

is defined to be an accurate model of the experimental observations. In Section 1.5.4, the method for evaluation of part (a) and (b) is discussed but how can randomness (c) be measured?

An obvious and useful technique is to visually examine the difference table for patterns or regions of like signs and magnitudes. The example difference table in Table 1.5.1 shows three distinct regions of like signs. These three regions are an upper and lower diagonal area of negative numbers and a large diagonal area of positive numbers. Notice that the positive numbers are large in magnitude, with an average greater than 3.0, and the negative numbers are small in magnitude with an average of about -0.5. The presence of these patterns indicate two things. First, the errors are not randomly distributed. Secondly, model error is dependent upon the time and depth the bin is sampled. How can this randomness be quantified such that an analytical criteria for model accuracy can be stated?

The difference table is a two-way classification of model error. Each error or element in the table is classified according to the depth and time the observation was made. A simple method of testing randomness would be to compare column and row means to see if they are equal to each other. This criteria is stated as the following two null hypotheses:

$$H_{o_1}: \bar{D}_1 = \bar{D}_2 = \ldots = \bar{D}_{n_d} \qquad (1.5.15)$$

$$H_{o_2}: \bar{T}_1 = \bar{T}_2 = \ldots = \bar{T}_{n_t} \qquad (1.5.16)$$

$\bar{D}_j$ = The average model error at j^{th} depth

$\bar{T}_i$ = The average model error at the i^{th} time

n_d = Number of depth observations

n_t = Number of time observations

These two hypotheses together can be interpreted as asking: does the model predict equally well throughout the test?

To test these hypotheses (equations (1.5.15) and (1.5.16)) paired t-test combinations can be used; but, this technique is abandoned in favor of the analysis of variance procedure. This method of analysis states that if equations (1.5.15) and (1.5.16) are true then the variations among the means observed are due to random independent sampling from the same population. To test this hypothesis two non-biased estimates of the population variance, within classification (S_w^2) and between classification (S_b^2) are compared. If they are different, the null hypothesis is rejected. A classification would be either depth or time in our tests. If there is a measurable difference among classifications, we would expect the between classification variance estimate S_b^2 to be larger than the within classification variance estimate S_w^2.

The ratio of two variances is a random variable whose distribution is called the F distribution. As with the t-test, it is necessary to define the confidence level for this test. The F distribution has the following appearance:

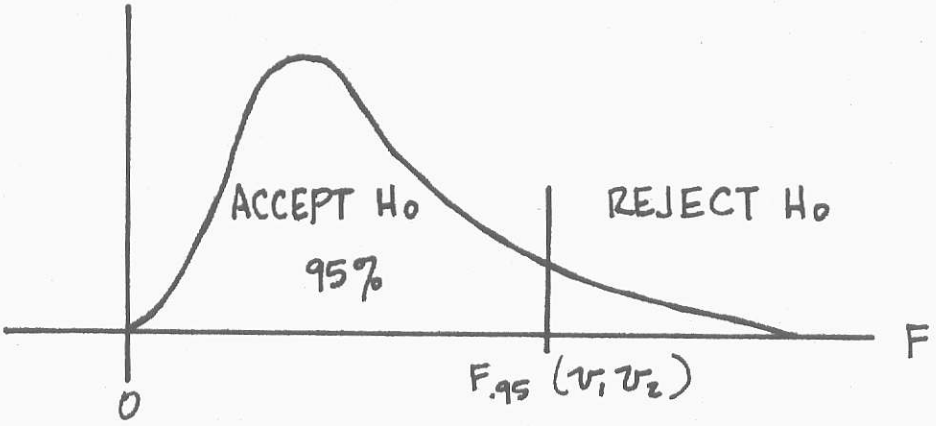


Figure 1.5.5 a F Distribution

We wish to find the table value $F_{.95}(\nu_1,\nu_2)$ of the F distribution such that the probability of a smaller F statistic is 95% where ν_1 is the degrees of freedom for the numerator and ν_2 degrees of freedom for denominator. This tabled F-ratio (F_t) is compared with the sample calculated ratio $F_c(\nu_1,\nu_2) = \frac{S_w^2}{S_b^2}$. If the computed F-ratio F_c is greater than the tabled value F_t, the null hypothesis is rejected.

The calculation of the two-way analysis of variance is best illustrated with an example. Table 1.5.4 shows calculation of our numerical example.

Table 1.5.4 Analysis of Variance (Model I)

H_{o_1}: $D_1 = D_2 = \ldots = D_5$ H_{o_2}: $T_1 = T_2 = \ldots T_8$

	D_1	D_2	D_3	D_4	D_5	Sum	Mean
T_1	1.86	.43	-.07	-.42	-.46	1.37	.268
T_2	3.23	2.72	-.08	-.28	-.42	5.17	1.034
T_3	3.59	5.51	3.97	1.00	-.39	13.68	2.736
T_4	1.72	4.61	7.80	8.17	.55	22.85	4.57
T_5	-.06	2.40	5.16	9.28	8.94	25.72	5.144
T_6	-.96	-.29	2.63	3.31	5.00	9.69	1.938
T_7	-.74	-.23	.41	2.08	3.40	4.92	.984
T_8	-.66	.25	.90	1.23	.58	2.30	.460
Sum	7.98	15.40	20.72	24.37	17.20	85.67	
Mean	.998	1.925	2.590	3.046	2.150		10.709

$$\text{Correction} = \frac{(85.67)^2}{(8)\cdot(5)} = 183.4837$$

$$\text{Depth} = \frac{(7.98)^2 + (15.40)^2 + \ldots}{8} - C = \frac{1619.8957}{8} - 183.4837 = 19.0032$$

$$\text{Time} = \frac{(1.37)^2 + (5.17)^2 + \ldots}{5} - C = \frac{1522.7}{5} - 183.4837 = 121.0564$$

$$\text{Total} = (1.86)^2 + (.43)^2 + \ldots + (1.23)^2 + (.58)^2 - C = 496.5153 - 183.4837$$

$$= 313.0316$$

Source	DF	SS	MS	F_c	F Table
Time	7	121.0564	17.2938	11.1511	$F_{.95}(7,28) = 2.36$
Depth	4	19.0032	4.7508	3.0633	$F_{.95}(4,28) = 2.71$
Error	28	43.4241	1.5509		
Total	39	313.0316			

Decision

Since $F_{C_T} >> F_{table}$ Reject H_{o_2}

Since $F_{C_D} > F_{table}$ Reject H_{o_1}

NOTE: Our numerical example would normally not be tested with analysis of variance because of its failure in Section 1.5.4, but is used here as an example.

Due to the increased complexity of calculation with several experimental tests, the computer-based statistical package known as AARDVARK (Kemp(73)) was used for computation of AOV tables. This package performs factorial analysis of variance testing with calculation according to a user-specified model. This model is used to indicate the type of analysis which is to be performed and allows the user to label his variables on the resulting computer print-out.

The AARDVARK analysis of variance (AOV) model used for testing a grain drying model's difference table is:

AOV Model I:

$$X_{ij} = T_i + D_j + E_{ij} \qquad \begin{array}{l} i = 1,2, \ldots, n_t \\ j = 1,2, \ldots, n_d \end{array} \tag{1.5.17}$$

X_{ij} = The sample moisture error at the i^{th} time and j^{th} depth

T_i = i^{th} time component of moisture error

D_j = j^{th} depth component of moisture error

E_{ij} = A random element

n_t = number of time observations

n_d = number of depth observations

Since in section 1.5.4 we have tested that $\bar{X} = 0.0$, we know that $\bar{T}_i = \bar{D}_j = 0.0$. Snedecor(71) gives the following assumptions for the model equation (1.5.17):

1. Row and column effects are considered additive.
2. The E_{ij} are independent random variables, normally distributed with mean 0.0 and variance (σ^2).

NOTE: The interpretation of the analysis of variance (AOV) results are reversed from normal AOV conclusions. This is because in model testing, a significant effect in the difference table indicates an assignable cause and this implies a weak model.

1.5.6 Model Validation Summary

In order to perform the validation testing the following assumptions have been made:

✓1. The experimental observation error E_o is distributed normally with mean zero and variance $\sigma^2_{E_o}$.

✓2. Each observation is randomly obtained from the same population.

✓3. Each observation is an independent observation.

The model validation procedure consists of three steps each of which will yield increasing confidence in the model if passed successfully:

(*)1. Formation of the difference table of observed minus predicted.

(*)2. The t-test for mean model error $\bar{X}$ equal to zero. (Adequate)

✓(*)3. The AOV test for randomness of model errors. (Accurate)

Therefore, to accept a model to be validated as accurate, we must accept the three hypotheses stated in equations 1.5.13, 1.5.15, 1.5.16. Then this model is said to accurately predict the experimental results. ✓

1.6 Multiple Model Comparison and Validation

Grain drying models undergo refinements to improve their accuracy, or perhaps are cast aside to start with a fresh set of basic assumptions. The problem which then confronts the model builder is how to compare his current model with his previous attempts, or perhaps with an accepted model from the literature? We could use the methods of Section 1.5.

1.6.1 Model Comparison (AOV Model II)

Using the procedure given in Section 1.5 to evaluate n_m models using n_t tests would require $n_m \cdot n_t$ paired t-tests and $n_m \cdot n_t$ two-way AOV tests and then final comparison of each of the results. We wish to simply choose the model(s) with the best prediction ability and test them for accuracy.

As in Section 1.5.4 we wish to distinguish which model has the smallest mean error for a particular test. If we assume that all the models perform equally well, we would expect that their error means $\bar{E}_{m_i}$ are equal. This is stated as a null hypothesis. $\bar{M}_i$ is an abbreviation for $\bar{E}_{m_i}$ to be consistent with the AARDVARK model:

$$H_o: \bar{M}_1 = \bar{M}_2 = . . . = \bar{M}_{nm} \qquad (1.6.1)$$

$\bar{M}_i$ = mean drying model error for model i with a particular experiment.

nm = number of drying models being compared.

In accordance with Section 1.5, the most efficient method of testing 1.6.1 is by the proper construction of a factorial analysis of variance (AOV). This AOV allows the experimenter to analyze the effect of each of these models upon prediction accuracy.

The calculation of the three factorial analysis of variance was performed by AARDVARK using the following model notation:

AOV Model II

$$X_{ijk} = M_i + T_j + D_k + MT_{ij} + MD_{ik} + TD_{jk} + E_{ijk} \quad (1.6.2)$$

$i = 1 \ldots nm$ $\qquad j = 1 \ldots nt$ $\qquad k = 1 \ldots nd$

X_{ijk} = Moisture Error (difference) of the ith model, at the jth time and kth depth.

The main components of the moisture error are defined as:

M_i = Grain drying model i,

T_j = Drying time j,

D_k = Drying depth k.

The interactions between main components are defined as:

MT_{ij} = Model i with time j for all depths,

MD_{ik} = Model i with depth k for all times,

TD_{jk} = Time i with depth k for all models.

E_{ijk} = The random element independently sampled, which is assumed to be normally distributed with mean (0.0) and variance (σ^2).

nm = number of models.

nd = number of depth.

nt = number of time observations.

To test the hypothesis (1.6.1), an appropriate F-ratio of between cell variance to within cell variance is calculated. H_0 equation (1.6.1) is accepted or rejected by comparing the F-ratio:

$$F_c = \frac{s_m^2}{s_{error}^2}$$

s_m^2 = model variance estimate $\nu_1 = nm - 1$

s_{error}^2 = within classification variance estimate

$\nu_2 = (nm - 1)(nt - 1)(nd - 1)$

Table 1.6.1 shows the results of the AARDVARK analysis of variance for AOV Model II. The components of the model (1.6.2) are listed with the associated sums of squares, degrees of freedom, mean square and calculated F-ratios (F_c). The alpha hat column shows the calculated probability of a larger F_c given the two associated degrees of freedom. This probability is the calculated area under the F distribution to the right of the F_c as shown in Figure 1.5.6. Alpha hat is the probability of occurrence of a larger F-ratio due to random chance.

The results of our example of AOV Model II shows a comparison of 4 models with 8 time and 5 depth classifications. Since our confidence level was chosen as 95% then the probability of a larger F-ratio is seen to be 5%. An effect is significant if the calcualted alpha hat is smaller

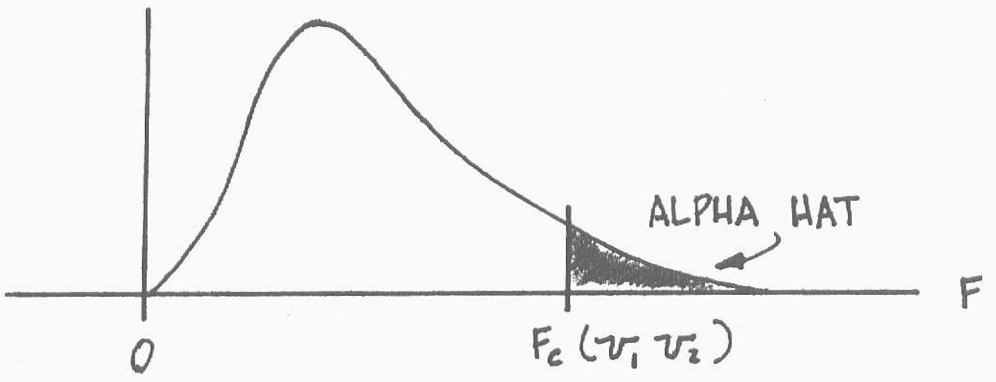


Figure 1.6.1 F-Distribution

Table 1.6.1 Example Factorial AOV (AARDARK)

Moisture Error

Due to	Sum of Squares	DF	Mean Square	F	Alpha Hat
M	15.015241623	3	5.005080223	4.857435226	0.00364
T	144.250961304	7	20.607269287	19.999374390	0.00000
D	40.299224854	4	10.074806213	9.777609825	0.00000
MT	19.446746826	21	0.926035523	0.898718476	0.59293
MD	10.737632751	12	0.894902690	0.868407011	0.58136
TD	273.844726563	28	9.780168533	9.491663933	0.00000
ERROR	86.553222656	84	1.030395508		
TOTAL	590.148193359	159			

than .05. The decision rule is to reject H_0 if alpha hat < .05.

In Table 1.6.1 each component of the AOV Model II equation (1.6.2) are listed as several rows in the analysis of variance table. The alpha hat corresponding to model component (M) is .004. Since .004 < .05, we reject H_0 equation (1.6.1) and state that there is a significant difference among model errors.

NOTE: Each component of the AOV Model II equation (1.6.2) was found significant except the MT and MD components. This indicates that each model is significantly different according to time and depth. But no significant effect exists between model and depth or model and time.

If there is a significant difference to be found among models, then a method of multiple ranking from Section 1.4.2 is used.

1.6.2 Least Significant Difference (LSD)

The least significant difference method ranks the model error means in descending order. This ranking will conclude which model has the smallest error mean $\bar{M}_i$.

The smallest difference between two sample means which can be stated as significantly different with a given level of confidence is called the Least Significant Difference (LSD). The LSD is calculated according to the following formula:

$$LSD = s_{\bar{D}} \cdot t_{.95}\,(a(N-1)) \qquad (1.6.3)$$

$$s_{\bar{D}} = \frac{2s^2}{N}$$

s^2 = Mean square error

N = Number of observations (differences) in experiment

a = Number of drying models

$t_{.95}(a(N-1))$ = Table Student's t statistic with a(N=1) degrees of freedom

The model means are ranked from greatest to smallest. The best model is the one whose error mean (M_i) lies closest to zero.

The validation procedure of Sections 1.5.4 and 1.5.5 are applied to the best model. It is seen that the t-test of the sample means is analogous to the LSD tests just performed. Therefore, if the best model has a mean error which lies within the range of ± LSD, the model is confirmed to be adequate.

Section 1.5.5 is then applied to the adequate model or models. Should more than one model be accepted as accurate according to AOV Model I equation (1.5.15), then the drying model with the smallest error mean square from AOV Model I is chosen as the most accurate model.

1.6.3 Multiple Model Summary

Multiple Model comparison and validation is simple and straightforward if the following computational steps are followed:

1. the difference table is formed for each model,
2. model uniqueness is determined by testing H_0 (1.6.1) with the evaluation of AOV Model II (1.6.2),
3. best model is determined by ranking model means with $LSD_{.95}$,

4. an adequate model is determined by reusing LSD to test H_0 (1.5.11),
5. an accurate model is determined by testing H_0 (1.5.15 and 1.5.16) with the evaluation of AOV Model I (1.5.17),
6. the most accurate model is defined as an accurate model with the smallest possible error mean square from step 5.

As the model successfully completes each step of the testing procedure while in direct competition with other models, more confidence is placed upon the model's prediction ability. If the model has been chosen in step 6 to be the most accurate model, it is also defined as a valid model of the experimental results.

1.7 Experimental Error (Bartlett's Test)

In sections 1.5 and 1.6 we have assumed that each entry in the difference table is an independent observation from the same population of model errors. Two questions become apparent from these assumptions. First, is the variation within a single experiment consistent for analysis of variance testing? Secondly, is the variation between drying experiments consistent. This consistency between experiments is important if multiple model performance is composed of several years of testing.

The 'within experiment' variation is tested in the AARDVARK tests for homogeneity of variance. The Bartlett's test for variation between experiments will be discussed. The decisions resulting from the test statistic (χ_B^2) are interpreted in the same fashion for both applications.

If the same population is actually sampled, then sample estimates of the error variance (s_i^2) for each test should estimate the same population variance (σ^2). We can hypothesize that the sample variance are equal.

$$H_o: \sigma_{E_1}^2 = \sigma_{E_2}^2 = . . . = \sigma_{E_a}^2 \qquad (1.7.1)$$

$\sigma_{E_i}^2$ = experimental error variance for experiment i

a = number of experiments being compared.

The Bartlett's test for homogeneity of variance is used to test the null hypothesis (1.7.1). The calculation of the Bartlett test statistic is according to the formula: Winer(62)

$$\chi_B^2(a-1) = M/C \qquad (1.7.2)$$

$$M = 2.3026 \left\{ \left(\sum_{i=1}^{a} f_i\right) \log (\bar{S}^2) - \sum_{i=1}^{a} \left[f_i \log (S_i^2)\right] \right\} \qquad (1.7.3)$$

$$C = 1 + \frac{1}{3(a-1)} \left[\sum_{i=1}^{a} \left(\frac{1}{f_i}\right) - \frac{1}{\sum_{i=1}^{a} f_i} \right] \qquad (1.7.4)$$

$$\bar{S}^2 = \frac{\sum_{i=1}^{a} f_i S_i^2}{\sum_{i=1}^{a} f_i} \qquad (1.7.5)$$

a = number of variances being compared

f_i = degrees of freedom for the i^{th} drying test

s_i = standard deviation for the i^{th} drying test.

The Bartlett statistic is distributed according to a chi-square sampling distribution (χ^2).

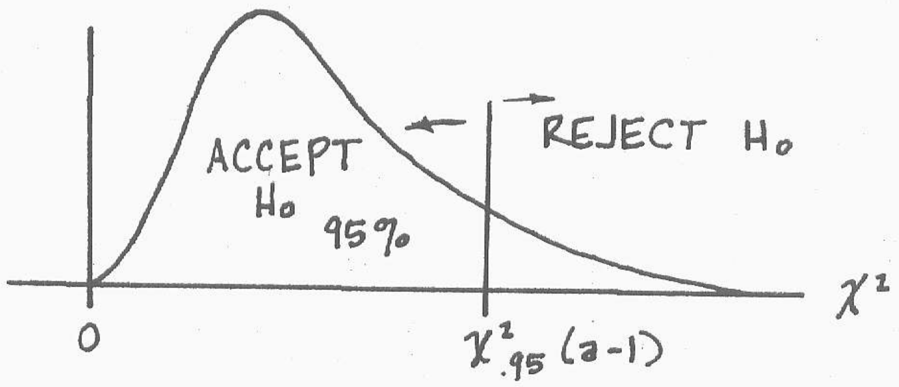


Figure 1.7.1 A Chi-square Distribution

The probability of a χ^2 larger than $\chi^2_{.95}(a-1)$ due to random chance alone is .05. Then the decision rule is reject H_0 (1.7.1) if $\chi^2_B > \chi^2_{.95}(a-1)$. An example of calculation is given in Table 1.7.1. This is a useful test to locate trouble within both experimental procedure as well as validation procedure. If applied to experimental methods, a decrease in experimental error variance due to refinements in technique can be measured. Control limits can then be set according to existing experimental accuracy. Large experimental error is then cause to discount validation conclusions for that particular experiment.

Validation procedures can be tested in an ad hoc fashion by the Bartlett test. If model comparisons are made which show consistent experimental error but another mode shows fluctuating error variances a source should be sought. For example keypunch errors in weather data. If one model is almost consistently the best model but significantly fails one experiment, and the Bartlett test indicates a difference in error variance, then perhaps model inputs are not consistent.

Table 1.7.1 Bartlett's Test Example

Given the following information about two example difference tables.

$$|\bar{X}_1| = 2.3948 \qquad |\bar{X}_2| = 1.8725$$

$$\bar{X}_1 = 2.1418 \qquad \bar{X}_2 = 1.6122$$

$$S_1 = 2.8330 \qquad S_2 = 2.2041$$

$$S_1^2 = 8.0259 \qquad S_2^2 = 4.8581$$

$$n_1 = 40 \qquad n_2 = 40$$

degree freedom $f_1 = (8-1)(5-1) = 28$ $\qquad f_2 = (8-1)(5-1) = 28$

$$H_o\colon \ \sigma_{e_1}^2 = \sigma_{e_2}^2$$

$$M = 2.3026 \left((\textstyle\sum_1 f_i) \log(\bar{S}^2) - \sum f_i \ \log S_i^2 \right) \qquad \bar{S}^2 = \frac{28(8.0259) + 28(4.8581)}{56}$$

$$= 2.3026 \ \{(56) \log (6.4420) - [28 \log (8.0259) + 28 \log (4.8581)]\}$$

$$= 6.4420$$

$$= 2.3026 \ [45.3051 - 44.5468]$$

$$= 2.3026 \ (.7583) = 1.7460$$

$$C = 1 + \frac{1}{3(a-1)} \left[\frac{1}{28} + \frac{1}{28} - \frac{1}{56}\right]$$

$$= \left[1 + \frac{1}{3} \left(\frac{1}{14} - \frac{1}{56}\right)\right] = 1.0179$$

$$\chi_B^2 = \frac{M}{C} = \frac{1.7460}{1.0179} = 1.7154 \qquad \chi_{.95}^2(1) = 3.8$$

Since $\chi_B^2 < \chi_+^2$; decision is to accept H_o.

The result might be to check weather data and grain conditions (weight, moisture, etc.) between models for consistency.

1.8 Experimental Method for Drying Model Validation

Natural aeration grain drying experiments are simple to conduct. However to assure that the proper data are collected for validation, certain design and equipment requirements should receive consideration. These criteria should provide complete and acceptable data for grain drying model validations.

1.8.1 Equipment

1. Bin with a sampling depth of at least five feet.
2. Thermocouples to record grain temperatures at the same depths being sampled by moisture probings
3. Fan designed for the particular range of airflows of interest, eg. 10-30 cfm/ft^2.
4. Accurate airflow measurement devices, e.g. a vane anemometer with reduction cone, to measure airflow accurately during the test.
5. Hygrothermograph to record the experimental weather data at the experimental site.
6. Grain probe and sampling funnel to facilitate handling of moisture samples. Grain samples from each probing should not be mixed.
7. A suitable air oven for official determination of moisture content of grain samples.

8. An alternative to number 2 and 5 should be a recording sensor in plenum chamber which measures dry bulb and dew point temperatures.
9. Truck scales to weigh incoming wet grain, fine material which is separated and dry grain which is sold.

1.8.2 Experimental Procedure

Upon filling

Freshly harvested grain should be cleaned, weighed and sampled for moisture content after loading into the bin. The depth of grain should be at least five feet to allow for five depth samples to be made. From the sample determine the moisture content, fine material, percent damage and test weight. Initial grain temperature should be recorded and then the fan turned on. The airflow should then be measured.

A 2,000 gram sample should be taken and allowed to dry to safe storage moisture content at room conditions. Each day the density of the 2,000 gram sample should be tested and recorded with the moisture content. These density fluctuations during drying are recorded to evaluate the amount of grain shrinkage during drying.

Duration of Test

Airflow rate should be monitored by recording plenum pressures. If the plenum pressure changes more than 5%, air flow should be measured. A sampling schedule should be designed to provide at least 8 to 10 observations during the drying period, (grain moisture > 15.5% wb). Sampling should be done approximately along two randomly selected diameters as shown in Figure 1.8.1. The location of the sampling locations are at r_1 and r_2 distances from the center of the bin. The radial distances are determined such that the areas A, B and C in Figure 1.8.1 are equal. $r_1 = .5774(R)$ and $r_2 = .8165(R)$ where R is the radius of the drying bin.

The grain samples taken at each of the five probe locations and at each depth should be placed in separate polyethylene bags to reduce moisture loss during transportation to the laboratory. Moisture content should be determined for each sample by ASAE oven moisture standards.

The benefit of these five replications within the same horizontal layer is to reduce our observational error (E_o) as discussed in Section 1.5.1 and 1.5.2. This data will yield information about the observed moisture (1.5.8). Recall that moisture content is known to depend upon sampling location according to equation 1.5.8. Data collection in this fashion will improve the analysis of variance by reducing the pure error (E_{ij}) term in the AOV Model I equation 1.5.17. The difference table would be formed in the same manner for each of the five locations. This would yield five replications at each depth and layer. This improves the estimate of the within cell variance and allows the next order interactions to be tested. The AOV Model I (1.5.17) would then become:

$$X_{ij} = T_i + D_j + TD_{ij} + E_{ijk} \qquad (1.8.1)$$

$i = 1, 2, \ldots nt$

$j = 1, 2, \ldots nd$

$k = 1, 2, \ldots nd$

X_{ij} = Moisture error (difference) at time i and depth j

The main effects are defined:

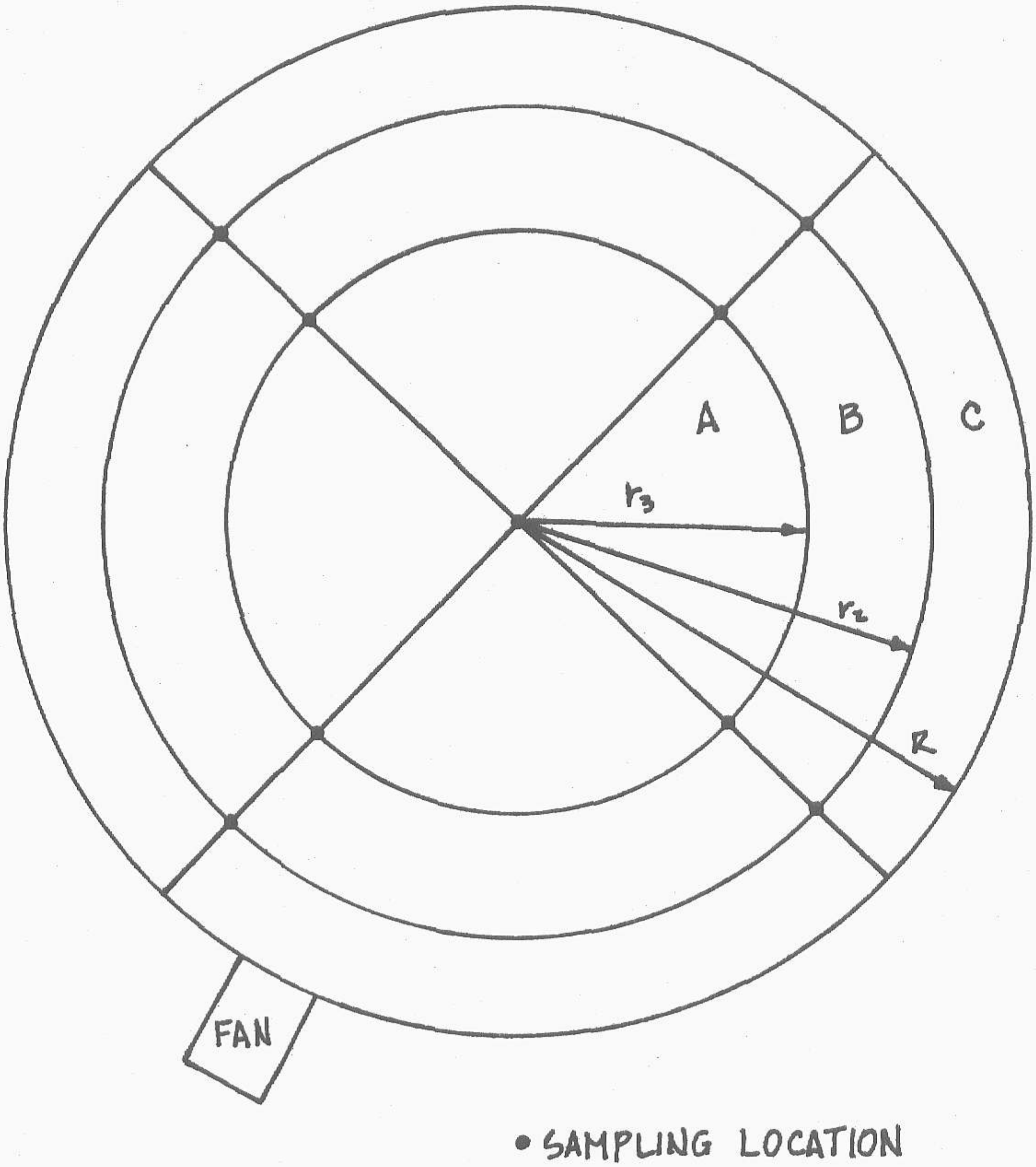


Figure 1.8.1 Sampling Pattern for Grain Drying Experiment

r_1 = .5774 x R   Areas A,B,C are equivalent.

r_2 = .8165 x R

R = Radius of bin

Main effects upon moisture error are defined:

M_i = Model i,

T_j = Drying time j,

D_k = Drying depth k.

The interactions between main components are defined:

MT_{ij} = Model i with time j for all depths,

MD_{ik} = Model i with depth k for all times,

TD_{jk} = Time j with depth k for all models,

MTD_{ijk} = Model i with time j with depth k for all replications.

E_{ijkl} = Random element independently sampled, which is assumed to be normally distributed with mean 0.0 and variance σ^2.

The dimensions of this AOV Model are:

nm = number of mathematical models for comparison,

nt = number of time levels,

nd = number of depth levels,

nr = number of replications across the drying bin.

Analysis of the replications across the bin allowing the A-A and B-B diameters of Figure 1.8 will indicate the magnitude of the components in the observation error E_o as stated in equation 1.5.2.

Completion of Test

A list of final measurements are as follows:

1. final grain sampling to determine moisture contents,
2. final airflow measurements,
3. final drying bed thickness,

4. final grain quality should be determined,
5. dry grain is unloaded and weighed.

1.8.3 Experimental Method Summary.

The benefit of moisture replications within a sampled layer are two fold. First the analysis of variance model error term (E_{ijk}) is reduced which increases the power of the F-test. The second benefit will be to determine if a layer within the model can be assumed to be uniform. If a wide variation exists and is measured then the model accuracy is simply determined by this limiting assumption. If we try to improve model accuracy by modifying equation 1.5.8 to approximate the form of equation 1.5.9 moisture replications are manditory.

1.9 Actual Experimental Methods

Natural air grain drying experiments were conducted at the grain Marketing Research Center (GMRC) USDA,ARS at Manhattan, Kansas. The results of these tests were supplied by the grain handling division, Mr. George Foster, Research Leader, and Mr. Harry Converse, Agricultural Engineer. A brief summary of initial experimental conditions is given in Table 1.9.1.

Equipment

1. 2-18 foot diameter bins and 2-15 foot diameter bins with false perforated flooring. (one natural and one solar supplemented). Two thermocouple cables per bin with recording potentiometers.
2. Sectioned grain probe whose schematic drawing is show in Figure 1.9.2.

3. Steinlite moisture meter and vacuum oven.
4. Rotary cleaner for removing fine material before loading bin.
5. Actual weather data supplied by the Kansas State University Agricultural Experiment Station Weather Data Library, Dr. Dean Bark, Meteorologist. Bark (74,75)

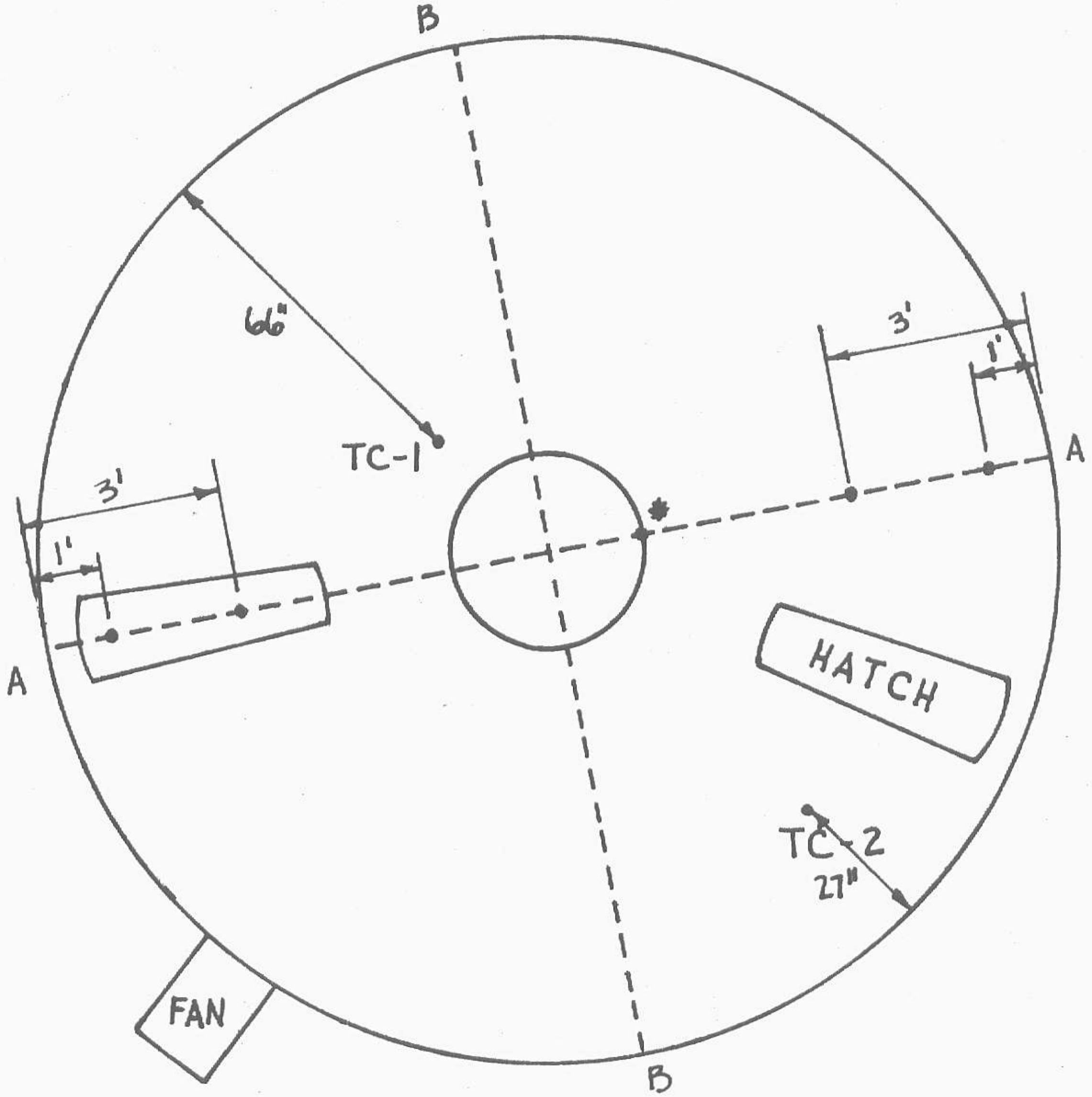
Experimental Procedure

Yellow dent corn was weighed in Wamego and brought to the GMRC by truck. The grain was cleaned prior to loading into the drying bins. The tare weight of the truck was measured, and grain weight was calculated, after subtracting the weight of screenings removed by cleaner. Moisture contents were measured during filling to equalize the moisture between the two test bins. A methyl-green stain test was performed to determine the percent kernel damage as defined by Steele(67).

After the bins were filled the grain was sampled according to the pattern in Figure 1.9.2 and the fans were started. Grain sampling was done on Monday, Wednesday and Friday with each of the five probe locations in depth combined with other samples taken at the same depth. This formed a composite sample of 250 grams to determine a Steinlite moisture content. Samples were placed in polyethylene bags to prevent moisture losses until measurements were taken. Occassional ASAE standard air oven moisture measurements were done to 'spot check' the Steinlite measurements. Actual test weather data and moisture measurements used during the computer analysis are listed in Appendix A as used for future reference.

Table 1.9.1 Experimental Drying Conditions

	1-N	1-S	2-N	2-S	3-N	3-S
	9-23-74 6 pm		9-24-75 5 pm		10-15-75 4 pm	
	480		279		216	
Grain Weight (lbs)	39,300.	36,570.	109,000.	110,000.	26,750.	27,750.
Total Airflow (cfm)	1774.	1520.	7365.	7626.	1949.	1780.
Moisture (w.b.)	22.6	22.6	21.97	23.81	22.94	23.52
Temperature (^oF)	70.5	69.6	74.7	74.6	74.2	72.5
Diameter (ft)	15.	15.	18.	18.	15.	15.

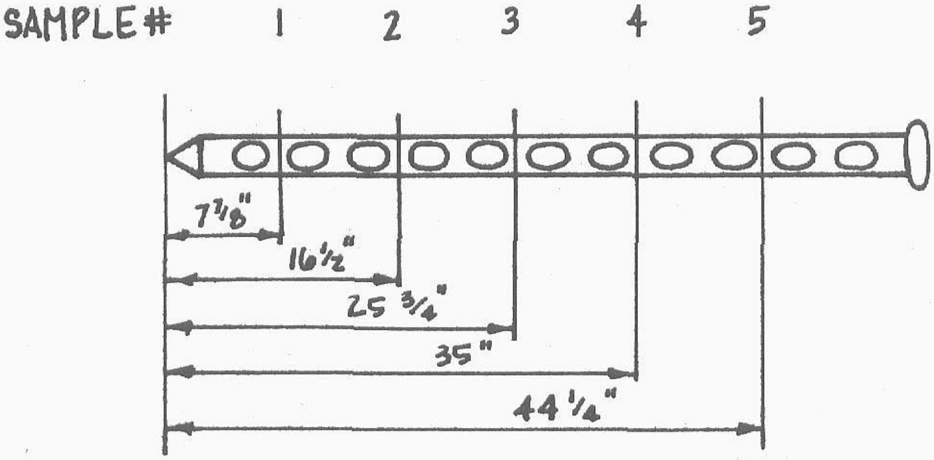


* CENTER SAMPLE MAY BE TAKEN ANYWHERE UNDER FILL HOLE

LAYOUT AND SAMPLING PATTERN - 15' ϕ BINS

Figure 1.9.1 Actual Sampling Pattern

Sampling Probe for Test #1-N and 1-S
1974



Sampling Probe for Tests #2-N, 2-S, 3-N, and 3-S
1975

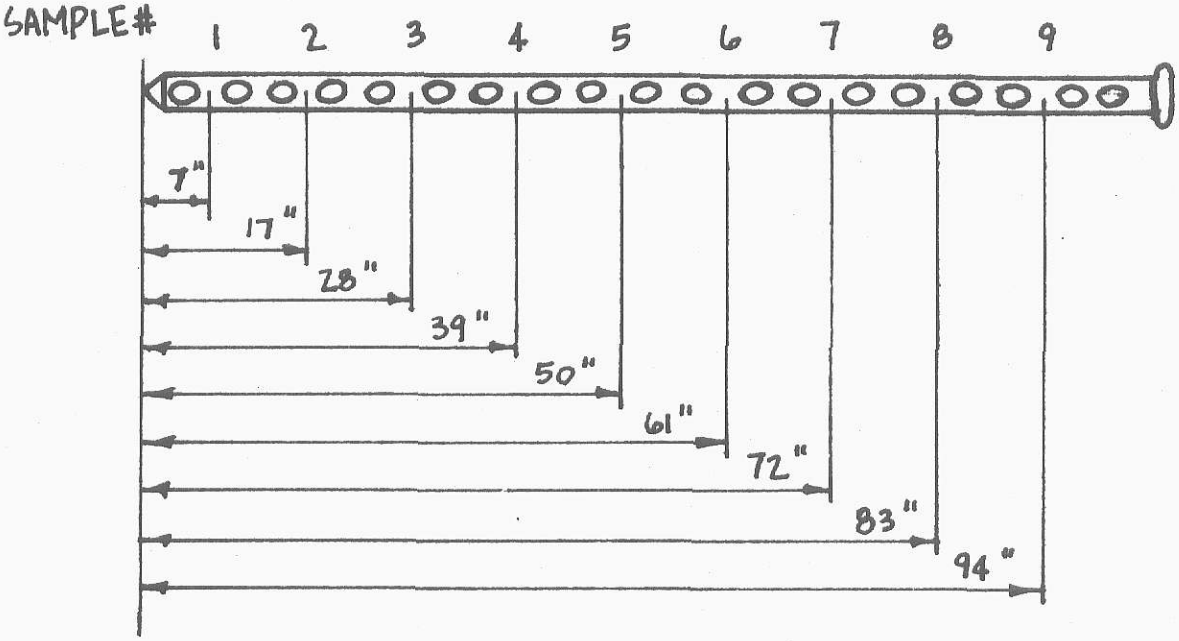


Figure 1.9.2 Sectioned Experimental Grain Probes used for Sampling During Drying Experiments.

1.10 Grain Shrinkage

Lorenzen(58) supplied five data points for change in testweight of yellow dent corn during drying. Spencer(72) recognized the effect of grain shrinkage in his modeling of drying of wheat in two foot beds. His function was found not to be applicable directly to corn drying studies. Foster(75) during the drying tests of 1975 recorded testweight fluctuations for corn during the drying experiments. The data from the above sources for corn is listed in Table 1.10.1. Regression Analysis of the data yielded a simple linear equation as being sufficient for density determinations. Quadratic and cubic polynomials were tested and not found to contribute significantly to the minimization of the error sum of squares. The following FORTRAN equation was determined to describe the density function:

$$\mathrm{DENSY} = 49.354 - 27{,}825 * \mathrm{MW} \tag{1.10.1}$$

MW = moisture (wb)

DENSY = density of wet grain ($\mathrm{lbs/ft^3}$)

The grain drying models all contain "thin layers" which are used to approximate fluctuations within the bed. These layers undergo shrinkage during drying with the result being a lower grain height in the bin after drying. The midpoint height of each layer is assumed to be the location of each predicted value. The height above the bin floor of each layer is calculated as the sum of thicknesses of the layers below it and one half the thickness of the measured layer. The thickness of each layer is calculated by:

$$\mathrm{THICK} = \frac{\mathrm{DW} \cdot (1 + \mathrm{MW})}{(\mathrm{AREA} \cdot \mathrm{DENSY})}$$

THICK = thickness (ft)

DW = dry weight

MW	DENSY	MW	DENSY
0.0730	47.00	0.1650	44.16
0.1247	46.32	0.1678	44.64
0.1255	46.24	0.1716	44.08
0.1263	46.24	0.1733	43.52
0.1266	46.16	0.1740	45.52
0.1267	45.12	0.1800	43.84
0.1269	45.68	0.1816	44.16
0.1275	45.04	0.1866	43.68
0.1275	46.16	0.1896	45.12
0.1280	46.40	0.1920	43.00
0.1291	45.12	0.1982	43.52
0.1291	45.96	0.1984	44.08
0.1300	46.00	0.1992	43.84
0.1304	45.76	0.1997	43.76
0.1312	45.44	0.2002	43.76
0.1336	45.20	0.2015	43.52
0.1339	45.12	0.2021	43.12
0.1395	45.68	0.2021	43.20
0.1435	44.80	0.2042	44.00
0.1470	45.44	0.2047	43.52
0.1490	45.44	0.2059	43.92
0.1515	45.44	0.2087	42.96
0.1530	45.76	0.2134	43.60
0.1533	45.36	0.2134	43.52
0.1535	45.44	0.2144	43.52
0.1560	45.36	0.2152	42.72
0.1573	45.80	0.2176	42.96
0.1590	44.96	0.2180	42.32
0.1593	45.20	0.2401	43.12
0.1600	45.03	0.2490	41.00
0.1620	45.00	0.2519	42.88
0.1630	45.20	0.2610	42.88
0.1637	45.36	0.2615	43.04

Table 1.10.1 Density Measurements of Yellow Dent Corn at Several Moisture Contents.

Courtesy Grain Marketing Research Center

MW = moisture wb decimal

AREA = area of bin floor (ft^2)

DENSY = density of wet grain (#/ft^3)

For the first series of tests it was seen that this equation gave a bed depth shrinkage of 6.4 inches which was consistent with the observed shrinkage. This grain shrinkage is a movement of the grain past the sensing location which are at fixed intervals. The model predicted depths will vary according to moisture content. The problem is that model predictions do not correspond to the observed locations.

One method of solving this problem is seen in Table 1.5.1, the model values which correspond as closely as possible were chosen for the predicted table. This method of choosing values contributes to the error of observation E_0 as discussed in section 1.5. The model is in effect penalized because its predictions can not be sampled from the actual locations for comparison.

An alternative would be to interpolate between model values to the point (time,depth) of observation. This would assume that the model surface in the neighborhood of the sampled point is smooth so that interpolation error is small. Figure 1.5.3 shows support of this assumption. "The two most common forms of the interpolating polynomial for arbitrarily spaced base points are, Newton's divided difference polynomial and Lagrange's interpolating polynomial", Carnahan(69). The Lagrangian method of interpolation was chosen because of the generality of the interpolating polynomial.

Our objective is the desired value y at an observed location x. The Lagrangian polynomial is:

$$y(x) = \prod_{i=\min}^{\min+d} L_i(x) y_i \qquad (1.10.2)$$

where

$$L_i(x) = \prod_{\substack{j=\min \\ j \neq i}}^{\min+d} \frac{(x - x_j)}{(x_i - x_j)} \qquad i = \min, \min+1, \ldots \min+d \qquad (1.10.3)$$

The order and spacing of the base points for this method is completely arbitrary. However if the base points are in ascending order and the points surround the desired value (x), the interpolation error is greatly minimized.

To use this method for our problem requires a two dimensional interpolation. This interpolation in two dimensions upon the third is performed one dimension at a time. For our particular application at each simulated time the moistures are interpolated to the appropriate depths as observed during probing. After all of the data has been interpolated in the depth dimension, it is interpolated in the time dimension. The result is shown for our example as Table 1.10.1 Notice that the model error indicated in Table 1.10.1 is significantly less than the error computed by matching layers given in Table 1.5.1.

A FORTRAN program (LAGRANGE) was written and verified to perform the interpolation of the model predictions and calculate the difference tables. The following modification to the interpolating equations 1.10.2 and 1.10.3 were made. The new equations used in LAGRANGE are given as

$$L_i(x) = \frac{C/(x - x_i)}{\prod_{j=\min}^{\min+d} (x_i - x_j)} \qquad i = \min, \min+1, \ldots, \min+d,\ x \neq x_i \tag{1.10.4}$$

where

$$C = \prod_{j=\min}^{\min+d} (x - x_j) \qquad j = \min, \min+1, \ldots, \min+d$$

This change represents a savings of d^2 multiplications and d^2 subtractions, at the expense of d+1 divisions. A complete source listing of the FORTRAN program LAGRANGE is given for reference in Appendix B.

1.11 Summary of Model Evaluation Procedure

Mathematical model validation methods from both agricultural and industrial engineering literature were combined to yield a proposed validation procedure. This method of validation assumes standard statistical models for data analysis. Therefore additional statistical theory development is not necessary, providing the stated assumptions are met.

To accurately compare model results with experimental results grain shrinkage was experimentally observed and incorporated into a functional relationship. This density equation allowed model determination of depths for each layer at each time interval. A two dimensional interpolation method was performed upon the data to yield appropriate values for comparison. This interpolation was shown to reduce the model error mean.

Accurate experimental measurements were found to be mandatory for model validation studies, however consistent moisture measurement methods were important for comparison of models.

Although the procedure is stated for moisture content throughout this chapter, grain temperature can be analyzed in exactly the same fashion. All tests and procedures hold for grain temperature with the model hypothesis being stated as a cooling model rather than a drying model.

1.12 Areas for Future Research

Improved airflow measurements are needed for grain drying research. Possible location of probing ports on the outside of deep bins would reduce sampling effort and minimize grain bed disturbance. Vertical sampling results in loose fill column of grain surrounding the probed location which results in an airflow chimney effect.

Application of a statistic such as Hay's(73) ω^2 which is analogous to the correlation coefficient, should be applied to all analysis of variance models. This ω^2 is interpreted to mean the proportion of the variation of the dependent variable (moisture error) explained by the desired independent variable (say depth or time). This would lead to efficient model refinement and retesting. This statistic was discovered too late to be successfully incorporated in this work. The author notes the benefit of this statistic and strongly suggests the reader locate the quoted reference.

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Chapter 2

EQUILIBRIUM MODELS

2.0 Introduction

Primary emphasis of current drying model research as been in two distinct areas. These areas of intensive study center around the equilibrium (static) model and the drying model (dynamic). This chapter is devoted to the equation development, computer adaptation and validation of current equilibrium models.

2.1 Literature Review

The equilibrium model was developed according to Thompson(72) for "... storage situations, or more specifically, low temperature, low airflow conditions." The equilibrium philosophy has developed from its inception by Bloome and Shove(71) to a refined set of equations and solution method proposed by Thompson(72). From Chapter One, we recall that the equilibrium model is one which displays the relationship between the system attributes when the system is static. Thompson(72) put forth this observation, "During ambient temperature aeration with low airflow rates, it appears that the air and the grain approach true equilibrium, especially when the drying time increment is one hour or more." Equilibrium can then be defined as the time where no further heat or mass transfer will take place. An equilibrium model is defined to be a group or system of equations which will allow a computer to calculate the static dependent variables over a given time span.

Three fundamental assumptions of equilibrium grain drying models are given for clarity.

1. Equilibrium of mass and heat content is obtained between the air and grain at the end of each time interval, Δt.
2. Heat transfer between the air and grain is adiabatic.
3. Total mass of the system of air and grain remains constant during each time interval, Δt.

The first model which incorporates these assumptions into a workable mathematical model was given by Bloome and Shove(71). This model was called a "Near Equilibrium Model", because equilibrium was approximated by the use of air and grain state points to determine the appropriate equations which apply. Because the solution method is not direct, equilibrium was only approximated.

Thompson(72) developed the first true equilibrium model. His equilibrium model incorporated the three assumptions of equilibrium into a time sequence to predict grain conditions with respect to time.

Alam(73) made an adaptation of the Bloome and Shove model to soybean drying. Experimental model validation was performed and the equilibrium model accuracy was apparently found to be unsatisfactory. Alam states, " . . . the soybean drying model predicts moisture profiles in the drying column quite similar to those experimentally observed. Several factors may be responsible for the disagreement that does occur, . . . A modification was made to the Model* it was assumed, . . . complete equilibrium was not reached in the first layers but might be reached in the final layers, . . ." The modification was stated as:

$$WI_{(j+1)} = WO_j \left(.98 + .02 \frac{j}{j_{max}}\right) \qquad j = 1,2, \ldots, j_{max}$$

$WI_{(j+1)}$ = Absolute humidity of air going into layer j + 1.

WO_j = Absolute humidity of air coming out of layer j.

j = The current layer of model calculation.

Alam(73) supports this modification by stating, "Several combinations from 95 to 99 percent were tried and 98 percent gave the best fit."

In this experiment the mass airflow rate was given as 5.13 cfm/ft^2 (ft/min). This would indicate that for soybeans, equilibrium models are not adequate for mass flow rates above 5.13 ft./min. A grain drying model should only be used within its range of application. Alam(73) determined that 5.13 ft./min. was an airflow rate which the equilibrium model could not handle. Thompson(72) stated that, "High grain to air ratios (lb. grain/lb. air) cause dynamic changes in the state point of the aerating air with minimal changes in the moisture content of the grain." Validation of equilibrium models can be stated as two important questions:

1) Within what range of air flow rates can the equilibrium model be validated as an accurate model?
2) How can the range of accuracy be widened?

2.2 Equilibrium Model EQ 1

An equilibrium model was coded for application in FORTRAN IV and debugged by Thompson(74). This FORTRAN program was courteously supplied by Dr. T. L. Thompson to the author and is included for reference in Appendix C. This equilibrium model will be referred to as EQ 1 throughout this study.

2.2.1 EQ 1 Equilibrium Equations

To give a background for understanding model behavior, the equations and assumptions of the model will be clearly defined for the calculations of a "thin layer" in equilibrium.

Heat Balance: Thompson(72) (2.2.1)

$$.24T_o + H_o(1060.8 + .45T_o) + CG_o + (H_f - H_o)(G_o - 32.) = .24T_f + H_f(1060.8 + .45T_f) + CT_f$$

(BTU/lb. dry air)

T_o = Initial air temperature (^oF)

T_f = Final air and grain temperature (^oF)

H_o, H_f = Initial and final air absolute humidity (lb. H_2O/lb. dry air)

C = Specific heat of grain (BTU/lb. wet grain)

G_o = Initial grain temperature (^oF)

Specific Heat Equation: Kazarian and Hall(65) (2.2.2)

$$C = (.35 + .00851 \cdot M_w)(R')$$

(BTU/lb. dry air . ^oF)

M_w = Grain moisture percent wb

R' = lb. wet grain/lb. dry air

Mass Balance Equation: Thompson(72) (2.2.3)

$$((M_o - M_f)/100) \cdot R) = (H_f - H_o)$$

(lb. H_2O/lb. dry air)

H_o, H_f = Initial, final absolute humidities (lb. H_2O/lb. dry air)

M_o, M_f = Initial, final grain moisture content percent db.

R = Dry grain-to-air ratio (lb. dry grain/lb. dry air)

Equilibrium Relative Humidity Equation: Thompson, Peart, and Foster(68) (2.2.4)

$$ERH = 1.0 - \exp(K(T_f + C)M_f^N)$$

(decimal)

ERH = Equilibrium relative humidity of air (decimal)

T_f = Final grain temperature (^oF)

M_f = Final moisture content (decimal db.)

Constants:

K = -3.82 E-05

C = 50.0

N = 2.0

Relative Humidity of Moist Air Equation: Brooker(67) (2.2.5)

$$RHA = \frac{(P_{atm} \cdot H_f)}{(.6219 + H_f) \cdot P_s} \qquad \frac{(psia)}{(psia)}$$

RHA = Relative Humidity of Moist Air (decimal)

P_{atm} = Pressure of atmosphere (psia)

H_f = Final absolute humidity of air (lb. H_2O/lb. dry air)

P_s = Saturation pressure of water vapor at T (psia)

Saturation Pressure Equation: Brooker(72) (2.2.6)

If $491.69 \leq T \leq 959.69$

$$P_s = R_o \exp[(A+BT+CT^2+DT^3+ET^4)/(FT+GT^2)] \quad \text{(psia)}$$

If $459.69 \leq T \leq 491.69$

$$P_s = \exp(23.3924 - \frac{11286.65}{T} - .46075 \ln(T)) \text{ (psia)} \tag{2.2.7}$$

P_s = Saturation pressure at temperature T (psia)

R_o = Universal gas constants = (3206.1822 ft.-lb.)

T = Absolute temperature (^oR)

Constants:

A = -.274055 E 05

B = .541896 E 02

C = -.451370 E -01

D = .215321 E -04

E = -.462027 E -08

F - .241613 E 01

G - -.121547 E -02

Double precision constants are given in Brooker et.al(74).

Measure of Equilibrium Equation: Thompson(72)

$$ERH - RH_{air} = EPS \tag{2.2.8}$$

ERH = Equilibrium relative humidity of air

RH_{air} = Relative humidity of air

EPS = Epsilon, small acceptable value close to zero

2.2.2 Discussion of Equations:

The heat balance Equation 2.2.1 simply states that the initial heat content of the system is equal to the final heat content. To define heat content, a reference temperature of $32^{\circ}F$ is assumed. The first two components of the left and right hand side represent the total heat content of moist air. The first is the heat content of dry air above $32^{\circ}F$, Henderson(68). And the second is the heat content of water vapor within the air above $32^{\circ}F$, Henderson(68).

The third component of the left and right hand side is the total heat content of wet grain expressed in consistent units of BTU/lb. dry air. Since some small amount of drying will take place during the time period, the moisture content of the grain will decrease and the specific heat will decrease. The fourth component on the left hand side of the heat balance is this difference in heat content since the same specific heat (C) is used on both sides of the equation.

Equation 2.2.2 was originally published by Kazarian and Hall(65). This equation is modified to yield units which are consistent with equation 2.2.1.

Equation 2.2.3 is the statement of the third equilibrium assumption, conservation of mass. This equation is interpreted to mean the initial total mass of the system is equal to the final total mass. The units of this equation are lb. H_2O/lb. dry air.

Equation 2.2.4 is an equilibrium relative humidity equation given by Henderson(52), and modified by Thompson, Peart and Foster(68). This modified equation assumes that absolute zero is $-50^{\circ}F$ for absorbed water.

Equation 2.2.5 is the psychrometric equation relating relative humidity of the air to temperature and absolute humidity. This equation was published in Brooker(67). Equations 2.2.6 and 2.2.7 are spline-function definitions of saturation pressure (psia) for absolute temperature (^{O}R).

Equation 2.2.8 is an equation which indicates how nearly the two estimates of relative humidity correspond. When the difference of these two values is less than an arbitrarily small number (epsilon) equilibrium has been achieved.

2.2.3 Solution Method

Thompson(72) states, "The system of equations just presented can be reduced to simplest form consisting of three equations and three unknowns. Direct solution of these equations is not easily obtained, but with a search technique a rapid approximation is found." This solution method is discussed in Chapter One of Crandall(56), "Equilibrium Problems in Systems with a Finite Number of Degrees of Freedom." The solution procedure is called, "iteration by single steps". The algorithm is given as follows:

1. Estimate the final humidity of the air (H_f).
   This can be effectively done by letting $H_f = H_o$.
2. Solve the heat balance (2.2.1) for T_f.
3. Solve the mass balance (2.2.3) for M_f.
4. Solve equilibrium relative humidity equation (2.2.4) for EHR.
5. Solve equation 2.2.5 for RH_{air}.
6. Evaluate equation 2.2.8. If the difference is greater than Epsilon, use the search technique developed by Thompson and Peart(68) to estimate a better H_f and return to Step 2.

7. If the evaluated difference of Step 6 is smaller than Epsilon, then equilibrium conditions have been achieved, and are T_f, H_f, M_f and ERH. Now go to the next layer for solution.

2.2.4 Assumptions and Application

The assumptions of the EQ 1 model as stated in Thompson(72) are:

1. True equilibrium is achieved between the air and the grain for the drying time interval.
2. The law of conservation of mass and energy is observed.
3. No hysteresis exists between the desorption and absorption isotherms.

When a mathematical model is coded for analysis on a digital computer, additional assumptions are made. These assumptions are made to decrease the programming effort. The simplifying assumptions are two-fold in nature. They tend to limit either the precision of equilibrium calculation or the physical configuration the drying system is allowed to assume.

The assumptions which would directly affect the accuracy of the equilibrium approximation are as follows:

1. The drying bin is assumed to be air-tight and the exhaust air from one layer is input to the next layer,
2. Input air to the first layer is that specified by the input weather data, with the possibility of adding small amounts of artificial heat. This data must be dry bulb and dewpoint temperature,
3. A three-hour time interval will insure that equilibrium is actually achieved,

4. The atmospheric pressure is assumed to be sea level pressure (P_{atm} = 14.696 psia),
5. Twelve "thin layers" normal to airflow (cross flow) are adequate to insure model accuracy,
6. The heat produced within the grain during a time interval is equal to the heat of combustion of the amount of dry matter loss incurred during the time period,
7. The water produced by combustion is assumed to be in liquid form within the kernel, and therefore increases the moisture content.

The assumptions which tend to limit the range of model applicability are:

1. The stored grain is assumed to be yellow dent corn,
2. The grain is loaded in the bin and aeration started immediately,
3. All yellow dent corn is assumed to have 30% mechanical damage as defined by Steele and Saul(69),
4. Dry matter loss can be accurately predicted and is a good indicator of corn quality, Steele(67),
5. Dry matter loss is used to indicate drying system success for storage comparisons.

The equations for dry matter loss which are taken from Steele(67) are given in FORTRAN as follows:

$$DML_i = 0.0883*(\exp(.006*EQST_i) - 1) + 0.00102\text{-}EQST_i \qquad (2.3.1)$$

$$EQST_i = \sum_{j=1}^{i} N*TINC/(M_{M_j} \cdot M_{T_j} \cdot M_D) \qquad (2.3.2)$$

Moisture multiplier (M_{M_j}): for $13 \leq M_{wb_j} \leq 35$

$$M_{M_j} = 0.103 * (EXP(455./M_{db_j} ** 1.53) - 0.00845 * M_{db_j} + 1.558) \qquad (2.3.3)$$

Temperature Multiplier (M_{T_j}): for $T_{G_j} \leq 60\ ^oF$ or $M_{wb_j} \leq 19\%$

$$M_{T_j} = 32.3 * EXP(-3.48 * (T_{G_j}/60.)) \qquad (2.3.4)$$

If $T_{g_j} > 60\ ^oF$ and $19\% < M_{wb_j} \leq 28\%$

$$M_{T_j} = 32.3 * EXP(-3.48 * (T_{G_j}/60.)) + (M_{wb_j}-19.)/100. * EXP(0.61 * ((T_{G_j}-60.)/60.)) \qquad (2.3.5)$$

If $T_{G_j} > 60\ ^oF$ and $M_{wb_j} > 28\%$

$$M_{T_j} = 32.3 * EXP(-3.48 * (T_{G_j}/60.)) + .09 * EXP(0.61 * ((T_{G_j}-60.)/60.)) \qquad (2.3.6)$$

Damage Multiplier (M_D):

$$M_D = 2.08 \exp (-0.0239 \cdot PD) \qquad (2.3.7)$$

Saul(70) reported that the temperature multiplier at low temperature was more closely approximated by:

for $T_{G_j} \leq 60\ ^oF$

$$M_{T_j} = 128.76 * EXP(-4.68 * (T_{G_j}/60.)) \qquad (2.3.8)$$

DML_i = Total dry matter loss up to time i (percent)

$EQST_i$ = Equivalent storage time from time equals 1 to i (hours)

NTINC = Time increment of drying model (hours)

M_{M_j} = Moisture multiplier for time j

M_{T_j} = Temperature multiplier for time j

M_D = Damage multiplier

M_{db_j} = Grain moisture percent dry basis at time j

M_{wb_j} = Grain moisture percent wet basis at time j

T_{G_j} = Grain temperature (^{o}F) at time j

PD = Percent kernel damage as defined in Steele(67).

2.2.5 Hysteresis EQ 2

Recall that the third assumption listed by Thompson(72) was that EQ 1 assumes no hysteresis exists between absorption and desorption isotherms. Thompson(74) has coded an option into the EQ 1 model which allows hysteresis to be modeled. This option, in effect, creates a new model for natural aeration, and this new model will be included in the validation study. For convenience this model will be referred to as EQ 2.

Thompson(74) gave a FORTRAN listing of EQ 1 with EQ 2 option which is given as used in Appendix C.

2.3 Equilibrium Model Validation

2.3.1 Validation with Test 1-N

During the Fall of 1974, model validation experiments were conducted at the Grain Marketing Research Center. The EQ 1 model was obtained and modifications were made to allow the model output to be analyzed by program LAGRANGE. Great care was taken to insure that no alteration in the original calculational method or data storages was made. These modifications were made by the addition of the subroutine OUTPUT, which is also given in Appeindix C.

Experimental data from Test 1-N was used extensively throughout the Winter of 1974 to test the validation of the EQ 1, EQ 2 models and debug the OUTPUT and LAGRANGIAN programs.

The validation procedure outlined in Section 1.5 was applied to Test 1-N using models EQ 1 and EQ 2. Tables 2.3.1 and 2.3.2 show the actual values, model (EQ 1 or EQ 2) predicted and the differenced tables. Table 2.3.3 shows the results of the AOV Model II. We can accept H_o: $M_1 = M_2$ that the two models are equivalent. Forming the t statistic for Model 1 gives $t_c = 4.63$. We conclude that neither model is adequate or accurate for Test 1-N.

The analysis of variance procedure assumes that the difference tables are normally distributed. Several tests can be performed based on the hypothesis H_o: X_{i_j} are normally distributed. The AARDVARK package performs these tests with the results summarized in Table 2.3.4 with normality of data being accepted as sufficiently close for the analysis of variance technique 2.3.2 discussion.

We have concluded that although EQ 1 appears to be the best model, a significant difference between models could not be detected. It was also found that EQ 1 could not be stated as an adequate model for the validation test 1-N. We observe in the difference table that overdrying occurs along the drying zone. The model has predicted the top layer (44.25 inches) is dry ($M_M = 11.7\%$) at time = 332 hours, however the actual moisture measurements indicate $M_A = 14.23$ at 480 hours. This is a time difference of 148 hours which is a 31% relative error. To visualize the behavior of this model, the reader is referred

Table 2.3.1 EQ 1 with Test 1-N Validation Results

```
       ACTUAL GRAIN MOISTURE CONTENTS   TEST 1-N

          7.88     16.50     25.75     35.00     44.25
      ------------------------------------------------
 44.|   0.2153    0.2256    0.2211    0.2173    0.2167
 92.|   0.1675    0.2249    0.2220    0.2210    0.2190
161.|   0.1265    0.1695    0.2160    0.2165    0.2138
213.|   0.1220    0.1468    0.1868    0.2133    0.2120      ACTUAL
260.|   0.1293    0.1430    0.1638    0.2035    0.2168
332.|   0.1360    0.1362    0.1558    0.1587    0.1694
382.|   0.1408    0.1405    0.1445    0.1584    0.1657
480.|   0.1466    0.1406    0.1411    0.1447    0.1423
```

```
       MODEL EQ 1 VERIFICATION STUDY   TEST 1-N

          7.88     16.50     25.75     35.00     44.25
      ------------------------------------------------
 44.|   0.2008    0.2209    0.2214    0.2213    0.2214
 92.|   0.1396    0.2037    0.2230    0.2236    0.2232
161.|   0.0939    0.1264    0.1953    0.2176    0.2181
213.|   0.1037    0.1004    0.1233    0.1996    0.2173      PREDICTED
260.|   0.1271    0.1172    0.1107    0.1227    0.2002
332.|   0.1458    0.1377    0.1277    0.1204    0.1173
382.|   0.1474    0.1429    0.1398    0.1338    0.1274
480.|   0.1510    0.1372    0.1320    0.1350    0.1387
```

```
MODEL  EQ 1  (ACTUAL - PREDICTED) IN PERCENT WET BASIS TEST 1-N

          7.88     16.50     25.75     35.00     44.25
      ------------------------------------------------
 44.|     1.45      0.47     -0.03     -0.40     -0.47
 92.|     2.79      2.12     -0.10     -0.26     -0.42
161.|     3.26      4.31      2.07     -0.11     -0.43
213.|     1.83      4.64      6.35      1.37     -0.53      DIFFERENCE
260.|     0.22      2.58      5.31      8.08      1.66
332.|    -0.98     -0.15      2.81      3.83      5.21
382.|    -0.66     -0.24      0.47      2.46      3.83
480.|    -0.44      0.34      0.91      0.97      0.36

      MEAN ABSOLUTE DEVIATION =          1.8725 ×

               MEAN DEVIATION =          1.6122

           STANDARD DEVIATION =          2.2041
```

Table 2.3.2 EQ 2 with Test 1-N Validation Results

Actual Grain Moisture Contents Test 1-N

	7.88	16.50	25.75	35.00	44.25	
44.	0.2153	0.2256	0.2211	0.2173	0.2167	
92.	0.1675	0.2249	0.2220	0.2210	0.2190	
161.	0.1265	0.1695	0.2160	0.2165	0.2138	
213.	0.1220	0.1468	0.1868	0.2133	0.2120	ACTUAL
260.	0.1293	0.1430	0.1638	0.2035	0.2168	
332.	0.1360	0.1362	0.1558	0.1587	0.1694	
382.	0.1408	0.1405	0.1445	0.1584	0.1657	
480.	0.1466	0.1406	0.1411	0.1447	0.1423	

Model EQ 2 Verification Study Test 1-N

	7.88	16.50	25.75	35.00	44.25	
44.	0.2030	0.2209	0.2215	0.2213	0.2211	
92.	0.1417	0.2053	0.2231	0.2241	0.2229	
161.	0.0943	0.1272	0.1975	0.2176	0.2179	
213.	0.0945	0.1016	0.1304	0.2015	0.2169	PREDICTED
260.	0.1133	0.1043	0.1170	0.1385	0.2065	
332.	0.1338	0.1214	0.1167	0.1203	0.1289	
382.	0.1353	0.1289	0.1237	9.1221	0.1282	
480.	0.1372	0.1282	0.1269	0.1252	0.1249	

Model EQ 2 (Actual - Predicted) in Percent Wet Basis Test 1-N

	7.88	16.50	25.75	35.00	44.25	
44.	1.23	0.47	-0.04	-0.40	-0.44	
92.	2.58	1.96	-0.11	-0.31	-0.39	
161.	3.22	4.23	1.85	-0.11	-0.41	
213.	2.75	4.52	5.64	1.18	-0.49	DIFFERENCE
260.	1.60	3.87	4.68	6.50	1.03	
332.	0.22	1.48	3.91	3.84	4.05	
382.	0.55	1.16	2.08	3.63	3.75	
480.	0.94	1.24	1.42	1.95	1.74	

MEAN ABSOLUTE DEVIATION = 2.0486

MEAN DEVIATION = 1.9135

STANDARD DEVIATION = 1.8638

Table 2.3.3 Analysis of Variance Table for AOV Model II

Source	SS	DF	MS	F	Alpha Hat ($\hat{\alpha}$)
M	1.67	1	1.67	.51	.4763
T	87.54	7	12.51	3.84	.0014**
D	17.14	4	4.28	1.32	.2729
Error	218.10	67	3.26		
Total	324.45	79			

[**] Significant at .99 confidence level.

Table 2.3.4 Tests for Normality

H_{o_1}: $X_{ij} \sim N(\bar{\bar{E}}_M, \sigma^2)$

KURTOSIS

H_{o_2} KURTOSIS = 3.0

STAT = 3.1556 Alpha Hat > .10

Decision Accept H_{o_2}

SKEWNESS

H_{o_3} SKEWNESS = 0.0

STAT = .8678 Alpha Hat = .02

Decision Reject H_{o_3}

BARTLETT'S TEST

H_{o_4}: $\sigma^2 = \sigma^2 = \ldots = \sigma^2$

$X_B^2 = 1.0033$ d.f. = 1 Alpha Hat = .3165

Decision Accept H_{o_4}.

Final decision is to accept H_{o_1} although some skewness is present.

The analysis of variance technique is still sensitive.

to the example three dimensional surface in Chapter 1, Figure 1.5.6. This example surface is made using the data from the validation of EQ 1 with test 1-N. Model overdrying and rewetting can be seen to be exaggerated representations of the actual results. The large ridge moving along the diagonal of the difference table is representing the overdrying by the model within the "drying zone".

2.3.2 Conclusions

Since neither model was accepted as adequate, modeling assumptions should be reviewed. Areas of model improvement should be investigated to determine the largest limiting factor. Refinement of the equilibrium model with respect to the limiting factor should measureably improve model accuracy.

2.4 Development of a Revised Equilibrium Model (EQ 3)

At this point, there were two possible directions of work, either assume that the equilibrium theory is applicable and revise the current equilibrium model to improve accuracy or develop a new theoretical model with fewer limiting assumptions, hoping to improve accuracy. Modification was chosen as the desired alternative, because an equilibrium model was available for modification and equilibrium model accuracy could not be accepted or rejected with the limited test data available. For convenience, the revised equilibrium model will be referred to as EQ 3.

The main objectives for modification of equilibrium model are,

1. the model must be computationally efficient,
2. the model must be easily understood and maintained by a second party,
3. the revised model (EQ 3) should be statistically more accurate according to H_0 (1.6.1), AOV Model II (1.6.2).

2.4.1 Assumptions

The three basic assumptions of the theoretical equilibrium model (see section 2.1) are the fundamental basis for the revised equilibrium model. The assumption for the revised model which directly affect the calculational accuracy are stated:

A.1 Equilibrium of heat and mass transfer is obtained for <u>each</u> modeled layer at each time increment.

A.2 Equilibrium relative humidity (ERH) of the grain is more accurately described by the Chung-Pfost (67) ERH Equation 2.4.3.

A.3 The drying bin is air tight, with exhaust air from one layer being input to the next layer.

A.4 Time intervals of 1,2,3, or 4 hours will be available for accuracy determinations.

A.5 Input air to the first layer is supplied as weather data with the possibility of adding small amounts of artifical heat. This weather data should be easily measured in the developing countries such as dry bulb and relative humidity.

A.6 Atmospheric pressure is supplied as weather data or the desired model altitude is given.

A.7 The thickness of the "thin layers" is controlled for optimum accuracy with the number of thin layers being variable.

A.8 The heat produced within the grain mass is equal to the heat of combustion of the amount of dry matter loss incured within the time period.

The following assumptions are those which will tend to limit the applicability of the revised model.

A.9 The stored grain to be dried is assumed to be one of the following grains: yellow dent corn, rough rice, grain sorghum, soybean, millet, chick pea, sesame, ground nut in pod and wheat. An array is provided to store emperical constants for each of these.

A.10 Wet grain is loaded into the bin and after a possible delay aeration is started.

A.11 Mechanical damage as defined by Steele(69) is measured and given as input data.

A.12 Dry matter loss can be accurately predicted and is a good indicator of corn quality. Steele(67), Equations 2.3.1 - 2.3.8.

A.13 Of the grains in Part 1, corn is felt to be the most deterioration prone. If the stored grain is dryed before corn would have deteriorated the system is termed successful.

A.14 Grain within the bin is homogeneous, and can be represented by one square foot column composed of thin layers.

2.4.2 Equations for the Revised Equilibrium Model

To aid in the understanding and maintenance of the computer program by a second party, equations were formulated in a consistent manner. However, the equations on dry matter loss in Section 2.3 by Steele(67) have not been modified.

The modeled grain drying system will be thought of as a one-foot square column of grain composed of several layers Δh thick. Each layer is represented by Figure 2.4.1 with the final attributes calculated at the end of the time interval. These final conditions of the air are then initial air conditions for the next layer above in the bin. Each equation is consistent with a square foot and time increment (NTINC) as units. The left hand side of the mass and energy balances represent the initial system and the right hand side represent the equilibrium condition at the end of the time period. Although the system as shown in Figure 2.4.1 contains three unknowns in simplest form, our system will utilize four unknowns as listed with relative humidity being a known mathematical degeneracy. Since we have four unknowns we must have four equations for equilibrium solution.

Heat Balance Equation: Thompson(72); Treybal(55)

$$\begin{aligned} &.24(\mathrm{ALB})\mathrm{TO} + \mathrm{ALB}(\mathrm{HO})(1060.8 + .45 \cdot \mathrm{TO}) \\ &\quad + \mathrm{GLB}(\mathrm{MO} + 1.)\cdot[.35 + .851(\tfrac{\mathrm{MO}}{1+\mathrm{M})}) \cdot \mathrm{TG}] \quad = \\ &.25(\mathrm{ALB})\mathrm{TE} + \mathrm{ALB}(\mathrm{HE})(1060.8 + .45\ \mathrm{TE}) \\ &\quad + \mathrm{GLB}(\mathrm{ME} + 1.)\cdot[.35 + .851(\tfrac{\mathrm{ME}}{1+\mathrm{ME}}) \cdot \mathrm{TE}] \end{aligned} \qquad (2.4.1)$$

This equation has a reference temperature of 32°F and units of $(\mathrm{BTU/ft}^2 \cdot \mathrm{NTINC})$.

These equations are presented with variables as they are used in the FORTRAN application of this model to aid in program understanding.

ALB = Pounds of dry air per ft^2 · NTINC
GLB = Pounds of dry grain per ft^2 · NTINC · layer
NTINC = Time increment (integer hours)
T0 = Initial air temperature ($^{\circ}$F)
TG = Initial grain temperature ($^{\circ}$F)
M0,ME = Initial and equilibrium grain moisture content decible db.
TE = Equilibrium air and grain temperature $^{\circ}$F
H0,HE = Initial and equilibrium absolute humidity of the air
(lbs H_2O/lbs dry air)

This equation is basically the same as 2.2.1 except for the conversion of units and that the specific heat of the corn, Kazarian and Hall(65), is explicitly in the equation and varies from the initial moisture content to the final moisture content. Moisture dry basis replaces wet basis in the specific heat equation and is used exclusively in the equilibrium equations.

Mass Balance Equation: Treybal(55)

$$ALB(HO) + GLB(MO) = ALB(HE) + GLB(ME) \qquad (2.4.2)$$

The units of this equation are (pounds of H_2O/ft^2 NTINC). This equation states that mass is conserved within the system during a given time increment.

Equilibrium Relative Humidity Equation: Chung(66)

$$Ln(ERH) = \frac{PA}{R(TE+PC)} \exp(-PB \cdot ME) \qquad (2.4.3)$$

ERH = Equilibrium relative humidity decimal

PA,PB,PC = Fitted constants for a particular grain

R = Universal gas constant 1.987 (KCAL/KMOL$\cdot^{o}$K)

PA = 1110.4268

PB = 16.9534

PC = 21.8947

The Chung-Pfost(67) equilibrium relative humidity equation was chosen because it was felt to be more accurate in predicting ERH and the derivatives of this equation are easily calculated.

Absolute Humidity of Moist Air Equation: Brooker(67)

$$HE = \frac{.6219 * (ERH * PS)}{ATM - (ERH * PS)} \qquad (2.4.4)$$

The units of this equation are lbs. H_2O/lbs dry air.

PS = Saturation pressure of water vapor at temperature TE (psia)

ATM = Atmospheric pressure (psia)

This equation can be said to be the redundancy equation of our theoretical system of four equations 2.4.1 - 2.4.4 and four unknowns, TE, HE, ME, ERH. The equilibrium point is therefore defined to be the particular TE, HE, ME, ERH which satisfy equations 2.4.1 through 2.4.4 simultaneously given TO, HO, MO, RHA, TG, ALB, GLB, and ATM.

2.4.3 Solution Method (Newton - Raphson)

Simultaneous solution methods for nonlinear, well-behaved equations have been proposed in great numbers in the operations research literature.

The desired solution method should satisfy the following requirements:

1. The technique should be well-known and documented in the literature.
2. The procedure should be an efficient algorithm with rapid convergence assured but insensitive to initial values (guesses).

Newton-Raphson Method:

The solution of one equation in one unknown is very common in the literature (Carnahan et al (69), Haming(71), Pennington(70), James et al (67)). This method is efficient for smooth monotonic functions whose first derivative is continuous. The method is self-correcting for poor initial approximations. The Newton-Raphson method can be derived for systems with two or more degrees of freedom in one of two ways:

1. Expanding a Taylor series (Milne(49)),
2. Application of the relaxation method to solution of non-linear equations (Crandal(56)).

For brevity, I will show the extension into the Taylor series expansion given in Milne(49). We assume two non-linear equations in two unknowns:

$$F(x,y) = 0 \qquad G(x,y) = 0 \tag{2.4.5}$$

If some point (x_i,y_i) is determined to be an initial estimate of the solution, a closer point (x_{i+1},y_{i+1}) can be obtained as follows:

$$\text{Let } x_{i+1} - x_i = \Delta x \text{ and } y_{i+1} - y_i = \Delta y \tag{2.4.6}$$

Let F(x,y) and G(x,y) be expanded in Taylor's series and assume (x_{i+1},y_{i+1}) is a solution, i.e. $F(x_{i+1},y_{i+1}) = G(x_{i+1},y_{i+1}) = 0$.

Then we obtain:

$$0 = F(x_i,y_i) + \frac{\partial F(x,y)}{\partial x}\bigg|_{x_iy_i} \Delta x + \frac{\partial F(x,y)}{\partial y}\bigg|_{x_iy_i} \Delta y + \ldots \qquad (2.4.7)$$

$$0 = G(x_i,y_i) + \frac{\partial G(x,y)}{\partial x}\bigg|_{x_iy_i} \Delta x + \frac{\partial G(x,y)}{\partial y}\bigg|_{x_iy_i} \Delta y + \ldots \qquad (2.4.8)$$

Assuming that the second and higher order derivatives are small and can be neglected, we solve equations 2.4.7 and 2.4.8 for Δx and Δy.

Let J represent the Jacobian Matrix of partial derivatives and F and G represent the two functions, all evaluated at the current solution value (x_iy_i).

$$[J] = \begin{pmatrix} \frac{\partial F}{\partial x} & \frac{\partial F}{\partial y} \\ \frac{\partial G}{\partial x} & \frac{\partial G}{\partial y} \end{pmatrix}\Bigg|_{(x_iy_i)} \qquad (2.4.9)$$

$$F = F(x,y) \quad \text{and} \quad G = G(x,y) \qquad (2.4.10)$$

Then the equations 2.4.7 and 2.4.8 can be stated in matrix notation as:

$$[J] \cdot \begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} = - \begin{pmatrix} F \\ G \end{pmatrix} \qquad (2.4.11)$$

Solving 2.4.11 for Δx and Δy yields:

$$\begin{pmatrix}\Delta x\\ \Delta y\end{pmatrix} = -\,[J]^{-1} \times \begin{pmatrix}F\\ G\end{pmatrix} \tag{2.4.12}$$

Substituting back into equations (2.4.6) yields the following in matrix form:

$$\begin{pmatrix}x\\ y\end{pmatrix}_{i+1} = \begin{pmatrix}x\\ y\end{pmatrix}_{i} + \begin{pmatrix}\Delta x\\ \Delta y\end{pmatrix} \tag{2.4.13}$$

The new approximations to the solution can then be stated as the following recursion formulas:

$$x_{i+1} = x_i + \Delta x \tag{2.4.14}$$

$$y_{i+1} = y_i + \Delta y \tag{2.4.15}$$

Equations 2.4.9 and 2.4.10 are recursive formulas for successively correcting the current estimate of the solution (x_i, y_i) to obtain an improved estimate (x_{i+1}, y_{i+1}) as stated by Crandal(56).

For convenience, consistency and clarity of definition, the FØRTRAN variables which apply to the Newton Raphson solution are defined as follows:

$$\text{The Column Vector } \begin{pmatrix}F(1)\\ F(2)\\ F(3)\\ F(4)\end{pmatrix}\Bigg|_{\substack{EQ(1),\ EQ(2)\\ EQ(3),\ EQ(4)}} \text{ is analogous to } \begin{pmatrix}F\\ G\end{pmatrix}\Bigg|_{x_i y_i} \text{ in equation} \quad (2.4.10)$$

$$\text{The Column Vector } \begin{pmatrix} \text{Delta (1)} \\ \text{Delta (2)} \\ \text{Delta (3)} \\ \text{Delta (4)} \end{pmatrix} \begin{matrix} \text{is analogous} \\ \text{to} \end{matrix} \begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} \text{ of equation} \qquad (2.4.12)$$

$$\text{The Matrix } \left. \begin{pmatrix} A(1,1) & A(1,2) & A(1,3) & A(1,4) \\ A(2,1) & A(2,2) & A(2,3) & A(2,4) \\ A(3,1) & A(3,2) & A(3,3) & A(3,4) \\ A(4,1) & A(4,2) & A(4,3) & A(4,4) \end{pmatrix} \right|_{\substack{EQ(1),\ EQ(2) \\ EQ(3),\ EQ(4)}}$$

is analogous to the

Jacobian Matrix [J] of Equation 2.4.9

A more helpful definition of the general term of our Jacobian matrix is:

$$A(I,K) \Bigg|_{\substack{EQ(1),\ EQ(2) \\ EQ(3),\ EQ(4)}} = \frac{\partial F(I)}{\partial EQ(K)} \Bigg|_{\substack{EQ(1),\ EQ(2) \\ EQ(3),\ EQ(4)}} \qquad (2.4.16)$$

The current column vector of solutions:

$$\begin{pmatrix} EQ(1) \\ EQ(2) \\ EQ(3) \\ EQ(4) \end{pmatrix} = \begin{pmatrix} TE \\ HE \\ ME \\ ERH \end{pmatrix} \text{ is analogous to } \begin{pmatrix} x_i \\ y_i \end{pmatrix} \text{ of equation (2.4.13)}$$

The equation for each successive correction (Δx) given by equation 2.4.12 without the minus sign is:

$$\begin{bmatrix}\text{Delta (1)}\\ \text{Delta (2)}\\ \text{Delta (3)}\\ \text{Delta (4)}\end{bmatrix} = \begin{bmatrix}\text{A(1,1(} & \text{A(1,2)} & \text{A(1,3)} & \text{A(1,4)}\\ \text{A(2,1)} & \text{A(2,2)} & \text{A(2,3)} & \text{A(2,4)}\\ \text{A(3,1)} & \text{A(3,2)} & \text{A(3,3)} & \text{A(3,4)}\\ \text{A(4,1)} & \text{A(4,2)} & \text{A(4,3)} & \text{A(4,4)}\end{bmatrix}^{-1} \times \begin{bmatrix}\text{F(1)}\\ \text{F(2)}\\ \text{F(3)}\\ \text{F(4)}\end{bmatrix} \qquad (2.4.17)$$

And the formula 2.4.13 with the minus sign becomes:

$$\begin{bmatrix}\text{EQ(1)}\\ \text{EQ(2)}\\ \text{EQ(3)}\\ \text{EQ(4)}\end{bmatrix} = \begin{bmatrix}\text{EQ(1)}\\ \text{EQ(2)}\\ \text{EQ(3)}\\ \text{EQ(4)}\end{bmatrix} - \begin{bmatrix}\text{Delta (1)}\\ \text{Delta (2)}\\ \text{Delta (3)}\\ \text{Delta (4)}\end{bmatrix} \qquad (2.4.18)$$

2.4.4 Newton Raphson Solution of Equilibrium

To apply the Newton-Raphson technique to the equilibrium system of equations, they must be in the form of equation 2.4.5. Transforming equations 2.4.1 through 2.4.4 yields the following FORTRAN formulas:

Heat Balance Equation:

F(1) = (.24*ALB*(T0-TE))+(1060.8*ALB*(H0-HE))+(.45*ALB*
(HO*T0-HE*TE))+(CA*GLB*(M0.+1.)*TG)+(CB*GLB*TG*M0)
-(CA*GLB*(MET+1.)*TE)-(CB*GLB*ME*TE) (2.4.19)

CA = .35

CB = .851 Kazarian Hall(65)

Mass Balance Equation:

F(2) = (ALB*HE)-(ALB*H0)+(GLB*ME)-(GLB*M0) (2.4.20)

Chung-Pfost Equilibrium Relative Humidity Equation:

F(3) = ERH - EXP]-PA/(RØ*(TE+PC))*EXP(-PB*ME)] (2.4.21)

RØ = 1.987 PA = 1110.4268 PB = 16.9534 PC = 21.8947

Absolute Humidity of Moist Air:

F(4) = HE-((.6219*(ERH*PS))/(ATM-(ERH*PS))) (2.4.22)

NOTE: Equations 2.4.19 through 2.4.22 are equivalent to the equations 2.4.1 through 2.4.4 with the left hand side minus the right hand side. At the point defined to be equilibrium, these values F(1) through F(4) should be sufficiently close to zero. The form of equations 2.4.19 and 2.4.20 were written to minimize machine roundoff error.

The formulas for calculation of the Jacobian Matrix A are given in FØRTRAN form as:

A(1,1) = -(.24*ALB)-(.45*ALB*HE)-(GLB*CA*(ME+1.))-(CB*GLB*ME) (2.4.23)

A(1,2) = -(1060.8*ALB)-(.45*ALB*TE) (2.4.24)

A(1,3) = -1.201*GLB*TE (2.4.25)

A(1,4) = 0.0 (2.4.26)

A(2,1) = 0.0 (2.4.27)

A(2,2) = ALB (2.4.28)

A(2,3) = GLB (2.4.29)

```
A(2,4) = 0.0                                                    (2.4.30)

A(3,1) = EXP(-PA/(RO*(TE+PC))*EXP(-PB*ME))*(EXP(-PB*ME)*

         (-PA/(RO*(TE+PC)**2)))                                 (2.4.31)

A(3,2) = 0.0                                                    (2.4.32)

A(3,3) = EXP(-PA/(RO*(TE+PC))*EXP(-PB*ME))*(-PA/(RO*(TE+PC))*

         EXP(-PB*ME)*(-PB))                                     (2.4.33)

A(3,4) = -1.                                                    (2.4.34)

A(4,1) = ((ATM-ERH*PS)*(-.6219*ERH*PPS)-(-.6219*ERH*PS)*

         (-ERH*PPS))/((ATM-ERH*PS)*(ATM-ERH*PS))                (2.4.35)
```

$$PPS = \frac{\partial PS}{\partial TE}$$

```
PPS = (B2*(B1*B4-B3*B6))/B5

 B1 = F*TR-G*TR*TR

 B2 = PS

 B3 = A1+TR*(B+TR*(C+TR*(D+TR*E)))

 B4 = B+TR*(2.*C+TR*(3.*D+TR*(4.+E)))

 B5 = B1*B1

 B6 = F-2.*G*TR
```

A1,B,C,D,E,F,G constants for calculation of PS, Brooker(74)

If TE $\leq$ 32.

$$PPS = ((11286.6/(TR*TR))-(.46057/TR))*PS$$

$$A(4,2) = 1.0 \qquad (2.4.36)$$

$$A(4,3) = 0.0 \qquad (2.4.37)$$

$$A(4,4) = ((ATM-ERH*PS)*(-.6219*PS)-(.6219*ERH*PS)*PS)/ ((ATM-ERH*PS)*(ATM-ERH*PS)) \qquad (2.4.38)$$

The final requirement of this solution method is the determination of sufficient accuracy. In this case, how can the precision of the equilibrium estimate be determined? If the successive corrections (Delta(I)) to the important variables of the system are less than what can be detected with field equipment, then the equilibrium approximation is exact enough. Further iterations will only produce equivalent results.

For natural air grain drying studies, grain temperature can be measured to within $\pm$ 5^{O}F and grain moisture to within $\pm$.1% wb. To be within these limits, the maximum values for the iterative solution were chosen as:

$$|Delta(1)| \leq .05 \quad \text{and} \quad |Delta(3)| \leq .0005 \qquad (2.4.39)$$

The FØRTRAN subroutine EQLBRM was coded and debugged to solve the equilibrium equations 2.4.20 through 2.4.22 with the Newton-Raphson technique outlined in this section. Standard IBM subroutines from the Scientific Subroutine Package(70) were used to perform the matrix operations of matrix inversion (MINV) and matrix multiplication (GMPRD).

When this method (EQ3) was applied to the Test 1 data, 1920 equilibrium solutions were required. Of these 1920 solutions excessive cycling occurred within the EQLBRM subroutine in 6 solutions. Excessive cycling for the Newton-Raphson method was defined to be a solution which did not meet the convergence criteria, equations (2.4.39), in less than 10 iterations. The mean and standard deviation of the iterations required for equilibrium solution are 2.12 and .66 respectively.

This cycling occurred only in the first layer whenever the initial moisture content (M0) was less than 10% db and the relative humidity of the air (RH) corresponded to the equilibrium relative humidity ERH at the initial moisture content MO. Each of the DELTA(3) corrections were alternating sign but the magnitude of DELTA(3) remained at 0.008. A dampening coefficient (DMC = .5) was multiplied by the DELTA vector after five iterations and the cycling remained. Then the dampening coefficient (DMC) itself was multiplied by .5 after each iteration above 5. This method was successful in elimination of the convergence problem for all tests studied.

The following is a tally of the most difficult convergence problem of all six validation studies:

Number of Iterations	1	2	3	4	5	6	7	8	9	10
Observed Frequency	229	1276	387	22	0	0	6	0	0	0

It was noted that all calculations requiring more than three iterations involved the first two layers above the plenum floor. Our observations indicate that when a large climatic change occurs, the difference in air and grain state points is absorbed by the first or second layer. This phenomenon points out the effect of equilibrium assumption A.1. (Section 2.4.1).

2.4.5 Additional Refinements

Since a drying period may last twenty days or longer, large numbers of equilibrium solutions (1920) must be performed and accuracy of each solution is critical to prevent error accumulation. Therefore accuracy and computational speed are very important to grain drying models. A critical review of this method indicated that the matrix inversion step was the most time consuming in the algorithm. Improvement of this step would greatly improve overall calculational speed. Again using the matrix notation restated for an n dimensioned problem yields:

$J^{(n \times n)}$ = Jacobian Matrix of Partial Derivatives

$I^{(n \times n)}$ = Identity Matrix

If J^{-1} is the inverse of J then recall that:

$$J^{-1} J = I \qquad (2.4.40)$$

Now, suppose there exists a matrix $Q^{(n \times n)}$ such that

$$Q \times J \times I = IQ \qquad (2.4.41)$$

Then by equation 2.4.40, we know: $Q = J^{-1}$

Analogous to equation 2.4.12, we have:

$$D^{(n \times 1)} = -J^{-1(n \times n)} F^{(n \times 1)} \qquad (2.4.42)$$

Then by substituting 2.4.42 into 2.4.41, we show that:

$$J^{-1} J F = I D \qquad (2.4.43)$$

If the augmented matrix (JF) of the system of n linear equations is transformed into I D then the matrix inversion is not necessary.

The reduction of the augmented matrix (JF) to the solutions (I D) is performed by the Gauss-Jordan method (Pennington(70)). Complete pivoting was incorporated to hopefully minimize roundoff error and therefore improve accuracy. Complete pivoting is the selection of the element largest in magnitude as the basis for the next step in the Gauss-Jordan elimination. Alternate views of the benefits or complications of pivoting are discussed in Pennington(70), and Haming(71).

This approach to the solution resulted in faster overall convergence and improved accuracy. The amount of accuracy increase was found to be one decimal place in all off-diagonal elements of the computed identity matrix (I). Because of this increase in accuracy, no dampening coefficient was required. However, the total number of iterations was not appreciably affected.

The FORTRAN subroutine GAUSS was written to perform this algorithm upon the supplied augmented matrix A in row vector form. The element in row vector form of the augmented matrix can be determined by:

Old Method		New Method		
A(I,J)	=	A((I-1)*N+J)	I = 1,2, ..., N J = 1,2, ..., N	(2.4.44)

This row vector notation reduces computation time required for the subscript location. A source listing of the subroutine GAUSS is given in Appendix D. This completes the development of the revised equilibrium model, and is referred to as EQ 3 throughout this text.

2.5 Multiple Model Validation

Section 1.9 outlined the six natural aeration corn drying validation studies performed at the Grain Marketing Research Center USDA (ARS). These paired tests were labeled Tests 1, 2 and 3 for convenience as in Table 1.9.1. The paired experiments are composed of one natural air drying test and one with solar heat supplementation.

Mathematical model inputs are the initial conditions of the test given in Table 1.9.1 and the historical weather data for the experimental period. Equilibrium models EQ 1 and EQ 2 require dry bulb and dew point temperatures as input data. Since dew point data is not normally measured, it was calculated. The FORTRAN subroutine DEWPT was used to calculate the dew point temperature of the outside air. The outside air is that given by Bark (74, 75) which is sampled at the Kansas State University Dairy Barn located about one mile from the test bins.

Data to be used for the model validation should reflect the conditions which are present in the plenum chamber beneath the bin. Adiabatic heating was assumed to be present across the aeration fan. Therefore, the measured plenum dry bulb and the previously calculated dew point were paired and used as input to models EQ 1 and EQ 2. This combination of dry bulb and dew point for the EQ 1 and EQ 2 models was converted to dry bulb and relative humidity for input to the EQ 3 model. All weather data for this test was taken on a 3-hour basis. The interested reader is again referred to Appendix A for all experimental data involved in these six drying experiments.

2.5.1 Test 1

Tables 2.5.1, 2.5.2 and 2.5.3 show the formation of the difference tables for models EQ 1, EQ 2 and EQ 3 respectively. Each difference table shows that these models are too dry in their predictions. This fact is shown by the large positive numbers down the diagonal of the difference table. There is a definite difference in the appearance of Table 2.5.2, from the others. This table has only one region of negative error. Note also that the absolute mean is larger than the standard deviation.

The results of AOV Model II are given in Table 2.5.4, for Test 1-N. This table shows that there is a significant difference between models. The EQ 2 model was found to be significantly less accurate than EQ 1 and EQ 3. The best model for this test is a tie between EQ 1 and EQ 3. Since neither of models EQ 1 or EQ 3 has a mean which lies within the region $\pm LSD_{.95} = \pm .2283$, neither model can be claimed as adequate for Test 1-N.

Test 1-S was conducted concurrently with Test 1-N, and the plenum conditions were calculated as previously described. The main difference between the two experiments is that the measured temperatures in the plenum chamber were at times 15 to 20^{o}F higher than ambient temperature. Therefore, as with subsequent solar tests, relative humidities in the plenum chamber were lowered to 20-30% during warm days.

The validation tables for this experiment are given in Tables 2.5.5, 2.5.6 and 2.5.7. These tables have a remarkable resemblance to that in Test 1-N, but the maximum errors are larger as we would expect from our observation of the weather data. The results of AOV Model II are given in Table 2.5.8. All of the AOV Model II components are significant. This means that probably none of the models are adequate predictors of this system. Model ranking using the LSD method shows that the EQ 3 model is a significantly better predictor than the other models. But the $LSD_{.95}$ is .1897 and the EQ 3 model fails to qualify as an adequate model for Test 1-S.

2.5.2 Test 2

The two paired studies of this group were performed in the larger bins 18 ft. in diameter. The drying bed thickness was in excess of 10 feet and the air flow velocities were approximately 30 (cfm/ft^2) which meant that the traverse time for the air to flow through the grain mass is approximately 10 seconds. The purpose of these studies was to analyze the drying model sensitivity to grain bed thickness and airflow rate.

With grain depths in excess of 10 feet vertical, probing for moisture was very difficult. Therefore, only three moisture probings were made during the test. This lack of time observations will mean that the time effect will not be properly tested in the analysis of variance. However, the number of depth observations was large enough to adequately test the depth effect in the analysis of variance.

The validation tables for EQ 1, EQ 2 and EQ 3 are given in Tables 2.5.9, 2.5.10, and 2.5.11. Table 2.5.12 shows the results of the AOV Model II for Test 2-N. The EQ 3 model was found to be the best model according to the LSD ranking. With the $LSD_{.95} = 0.1619$ the EQ 3 model was found to be an adequate model of Test 2-N.

The analysis of model accuracy using AOV Model I has been performed and is summarized in Table 2.5.13. Model errors were found to be affected by depth and its affect is significant at the .05 protection level. It is then concluded that the EQ 3 has failed this last test of error distribution and is not qualified as an accurate model of Test 2-N. The two models EQ 1 and Eq 2 were not significantly different from each other.

Tables 2.5.14, 2.5.15 and 2.5.16 show that EQ 3 has the smallest mean deviation. Table 2.5.17 gives the results of AOV Model II for Test 2-S. There is a significant difference between models. The LSD test shows that EQ 3 is the best model and that it is also an adequate model. ($LSD_{.95} = 0.2598$) No significant difference was found between EQ 1 and EQ 2. Table 2.5.18 shows the results of the AOV Model I test for prediction accuracy. Again the depth effect is significant and model EQ 3 does not qualify as an accurate model.

2.5.3 Test 3

These two experiments were to be conducted as repeats of the conditions of 1974 (Test 1). However, due to a very dry fall climate, moist corn was very scarce. The result being that this study was conducted with less than the desired amount of corn. This one shortcoming had an definite effect upon the test results. First, the grain bed thickness was very shallow which increased the airflow rate. Secondly, the dry climate coupled with the increased air flow rate produced a test which yielded sparse data during the drying period.

The validation results of each model for Test 3-N is given in Table 2.5.19, 2.5.20 and 2.5.21. This test appears to be consistent with the other tests with model overdrying taking place. The overdrying within the drying zone is less prevalent than with other tests, and since only three depth observations were possible, the depth effect in the AOV models will be difficult to identify.

Table 2.5.22 shows that significant model differences are apparent. But the $LSD_{.95} = .2969$ and Model EQ 3, although the best model, is not an adequate model. Again, there is no significant difference between models EQ 1 and EQ 2.

The validation results for models EQ 1, EQ 2, and EQ 3 are given in Tables 2.5.23, 2.5.24, and 2.5.25. The evaluation of AOV Model II in Table 2.5.26 shows that significant differences exist between models. The $LSD_{.95} = 0.6156$ which indicates that EQ 3 is significantly the best model but is not an adequate model. Again, no significant difference was found between models EQ 1 and EQ 2.

Table 2.5.1 Validation of Test 1-N using Model EQ 1

Actual Grain Moisture Contents Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	0.2153	0.2256	0.2211	0.2173	0.2167
92.	0.1675	0.2249	0.2220	0.2210	0.2190
161.	0.1265	0.1695	0.2160	0.2165	0.2138
213.	0.1220	0.1468	0.1868	0.2133	0.2120
260.	0.1293	0.1430	0.1638	0.2035	0.2168
332.	0.1360	0.1362	0.1558	0.1587	0.1694
382.	0.1408	0.1405	0.1445	0.1584	0.1657
480.	0.1466	0.1406	0.1411	0.1447	0.1423

Model EQ 1 Verification Study Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	0.2008	0.2209	0.2214	0.2213	0.2214
92.	0.1396	0.2037	0.2230	0.2236	0.2232
161.	0.0939	0.1264	0.1953	0.2176	0.2181
213.	0.1037	0.1004	0.1233	0.1996	0.2173
260.	0.1271	0.1172	0.1107	0.1227	0.2002
332.	0.1458	0.1377	0.1277	0.1204	0.1173
382.	0.1474	0.1429	0.1398	0.1338	0.1274
480.	0.1510	0.1372	0.1320	0.1350	0.1387

Model EQ 1 (Actual - Predicted) in Percent Wet Basis Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	1.45	0.47	-0.03	-0.40	-0.47
92.	2.79	2.12	-0.10	-0.26	-0.42
161.	3.26	4.31	2.07	-0.11	-0.43
213.	1.83	4.64	6.35	1.37	-0.53
260.	0.22	2.58	5.31	8.08	1.66
332.	-0.98	-0.15	2.81	3.83	5.21
382.	-0.66	-0.24	0.47	2.46	3.83
480.	-0.44	0.34	0.91	0.97	0.36

MEAN ABSOLUTE DEVIATION = 1.8725 ✓

MEAN DEVIATION = 1.6122 ✓

STANDARD DEVIATION = 2.2041 ✓

Table 2.5.2 Validation of Test 1-N using Model EQ 2

Actual Grain Moisture Contents Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	0.2153	0.2256	0.2211	0.2173	0.2167
92.	0.1675	0.2249	0.2220	0.2210	0.2190
161.	0.1265	0.1695	0.2160	0.2165	0.2138
213.	0.1220	0.1468	0.1868	0.2133	0.2120
260.	0.1293	0.1430	0.1638	0.2035	0.2168
332.	0.1360	0.1362	0.1558	0.1587	0.1694
382.	0.1408	0.1405	0.1445	0.1584	0.1657
480.	0.1466	0.1406	0.1411	0.1447	0.1423

Model EQ 2 Verification Study Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	0.2030	0.2209	0.2215	0.2213	0.2211
92.	0.1417	0.2053	0.2231	0.2241	0.2229
161.	0.0943	0.1272	0.1975	0.2176	0.2179
213.	0.0945	0.1016	0.1304	0.2015	0.2169
260.	0.1133	0.1043	0.1170	0.1385	0.2065
332.	0.1338	0.1214	0.1167	0.1203	0.1289
382.	0.1353	0.1289	0.1237	0.1221	0.1282
480.	0.1372	0.1282	0.1269	0.1252	0.1249

Model EQ 2 (Actual - Predicted) in Percent Wet Basis Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	1.23	0.47	-0.04	-0.40	-0.44
92.	2.58	1.96	-0.11	-0.31	-0.39
161.	3.22	4.23	1.85	-0.11	-0.41
213.	2.75	4.52	5.64	1.18	-0.49
260.	1.60	3.87	4.68	6.50	1.03
332.	0.22	1.48	3.91	3.84	4.05
382.	0.55	1.16	2.08	3.63	3.75
480.	0.94	1.24	1.42	1.95	1.74

MEAN ABSOLUTE DEVIATION = 2.0486

MEAN DEVIATION = 1.9135

STANDARD DEVIATION = 1.8638

Table 2.5.3 Validation of Test 1-N using Model EQ 3

Actual Grain Moisture Contents Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	0.2153	0.2256	0.2211	0.2173	0.2167
92.	0.1675	0.2249	0.2220	0.2210	0.2190
161.	0.1265	0.1695	0.2160	0.2165	0.2138
213.	0.1220	0.1468	0.1868	0.2133	0.2120
260.	0.1293	0.1430	0.1638	0.2035	0.2168
332.	0.1360	0.1362	0.1558	0.1587	0.1694
382.	0.1408	0.1405	0.1445	0.1584	0.1657
480.	0.1466	0.1406	0.1411	0.1447	0.1423

Model EQ 3 Verification Study Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	0.2022	0.2200	0.2211	0.2210	0.2210
92.	0.1420	0.2042	0.2224	0.2229	0.2228
161.	0.0988	0.1230	0.1911	0.2170	0.2179
213.	0.1134	0.1095	0.1159	0.1872	0.2172
260.	0.1332	0.1255	0.1197	0.1211	0.1850
332.	0.1494	0.1431	0.1340	0.1273	0.1228
382.	0.1517	0.1469	0.1448	0.1402	0.1345
480	0.1549	0.1417	0.1361	0.1388	0.1429

Model EQ 2 (Actual - Predicted) in Percent Wet Basis Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	1.31	0.56	0.00	-0.37	-0.43
92.	2.55	2.07	-0.04	-0.19	-0.38
161.	2.77	4.65	2.49	-0.05	-0.41
213.	0.86	3.73	7.09	2.61	-0.52
260.	-0.39	1.75	4.41	8.24	3.18
332.	-1.34	-0.69	2.18	3.14	4.66
382.	-1.09	-0.64	-0.03	1.82	3.12
480.	-0.83	-0.11	0.50	0.59	-0.06

MEAN ABSOLUTE DEVIATION = 1.7962

MEAN DEVIATION = 1.4179

STANDARD DEVIATION = 2.2406

Table 2.5.4 Multiple Model Validation of EQ 1, EQ 2 and EQ 3 for Test 1-N

```
SOURCE OF |  SUMS OF     |      |   MEAN      |    F    |
VARIATION |  SQUARES     | D.F. |   SQUARE    |  RATIO  | ALPHA HAT
          |              |      |             |         |
----------+--------------+------+-------------+---------+----------
          |              |      |             |         |
    M     |     4.7952   |    2 |    2.3976   |   9.20  |  0.0004
    T     |   132.7240   |    7 |   18.9606   |  72.77  |  0.0000
    D     |    28.4997   |    4 |    7.1249   |  27.35  |  0.0000
    MT    |    10.2824   |   14 |    0.7345   |   2.82  |  0.0030
    MD    |     4.9056   |    8 |    0.6132   |   2.35  |  0.0294
    TD    |   318.0659   |   28 |   11.3595   |  43.60  |  0.0000
          |              |      |             |         |
----------+--------------+------+-------------+---------+----------
          |              |      |             |
   ERROR  |    14.5901   |   56 |    0.2605   |
          |              |      |             |
----------+--------------+------+-------------+
          |              |      |
   TOTAL  |   513.8635   |  119 |
          |              |      |
```

Table 2.5.5 Validation of EQ 1 using Test 1-S

Actual Grain Moisture Contents Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	0.2146	0.2190	0.2185	0.2179	0.2158
92.	0.1570	0.2217	0.2205	0.2200	0.2169
161.	0.1158	0.1633	0.2148	0.2113	0.2100
213.	0.1085	0.1368	0.1955	0.2110	0.2090
260.	0.1153	0.1317	0.1545	0.1830	0.2090
332.	0.1237	0.1266	0.1460	0.1512	0.1532
378.	0.1257	0.1294	0.1365	0.1534	0.1445
480.	0.1329	0.1288	0.1300	0.1305	0.1323

Model EQ 1 Verification Study Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	0.2006	0.2225	0.2225	0.2223	0.2223
92.	0.1221	0.2005	0.2243	0.2239	0.2238
161.	0.0830	0.1135	0.1958	0.2178	0.2189
213.	0.0915	0.0868	0.1122	0.2031	0.2174
260.	0.1155	0.1033	0.0965	0.1109	0.2081
332.	0.1362	0.1276	0.1165	0.1080	0.1047
378.	0.1320	0.1285	0.1276	0.1214	0.1143
480.	0.1426	0.1270	0.1180	0.1190	0.1246

Model EQ 1 (Actual - Predicted) in Percent Wet Basis Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	1.40	-0.35	-0.40	-0.44	-0.65
92.	3.49	2.12	-0.38	-0.39	-0.69
161.	3.28	4.98	1.90	-0.65	-0.89
213.	1.70	5.00	8.33	0.79	-0.84
260.	-0.02	2.84	5.80	7.21	0.09
332.	-1.25	-0.10	2.95	4.32	4.85
378.	-0.63	0.09	0.89	3.20	3.02
480.	-0.97	0.18	1.20	1.15	0.77

MEAN ABSOLUTE DEVIATION = 2.0047

MEAN DEVIATION = 1.5725

STANDARD DEVIATION = 2.4356

Table 2.5.6 Validation of EQ 2 using Test 1-S

Actual Grain Moisture Contents Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	0.2146	0.2190	0.2185	0.2179	0.2158
92.	0.1570	0.2217	0.2205	0.2200	0.2169
161.	0.1158	0.1633	0.2148	0.2113	0.2100
213.	0.1085	0.1368	0.1955	0.2110	0.2090
260.	0.1153	0.1317	0.1545	0.1830	0.2090
332.	0.1237	0.1266	0.1460	0.1512	0.1532
378.	0.1257	0.1294	0.1365	0.1534	0.1445
480.	0.1329	0.1288	0.1300	0.1305	0.1323

Model EQ 2 Verification Study Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	0.2026	0.2224	0.2221	0.2220	0.2222
92.	0.1241	0.2033	0.2241	0.2236	0.2236
161.	0.0847	0.1144	0.1989	0.2179	9.2184
213.	0.0821	0.0875	0.1215	0.2052	0.2170
260.	0.1026	0.0909	0.1018	0.1280	0.2141
332.	0.1237	0.1117	0.1030	0.1071	0.1167
378.	0.1206	0.1169	0.1111	0.1099	0.1133
480.	0.1277	0.1153	0.1143	0.1133	0.1131

Model EQ 2 (Actual - Predicted) in Percent Wet Basis Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	1.20	-0.34	-0.36	-0.41	-0.64
92.	3.29	1.84	-0.36	-0.36	-0.67
161.	3.11	4.89	1.59	-0.66	-0.84
213.	2.64	4.93	7.40	0.58	-0.80
260.	1.27	4.08	5.27	5.50	-0.51
332.	0.00	1.49	4.30	4.41	3.65
378.	0.51	1.25	2.54	4.35	3.12
480.	0.52	1.35	1.57	1.72	1.92

MEAN ABSOLUTE DEVIATION = 2.1557

MEAN DEVIATION = 1.8579

STANDARD DEVIATION = 2.1562

Table 2.5.7 Validation of EQ 3 using Test 1-S

Actual Grain Moisture Contents Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	0.2146	0.2190	0.2185	0.2179	0.2158
92.	0.1570	0.2217	0.2205	0.2200	0.2169
161.	0.1158	0.1633	0.2148	0.2113	0.2100
213.	0.1085	0.1368	0.1955	0.2110	0.2090
260.	0.1153	0.1317	0.1545	0.1830	0.2090
332.	0.1237	0.1266	0.1460	0.1512	0.1532
378.	0.1257	0.1294	0.1365	0.1534	0.1445
480.	0.1329	0.1288	0.1300	0.1305	0.1323

Model EQ 3 Verification Study Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	0.2053	0.2227	0.2231	0.2227	0.2223
92.	0.1363	0.2044	0.2245	0.2242	0.2238
161.	0.0952	0.1246	0.1975	0.2185	0.2188
213.	0.1083	0.1038	0.1212	0.2006	0.2185
260.	0.1233	0.1166	0.1121	0.1271	0.2069
332.	0.1408	0.1328	0.1245	0.1185	0.1191
378.	0.1446	0.1378	0.1345	0.1296	0.1246
480.	0.1540	0.1385	0.1319	0.1331	0.1351

Model EQ 3 (Actual - Predicted) in Percent Wet Basis Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	0.93	-0.37	-0.46	-0.48	-0.65
92.	2.07	1.73	-0.40	-0.42	-0.69
161.	2.06	3.87	1.73	-0.72	-0.88
213.	0.02	3.30	7.43	1.04	-0.95
260.	-0.80	1.51	4.24	5.59	0.21
332.	-1.71	-0.62	2.15	3.27	3.41
378.	-1.89	-0.84	0.20	2.38	1.99
480.	-2.11	-0.97	-0.19	-0.26	-0.28

MEAN ABSOLUTE DEVIATION = 1.6199

MEAN DEVIATION = 0.8362

STANDARD DEVIATION = 2.1207

Table 2.5.8 Multiple Model Validation of EQ 1, EQ 2, EQ 3 for Test 1-S

```
SOURCE OF |   SUMS OF    |      |    MEAN    |    F    |
VARIATION |   SQUARES    | D.F. |   SQUARE   |  RATIO  | ALPHA HAT
          |              |      |            |         |
----------+--------------+------+------------+---------+----------
          |              |      |            |         |
   M      |    22.2631   |   2  |   11.1315  |  61.84  |  0.0000
   T      |   121.6864   |   7  |   17.3838  |  96.58  |  0.0000
   D      |    55.1867   |   4  |   13.7967  |  76.65  |  0.0000
   MT     |    11.6578   |  14  |    0.8327  |   4.63  |  0.0000
   MD     |     5.4574   |   8  |    0.6822  |   3.79  |  0.0013
   TD     |   384.3494   |  28  |   13.7268  |  76.26  |  0.0000
          |              |      |            |         |
----------+--------------+------+------------+---------+----------
          |              |      |            |
   ERROR  |    10.0798   |  56  |    0.1800  |
          |              |      |            |
----------+--------------+------+------------+
          |              |      |
   TOTAL  |   610.6812   | 119  |
          |              |      |
```

Table 2.5.9 Validation of Model EQ 1 with Test 2-N

Actual Grain Moisture Contents Test 2-N

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
115.	0.1534	0.1524	0.1571	0.1647	0.1768	0.1887	0.1920	0.1931	0.1905
186.	0.1467	0.1479	0.1509	0.1528	0.1558	0.1601	0.1672	0.1740	0.1785
279.	0.1224	0.1215	0.1216	0.1217	0.1233	0.1256	0.1292	0.1337	0.1377

Model EQ 1 Verification Study Test 2-N

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
115.	0.1709	0.1588	0.1467	0.1409	0.1497	0.1789	0.2023	0.2100	0.2099
186.	0.1507	0.1469	0.1500	0.1499	0.1489	0.1478	0.1497	0.1616	0.1840
279.	0.1359	0.1171	0.1093	0.1072	0.1071	0.1111	0.1186	0.1283	0.1378

Model EQ 1 (Actual - Predicted) in Percent Wet Basis Test 2-N

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
115.	-1.75	-0.64	1.04	2.38	2.71	1.01	-1.03	-1.69	-1.94
186.	-0.40	0.10	0.09	0.29	0.69	1.23	1.75	1.24	-0.55
279.	-1.35	0.44	1.23	1.45	1.62	1.45	1.06	0.54	-0.01

MEAN ABSOLUTE DEVIATION = 1.0997

MEAN DEVIATION = 0.4062

STANDARD DEVIATION = 1.2520

Table 2.5.10 Validation of Model EQ 2 with Test 2-N

Actual Grain Moisture Contents Test 2-N

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
115.	0.1534	0.1524	0.1571	0.1647	0.1768	0.1887	0.1920	0.1931	0.1905
186.	0.1467	0.1479	0.1509	0.1528	0.1558	0.1601	0.1672	0.1740	0.1785
279.	0.1224	0.1215	0.1216	0.1217	0.1233	0.1256	0.1292	0.1337	0.1377

Model EQ 2 Verification Study Test 2-N

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
115.	0.1602	0.1453	0.1389	0.1487	0.1616	0.1863	0.2047	0.2090	0.2101
186.	0.1418	0.1415	0.1419	0.1423	0.1451	0.1492	0.1573	0.1731	0.1928
279.	0.1250	0.1068	0.1025	0.1080	0.1126	0.1152	0.1196	0.1260	0.1348

Model EQ 2 (Actual - Predicted) in Percent Wet Basis

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
115.	-0.68	0.71	1.82	1.60	1.52	0.24	-1.27	-1.59	-1.96
186.	0.49	0.64	0.90	1.05	1.07	1.09	0.99	0.09	-1.43
279.	-0.26	1.47	1.91	1.37	1.07	1.04	0.96	0.77	0.29

MEAN ABSOLUTE DEVIATION = 1.0471

MEAN DEVIATION = 0.5146

STANDARD DEVIATION = 1.0655

Table 2.5.11 Validation of Model EQ 3 with Test 2-N

Actual Grain Moisture Contents Test 2-N

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
115.	0.1534	0.1524	0.1571	0.1647	0.1768	0.1887	0.1920	0.1931	0.1905
186.	0.1467	0.1479	0.1509	0.1528	0.1558	0.1601	0.1672	0.1740	0.1785
279.	0.1224	0.1215	0.1216	0.1217	0.1233	0.1256	0.1292	0.1337	0.1377

Model EQ 3 Verification Study Test 2-N

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
115.	0.1736	0.1624	0.1517	0.1484	0.1604	0.1864	0.2059	0.2121	0.2133
186.	0.1556	0.1512	0.1533	0.1541	0.1532	0.1532	0.1580	0.1722	0.1920
279.	0.1409	0.1238	0.1157	0.1127	0.1128	0.1157	0.1216	0.1303	0.1410

Model EQ 3 (Actual - Predicted) in Percent Wet Basis Test 2-N

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
115.	-2.02	-1.00	0.54	1.63	1.64	0.23	-1.39	-1.90	-2.28
186.	-0.89	-0.33	-0.24	-0.13	0.26	0.69	0.92	0.18	-1.35
279.	-1.85	-0.23	0.59	0.90	1.05	0.99	0.76	0.34	-0.33

MEAN ABSOLUTE DEVIATION = 0.9123

MEAN DEVIATION = -0.1182

STANDARD DEVIATION = 1.1232

Table 2.5.12 Multiple Model Validation of EQ 1, EQ 2 and EQ 3 for Test 2-N

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
M	6.2075	2	3.1038	36.60	0.0000
T	8.5168	2	4.2584	50.21	0.0000
D	55.5751	8	6.9469	81.91	0.0000
MT	0.1452	4	0.0363	0.43	0.7873
MD	5.7961	16	0.3623	4.27	0.0002
TD	30.4011	16	1.9001	22.40	0.0000
ERROR	2.7140	32	0.0848		
TOTAL	109.3560	80			

Table 2.5.13 Testing EQ 3 Prediction Accuracy of Test 2-N

```
SOURCE OF |   SUMS OF    |      |    MEAN     |    F    |
VARIATION |   SQUARES    | D.F. |   SQUARE    |  RATIO  | ALPHA HAT
          |              |      |             |         |
----------+--------------+------+-------------+---------+----------
          |              |      |             |         |
    T     |     2.5519   |    2 |    1.2759   |  2.01   |  0.1661
    D     |    20.1706   |    8 |    2.5213   |  3.98   |  0.0091
          |              |      |             |         |
----------+--------------+------+-------------+---------+----------
          |              |      |             |
  ERROR   |    10.1441   |   16 |    0.6340   |
          |              |      |             |
----------+--------------+------+-------------+
          |              |      |
  TOTAL   |    32.8666   |   26 |
          |              |      |
```

Table 2.5.14 Validation of Test 2-S using Model EQ 1

Actual Grain Moisture Contents Test 2-S

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
116.	0.1451	0.1485	0.1550	0.1698	0.1954	0.2168	0.2134	0.2089	0.2060
186.	0.1420	0.1445	0.1481	0.1524	0.1579	0.1683	0.1849	0.1968	0.2019
279.	0.1198	0.1185	0.1185	0.1196	0.1205	0.1229	0.1262	0.1306	0.1349

Model EQ 1 Verification Study Test 2-S

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
116.	0.1623	0.1564	0.1438	0.1376	0.1532	0.1978	0.2245	0.2280	0.2280
186.	0.1505	0.1437	0.1459	0.1463	0.1440	0.1423	0.1481	0.1756	0.2113
279.	0.1129	0.1196	0.1149	0.1103	0.1078	0.1080	0.1111	0.1174	0.1269

Model EQ 1 (Actual - Predicted) in Percent Wet Basis Test 2-S

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
116.	-1.72	-0.79	1.12	3.22	4.22	1.90	-1.11	-1.91	-2.20
186.	-0.85	0.08	0.22	0.61	1.39	2.60	3.68	2.12	-0.94
279.	0.69	-0.11	0.36	0.93	1.27	1.49	1.51	1.32	0.80

MEAN ABSOLUTE DEVIATION = 1.4504

MEAN DEVIATION = 0.7364

STANDARD DEVIATION = 1.6461

Table 2.5.15 Validation of Test 2-S using Model EQ 2

Actual Grain Moisture Contents Test 2-S

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00	105.00
116.	0.1451	0.1485	0.1550	0.1698	0.1954	0.2168	0.2134	0.2089	0.2060	0.2034
186.	0.1420	0.1445	0.1481	0.1524	0.1579	0.1683	0.1849	0.1968	0.2019	0.1959
279.	0.1198	0.1185	0.1185	0.1196	0.1205	0.1229	0.1262	0.1306	0.1349	0.0

Model EQ 2 Verification Study Test 2-S

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00	105.00
116.	0.1513	0.1403	0.1344	0.1458	0.1692	0.2079	0.2261	0.2285	0.2273	0.2277
186.	0.1405	0.1366	0.1368	0.1376	0.1398	0.1444	0.1599	0.1926	0.2192	0.2174
279.	0.1058	0.1092	0.1064	0.1050	0.1059	0.1072	0.1114	0.1180	0.1290	0.1473

Model EQ 2 (Actual - Predicted) in Percent Wet Basis Test 2-S

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00	105.00
116.	-0.62	0.82	2.06	2.40	2.62	0.89	-1.27	-1.96	-2.13	-2.43
186.	0.15	0.79	1.13	1.48	1.81	2.39	2.50	0.42	-1.73	-2.15
279.	1.40	0.93	1.21	1.46	1.46	1.57	1.48	1.26	0.59	0.0

MEAN ABSOLUTE DEVIATION = 1.4860
MEAN DEVIATION = 0.6384
STANDARD DEVIATION = 1.5246

Table 2.5.16 Validation of Test 2-S using Model EQ 3

```
                ACTUAL GRAIN MOISTURE CONTENTS  TEST 2-S

          7.00    17.00    28.00    39.00    50.00    61.00    72.00    83.00    94.00
      ---------------------------------------------------------------------------------
116.|   0.1451   0.1485   0.1550   0.1698   0.1954   0.2168   0.2134   0.2089   0.2060
186.|   0.1420   0.1445   0.1481   0.1524   0.1579   0.1683   0.1849   0.1968   0.2019
279.|   0.1198   0.1185   0.1185   0.1196   0.1205   0.1229   0.1262   0.1306   0.1349


                 MODEL EQ 3 VERIFICATION STUDY  TEST 2-S

          7.00    17.00    28.00    39.00    50.00    61.00    72.00    83.00    94.00
      ---------------------------------------------------------------------------------
116.|   0.1634   0.1590   0.1486   0.1464   0.1681   0.2073   0.2283   0.2316   0.2318
186.|   0.1554   0.1484   0.1491   0.1496   0.1484   0.1488   0.1608   0.1906   0.2201
279.|   0.1409   0.1215   0.1118   0.1080   0.1074   0.1089   0.1128   0.1196   0.1312


      MODEL  EQ 3  (ACTUAL - PREDICTED) IN PERCENT WET BASIS TEST 2-S

          7.00    17.00    28.00    39.00    50.00    61.00    72.00    83.00    94.00
      ---------------------------------------------------------------------------------
116.|    -1.83    -1.05     0.64     2.34     2.73     0.95    -1.49    -2.27    -2.58
186.|    -1.34    -0.39    -0.10     0.28     0.95     1.95     2.41     0.62    -1.82
279.|    -2.11    -0.30     0.67     1.16     1.31     1.40     1.34     1.10     0.37


                MEAN ABSOLUTE DEVIATION =          1.3152

                         MEAN DEVIATION =          0.1831

                     STANDARD DEVIATION =          1.5349
```

Table 2.5.17 Multiple Validation of EQ 1, EQ 2, and EQ 3 for Test 2-S

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
M	6.9661	2	3.4830	15.93	0.0000
T	9.7126	2	4.8563	22.22	0.0000
D	83.2660	8	10.4083	47.61	0.0000
MT	0.4303	4	0.1076	0.49	0.7415
MD	8.2669	16	0.5167	2.36	0.0187
TD	69.5571	16	4.3473	19.89	0.0000
ERROR	6.9951	32	0.2186		
TOTAL	185.1942	80			

Table 2.5.18 Testing EQ 3 Prediction Accuracy of Test 2-S

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
T	3.2640	2	1.6320	1.21	0.3248
D	36.3293	8	4.5412	3.36	0.0187
ERROR	21.6254	16	1.3516		
TOTAL	61.2187	26			

Table 2.5.19 Validation of Model EQ 1 for Test 3-N

Actual Grain Moisture Contents Test 3-N

	7.00	17.00	28.00
41.	0.1730	0.2277	0.2314
113.	0.1379	0.1664	0.2128
163.	0.1280	0.1366	0.1716
211.	0.1340	0.1328	0.1377
217.	0.1299	0.1372	0.1470

Model EQ 1 Verification Study Test 3-N

	7.00	17.00	28.00
41.	0.1694	0.2198	0.2196
113.	0.1151	0.1490	0.2186
163.	0.1195	0.1125	0.1584
211.	0.1334	0.1214	0.1155
217.	0.1361	0.1232	0.1162

Model EQ 1 (Actual - Predicted) in Percent Wet Basis Test 3-N

	7.00	17.00	28.00
41.	0.36	0.79	1.18
113.	2.28	1.74	-0.58
163.	0.85	2.41	1.32
211.	0.06	1.14	2.22
217.	-0.62	1.40	3.08

MEAN ABSOLUTE DEVIATION = 1.3362

MEAN DEVIATION = 1.1758

STANDARD DEVIATION = 1.0796

Table 2.5.20 Validation of Model EQ 2 for Test 3-N

Actual Grain Moisture Contents Test 3-N

	7.00	17.00	28.00
41.	0.1730	0.2277	0.2314
113.	0.1379	0.1664	0.2128
163.	0.1280	0.1366	0.1716
211.	0.1340	0.1328	0.1377
217.	0.1299	0.1372	0.1470

Model EQ 2 Verification Study Test 3-N

	7.00	17.00	28.00
41.	0.1729	0.2194	0.2201
113.	0.1138	0.1537	0.2187
163.	0.1058	0.1169	0.1699
211.	0.1201	0.1144	0.1199
217.	0.1204	0.1144	0.1198

Model EQ 2 (Actual - Predicted) in Percent Wet Basis Test 3-N

	7.00	17.00	28.00
41.	0.01	0.83	1.13
113.	2.41	1.27	-0.59
163.	2.22	1.97	0.17
211.	1.39	1.84	1.78
217.	0.95	2.28	2.72

MEAN ABSOLUTE DEVIATION = 1.4375

MEAN DEVIATION = 1.3592

STANDARD DEVIATION = 0.9593

Table 2.5.21 Validation of Model EQ 3 for Test 3-N

```
ACTUAL GRAIN MOISTURE CONTENTS  TEST 3-N

            7.00     17.00     28.00
        -------------------------
   41.|   0.1730   0.2277   0.2314
  113.|   0.1379   0.1664   0.2128
  163.|   0.1280   0.1366   0.1716
  211.|   0.1340   0.1328   0.1377
  216.|   0.1299   0.1372   0.1470
```

```
MODEL EQ 3 VERIFICATION STUDY  TEST 3-N

            7.00     17.00     28.00
        -------------------------
   41.|   0.1713   0.2228   0.2231
  113.|   0.1216   0.1512   0.2206
  163.|   0.1251   0.1194   0.1641
  211.|   0.1381   0.1260   0.1204
  216.|   0.1403   0.1275   0.1208
```

```
MODEL  EQ 3  (ACTUAL - PREDICTED) IN PERCENT WET BASIS TEST 3-N

            7.00     17.00     28.00
        -------------------------
   41.|    0.17     0.49      0.83
  113.|    1.63     1.52     -0.78
  163.|    0.29     1.72      0.75
  211.|   -0.41     0.68      1.73
  216.|   -1.04     0.97      2.62
```

```
MEAN ABSOLUTE DEVIATION =          1.0427

         MEAN DEVIATION =          0.7451

     STANDARD DEVIATION =          1.0118
```

Table 2.5.22 Multiple Model Validation of EQ 1, EQ 2 and EQ 3 for Test 3-N

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
M	2.9991	2	1.4995	10.20	0.0014
T	3.1121	4	0.7780	5.29	0.0066
D	3.8189	2	1.9094	12.98	0.0004
MT	1.4313	8	0.1789	1.22	0.3500
MD	2.5686	4	0.6421	4.37	0.0141
TD	30.2362	8	3.7795	25.70	0.0000
ERROR	2.3528	16	0.1471		
TOTAL	46.5191	44			

Table 2.5.23 Validation Results of Model EQ 1 for Test 3-S

Actual Grain Moisture Contents Test 3-S

	7.00	17.00	28.00
42.	0.1806	0.2337	0.2389
114.	0.1307	0.1668	0.2152
162.	0.1207	0.1308	0.1844
211.	0.1238	0.1256	0.1363
217.	0.1201	0.1289	0.1479

Model EQ 1 Verification Study Test 3-S

	7.00	17.00	28.00
42.	0.1538	0.2200	0.2199
114.	0.1062	0.1234	0.2151
162.	0.1155	0.1052	0.1223
211.	0.1282	0.1162	0.1094
217.	0.1288	0.1185	0.1108

Model EQ 1 (Actual - Predicted) in Percent Wet Basis Test 3-S

	7.00	17.00	28.00
42.	2.68	1.37	1.90
114.	2.45	4.34	0.01
162.	0.52	2.56	6.21
211.	-0.44	0.94	2.69
217.	-0.87	1.04	3.71

MEAN ABSOLUTE DEVIATION = 2.1159

MEAN DEVIATION = 1.9408

STANDARD DEVIATION = 1.8965

Table 2.5.24 Validation Results of Model EQ 2 for Test 3-S

Actual Grain Moisture Contents Test 3-S

	7.00	17.00	28.00
42.	0.1806	0.2337	0.2389
114.	0.1307	0.1668	0.2152
162.	0.1207	0.1308	0.1844
211.	0.1238	0.1256	0.1363
217.	0.1201	0.1289	0.1479

Model EQ 2 Verification Study Test 3-S

	7.00	17.00	28.00
42.	0.1832	0.2325	0.2319
114.	0.1041	0.1664	0.2316
162.	0.1017	0.1110	0.2083
211.	0.1136	0.1070	0.1156
217.	0.1134	0.1071	0.1157

Model EQ 2 (Actual - Predicted) in Percent Wet Basis Test 3-S

	7.00	17.00	28.00
42.	-0.26	0.12	0.70
114.	2.66	0.04	-1.64
162.	1.90	1.98	-2.39
211.	1.02	1.86	2.07
217.	0.67	2.18	3.22

MEAN ABSOLUTE DEVIATION = 1.5139

MEAN DEVIATION = 0.9413

STANDARD DEVIATION = 1.5732

Table 2.5.25 Validation of EQ 3 for Test 3-S

Actual Grain Moisture Contents Test 3-S

	7.00	17.00	28.00
42.	0.1806	0.2337	0.2389
114.	0.1307	0.1668	0.2152
162.	0.1207	0.1308	0.1844
211.	0.1238	0.1256	0.1363
216.	0.1201	0.1289	0.1479

Model EQ 3 Verification Study Test 3-S

	7.00	17.00	28.00
42.	0.1734	0.2295	0.2293
114.	0.1146	0.1503	0.2279
162.	0.1203	0.1128	0.1784
211.	0.1317	0.1198	0.1147
216.	0.1324	0.1218	0.1155

Model EQ 3 (Actual - Predicted) in Percent Wet Basis Test 3-S

	7.00	17.00	28.00
42.	0.72	0.42	0.96
114.	1.61	1.65	-1.27
162.	0.04	1.80	0.60
211.	-0.79	0.58	2.16
216.	-1.23	0.71	3.24

MEAN ABSOLUTE DEVIATION = 1.1858

MEAN DEVIATION = 0.7458

STANDARD DEVIATION = 1.2527

Table 2.5.26 Multiple Model Validation of EQ 1, EQ 2 and EQ 3 for Test 3-S

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
M	18.4538	2	9.2269	14.59	0.0002
T	6.8823	4	1.7206	2.72	0.0667
D	14.5424	2	7.2712	11.50	0.0008
MT	4.5186	8	0.5648	0.89	0.5439
MD	2.0922	4	0.5230	0.83	0.5270
TD	57.4686	8	7.1836	11.36	0.0000
ERROR	10.1169	16	0.6323		
TOTAL	114.0748	44			

2.5.4 Summary of Validation Results

All tests indicate that the three equilibrium models predict a more rapid drying rate than was observed. Although the refined equilibrium model was consistently found to be the best of the three models, adequacy was shown for only two tests, Table 2.5.27. The EQ 3 model was not found to be an accurate model for any of the tests studied.

Consistent model behavior was found to be: decreasing model accuracy with increasing time until midway through the test, then model accuracy would improve until the conclusion of the test. The reason for this phenomena is simply that the grain at the conclusion of the test is in equilibrium with the outside air for all practical purposes. This same behavior was exhibited with respect to depth of the drying bed. It is then easy to undertand why the time, depth and time x depth components in the analysis of variance were very significant.

Because of the lack of prediction accuracy, it was concluded that the equilibrium models were not satisfactory mathematical prediction models of these validation tests.

2.6 Conclusions

1. The refined equilibrium model was found to be the best of the models tested.
2. None of these equilibrium models can be shown to be accurate models of the natural aeration drying system.
3. The overall results of these tests would indicate that true equilibrium does not exist under these conditions (three hours time increment). Not all of the drying air potential for moisture removal is utilized before the air actually leaves the bin.

Table 2.5.27 Validation Summary

Test	Best Model	Adequate	Accurate	Smallest Standard Deviation
1-N	EQ 1 & EQ 3			EQ 2
1-S	EQ 3			EQ 2
2-N	EQ 3	EQ 3		EQ 2
2-S	EQ 3	EQ 3		?
3-N	EQ 3			EQ 2
3-S	EQ 3			EQ 3

2.7 Areas of Future Research

Since the equilibrium assumption as given by these three models is not sufficiently accurate in most cases, the model building assumptions should be reviewed to develop a more accurate model. This new model should exhibit a fractional step toward equilibrium rather than complete equilibrium.

Additional grain drying studies need to be performed to decrease the possibility that random error is responsible for our conclusions. These drying studies should be performed according to the experimental procedures outlined in Section 1.8. Drying studies of grain other than corn should also be performed and in a like fashion.

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DRYING MODELS

CHAPTER 3

3.1 Introduction

"Grain drying is a process of simultaneous heat and mass transfer. The heat required to evaporate the moisture is removed from the product surface, thus cooling the product. A drying medium is required to heat the product to continue drying and to transport the moisture which has been removed. This drying medium is usually air in most grain drying application." (Bakker-Arkema '71)

If the grain temperature is sufficiently low, the mass transfer within the upper layers can be reversed and condensation will immediately occur. Therefore, it is necessary to accurately predict both moisture removal (drying) and moisture addition (condensation) to effectively model a low temperature aeration system.

3.2 Literature Review

When biological products are dried in a batch process, they will display both a constant rate and falling rate drying periods (Brooker, Bakker-Arkema, Hall '74). This phenomena is analogous to Newton's Law of Cooling.

Newton's Law of Cooling: "The rate of change in temperature of a body surrounded by a medium at constant temperature is proportional to the difference in temperature between the body and the surrounding medium when the temperature is small."

$$\frac{dT}{d\theta} = -K_T(T-T_e) \qquad (3.2.1)$$

T = Temperature

θ = Time

K_T = Heat Transfer coefficient

T_e = external temperature.

Thus, the rate of cooling is proportional to the force exerted by the temperature difference in the system. In grain drying, the rate of drying is assumed to be proportional to the drying force exerted by the drying medium upon the grain. This drying force can be stated as the pressure difference between the water vapor of the grain and the vapor pressure of the air. Thus a valid equation for the drying rate can be written as follows:

$$\frac{dM}{d\theta} = -K_D(PV_g - PV_a) \text{ (Rodeiguez-Arias (56))} \qquad (3.2.2)$$

M = Moisture Content Decimal db,

θ = Time (hr),

K = Mass diffusion coefficient decimal db/hr-psia,

PV_g = Water vapor pressure of grain, psia,

PV_a = Water vapor pressure of air, psia.

If grain moisture is assumed to be linearly dependent upon grain vapor pressure, then equation 3.2.2 becomes:

$$\frac{dM}{d\theta} = -k(M-ME) \qquad (3.2.3)$$

By separating variables and integrating with respect to the boundary conditions, the drying equation has the following closed form solution: (Hall 57)

$$\frac{\bar{M}-ME}{MO-ME} = \exp(-k\theta) \tag{3.2.4}$$

The left hand side of equation 3.2.4 is referred to in the literature as the Moisture Ratio (MR) and is a dimensionless quantity. Solving equation 3.2.4 for the final moisture content gives:

$$\bar{M} = ME + \exp(-k\theta)*(MO-ME) \tag{3.2.5}$$

$\bar{M}$ = Average moisture content of a thin layer decimal db,

ME = Equilibrium moisture content of the grain in a thin layer, decimal db,

MO = Original moisture content of the grain in a thin layer,

θ = Time,

k = Drying constant decimal

This equation will be referred to as the Moisture Ratio Drying Model (MR), with the difference being in the definition of the equilibrium moisture content. For the evaluation of this model, the equilibrium moisture content is the true value of the equilibrium moisture content as found by first solving an equilibrium model of Chapter 2 and then calculating the resultant final moisture content from Equation 3.2.5.

If, however, the linear dependence of grain moisture upon saturation pressure is not acceptable, then provided a good representation of the equilibrium relative humidity is available, the vapor pressure of the grain can be calculated. For a small time increment Δt and recalling the definition of relative humidity (PVG = ERH*PSG and PVA = RHA*PSA) Equation 3.2.2 can be approximated by:

$$\frac{MF\text{-}MO}{NTINC} = -DC*(ERH*PSTG-RHA*PS_a) \qquad (3.2.6)$$

MF,MO = Final and original moisture content dry basis

NTINC = Small time increment (hr)

DC = Diffisuion coefficient (decimal dry basis/hr · psia)

ERH = Equilibrium Relative Humidity dec.

PSTG = Saturation pressure at the temperature of the grain, TG.

Solving Equation 3.2.6 for the desired final moisture content (MF), yields the following mass diffusion equation, which will be used in grain dryer modeling:

$$MF = MO-DC*NTINC*ERH*PSTG-RHA*PSTA) \qquad (3.2.7)$$ *

Although Brooker, Bakker-Arkema and Hall (74) discuss six possible mechanisms which attempt to explain the drying phenomena, only these two methods were considered in this study. The Moisture Ratio (MR) Equation 3.2.5 is considered to be a semi-theoretical approach and the Mass Diffusion (DRY) (hydrodynamic flow according to Drying of Cereal Grains, (74)), Equation 3.2.7 is a theoretical extension of Newton's law of cooling.

3.3 Model Development

Bakker-Arkema et al (74) stated, "Not one of the theoretical or semi-theoretical equations presented represents the drying process of cereal grains accurately over the full moisture content range from M_0 to M_e." In order to achieve the desired accuracy,empirical equations are to be used.

Since the moisture ratio model is a simple extension to the equilibrium model, it was tested first. If, however, it shows increased accuracy over the equilibrium model, then the mass diffusion model should be tested. The mass diffusion model is considered to be more accurate and computationally efficient.

3.3.1 Moisture Ratio Model MR

The moisture ratio equation in simplest form is expressed as:

$$\frac{\bar{M} - ME}{MO - ME} = \exp(-k\theta) \qquad (3.3.1)$$

solving for the average moisture content within a layer ($\bar{M}$) yields:

$$\bar{M} = ME + (MO - ME) \cdot \exp(-k\theta) \qquad (3.3.2)$$

Using the same approach as with the equilibrium models according to time interval, a small time interval is used NTINC (hr). The initial moisture content of that layer is used for MO, and the ME is the simultaneous solution of the equilibrium model which calculates the true equilibrium state. In order to find appropriate values of k for the MR equation, several model runs must be made for each test to determine which constant gives the best accuracy. The best accuracy is that difference table with the smallest standard deviation.

Since the time interval is the same throughout the modeled period, a collection of terms was made to simplify the determination of appropriate k values. With this done, our first equation of the MR model is a simplification of Equation 3.3.2 as follows:

$$MF = ME + (MO - ME) * DK \qquad (3.3.3)$$

MF = Final moisture content dry basis

MO = Original moisture content

ME = Equilibrium moisture content from the equilibrium model ✓

DK = Simplified form of the drying constant (DK = exp(-k * NTINC))

It is apparent that this method is deterministic but is implicitly dependent upon the equilibrium model to supply the equilibrium moisture contents. This model will not be as efficient for calculations as the equilibrium model. However, the accuracy must be significantly better, according to AOV Model II, than the equilibrium models to be accepted.

Once the final moisture content of the grain for a particular layer is known, the mass balance equation is solved for the final absolute humidity of the air as follows:

$$HF = (MO-MF)*GLB/ALB + HO \tag{3.3.4}$$

HO = Original absolute humidity of the air (lbs. H_2O/lbs. air),

HF = Final absolute humidity of the air (lbs. H_2O/lbs. air),

MO = Original moisture content of the grain (lbs. H_2O/lbs. grain),

MF = Final moisture content of the grain (lbs. H_2O/lbs. grain),

GLB = Pounds of dry grain/ft^2 x layer,

ALB = pounds of dry air/ft^2.

The final temperature of the grain (TF) is assumed to be equal to the air temperature at the end of the time increment NTINC and is calculated from the heat balance which is:

$$\begin{aligned} TF = {} & (.24*ALB*TO+ALB*HO*(1060.8+.45*TO)- \\ & ALB*HF*1060.8+GLB*(MO+1.)*(.35+.851* \\ & (MO/(1.+MO)))*TG)/(.24*ALB+ALB*HF* \\ & .45+GLB*(MF+1.)*(.35+.851*MF/(1.+MF))) \end{aligned} \tag{3.3.5}$$

The final relative humidity of the exit air is calculated using the final temperature of the air and final absolute humidity.

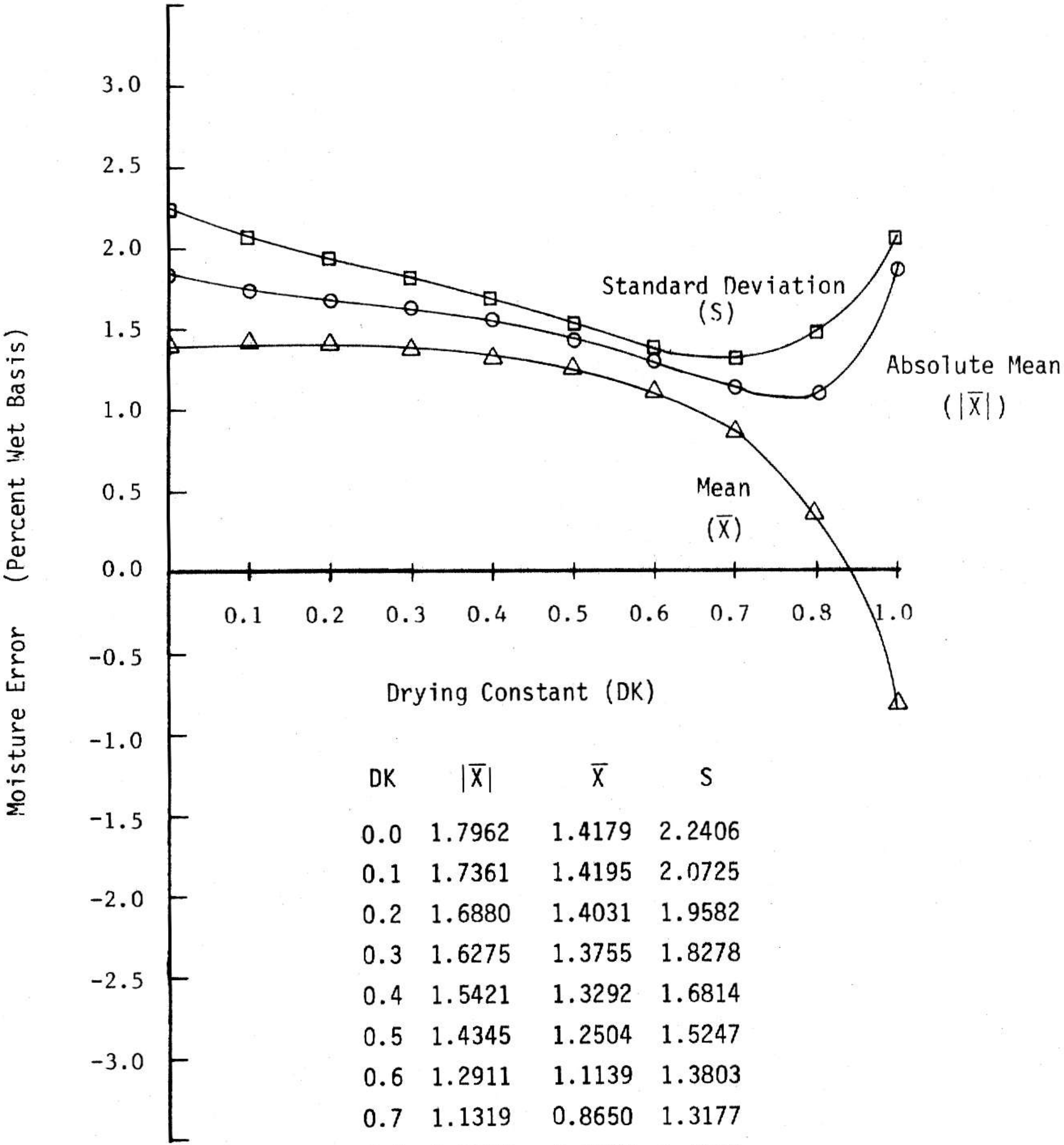
$$RHF = \frac{(ATM * HF) * PS}{(.6219 + HF)} \tag{3.3.6}$$

This set of equations is consistent with those given for the equilibrium models of Chapter 2. The DK of Equation 3.3.3 may be interpreted as the partial step this grain moisture will take toward equilibrium.

3.3.2 Moisture Ratio Model Behavior

With a drying constant DK equal to zero, the MR model is simply the EQ 3 model. As the drying constant increases, the proportion of predicted drying will become less and less. The validation of this model can be done by finding the DK which gives optimum MR prediction accuracy. Assuming that the equilibrium model would specify the total available drying potential with the initial conditions, prediction accuracy should increase with increasing DK. The results of the modeling runs are summarized in Figures 3.3.1 through 3.3.6. As stated in Chapter 1, the optimum difference table contains small errors, randomly distributed with the smallest possible error variance. Therefore, the optimum difference table will be that which contains the minimum standard deviation.

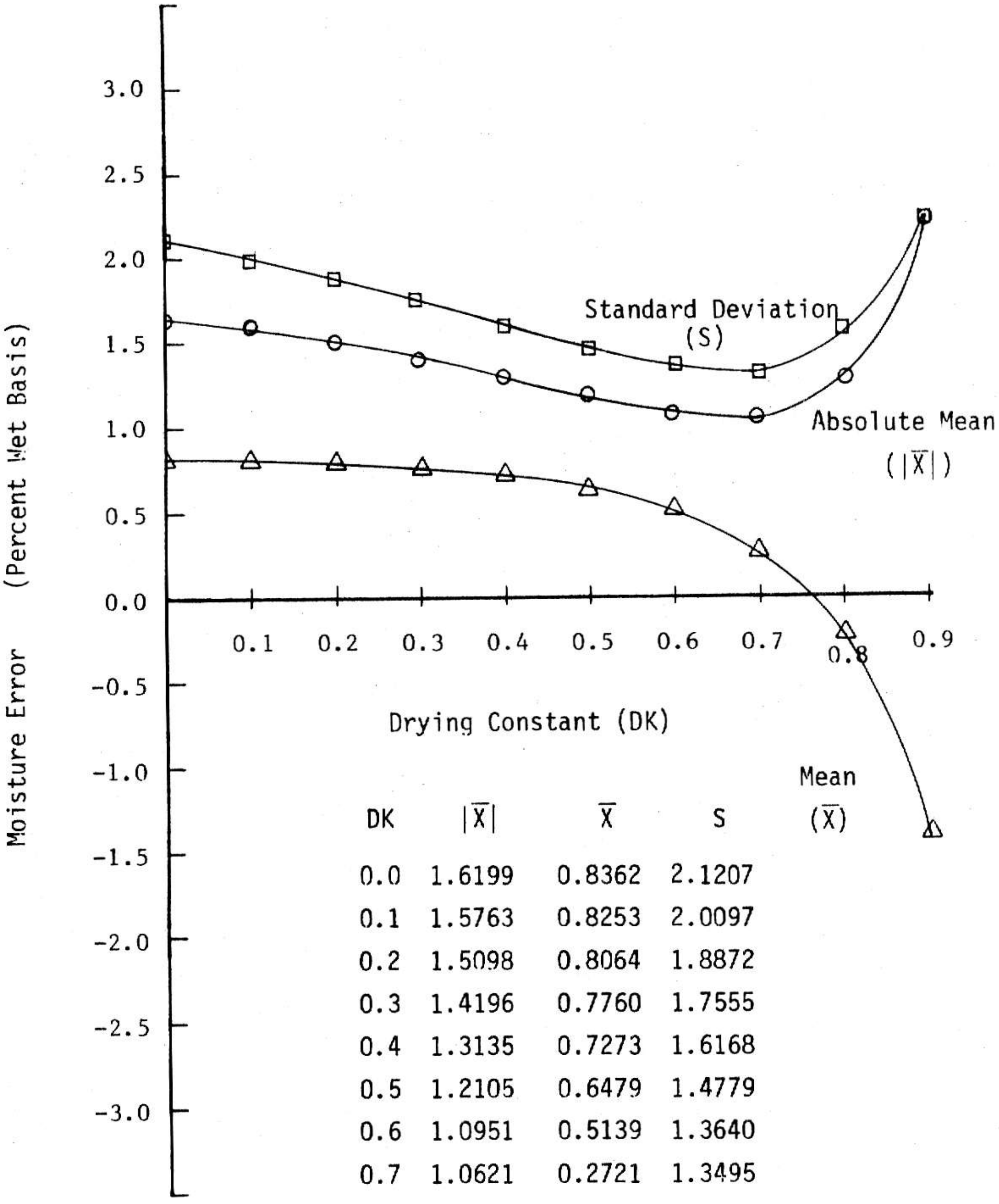
All of the six tests gave results consistent with expected behavior of the standard deviation. As the predicted moisture content was increased from the equilibrium value toward the initial moisture content, accuracy gradually increased until an optimum was reached. Further movement past this optimum produced sharp increases in the error standard deviation, as seen in Figures 3.3.1 to 3.3.6.



DK	$\lvert\bar{X}\rvert$	$\bar{X}$	S
0.0	1.7962	1.4179	2.2406
0.1	1.7361	1.4195	2.0725
0.2	1.6880	1.4031	1.9582
0.3	1.6275	1.3755	1.8278
0.4	1.5421	1.3292	1.6814
0.5	1.4345	1.2504	1.5247
0.6	1.2911	1.1139	1.3803
0.7	1.1319	0.8650	1.3177
0.8	1.0902	0.3670	1.4846
0.9	1.8639	-0.8412	2.0502

Figure 3.3.1 Effect of Drying Constant DK upon MR Model Prediction Accuracy.

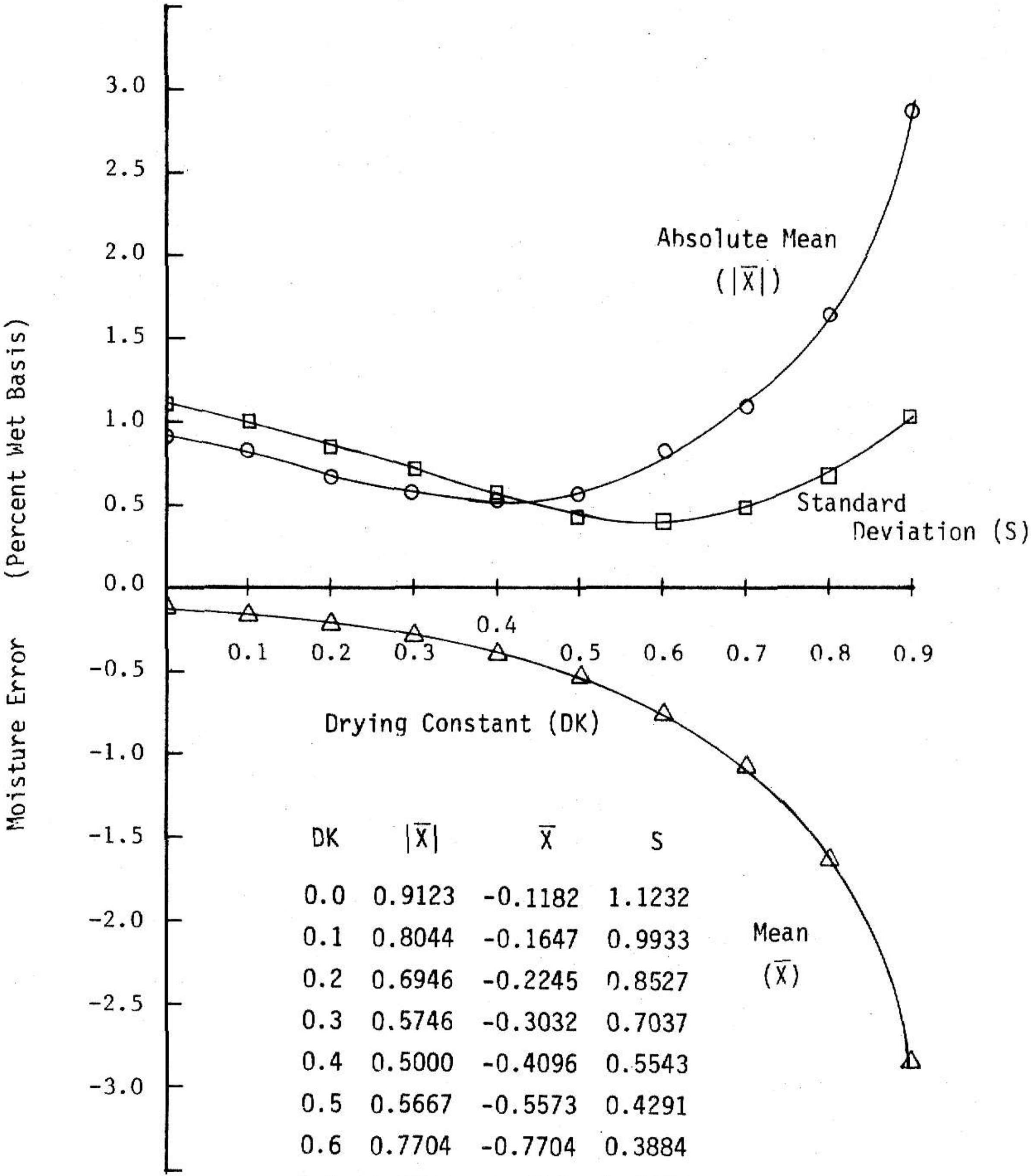
Test 1-N



DK	$\lvert\bar{X}\rvert$	$\bar{X}$	S
0.0	1.6199	0.8362	2.1207
0.1	1.5763	0.8253	2.0097
0.2	1.5098	0.8064	1.8872
0.3	1.4196	0.7760	1.7555
0.4	1.3135	0.7273	1.6168
0.5	1.2105	0.6479	1.4779
0.6	1.0951	0.5139	1.3640
0.7	1.0621	0.2721	1.3495
0.8	1.2831	-0.2128	1.5860
0.9	2.2170	-1.4090	2.2491

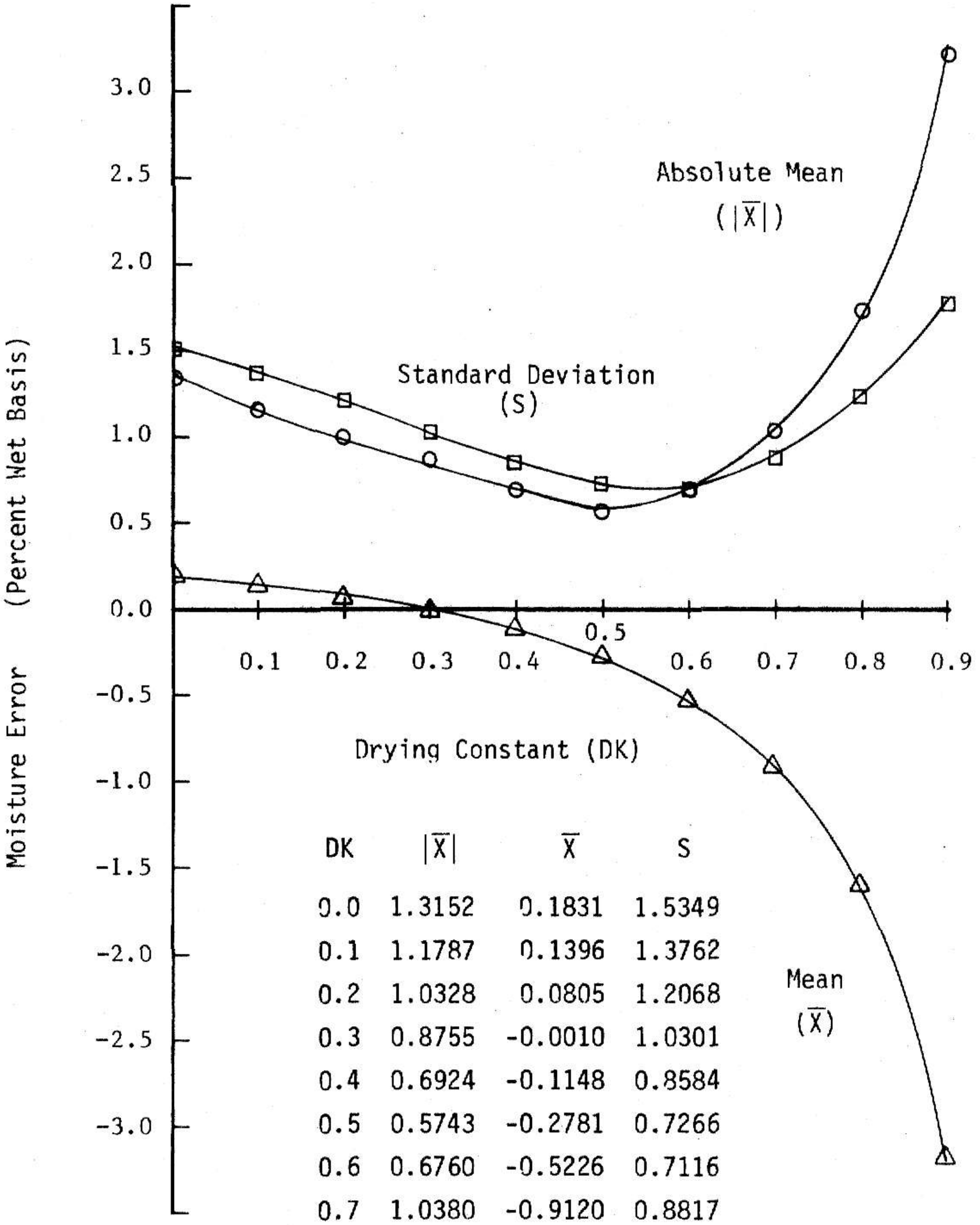
Figure 3.3.2 Effect of Drying Constant (DK) upon MR Model Prediction Accuracy.

Test 1-S



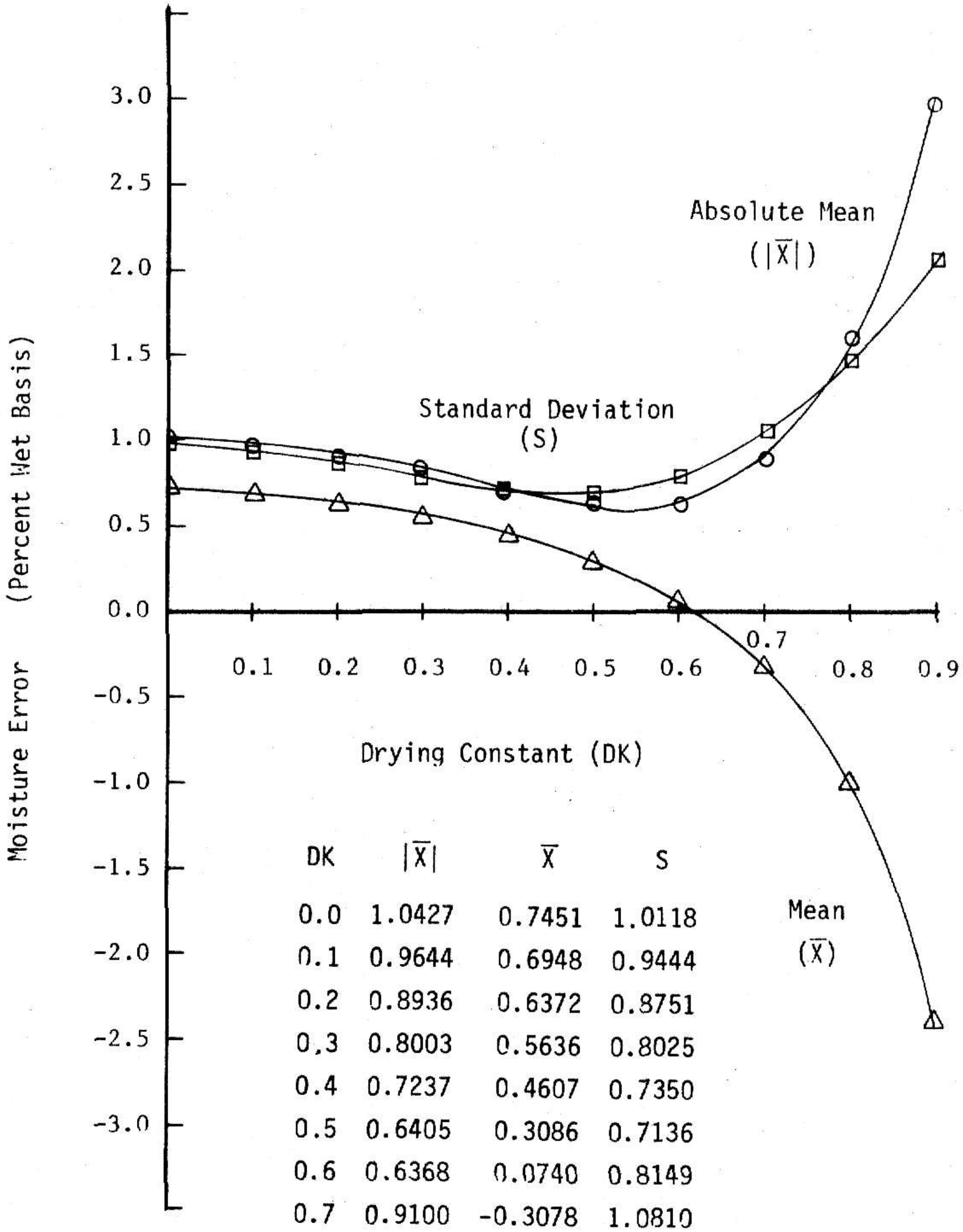
DK	$\lvert\bar{X}\rvert$	$\bar{X}$	S
0.0	0.9123	-0.1182	1.1232
0.1	0.8044	-0.1647	0.9933
0.2	0.6946	-0.2245	0.8527
0.3	0.5746	-0.3032	0.7037
0.4	0.5000	-0.4096	0.5543
0.5	0.5667	-0.5573	0.4291
0.6	0.7704	-0.7704	0.3884
0.7	1.0965	-1.0965	0.4822
0.8	1.6560	-1.6560	0.6760
0.9	2.8737	-2.8737	1.0247

Figure 3.3.3 Effect of Drying Constant upon MR Model Prediction Accuracy. Test 2-N



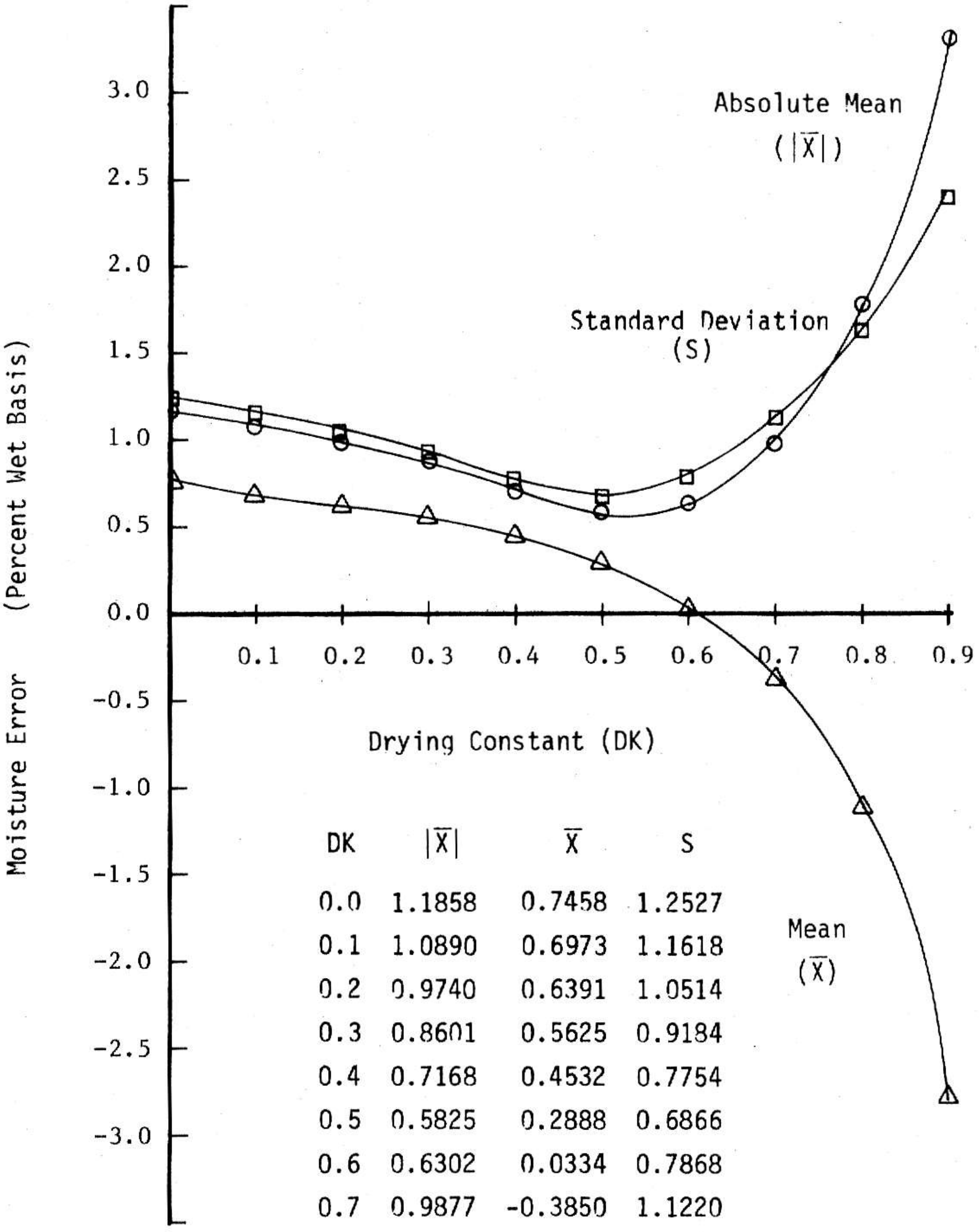
DK	$|\overline{X}|$	$\overline{X}$	S
0.0	1.3152	0.1831	1.5349
0.1	1.1787	0.1396	1.3762
0.2	1.0328	0.0805	1.2068
0.3	0.8755	-0.0010	1.0301
0.4	0.6924	-0.1148	0.8584
0.5	0.5743	-0.2781	0.7266
0.6	0.6760	-0.5226	0.7116
0.7	1.0380	-0.9120	0.8817
0.8	1.7230	-1.6071	1.2295
0.9	3.2153	-3.1765	1.7951

Figure 3.3.4 Effect of Drying Constant upon MR Model Prediction Accuracy.
Test 2-S



DK	$\lvert\overline{X}\rvert$	$\overline{X}$	S
0.0	1.0427	0.7451	1.0118
0.1	0.9644	0.6948	0.9444
0.2	0.8936	0.6372	0.8751
0.3	0.8003	0.5636	0.8025
0.4	0.7237	0.4607	0.7350
0.5	0.6405	0.3086	0.7136
0.6	0.6368	0.0740	0.8149
0.7	0.9100	-0.3078	1.0810
0.8	1.6173	-0.9922	1.4910
0.9	2.9836	-2.4821	2.080

Figure 3.3.5 Effect of Drying Constant (DK) upon MR Prediction Accuracy.
Test 3-N



DK	$\lvert\overline{X}\rvert$	$\overline{X}$	S
0.0	1.1858	0.7458	1.2527
0.1	1.0890	0.6973	1.1618
0.2	0.9740	0.6391	1.0514
0.3	0.8601	0.5625	0.9184
0.4	0.7168	0.4532	0.7754
0.5	0.5825	0.2888	0.6866
0.6	0.6302	0.0334	0.7868
0.7	0.9877	-0.3850	1.1220
0.8	1.7909	-1.1417	1.6377
0.9	3.3279	-2.7996	2.4039

Figure 3.3.6 Effect of Drying Constant (DK) upon MR Model Accuracy.
Test 3-S

This sharp increase is expected because when the initial moisture content is approached as a constant prediction for the test; this means that no moisture was removed throughout the test.

The standard deviation is seen to behave in a consistent fashion from test to test. The mean of test 2-N and 2-S, Figures 3.3.3 and 3.3.4, appears to be small compared with the other tests. If the curve representing the mean were raised with the shape intact, the absolute mean curve would decrease below the standard deviation curve.

Test 2-N, Figure 3.3.3, shows a definite inconsistency with the understanding of the equilibrium model gained by observance of the MR model behavior. This chart says that more drying occurred in the actual test than what the model predicts. It has been accepted by the author that the equilibrium model will effectively calculate the upper limit to drying or maximum amount of moisture removal.

Inputs for Test 2-N have been carefully reviewed with actual data, the output inspected and no discrepancy could be found.

FACTORS WHICH AFFECT THE DRYING CONSTANT.

Tables 3.3.1 through Table 3.3.3 summarize the optimum drying constant (DK) for each of the validation studies. Table 3.3.2 shows the effect of airflow rate, plenum temperature and weight of grain per layer upon the drying constant (DK). Note that the only true correlation which can be said to exist is shown in Table 3.3.3. I have concluded that the optimum drying constant (DK) varies with the percentage of drying system sampled.

Table 3.3.1 Optimum Drying Constants for MR Model

	Optimum Drying Constant (DK)	
Study	Natural	Solar
1	.7	.7
2	.6	.6
3	.5	.5

Table 3.3.2 Analysis of Optimum Drying Constant.

Study	Airflow (ft/min)	Optimum (DK)
1-S	8.6	.7
1-N	10.0	.7
3-S	10.1	.5
3-N	11.0	.5
2-N	28.9	.6
2-S	30.0	.6

Study	Temperature Avg. Plenum	Optimum (DK)
3-N	58.2	.5
1-N	58.3	.7
2-N	58.3	.6
2-S	59.3	.6
3-S	60.8	.5
1-S	62.0	.7

Study	Grain/Layer (lb)	Optimum DK
3-N	15.1	.5
3-S	15.9	.5
1-S	20.7	.7
1-N	22.2	.7
2-N	42.8	.6
2-S	43.2	.6

Table 3.3.3 The Effect of Drying Sample Size Upon Optimum Drying Constant

Study	Number of Observations	Number of Observations Above 15.5% wb	% Above ≥15.5	Optimum (DK)
1-N	40	25	63	.7
1-S	40	19	48	.7
2-N	27	12	44	.6
2-S	27	12	44	.6
3-N	15	6	40	.5
3-S	15	6	40	.5

✱3.3.3 Mass Diffusion Model (DRY 4)

The natural aeration drying is a continuous process with changes in moisture content and temperature of the air and grain occuring simultaneously. This process is to be modeled by calculating air and grain state points across the grain bed with the passage of time. The continuous variable of time is approximated by taking small time increments or steps. This is to give the appearance of change with respect to time. The continuous variable of grain depth in the drying bin is modeled by taking small depth increments or layers.

This system is simplified by assuming a one-foot square column of grain will be arbitrarily selected within the bin. We assume that the changes within this theoretical column will reflect the fluctuations throughout the drying bin. Since the thickness of these layers will change with moisture content, they are calculated on an equal dry weight basis.

The airflow is assumed to be from bottom to top, with the exhaust air of the i^{th} layer being the input air to the $i+1^{th}$ layer, at any given time (j) and layer (i). This is then a system with five known attributes:

1. TO = Initial air temperature (^{o}F),
2. HO = Initial absolute humidity of air (lb. H_2O/lb. air),
3. RHA = Relative Humidity of air (decimal),
4. TG = Initial grain temperature (^{o}F),
5. MO = Initial grain moisture content (lb. H_2O/lb. grain).

We wish to calculate the final conditions as the air exits this layer just as the time t becomes t + Δt. To do this, we use four equations to determine each of the four unknowns, TF, HF, MF, RHF. A visualization of the i^{th} j^{th} layer (time i, layer j) is shown in Figure 3.3.7.

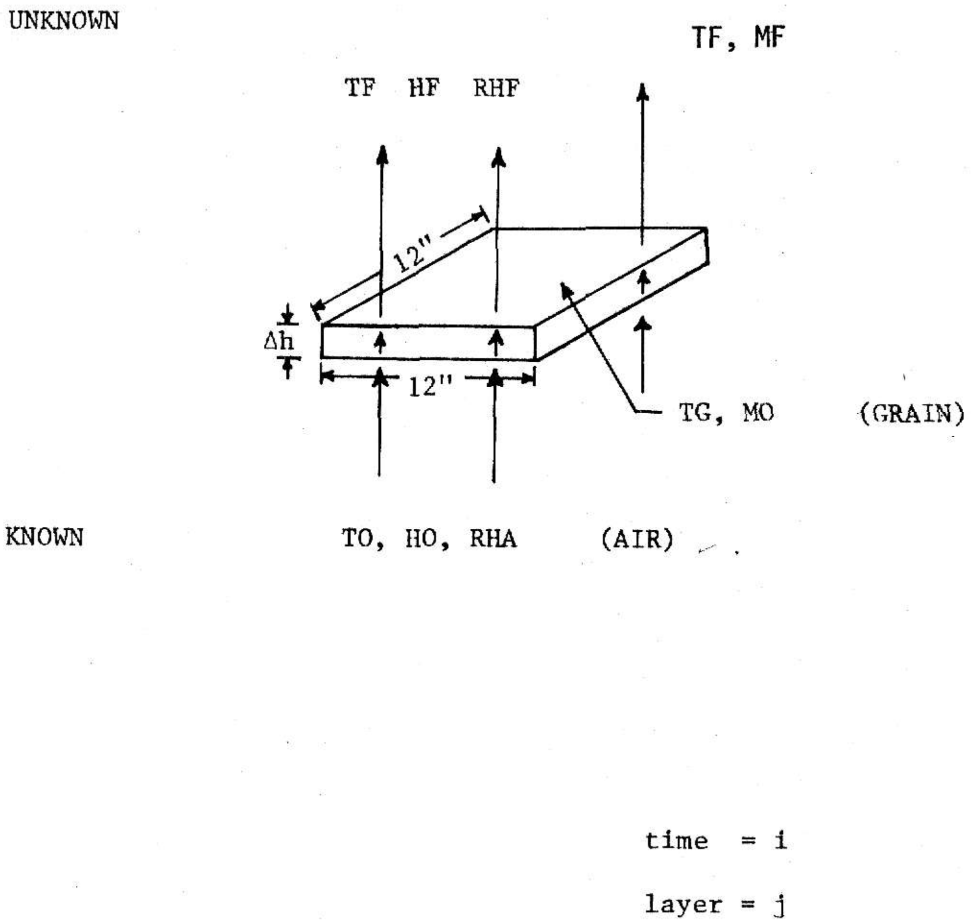


Figure 3.3.7 The Visualization of a Modeled Layer

3.3.4 Validation of DRY 4 Model with Test 1-N

1. Mass diffusion is assumed to be the governing process for the natural aeration system and is given as Equation 3.3.7.
2. Since a constant (DC) is used for the diffusion coefficient throughout the test, no temperature or moisture gradients are assumed to exist within each grain particle.
3. Heat transfer is implicitly defined by the mass transfer given and is therefore deterministic.
4. Final air temperature is equal to final grain temperature.
5. Airflow is plug type which means that the total weight of air for a time increment Δt is considered present at time t_i.
6. Heat transfer is adiabatic with no conduction losses laterally from the layer.
7. The total mass of the system remains constant within the time interval and mixing does not occur between layers.
8. The bin is assumed to be air tight with atmospheric pressure or site elevation given.
9. Density fluctuations do exist over time and are given as functions of moisture content only.

3.3.5 Validation of DRY 4 Model with Test 1-S

The mass diffusion model was chosen to be tested against the experimental data because of its theoretically greater accuracy. The diffusion model will also be deterministic and a more efficient, computer model.

* The final moisture content of a layer is determined by the following mass diffusion equation: Rodriguez-Arias (56)

$$MF = MO - DC*NTINC*(ERH*PSTG-RHA*PSA) \qquad (3.3.7)$$

The equilibrium relative humidity for the grain is calculated from the Chung-Pfost equilibrium relative humidity equation as follows:

Chung-Pfost (67)

$$ERH = Exp(-PA/(RO*(TG+PC))*Exp(-PB*M)) \qquad (3.3.8)$$

ERH = Equilibrium Relative Humidity of the grain at TG, M0

PSTG = Saturation vapor pressure of water at initial grain temperature (TG)

PSA = Saturation vapor pressure of water at initial air temperature (T0)

RO = Universal Gas Constant 1.987 Kcal/Kmol · K

Saturation pressure is given by the following equation:

Brooker (74) $491 < T < 959.69$

$$PS = R*exp((A+B*T+C*T^2+D+T^3+E*T^4)/(F*T-G*T^2)) \qquad (3.3.9)$$

$459.69 < T < 491.69$ see section (2.2.7)

$$PS = exp(23.3924-(11286.69/T)-0.46057*ALOG(T)) \qquad (3.3.10)$$

For Constants and Nomenclature see section 2.2.6

The absolute humidity is calculated by solving the mass balance equation using the calculated value of moisture content.

$$HF = HO + (MO-MF) * GLB/ALB \qquad (3.3.11)$$

The final temperature of the grain is assumed to be equal to the final air temperature. This value is obtained by solving the heat balance equation used in the EQ 3 model for final temperature (TF).

Thompson (72)

$$\begin{aligned}TF = {} & (.24*ALB*TO+ALB*HO*(1060.8+.45*TO)- \\ & ALB*HF*1060.8+GLB*(MO+1.)*(.35+.851* \\ & (MO/(1.+MO)))*TG)/(.24*ALB+ALB*HF* \\ & .45+GLB*(MF+1.)*(.35+.851*MF/(1.+MF)))\end{aligned} \tag{3.3.12}$$

Relative humidity of the exit air is found by the equation given for relative humidity in the EQ 3 model (Brooker (74)).

$$RHF = (ATM*HF*PS_{TF})/(.6219+HF) \tag{3.3.13}$$

This proposed diffusion model was programmed and verified in FORTRAN IV G and will be referred to as the DRY 4 model for convenience. The DRY 4 model is given in Appendix D.

Corn drying data given in Rodriquez-Arias (56) was used to determine initial estimates for the mass diffusion coefficient DC in Equation 3.3.7. It was found that the diffusion coefficient did fluctuate throughout the drying tests. The calculated diffusion coefficient decreased in magnitude as the experiment progressed. However, the value .02 best described the drying region above 15.5% wb. This value will be used as a starting estimate for the DRY 4 model validation tests (DC = .02 decimal dry basis/hr.-psia).

3.3.6 Multiple Model Validation EQ 1, EQ 2, EQ 3, DRY 4 TEST 1-N

The results of the DRY 4 model are given in Tables 3.3.4 and 3.3.5. The difference tables for the natural aeration and the solar tests are seen to be predominately positive as with the equilibrium models. The Analysis of Variance model for comparison of the four drying models, EQ 1, EQ 2, EQ 3 and DRY 4 was evaluated. The resultant AOV table is given in Table 3.3.6 The F ratio test indicates a significant model effect upon the error means. It is concluded that at least one model is significantly better than the others. The method of Least Significant Difference (LSD) was used to find the best model. The DRY 4 is significantly more accurate than EQ 1 and EQ 2. Since the DRY 4 mean is also significantly different from zero, it cannot be considered an adequate model for TEST 1. The DRY 4 model produced predictions that were equivalent to the EQ 3 model.

Both the solar and natural portions of the first test indicate that a diffusion coefficient of .02 is not adequate for model predictions of TEST 1.

Table 3.3.4 Validation of DRY 4 Model with Test 1-N

Actual Grain Moisture Contents Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	0.2153	0.2256	0.2211	0.2173	0.2167
92.	0.1675	0.2249	0.2220	0.2210	0.2190
161.	0.1265	0.1695	0.2160	0.2165	0.2138
213.	0.1220	0.1468	0.1868	0.2133	0.2120
260.	0.1293	0.1430	0.1638	0.2035	0.2168
332.	0.1360	0.1362	0.1558	0.1587	0.1694
382.	0.1408	0.1405	0.1445	0.1584	0.1657
480.	0.1466	0.1406	0.1411	0.1447	0.1423

Model DRY 4 Verification Study of Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	0.2075	0.2127	0.2160	0.2180	0.2191
92.	0.1769	0.1957	0.2075	0.2141	0.2179
161.	0.1282	0.1558	0.1791	0.1943	0.2029
213.	0.1192	0.1353	0.1574	0.1772	0.1904
260.	0.1302	0.1333	0.1452	0.1633	0.1803
332.	0.1394	0.1362	0.1366	0.1432	0.1559
382.	0.1445	0.1416	0.1402	0.1423	0.1495
480.	0.1479	0.1440	0.1417	0.1411	0.1424

Model DRY 4 (Actual - Predicted) in Percent Wet Basis Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	0.78	1.29	0.51	-0.07	-0.24
92.	-0.94	2.92	1.45	0.69	0.11
161.	-0.17	1.37	3.69	2.22	1.09
213.	0.28	1.15	2.94	3.61	2.16
260.	-0.09	0.97	1.86	4.02	3.65
332.	-0.34	0.00	1.92	1.55	1.35
382.	-0.37	-0.11	0.43	1.61	1.62
480.	-0.13	-0.34	-0.06	0.36	-0.01

MEAN ABSOLUTE DEVIATION = 1.2116
MEAN DEVIATION = 1.0680
STANDARD DEVIATION = 1.3015

Table 3.3.5 Validation of DRY 4 Model with Test 1-S

Actual Grain Moisture Contents Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	0.2146	0.2190	0.2185	0.2179	0.2158
92.	0.1570	0.2217	0.2205	0.2200	0.2169
161.	0.1158	0.1633	0.2148	0.2113	0.2100
213.	0.1085	0.1368	0.1955	0.2110	0.2090
260.	0.1153	0.1317	0.1545	0.1830	0.2090
332.	0.1237	0.1266	0.1460	0.1512	0.1532
378.	0.1257	0.1294	0.1365	0.1534	0.1445
480.	0.1329	0.1288	0.1300	0.1305	0.1323

Model DRY 4 Verification Study of Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	0.2085	0.2153	0.2187	0.2202	0.2209
92.	0.1676	0.1966	0.2099	0.2158	0.2211
161.	0.1168	0.1530	0.1808	0.1964	0.2092
213.	0.1101	0.1278	0.1556	0.1800	0.1929
260.	0.1189	0.1217	0.1367	0.1613	0.1816
332.	0.1311	0.1271	0.1266	0.1345	0.1519
378.	0.1384	0.1342	0.1314	0.1331	0.1425
480.	0.1449	0.1392	0.1358	0.1342	0.1347

Model DRY 4 (Actual - Predicted) in Percent Wet Basis Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	0.61	0.37	-0.02	-0.23	-0.51
92.	-1.06	2.51	1.06	0.42	-0.42
161.	-0.10	1.03	3.40	1.49	0.08
213.	-0.16	0.90	3.99	3.10	1.61
260.	-0.36	1.00	1.78	2.17	2.74
332.	-0.74	-0.05	1.94	1.67	0.13
378.	-1.27	-0.48	0.51	2.03	0.20
480.	-1.20	-1.04	-0.58	-0.37	-0.24

MEAN ABSOLUTE DEVIATION = 1.0897

MEAN DEVIATION = 0.6472

STANDARD DEVIATION = 1.3379

Table 3.3.6 Multiple Model Validation EQ1, EQ2, EQ3, DRY 4 Test 1-N.

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
M	15.0152	3	5.0051	4.86	0.0036
T	144.2510	7	20.6073	20.00	0.0000
D	40.2992	4	10.0748	9.78	0.0000
MT	19.4467	21	0.9260	0.90	0.5929
MD	10.7376	12	0.8948	0.87	0.5814
TD	273.8447	28	9.7802	9.49	0.0000
ERROR	86.5532	84	1.0304		
TOTAL	590.1482	159			

3.3.7 Conclusions of the Mass Diffusion Comparison

The DRY 4 model applied to all six tests with DC = .02 and was found to have the smallest mean error. The diffusion model was found to be the best of the four models tested in all of the tests, with the exception of Test 2-N. The drying model was found to be statistically adequate in three of the six tests, and accurate in one of the six. The critical error variance as represented by the sample standard deviation yielded the result that the DRY 4 model had the smallest standard deviation in the first four tests and of approximately equivalent magnitude in the other two.

The DRY 4 model was the most computationally efficient of the grain drying models. As a comparison, the average execution time for the same six tests required 75 seconds for the equilibrium models and 50 seconds for the DRY 4 model. These are average figures for the CPU time (Central Processing Unit) on an IBM 370/158, executing a load module from a disk data set. These load modules were created by a FORTRAN IV G level IBM compiler in all cases.

Without any further refinement, it has been found that the DRY 4 model is a better predictor than either of the previously tested equilibrium models, and is more efficient. However, the diffusion model can and should be tuned using the experimental data for optimum prediction accuracy. The next section of this chapter deals with diffusion model assumptions, their revision and modification by model tuning.

3.4 Mass Diffusion Model Refinement

The drying model (DRY 4) just proposed does not explicitly include airflow rate (cfm/ft^2) or drying air temperature in the governing mass diffusion equation. Therefore, the diffusion coefficient (DC) is thought to be affected by these factors consistent with other drying models (Barre (71)).

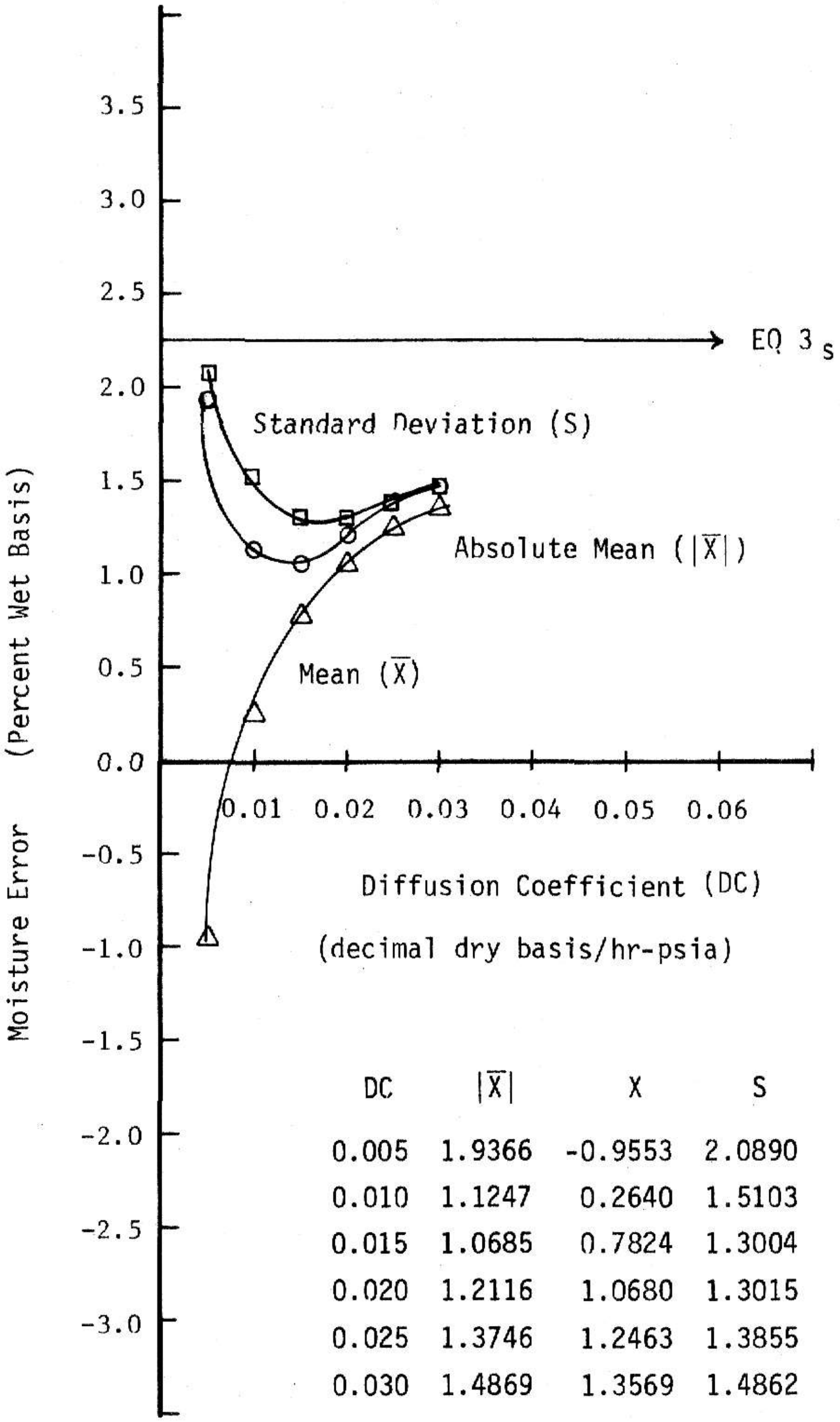
Several modeling runs were made for each test to determine the optimum value of DC for each test. This optimum value of DC should yield a difference table with the smallest standard deviation, and small errors distributed randomly. It is hoped that with these optimum values of DC for these tests, inferences can be made as to the effect of airflow upon the mass diffusion coefficient.

3.4.1 Test 1

Figures 3.4.1 and 3.4.2 give the results of varying the diffusion coefficient upon the DRY 4 model prediction accuracy. The minimum standard deviation occurs at 0.015 for both tests, which is as we would expect. Recall that DC = 0.02 gave results which were overdry and by reducing the coefficient by 0.005, the amount of overdrying is decreased. The Figures 3.4.1 and 3.4.2 also show the standard deviation of the EQ 3 model as a straight line for each test as a comparison.

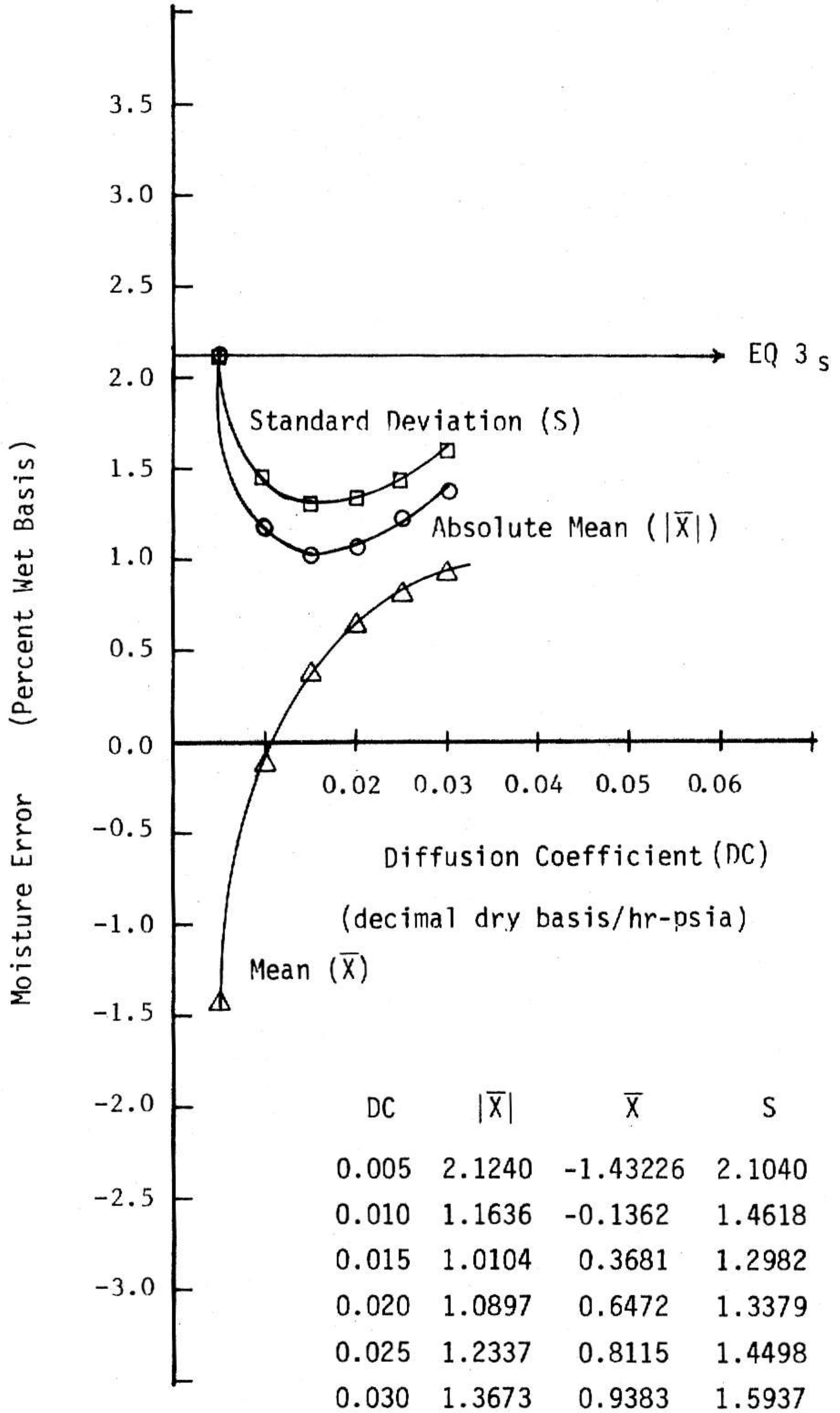
3.4.2 Test 2

Figures 3.4.3 and 3.4.4 show the effect of varying the diffusion coefficient upon the difference table descriptive statistics. The optimum is located at DC = 0.035 for 2-N and 2-S. In both cases, it



DC	$|\overline{X}|$	X	S
0.005	1.9366	-0.9553	2.0890
0.010	1.1247	0.2640	1.5103
0.015	1.0685	0.7824	1.3004
0.020	1.2116	1.0680	1.3015
0.025	1.3746	1.2463	1.3855
0.030	1.4869	1.3569	1.4862

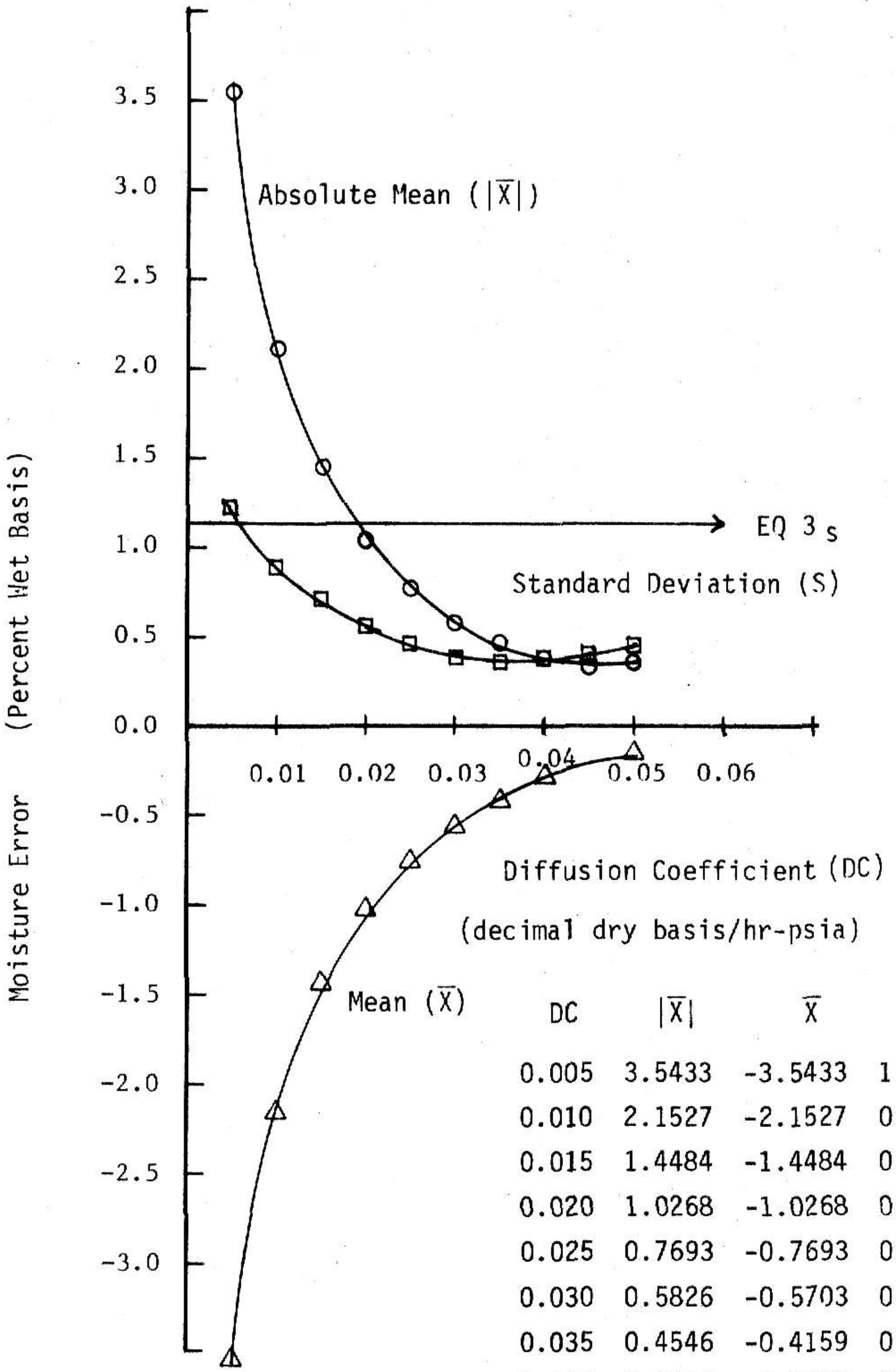
Figure 3.4.1 Effect of Diffusion Coefficient upon Model Prediction Accuracy for Test 1-N.



DC	$\lvert\bar{X}\rvert$	$\bar{X}$	S
0.005	2.1240	-1.43226	2.1040
0.010	1.1636	-0.1362	1.4618
0.015	1.0104	0.3681	1.2982
0.020	1.0897	0.6472	1.3379
0.025	1.2337	0.8115	1.4498
0.030	1.3673	0.9383	1.5937

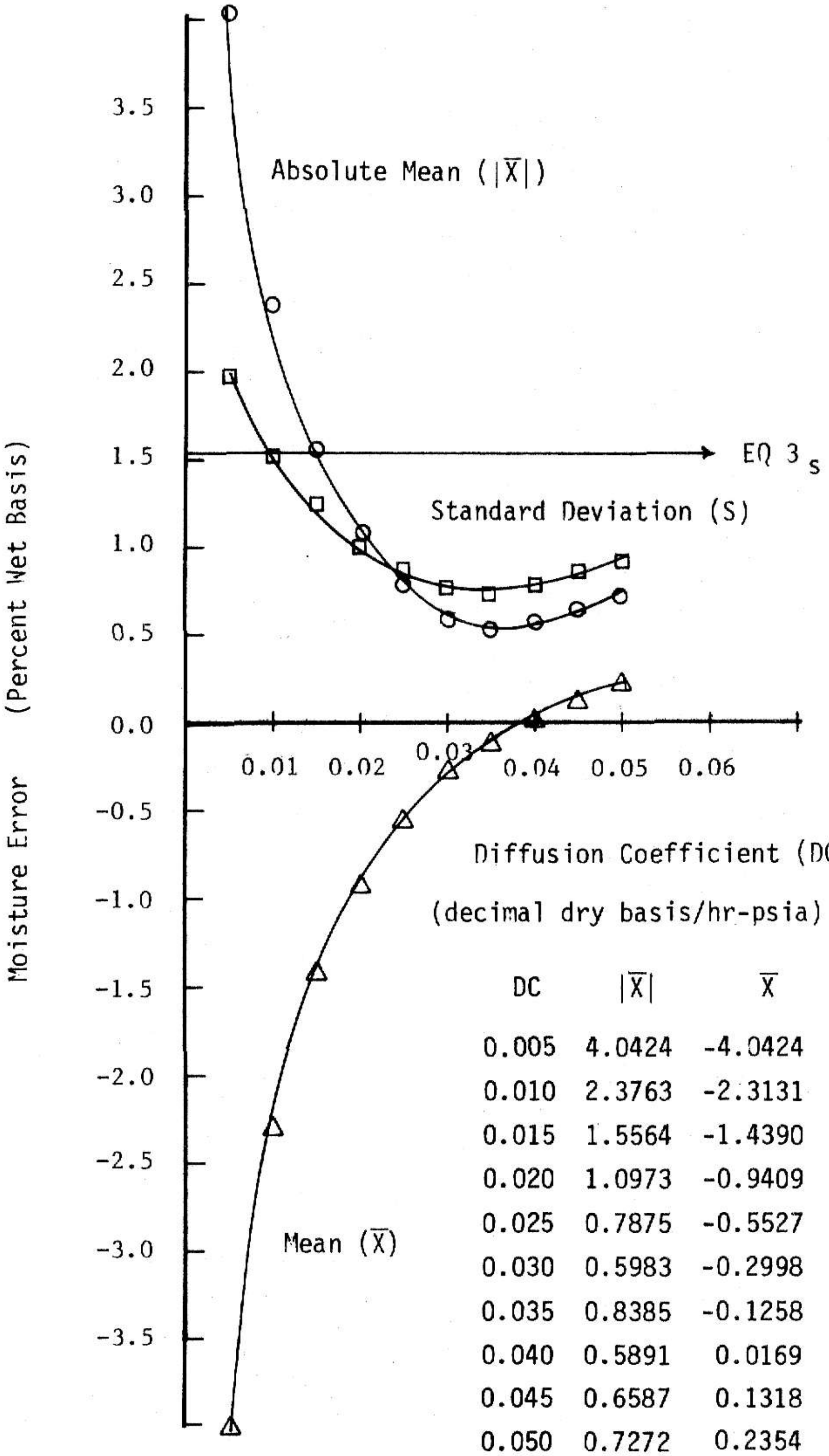
Figure 3.4.2 Effect of Diffusion Coefficient upon Model Prediction Accuracy.

Test 1-S



DC	|X̄|	X̄	S
0.005	3.5433	-3.5433	1.2276
0.010	2.1527	-2.1527	0.8858
0.015	1.4484	-1.4484	0.7102
0.020	1.0268	-1.0268	0.5649
0.025	0.7693	-0.7693	0.4620
0.030	0.5826	-0.5703	0.3969
0.035	0.4546	-0.4159	0.3751
0.040	0.3619	-0.2956	0.3972
0.045	0.3329	-0.2345	0.4005
0.050	0.3501	-0.1575	0.4421

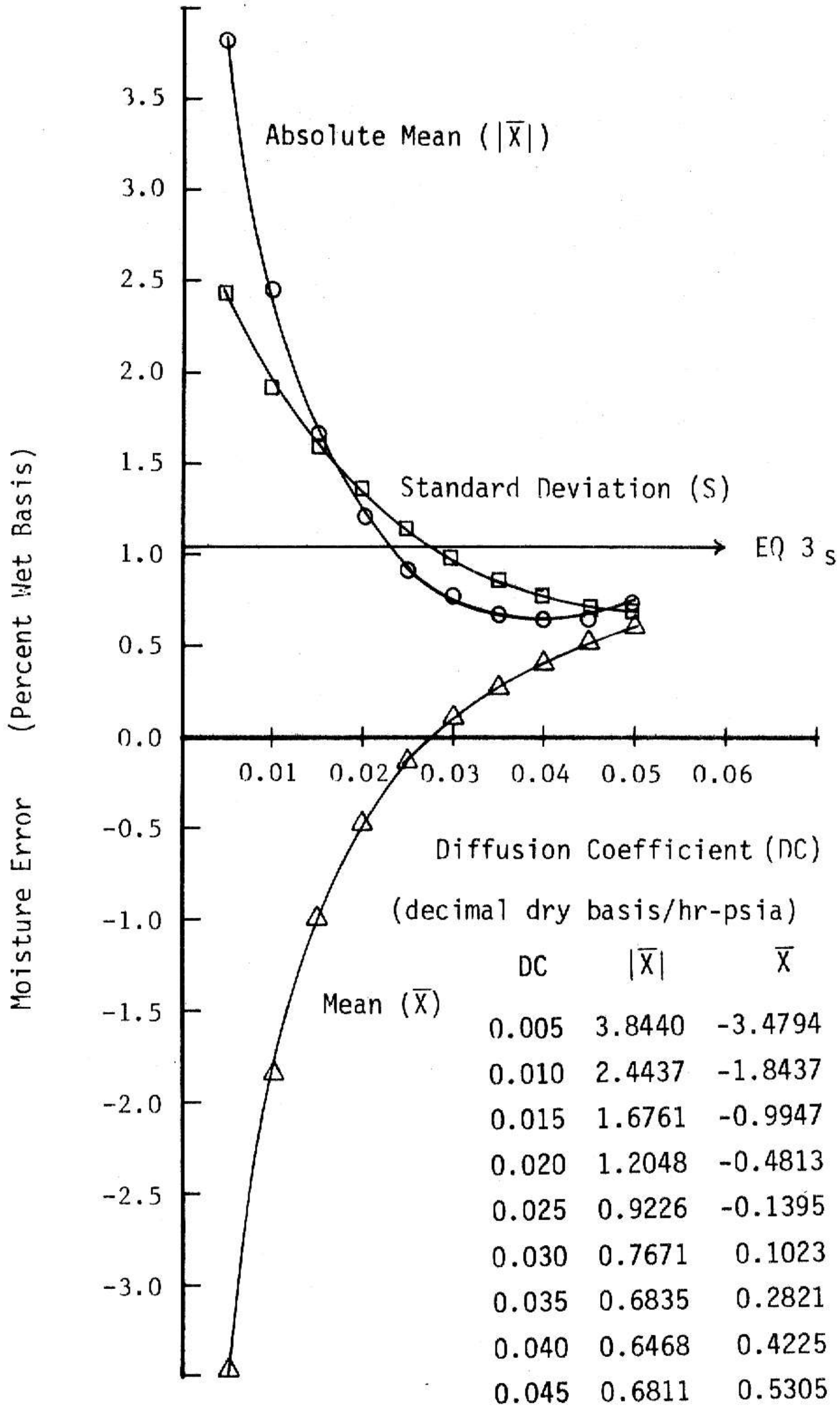
Figure 3.4.3 Effect of Diffusion Coefficient upon DRY 4 Model Accuracy. Test 2-N



DC	|X̄|	X̄	S
0.005	4.0424	-4.0424	1.9684
0.010	2.3763	-2.3131	1.5167
0.015	1.5564	-1.4390	1.2344
0.020	1.0973	-0.9409	1.0217
0.025	0.7875	-0.5527	0.8613
0.030	0.5983	-0.2998	0.7648
0.035	0.8385	-0.1258	0.7475
0.040	0.5891	0.0169	0.7976
0.045	0.6587	0.1318	0.8522
0.050	0.7272	0.2354	0.9111

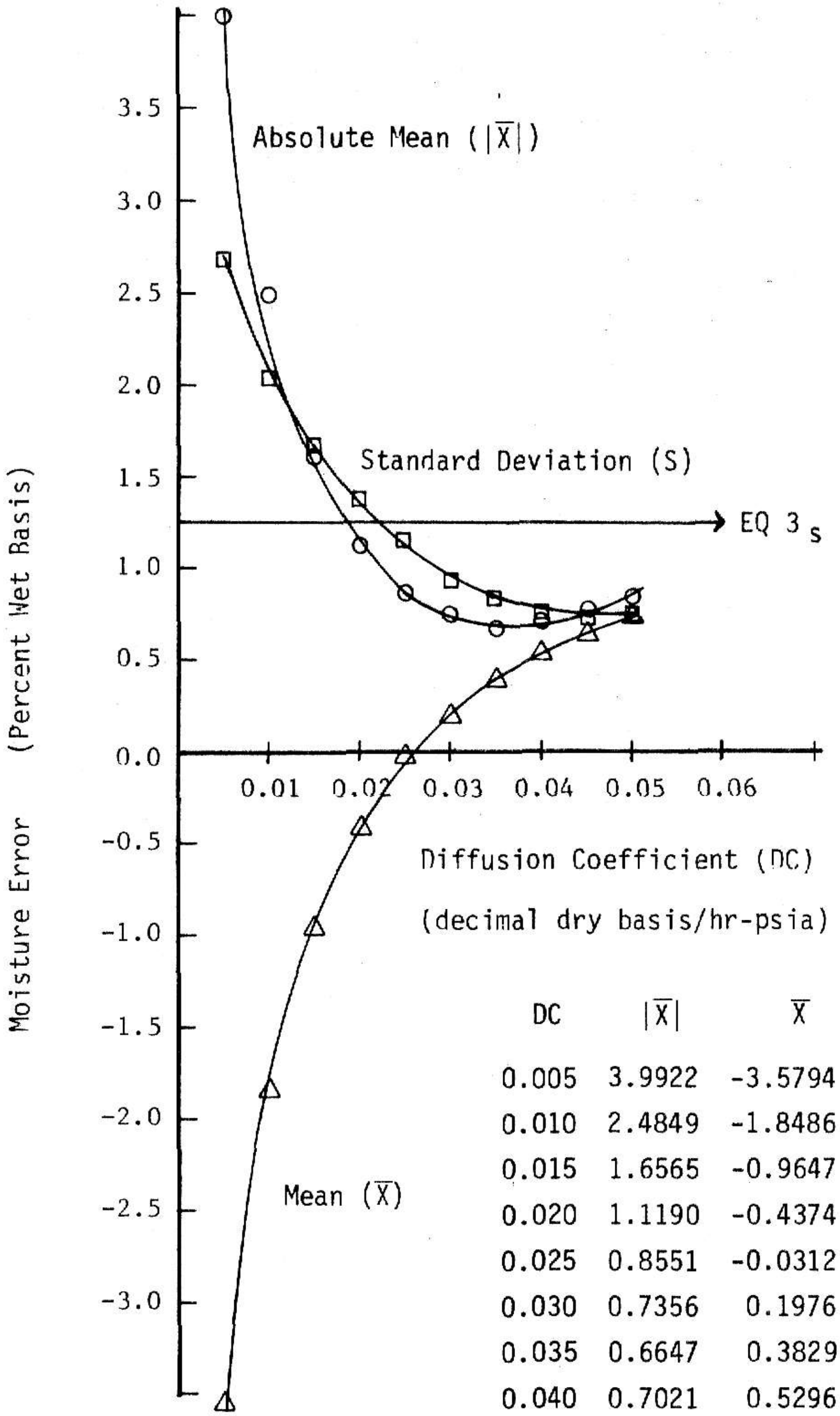
Figure 3.4.4 Effect of Diffusion Coefficient upon Model DRY 4 Accuracy.

Test 2-S



DC	|X̄|	X̄	S
0.005	3.8440	-3.4794	2.4356
0.010	2.4437	-1.8437	1.9255
0.015	1.6761	-0.9947	1.6115
0.020	1.2048	-0.4813	1.3627
0.025	0.9226	-0.1395	1.1560
0.030	0.7671	0.1023	0.9901
0.035	0.6835	0.2821	0.8630
0.040	0.6468	0.4225	0.7703
0.045	0.6811	0.5305	0.7104
0.050	0.7236	0.6170	0.6734

Figure 3.4.5 Effect of Diffusion Coefficient upon DRY 4 Model Accuracy.
Test 3-N



DC	$\lvert\overline{X}\rvert$	$\overline{X}$	S
0.005	3.9922	-3.5794	2.6874
0.010	2.4849	-1.8486	2.0417
0.015	1.6565	-0.9647	1.6369
0.020	1.1190	-0.4374	1.3183
0.025	0.8551	-0.0312	1.1195
0.030	0.7356	0.1976	0.9439
0.035	0.6647	0.3829	0.8198
0.040	0.7021	0.5296	0.7323
0.045	0.7620	0.6360	0.7209
0.050	0.8340	0.7344	0.7640

Figure 3.4.6 Effect of Diffusion Coefficient (DC) upon DRY 4 Model Accuracy. Test 3-S

is seen that the parameters of the difference table at the optimum point for the DRY 4 model are much smaller than the EQ 3 model statistics.

3.4.3 Test 3

Figures 3.4.5 and 3.4.6 show the behavior of the two portions of Test 3 with respect to changing diffusion coefficient. The optimum point is seen to be 0.050 for the natural and 0.045 for the solar test.

Comparing the natural and solar shows that the optimum diffusion coefficient DC is greater for the solar test. Which could indicate that the inlet air temperature has an effect upon the diffusion coefficient.

3.4.4 Conclusions to the Model Refinement

Each of the six tests were found to have an optimum diffusion coefficient which are tabulated in Table 3.4.1. To insure accuracy of the model for prediction using other than experimental data, a method of controlling model accuracy should be determined. Two major areas of accuracy dependence are thought to be:

1. The diffusion coefficient,
2. Depth increment between modeled layers.

The diffusion coefficient has been shown to vary from test to test but what is the major contributing factor? From the previous dryer research Bakker-Arkema (74), Hukill (60), Hustrulid (66) have shown factors which affect dryer performance to be airflow rate, grain temperature, drying air temperature and product moisture content. Several airflow rates were studied in the course of these tests. Table 3.4.2 shows the effect of airflow rate upon the optimum value of the diffusion coefficient DC . It shows a wide variability between tests 1 and 3. These two sets of tests were close replications of each other for airflow rate.

Average plenum air temperatures were computed to compare with the variability of DC. As seen in Table 3.4.2 that essentially all of the six tests had about the same mean plenum temperature throughout the test. Therefore, the effect of plenum temperatures is not observable with this set of test data.

Each test was modeled using 10 theoretical layers, with the weight of grain per layer allowed to change accordingly. Table 3.4.2 shows the comparison between the weight of grain per layer and the diffusion coefficient. A precise statement on the amount of correlation between grain weight per layer and optimum diffusion coefficient can not be made from the present set of drying data.

The duration and conditions of each test vary with respect to observed moisture content. A nominal moisture content of 15.5% wb is used as a criterion for a storage moisture level. The moisture observations below this value are considered dry and those above as in the process of drying. Table 3.4.3 shows the number of sample points greater than 15.5% and the optimum diffusion coefficient. This table indicates an important factor which influences drying model testing.

The analysis of variance technique is insensitive to the best, most accurate model of the drying system if the test results do not reflect the desired system behavior. This means that although our tests were performed as aeration drying studies, our measured results do not completely

Table 3.4.1 Optimum Diffusion Coefficients (DC).

Study	Natural	Solar
1	0.015	0.015
2	0.035	0.035
3	0.050	0.045

Table 3.4.2 Analysis of Optimum Diffusion Coefficients (DC).

Study	Airflow (ft/min)	Optimum DC
1-S	8.6	0.015
1-N	10.0	0.015
3-S	10.1	0.045
3-N	11.0	0.050
2-N	28.9	0.035
2-S	30.0	0.035

Study	Temperature Agv. Plenum	Optimum DC
3-N	58.2	0.050
1-N	58.3	0.015
2-N	58.3	0.035
2-S	59.3	0.035
3-S	60.8	0.045
1-S	62.0	0.015

Study	Grain/Layer (lb)	Optimum DC
3-N	15.1	0.050
3-S	15.9	0.045
1-S	20.7	0.015
1-N	22.2	0.015
2-N	42.8	0.035
2-S	43.2	0.035

Table 3.4.3 The Effect of Drying Sample Size Upon Optimum Diffusion Coefficient.

Study	Number of Observation	Number of Observations Above 15.5% wb	% Observed ≥ 15.5	Optimum (DC)
1-N	40	25	63	.015
1-S	40	19	48	.015
2-N	27	12	44	.035
2-S	27	12	44	.035
3-N	15	6	40	.050
3-5	15	6	40	.045

reflect this system. As an example, note that the last observation in Test 2-N and 2-S is at 279 hours, and that the maximum moisture is 13.7% wb. The same occurred at the end of Test 3-N and 3-S with the samples at 211 and 216 hours being well below the critical storage moisture levels.

The analysis of variance tests will select that model which will best fit all of the experimental data. Therefore, a precise statement of experimental design and desired model behavior is necessary. The model should predict the moisture content within the bin until the top layer has been successfully dried to the desired critical moisture content (M_c = 15.5% w.b.). The experiment should be conducted in such a fashion that the last sample probing has the moisture content of the top layer equal to M_c. During the study, more or fewer samples can be taken depending upon the progress of the drying zone.

3.5 Multiple Model Validation of EQ3 vs MR vs DRY 4.

3.5.1 Results for Tests 1,2,3

The best model performances from Sections 3.3 (MR) vs 3.4 (DRY 4) were compared against EQ 3 using AOV Model II (1.6.2). The main interest in this section is the close scrutuny of model performance.
In this section we are attempting to test the three best models for natural aeration graph drying.

The analysis of the natural and solar portions of Test 1 is given in Table 3.5.1 through 3.5.8. The results show that the DRY 4 model is the best model for Test 1-N but does not satisfy our definition of adequate (1.5.4). All models were adequate for Test 1-S. Note the DRY 4 model has the smallest standard deviation as seen in Table 3.5.5. A major difference is seen between the two drying models (MR, DRY 4) vs the equilibrium model (EQ3). This is how the large diagonal elements of the EQ3 model have been reduced in magnitude in the models MR vs DRY 4.

The numeric results of Test 2 validations is given in Table 3.5.9 - 3.5.14. Model EQ3 was adequate and accurate for Test 2-N. In Test 2-N the equilibrium model failed to predict enough drying (mean deviation Table 2.5.11, also Figure 3.3.3). However, the DRY 4 model was found to have a significantly smaller standard deviation than EQ3. Because of the lack of drying data ($M_W \geq 15.5\%$ wb), the DRY 4 model is again seen to be the most robust of the models tested. A robust model is one which preforms well even when applied outside of its intended limits. In this case the DRY 4 model is being used for a storage model, which is an equilibrium condition.

Table 3.5.1 Difference Tables for Validation of EQ3, MR, DRY 4 for Test 1-N

Model DRY 4 DC = 0.015 (Actual - Predicted) in Percent Wet Basis Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	0.51	1.20	0.50	-0.04	-0.20
92.	-1.54	2.78	1.54	0.85	0.29
161.	-1.22	0.77	3.58	2.37	1.25
213.	-0.46	0.27	2.40	3.49	2.20
260.	-0.30	0.30	1.03	3.47	3.42
332.	-0.29	-0.22	1.35	0.77	0.65
382.	-0.27	-0.17	0.10	1.00	0.86
480.	-0.01	-0.35	-0.18	0.10	-0.48

Model MR DK = .7 (Actual - Predicted) in Percent Wet Basis Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	0.45	1.06	0.35	-0.17	-0.32
92.	-1.41	2.80	1.45	0.72	0.14
161.	-0.97	1.04	3.61	2.20	0.99
213.	-0.21	0.76	2.76	3.54	2.00
260.	-0.11	0.74	1.57	3.83	3.47
332.	-0.50	-0.25	1.54	1.11	0.95
382.	-0.32	-0.20	0.19	1.25	1.19
480.	-0.14	-0.38	-0.14	0.23	-0.24

Model EQ 3 (Actual - Predicted) in Percent Wet Basis Test 1-N

	7.88	16.50	25.75	35.00	44.25
44.	1.27	0.61	0.00	-0.37	-0.43
92.	2.27	2.51	0.02	-0.19	-0.38
161.	2.62	4.43	2.83	0.06	-0.41
213.	0.88	3.70	6.69	3.03	-0.38
260.	-0.38	1.77	4.38	7.86	3.34
332.	-1.25	-0.64	2.18	3.14	4.56
382.	-1.00	-0.64	0.04	1.87	3.12
480.	-0.79	-0.14	0.41	0.57	0.02

Table 3.5.2 Comparison of Difference Table Summary Statistics for EQ3, MR, DRY 4 using Test 1-N.

```
SUMMARY STATISTICS FOR MODEL DRY 4 TEST 1-N

  MEAN ABSOLUTE DEVIATION =          1.0695

           MEAN DEVIATION =          0.7836

       STANDARD DEVIATION =          1.3011
```

```
SUMMARY STATISTICS FOR MODEL MR TEST 1-N

  MEAN ABSOLUTE DEVIATION =          1.1319

           MEAN DEVIATION =          0.8650

       STANDARD DEVIATION =          1.3177
```

```
SUMMARY STATISTICS FOR MODEL EQ 3 TEST 1-N

  MEAN ABSOLUTE DEVIATION =          1.7791

           MEAN DEVIATION =          1.4292

       STANDARD DEVIATION =          2.1712
```

Table 3.5.3 Multiple Model Validation of EQ3, MR, DRY 4, for Test 1-N

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
M	9.9177	2	4.9588	3.65	0.0322
T	76.5877	7	10.9411	8.06	0.0000
D	51.0066	4	12.7516	9.40	0.0000
MT	9.1623	14	0.6545	0.48	0.9332
MD	1.8678	8	0.2335	0.17	0.9938
TD	103.2541	28	3.6876	2.72	0.0007
ERROR	75.9806	56	1.3568		
TOTAL	327.7769	119			

Table 3.5.4 Difference Tables for Validation of EQ3, MR, DRY 4 for Test 1-S

Model DRY 4 DC=0.015 (Actual - Predicted) in Percent Wet Basis Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	0.32	0.30	0.01	-0.19	-0.45
92.	-1.78	2.41	1.16	0.63	-0.24
161.	-1.13	0.38	3.27	1.79	0.26
213.	-0.72	-0.08	3.36	3.13	1.48
260.	-0.44	0.33	0.83	1.69	2.48
332.	-0.60	-0.18	1.36	0.78	-0.68
378.	-1.11	-0.43	0.23	1.36	-0.72
480.	-1.08	-1.04	-0.67	-0.59	-0.71

Model MR DK=.7 (Actual - Predicted) in Percent Wet Basis Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	0.40	0.28	-0.07	-0.27	-0.55
92.	-1.88	2.61	1.21	0.47	-0.22
161.	-1.53	0.53	3.31	1.39	0.32
213.	-0.99	0.05	3.51	2.93	1.25
260.	-0.66	0.29	0.95	1.66	2.31
332.	-0.96	-0.45	1.20	0.69	-0.77
378.	-1.38	-0.68	0.07	1.27	-0.77
480.	-1.27	-1.18	-0.76	-0.66	-0.76

Model EQ 3 (Actual - Predicted) in Percent Wet Basis Test 1-S

	7.88	16.50	25.75	35.00	44.25
44.	0.93	-0.37	-0.46	-0.48	-0.65
92.	2.07	1.73	-0.40	-0.42	-0.69
161.	2.06	3.87	1.73	-0.72	-0.88
213.	0.02	3.30	7.43	1.04	-0.95
260.	-0.80	1.51	4.24	5.59	0.21
332.	-1.71	-0.62	2.15	3.27	3.41
378.	-1.89	-0.84	0.20	2.38	1.99
480.	-2.11	-0.97	-0.19	-0.26	-0.28

Table 3.5.5 Comparison of Difference Table Summary Statistics for EQ3, MR, DRY 4 using Test 1-S.

```
SUMMARY STATISTICS FOR MODEL DRY 4 TEST 1-S

  MEAN ABSOLUTE DEVIATION =          1.0104

            MEAN DEVIATION =          0.3681

        STANDARD DEVIATION =          1.2982
```

```
SUMMARY STATISTICS FOR MODEL MR TEST 1-S

  MEAN ABSOLUTE DEVIATION =          1.0621

            MEAN DEVIATION =          0.2721

        STANDARD DEVIATION =          1.3495
```

```
SUMMARY STATISTICS FOR MODEL EQ 3 TEST 1-S

  MEAN ABSOLUTE DEVIATION =          1.6199

            MEAN DEVIATION =          0.8362

        STANDARD DEVIATION =          2.1207
```

Table 3.5.6 Multiple Model Validation of EQ3, MR, DRY 4 for Test 1-S

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
M	7.2801	2	3.6400	2.26	0.1142
T	69.9963	7	9.9995	6.20	0.0000
D	64.0019	4	16.0005	9.92	0.0000
MT	6.8365	14	0.4883	0.30	0.9915
MD	1.8500	8	0.2312	0.14	0.9967
TD	79.3113	28	2.8325	1.76	0.0368
ERROR	90.3422	56	1.6133		
TOTAL	319.6184	119			

Table 3.5.7 Testing MR Model Accuracy for Test 1-S (AOVI).

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
T	19.2365	7	2.7481	2.76	0.0259
D	24.0149	4	6.0037	6.03	0.0012
ERROR	27.8655	28	0.9952		
TOTAL	71.1169	39			

Table 3.5.8 Testing DRY 4 Model Accuracy for Test 1-S (AOVI).

```
SOURCE OF  |  SUMS OF      |       |   MEAN      |   F     |
VARIATION  |  SQUARES      | D.F.  |  SQUARE     |  RATIO  | ALPHA HAT
           |               |       |             |         |
-----------+---------------+-------+-------------+---------+----------
           |               |       |             |         |
    T      |   18.3026     |    7  |   2.6146    |  2.80   |  0.0245
    D      |   21.1838     |    4  |   5.2960    |  5.66   |  0.0018
           |               |       |             |         |
-----------+---------------+-------+-------------+---------+----------
           |               |       |             |
   ERROR   |   26.1896     |   28  |   0.9353    |
           |               |       |             |
-----------+---------------+-------+-------------+
           |               |       |
   TOTAL   |   65.6760     |   39  |
           |               |       |
```

Table 3.5.9 Difference Tables for Validation of EQ3, MR, DRY 4 for Test 2-N.

MODEL DRY 4 DC=0.035 (ACTUAL - PREDICTED) IN PERCENT WET BASIS TEST 2-N

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
115.	-0.76	-0.61	-0.45	-0.35	0.23	0.29	-0.12	-0.57	-1.15
186.	-0.39	-0.33	-0.15	-0.19	-0.27	-0.47	-0.48	-0.53	-0.73
279.	-0.36	-0.16	-0.03	-0.11	-0.20	-0.39	-0.62	-0.92	-1.42

MODEL MR DK=.6 (ACTUAL - PREDICTED) IN PERCENT WET BASIS TEST 2-N

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
115.	-1.02	-1.14	-1.07	-0.98	-0.55	-0.11	-0.41	-0.79	-1.42
186.	-0.80	-0.67	-0.50	-0.60	-0.77	-0.94	-0.92	-0.94	-1.12
279.	-0.52	-0.29	-0.18	-0.26	-0.38	-0.60	-0.87	-1.21	-1.74

MODEL EQ 3 (ACTUAL - PREDICTED) IN PERCENT WET BASIS TEST 2-N

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
115.	-2.02	-1.00	0.54	1.63	1.64	0.23	-1.39	-1.90	-2.28
186.	-0.89	-0.33	-0.24	-0.13	0.26	0.69	0.92	0.18	-1.35
279.	-1.85	-0.23	0.59	0.90	1.05	0.99	0.76	0.34	-0.33

Table 3.5.10 Comparison of Difference Table Summary Statistics for EQ3, MR, DRY 4 using Test 2-N.

```
SUMMARY STATISTICS FOR MODEL DRY 4 TEST 2-N

   MEAN ABSOLUTE DEVIATION =          0.4546

              MEAN DEVIATION =       -0.4159

          STANDARD DEVIATION =        0.3751

    SUMMARY STATISTICS FOR MODEL MR TEST 2-N

   MEAN ABSOLUTE DEVIATION =          0.7704

              MEAN DEVIATION =       -0.7704

          STANDARD DEVIATION =        0.3884


 SUMMARY STATISTICS FOR MODEL EQ 3 TEST 2-N

   MEAN ABSOLUTE DEVIATION =          0.9123

              MEAN DEVIATION =       -0.1182

          STANDARD DEVIATION =        1.1232
```

Table 3.5.11 Multiple Model Validation of EQ3, MR, DRY 4 for Test 2-N

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
M	5.7379	2	2.8689	9.46	0.0006
T	1.0391	2	0.5196	1.71	0.1965
D	16.1286	8	2.0161	6.64	0.0000
MT	1.6817	4	0.4204	1.39	0.2610
MD	8.3055	16	0.5191	1.71	0.0959
TD	3.5745	16	0.2234	0.74	0.7382
ERROR	9.7088	32	0.3034		
TOTAL	46.1760	80			

Table 3.5.12 Difference Tables for Validation of EQ3, MR, DRY 4 for Test 2-S

Model DRY 4 DC=0.035 (Actual - Predicted) in Percent Wet Basis Test 2-S

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
116.	-1.11	-0.77	-0.66	0.11	0.88	1.83	0.80	-0.51	-1.40
186.	-0.52	-0.32	-0.08	0.07	-0.10	-0.02	0.57	0.60	0.15
279.	-0.25	-0.03	0.16	0.26	0.15	-0.02	-0.37	-0.96	-1.83

Model MR DK=.6 (Actual - Predicted) in Percent Wet Basis Test 2-S

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
116.	-1.17	-1.09	-1.23	-0.92	0.36	1.37	0.15	-0.94	-1.67
186.	-1.03	-0.69	-0.44	-0.40	-0.56	-0.52	0.01	0.10	-0.31
279.	-0.53	-0.24	-0.03	0.07	-0.05	-0.25	-0.64	-1.27	-2.22

Model EQ 3 (Actual - Predicted) in Percent Wet Basis Test 2-S

	7.00	17.00	28.00	39.00	50.00	61.00	72.00	83.00	94.00
116.	-1.83	-1.05	0.64	2.34	2.73	0.95	-1.49	-2.27	-2.58
186.	-1.34	-0.39	-0.10	0.28	0.95	1.95	2.41	0.62	-1.82
279.	-2.11	-0.30	0.67	1.16	1.31	1.40	1.34	1.10	0.37

Table 3.5.13 Comparison of Difference Table Summary Statistics for EQ3, MR, DRY 4 using Test 2-S.

```
SUMMARY STATISTICS FOR MODEL DRY 4 TEST 2-S

  MEAN ABSOLUTE DEVIATION =             0.5385

           MEAN DEVIATION =            -0.1258

       STANDARD DEVIATION =             0.7475


SUMMARY STATISTICS FOR MODEL MR TEST 2-S

  MEAN ABSOLUTE DEVIATION =             0.6760

           MEAN DEVIATION =            -0.5226

       STANDARD DEVIATION =             0.7116


SUMMARY STATISTICS FOR MODEL EQ 3 TEST 2-S

  MEAN ABSOLUTE DEVIATION =             1.3152

           MEAN DEVIATION =             0.1831

       STANDARD DEVIATION =             1.5349
```

Table 3.5.14 Multiple Model Validation of EQ3, MR, DRY 4 for Test 2-S

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
M	6.7789	2	3.3895	4.88	0.0142
T	1.1344	2	0.5672	0.82	0.4511
D	37.6717	8	4.7090	6.78	0.0000
MT	2.8543	4	0.7136	1.03	0.4085
MD	10.6190	16	0.6637	0.95	0.5226
TD	14.3776	16	0.8986	1.29	0.2601
ERROR	22.2396	32	0.6950		
TOTAL	95.6756	80			

Table 3.5.15 Difference Tables for Validation of EQ3, MR, DRY 4 for Test 3-N.

```
MODEL DRY 4 DC=0.050) (ACTUAL - PREDICTED) IN PERCENT WET BASIS TEST 3-N
                                  7.00     17.00     28.00
                             --------------------------
                      41.|    -0.64      1.79      1.16
                     113.|     0.72      0.05      1.12
                     163.|     0.24      0.64      0.11
                     211.|     0.20      0.68      0.58
                     216.|    -0.16      1.11      1.66
```

```
MODEL MR DK=.5 (ACTUAL - PREDICTED) IN PERCENT WET BASIS TEST 3-N

                                  7.00     17.00     28.00
                             --------------------------
                      41.|    -1.25      1.38      1.00
                     113.|     0.45     -0.22      0.66
                     163.|     0.33      0.45     -0.27
                     211.|    -0.22      0.49      0.21
                     216.|    -0.53      0.87      1.28
```

```
MODEL EQ 3 (ACTUAL - PREDICTED) IN PERCENT WET BASIS TEST 3-N

                                  7.00     17.00     28.00
                             --------------------------
                      41.|     0.17      0.49      0.83
                     113.|     1.63      1.52     -0.78
                     163.|     0.29      1.72      0.75
                     211.|    -0.41      0.68      1.73
                     216.|    -1.04      0.97      2.62
```

Table 3.5.16 Comparison of Difference Table Summary Statistics for EQ3, MR, DRY 4 using Test 3-N

Summary Statistics for Model DRY 4 Test 3-N

Mean Absolute Deviation = 0.7236

Mean Deviation = 0.6170

Standard Deviation = 0.6734

Summary Statistics for Model MR Test 3-N

Mean Absolute Deviation = 0.6405

Mean Deviation = 0.3086

Standard Deviation = 0.7136

Summary Statistics for Model EQ 3 Test 3-N

Mean Absolute Deviation = 1.0427

Mean Deviation = 0.7451

Standard Deviation = 1.0118

Table 3.5.17 Multiple Model Validation of EQ3, MR, DRY 4 for Test 3-N

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
M	2.9898	2	1.4949	2.92	0.0831
T	0.4781	4	0.1195	0.23	0.9155
D	7.9953	2	3.9976	7.80	0.0043
MT	0.8830	8	0.1104	0.22	0.9831
MD	0.1168	4	0.0292	0.06	0.9933
TD	9.8300	8	1.2288	2.40	0.0649
ERROR	8.1962	16	0.5123		
TOTAL	30.4893	44			

Table 3.5.18 Difference Tables for Validation of EQ3, MR, DRY 4 for Test 3-S.

MODEL DRY 4 DC=0.045 (ACTUAL - PREDICTED) IN PERCENT WET BASIS TEST 3-S

	7.00	17.00	28.00
42.	-0.32	1.70	1.28
114.	0.71	-0.07	1.02
162.	0.05	0.52	0.95
211.	-0.18	0.60	0.73
216.	-0.37	0.89	2.03

MODEL MR DK=.5 (ACTUAL - PREDICTED) IN PERCENT WET BASIS TEST 3-S

	7.00	17.00	28.00
42.	-0.77	1.40	1.14
114.	0.39	-0.26	0.25
162.	0.09	0.24	0.30
211.	-0.55	0.38	0.18
216.	-0.63	0.66	1.50

MODEL EQ 3 (ACTUAL - PREDICTED) IN PERCENT WET BASIS TEST 3-S

	7.00	17.00	28.00
42.	0.72	0.42	0.96
114.	1.61	1.65	-1.27
162.	0.04	1.80	0.60
211.	-0.79	0.58	2.16
216.	-1.23	0.71	3.24

Table 3.5.19 Comparison of Difference Table Summary Statistics for EQ3, MR, DRY 4 using Test 3-S.

```
SUMMARY STATISTICS FOR MODEL DRY 4 TEST 3-S

MEAN ABSOLUTE DEVIATION =            0.7620

          MEAN DEVIATION =           0.6360

      STANDARD DEVIATION =           0.7209
```

```
SUMMARY STATISTICS FOR MODEL MR TEST 3-S

MEAN ABSOLUTE DEVIATION =            0.5825

          MEAN DEVIATION =           0.2888

      STANDARD DEVIATION =           0.6866
```

```
SUMMARY STATISTICS FOR MODEL EQ 3 TEST 3-S

MEAN ABSOLUTE DEVIATION =            1.1858

          MEAN DEVIATION =           0.7458

      STANDARD DEVIATION =           1.2527
```

Table 3.5.20 Multiple Model Validation of EQ3, MR, DRY 4 for Test 3-S

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
M	17.5320	2	8.7660	23.28	0.0000
T	5.0908	4	1.2727	3.38	0.0348
D	2.8715	2	1.4358	3.81	0.0443
MT	3.2883	8	0.4110	1.09	0.4171
MD	7.1790	4	1.7947	4.77	0.0101
TD	12.1265	8	1.5158	4.02	0.0086
ERROR	6.0256	16	0.3766		
TOTAL	54.1138	44			

Table 3.5.21 Testing MR Model Accuracy for Test 3-S (AOVI).

SOURCE OF VARIATION	SUMS OF SQUARES	D.F.	MEAN SQUARE	F RATIO	ALPHA HAT
T	0.7609	4	0.1902	0.47	0.7550
D	2.6307	2	1.3153	3.27	0.0916
ERROR	3.2165	8	0.4021		
TOTAL	6.6080	14			

Table 3.5.22 Testing DRY 4 Modèl Accuracy for Test 3-S (AOVI).

```
SOURCE OF |    SUMS OF     |       |    MEAN     |    F     |
VARIATION |    SQUARES     | D.F.  |   SQUARE    |  RATIO   | ALPHA HAT
          |                |       |             |          |
----------+----------------+-------+-------------+----------+----------
          |                |       |             |          |
    T     |      0.5881    |    4  |    0.1470   |   0.41   |  0.7968
    D     |      3.8089    |    2  |    1.9045   |   5.32   |  0.0340
          |                |       |             |          |
----------+----------------+-------+-------------+----------+----------
          |                |       |             |
  ERROR   |      2.8663    |    8  |    0.3583   |
          |                |       |             |
----------+----------------+-------+-------------+
          |                |       |
  TOTAL   |      7.2634    |   14  |
          |                |       |
```

For the solar portion of Test 2 the MR vs DRY 4 have significantly smaller standard deviations than EQ3. However, both EQ3 vs DRY 4 were chosen as adequate models. Again, the DRY 4 model was also selected as the best model because of its smaller standard deviation.

Recall that for these tests only six observations were in the drying region ($M_w \geq 15.5\%$). This means that for the major portion of this test the grain system was in equilibrium with the atmosphere. This is seen by comparing the drying constant DK = 0.05 for this test vs DK = 0.7 for Test 1. The MR model is the best model by comparison of means. The MR model is adequate and accurate for Test 3-S. But by comparing the standard deviations it is seen that the DRY 4 model is statistically equivalent to the MR model.

3.5.2 Multiple Model Validation Conclusions

Table 3.5.23 summarizes the results of this test. We have shown that the DRY 4 model is comparable to the other models in adequacy, but more importantly has shown a significantly smaller standard deviation. Because of the difficulties with our experimental data just discussed the DRY 4 model was found to be the best model for application to natural aeration drying studies.

Table 3.5.23 Summary of Drying Model Validation.

Test	Smallest Standard Deviation	Adequate	Accurate
1-N	DRY4		
1-S	DRY4	EQ3,MR,DRY4	
2-N	DRY4	EQ3	EQ3
2-S	MR	EQ3,DRY4	
3-N	DRY4		
3-S	MR	MR	MR

3.6 Drying Model Conclusions

Both dynamic models were found to be significantly more accurate than the equilibrium models as measured by error standard deviation. Both models are, therefore, more acceptable as research tools for studies involving airflow rates in the range of 10 to 30 cfm/ft^2.

The mass diffusion model was chosen for further development because its total efficiency was greatest. Total efficiency means that the DRY 4 model was more accurate than the equilibrium models, required less calculational time and is more easily understood and maintained. The latter being a benefit in adapting the model to alternate drying configurations and fan management. The diffusion model is applicable to any type of seed grain once the properties of specific heat, equilibrium relative humidity (ERH), density (DENSY), and the appropriate diffusion coefficient (DC) are known. To emphasize our meaning Figure 3.6.1 shows the DRY 4 model response to the test 1-N conditions. This should be compared with Figure 1.5.3 which shows the response of the EQ1 model to Test 1-N. We have now produced a surface which more closely represents the physical phenomena.

3.7 Areas of Future Research

Adequate experiments should be performed to develop the functional relationship for the diffusion coefficient (DC). From Table 3.4.3, it is seen that the DC varies with moisture content, evaluation of this function with adequate drying data will increase model accuracy and flexibility. Close measurement of air flow rate is required for strict model evaluation and validation. Weather variables should be closely monitored at the experimental site and recorded. Moisture contents

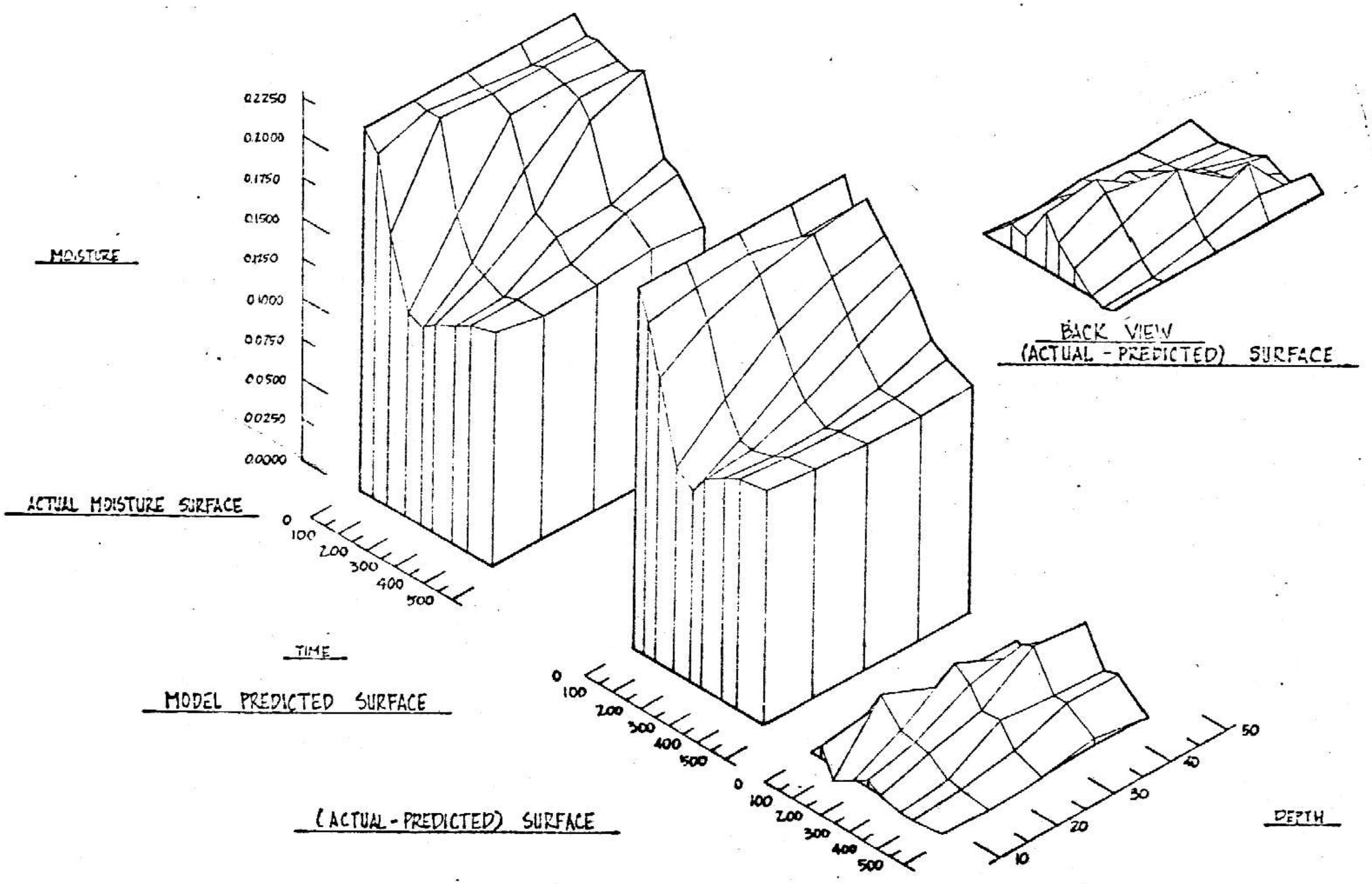


Figure 3.6.1 Example of the Experimental, Diffusion Model and Differenced Drying Surfaces for Test 1-N

should be performed using official oven standards with the time and depth of each sample recorded. The experimental design should contain at least 50 observations within the difference table, with replications within layers. All data should be sampled before the top layer drys below the critical moisture content (M_c). Further analysis of existing drying data may lead to a plausible form of the diffusion coefficient function. For example:

$$DC_{ij} = f(TG_{ij}, MO_{ij}, ALB) \qquad (3.7.1)$$

i^{th} time increment

j^{th} layer

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CHAPTER 4

EQUILIBRIUM MOISTURE CONTENT DATA AND MODELS

4.1 Literature Review

Many equations have been developed in the literature to describe the adsorption-desorption phenomena in biological products. Several questions naturally arise in conjunction with this research. Which of the several equilibrium moisture content (EMC) equations actually describe the experimental data adequately? Which experimental methods are adequate? What differences are detectable among varieties of the same specie of grain? These are just a few of the recurring questions about equilibrium data.

In this work we will focus our attention upon four main equations with an additional equation considered as a special case. These equations will be discussed in the chronological order, with increasing complexity.

Thompson (72) modified the basic Henderson equation given in Henderson(52). Thompson's modification to the Henderson equation was to add a constant to the ambient temperature. This has the practical effect of moving the temperature of absolute zero to a higher level. The modified sorption equation is as follows:

$$ERH = 1.0 - EXP(K (T+C) M_p^N) \qquad (4.1.1)$$

ERH = Equilibrium Relative Humidity (decimal),
M_p = Moisture Content (percent dry basis),
T = Temperature (^{o}C),
K,N,C = Empirical Constants

Chung(67) developed a new general isotherm equation which has been modified by a temperature constant for absolute zero for the general biological product under consideration. This modified Chung-Pfost equation is as follows:

$$\mathrm{Ln}(\ \mathrm{ERH}\ ) = (-A/(R(T+C)))\ \mathrm{EXP}(-B\ M) \qquad (4.1.2)$$

ERH = Equilibrium Relative Humidity (decimal),
M = Moisture Content (decimal dry basis),
T = Temperature ($^{\circ}$C),
R = Universal Gas Constant (1.987 Kcal/Kmol-$^{\circ}$K),
A,B,C Empirical Constants.

Day(65) developed a more complex four constant equation to describe the isotherms of wheat. This equation was developed as an empirical extension to the original Henderson Equation. This empirical modification has the following form:

$$\mathrm{ERH} = 1.0 - \mathrm{EXP}(\ P_1\ T^{P_2}\ (M_p)^{P_3\ T^{P_4}}\ ) \qquad (4.1.3)$$

ERH = Equilibrium Relative Humidity (decimal)
M_p = Moisture Content (percent dry basis)

T = Temperature ($^{\circ}$C)
P_1, P_2, P_3, P_4 = Empirical Constants

Chen(69,71) developed an equation, which also has four empirical constants. The extended equation has the form:

$$\mathrm{ERH} = \mathrm{EXP}(\ G_1\ TK^{H_1}\ \mathrm{EXP}(\ G_2\ TK^{H_2}\ M)) \qquad (4.1.4)$$

ERH = Equilibrium Relative Humidity (decimal)
M = Moisture Content (decimal dry basis)
TK = Temperature ($^{\circ}$K)
G_1, H_1, G_2, H_2 = Empirical Constants

Each of these four equations can be considered and used as either an equilibrium relative humidity (ERH) or equilibrium moisture content (EMC) equation depending upon which variable is considered to be the controlled or dependent variable. The equations 4.1.1, 4.1.2, 4.1.3, and 4.1.4 are known as equilibrium relative humidity equations.

A more complex equation has been developed by Strohman(67). This equation can not be solved explicitly for moisture content and therefore can only be considered as an ERH model. This equation has the following form:

$$ERH = \mathrm{Exp}(\ A\ \mathrm{Exp}(-BM)\mathrm{LN}(PS)\ -C\ \mathrm{Exp}(-DM)\ ) \qquad (4.1.5)$$

ERH = Equilibrium Relative Humidity (decimal)
M = Moisture Content (decimal dry basis)
PS = Saturation Vapor Pressure (kPa)
A,B,C,D = Emperical Constants

This equation is a four constant equation but has additional constants required to calculate the saturation pressure PS.

4.2 Actual Data and Background (Yellow Dent Corn)

Rodriguez-Arias(56) used yellow dent corn purchased from a local (East Lansing) elevator during the fall of 1954 and stored at 40°F until testing. The experimental technique was to control the temperature and relative humidity until equilibrium and measure the moisture content. This data is considered to be EMC data. The temperature was controlled in a thermostatically controlled storage cabinet. The relative humidity was controlled with a saturated salt solution in a moisture-tight glass jar.

Chung(66) used Dekalb 3x1 yellow dent hybrid corn for his isotherm determinations. The experimental technique was to place small amounts of grain in temperature and relative humidity controlled flasks. The relative humidity was controlled by placing the sample over a solution of sulfuric acid. The temperature was controlled in a storage cabinet. This technique also yields EMC data.

Gustafson(74) used Dekalb XL-66 hybrid yellow dent corn. Several different chemically-pure salts were used to control the relative humidity, with constant temperature in a storage chamber. This technique will also yield data considered to be EMC data, or data which indicates that the moisture content is the dependent variable of the system.

Pixton(71,74) used a method which allows the wet grain to control the air relative humidity within a temperature controlled chamber. When equilibrium is achieved the relative humidity is measured directly by a dew point thermocouple. The dependent variable of this system is relative humidity and the data is termed ERH data. This experimental technique is more rapidly determined. The main question unanswered is if this technique is statistically more accurate or equivalent to the other methods.

The actual data used for the calculations in this chapter is given in Appendix E.

4.3 Factors Which Affect EMC-ERH Data Accuracy

The observed and/or reported moisture data is composed of several factors. These can best be seen in model form. A possible model is posed as follows:

$$M_r = M_a + E_o \tag{4.3.1}$$

$$E_o = E_i + E_m + E_v + E_s + E_r \tag{4.3.2}$$

M_r = Reported Moisture Content (db),
M_a = Actual Moisture (db),
E_o = Error of Observation,
E_i = Error due to Investigator,
E_m = Error due to Experimental Method,
E_v = Error due to Grain Variety,
E_s = Error due to Interpolating Smoothing,
E_r = Random Error term.

We wish to test each of the proposed contributions to the error model for statistical significance. This will result in a more complete understanding of proper experimental designs in the future. As in the case of some of the components, this will suggest the need for additional data with certain of the combinations held constant to determine their significance. How will these combinations be tested?

4.4 Analysis of Error Factors (Statistical Techniques)

4.4.1 Comparison of EMC-ERH Data (Miliken(75))

If a model of the equilibrium moisture phenomena can be accepted as adequate then the technique of partitioning the sum of squares error from the linear least squares can be applied. This technique can be applied as follows to two different groups of EMC-ERH data.

To determine whether a distinct significant difference exists between two different groups or classes of data requires the same statistical procedure. First select a suitable hypothesis such as:

$$H_0: \text{ Class 1} = \text{Class 2} \quad (\beta_1 = \beta_2). \tag{4.4.1}$$

where β_1 and β_2 are the vectors of coefficients for model 1 and model 2 respectively.

Then fit the equilibrium model of your choice from Section 4.1 with 'q' parameters to Class 1 and calculate the sum of squares error, SSE(1). Then fit the model to Class 2 and calculate the sum of squares error, SSE(2). Pooling the two sums of squares yields:

$$SSE = SSE(1) + SSE(2) \; . \tag{4.4.2}$$

Now a combined set of data, Class 1 and Class 2 are fitted with the model yielding the sum of squares error SSE(0). The sum of squares hypothesis is then calculated.

$$SSH_0 \; (\beta_1 = \beta_2) = SSE(0) - SSE. \tag{4.4.3}$$

A calculated F statistic is formed.

$$F_c \; (q, n-2q) = (SSH_0/q)_{/ \; (SSE/(n-2q))} \tag{4.4.4}$$

F_c = Calculated F ratio statistic

q = number of parameters in the ERH-EMC model used in the analysis
n = total number of observations in Class 1 and Class 2.

The decision rule is:

Reject H_0 (4.4.1) if and only if $F_c \geq F_{.95}(q, n-2q)$.

4.4.2 Comparison of EMC-ERH Equations (Miliken(75))

We also wish to evaluate the accuracy of two equilibrium equations as compared to each other. Again a partitioning of the sum of squares technique will be used. The equilibrium equations can be shown to be of the form of:

$$\text{Model 1:}\quad Y = f_1\,(\underline{X}, \beta_1) + \varepsilon_1 \qquad q_1 \text{ parameters,} \tag{4.4.5}$$

$$\text{Model 2:}\quad Y = f_2\,(\underline{X}, \beta_2) + \varepsilon_1 \qquad q_2 \text{ parameters.} \tag{4.4.6}$$

These two models are compared by evaluating the contribution of one model given the presence of the other. This means, 'Can a significant portion of the residuals be explained by the inclusion of another model?'. This is stated as the two following hypotheses:

Ho_1: Model 1 is adequate in the presence of model 2 (4.4.7).

Ho_2: Model 2 is adequate in the presence of model 1 (4.4.8).

The procedure is to fit the EMC-ERH data to Model 1 and calculate SSE(1). Then fit the data to Model 2 and get SSE(2). Finally fit the data to Model 1 plus Model 2 to calculate SSE(1,2). Now the sum of square hypothesis can be formed by:

$$SSHo_1 = SSE(1) - SSE(1,2), \tag{4.4.9}$$

$$SSHo_2 = SSE(2) - SSE(1,2). \tag{4.4.10}$$

The F statistic is then calculated by the following formulae:

$$Ho_1:\quad F_c(q_1, n-q_1-q_2) = (SSHo_1/\ q_1)/\ (SSE(1,2)/(n-q_1-q_2)) \tag{4.4.11}$$

$$Ho_2:\quad F_c(q_2, n-q_1-q_2) = (SSHo_2/\ q_2)/\ (SSE(1,2)/(n-q_1-q_2)) \tag{4.4.12}$$

The decision rule for this test is to reject Ho (4.4.7 or 4.4.8) if and only if $F_c\ (n_i, n_j) \geq F_{.95}\ (n_i, n_j)$.

4.4.3 Non-Linear Least Squares Algorithm (GAUSHAUS)

Each of the techniques previously described require the use of a non-linear least squares algorithm. We have choosen a FORTRAN program which is currently available through the SHARE library of IBM user programs. The program name is GAUSHAUS which was originally written at the University of Wisconsin by D.A. Meeter, and has been revised and submitted to SHARE by F.S. Wood(69) from AMOCO Oil Company.

The program uses a Marquart search technique to minimize the residual sum of squares. The modifications made to the program for our analysis were three fold. First, the program calculations were modified to double-precision for accuracy. Secondly, nine subroutines were written to solve each of the four EMC-ERH models and one ERH only model. Finally an additional plotting routine was incorporated to facilitate the analysis of model fit by each data classification. These graphs include the marginal frequency distribution within each cell. This allows a visual evaluation of model behavior with respect to each variable subclass, and a time variable controlled by the investigator.

If the following criterion was met for all of the coefficients $\hat{\beta}_k^{(i+1)}$ then the program is said to have converged to a least-squares solution.

$$\frac{|\hat{\beta}_k^{(i)} - \hat{\beta}_k^{(i+1)}|}{|\hat{\beta}_k^{(i+1)}| + \delta} < \varepsilon \qquad \begin{array}{l} \varepsilon = 0.001 \\ \delta = 0.0001 \end{array} \qquad (4.4.13)$$

The user supplies the controlling value for epsilon(ε) when the parameters of the model are initialized.

4.5 Analysis of Error due to Investigator (yellow dent corn)

4.5.1 Results

By fitting the Chung-Pfost model to several combinations of EMC data, differences among authors or groups of authors was determined. Since an author or group of authors can be considered as a class of data, the technique of section 4.4.1 is used.

We have four authors from section 4.2 which are abreviated RODR (Rodriguez-Arias(56), PIXE (Pixton(74)English), PIXA (Pixton(74) American), CHUN (Chung(66), GUST (Gustafson(74)).

For clarity the first combination will be tested with the calculations shown in full. Each of the fifteen combinations of the four sets of data was fit with the Chung-Pfost equation and the sum of squares calculated. These combinations are given in Table 4.5.1.

H_0: RODR = PIXT,CHUNG,GUST (R = PCG)

	S.S.	df
SSE(1) : SSE(R)	= 0.04961858	69
SSE(2) : SSE(PCG)	= 0.10138121	68
SSE(0) : SSE(RPCG)	= 0.22192719	140

$$SSE = SSE(1) + SSE(2) = 0.15099979$$

$$SSHo = SSE(0) - SSE = 0.07092740$$

$$F_c(3.137) = (0.07092740/3)/(0.15099979/137) = 21.5$$

$$F_{.95}(3,137) = 3.95$$

Decision: Reject Ho. We then conclude that the Rodriguez population is significantly different from the combination of the Pixton, Chung, and Gustafson populations.

The remainder of the twenty-five (25) hypotheses and their conclusions are summarized in Table 4.5.2. As can be seen from this table that nearly all combinations are significantly different from each other with six exceptions. The combination that is the easiest to explain is that where the Rodriguez data is not significantly different from the Gustafson data when considered by themselves. This is reasonable since both men used the EMC technique over saturated salt solutions. I am, however, at a loss to explain logically the five remaining equivalent combinations involving groups of more than one author per group.

Figure 4.5.1-4.5.3 show the resulting residuals from a fit of all yellow dent corn data. Figure 4.5.1 shows the model fit error plotted on a cummulative normal scale. If this line is a straight diagonal then the errors are distributed normally and the model is termed an adequate representation of the data. The horizontal dashed line in all graphs is at residual = 0.0. This line shows the variability of the data about the fitted model.

Notice the differences apparent among authors in Figure 4.5.2. In Figure 4.5.3 the residuals are plotted against increasing x(2) which is relative humidity. Note in this figure the rapidly increasing error above 75% RH. Perhaps a pictorial model will help to explain our conclusions.

4.5.2 Author Population Pictorial Model (Venn Diagram).

Let the following circles which are sized according to population size represent the four populations of data. A crude Venn diagram Figure 4.5.4 results.

Table 4.5.1 Summary of Non-Linear Least Squares Results

R = Rodrigues Data	72 observations
P = Pixton Data	30 observations
C = Chung Data	17 observations
G = Gustafson Data	24 observations

Variables	S.S.	d.f.
R	0.04961858	69
P	0.01247110	27
C	0.00431947	14
G	0.02256313	21
RP	0.10005777	99
RC	0.16210895	86
RG	0.07967805	93
PC	0.02777622	44
PG	0.04645211	51
CG	0.07666057	38
RPC	0.20429536	116
RPG	0.12527302	123
PCG	0.10138121	68
RCG	0.18801553	110
RPCG	0.22192719	140

Table 4.5.2 Summary of Author Hypotheses and Decisions.

R - Rodriguer-Arias P - Pixton C-Chung G - Gustafson

H_0	F_c	Accept Ho @	Confidence Level
R = PCG	21.5		
R = PC	61.8		
R = PG	12.2		
R = CG	17.4		
R = P	19.6		
R = C	64.2		
R = G	3.11	*	$F_{.99}(3,90) = 4.05$
RP = CG	11.7		
RC = PG	2.93	**	$F_{.95}(3,137) = 3.95$
RG = PC	48.6		
P = RCG	4.89		
P = RC	6.41		
P = RG	14.4		
P = CG	2.98	**	$F_{.95}(3,65) = 4.13$
P = C	8.94		
P = G	5.21		
C = RPG	32.5		
C = RP	36.1		
C = RG	44.2		
C = PG	21.6		
C = G	21.6		
G = RPC	-0.99	**	$F_{.95}(3,137) = 2.65$
G = RP	0.87	**	$F_{.95}(3,120) = 2.68$
G = RC	0.65	**	$F_{.95}(3,107) = 2.70$
G = PC	22.0		

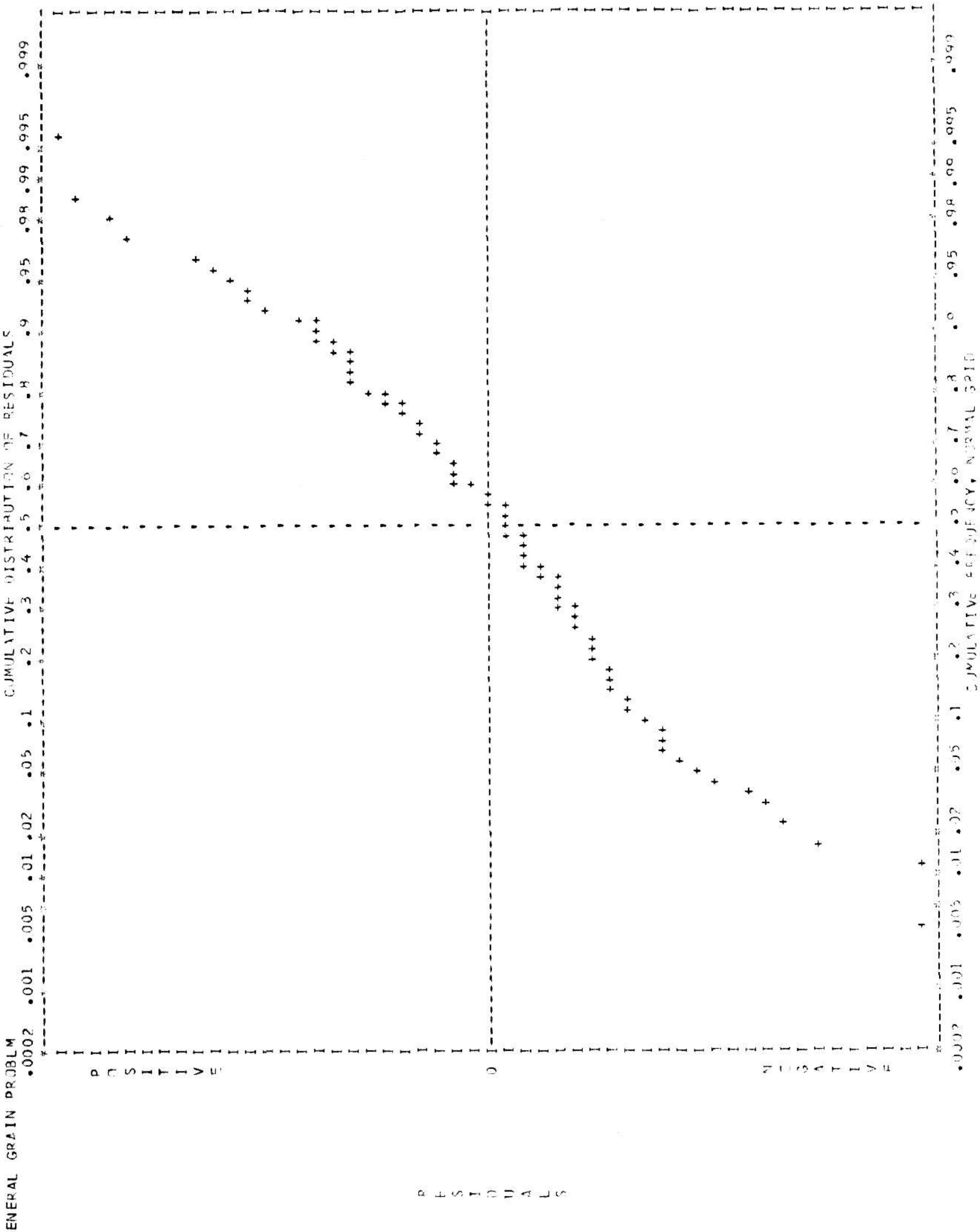

Figure 4.5.1 Residual Error Plotted on a Normal Grid

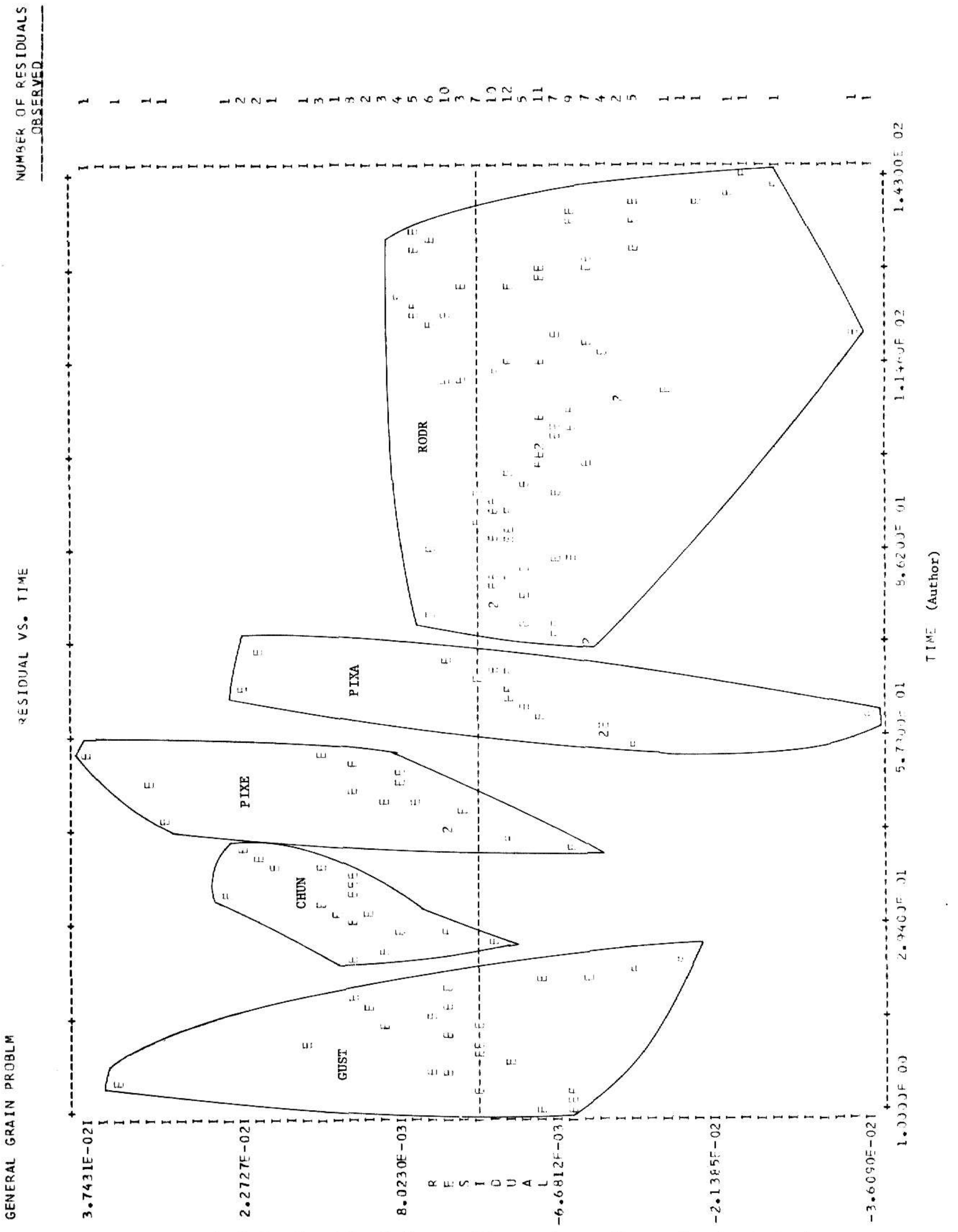

Figure 4.5.2 Residual Error Plotted vs Chronological Order

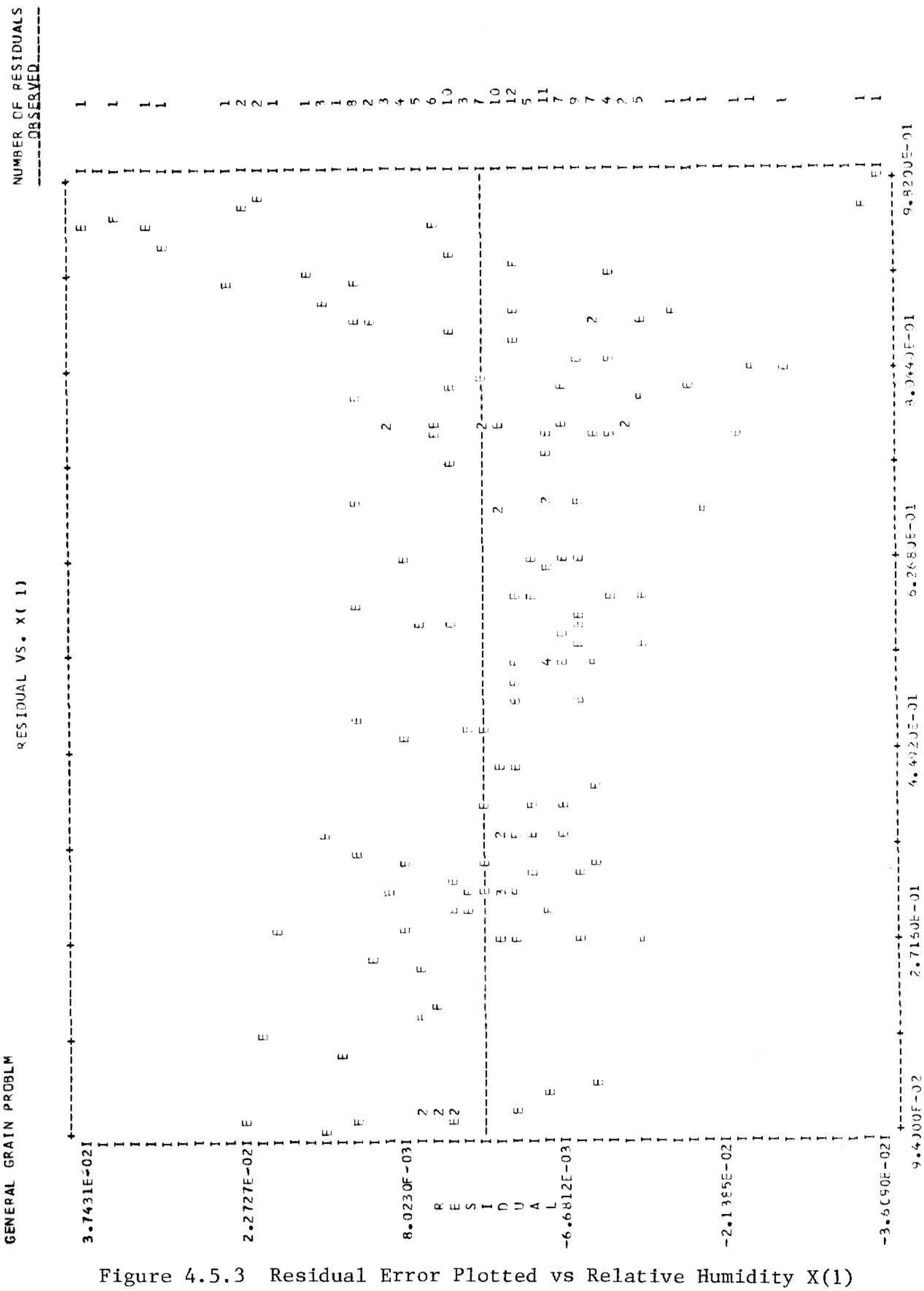

Figure 4.5.3 Residual Error Plotted vs Relative Humidity X(1)

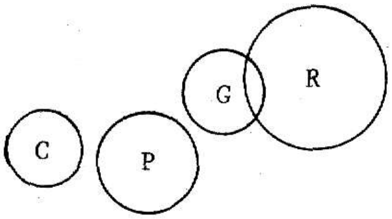

Figure 4.5.4 Pictorial Model of Corn EMC data

R - Rodriguez 72, P - Pixton 30, G - Gustafson 24, C - Chung 17.

This model adequately describes the observed combinations of accepted hypotheses. By circling the following combinations the corresponding pictorial overlap corresponds to the observed results.

Ho	Pictorial description	
R = G	Notice overlap of population R and G	Fig. 4.5.5
RC = PG	Notice overlap of elipse PG with elipse RC	Fig. 4.5.6
P = CG	Notice overlap of elipse CG with circle P	
G = RPC	Note circle G overlaps elipse RPC	
G = RP	Note circle G overlaps elipse RP	
G = RC	Note circle G overlaps elipse RC	

Now we have a model that explains the accepted hypotheses from the Section 4.5.1. Now what useful inferences can be made from this representation?

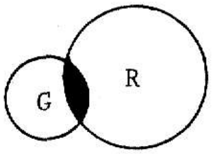

Figure 4.5.5 Intersection of Populations R,G.

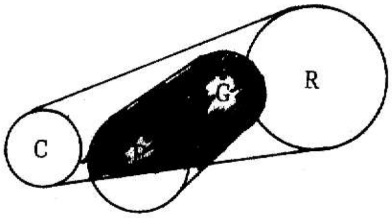

Figure 4.5.6 Intersection of Populations RC, PG.

From the pictorial model (4.5.2) we would expect that population R is very different from C, which is supported by $F_c(R,C) = 64.2$. Also we would expect that R is different from PC $F_c(R,PC = 61.8$. This predictive ability suggests an underlying mechanism which has caused the shape of this pictorial model. Because this is a three dimensional problem, our pictorial model can not be expected to accurately predict each of the twenty-five hypotheses tested. However, if the model were built in three dimensions as with styrofoam balls and sticks its accuracy of representation will increase. Our model is a two dimensional representation of this three dimensional phenomena (relative humidity, temperature, moisture content) viewing parallel to the z axis onto the x-y plane. The z axis is relative humidity and the x-y correspond to moisture content and temperature.

To determine which is x and which is y a brief summary of the ranges of the data would be useful.

Table 4.5.3 Summary of the Ranges of the Data

Author according to the model	Number of Temperatures	Number of Moistures	Observed
Chung	2	8	17
Pixton	3	5	30
Gustafson	4	7	24
Rodriguez	6	11	72

From this summary we would infer that the x axis corresponds remarkably to the range of experimental temperatures investigated by the author.

4.5.3 Conclusions

We have seen that the results of the analysis are adequately predicted by Figure 4.5.4. The major difference evident from this figure is that the experimental design should be designed in such a way to include enough temperature and moisture combinations. The wider the range of temperatures, the more different the population. This seems to mean that once an adequate number of moisture determinations have been made, the number of temperature combinations is also important. Therefore if two authors, techniques or varieties are to be compared in a rigorous manner, the same experimental design must be adhered to by both investigators, varieties, etc.

4.6 Analysis of Error Attributed to Variety.

Because of the conclusions just stated, the same author must use the same procedure on two different varieties before true differences can be statistically tested for significance. Since one investigator did not use two different methods on the same sample a test for significance between experimental methods is not possible. Pixton(74) reported on two varieties of yellow dent corn, American and English, with the following results.

Ho: PIXE = PIXA

		df
SSE(1)	SSE(PIXE) = 0.00128236	12
SSE(2)	SSE(PIXA) = 0.00061404	12
SSE(0)	SSE(PIXE+PIXA) = 0.01247110	27

SSE = 0.00189640

$F_c\ (3, 24) = 44.6$

SSHo = 0.01057470

Decision: Reject Ho. We conclude that there is a distinct significant difference between maize from England and maize from the United States.

4.7 Analysis of Error Attributed to Smoothing EMC-ERH Data

The standard method of reporting equilibrium data is in tabular form at even increments of temperature and relative humidity. To obtain actual experimental results at these conditions is very difficult, so an interpolation is made. The actual data is plotted and a smooth curve drawn through the points, with the values of the curve at the desired conditions recorded and published as equilibrium data. This technique introduces an additional portion of error to the observed data, see equation 4.3.2. What is the contribution of the E_s term to the total error of observation (E_o)?

To compare the effect of smoothing or interpolating, two classes of data are required by the same author, using the same experimental technique. The interpolation should be done by the author himself if possible, and, if not, by a reputable authority in the field. The data which is used for this investigation is that data for yellow dent corn measured by Rodriguez-Arias(56), and reported by Brooker, et. al.(74). Both sets of data are also included in Appendix E. We now wish to test the hypothesis that the two populations are equivalent.

Ho: Rodriguez Interpolated (RODI) = Rodriguez Actual (RODR)

SSE(1)	SSE(RODI)	= 0.04732111	51
SSE(2)	SSE(RODR)	= 0.01247110	69
SSE(0)	SSE(RODI+RODR)	= 0.09837570	123

SSE = 0.05979221

SSHo = 0.03858349

$F_c(3,120) = 25.8$

$F_{.99}(3,120) = 3.95$

Decision: Reject Ho. We conclude that a significant error has been introduced when the actual experimental data is interpolated for publication.

4.8 Evaluation of EMC-ERH Model Accuracy

To evaluate the accuracy of one equation vs another, partitioning the sum of squares technique from Section 4.4.2 is used. Testing the two three constant equations, Henderson-Thompson Model(1) and Chung-Pfost Model(2) yields the following results:

Ho_1: The Henderson-Thompson model is adequate in the presence of the Chung-Pfost Model

	SS	df
SSE(1)		140
SSE(2)		140
SSE(1,2)	= 0.20084081	137

$SSHo_1 = SSE(1) - SSE(1,2) = 0.05910030$

$F_c(3,137 = 0.288$ $\qquad F_{.95}\ (3,137) = 3.95$

Decision: Accept Ho_1. We conclude that the Henderson-Thompson model is adequate in the presence of the Chung-Pfost model.

Ho_2: The Chung-Pfost model is adequate in the presence of the Henderson-Thompson Model.

$SSHo_2 = SSE(2) - SSE(1,2) = 0.02653220$

$F_c(3,137) = 0.129$ $\qquad F_{.95}(3,137) = 3.95$

Decision: Accept Ho_2. We conclude that the Chung-Pfost Model is adequate in the presence of the Henderson-Thompson Model.

We conclude that there is no statistically significant difference in the predictive accuracy between the Chung-Pfost and the Henderson-Thompson equations. We have attempted to extend this procedure to test the other equations from Section 4.1. It was found that the GAUSHAUS program does not efficiently converge with the Day-Nelson and the Chen-Clayton equations.

Table 4.8.1 Models Compared Using Actual Corn Data.

Equations	Sum of Squares	Standard Error of Estimate (RH)	Number of Iterations
Henderson-Thompson (4.1.1)			
$RH = 1. - EXP[-K \cdot (T + C) \cdot M_p^N]$	0.2541	0.0426	8
Chung-Pfost (4.1.2)			
$RH = EXP(\frac{-A}{R(T + C)} \cdot EXP(-B \cdot M_D))$	0.2218	0.0398	6
Day-Nelson (4.1.3)			
$RH = 1. - EXP(A' \cdot M_p^{B'})$	0.3773	0.0521	60+
$A' = P_1 T^{P_2}$			
$B' = \frac{P_3}{T^{P_4}}$			
Chen-Clayton (4.1.3)			
$RH = [-A' \cdot EXP(-B' \cdot M_D)]$	0.2039	0.0383	60+
$A' = \frac{G_1}{T_K^{H_1}}$			
$B' = G_2 T_K^{H_2}$			
Strohman-Yoerger (4.1.5)			
$RH = EXP(A' \cdot EXP(-B' \cdot M_p) \ln(P_s) -$	0.1722	0.0352	10
$C' \cdot EXP(-D' \cdot M_p)$			

By examining the partial derivatives of these equations with respect to their empirical constants the reason for this violent behavior is apparent. These derivatives approach infinity exponentially in a vertical or horizontal direction. This behavior upsets the convergence of the Newton method. The convergence criteria (4.4.13) for the ratio of change of the coefficients is never satisfied. This leads to exhaustive computing iterations and eliminates the rigorous equation comparison.

Table 4.8.1 shows the resulting sum of squares, number of iterations, standard error and number of coefficients for each of the models tested. Notice that there does not appear to be any real difference between the five equations compared. But what is more important is the amount of calculation involved for the equations containing more than three coefficients. These also require a sophisticated calculator or computer to solve for field application. The Strochman-Yoerger equation appears to have good prediction accuracy but is a hybrid equation with 5+ constants. The reason for 5+ notation is that four empirical constants are present but an additional independent variable of saturation pressure PS is used. Now if a suitable subroutine such as SATPS (Brooker(67), Wilhelm(76)) is used to calculate the saturation pressure, an additional seven constants are required.

4.9 EMC-ERH of Other Important Food Grains

Equilibrium moisture data was obtained for the other important food grains. This data was used to calculate the coefficients for the Henderson-Thompson and Chung-Pfost equations. These coefficients and standard errors are given in Tables 4.9.1 and 4.9.2. Most of the available data is

Table 4.9.1 Equilibrium Moisture Content Constants.

	Henderson - Thompson			
Grain	K	N	C	Standard Error Moisture
Yellow Dent Corn	8.65	1.86	49.8	0.0126
Peanut, Kernel	6.50	1.49	50.5	0.0126
Rice, Rough	1.91	2.44	51.1	0.0097
Sorghum	8.53	2.47	11.3	0.0086
Soybean	5.03	1.36	43.0	0.0164
Wheat, Hard	2.30	2.28	55.8	0.0070

K = all constants are multiplied x 10^{-5}

Table 4.9.2 Equilibrium Moisture Content Constants.

Chung - Pfost

Grain	A	B	C	E	F	Standard Error Moisture
Yellow Dent Corn	620	16.9	30.2	.379	.058	0.012
Peanut, Kernel	506	29.2	33.8	.212	.034	0.013
Rice, Rough	1181	21.7	35.7	.325	.046	0.013
Sorghum	2185	19.6	102.	.391	5.09	0.008
Soybean	275	14.9	24.5	.375	6.68	0.017
Wheat, Hard	1052	17.6	50.9	.395	5.67	0.006

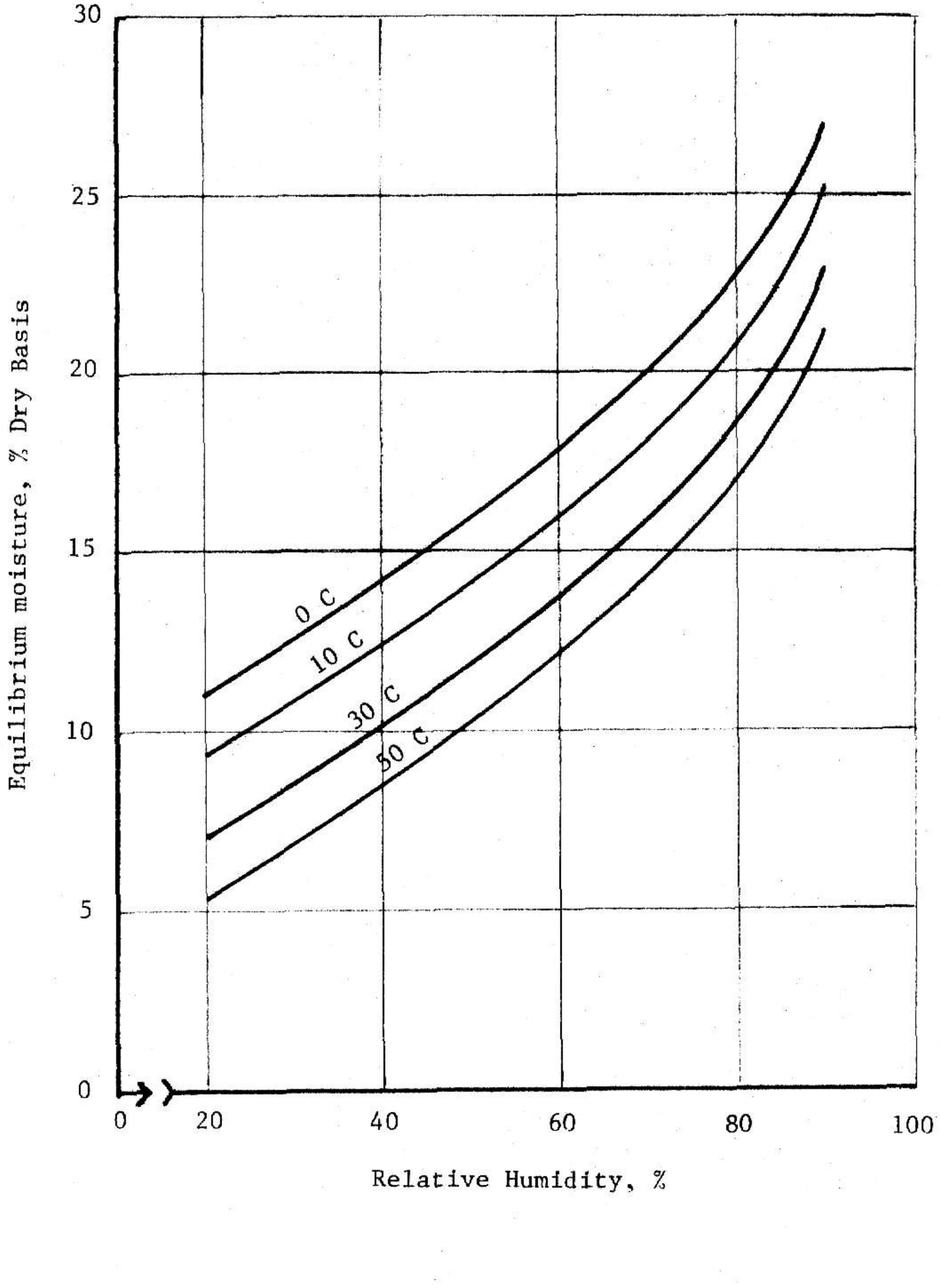

Figure 4.9.1 Equilibrium Moisture Content, Yellow Dent Corn, Desorption.

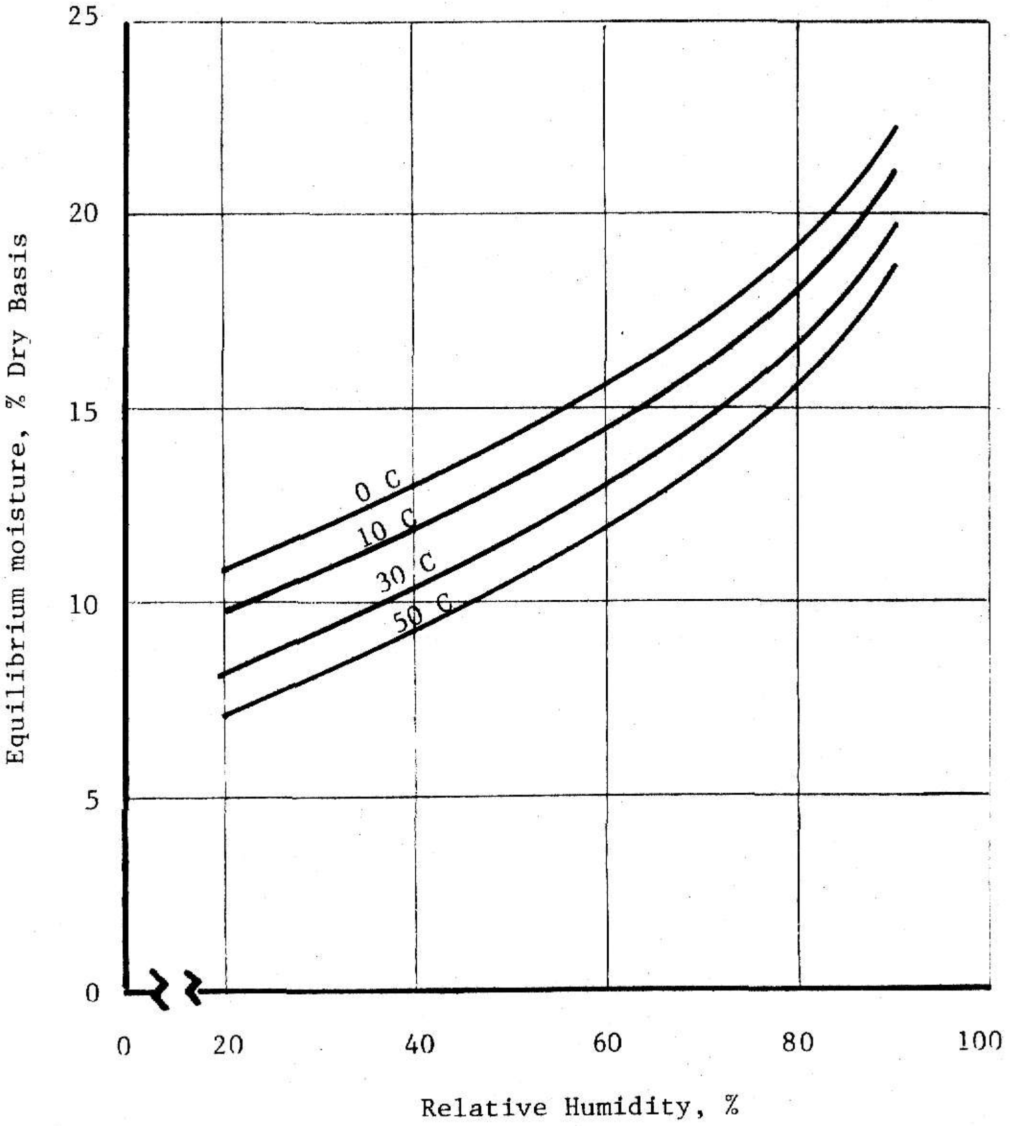

Figure 4.9.2 Equilibrium Moisture Content, Soft Wheat.

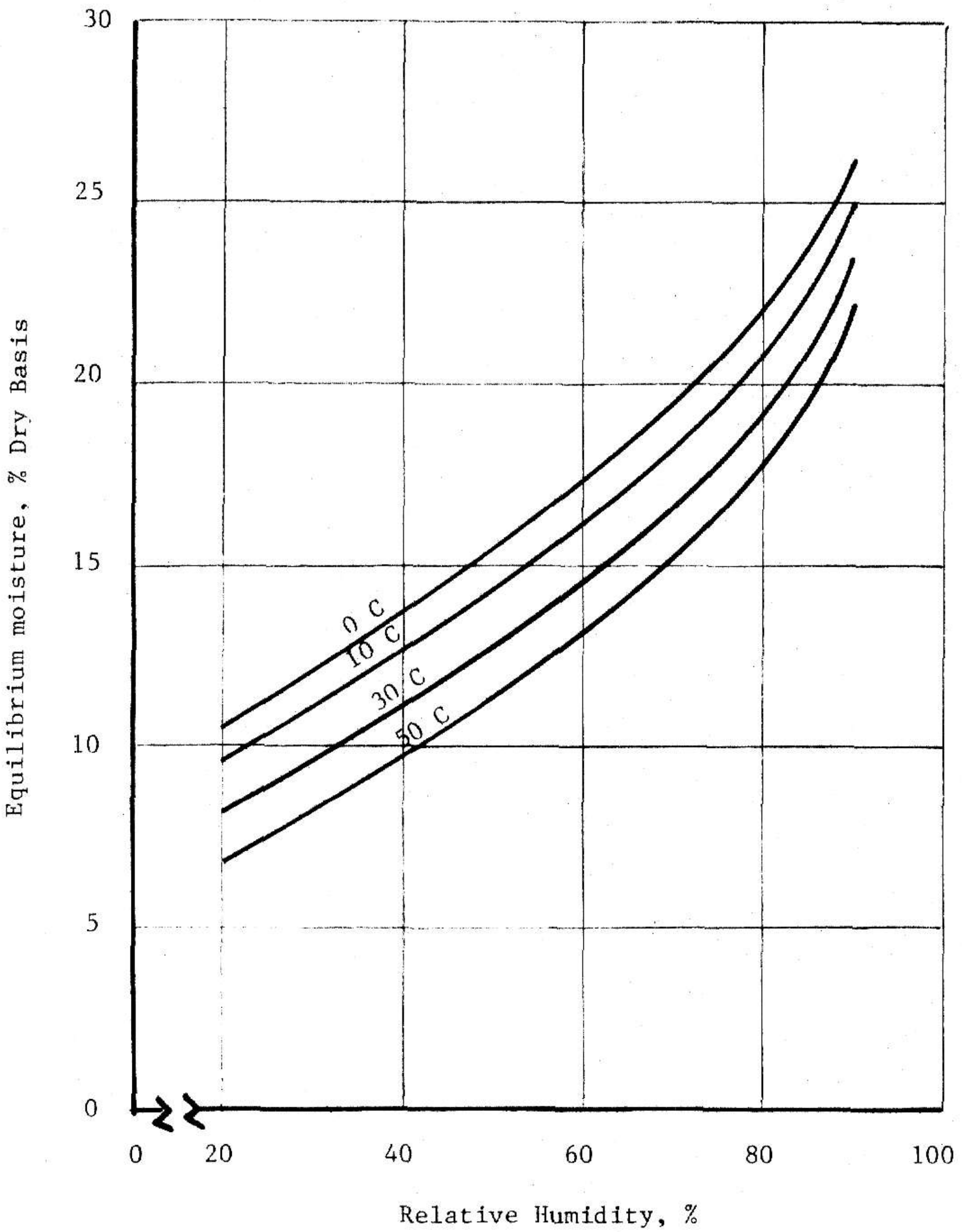

Figure 4.9.3 Equilibrium Moisture Content, Hard Wheat.

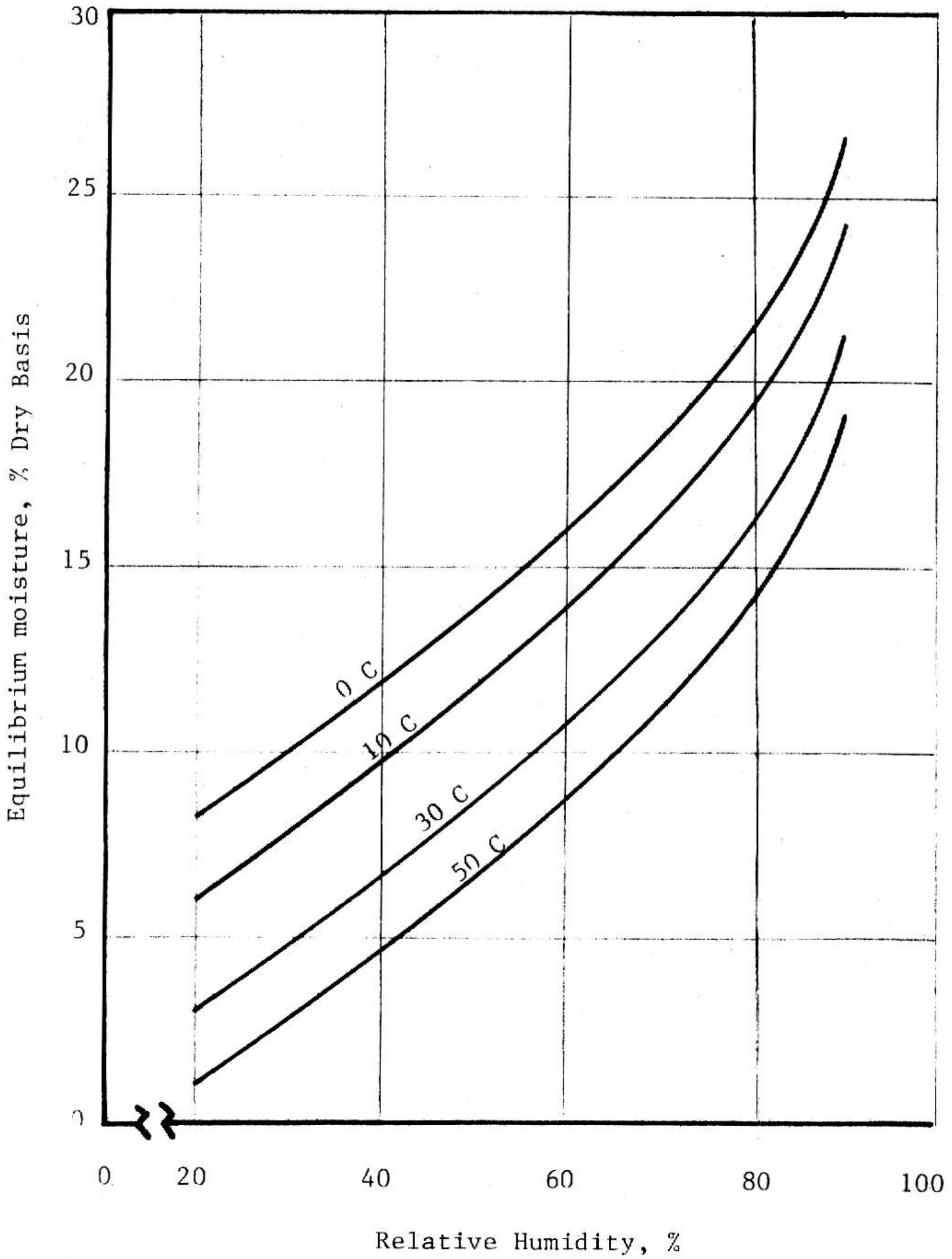

Figure 4.9.4 Equilibrium Moisture Content, Soybeans.

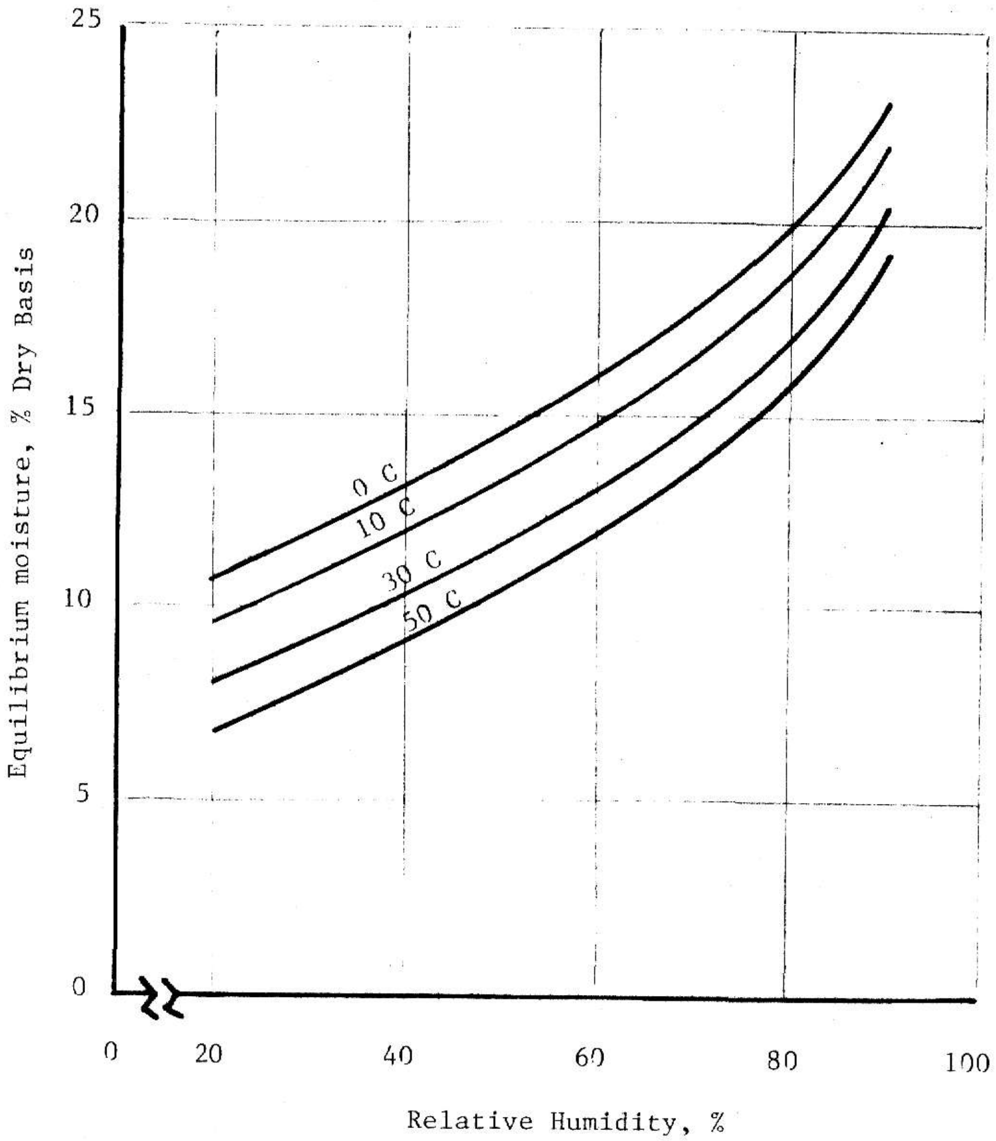

Figure 4.9.5 Equilibrium Moisture Content, Rough Rice.

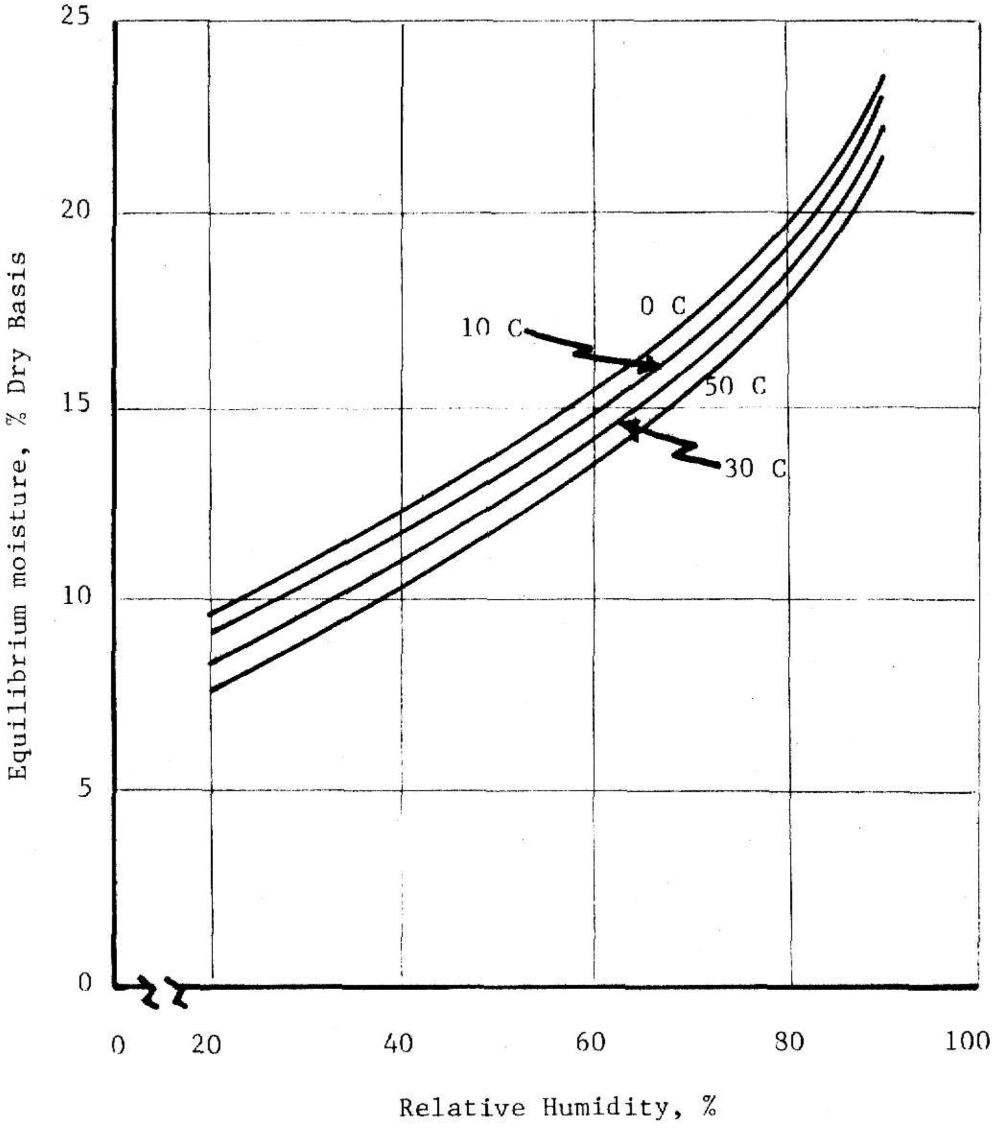

Figure 4.9.6 Equilibrium Moisture Content, Sorghum.

given for the desorption isotherm whenever possible, to make them most applicable to the design of dryers. Whenever the data includes adsorption values or mixed adsorption and desorption, it is noted in the references. All of the actual food grain data used in the analysis, is given in Appendix E. The constants for the Chung-Pfost equation were used to compute point which were plotted in Figures 4.9.1 - 4.9.6.

4.10 Conclusions

It has been shown that all of the error components of the error model (4.3.2) contribute significantly to the observed error. The result is that for dryer design the engineer should be aware of the source of the data used in the design calculation and incorporate an appropriate safety factor. Intermediate points can be calculated using either the Henderson-Thompson or the Chung-Pfost equation with adequate accuracy. The best method for design would be to test the actual grain variety to be dried prior to dryer design. In the event that this technique cannot be done the included graphs (4.9.1-4.9.6) furnish approximate results using the best known historical data. As the relative humidity increases from 10 to 90 percent the standard error was found to undergo a three-fold increase. Therefore EMC-ERH curves extended past 90 percent are very crude approximations to actual data.

4.11 Areas of Future Research

Appropriate data to test the effect of experimental technique is necessary to optimize the total research effort in this field. The method which Pixton(71) has published is a more efficient method and is desirable if its accuracy can be verified by additional research.

All equilibrium moisture equations which are developed in the future must justify their use of additional constants above the three constant models. Also they must have a significantly better accuracy to justify their publication.

As seen in Table 4.8.1 if a 95% confidence interval is constructed, a ± 3% db band must be drawn around each of the curves in Figures 4.9.1 - 4.9.6. This indicates the need to show all actual data on EMC curves as a band width when plotting published curves from data, as well as publishing *actual* data in tabular form. This will reduce the possibility of misuse of these curves by inexperienced engineers placed in a tropical drying situation for the first time.

4.12 REFERENCES:

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APPENDIX
A

ACTUAL WEATHER
DATA

A-1

INPUTS FOR
EQ 1 & EQ 2

```
//EQ1       JOB (498583278,BHA4SLE4,,5),'MAURER.EQ1',TIME=(1,20)
// EXEC FORTGG,P=STORAGE
//STEPLIB DD DSN=OS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='EQ#1.T#1NPLN.0312',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=(NEW,KEEP),
// DCB=(BLKSIZE=13030,RECFM=VS),
// LABEL=(40,,,OUT)
//GO.FT03F001 DD SYSOUT=A
//GO.FT09F001 DD SYSOUT=A,DCB=(RECFM=UA,BLKSIZE=133)
//GO.FT04F001 DD DDNAME=SYSIN1
//SYSIN1 DD *
MODEL VERIFICATION STUDY:  EQ#1  USING ACTUAL PLENUM DATA, TEST#1-N-PLN
       160          12
//GO.SYSIN DD *
7654321M IRTEK            111111111111
0.0002790.0002950.0003120.0003300.0003500.0003700.0003910.0004130.0004370.000461
0.0004870.0005140.0005430.0005730.0006050.0006380.0006730.0007100.0007480.000789
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  63  41  56  39  52  39  53  47  52  48  56  44  60  48  57  50   3TEST#1-N-PLN
  57  51  54  52  54  50  52  51  51  50  50  49  68  40  76  38   3TEST#1-N-PLN
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  56  44  53  49  54  49  54  50  54  51  54  51  56  53  56  50   3TEST#1-N-PLN
MODEL VERIFICATION STUDY:  EQ#1  USING ACTUAL PLENUM DATA, TEST#1-N-PLN
  9 24 74  22.6 70.5 2.76   3.642.8  15.
           60. 2.76
/*
// EXEC FORTGG,P=LAGRANGE,TIME=(,10)
//STEPLIB DD DSN=OS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='EQ#1.T#1NPLN.0312',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=SHR,
// LABEL=(40,,,IN)
//GO.SYSIN DD *
  8  5  3     3  4  1  1
** TEST #1-NPLN ** WEIGHTED GRAIN MOISTURE CONTENTS FROM GMRC ** 9/23/74 @ 6PM
7.875 16.525.75  35.44.25
(F4.0,12F4.4,28X)
```

```
(' ',F7.0,1X,'|',12F8.4)
(' ',T40,F7.0,'|',12F8.4)
(' ',T40,F7.0,'|',12F8.2)
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  9216752249222022102190       WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
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/*
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// DCB=(BLKSIZE=13030,RECFM=VS),
// LABEL=(41,,,OUT)
//GO.FT03F001 DD SYSOUT=A
//GO.FT09F001 DD SYSOUT=A,DCB=(RECFM=UA,BLKSIZE=133)
//GO.FT04F001 DD DDNAME=SYSIN1
//SYSIN1 DD *
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//GO.SYSIN DD *
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  61  51  53  52  52  50  52  51  49  50  58  49  86  40  93  38   3TEST#1-S-PLN
  80  39  57  46  57  53  55  54  54  60  67  62  91  49  97  39   3TEST#1-S-PLN
  85  37  66  47  62  50  60  57  62  57  63  65  86  54  73  51   3TEST#1-S-PLN
  65  56  62  56  59  57  58  36  53  31  54  29  54  38  77  20   3TEST#1-S-PLN
  70  23  49  22  42  32  40  34  40  33  58  27  87  28  94  28   3TEST#1-S-PLN
  83  28  62  32  57  26  50  22  49  22  55  30  75  27  81  29   3TEST#1-S-PLN
  69  29  51  34  42  33  40  31  37  33  54  30  81  36  78  35   3TEST#1-S-PLN
  65  31  53  26  47  25  42  26  39  29  52  29  73  28  70  31   3TEST#1-S-PLN
  61  32  50  34  51  36  48  42  49  46  59  50  84  47  80  48   3TEST#1-S-PLN
  79  52  66  54  63  56  61  55  60  56  68  55  69  55  90  54   3TEST#1-S-PLN
  81  58  70  56  66  57  64  56  65  58  61  59  72  62  76  59   3TEST#1-S-PLN
  74  69  70  70  59  60  55  51  52  48  51  45  57  41  71  34   3TEST#1-S-PLN
  59  28  47  33  42  35  38  33  37  32  50  36  66  26  76  25   3TEST#1-S-PLN
  63  26  47  31  43  39  47  42  44  43  50  46  61  51  81  47   3TEST#1-S-PLN
  71  53  52  54  50  50  51  48  46  44  60  39  82  38  86  36   3TEST#1-S-PLN
  74  41  56  46  51  46  52  45  51  46  64  53  90  39  95  42   3TEST#1-S-PLN
  80  42  68  51  64  52  64  53  65  54  65  57  72  58  76  62   3TEST#1-S-PLN
  71  65  66  63  63  62  64  62  57  50  55  47  62  46  69  44   3TEST#1-S-PLN
  56  44  54  49  54  49  54  50  54  51  54  51  56  53  56  50   3TEST#1-S-PLN
MODEL VERIFICATION STUDY:  EQ#1  USING ACTUAL PLENUM DATA, TEST#1-S-PLN
  9 24 74   22.6 69.6 2.54    3.598.2  15.
            60. 2.54
```

```
/*
// EXEC FORTGG,P=LAGRANGE,TIME=(,10)
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='EQ#1.T#1SPLN.0312',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=SHR,
// LABEL=(41,,,IN)
//GO.SYSIN DD *
  8  5  3      3  4  1  2
** TEST #1-S-PLN ** WEIGHTED GRAIN MOISTURE CONTENTS FROM GMRC ** 9/23/74 @ 6PM
7.875 16.525.75  35.44.25
(F4.0,12F4.4,28X)
(' ',F7.0,1X,'|',12F8.4)
(' ',T40,F7.0,'|',5F8.4)
(' ',T40,F7.0,'|',5F8.2)
  442146219021852179215 8     WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN         1
   921570221722052200216 9    WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN         2
 1611158163321482113210 0     WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN         3
 2131085136819552110209 0     WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN         4
 2601153131715451830209 0     WEIGHTED  GRAIN MOISTURF DATA TEST#1-S-PLN         5
 3321237126614601512153 2     WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN         6
 3781257129413651534144 5     WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN         7
 4801329128813001305132 3     WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN         8
/*
// EXEC FORTGG,P=STORAGE
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='EQ#1.T#2NPLN.0312',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=(NEW,KEEP),
// DCB=(BLKSIZE=13030,RECFM=VS),
// LABEL=(42,,,OUT)
//GO.FT03F001 DD SYSOUT=A
//GO.FT09F001 DD SYSOUT=A,DCB=(RECFM=UA,BLKSIZE=133)
//GO.FT04F001 DD DDNAME=SYSIN1
//SYSIN1 DD *
MODEL VERIFICATION STUDY:  EQ#1  USING ACTUAL PLENUM DATA, TEST#2-N-PLN
        96        12
//GO.SYSIN DD *
7654321M IRTEK              111111111111
0.0002790.0002950.0003120.0003300.0003500.0003700.0003910.0004130.0004370.000461
0.0004870.0005140.0005430.0005730.0006050.0006380.0006730.0007100.0007480.000789
0.0008310.0008760.0009220.0009710.0010220.0010760.0011330.0011920.0012530.001318
0.0013860.0014570.0015310.0016090.0016910.0017760.0018650.0019580.0020560.002157
0.0022640.0023750.0024910.0026130.0027400.0028720.0030100.0031550.0033050.003463
0.0036270.0037690.0039250.0040870.0042550.0044280.0046080.0047950.0049880.005188
0.0053950.0056100.0058320.0060620.0063000.0065460.0068010.0070650.0073380.007620
0.0079120.0082140.0085260.0088480.0091820.0095270.0098830.0102510.0106320.011025
0.0114310.0118500.0122830.0127310.0131920.0136690.0141610.0146700.0151940.015736
0.0162940.0168710.0174660.0180790.0187130.0193650.0200390.0207340.0214510.022190
   9  24  75  12
  60  46  53  42  47  45  42  42  40  40  46  44  61  41  65  33    3TST2NPLN    1
  64  32  53  36  47  43  44  42  42  41  53  45  67  41  72  37    3TST2NPLN    2
  71  38  63  37  60  38  57  35  57  36  66  57  73  64  72  55    3TST2NPLN    3
  64  56  60  47  57  43  54  53  53  51  53  52  61  58  60  56    3TST2NPLN    4
  60  53  57  51  56  55  54  53  49  49  53  48  66  43  71  42    3TST2NPLN    5
  71  44  62  51  59  53  60  55  60  57  59  57  59  55  58  54    3TST2NPLN    6
  59  56  56  51  52  41  46  43  43  40  46  43  57  37  63  34    3TST2NPLN    7
  63  34  54  43  49  44  47  42  43  40  47  42  60  39  68  38    3TST2NPLN    8
  67  39  60  39  56  37  48  39  49  40  53  40  65  37  72  38    3TST2NPLN    9
  71  38  62  38  59  38  55  42  53  43  58  43  70  42  74  38    3TST2NPLN   10
  72  39  65  37  61  41  57  41  56  43  58  42  68  44  74  45    3TST2NPLN   11
  73  46  63  53  57  54  55  51  54  52  56  48  69  43  80  41    3TST2NPLN   12
```

```
MODEL VERIFICATION STUDY:  EQ#1  USING ACTUAL PLENUM DATA, TEST#2-N-PLN
  9 24 75 21.97 74.7  4.1   3.1797.  18.
            60.  4.1
/*
// EXEC FORTGG,P=LAGRANGE,TIME=(,10)
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='EQ#1.T#2NPLN.0312',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=SHR,
// LABEL=(42,,,IN)
//GO.SYSIN DD *
  3  9  3     3  4  1  3
**  TEST #2-N-PLN  **  OVEN GRAIN MOISTURE CONTENTS FROM GMRC  ** 9/24/75 @ 5 PM
   7.  17.  28.  39.  50.  61.  72.  83.  94. 105.
(F4.0,12F4.4,28X)
(' ',F7.0,1X,'|',12F8.4)
(' ',T40,F7.0,'|',12F8.4)
(' ',T40,F7.0,'|',12F8.2)
 1151534152415711647176813871920193119051905GRAIN MOISTURE DATA TEST#2-N-PLN ST1
 1861467147915091528155816011672174017851785GRAIN MOISTURE DATA TEST#2-N-PLN OV2
 279122412151216121712331256129213371377     GRAIN MOISTURE DATA TEST#2-N-PLN OV3
/*
// EXEC FORTGG,P=STORAGE
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='EQ#1.T#2SPLN.0312',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=(NEW,KEEP),
// DCB=(BLKSIZE=13030,RECFM=VS),
// LABEL=(43,,,OUT)
//GO.FT03F001 DD SYSOUT=A
//GO.FT09F001 DD SYSOUT=A,DCB=(RECFM=UA,BLKSIZE=133)
//GO.FT04F001 DD DDNAME=SYSIN1
//SYSIN1 DD *
MODEL VERIFICATION STUDY:  EQ#1  USING ACTUAL PLENUM DATA, TEST#2-S-PLN
      96          12
//GO.SYSIN DD *
7654321M IRTFK          111111111111
0.0002790.0002950.0003120.0003300.0003500.0003700.0003910.0004130.0004370.000461
0.0004870.0005140.0005430.0005730.0006050.0006380.0006730.0007100.0007480.000789
0.0008310.0008760.0009220.0009710.0010220.0010760.0011330.0011920.0012530.001318
0.0013860.0014570.0015310.0016090.0016910.0017760.0018650.0019580.0020560.002157
0.0022640.0023750.0024910.0026130.0027400.0028720.0030100.0031550.0033050.003463
0.0036270.0037690.0039250.0040870.0042550.0044280.0046080.0047950.0049880.005188
0.0053950.0056100.0058320.0060620.0063000.0065460.0068010.0070650.0073380.007620
0.0079120.0082140.0085260.0088480.0091820.0095270.0098830.0102510.0106320.011025
0.0114310.0118500.0122830.0127310.0131920.0136690.0141610.0146700.0151940.015736
0.0162940.0168710.0174660.0180790.0187130.0193650.0200390.0207340.0214510.022190
   9   24   75   12
  63   45   52   45   46   45   41   42   39   40   47   44   68   41   73   33    3TST2SPLN    1
  67   32   52   36   46   43   43   42   41   41   54   45   73   41   78   37    3TST2SPLN    2
  72   38   62   37   59   38   57   35   60   36   65   57   78   64   79   55    3TST2SPLN    3
  69   56   60   47   57   43   55   53   55   51   56   52   63   58   62   56    3TST2SPLN    4
  61   53   56   51   55   55   52   53   48   49   55   48   73   43   80   42    3TST2SPLN    5
  73   44   62   51   58   53   60   55   60   57   60   57   59   55   58   54    3TST2SPLN    6
  59   56   55   51   51   41   45   43   42   40   48   43   62   37   67   34    3TST2SPLN    7
  65   34   52   43   48   44   45   42   41   40   48   42   67   39   74   38    3TST2SPLN    8
  69   39   59   39   55   34   50   21   48   17   55   29   72   44   79   59    3TST2SPLN    9
  72   63   61   50   56   32   54   21   52   21   59   29   76   49   81   58    3TST2SPLN   10
  74   61   65   51   59   38   57   31   55   29   60   46   75   64   81   68    3TST2SPLN   11
  75   73   61   57   56   33   54   22   54   20   56   48   69   43   80   41    3TST2SPLN   12
MODEL VERIFICATION STUDY:  EQ#1  USING ACTUAL PLENUM DATA, TEST#2-S-PLN
  9 24 75 23.81 74.6 4.31    3.1771.  18.
```

```
            60. 4.31
/*
//GO EXEC FORTGG,P=LAGRANGE
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='EQ#1.T#2SPLN.0312',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=SHR,
// LABEL=(43,,,IN)
//GO.SYSIN DD *
  3  9  3     3  4  1  4
**  TEST #2-S-PLN  **        GRAIN MOISTURE CONTENTS FROM GMRC   ** 9/24/75 @ 5 PM
   7.  17.  28.  39.  50.  61.  72.  83.  94. 105.
(F4.0,12F4.4,28X)
(' ',F7.0,1X,'|',12F8.4)
(' ',T40,F7.0,'|',10F8.4)
(' ',T40,F7.0,'|',10F8.2)
 116145114851550169819542168213420892O602034  TEST#2-S-PLN 10/15/75  OVEN 1 OF 3
 186142014451481152415791683184919682O191959  TEST#2-S-PLN 10/15/75  OVEN 2 OF 3
 279119811851185119612051229126213061349      TEST#2-S-PLN 10/15/75  OVEN 3 OF 3
/*
// EXEC FORTGG,P=STORAGE
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='EQ#1.T#3NPLN.0312',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=(NEW,KEEP),
// DCB=(BLKSIZE=13030,RECFM=VS),
// LABEL=(44,,,OUT)
//GO.FT03F001 DD SYSOUT=A
//GO.FT09F001 DD SYSOUT=A,DCB=(RECFM=UA,BLKSIZE=133)
//GO.FT04F001 DD DDNAME=SYSIN1
//SYSIN1 DD *
MODEL VERIFICATION STUDY:  EQ#1  USING ACTUAL PLENUM DATA, TEST#3-N-PLN
       72          12
//GO.SYSIN DD *
7654321M IRTEK           111111111111
0.0002790.0002950.0003120.0003300.0003500.0003760.0003910.0004130.0004370.000461
0.0004870.0005140.0005430.0005730.0006050.0006380.0006730.0007100.0007480.000789
0.0008310.0008760.0009220.0009710.0010220.0010760.0011330.0011920.0012530.001318
0.0013860.0014570.0015310.0016090.0016910.0017760.0018650.0019580.0020560.002157
0.0022640.0023750.0024910.0026130.0027400.0028720.0030100.0031550.0033050.003463
0.0036270.0037690.0039250.0040870.0042550.0044280.0046080.0047950.0049830.005188
0.0053950.0056100.0058320.0060620.0063000.0065460.0068010.0070650.0073380.007620
0.0079120.0082140.0085260.0088480.0091820.0095270.0098830.0102510.0106320.011025
0.0114310.0118500.0122830.0127310.0131920.0136690.0141610.0146700.0151940.015736
0.0162940.0168710.0174660.0180790.0187130.0193650.0200390.0207340.0214510.022190
  10  15  75   9
  61  31  52  34  44  37  40  37  38  34  39  35  55  32  65  29   3TST3NPLN   1
  66  30  60  32  56  36  54  44  52  45  50  44  56  42  63  33   3TST3NPLN   2
  62  30  54  31  48  33  42  35  38  35  37  36  53  35  62  31   3TST3NPLN   3
  63  29  54  32  47  36  41  36  39  35  39  38  57  32  68  33   3TST3NPLN   4
  70  33  62  38  56  37  54  40  49  43  46  42  62  41  79  35   3TST3NPLN   5
  81  34  72  37  66  43  59  48  45  43  42  40  62  43  71  47   3TST3NPLN   6
  76  51  69  53  71  53  69  57  67  58  67  58  73  57  79  55   3TST3NPLN   7
  80  55  74  58  70  60  68  59  65  60  64  60  69  57  71  55   3TST3NPLN   8
  72  55  68  54  55  50  51  47  49  44  46  41  49  34  54  31   3TST3NPLN   9
MODEL VERIFICATION STUDY:  EQ#1  USING ACTUAL PLENUM DATA, TEST#3-N-PLN
 10 15 75 22.94 74.2 4.12   3.435.6  15.
            60. 4.12
/*
//GO EXEC FORTGG,P=LAGRANGE
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='EQ#1.T#3NPLN.0312',
```

```
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=SHR,
// LABEL=(44,,,IN)
//GO.SYSIN DD *
  5  3  3     3  4  1  5
**  TEST #3-N-PLN  **  GRAIN MOISTURE CONTENTS FROM GMRC  **  STARTING 10/15/75
   7.  17.  28.  39.
(F4.0,12F4.4,28X)
(' ',F7.0,1X,'|',12F8.4)
(' ',T40,F7.0,'|',10F8.4)
(' ',T40,F7.0,'|',10F8.2)
  41173022772314 2136           TEST-3-N-PLN    STEINLITE DATA 10/15/75        1 OF 5
 113137916642128 2259           TEST-3-N-PLN    STEINLITE DATA 10/15/75        2 OF 5
 163128013661716                TEST-3-N-PLN    STEINLITE DATA 10/15/75        3 OF 5
 211134013281377                TEST-3-N-PLN    STEINLITE DATA 10/15/75        4 OF 5
 216129913721470                TEST-3-N-PLN    STEINLITE DATA 10/15/75        5 OF 5
/*
// EXEC FORTGG,P=STORAGE
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='EQ#1.T#3SPLN.0312',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=(NEW,KEEP),
// DCB=(BLKSIZE=13030,RECFM=VS),
// LABEL=(45,,,OUT)
//GO.FT03F001 DD SYSOUT=A
//GO.FT09F001 DD SYSOUT=A,DCB=(RECFM=UA,BLKSIZE=133)
//GO.FT04F001 DD DDNAME=SYSIN1
//SYSIN1 DD *
MODEL VERIFICATION STUDY:  EQ#1  USING ACTUAL PLENUM DATA, TEST#3-S-PLN
         72          12
//GO.SYSIN DD *
7654321M IRTEK             111111111111
0.0002790.0002950.0003120.0003300.0003500.0003700.0003910.0004130.0004370.000461
0.0004870.0005140.0005430.0005730.0006050.0006380.0006730.0007100.0007480.000789
0.0008310.0008760.0009220.0009710.0010220.0010760.0011330.0011920.0012530.001318
0.0013860.0014570.0015310.0016090.0016910.0017760.0018650.0019580.0020560.002157
0.0022640.0023750.0024910.0026130.0027400.0028720.0030100.0031550.0033050.003463
0.0036270.0037690.0039250.0040870.0042550.0044280.0046080.0047950.0049880.005188
0.0053950.0056100.0058320.0060620.0063000.0065460.0068010.0070650.0073350.007620
0.0079120.0082140.0085260.0088430.0091820.0095270.0098830.0102510.0106320.011025
0.0114310.0118500.0122830.0127310.0131920.0136690.0141610.0146700.0151940.015736
0.0162940.0168710.0174660.0180790.0137130.0193650.0200390.0207340.0214510.022190
  10  15  75   9
  64  31  52  34  45  37  41  37  39  34  40  35  65  32  74  29   3TST3SPLN   1
  71  30  60  32  57  36  54  44  53  45  51  44  63  42  71  33   3TST3SPLN   2
  67  30  54  31  48  33  42  35  39  35  40  36  63  35  71  31   3TST3SPLN   3
  68  29  54  32  47  36  42  36  39  35  41  38  67  32  77  33   3TST3SPLN   4
  74  33  61  38  56  37  54  40  49  43  49  42  72  41  86  35   3TST3SPLN   5
  83  34  71  37  65  43  57  48  45  43  45  40  70  43  77  47   3TST3SPLN   6
  78  51  67  53  70  53  68  57  66  58  68  58  82  57  86  55   3TST3SPLN   7
  84  55  74  58  70  60  67  59  65  60  65  60  75  57  73  55   3TST3SPLN   8
  73  55  68  54  56  50  53  47  51  44  48  41  59  34  64  31   3TST3SPLN   9
MODEL VERIFICATION STUDY:  EQ#1  USING ACTUAL PLENUM DATA, TEST#3-S-PLN
 10 15 75 23.52 74.2 3.97   3.448.5  15.
            60. 3.97
/*
//GO EXEC FORTGG,P=LAGRANGE
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='EQ#1.T#3SPLN.0312',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=SHR,
// LABEL=(45,,,IN)
//GO.SYSIN DD *
```

```
  5  3  3     3  4  1  6
**  TEST #3-S-PLN  **  GRAIN MOISTURE CONTENTS FROM GMRC  **  STARTING 10/15/75
   7.  17.  28.  39.
(F4.0,12F4.4,28X)
(' ',F7.0,1X,'|',12F8.4)
(' ',T40,F7.0,'|',10F8.4)
(' ',T40,F7.0,'|',10F8.2)
41.51806233723892322        TEST-3-S-PLN   STEINLITE DATA 10/15/75       1 OF 5
 1141307166821522173        TEST-3-S-PLN       OVEN  DATA 10/15/75       2 OF 5
 162120713081844            TEST-3-S-PLN   STEINLITE DATA 10/15/75       3 OF 5
 2111238125613631675        TEST-3-S-PLN        OVEN DATA 10/15/75       4 OF 5
 2161201128914791683        TEST-3-S-PLN        OVEN DATA 10/15/75       5 OF 5
/*
```

A-2

INPUTS FOR
EQ 3 & DRYER

```
/*TAPE9
// FXEC RINGWTR,PARM=9939SM
// EXEC FORTGG,P=KSUDRYER
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='DRY.02-1NPLN-0310',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=(NEW,KEEP),
// DCB=(BLKSIZE=13030,RECFM=VS),
// LABEL=(52,,,OUT)
//GO.FT13F001 DD DUMMY
//GO.FT03F001 DD DDNAME=SYSIN1
//SYSIN1 DD *
160 3 1.01 6344 0.00 5652 0.00 5260 0.00 5381 0.00 5285 0.00 5664 0.00TST1NPLN 1
 6064 0.00 5777 0.00 5780 0.00 5495 0.00 5487 0.00 5297 0.00 5195 0.00TST1NPLN 2
 5098 0.00 6836 0.00 7625 0.00 7329 0.00 5766 0.00 5883 0.00 5694 0.00TST1NPLN 3
 5599 0.00 6099 0.00 7540 0.00 8222 0.00 7823 0.00 6847 0.00 6460 0.00TST1NPLN 4
 6089 0.00 6284 0.00 6299 0.00 7056 0.00 6854 0.00 6474 0.00 6379 0.00TST1NPLN 5
 6284 0.00 5941 0.00 5442 0.00 5240 0.00 5160 0.00 6516 0.00 6321 0.00TST1NPLN 6
 5131 0.00 4365 0.00 4078 0.00 4077 0.00 4842 0.00 7020 0.00 7716 0.00TST1NPLN 7
 7617 0.00 6232 0.00 5828 0.00 5031 0.00 4440 0.00 4654 0.00 5731 0.00TST1NPLN 8
 6328 0.00 6129 0.00 5250 0.00 4367 0.00 4265 0.00 3980 0.00 4555 0.00TST1NPLN 9
 6337 0.00 6829 0.00 6231 0.00 5432 0.00 4840 0.00 4448 0.00 4160 0.00TST1NPLN10
 4358 0.00 5634 0.00 5836 0.00 5641 0.00 5152 0.00 5058 0.00 5073 0.00TST1NPLN11
 5086 0.00 5486 0.00 6848 0.00 7341 0.00 7447 0.00 6762 0.00 6475 0.00TST1NPLN12
 6278 0.00 6282 0.00 6375 0.00 6765 0.00 7548 0.00 7555 0.00 7160 0.00TST1NPLN13
 6771 0.00 6671 0.00 6578 0.00 6193 0.00 6590 0.00 6970 0.00 7388 0.00TST1NPLN14
 7195 0.00 6099 0.00 5586 0.00 5286 0.00 5181 0.00 5169 0.00 5742 0.00TST1NPLN15
 5534 0.00 4954 0.00 4469 0.00 4077 0.00 3879 0.00 4377 0.00 5235 0.00TST1NPLN16
 5827 0.00 5630 0.00 4852 0.00 4580 0.00 4685 0.00 4688 0.00 4892 0.00TST1NPLN17
 5391 0.00 6552 0.00 6760 0.00 5595 0.00 5196 0.00 5384 0.00 4887 0.00TST1NPLN18
 5359 0.00 6439 0.00 7128 0.00 6838 0.00 5767 0.00 5279 0.00 5376 0.00TST1NPLN19
 5377 0.00 5787 0.00 7329 0.00 7927 0.00 7630 0.00 6952 0.00 6660 0.00TST1NPLN20
 6564 0.00 6666 0.00 6674 0.00 6577 0.00 7172 0.00 7180 0.00 6884 0.00TST1NPLN21
 6687 0.00 6589 0.00 5776 0.00 5477 0.00 5668 0.00 5957 0.00 5665 0.00TST1NPLN22
 5385 0.00 5484 0.00 5486 0.00 5491 0.00 5491 0.00 5691 0.00 5679 0.00TST1NPLN23
//GO.FT04F001 DD DDNAME=SYSIN2
//SYSIN2 DD *
          3        .015
/*
//GO.SYSIN DD *
KSUDRYER SIMULATION OF NATURAL-AIR CORN DRYING;   VERIFICATION WITH TEST#1-N-PLN
     22.60         70.5      1775.     39300.         15.          20.    10    1
/*
// EXEC FORTGG,P=LAGRANGE,TIME=(,10)
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='DRY.02-1NPLN-0310',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=SHR,
// LABEL=(52,,,IN)
//GO.SYSIN DD *
  8  5  3     3  4
** TEST #1-NPLN ** WEIGHTED GRAIN MOISTURE CONTENTS FROM GMRC ** 9/23/74 @ 6PM
7.875 16.525.75  35.44.25
(F4.0,12F4.4,28X)
(' ',F7.0,1X,'|',12F8.4)
(' ',T40,F7.0,'|',12F8.4)
(' ',T40,F7.0,'|',12F8.2)
  442153225622112173 2167      WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
  921675224922202210 2190      WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
 1611265169521602165 2138      WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
 2131220146818682133 2120      WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
 2601293143016382035 2168      WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
```

```
 332136013621558158716 94     WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
 382140814051445158416 57     WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
 480146614061411144714 23     WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
/*
// EXEC FORTGG,P=KSUDRYER
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='DRY.02-1SPLN-0310',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=(NEW,KEEP),
// DCB=(BLKSIZE=13030,RECFM=VS),
// LABEL=(52,,,OUT)
//GO.FT13F001 DD DUMMY
//GO.FT03F001 DD DDNAME=SYSIN1
//SYSIN1 DD *
160 3 1.01 6640 0.00 5450 0.00 5060 0.00 5375 0.00 5176 0.00 6360 0.00TST1SPLN 1
 7660 0.00 6272 0.00 6174 0.00 5388 0.00 5294 0.00 5297 0.00 4999 0.00TST1SPLN 2
 5898 0.00 8630 0.00 9322 0.00 8023 0.00 5755 0.00 5780 0.00 5587 0.00TST1SPLN 3
 5492 0.00 6760 0.00 9130 0.00 9722 0.00 8530 0.00 6650 0.00 6262 0.00TST1SPLN 4
 6080 0.00 6284 0.00 6384 0.00 8656 0.00 7360 0.00 6577 0.00 6285 0.00TST1SPLN 5
 5990 0.00 5840 0.00 5342 0.00 5440 0.00 5456 0.00 7718 0.00 7018 0.00TST1SPLN 6
 4932 0.00 4260 0.00 4078 0.00 4083 0.00 5847 0.00 8720 0.00 9414 0.00TST1SPLN 7
 8314 0.00 6230 0.00 5725 0.00 5030 0.00 4940 0.00 5545 0.00 7530 0.00TST1SPLN 8
 8126 0.00 6925 0.00 5145 0.00 4253 0.00 4063 0.00 3780 0.00 5455 0.00TST1SPLN 9
 8133 0.00 7828 0.00 6527 0.00 5331 0.00 4737 0.00 4248 0.00 3960 0.00TST1SPLN10
 5260 0.00 7334 0.00 7032 0.00 6134 0.00 5050 0.00 5158 0.00 4870 0.00TST1SPLN11
 4980 0.00 5980 0.00 8446 0.00 8036 0.00 7941 0.00 6656 0.00 6365 0.00TST1SPLN12
 6173 0.00 6076 0.00 6870 0.00 6955 0.00 9046 0.00 8148 0.00 7056 0.00TST1SPLN13
 6664 0.00 6469 0.00 6573 0.00 6190 0.00 7287 0.00 7670 0.00 7456 0.00TST1SPLN14
 7060 0.00 5584 0.00 5592 0.00 5293 0.00 5184 0.00 5772 0.00 7145 0.00TST1SPLN15
 5933 0.00 4752 0.00 4272 0.00 3874 0.00 3782 0.00 5080 0.00 6634 0.00TST1SPLN16
 7626 0.00 6328 0.00 4750 0.00 4380 0.00 4782 0.00 4488 0.00 5092 0.00TST1SPLN17
 6188 0.00 8150 0.00 7154 0.00 5292 0.00 5096 0.00 5190 0.00 4690 0.00TST1SPLN18
 6066 0.00 8236 0.00 8625 0.00 7433 0.00 5660 0.00 5182 0.00 5291 0.00TST1SPLN19
 5196 0.00 6490 0.00 9028 0.00 9525 0.00 8026 0.00 6850 0.00 6460 0.00TST1SPLN20
 6462 0.00 6564 0.00 6574 0.00 7272 0.00 7672 0.00 7180 0.00 6690 0.00TST1SPLN21
 6393 0.00 6495 0.00 5782 0.00 5586 0.00 6276 0.00 6968 0.00 5670 0.00TST1SPLN22
 5488 0.00 5484 0.00 5486 0.00 5491 0.00 5491 0.00 5691 0.00 5679 0.00TST1SPLN23
/*
//GO.FT04F001 DD DDNAME=SYSIN2
//SYSIN2 DD *
         3        .015
/*
//GO.SYSIN DD *
KSUDRYER SIMULATION OF NATURAL-AIR CORN DRYING;   VERIFICATION WITH TEST#1-S-PLN
     22.60        69.6       1520.    36570.        15.        20.    10    1
/*
// EXEC FORTGG,P=LAGRANGE,TIME=(,10)
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='DRY.02-1SPLN-0310',
// UNIT=TAPE9,VOL=SER=9939SM,DISP=SHR,
// LABEL=(52,,,IN)
  8  5  3     4  4  4  2
** TEST #1-S-PLN ** WEIGHTED GRAIN MOISTURE CONTENTS FROM GMRC ** 9/23/74 @ 6PM
7.875 16.525.75  35.44.25
(F4.0,12F4.4,28X)
(' ',F7.0,1X,'|',12F8.4)
(' ',T40,F7.0,'|',5F8.4)
(' ',T40,F7.0,'|',5F8.2)
  442146219021852179 2158    WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN        1
  921570221722052200 2169    WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN        2
 1611158163321482113 2100    WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN        3
```

```
 21310851368195521102090      WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN          4
 26011531317154518302090      WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN          5
 33212371266146015121532      WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN          6
 37812571294136515341445      WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN          7
 48013291288130013051323      WEIGHTED  GRAIN MOISTURE DATA TEST#1-S-PLN          8
/*
// EXEC FORTGG,P=KSUDRYER
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='DRY.02-2NPLN-0310',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=(NEW,KEEP),
// DCB=(BLKSIZE=13030,RECFM=VS),
// LABEL=(52,,,OUT)
//GO.FT13F001 DD DUMMY
//GO.FT03F001 DD DDNAME=SYSIN1
//SYSIN1 DD *
 93 3 1.01 6058 0.00 5374 0.00 4793 0.00 4299 0.00 4099 0.00 4693 0.00TST2NPLN 1
 6148 0.00 6530 0.00 6430 0.00 5352 0.00 4786 0.00 4493 0.00 4296 0.00TST2NPLN 2
 5374 0.00 6739 0.00 7228 0.00 7130 0.00 6338 0.00 6044 0.00 5743 0.00TST2NPLN 3
 5745 0.00 6673 0.00 7373 0.00 7255 0.00 6475 0.00 6062 0.00 5759 0.00TST2NPLN 4
 5496 0.00 5393 0.00 5396 0.00 6190 0.00 6087 0.00 6078 0.00 5780 0.00TST2NPLN 5
 5696 0.00 5496 0.00 4999 0.00 5383 0.00 6643 0.00 7135 0.00 7138 0.00TST2NPLN 6
 6267 0.00 5980 0.00 6084 0.00 6090 0.00 5993 0.00 5937 0.00 5887 0.00TST2NPLN 7
 5990 0.00 5683 0.00 5266 0.00 4689 0.00 4389 0.00 4689 0.00 5747 0.00TST2NPLN 8
 6334 0.00 6334 0.00 5466 0.00 4983 0.00 4783 0.00 4389 0.00 4783 0.00TST2NPLN 9
 6046 0.00 6833 0.00 6736 0.00 6046 0.00 5649 0.00 4871 0.00 4971 0.00TST2NPLN10
 5361 0.00 6535 0.00 7229 0.00 7130 0.00 6241 0.00 5946 0.00 5561 0.00TST2NPLN11
 5369 0.00 5857 0.00 7036 0.00 7427 0.00 7230 0.00 6535 0.00 6148 0.00TST2NPLN12
 5755 0.00 5662 0.00 5855 0.00 6842 0.00 7436 0.00 7338 0.00 6370 0.00TST2NPLN13
 5786 0.00 5586 0.00 5493 0.00 14
//GO.FT04F001 DD DDNAME=SYSIN2
//SYSIN2 DD *
         3      .035
/*
//GO.SYSIN DD *
KSUDRYER SIMULATION OF NATURAL-AIR CORN DRYING;    VERIFICATION WITH TEST#2-N-PLN
    21.97        74.7        7365.    109000.        18.         20.    10    1
/*
// EXEC FORTGG,P=LAGRANGE,TIME=(,10)
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='DRY.02-2NPLN-0310',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=SHR,
// LABEL=(52,,,IN)
//GO.SYSIN DD *
  3  9  3     4  4  4  3
**  TEST #2-N-PLN  **  OVEN GRAIN MOISTURE CONTENTS FROM GMRC  ** 9/24/75 @ 5 PM
   7.  17.  28.  39.  50.  61.  72.  83.  94. 105.
(F4.0,12F4.4,28X)
(' ',F7.0,1X,'|',12F8.4)
(' ',T40,F7.0,'|',12F8.4)
(' ',T40,F7.0,'|',12F8.2)
 11515341524157116471768188719201931190519 05GRAIN MOISTURE DATA TEST#2-N-PLN ST1
 18614671479150915281558160116721740178517 85GRAIN MOISTURE DATA TEST#2-N-PLN OV2
 279122412151216121712331256129213371377        GRAIN MOISTURE DATA TEST#2-N-PLN OV3
/*
// EXEC FORTGG,P=KSUDRYER
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='DRY.02-2SPLN-0310',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=(NEW,KEEP),
// DCB=(BLKSIZE=13030,RECFM=VS),
// LABEL=(52,,,OUT)
```

```
//GO.FT13F001 DD DUMMY
//GO.FT03F001 DD DDNAME=SYSIN1
//SYSIN1 DD *
 93 3 1.01 6352 0.00 5277 0.00 4696 0.00 4199 0.00 3999 0.00 4789 0.00TST2SPLN 1
 6837 0.00 7323 0.00 6727 0.00 5254 0.00 4689 0.00 4396 0.00 4199 0.00TST2SPLN 2
 5472 0.00 7332 0.00 7823 0.00 7229 0.00 6239 0.00 5946 0.00 5743 0.00TST2SPLN 3
 6041 0.00 6575 0.00 7862 0.00 7944 0.00 6963 0.00 6062 0.00 5759 0.00TST2SPLN 4
 5593 0.00 5586 0.00 5686 0.00 6384 0.00 6281 0.00 6175 0.00 5683 0.00TST2SPLN 5
 5599 0.00 5299 0.00 4899 0.00 5577 0.00 7334 0.00 8026 0.00 7335 0.00TST2SPLN 6
 6267 0.00 5883 0.00 6084 0.00 6090 0.00 6090 0.00 5987 0.00 5887 0.00TST2SPLN 7
 5990 0.00 5586 0.00 5168 0.00 4593 0.00 4293 0.00 4883 0.00 6239 0.00TST2SPLN 8
 6729 0.00 6531 0.00 5271 0.00 4886 0.00 4589 0.00 4196 0.00 4880 0.00TST2SPLN 9
 6736 0.00 7427 0.00 6933 0.00 5947 0.00 5551 0.00 5066 0.00 4874 0.00TST2SPLN10
 5557 0.00 7228 0.00 7923 0.00 7229 0.00 6142 0.00 5651 0.00 5464 0.00TST2SPLN11
 5271 0.00 5955 0.00 7630 0.00 8122 0.00 7428 0.00 6535 0.00 5951 0.00TST2SPLN12
 5755 0.00 5564 0.00 6051 0.00 7533 0.00 8128 0.00 7536 0.00 6175 0.00TST2SPLN13
 5690 0.00 5490 0.00 5493 0.00 14
/*
//GO.FT04F001 DD DDNAME=SYSIN2
//SYSIN2 DD *
          3        .035
/*
//GO.SYSIN DD *
KSUDRYER SIMULATION OF NATURAL-AIR CORN DRYING;   VERIFICATION WITH TEST#2-S-PLN
     23.81         74.6      7626.    110000.          18.         20.    10     1
/*
//GO EXEC FORTGG,P=LAGRANGE
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='DRY.02-2SPLN-0310',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=SHR,
// LABEL=(52,,,IN)
//GO.SYSIN DD *
  3  9  3     4  4  4  4
**  TEST #2-S-PLN  **        GRAIN MOISTURE CONTENTS FROM GMRC  ** 9/24/75 @ 5 PM
   7.  17.  28.  39.  50.  61.  72.  83.  94. 105.
(F4.0,12F4.4,28X)
(' ',F7.0,1X,'|',12F8.4)
(' ',T40,F7.0,'|',10F8.4)
(' ',T40,F7.0,'|',10F8.2)
 116145114851550169819542168213420892060203 4  TEST#2-S-PLN 10/15/75  OVEN 1 OF 3
 186142014451481152415791683184919682019195 9  TEST#2-S-PLN 10/15/75  OVEN 2 OF 3
 279119811851185119612051229126213061349       TEST#2-S-PLN 10/15/75  OVEN 3 OF 3
/*
// EXEC FORTGG,P=KSUDRYER
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='DRY.02-3NPLN-0310',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=(NEW,KEEP),                 DATA0040
// DCB=(BLKSIZE=13030,RECFM=VS),                                        DATA0050
// LABEL=(52,,,OUT)
//GO.FT13F001 DD DUMMY
//GO.FT03F001 DD DDNAME=SYSIN1
//SYSIN1 DD *
 72 3 1.01 6132 0.00 5250 0.00 4476 0.00 4089 0.00 3885 0.00 3985 0.00TST3NPLN 1
 5542 0.00 6525 0.00 6626 0.00 6035 0.00 5647 0.00 5469 0.00 5277 0.00TST3NPLN 2
 5080 0.00 5659 0.00 6332 0.00 6230 0.00 5441 0.00 4856 0.00 4276 0.00TST3NPLN 3
 3889 0.00 3796 0.00 5350 0.00 6231 0.00 6327 0.00 5443 0.00 4765 0.00TST3NPLN 4
 4182 0.00 3985 0.00 3996 0.00 5739 0.00 6827 0.00 7025 0.00 6241 0.00TST3NPLN 5
 5649 0.00 5459 0.00 4980 0.00 4686 0.00 6246 0.00 7920 0.00 8118 0.00TST3NPLN 6
 7228 0.00 6643 0.00 5967 0.00 4593 0.00 4293 0.00 6250 0.00 7142 0.00TST3NPLN 7
 7642 0.00 6957 0.00 7153 0.00 6966 0.00 6773 0.00 6773 0.00 7357 0.00TST3NPLN 8
```

```
 7944 0.00 8042 0.00 7457 0.00 7071 0.00 6873 0.00 6584 0.00 6437 0.00TST3NPLN 9
 6966 0.00 7157 0.00 7255 0.00 6861 0.00 5583 0.00 5186 0.00 4983 0.00TST3NPLN10
 4683 0.00 4956 0.00 5441 0.00                                          TST3NPLN11
/*
//GO.FT04F001 DD DDNAME=SYSIN2
//SYSIN2 DD *
         3      .050
/*
//GO.SYSIN DD *
KSUDRYER SIMULATION OF NATURAL-AIR CORN DRYING;   VERIFICATION WITH TEST#3-N-PLN
     22.94      74.2     1949.    26750.       15.       20.   10    1
/*
//GO EXEC FORTGG,P=LAGRANGE
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='DRY.02-3NPLN-0310',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=SHR,
// LABEL=(52,,,IN)
//GO.SYSIN DD *
  5  3  3     4  4  4  5
**  TEST #3-N-PLN  **  GRAIN MOISTURE CONTENTS FROM GMRC  **  STARTING 10/15/75
   7.  17.  28.  39.
(F4.0,12F4.4,28X)
(' ',F7.0,1X,'|',12F8.4)
(' ',T40,F7.0,'|',10F8.4)
(' ',T40,F7.0,'|',10F8.2)
  41173022772314213 6          TEST-3-N-PLN    STEINLITE DATA 10/15/75       1 OF 5
 113137916642128225 9          TEST-3-N-PLN    STEINLITE DATA 10/15/75       2 OF 5
 163128013661716               TEST-3-N-PLN    STEINLITE DATA 10/15/75       3 OF 5
 211134013281377               TEST-3-N-PLN    STEINLITE DATA 10/15/75       4 OF 5
 216129913721470               TEST-3-N-PLN    STEINLITE DATA 10/15/75       5 OF 5
/*
// EXEC FORTGG,P=KSUDRYER
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='DRY02.THCM.3S0310',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=(NEW,KEEP),
// DCB=(BLKSIZE=13030,RECFM=VS),
// LABEL=(52,,,OUT)
//GO.FT13F001 DD DUMMY
//GO.FT03F001 DD DDNAME=SYSIN1                                          DATA0120
//SYSIN1 DD *                                                           DATA0130
 72 3 1.01 6429 0.00 5250 0.00 4573 0.00 4186 0.00 3982 0.00 4082 0.00TST3SPLN 1
 6529 0.00 7419 0.00 7122 0.00 6035 0.00 5745 0.00 5469 0.00 5374 0.00TST3SPLN 2
 5177 0.00 6346 0.00 7125 0.00 6725 0.00 5441 0.00 4856 0.00 4276 0.00TST3SPLN 3
 3985 0.00 4085 0.00 6335 0.00 7123 0.00 6823 0.00 5443 0.00 4765 0.00TST3SPLN 4
 4279 0.00 3985 0.00 4189 0.00 6727 0.00 7720 0.00 7422 0.00 6142 0.00TST3SPLN 5
 5649 0.00 5459 0.00 4980 0.00 4977 0.00 7233 0.00 8616 0.00 8317 0.00TST3SPLN 6
 7129 0.00 6545 0.00 5772 0.00 4593 0.00 4583 0.00 7038 0.00 7735 0.00TST3SPLN 7
 7839 0.00 6761 0.00 7055 0.00 6868 0.00 6675 0.00 6870 0.00 8243 0.00TST3SPLN 8
 8635 0.00 8437 0.00 7457 0.00 7071 0.00 6775 0.00 6534 0.00 6584 0.00TST3SPLN 9
 7554 0.00 7353 0.00 7353 0.00 6861 0.00 5680 0.00 5380 0.00 5177 0.00TST3SPLN10
 4877 0.00 5939 0.00 6429 0.00                                          TST3SPLN11
/*                                                                      DATA0370
//GO.FT04F001 DD DDNAME=SYSIN2                                          DATA0380
//SYSIN2 DD *                                                           DATA0390
         3      .045
/*                                                                      DATA0410
//GO.SYSIN DD *                                                         DATA0420
KSUDRYER SIMULATION OF NATURAL-AIR CORN DRYING;   VERIFICATION WITH TEST#3-S-PLN
     23.52      72.5     1780.    27750.       15.       20.   10    1
/*                                                                      DATA0450
```

```
//GO EXEC FORTGG,P=LAGRANGE
//STEPLIB DD DSN=DS082.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN='DRY02.THCM.3S0310',
// UNIT=TAPE9,VOL=(,RETAIN,SER=9939SM),DISP=SHR,
// LABEL=(52,,,IN)
//GO.SYSIN DD *
  5  3  3    4    4  4  6
**  TEST #3-S-PLN  **  GRAIN MOISTURE CONTENTS FROM GMRC  **  STARTING 10/15/75
   7.  17.  28.  39.
(F4.0,12F4.4,28X)
(' ',F7.0,1X,'|',12F8.4)
(' ',T40,F7.0,'|',10F8.4)
(' ',T40,F7.0,'|',10F8.2)
41.51806233723892322          TEST-3-S-PLN    STEINLITE DATA 10/15/75       1 OF 5
 1141307166821522173          TEST-3-S-PLN       OVEN  DATA 10/15/75       2 OF 5
 162120713081844              TEST-3-S-PLN    STEINLITE DATA 10/15/75       3 OF 5
 2111238125613631675          TEST-3-S-PLN         OVEN DATA 10/15/75       4 OF 5
 2161201128914791683          TEST-3-S-PLN         OVEN DATA 10/15/75       5 OF 5
/*
```

APPENDIX

B

LAGRANGE PROGRAM

```
      DIMENSION T(20),AX(20),XB(20),SD(20)
      DIMENSION AUTH(5),G(800),DEPA(20),IFMT(20),ATRIB(6)
      DIMENSION GMW(30),GT(30),SHOUR(400),SM(4800),SHT(960),SINT(960)
      DIMENSION SDEP(30),SDIF(960),HOUR(400)
      DIMENSION OFMT1(20),OFMT2(20),OFMT3(20)
      DIMENSION DML(30)
      DIMENSION OUTPUT(21),TITLE(20)
      DATA SCORE /'----'/
      DATA OUTPUT / 21*'    '/
      DATA ATRIB/'MOIS','TURE','    ','TEMP','ERAT','URE '/
    1 FORMAT(10I3,50X)
    2 FORMAT(20A4)
    3 FORMAT(' ',T40,8X,21A4)
    4 FORMAT('0',T45,'MEAN ABSOLUTE DEVIATION =',  F15.4,//,' ',T54,'MEA
     ¬N DEVIATION =',F15.4,//,' ',T50,'STANDARD DEVIATION =',F15.4)
    5 FORMAT(15F5.1)
    6 FORMAT('1',T25,20A4,//(T40,8X,10F8.2))
    7 FORMAT('0A',I3,'TH ORDER EQUATION WAS USED FOR LAGRANGIAN INTERPOL
     ¬ATION.',/,' THE FITTED DEPENDENT VARIABLE WAS ',3A4,'.')
    8 FORMAT('1',T25,20A4)
    9 FORMAT(4I2,F10.2)
   99 FORMAT('0OUTPUT WILL CONSIST OF:')
  100 FORMAT(6X,'INPUT DATA, DEPTH CORRECTED DATA, TIME CORRECTED DATA,
     ¬AND DIFFERENCED TABLES.')
  101 FORMAT(6X,'DEPTH CORRECTED DATA, TIME CORRECTED DATA, AND DIFFEREN
     ¬CED TABLES.')
  102 FORMAT(6X,'TIME CORRECTED DATA, AND DIFFERENCED TABLES.')
  103 FORMAT('0',I6,' COPIES OF THE DIFFERENCED TABLE WERE PUNCHED.')
  104 FORMAT('0',F25,20A4,//(T40,8X,10F8.2))
  105 FORMAT('0',T25,'DIFFERENCED TABLE FOR GRAIN MOISTURES (ACTUAL - SI
     ¬MULATED) IN PERCENT WET BASIS.'/)
  106 FORMAT('0',T25,'DIFFERENCED TABLE FOR GRAIN TEMPERATURES (ACTUAL -
     ¬ SIMULATED) IN DEGREES FAHRENHEIT'/)
  107 FORMAT(T40,8X,10F8.2)
  108 FORMAT('0')
      READ(5,1) NTOBS,NDOBS,ID,IAT,IPUNCH,IPRINT,IMODEL,ITEST
C
C  NTOBS, NUMBER OF TIME OBSERVATIONS   NDOBS = NUMBER OF DEPTH OBSERVATIONS
C  ID = DEGREE OF THE EQUATION USED FOR SMOOTHING
C  IAT =  ATTRIBUTE INDICATOR  0 = MOISTURE  1 = TEMPERATURE
C  IPUNCH = NUMBER OF PUNCHED COPIES OF THE DIFFERENCDD TABLE FOR AARDVARK ANAL.
C  IPRINT = PRINTING OPTION  0 = PRINT INPUT, AND DATA AFTER EACH INTERPOLATION
C        1 = PRINT ONLY AFTER EACH INTERPOLATION
C        2 = PRINT ONLY AFTER THE 2ND INTERPOLATION
C        3 = PRINT ONLY SIMULATED, ACTUAL, AND DIFFERENCED TABLES
C        4 = PRINT NO HEADING JUST THE TABLES OF #3 ABOVE.
C  IMODEL = INDICATOR VARIABLE FOR MATHEMATICAL MODEL
C        1 = EQ #1
C        2 = EQ #2
C        3= EQ #3
C        4 = KSUDRYER
C  ITEST = INDICATOR VARIABLE FOR ANOVA
C  1,1-N,  2,1-S,  3,2-N,  4,2-S,  5,3-N,  6,3-S
C
      NSCORE=2*NDOBS
      IF(NSCORE.GT.21) NSCORE=21
      IF(IPUNCH.GT.1) IPUNCH=1
      IF(IPRINT.NE.4) WRITE(6,99)
      IF(IPRINT.EQ.0) WRITE(6,100)
      IF(IPRINT.EQ.1) WRITE(6,101)
```

```
      IF(IPRINT.NE.4.AND.IPRINT.NE.1) WRITE(6,102)
      IF(IPRINT.NE.4) WRITE(6,103) IPUNCH
      READ(5,2) TITLE
C   IAT = ATTRIBUTE TYPE 0= MOISTURE  1= TEMPERATURE
C   IFMT = INPUT FORMAT
      IF(IPRINT.NE.4) WRITE(6,7) ID,(ATRIB(3*IAT+I),I=1,3)
C   OFMT = OUTPUT FORMAT
      READ(5,5) (DEPA(I),I=1,NDOBS)
      READ(5,2) IFMT
C   ECHO CHECK OUTPUT FORMAT OF THE INPUT MATRIX
      READ(5,2) OFMT1
C   FIRST AND SECOND INTERPOLATION TABLE FORMAT
      READ(5,2) OFMT2
C   DIFFERENCE TABLE OUTPUT FORMAT
      READ(5,2) OFMT3
      DO 18 I=1,NTOBS
      IM=(I-1)*NDOBS
   18 READ(5,IFMT) HOUR(I),(G(IM+J),J=1,NDOBS)
      DO 19 I=1,NSCORE
   19 OUTPUT(I)=SCORE
C
      READ(8) T
      IF(IPRINT.EQ.0) WRITE(6,104) T
      READ(8) NC,LAYR
      NY=NC*LAYR
      NYB=NC*NDOBS
      NT=NTOBS*NDOBS
      IT=0
      DO 30 IR=1,NC
      IM=(IR-1)*LAYR
      READ(8) NTIME,SDEP,GMW,GT,DML
      SHOUR(IR)=NTIME
      DO 20 L=1,LAYR
      TEMP=GMW(L)
      IF(IAT.EQ.1) TEMP=GT(L)
      SM(IM+L)=TEMP
   20 CONTINUE
      IF(IPRINT.EQ.0) WRITE(6,OFMT1) SHOUR(IR),(SDEP(J),J=1,LAYR)
      IF(IPRINT.EQ.0) WRITE(6,OFMT1) SHOUR(IR),(SM(IM+J),J=1,LAYR)
      CALL LAGRNG(DEPA,SHT,SDEP,SM,IT,ID,IR,LAYR,NY,NDOBS,NYB)
   30 CONTINUE
C
C  PRINT OUT INTERPOLATED TABLE AFTER DEPTH INTERPOLATION
C
      IF(IPRINT.GE.2) GO TO 45
      WRITE(6,6)    T,(DEPA(I),I=1,NDOBS)
      WRITE(6,3) OUTPUT
      DO 40 I=1,NC
      L=(I-1)*NDOBS
   40 WRITE(6,OFMT2) SHOUR(I),(SHT(L+J),J=1,NDOBS)
   45 CONTINUE
C
      IT=1
      CALL LAGRNG(HOUR,SINT,SHOUR,SHT,IT,ID,NDOBS,NC,NYB,NTOBS,NT)
C
C  PRINT OUT ACTUAL ATTRIBUTE TABLE
C
      WRITE(6,6) TITLE,(DEPA(I),I=1,NDOBS)
      WRITE(6,3) OUTPUT
      DO 35 I=1,NTOBS
```

```
      L=(I-1)*NDOBS
   35 WRITE(6,OFMT2) HOUR(I),(G(L+J),J=1,NDOBS)
C
C  PRINT OUT ATTRIBUTE TABLE AFTER INTERPOLATION ON TIME
C
      WRITE(6,108)
      WRITE(6,108)
      WRITE(6,104) T,(DEPA(I),I=1,NDOBS)
      WRITE(6,3) OUTPUT
      DO 50 I=1,NTOBS
      L=(I-1)*NDOBS
      WRITE(6,OFMT2)  HOUR(I),(SINT(L+J),J=1,NDOBS)
   50 CONTINUE
C
C  CREATION OF DIFFERENCE TABLES
C
      SUM=0.
      ASUM=0.
      SS=0.
      WRITE(6,108)
      WRITE(6,108)
      IF(IAT.EQ.0) WRITE(6,105)
      IF(IAT.EQ.1) WRITE(6,106)
      WRITE(6,107) (DEPA(I),I=1,NDOBS)
      WRITE(6,3) OUTPUT
      DO 170 IR=1,NTOBS
      IS=(IR-1)*NDOBS
      DO 160 L=1,NDOBS
      IF(IAT.EQ.0) SDIF(IS+L)=(G(IS+L)-SINT(IS+L))*100.
      IF(IAT.EQ.1) SDIF(IS+L)=(G(IS+L)-SINT(IS+L))
      IF(G(IS+L).NE.0.0) GO TO 150
      SDIF(IS+L)=0.0
      NT=NT-1
      GO TO 160
  150 CONTINUE
      SS=SS+SDIF(IS+L)*SDIF(IS+L)
      SUM=SUM+SDIF(IS+L)
      ASUM=ASUM+ABS(SDIF(IS+L))
  160 CONTINUE
      WRITE(6,OFMT3) HOUR(IR),(SDIF(IS+J),J=1,NDOBS)
  170 CONTINUE
      XBAR=SUM/NT
      AXBAR=ASUM/NT
      SDEV=SQRT((SS-(SUM*SUM)/NT)/(NT-1))
      WRITE(6,4) AXBAR,XBAR,SDEV
      IF(IPUNCH.EQ.0) GO TO 200
      WRITE(7,2) T
      DO 190 J=1,NTOBS
      DO 180 I=1,NDOBS
      IS=(J-1)*NDOBS
      WRITE(7,9) ITEST,IMODEL,J,I,SDIF(IS+I)
  180 CONTINUE
  190 CONTINUE
  200 RETURN
      END
```

```
      SUBROUTINE LAGRNG(XBAR,YBAR,X,Y,IT,ID,IR,NX,NY,IXB,IYB)
      DIMENSION XBAR(IXB),YBAR(IYB),X(NX),Y(NY)
      NX1=NX-1
      IF(IT.NE.0) GO TO 100
C   IS = ISTART POINT FOR THE (IR)TH ROW
      IS=(IR-1)*NX
C   ISY = ISTART YBAR POINTER FOR THE (IR)TH ROW
      ISY=(IR-1)*IXB
C  XBAR-ARRAY LOOP
      DO 60 IX=1,IXB
C  X-ARRAY SEARCH LOOP
      DO 15 IP=1,NX1
      IF(XBAR(IX).NE.X(IP)) GO TO 10
      YBAR(ISY+IX)=Y(IS+IP)
      GO TO 60
   10 CONTINUE
      IF(X(IP+1).GT.XBAR(IX)) GO TO  20
   15 CONTINUE
   20 CONTINUE
      ILESS=IP-ID/2
      IF(ILESS.LE.0) ILESS=1
      IF(ILESS.GT.NX-ID) ILESS=NX-ID
      IABOVE=ILESS+ID
C----------------------------------------|
C  |   NOW THIS CONDITION EXISTS:         |
C  |   X(ILESS) < XBAR(IX) < X(IABOVE)    |
C  |   AND THERE ARE ID+1 POINTS ON THIS  |
C  |   INTERVAL.                          |
C  |                                      |
C  |   LAGRANGIAN COEFFICIENT CALCULATION. |
C----------------------------------------|
      CFACT=1.
      DO 30 I=ILESS,IABOVE
   30 CFACT=CFACT*(XBAR(IX)-X(I))
      YB=0.0
      DO 50 I=ILESS,IABOVE
      XFACT=1.
      DO 40 J=ILESS,IABOVE
      IF(I.NE.J) XFACT=XFACT*(X(I)-X(J))
   40 CONTINUE
      YB=YB+Y(IS+I)*CFACT/(XFACT*(XBAR(IX)-X(I)))
   50 CONTINUE
      YBAR(ISY+IX)=YB
   60 CONTINUE
      RETURN
  100 CONTINUE
C  COLUMN LOOP
C  SMOOTHING ACROSS ROWS 1 THROUGH N
C
      DO 170 IC=1,IR
C  XBAR-SEQUENCE LOOP
      DO 160 IX=1,IXB
      ISY=(IX-1)*IR
C  X-ARRAY SEARCH LOOP
      DO 110 IP=1,NX
      IS=(IP-1)*IR
      IF(XBAR(IX).NE.X(IP)) GO TO 105
      YBAR(ISY+IC)=Y(IS+IC)
      GO TO 160
  105 CONTINUE
```

```
      IF(IP+1.GT.NX) GO TO 120
      IF(X(IP+1).GT.XBAR(IX)) GO TO 120
 110  CONTINUE
 120  CONTINUE
      ILESS =IP-ID/2
      IF(ILESS.LE.0)  ILESS=1
      IF(ILESS.GT.NX-ID) ILESS=NX-ID
      IABOVE=ILESS+ID
C----------------------------------------|
C  |  NOW THIS CONDITION EXISTS:         |
C  |  X(ILESS)< XBAR(IX) < X(IABOVE)     |
C  |  AND THERE ARE ID+1 POINTS ON THIS  |
C  |  INTERVAL.                          |
C  |                                     |
C  |  LAGRANGIAN COEFFICIENT CALCULATION.|
C----------------------------------------|
      CFACT=1.
      DO 130 I=ILESS,IABOVE
 130  CFACT=CFACT*(XBAR(IX)-X(I))
      YB=0.
      DO 150 I=ILESS,IABOVE
      XFACT=1.
      DO 140 J=ILESS,IABOVE
      IF(I.NE.J) XFACT=XFACT*(X(I)-X(J))
 140  CONTINUE
      IS=(I-1)*IR
      YB=YB+Y(IS+IC)*CFACT/(XFACT*(XBAR(IX)-X(I)))
 150  CONTINUE
      YBAR(ISY+IC)=YB
 160  CONTINUE
 170  CONTINUE
      RETURN
      END
```

```
//LKED.SYSLMOD DD DSN=DS082.LOADLIB,DISP=(OLD,KEEP),UNIT=SYSDA,SPACE=
//LKED.SYSIN DD *
 INCLUDE SYSLMOD(LAGRANGE)
 ENTRY MAIN
 NAME LAGRANGE(R)
/*
//COMPRESS PROC DSN=
//GO EXEC PGM=IEBCOPY,PARM=COMPRESS,TIME=(,20)
//SYSPRINT DD SYSOUT=A
//SYSUT1 DD DSN=&DSN,DISP=OLD
//SYSUT2 DD DSN=*.SYSUT1,DISP=OLD,VOL=REF=*.SYSUT1,SPACE=(0,0,RLSE)
//SYSIN DD DUMMY
//ENDPROC PEND
// EXEC COMPRESS,DSN='DS082.LOADLIB'
/*
```

APPENDIX

C

EQ 1 - EQ 2

```
CSTORAGE MODEL  REVISED   01/22/74
      DIMENSIONTEMHO(5840),HVDP(100),NDATE(6),AP(5),BP(5)
      DIMENSION TITLE(20)
      COMMONWB(13),G(13),H(13),TMI(13),FMO,HO,W,GO,DEP,Q,TINC,DM,CFMBU,I
     *DATE(3),K1,IWKDH(3),NDHEAT,T,TDRY,SUM(11),ID(40),E(4),L,EQVST(13)
     *,ISDATE(3),INO(20),KDATE,NOZERO,IOFF,QOUT(056),HDEOIF,CFMANG(7),
     *RHSTAT,ENERGY,FANON,QBU,BU,DIA,PRT,HP
      EQUIVALENCE(HVDP(1),WB(1))
      DATA AP/126.9,113.,78.,65.8,59./,BP/.966,.867,.768,.702,.628/
 300  FORMAT(20A4)
      READ(4,300) TITLE
      WRITE(8) TITLE
      NLAYRS=12
      READ(4,301) NTPS
 301  FORMAT(2I10,60X)
      WRITE(8) NTPS,NLAYRS
      READ (5,3)INO,PRT
   3  FORMAT(20A1,F10.0)
      IF(PRT.GT.0.)READ(5,4)HVDP
4     FORMAT(10F8.6)
      IQ=1
      KPRT=0
      NC=0
      READ(5 ,2)ISDATE,LDAYS
2     FORMAT(6I4)
      IF(LDAYS.GT.365)LDAYS=365
      IF(LDAYS.LT.1)LDAYS=1
      READ(5,23)(TEMHO(J),J=1,16),IHR,NDATE
  23  FORMAT(16F4.0,I4,6A2)
      IF(IHR.EQ.24)IQ=8
      M=LDAYS*2
      IF(IHR.EQ.3)M=LDAYS*16
      MS=M-1
      IF(LDAYS.GT.1) GO TO 110
      LDAYS=365
      M=LDAYS*16
      MS=M-1
      DO 100 J=17,MS,16
      DO 100 K=1,16
      L=J+K-1
 100  TEMHO(L)=TEMHO(K)
      GO TO 120
110   DO 12 K=17,MS,16
      MO=K+15
  12  READ(5,25)(TEMHO(J),J=K,MO)
25    FORMAT(16F4.0)
      IF(TEMHO(1).NE.0.OR.TEMHO(2).NE.0.OR.TEMHO(3).NE.0.OR.TEMHO(4).NE.
     *0.)GO TO 120
      KPRT=1
      TEMHO(1)=TEMHO(5)
      TEMHO(2)=TEMHO(6)
      TEMHO(3)=TEMHO(5)
      TEMHO(4)=TEMHO(6)
      MS=M-16
      DO 115J=17,MS,16
      TEMHO(J)=TEMHO(J-2)
      TEMHO(J+1)=TEMHO(J-1)
      TEMHO(J+2)=TEMHO(J+4)
115   TEMHO(J+3)=TEMHO(J+5)
122   FORMAT(' MIDNIGHT AND 3 AM WEATHER DATA SET EQUAL TO ADJACENT VA
```

```
      *LUES')
120    IF(PRT.GT.0.)GOTO51
       DO58J=1,100
       TABS=J-20.+459.69
       IF(J-52)57,47,47
47     PS=54.6329-12301.688/TABS-5.16923*ALOG(TABS)
       GOTO160
57     PS=23.3924-11286.6489/TABS-.46057*ALOG(TABS)
160    PS=EXP(PS)
58     HVDP(J)=53.35/85.78*PS/(14.696-PS)
       WRITE(3,4)HVDP
51     DO130J=2,M,2
       K=TEMHO(J)+20.
       IF(K.LT.1)K=1
       IF(K.GT.100)K=100
130    TEMHO(J)=HVDP(K)
10     CALLINITL
       WRITE(6,24)NDATE
       WRITE(3,24)NDATE
       IF(KPRT.GE.1)WRITE(6,122)
       IF(KPRT.GE.1)WRITE(3,122)
       HOEDIF=0.0
 24    FORMAT(' ****  WEATHER DATA IDENTIFICATION  ***- ',1X,6A2)
135    IF(TINC.LE.IQ*3+1)GOTO170
140    I=M-3
       DO150J=1,I,4
       K=J/2+1
       TEMHO(K)=(TEMHO(J)+TEMHO(J+2))/2.
150    TEMHO(K+1)=(TEMHO(J+1)+TEMHO(J+3))/2.
       M=M/2
       IQ=2*IQ
       GOTO135
170    TINC=IQ*3
       L=(L-1)/IQ+1
11     N=0
       DEPT=BU*1.25*4/(3.14*DIA**2)
       K=1
14     PK=K
       SP=(DEPT*1.5)*(CFMBU*DEPT*.8/AP(K))**(1./BP(K))
       S=SP/DEPT
       K=1
       IF(S.GT..01) K=2
       IF(S.GT..025) K=3
       IF(S.GT..07) K=4
       IF(S.GT.2.) K=5
       IF(K.NE.PK) GO TO 14
       CFM=CFMBU*BU
       HP=SP*CFM*62.4/(33000.*.5*12.)
       WRITE(6,35) HP,SP,DIA,BU
       WRITE(3,35) HP,SP,DIA,BU
35     FORMAT(F6.2,' HP',F6.2,' SP',F6.2,' DIA',F6.0,' BU')
       Y=WB(1)
       READ(5,33) RHSTAT,ADHEAT,CFMANG,QBU,DELAY
C     *********  NOTE  FORMAT CHANGES *********
33     FORMAT(16F5.1)
       CALLQAER(QOUT,CFMANG,DEP,Y)
       NDHEAT=ADHEAT
       NWKS=CFMANG(1)
       CFMBU=CFMANG(2)
       IF(CFMANG(7).LE.0.)CFMANG(7)=.01
```

```
      CALLT8HDG
34    Q1=CFMANG(2)*4.5*DEP/1.25
      Q2=CFMANG(7)*4.5*DEP/1.25
      IF(L.LT.1)L=1
      IF(L.GT.M)L=M
   40 DO 666 I=L,M,2
      AMB=TEMHO(I)+.001
      HO=TEMHO(I+1)+.000005
      KDATE=IWKDH(2)
      IWK=IWKDH(1)
      IWKDH(1)=T/168.
      IWKDH(2)=T/24.-IWKDH(1)*7.
      IWKDH(3)=T-IWKDH(2)*24.-IWKDH(1)*168.
      IF(KDATE-IWKDH(2))71,75,71
 71   J=(I-1)*IQ/16
      CALL DATE(IDATE,ISDATE,J)
75    T=T+TINC
      K=IWKDH(2)*8+IWKDH(3)/3+1
      L2=K+IQ-1
      SON=0.
      DO80J=K,L2
      J2=J
      IF(J2.GT.56)J2=J2-56
80    SON=SON+QOUT(J2)
      FANON=FANON+SON
      IF(NDHEAT.LE.0.)GO TO 76
      RH=RHAIR(AMB,HO)*100.
      IF(RH.LE.RHSTAT)GO TO 76
      HEAT=NDHEAT
      TE=AMB+NDHEAT
      NOB=0
      RH1=RHAIR(TE,HO)*100.
77    X2=AMB+HEAT*(RH-RHSTAT)/(RH-RH1)
      RH1=RHAIR(X2,HO)*100.
      NOB=NOB+1
      IF(ABS(RH1-RHSTAT).LE.1..OR.ABS(RH1-RHSTAT).LE.10..AND.X2.GE.TE+5.
     *.OR.NOB.GT.10)GO TO 78
      HEAT=X2-AMB
      GOTO77
78    IF(X2.GT.TE)X2=TE
      Q=QBU
      IF(Q.LE.0.0) Q=BU
      ENERGY=ENERGY+(X2-AMB)*SON*CFMBU*Q*.25*.075*.01757
      AMB=X2
76    DO50J=2,13
      C=.35+.851*WB(J)
      CONST=DEP/12.*.225*4./(7.*DM*C)
      GO=G(J)
      WBO=WB(J)
      Z=SAFES(GO,WBO)
      G(J) = G(J) + (.104/Z+(AMB-G(J))*CONST)*TINC
      DB=WBO/(1.0-WBO)+.003*TINC/Z
      WB(J)=DB/(1.0+DB)
50    EQVST(J)=EQVST(J)+TINC*230./Z
      TDRY=AMB
      N=N+1
      H(1)=HO
      FRAC=SON/TINC
      IF(SON.LE.0.01)GOTO82
      Q=Q1
```

```
      CALLCR(FRAC)
82    FRAC=1.-FRAC
      H(1)=HO
      TDRY=TEMHO(I)+0.001
      Q=Q2
      IF(FRAC.LE.0.01.OR.Q.LE.0.0)GOTO84
      CALL CR(FRAC)
      IF(T.EQ.DELAY) GO TO 99
84    IF(IWK-IWKDH(1))60,70,60
60    CALLWKAVE(N)
      IF(IWKDH(1).LT.NWKS)GO TO 231
   99 READ(5,33)RHSTAT,ADHEAT,CFMANG,QBU2,W23
      CALL QAER(QOUT,CFMANG,DEP,Y)
      IF(CFMANG(7).LE.0.)CFMANG(7)=.01
      Q1=CFMANG(2)*4.5*DEP/1.25
      Q2=CFMANG(7)*4.5*DEP/1.25
      NDHEAT=ADHEAT
      NWKS=NWKS+CFMANG(1)
      IF(QBU2.LE.0.0)GO TO 231
      IF(QBU.LE.0.0)GO TO 74
      IF(W23.GT.0.0)W=W23
      IF(W.LT.1)W=W*100.
      W23=W*.01
      CALL TRANS(QBU,WB,QBU2,W23)
      CALL TRANS(QBU,G,QBU2,GO)
      CALL TRANS(QBU,EQVST,QBU2,0.0)
74    QBU=QBU+QBU2
231   X=0.0
      Y=0.0
      DO 62J=2,13
      IF(TMI(J).GT.X)X=TMI(J)
      IF(WB(J) .GT. Y) Y=WB(J)
62    CONTINUE
      IF(X-2.5)64,210,210
64    IF(Y  -    .05)210,210,63
63    CALL QAER(QOUT,CFMANG,DEP,Y)
      IF(PRT.LE.0..OR.IWKDH(1)/2.NE.IWKDH(1)/2.)GOTO70
      CALLTBHDG
70    CONTINUE
      CALL OUTPUT(T,G,WB,TMI,ID,TINC,NC, BU,DIA,IOFF)
  666 CONTINUE
      CALLWKAVE(N)
210   WRITE(3,200)
200   FORMAT(70X,'X')
220   IF(NWKS.GE.LDAYS/7)GO TO 10
      READ(5,33)RHSTAT,ADHEAT,CFMANG
      NWKS=NWKS+CFMANG(1)
      GO TO 220
      END
```

```
      SUBROUTINE OUTPUT(T,G,WB,TMI,ID,DT,NC,DBU,DIA,IOFF)
C
C  SUBROUTINE OUTPUT WRITTEN AT KSU JANUARY 1975 FOR SIMULATION VALIDATION STUDY
C     CURRENT REVISION MADE MARCH 1976.
C
      DIMENSION G(1),WB(1),TMI(1),ID(40)
      DIMENSION DEPS(30),GMW(30),GT(30),DML(30)
  1   FORMAT(' THOMPSON: TIME, GRAIN MOISTURES, DEPTHS EQ#1'//)
  2   FORMAT(' THOMPSON: TIME,GRAIN TEMPERATURES, DEPTHS'//)
  3   FORMAT(' THOMPSON: TIME, GRAIN MOISTURES, DEPTHS EQ#2'//)
  5   FORMAT(13I5,5X,'EQ#1',1X,I5)
  6   FORMAT(13I5,5X,'EQ#2',1X,I5)
  7   FORMAT(' ',10X,12F8.3)
  8   FORMAT('(F5.0,12F5.4,15X)')
  9   FORMAT('(F5.0,12F5.3,15X)')
  10  FORMAT('(F5.0,12F5.1,15X)')
  100 FORMAT(' ',40A2)
 111  FORMAT(' ',F5.0,5X,12F8.4)
C ------------------------------------------------------------------------
      NTIME=T
      IF(T.NE.DT) GO TO 15
      AREA=3.14159*DIA**2/4.
      WRITE(9,100) ID
      IF(IOFF.EQ.0) WRITE(9,1)
      IF(IOFF.EQ.1) WRITE(9,3)
  15  CONTINUE
      NC=NC+1
      DEPTH=0.
      DO 20 I=2,13
      GMW(I-1)=WB(I)
      GT(I-1)=G(I)
      DML(I-1)=TMI(I)
      SMT=WB(I)
      DENSY=49.35405-27.82596*SMT
      THICK=DBU*47.32/(AREA*(1.-SMT)*DENSY)
      DEPTH=DEPTH+THICK
      DEPS(I-1)=DEPTH-.5*THICK
  20  CONTINUE
      WRITE(8) NTIME,DEPS,GMW,GT,DML
      WRITE(9,111) T,(WB(I),I=2,13)
      WRITE(9,7) (DEPS(I),I=1,12)
C ------------------------------------------------------------------------
      RETURN
      END
```

```
CINITL
      SUBROUTINEINITL
      DIMENSIONA(11),KUNIT(11)
      COMMONWB(13),G(13),H(13),TMI(13),FMO,HO,W,GO,DEP,Q,TINC,DM,CFMBU,I
     *DATE(3),K1,IWKDH(3),NDHEAT,T,TDRY,SUM(11),ID(40),E(4),L,EQVST(13)
     *,ISDATE(3),INO(20),KDATE,NOZERO,IOFF,QOUT(056),HOEDIF,C(7),
     *RHSTAT,ENERGY,FANON,QBU,BU,DIA,PRT,HP
      READ(5 ,10,END=40)ID
10    FORMAT(40A2)
      READ(5 ,20,END=40)IDATE,W,GO,CFMBU,TINC,BU,DIA,PRT,OFF
20    FORMAT(3I3,1X,8F5.1,2I2)
      IF(BU.LE.0.)BU=6000.
      IF(DIA.LE.0.)DIA=24.
      IOFF=OFF
      IF(W.LE.1)W=W*100.
      IF(W.LE.5.)GO TO 40
      L=(KDAY(IDATE)-KDAY(ISDATE))*16+1
      ENERGY=0.0
      T=0.0
      DEP=12
      HO=0.005
      KDATE=-1
      DO25J=1,4
25    E(J)=0.0
      FANON=0
      WRITE(3,41)
41    FORMAT('1')
      DO27J=1,11
      KUNIT(J)=8-J
27    A(J)=CFMBU*12./(J+1)
      WRITE(3,28)ID,A,(KUNIT(J),J=1,7)
28    FORMAT(1X,40A2/10X,'CFM/BU'/2X,11F7.3/1X,'UNIT',I2,2I7,4I14,4X,
     *'WKS  CFM/BU  HRS/DAY  TIME DAYS/WK  WBMAX  CFM/BU2'/9X,14
     *('+----'),'+',2X,'DHEAT RHSTAT FANON  ENERGY AKWHR WB(1) TAVE ',
     *'RHAVE')
      DO30J=1,13
      IF(J.LE.11)SUM(J)=0.0
      WB(J)=W*.01
      EQVST(J)=0.
      TMI(J)=0.0
      H(J)=HO
30    G(J)=GO
      DO32J=1,3
32    IWKDH(J)=0
      FMO=W/(100.-W)
      DM=DEP/12.*47.3/1.25
      NOZERO=0
      RETURN
   40 STOP
      END
```

```
CQAER
      SUBROUTINE QAER(QOUT,C,DEP,WBMAX)
      DIMENSION QOUT(056),C(7)
C     C(1) WEEKS WITH C(2) CFM/BU FOR C(3) HOURS/DAY
C     STARTING C(4) HOURS, C(5) DAYS/WEEK IF WBMAX IS LESS
C     THAN C(6) %W.B. OTHERWISE C(7) CFM/BU.
      IF(C(2).LE.0.) C(2)=.01                                         SAM
      IF(C(3).GT.24.)C(3)=24.
      IF(C(4).GT.24.)C(3)=0.
      IF(C(6).LT.1.0)C(6)=C(6)*100.
      IF(C(3).GT.0.0.AND.WBMAX.LT.C(6)/100.) GO TO 20
      DO 10J=1,56
10    QOUT(J  )=3.
      RETURN
20    DO 30J=1,56
30    QOUT(J  )=0.
      DO40J=1,16
      IF(J*3.LE.C(4).OR.(J-1)*3.GE.C(4)+C(3))GOTO40
      T=C(4)+C(3)
      IF(T.GT.J*3)T=J*3
      S=C(4)
      IF(S.LT.(J-1)*3)S=(J-1)*3
      K=J
      IF(K.GT.8)K=K-8
      QOUT(K)=T-S
40    CONTINUE
      K=C(5)
      IF(K.LE.0)K=7
      IF(K.GT.7)K=7
      DO 60 J=1,8
      GOTO(60,50,48,46,44,42,41),K
41    QOUT(J+40)=QOUT(J)
42    QOUT(J+24)=QOUT(J)
44    QOUT(J+8)=QOUT(J)
46    QOUT(J+48)=QOUT(J)
48    QOUT(J+16)=QOUT(J)
50    QOUT(J+32)=QOUT(J)
60    CONTINUE
      RETURN
      END
```

```
CTBHOG
       SUBROUTINECTBHOG
       COMMONWB(13),G(13),H(13),TMI(13),FMO,HO,W,GO,DEP,Q,TINC,DM,CFMBU,I
      *DATE(3),K1,IWKDH(3),NOHEAT,T,TDRY,SUM(11),ID(40),E(4),L,EQVST(13)
      *,ISDATE(3),INO(20),KDATE,NOZERO,IOFF,QOUT(056),HOEDIF,C(7),
      *RHSTAT,ENERGY,FANON,QBU,BU,DIA,PRT,HP
       IF(PRT.GE.1.) GO TO 10
       WRITE(6,41) ID
41     FORMAT(20X,40A2/19X,'TIME        TAVE        RHPLOT     FANON       ',
      *'ENER        KWHR        QN          QBU         TINC')
       RETURN
10     WRITE(6 ,20)
       IF(IOFF .EQ. 1) WRITE(6,21)
   21  FORMAT('+',68X,'(WITH HYSTERISIS)')
  20   FORMAT(1H1,25X,'SIMULATION OF HIGH MOISTURE CORN STORAGE')
       WRITE( 6,40)ID
40     FORMAT(20X40A2)
       WRITE(6,45) C(1),C(2)
45     FORMAT(2X,F5.0,' WEEKS',F5.2,' CFM/BU')
       IF(C(3).LE.0.0) GO TO 47
       WRITE(6,46)(C(J),J=3,7)
46     FORMAT('+',24X,' FOR',F5.0,' HRS/DAY STARTING',F5.0,' HOURS',
      CF3.0,' DAYS/WK IF WBMAX .LT.',F5.1,' OTHERWISE',F5.2,' CFM/BU')
       GO TO 49
47     WRITE(6,48)
48     FORMAT('+',24X,' CONTINUOUS AERATION')
49     WRITE( 6,50)W,DEP,NOHEAT,RHSTAT
50     FORMAT(16X'         MOISTURE CONTENT(WB)',F7.3,'           DEPTH',F7
      *.2,' FT',4X,'HEAT',I3,' DEG',3X,'D',3X,' WITH RH.GT.',F5.0,' PER
      *CENT'/20X,'MOISTURE CONTENT',10X,'TEMPERATURE',7X,'PERCENT DM DECO
      *MPOSITION    W A  H'/2X,'AMB   ABS H       MIN      AVE    MAX
      *MAX    AVE   MIN        MIN       AVE        MAX       K Y  R       DATE'
      *,F8.1,' %RH')
       RETURN
       END
```

```
CSAFES    SUBPROGRAM SAFES
      FUNCTIONSAFES(T,WB)
      W=WB*100.
      DM=1.0
      TR=230.0
      DB=W/(100.-W)*100.
      XMM=.103*(EXP(455./DB**1.53)-.00845*DB+1.558)
      IF(T-60.)10,20,20
10    XMT=128.76*EXP(-.081*T)
      GOTO70
20    IF(W-19.)30,30,40
30    W=19.
40    IF(W-28.)60,60,50
50    W=28.
60    XMT=32.3*EXP(-3.48*T/60.)+(W-19.)*.01*EXP(.61*(T-60.)/60.)
70    SAFES=TR*XMM*XMT*DM
      RETURN
      END
```

```
CCR
      SUBROUTINECR(FRAC)
      DIMENSIONX(11),IMAX(11),DB(13)
      COMMONWB(13),G(13),H(13),TMI(13),FMO,HO,W,GO,DEP,Q,TINC,DM,CFMBU,I
     *DATE(3),K1,IWKDH(3),NDHEAT,T,TDRY,SUM(11),ID(40),E(4),L,EQVST(13)
     *,ISDATE(3),INO(20),KDATE,NOZERO,IOFF,QOUT(056),HOEDIF,C(7)
     *,RHSTAT,ENERGY,FANON,QBU,BU,DIA,PRT,HP
      R=Q*TINC*FRAC/DM
      X(1)=TDRY
      X(2)=H(1)
10    DO20K=1,12
      IF(K.LE.11)IMAX(K)=0
      L=K+1
      H(L)=H(K)
20    CALLEQRH(TDRY,R)
      DO30K=2,13
      TO=EQVST(K)
      TMI(K)=.0883*(EXP(.006*TO)-1)+.00102*TO
30    DB(K)=WB(K)/(1.0-WB(K))
      D=AVE(DB,2,13)
      DO40J=3,11
   40 X(J)=1000.
      X(4)=D/(1.+D)*100.
      X(7)=AVE(G,2,13)
      X(10)=AVE(TMI,2,13)
      X(5)=0.0
      X(6)=0.0
      X(11)=0.0
      DO160J=2,13
      IF(X(3)-WB(J))60,60,50
   50 X(3)=WB(J)
      IMAX(3)=J-1
60    IF(X(5)-WB(J))70,80,80
70    X(5)=WB(J)
      IMAX(5)=J-1
80    IF(X(6)-G(J))90,100,100
90    X(6)=G(J)
      IMAX(6)=J-1
100   IF(X(8)-G(J))120,120,110
110   X(8)=G(J)
      IMAX(8)=J-1
120   IF(X(9)-TMI(J))140,140,130
130   X(9)=TMI(J)
      IMAX(9)=J-1
140   IF(X(11)-TMI(J))150,160,160
150   X(11)=TMI(J)
      IMAX(11)=J-1
160   CONTINUE
      X(3)=X(3)*100.
      X(5)=X(5)*100.
      DO170K=1,11
170   SUM(K)=SUM(K)+X(K)*FRAC
      DO176J=1,11
      IF(IMAX(J)-10)176,174,174
174   IMAX(J)=0
176   CONTINUE
      IF( PRT.LE.0..OR.KDATE.EQ.IWKDH(2))GOTO200
190   WRITE( 6,180)(X(J),J=1,3),IMAX(3),(X(J),J=4,5),IMAX(5),X(6),IMAX(6
     *),(X(J),J=7,8),IMAX(8),X(9),IMAX(9),(X(J),J=10,11),IMAX(11),IWKDH,
     *IDATE,Q
```

```
180   FORMAT(F6.1,F8.5,F8.4,'(',I1,')',2F6.2,'(',I1,')',F6.1,'(',I1,')',
     *2F5.1,'(',I1,')',F8.4,'(',I1,')',2F7.4,'(',I1,')',I3,I2,I3,4X,I2,'
     */',I2,'/',I2,F10.5)
 200  RETURN
      END
```

```
CEQRH
      SUBROUTINEEQRH(T,R)
      COMMONWB2(13),G2(13),H2(13),TMI(13),FMO,HO,W,GO,DEP,Q,TINC,DM,CFMB
     *U,IDATE(3),K1,IWKDH(3),NOHEAT,TO,TDRY,SUM(11),ID(40),E(4),L,EQVST(
     *13),ISDATE(3),INO(20),KDATE,NOZERO,IOFF,QOUT(056),HOEDIF,CB(7)
     *,RHSTAT,ENERGY,FANON,QBU,BU,DIA,PRT,HP
      JRH=4
      WB=WB2(L)
      IPRT=-1
      MM=1
      G=G2(L)
      HO=H2(L)
      C=(.35+.851*WB)/(R*(1.-WB))
      DB=WB/(1.-WB)
      ICOND=0
      ERH=(1.0-EXP(-3.82E-5*(T+50.)*(DB*100)**2))*100.
      HOE=RHAIR(T,ERH)
      IF(IOFF .LE. 0) GO TO 20
      FME = DB*100
      DF=((.24+.45*HO)*T+C*G) / (.24+.45*HO + C)
      RH = RHAIR(DF,HO)
      ERH = 1.0-EXP(-3.82E-5*(DF+50.)*FME**2)
      IF(RH    .LT. ERH) GO TO 20
      REWET = 1.-EXP(-1.045E-4*(DF+50.)*FME**1.72)
      IF( RH .LT. REWET) GO TO 89
      ICOND = 1
20    DELL=(1094.-.57*T)*4.35*EXP(-28.25*DB)
      IPRT=IPRT+1
      NO=0
      N=0
      H=HO
      IF(HO.GT.HOE)H=HOE
C     PRINT,H,T,DELL,HO,G,C
30    DF=((.24+.45*HO)*T-(H-HO)*(1060.8+DELL+32.-G)+C*G)/(.24+.45*H+C)
      FME=(DB-(H-HO)*R)*100.0
      IF(FME-.05)35,36,36
35    H=(DB-.005)/R+HO
      NO=NO+1
      IF(NO.GT.10) GO TO 34
      GOTO30
   34 WRITE(6,33)
   33 FORMAT(' NO.GT.10 IN EQRH')
36    RH = RHAIR(DF,H)
      ERH=1.0-EXP(-3.82E-5*(DF+50.)*FME**2)
      IF( ICOND .EQ. 1) ERH = 1.-EXP(-1.045E-4*(DF+50.)*FME**1.72)
      DEL=RH - ERH
      NO=0
      NOZERO=NOZERO+1
      PH=H
      IF(IPRT.LE.0)GO TO 100
      WRITE(6,10)H,DF,FME,RH,ERH,DEL,JRH,N
10    FORMAT(6F8.4,2I4)
      GO TO 110
100   IF(N.EQ.5.AND.MM.GE.3.AND.MM.LE.4.OR.N.GE.11) GO TO 20
110   CALLZERO(JRH,0.0,H,DEL,E,.010,M,N,MM)
      IF(N.GE.2) GO TO 80
      RH1=RHAIR(T,H)
      IF(RH1.LE.1) GO TO 80
      H=PH+(H-PH)*(.99-RH)/(RH1-RH)
      PH=PH+.0005
```

```
      IF(H.LT.PH) H=PH
80    GOTO(30,90),M
89    ICOND=2
      H=HO
      FME= DB*100
90    T=DF
      WB2(L)=FME/(100.+FME)
      G2(L)=DF
      H2(L)=H
      HOE=ABS(HOE-H)
      IF(HOE.GT.HOEDIF)HOEDIF=HOE
      RETURN
      END
```

```
CRHAIR SUBPROGRAM
      FUNCTIONRHAIR(TS,HS)
      DOUBLE PRECISION R,A,B,C,D,E,F,G,T,H,PS
      DATA R,A  /0.3206182232D04, -.2740552583614256D05/
      DATA B,C / .5418960763239505D02, -.4513703841126545D-01/
      DATA D,E / .2153211916363544D-04, -.4620266568199822D-08/
      DATA F,G / .2416127209874D01, .1215465167060546D-02/
      T=TS+459.69D0
      H=HS
      IF(TS.GT.32.)GO TO 1
      PS=DEXP(54.6329D0-12301.688D0/T-5.16923D0*DLOG(T))
      RHAIR=(14.696D0*H/((H+.6219D0))/PS)
      GO TO 10
    1 PS=DEXP((A+B*T+C*T**2+D*T**3+E*T**4)/(F*T-G*T**2))*R
      RHAIR=(14.696D0*H/(H+.6219D0))/PS
C***  IF HS GREATER THAN 1 ROUTINE CALCULATES H INSTEAD OF RHAIR
10    IF(HS.LT.1.)RETURN
      P=PS
      RHAIR=HS*P*.01*.6219/(14.696-HS*.01*P)
      RETURN
      END
```

```
CWKAVE
      SUBROUTINEWKAVE(N)
      DIMENSIONDB(13),AMAX(6),IMAX(6),AMA(3),A(11),B(11),IPLOT(71)
      COMMONWB(13),G(13),H(13),TMI(13),FMO,HO,W,GO,DEP,Q,TINC,DM,CFMBU,I
     *DATE(3),K1,IWKDH(3),NOHEAT,T,TDRY,SUM(11),ID(40),E(4),L,EQVST(13)
     *,ISDATE(3),INO(20),KDATE,NOZERO,IOFF,QOUT(056),HOEDIF,C(7),
     *RHSTAT,ENERGY,FANON,QBU,BU,DIA,PRT,HP
      IF(N)900,900,5
5     DO10J=1,11
10    SUM(J)=SUM(J)/N
      DO11J=1,13
11    DB(J)=WB(J)/(1.-WB(J))
      DO111J=1,6
111   IMAX(J)=1
      AMAX(1)=WB(2)
      AMAX(2)=WB(2)
      AMAX(3)=G(2)
      AMAX(4)=G(2)
      AMAX(5)=TMI(2)
      AMAX(6)=TMI(2)
      IF(PRT.LE.0.)GOTO26
      WRITE( 6,25)(SUM(K),K=1,2)
25    FORMAT(F6.1,F8.5,' WEEK AVERAGE ')
26    SDB=DB(2)
      SG=G(2)
      STMI=TMI(2)
      DO101J=3,13
      SDB=SDB+DB(J)
      SG=SG+G(J)
      STMI=STMI+TMI(J)
      L=J-1
      ADB=SDB/(L)
      AWB=ADB/(1.+ADB)*100.
      A(J-2)=AWB
      AG=SG/L
      ATMI=STMI/L
      IF(AMAX(1)-WB(J))17,17,14
14    AMAX(1)=WB(J)
      IMAX(1)=J-1.
17    IF(AMAX(2)-WB(J))21,21,22
21    AMAX(2)=WB(J)
      IMAX(2)=J-1.
22    IF(AMAX(3)-G(J))31,31,33
31    AMAX(3)=G(J)
      IMAX(3)=J-1.
33    IF(AMAX(4)-G(J))42,42,44
44    AMAX(4)=G(J)
      IMAX(4)=J-1.
42    IF(AMAX(5)-TMI(J))55,55,56
56    AMAX(5)=TMI(J)
      IMAX(5)=J-1.
55    IF(AMAX(6)-TMI(J))71,71,68
71    AMAX(6)=TMI(J)
      IMAX(6)=J-1.
68    CFM=CFMBU*12./L
      DO23K=1,6
      IF(IMAX(K)-10.)23,28,28
28    IMAX(K)=0
23    CONTINUE
      DO120K=1,2
```

```
120   AMA(K)=AMAX(K)*100.
      AMA(3)=AMAX(3)
      B(J-2)=AMAX(6)
      IF(PRT.LE.0.)GOTO101
      WRITE( 6,69)AMA(1),IMAX(1),AWB,(AMA(K),IMAX(K),K=2,3),AG,(AMAX(K),
     *IMAX(K),K=4,5),ATMI,AMAX(6),IMAX(6),CFM
69    FORMAT(14X,F8.4,'(',I1,')',2F6.2,'(',I1,')',F6.1,'(',I1,')',2F5.1,
     *'(',I1,')',F8.4,'(',I1,')',2F7.4,'(',I1,')',F11.4,' CFM/BU')
101   CONTINUE
      QN=0
      Q1=C(2)*4.5*DEP/1.25-.01
      DO 300JL=1,56
300   QN=QN+QOUT(JL)
      Q=QBU
      IF(Q.LE.0.0) Q=BU
      ENER=ENERGY/Q
      AKWHR=(HP*.9*FANON+ENER)/Q
      TAVE=SUM(1)
      HAVE=SUM(2)
      RHPLOT=RHAIR(TAVE,HAVE)*100.
      WRITE( 6,50)IDATE,T,TAVE,RHPLOT,FANON,ENER,AKWHR,QN,QBU,TINC,
     *WB,AMA(1),IMAX(1),AWB,AMA(2),IMAX(2),G.AMA(3),IMAX(3),AG,
     *AMAX(4),IMAX(4),TMI,AMAX(5),IMAX(5),ATMI,AMAX(6),IMAX(6)
50    FORMAT(/5X,I2,'/',I2,'/',I2,9F10.2/' WB ',13F7.4,
     *F6.2,'(',I1,')',2F6.2,'(',I1,')'/' G  ',13F7.2,
     *F6.1,'(',I1,')',2F6.1,'(',I1,')'/' TMI',13F7.4,
     *F6.3,'(',I1,')',2F6.3,'(',I1,')')
      DO30J=1,11
30    SUM(J)=0.0
      N=0
      NOZERO=0
      IPLOT(1)=INO(10)
      DO211J=2,71
211   IPLOT(J)=INO(9)
      DO230J=1,11
      K=B(J)*50.+1.5
      IF(K.LT.1)K=1
      IF(K.GT.71)K=71
      IF(J.LE.3)IPLOT(K)=INO(J)
      IF(J.GE.4)GOTO220
      GOTO230
220   IF(J/2.EQ.J/2.)GOTO230
      IPLOT(K)=INO(J/2+2)
230   CONTINUE
      WRITE(3,240)(IDATE(J),J=1,2),IPLOT,C
240   FORMAT(2X,I2,'/',I2,2X,71A1,2X,7F7.2)
      IPLOT(1)=INO(10)
      DO210J=2,71
210   IPLOT(J)=INO(9)
      K=(AMA(2)-15.)*5.+1.5
      IF(K.LT.1)K=1
      IF(K.GT.71)K=71

      IPLOT(K)=INO(8)
      K=RHPLOT/2.+1.5
      IF(K.LE.1)K=1
      IF(K.GT.71)K=71
      IPLOT(K)=INO(11)
      K=TAVE+1.5
      IF(K.LT.1)K=1
```

```
      IF(K.GT.71)K=71
      IPLOT(K)=INO(12)
      K=ENER*10.+1.5
      IF(K.LE.1)GOTO242
      IF(K.GT.71)K=71
      IPLOT(K)=INO(13)
242   K=AKWHR*10.+1.5
      IF(K.LE.0)K=1
      IF(K.GT.71)K=71
      IPLOT(K)=INO(14)
      WRITE(3,241)IPLOT,NDHEAT,RHSTAT,FANON,ENERGY,AKWHR,WB(1),TAVE,
     *RHPLOT
241   FORMAT(9X,71A1,I4,4F7.1,F5.2,2F7.1)
900   RETURN
      END
```

```
CTRANS
      SUBROUTINE TRANS(Q,DB,DQ,DB1)
      DIMENSION DB(13),D(30)
      DO 2J=1,13
2     D(J)=DB(J)
      DO 4J=14,30
4     D(J)=DB1
      R=1+DQ/Q
      IF(R.LT.30./12.)GO TO 20
      WRITE(6,10)
      R=2.5
10    FORMAT(' DQ TOO BIG  - R SET TO 2.5')
20    DO 30L=2,13
      J=L-1
      S=0.
      TL=(J-1)*R+2
      KL=TL
      IF(TL.GT.KL)S=(KL+1-TL)*D(KL)
      TU=J*R+2
      KU=TU
      S=(TU-KU)*D(KU)+S
      KU=KU-1
      IF(TL.GT.KL)KL=KL+1
      IF(KU.LT.KL)GO TO 30
      DO 40K=KL,KU
40    S=S+D(K)
30    DB(L)=S/R
      DB(1)=DB1
      WRITE(6,50)DB
50    FORMAT (4X,13F7.3)
      RETURN
      END
```

```
CAVE
      FUNCTIONAVE(A,J,K)
      DIMENSIONA(13)
      AN=K-J+1
      S=0
      DO10L=J,K
10    S=S+A(L)
      AVE=S/AN
      RETURN
      END
```

```
CKDAY     CONVERTS IDATE(M,D,Y) TO DAY OF THE YEAR 1 TO 365
      FUNCTICN KDAY(IDATE)
      DIMENSION IDATE(3),N(12)
      DATA N/31,28,31,30,31,30,31,31,30,31,30,31/
      K=0
      IF(IDATE(1).LE.1) GO TO 20
      L=IDATE(1)-1
      DO 10 J=1,L
10    K=K+N(J)
20    KDAY=K+IDATE(2)
      RETURN
      END
```

```
CDATE   CONVERTS KDAYS AFTER ISDATE(M,D,Y) BACK TO IDATE(M,D,Y)
      SUBROUTINE DATE(IDATE,ISDATE,K)
      DIMENSION IDATE(3),ISDATE(3),N(12)
      DATA N/31,28,31,30,31,30,31,31,30,31,30,31/
      L=KDAY(ISDATE)+K-1
      NYR=L/365
      IDATE(3)=ISDATE(3)+NYR
      J=L-365*NYR
      M=0
      DO 10 I=1,12
      M=M+N(I)
      IF(J.LE.M)GO TO 20
10    CONTINUE
20    IDATE(1)=I
      M=M-N(I)
      IDATE(2)=J-M
      RETURN
      END
```

```
      SUBROUTINEZERO(J,YD,X,Y,A,DEL,K,N,M)
      DIMENSIONA(4),IJ(4,3)
      DATAIJ/1,2,3,4,4,3,2,1,3,4,1,2/
      J1=1
      IF(N.LE.0)M=1
5     JP=J
      J=IJ(J,J1)
      IF(J.LE.2.AND.JP.LE.2)GOTO6
      IF(J.GE.3.AND.JP.GE.3)GOTO6
      Z=A(1)
      A(1)=A(3)
      A(3)=Z
      Z=A(2)
      A(2)=A(4)
      A(4)=Z
6     IF(J.LE.2)GOTO10
      X=-X
      A(1)=-A(1)
      A(3)=-A(3)
10    IF(J.EQ.1.OR.J.EQ.4)GOTO20
      YD=-YD
      Y=-Y
      A(2)=-A(2)
      A(4)=-A(4)
20    J1=1
      CALLTYPE1(J1,YD,X,Y,A,DEL,K,N,M)
1     FORMAT(45X,'T1 ',I4,8F7.2,4I5)
      IF(M.EQ.2.AND.J.GE.3)X=A(1)/2.5
      IF(M.EQ.3.AND.J.GE.3)X=A(1)*2.5
      IF(J.LE.2)GOTO30
      X=-X
      A(1)=-A(1)
      A(3)=-A(3)
30    IF(J.EQ.1.OR.J.EQ.4)GOTO50
      YD=-YD
      Y=-Y
      A(2)=-A(2)
      A(4)=-A(4)
50    IF(K.EQ.2)RETURN
C     WRITE(6,1)J1,YD,X,Y,A,DEL,K,N,M,J
      IF(J1.NE.1)GOTO5
      IF(N.LT.14)RETURN
      K=2
      WRITE(6,52)YD,X,Y,A
52    FORMAT(' DOES NOT CONVERGE ',7F10.5)
      RETURN
      END
      SUBROUTINETYPE1(J,YD,X,Y,A,DEL,K,N,M)
      DIMENSIONA(4)
      XL=A(1)
      YL=A(2)
      XU=A(3)
      YU=A(4)
      K=1
      IF(ABS(Y-YD)-ABS(DEL))2,2,6
2     K=2
      M=1
      GOTO35
6     N=N+1
      GOTO(10,20,37,55,21,21),M
```

```
10    XL=X
      X=2.5*X
      YL=Y
      M=2
      GOTO35
20    YU=Y
      XU=X
21    IF(YL-YU)30,40,40
30    J=2
      N=N-1
      K=3
      M=6
35    A(1)=XL
      A(2)=YL
      A(3)=XU
      A(4)=YU
      RETURN
37    YL=Y
      XL=X
40    IF(YL-YD)45,60,60
45    X=XL/100.
52    M=3
      XU=XL
      YU=YL
      GOTO70
53    K=2
      M=1
      WRITE(6,54)
54    FORMAT(' NOT WITHIN LIMITS')
      GOTO35
55    YU=Y
      XU=X
60    IF(YD-YU)65,80,80
65    XL=XU
      YL=YU
      X=XU*4.
      M=4
70    IF(N-6)35,35,53
80    IF(M-5)85,90,85
85    W=(YL-YD)/(YL-YU)*(XU-XL)+XL
      X=(XL+W)/2.
      M=5
      GOTO35
90    Y4=YL-(YL-YU)*(X-XL)/(XU-XL)
      IF(Y4-Y)100,130,130
100   J=3
      N=N-1
      K=3
      M=6
      GOTO35
130   IF(Y-YD)150,140,140
140   S=(X-XL)*(YL-YD)/(YL-Y)+XL
      W=((Y-YD)/(Y-YU))*(XU-X)+X
      XL=X
      YL=Y
      X=(S+W)/2.
      GOTO35
150   W=((X-XL)*(YL-YD))/(YL-Y)+XL
      S=((YD-YU)*(X-XU))/(Y-YU)+XU
      IF(XL-S)170,170,160
```

```
160     S=XL
170     XU=X
        YU=Y
        X=(S+W)/2.
        GOTO35
        END
/*
```

APPENDIX

D

EQ 3 - KSU DRYER

```
//KSUDRYER JOB (498583278,BH01RLE7,,3),'MAURER.DRYER',TIME=(,29)        DRYR0010
/*ROUTE  PUNCH DUMMY                                                     DRYR0020
/*TAPE9                                                                  DRYR0030
// EXEC RINGWTR,PARM=9939SM                                              DRYR0040
// EXEC FORTGCLG                                                         DRYR0050
//FORT.SYSIN DD *                                                        DRYR0060
      COMMON/DESAIR/CFMTOT,AREA,ELEVTN,T(20),IG                          DRYR0070
    1 FORMAT(20A4)                                                       DRYR0080
    2 FORMAT(' ',20A4)                                                   DRYR0090
      CALL DATAIN                                                        DRYR0100
   10 READ(5,1,END=100) T                                                DRYR0110
      WRITE(8) T                                                         DRYR0120
C                                                                        DRYR0130
C     IF(NVALID.NE.0) WRITE(NVALID) T                                    DRYR0140
C                                                                        DRYR0150
      WRITE( 6,2) T                                                      DRYR0160
      CALL WEATHR                                                        DRYR0170
      CALL DESIGN                                                        DRYR0180
      CALL TIME                                                          DRYR0190
      GO TO 10                                                           DRYR0200
  100 CONTINUE                                                           DRYR0210
      RETURN                                                             DRYR0220
      END                                                                DRYR0230
```

```
      SUBROUTINE DATAIN                                                 DRYR0240
      COMMON/WTRDAT/  NT,NPS,IDT,IDB(720),IRH(720),PATM(720),ITIME(720) DRYR0250
      COMMON/WTRLGE/ ELEV,A0,A1,A2,A3,FACTOR,C0,C1,C2,C3,AB(10)         DRYR0260
      COMMON/DESAIR/CFMTOT,AREA,ELEVTN,T(20),IG                         DRYR0270
    1 FORMAT(7(I3,I2,F5.2),10X)                                         DRYR0280
    2 FORMAT((' ',7(I3,I2,F5.2),10X))                                   DRYR0290
    3 FORMAT((' ',6(2I3,1X,F6.3,1X,I3,5X)))                             DRYR0300
    4 FORMAT('0',5X,'LIST OF WEATHER DATA CARD DECK',/)                 DRYR0310
    5 FORMAT('1','NUMBER OF DATA POINTS FOUND =',I5,'  NUMBER OF POINTS DRYR0320
     ¬SPECIFIED (NPS) =',I5)                                            DRYR0330
    6 FORMAT('0',5X,'LISTING OF WEATHER DATA WITH THE TIME POINTER',/)  DRYR0340
      N=1                                                               DRYR0350
      NT=0                                                              DRYR0360
   10 READ (3,1,END=30) NPS,IDT,ELEV, (IDB(NT+I),IRH(NT+I),PATM(NT+I),I=DRYR0370
     11,NPS)                                                            DRYR0380
      WRITE(6,4)                                                        DRYR0390
      WRITE(6,2) NPS,IDT,ELEV,(IDB(NT+I),IRH(NT+I),PATM(NT+I),I=1,NPS)  DRYR0400
      ITIME(1)= 0                                                       DRYR0410
      DO 20 I=1,NPS                                                     DRYR0420
   20 ITIME(N+I)=IDT+ITIME(N+I-1)                                       DRYR0430
      N= N+NPS                                                          DRYR0440
      NT=NT+NPS                                                         DRYR0450
      GO TO 10                                                          DRYR0460
   30 CONTINUE                                                          DRYR0470
      IF(I.LT.NPS) WRITE(6,5) I,NPS                                     DRYR0480
C              IF THERE HAS BEEN AN ERROR  ON INPUT OF WEATHER DATA STOP DRYR0490
      IF(I.LT.NPS) STOP                                                 DRYR0500
      ELEVTN=ELEV*1000.                                                 DRYR0510
C                                                                       DRYR0520
      CALL USSATM                                                       DRYR0530
C                                                                       DRYR0540
      IF(ELEV.NE.1.0) GO TO 50                                          DRYR0550
      DO 40 I=1,NT                                                      DRYR0560
   40 PATM(I)=PATM(I)*.4912*ELEV                                        DRYR0570
      WRITE(6,6)                                                        DRYR0580
      WRITE(6,3) (IDB(I),IRH(I),PATM(I),ITIME(I),I=1,NT)                DRYR0590
      RETURN                                                            DRYR0600
   50 CONTINUE                                                          DRYR0610
      DO 60 I=1,NT                                                      DRYR0620
   60 PATM(I)=29.9186*.4912*ELEV                                        DRYR0630
      WRITE(6,6)                                                        DRYR0640
      WRITE(6,3) (IDB(I),IRH(I),PATM(I),ITIME(I),I=1,NT)                DRYR0650
      RETURN                                                            DRYR0660
      END                                                               DRYR0670
```

```
      SUBROUTINE USSATM                                                 DRYR0680
      COMMON/WTRLGE/ ELEV,A0,A1,A2,A3,FACTOR,C0,C1,C2,C3,AB(10)         DRYR0690
      DIMENSION ALT(11),CONV(11)                                        DRYR0700
      DATA ALT/0.,1.,2.,3.,4.,5.,6.,7.,8.,9.,10./                       DRYR0710
      DATA CONV /1.,.9653,.9318,.8991,.8674,.8370,.8072,.7785,.7504,.723DRYR0720
     14,.6970 /                                                         DRYR0730
      IF(ELEV.GT.0.) GO TO 10                                           DRYR0740
      ELEV=1.0                                                          DRYR0750
      RETURN                                                            DRYR0760
   10 IF(ELEV.GT.10.) ELEV=ELEV/1000.                                   DRYR0770
      N1=ELEV                                                           DRYR0780
      IF(N1 .LE. 2) N1=2                                                DRYR0790
      IF (N1.GE. 10)  N1=9                                              DRYR0800
      A0=ALT(N1-1)                                                      DRYR0810
      A1=ALT( N1 )                                                      DRYR0820
      A2=ALT(N1+1)                                                      DRYR0830
      A3=ALT(N1+2)                                                      DRYR0840
      C0=CONV(N1-1)                                                     DRYR0850
      C1=CONV( N1 )                                                     DRYR0860
      C2=CONV(N1+1)                                                     DRYR0870
      C3=CONV(N1+2)                                                     DRYR0880
      DO 20 I=1,10                                                      DRYR0890
   20 AB(I)=0.0                                                         DRYR0900
C                                                                       DRYR0910
      CALL LAGRNG                                                       DRYR0920
C                                                                       DRYR0930
      ELEV=FACTOR                                                       DRYR0940
      RETURN                                                            DRYR0950
      END                                                               DRYR0960
```

```
      SUBROUTINE LAGRNG                                                 DRYR0970
      COMMON /WTRLGE/ T,T0,T1,T2,T3,X,X0,X1,X2,X3,Y,Y0,Y1,Y2,Y3,Z,Z0,Z1,DRYR0980
     1Z2,Z3                                                             DRYR0990
      DT0= T -T0                                                        DRYR1000
      DT1= T -T1                                                        DRYR1010
      DT2= T -T2                                                        DRYR1020
      DT3= T -T3                                                        DRYR1030
      D01= T0-T1                                                        DRYR1040
      D02= T0-T2                                                        DRYR1050
      D03= T0-T3                                                        DRYR1060
      D10= T1-T0                                                        DRYR1070
      D12= T1-T2                                                        DRYR1080
      D13= T1-T3                                                        DRYR1090
      D20= T2-T0                                                        DRYR1100
      D21= T2-T1                                                        DRYR1110
      D23= T2-T3                                                        DRYR1120
      D30= T3-T0                                                        DRYR1130
      D31= T3-T1                                                        DRYR1140
      D32= T3-T2                                                        DRYR1150
      F0=(DT1*DT2*DT3)/(D01*D02*D03)                                    DRYR1160
      F1=(DT0*DT2*DT3)/(D10*D12*D13)                                    DRYR1170
      F2=(DT0*DT1*DT3)/(D20*D21*D23)                                    DRYR1180
      F3=(DT0*DT1*DT2)/(D30*D31*D32)                                    DRYR1190
      X=F0*X0+F1*X1+F2*X2+F3*X3                                         DRYR1200
      Y=F0*Y0+F1*Y1+F2*Y2+F3*Y3                                         DRYR1210
      Z=F0*Z0+F1*Z1+F2*Z2+F3*Z3                                         DRYR1220
      RETURN                                                            DRYR1230
      END                                                               DRYR1240
```

```
      SUBROUTINE WEATHR                                                 DRYR1250
      COMMON/WTPDAT/  NT,NPS,IDT,IDB(720),IRH(720),PATM(720),ITIME(720) DRYR1260
      COMMON/WRTME/ITCALC,NTPS,DB(720),RH(720),PTM(720),AH(720),APD(720)DRYR1270
      COMMON /WTRLGE/ T,T0,T1,T2,T3,X,X0,X1,X2,X3,Y,Y0,Y1,Y2,Y3,Z,Z0,Z1,DRYR1280
     1Z2,Z3                                                             DRYR1290
      COMMON/BINC/GT(30),GM(30),DGLB(30),EQST(30),NLAYRS,NTINC,NTIME,PD DRYR1300
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,DC,DEN1,DEN2                       DRYR1310
    1 FORMAT(I10,F10.4)                                                 DRYR1320
    2 FORMAT('1',5X,'WEATHER DATA AS CALCULATED BY WEATHER SUBROUTINE ANDRYR1330
     ¬D COMUNICATED TO THE TIME SUBROUTINE',/)                          DRYR1340
    3 FORMAT((' ',6(F5.2,1X,F6.4,1X,F5.2,4X)))                          DRYR1350
C                                                                       DRYR1360
   10 READ(4,1,END=80) ITCALC,DC                                        DRYR1370
C                                                                       DRYR1380
      WRITE(6,1) ITCALC,DC                                              DRYR1390
      DO 20 I=1,NT                                                      DRYR1400
      DB(I)=IDB(I)                                                      DRYR1410
      RH(I)=IRH(I)                                                      DRYR1420
      PTM(I)=PATM(I)                                                    DRYR1430
      IF(NT.NE.NPS    .OR.  ITCALC.NE.IDT)  GO TO 30                    DRYR1440
   20 CONTINUE                                                          DRYR1450
      NTPS=NT                                                           DRYR1460
      GO TO 65                                                          DRYR1470
   30 K=2                                                               DRYR1480
      DO 60 I=2,NT                                                      DRYR1490
C                                                                       DRYR1500
C               ITPTR = CURRENT TIME POINTER                            DRYR1510
C                                                                       DRYR1520
   40 ITPTR=(K-1)*ITCALC                                                DRYR1530
      IF(ITIME(I) .NE. ITPTR)  GO TO 50                                 DRYR1540
      DB(K)=IDB(I)                                                      DRYR1550
      RH(K)=IRH(I)                                                      DRYR1560
      PTM(K)=PATM(I)                                                    DRYR1570
      GO TO 55                                                          DRYR1580
   50 IF(ITIME(I+1) .LT. ITPTR) GO TO 60                                DRYR1590
      J=I                                                               DRYR1600
      IF(I+2 .GT. NT) J=NT-2                                            DRYR1610
C                                                                       DRYR1620
C               T = THE DESIRED BASE POINT WERE DEPENDENT VARIABLES ARE DRYR1630
C                   TO BE CALCULATED FOR THE WEATHER VARIABLES X, Y AND Z DRYR1640
C                                                                       DRYR1650
      T =ITPTR                                                          DRYR1660
C                                                                       DRYR1670
C               CURRENT BASE POINTS FOR LAGRANGIAN INTERPOLATION TO TIME TDRYR1680
C                                                                       DRYR1690
      T0=ITIME(J-1)                                                     DRYR1700
      T1=ITIME( J )                                                     DRYR1710
      T2=ITIME(J+1)                                                     DRYR1720
      T3=ITIME(J+2)                                                     DRYR1730
      X0=IDB(J-1)                                                       DRYR1740
      X1=IDB( J )                                                       DRYR1750
      X2=IDB(J+1)                                                       DRYR1760
      X3=IDB(J+2)                                                       DRYR1770
      Y0=IRH(J-1)                                                       DRYR1780
      Y1=IRH(   J)                                                      DRYR1790
      Y2=IRH(J+1)                                                       DRYR1800
      Y3=IRH(J+2)                                                       DRYR1810
      Z0=PATM(J-1)                                                      DRYR1820
      Z1=PATM( J )                                                      DRYR1830
      Z2=PATM(J+1)                                                      DRYR1840
```

```
      Z3=PATM(J+2)                                                      DRYR1850
C                                                                       DRYR1860
      CALL LAGRNG                                                       DRYR1870
C                                                                       DRYR1880
C                 LAGRANGIAN INTERPOLATED VALUES                        DRYR1890
C                                                                       DRYR1900
      DB(K)=X                                                           DRYR1910
      RH(K)=Y                                                           DRYR1920
      PTM(K)=Z                                                          DRYR1930
C                                                                       DRYR1940
   55 K=K+1                                                             DRYR1950
      GO TO 40                                                          DRYR1960
   60 CONTINUE                                                          DRYR1970
      NTPS=K                                                            DRYR1980
      IF(ITPTR .GT. ITIME(NT)) NTPS=(ITIME(NT)/ITCALC)+1                DRYR1990
   65 CONTINUE                                                          DRYR2000
      DO 70 I=1,NTPS                                                    DRYR2010
      IF(RH(I) .GT. 1.) RH(I)=RH(I) *.01                                DRYR2020
   70 CONTINUE                                                          DRYR2030
      WRITE(6,2)                                                        DRYR2040
      WRITE(6,3) (DB(I),RH(I),PTM(I),I=1,NTPS)                          DRYR2050
      NTINC=ITCALC                                                      DRYR2060
      RETURN                                                            DRYR2070
   80 STOP                                                              DRYR2080
      END                                                               DRYR2090
```

```
      SUBROUTINE DESIGN                                                 DRYR2100
      COMMON/DESAIR/CFMTOT,AREA,ELEVTN,T(20),IG                         DRYR2110
      COMMON/GRAIN/ EMC(27),SPHEAT(18),DEN(18),DCS(9),GRAINS(9)         DRYR2120
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,DC,DEN1,DEN2                       DRYR2130
      COMMON/BINC/GT(30),GM(30),DGLB(30),EQST(30),NLAYRS,NTINC,NTIME,PD DRYR2140
      COMMON/LAYRC  /TO,HO,MO,RHA,TE,HE,ME,ERH,TG,ALB,GLB,ATM,LAYR      DRYR2150
      REAL MO,ME,MW                                                     DRYR2160
      COMPLEX*16 GRAINS                                                 DRYR2170
    1 FORMAT(6F10.0,2I5,10X)                                            DRYR2180
      READ(5,1) MW,TG,CFMTOT,WTGRN,DIA,PD,NLAYRS,IG                     DRYR2190
      ME=MW                                                             DRYR2200
      IF(IG.EQ.0) IG=1                                                  DRYR2210
      IF(IG.GT.9) IG=9                                                  DRYR2220
      IF(MW.GT..5) MW=MW*.01                                            DRYR2230
      MO=MW/(1.-MW)                                                     DRYR2240
      AREA=(3.14159*DIA*DIA)/4.                                         DRYR2250
C                                                                       DRYR2260
      PA=EMC(IG*3-2)                                                    DRYR2270
      PB=EMC(IG*3-1)                                                    DRYR2280
      PC=EMC(IG*3)                                                      DRYR2290
C                                                                       DRYR2300
      CA=SPHEAT(IG*2-1)                                                 DRYR2310
      CB=SPHEAT(IG*2)                                                   DRYR2320
C                                                                       DRYR2330
      DEN1=DEN(IG*2-1)                                                  DRYR2340
      DEN2=DEN(IG*2)                                                    DRYR2350
C                                                                       DRYR2360
      IF(DC.EQ.0.0) DC=DCS(IG)                                          DRYR2370
C                                                                       DRYR2380
      DENSY=DEN1+DEN2*MW                                                DRYR2390
      WGLB=WTGRN/(NLAYRS*AREA)                                          DRYR2400
      GLB=WGLB*(1.-MW)                                                  DRYR2410
      CFMFT2=CFMTOT/AREA                                                DRYR2420
      DEPTH=WTGRN/(DENSY*AREA)                                          DRYR2430
      CALL TABLE(WTGRN,NTINC,ME,DIA,NLAYRS,TG,CFMFT2,DEPTH,PD,WGLB)     DRYR2440
      DO 90 I=1,NLAYRS                                                  DRYR2450
      GT(I)=TG                                                          DRYR2460
      DGLB(I)=GLB                                                       DRYR2470
      EQST(I)=0.0                                                       DRYR2480
   90 GM(I)=MO                                                          DRYR2490
C  FAN MANAGEMENT AND BIN ENHANCEMENT LOGIC GOES HERE                   DRYR2500
      RETURN                                                            DRYR2510
      END                                                               DRYR2520
```

```
      SUBROUTINETABLE(WTGRN,NTINC,ME,DIA,NLAYRS,TG,CFMFT2,DEPTH,PD,WGLB)DRYR2530
      COMMON/DESAIR/CFMTOT,AREA,ELEVTN,T(20),IG                         DRYR2540
      COMMON /DRY/ BO,PA,PB,PC,CA,CB,DC,DEN1,DEN2                       DRYR2550
      COMMON/GRAIN/ EMC(27),SPHEAT(18),DEN(18),DCS(9),GRAINS(9)         DRYR2560
      COMPLEX*16 JBNAME,PARM(2)                                         DRYR2570
      COMPLEX*16 GRAINS                                                 DRYR2580
      REAL*8 CLASS,ACCT                                                 DRYR2590
      LOGICAL*1 OVLY(32)                                                DRYR2600
      EQUIVALENCE (OVLY(1),CLASS),(OVLY(9),ACCT),(OVLY(17),JBNAME),     DRYR2610
     X (PARM(1),OVLY(1))                                                DRYR2620
    1 FORMAT('0',4X,'T', T34,'DRYING BED HEIGHT ABOVE BIN FLOOR (INCHES)DRYR2630
     ¬',/,5X,'I',T56,'GRAIN MOISTURES (WB) AT EACH SENSING LOCATION',/, DRYR2640
     15X,'M',/,5X,'E',T15, '1-11-21   2-12-22   3-13-23   4-14-24   5-15DRYR2650
     ¬-25   6-16-26   7-17-27   8-18-28   9-19-29  10-20-30'/)          DRYR2660
    2 FORMAT(' ',120('*'))                                              DRYR2670
    3 FORMAT(' SIMULATION OF NATURAL-AIR GRAIN CONDITIONING  **  KANSAS DRYR2680
     ¬STATE UNIVERSITY  **   DEPARTMENT OF GRAIN SCIENCE AND INDUSTRY') DRYR2690
    4 FORMAT('  ',2A8,2X,'INITAL CONDITIONS',T41,'****',T49,'AERATION BIDRYR2700
     ¬N CONFIGURATION',T80,'**',T87,'MATHEMATICAL MODEL ATTRIBUTES')    DRYR2710
    5 FORMAT(' TOTAL WEIGHT OF GRAIN =',F8.0,' LBS.',T41,'****',T47,'TOTDRYR2720
     ¬AL AIRFLOW   =',F6.0,' CFM',T80,'**',T84,'MODELED TIME INTERVAL   DRYR2730
     ¬   =',I7,' HR')                                                   DRYR2740
    6 FORMAT(' MOISTURE CONTENT       =',F8.1,' %W.B.',T41,'****',T47,'DIDRYR2750
     ¬AMETER OF BIN =',F6.0,' FT',T80,'**',T84,'NUMBER OF MODELED LAYERSDRYR2760
     ¬   =',I7)                                                         DRYR2770
    7 FORMAT(' GRAIN TEMPERATURE      =',F8.1,' DEG F',T41,'****',T47,'AIDRYR2780
     ¬RFLOW IN BIN  =',F6.1,' CFM/FT2',T80,'**',T84,'DEPTH OF GRAIN IN BDRYR2790
     ¬IN         =',F7.1,' FT')                                         DRYR2800
    8 FORMAT(' STAIN-TEST DAMAGE      =',F8.0,' %',T41,'****',T47,'BIN ELDRYR2810
     ¬EVATION    =',F6.0,' FT',T80,'**',T84,'WEIGHT OF GRAIN PER LAYER  =DRYR2820
     ¬',F7.1,' LB')                                                     DRYR2830
    9 FORMAT(' ',T37,'MATHEMATICAL MODEL EMPIRICAL GRAIN PARAMETERS')   DRYR2840
   10 FORMAT(' CHUNG-PFOST EQUILIBRIUM MOISTURE EQUATION *** KAZARIAN-HADRYR2850
     ¬LL  SPECIFIC-HEAT EQUATION ** DENSITY EQUATION  DRYING CONSTANT') DRYR2860
   11 FORMAT('  A=',F10.4,'   B=',F8.4,'   C=',F8.4,'   ***',9X,'CA=',  DRYR2870
     ¬F6.3,4X,'CB=',F6.3,8X,'**  B0=',F6.2,'  B1=',F6.2,'  DC=',F6.3)   DRYR2880
   12 FORMAT(' ',120('-'))                                              DRYR2890
   13 FORMAT(' ',T47,'****',T76,'****')                                 DRYR2900
   14 FORMAT(' TITLE: ',20A4,5X,'INVESTIGATOR: ',A8,A6)                 DRYR2910
   15 FORMAT(' ')                                                       DRYR2920
      NPRINT=13                                                         DRYR2930
      WRITE(NPRINT,2)                                                   DRYR2940
      WRITE(NPRINT,13)                                                  DRYR2950
      WRITE(NPRINT,3)                                                   DRYR2960
      WRITE(NPRINT,13)                                                  DRYR2970
      WRITE(NPRINT,2)                                                   DRYR2980
      WRITE(NPRINT,4) GRAINS(IG)                                        DRYR2990
      WRITE(NPRINT,2)                                                   DRYR3000
      WRITE(NPRINT,5)  WTGRN,CFMTOT,NTINC                               DRYR3010
      WRITE(NPRINT,6)  ME,DIA,NLAYRS                                    DRYR3020
      WRITE(NPRINT,7)  TG,CFMFT2,DEPTH                                  DRYR3030
      WRITE(NPRINT,8)  PD,ELEVTN,WGLB                                   DRYR3040
      WRITE(NPRINT,15)                                                  DRYR3050
      WRITE(NPRINT,12)                                                  DRYR3060
      CALL KSUACT(PARM)                                                 DRYR3070
      WRITE(NPRINT,14) T,JBNAME                                         DRYR3080
      ACCT=0.0                                                          DRYR3090
      WRITE(NPRINT,12)                                                  DRYR3100
      WRITE(NPRINT,15)                                                  DRYR3110
      WRITE(NPRINT,9)                                                   DRYR3120
```

```
      WRITE(NPRINT,2)                                                   DRYR3130
      WRITE(NPRINT,10)                                                  DRYR3140
      WRITE(NPRINT,11)  PA,PB,PC,CA,CB,DEN1,DEN2,DC                     DRYR3150
      WRITE(NPRINT,12)                                                  DRYR3160
      WRITE(NPRINT,1)                                                   DRYR3170
      RETURN                                                            DRYR3180
      END                                                               DRYR3190
```

```
      SUBROUTINE TIME                                                   DRYR3200
      COMMON/WRTME/ITCALC,NTPS,DB(720),RH(720),PTM(720),AH(720),APD(720)DRYR3210
      COMMON/BINC/GT(30),GM(30),DGLB(30),EQST(30),NLAYRS,NTINC,NTIME,PD DRYR3220
      COMMON/LAYRC  /TO,HO,MO,RHA,TE,HE,ME,ERH,TG,ALB,GLB,ATM,LAYR      DRYR3230
      COMMON/NEWTON/ ICODE(10),KCODE(10)                                DRYR3240
      REAL MO,ME,MW                                                     DRYR3250
    1 FORMAT('0',T14,'****    STATUS OF INTERATION COUNTERS     ****')  DRYR3260
    2 FORMAT(' NUMBER OF ITERATIONS',6X,'1',4X,'2',4X,'3',4X,'4',4X,'5',DRYR3270
     ¬4X,'6',4X,'7',4X,'8',4X,'9',3X,'10')                              DRYR3280
    3 FORMAT(' DEWPT  SUBROUTINE',5X,10I5)                              DRYR3290
    4 FORMAT(' EQLBRM SUBROUTINE',5X,10I5)                              DRYR3300
    5 FORMAT(' ',72('-'))                                               DRYR3310
C                                                                       DRYR3320
C     IF(NVALID.NE.0) WRITE(NVALID) NTPS,NLAYRS                         DRYR3330
      WRITE(8) NTPS,NLAYRS                                              DRYR3340
C                                                                       DRYR3350
      CALL AIRFLO                                                       DRYR3360
C                                                                       DRYR3370
      NTIME=0                                                           DRYR3380
      DO 90 I=1,NTPS                                                    DRYR3390
      TO=DB(I)                                                          DRYR3400
      HO=AH(I)                                                          DRYR3410
      RHA=RH(I)                                                         DRYR3420
      ALB=APD(I)                                                        DRYR3430
      ATM=PTM(I)                                                        DRYR3440
C                                                                       DRYR3450
      CALL BIN                                                          DRYR3460
C                                                                       DRYR3470
      NTIME=NTIME+NTINC                                                 DRYR3480
C                                                                       DRYR3490
      CALL OUTPUT                                                       DRYR3500
C                                                                       DRYR3510
   90 CONTINUE                                                          DRYR3520
      WRITE(6,1)                                                        DRYR3530
      WRITE(6,2)                                                        DRYR3540
      WRITE(6,5)                                                        DRYR3550
      WRITE(6,3) KCODE                                                  DRYR3560
      WRITE(6,4) ICODE                                                  DRYR3570
      RETURN                                                            DRYR3580
      END                                                               DRYR3590
```

```
      SUBROUTINE OUTPUT                                                 DRYR3600
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,DC,DEN1,DEN2                       DRYR3610
      COMMON/BINC/GT(30),GM(30),DGLB(30),EQST(30),NLAYRS,NTINC,NTIME,PD DRYR3620
      DIMENSION DEPS(30),GMW(30),DML(30)                                DRYR3630
      DATA DML /30*0.0/                                                 DRYR3640
    2 FORMAT('0',I5,5X,10F11.3)                                         DRYR3650
    3 FORMAT(' ',10X,10F11.3)                                           DRYR3660
    9 FORMAT(' ',10X,10F11.4)                                           DRYR3670
      NPRINT=13                                                         DRYR3680
      DEPTH=0.                                                          DRYR3690
      DO 30 I=1,NLAYRS                                                  DRYR3700
      GMW(I)=GM(I)/(1.+GM(I))                                           DRYR3710
      WGLB=DGLB(I)/(1.-GMW(I))                                          DRYR3720
      DMLOSS=.0883*(EXP(.006*EQST(I))-1.)+.00102*EQST(I)                DRYR3730
      DML(I)=DMLOSS                                                     DRYR3740
      DENSY=49.35405-27.82596*GMW(I)                                    DRYR3750
      THICK=WGLB*12./DENSY                                              DRYR3760
      DEPTH=DEPTH+THICK                                                 DRYR3770
      DEPS(I)=DEPTH-.5*THICK                                            DRYR3780
   30 CONTINUE                                                          DRYR3790
      N1=1                                                              DRYR3800
   40 N2=(N1-1)+10                                                      DRYR3810
      IF(N2.GT.NLAYRS) N2=NLAYRS                                        DRYR3820
      IF(N1.EQ.1) WRITE(NPRINT,2) NTIME,(DEPS(I),I=N1,N2)               DRYR3830
      IF(N1.EQ.2) WRITE(NPRINT,3)  (DEPS(I),I=N1,N2)                    DRYR3840
      WRITE(NPRINT,9)(GMW(I),I=N1,N2)                                   DRYR3850
      N1=N1+10                                                          DRYR3860
      IF(N2.LT.NLAYRS) GO TO 40                                         DRYR3870
      WRITE(8) NTIME,DEPS,GMW,GT,DML                                    DRYR3880
C                                                                       DRYR3890
C     IF(NVALID.NE.0) WRITE(NVALID) NTIME,DEPS,GMW,GT,DML               DRYR3900
C                                                                       DRYR3910
      RETURN                                                            DRYR3920
      END                                                               DRYR3930
```

```
      SUBROUTINE AIRFLO
      COMMON/WRTME/ITCALC,NTPS,DB(720),RH(720),PTM(720),AH(720),APD(720)
      COMMON/DESAIR/CFMTOT,AREA,ELEVTN,T(20),IG
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS
      RWV=85.78
      DO 90 I=1,NTPS
      TA=DB(I)
      RHA=RH(I)
      PS=SATPS(TA)
      PV=RHA*PS
      AHM=(.6219*PV)/(PTM(I)-PV)
      VSA=(AHM*RWV*TR)/(144.*PV)
      APD(I)=(CFMTOT*(1.-AHM)*60.*ITCALC)/(VSA*AREA)
      AH(I)=AHM
   90 CONTINUE
C  FAN MANAGEMENT AND BIN ENHANCEMENT LOGIC GOES HERE
      RETURN
      END
```

```
      SUBROUTINE BIN                                                    DRYR4120
      COMMON/BINC/GT(30),GM(30),DGLB(30),EQST(30),NLAYRS,NTINC,NTIME,PD DRYR4130
      COMMON/LAYRC  /TO,HO,MO,RHA,TE,HE,ME,ERH,TG,ALB,GLB,ATM,LAYR      DRYR4140
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS                            DRYR4150
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,DC,DEN1,DEN2                       DRYR4160
      DIMENSION X(4),EQ(4)                                              DRYR4170
      EQUIVALENCE (TO,X(1)),(TE,EQ(1))                                  DRYR4180
      EQUIVALENCE (TE,TF),(HE,HF),(ME,MF),(ERH,RHF)                     DRYR4190
      REAL MO,ME,MW,MF                                                  DRYR4200
      DO 20 LAYR=1,NLAYRS                                               DRYR4210
      TG=GT(LAYR)                                                       DRYR4220
      MO=GM(LAYR)                                                       DRYR4230
      MW=MO/(1.+MO)                                                     DRYR4240
C                                                                       DRYR4250
C                CALCULATE DRY MARTER LOSS                              DRYR4260
C                                                                       DRYR4270
C DEQST  = DELTA EQUIVALENT STORAGE TIMES                               DRYR4280
C EQST   = EQUIVALENT STORAGE TIMES CUMULATIVE                          DRYR4290
C DMLOSS = DRYMATTER LOSS EXPRESSED AS A PERCENT                        DRYR4300
C PD     = PERCENT DAMAGE AS DEFINED BY STEELE(67)                      DRYR4310
C                                                                       DRYR4320
      DEQST=NTINC/EQCO2(TG,MW,PD,MO)                                    DRYR4330
      EQST(LAYR)=EQST(LAYR)+DEQST                                       DRYR4340
      DMLOSS=.0883*(EXP(.006*DEQST)-1.)+.00102*DEQST                    DRYR4350
      WGLB=GLB/(1.-MW)                                                  DRYR4360
      CC=CA+CB*MW                                                       DRYR4370
C                                                                       DRYR4380
C  HEAT OF COMBUSTION OF CORN = 6771.57 BTU/LB.                         DRYR4390
C DGLB = ARRAY CONTAINING DRY MATTER OF EACH LAYER                      DRYR4400
C                                                                       DRYR4410
      TG=TG+(DMLOSS*.01*GLB*6771.57)/(WGLB*CC)                          DRYR4420
      GLB=DGLB(LAYR)*(1.-.01*DMLOSS)                                    DRYR4430
      DGLB(LAYR)=GLB                                                    DRYR4440
      MO=(MO+.006*DMLOSS)/(1.-.01*DMLOSS)                               DRYR4450
      CALL DEWPT(DP,TO,RHA)                                             DRYR4460
      IF(TG.LE.DP) GO TO 10                                             DRYR4470
C                                                                       DRYR4480
      CALL DRYER(NTINC)                                                 DRYR4490
C                                                                       DRYR4500
      GT(LAYR)=TF                                                       DRYR4510
      GM(LAYR)=MF                                                       DRYR4520
      TO =TF                                                            DRYR4530
      HO=HF                                                             DRYR4540
      RHA=RHF                                                           DRYR4550
      GO TO 20                                                          DRYR4560
C                                                                       DRYR4570
 10   CALL EQLBRM                                                       DRYR4580
C                                                                       DRYR4590
      GT(LAYR)=TE                                                       DRYR4600
      GM(LAYR)=ME                                                       DRYR4610
      TO=TE                                                             DRYR4620
      HO=HE                                                             DRYR4630
      RHA=ERH                                                           DRYR4640
C                                                                       DRYR4650
 20   CONTINUE                                                          DRYR4660
      RETURN                                                            DRYR4670
      END                                                               DRYR4680
```

```
      SUBROUTINE DEWPT(DP,DB,RH)
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS
      COMMON/NEWTON/ ICODE(10),KCODE(10)
      T=DB+459.69
      PS=R*EXP((A1+T*(B+T*(C+T*(D+T*E))))/(T*(F-T*G)))
      IF(DB.LE.32.) PS=EXP(23.3924-11286.6/T-.46057*ALOG(T))
      PV=RH*PS
      N=0
      CK=1.
   10 PVDP=R*EXP((A1+T*(B+T*(C+T*(D+T*E))))/(T*(F-T*G)))
      N=N+1
      IF(T.LE.491.69) PVDP=EXP(23.3924-11286.6/T-.46057*ALOG(T))
      FY=PV-PVDP
      D1=F*T-G*T*T
      D2=R*EXP((A1+T*(B+T*(C+T*(D+T*E))))/(T*(F-T*G)))
      IF(DB.LE.32.) D2=EXP(23.3924-11286.6/T-.46057*ALOG(T))
      D3=A1+T*(B+T*(C+T*(D+T*E)))
      D4=B+T*(2.*C+T*(3.*D+T*4.*E))
      D5=D1*D1
      D6=F-2.*G*T
      DPVDP=D2*(D1*D4-D3*D6)/D5
      IF(T.LE.491.69)DPVDP=(11286.6/(T*T)-(.46057/T))*D2
      DFY=-DPVDP
      DELTA=FY/DFY
      IF(N.GE.5) CK=.5*CK
      T=T-DELTA*CK
      IF(ABS(DELTA).GT..001 .AND. N.LE.9) GO TO 10
      DP=T-459.69
      KCODE(N)=KCODE(N)+1
      RETURN
      END
```

```
      SUBROUTINE DRYER(NTINC)
      COMMON/LAYRC  /TO,HO,MO,RHA,TF,HF,MF,RHF,TG,ALB,GLB,ATM,LAYR
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,DC,DEN1,DEN2
      REAL*4 MC,MF
      PSTG=SATPS(TG)
      PSA=SATPS(TO)
      ERH=EXP(-PA/(RO*(TG+PC))*EXP(-PB*MO))
C
C            MASS DIFFUSION EQUATION
C
      MF=MO-NTINC*DC*(ERH*PSTG-RHA*PSA)
C
      HF=HO+(GLB/ALB)*(MO-MF)
      TF=(.24*ALB*TO+.45*ALB*HO*TO+1060.8*ALB*(HO-HF)+CA *GLB*(MO+1.)*TG
     ¬+CB  *GLB*TG*MO)/(.24*ALB+.45*ALB*HF+CB  *GLB*MF+CA *GLB*(MF+1.))
      PS=SATPS(TF)
      RHF=(HF*ATM)/(.6219*PS+HF*PS)
      RETURN
      END
```

```
      SUBROUTINE EQLBRM                                                 DRYR5200
      COMMON/LAYRC  /TO,HO,MO,RHA,TE,HE,ME,ERH,TG,ALB,GLB,ATM,LAYR      DRYR5210
      COMMON/ JORDAN/ A(20),DELTA(4),N                                  DRYR5220
      COMMON/NEWTON/ ICODE(10),KCODE(10)                                DRYR5230
      EQUIVALENCE (TO,X(1)),(TE,EQ(1))                                  DRYR5240
      DIMENSION X(4),EQ(4)                                              DRYR5250
      REAL*4 MC,ME                                                      DRYR5260
      N=4                                                               DRYR5270
      IOBS=0                                                            DRYR5280
      DMC=1.                                                            DRYR5290
C                                                                       DRYR5300
C             MAKE INITIAL GUESSES OF EQUILIBRIUM                       DRYR5310
C                                                                       DRYR5320
      DO 10 I=1,N                                                       DRYR5330
   10 EQ(I)=X(I)                                                        DRYR5340
C                                                                       DRYR5350
C             CALCULATE THE NEWTON RAPHSON AUGMENTED MATRIX ( A )       DRYR5360
C                                                                       DRYR5370
   20 CALL PARTAL                                                       DRYR5380
C                                                                       DRYR5390
C             SOLVE FOR DELTA BY GAUSS-JORDAN REDUCTION OF ( A )        DRYR5400
C                                                                       DRYR5410
      CALL GAUSS                                                        DRYR5420
C                                                                       DRYR5430
C             NEWTON-RAPHSON ITERATION COUNTER                          DRYR5440
C                                                                       DRYR5450
      IOBS=IOBS+1                                                       DRYR5460
C                                                                       DRYR5470
C             CORRECT CURRENT EQUILIBRIUM VALUES BY DELTA               DRYR5480
C                                                                       DRYR5490
      DO 30 I=1,N                                                       DRYR5500
   30 EQ(I)=EQ(I)-DELTA(I)*DMC                                          DRYR5510
      IF(IOBS.GE. 5) DMC=.5*DMC                                         DRYR5520
      AD1=ABS(DELTA(1))                                                 DRYR5530
      AD3=ABS(DELTA(3))                                                 DRYR5540
C                                                                       DRYR5550
C             IF EQUILIBRIUM ACCURACY REQUIREMENTS ARE NOT MET          DRYR5560
C             RECALCULATE A BETTER ESTIMATE OF EQUILIBRIUM              DRYR5570
C                                                                       DRYR5580
      IF((AD1.GT..05.OR.AD3.GT..0005).AND.IOBS.LT.10)GO TO 20           DRYR5590
      ICODE(IOBS)=ICODE(IOBS)+1                                         DRYR5600
      RETURN                                                            DRYR5610
      END                                                               DRYR5620
```

```
      SUBROUTINE PARTAL
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,DC,DEN1,DEN2
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS
      COMMON/LAYRC  /TO,HO,MO,RHA,TE,HE,ME,ERH,TG,ALB,GLB,ATM,LAYR
      COMMON/ JCRDAN/ A(20),DELTA(4),N
      REAL*4 MO,ME
      IF(TE.LE.0.) TE=0.
      IF(HE.LE.0.) HE=0.00001
      IF(HE.GE..05) HE=.05
      IF(ME.LE..05) ME=.05
      IF(ERH.LE..05) ERH=.05
      IF(ERH.GT.1.) ERH=.99
      PS=SATPS(TE)
      A(1)=-.24*ALB-.45*ALB*HE-GLB*CA *(ME+1.)-CB  *GLB*ME
      A(2)=-1060.8*ALB-.45*ALB*TE
      A(3)=-1.201*GLB*TE
      A(4)=0.
C
C   HEAT BALANCE EQUATION
C
      A(5)=.24*ALB*(TO-TE)+1060.8*ALB*(HO-HE)+.45*ALB*(HO*TO-HE*TE)+CA
     ¬*GLB*(MO+1.)*TG+CB  *GLB*TG*MO-CA *GLB*(ME+1.)*TE-CB  *GLB*ME*TE
C
      A(6)=0.
      A(7)=ALB
      A(8)=GLB
      A(9)=0.
C
C   MASS BALANCE EQUATION
C
      A(10)=ALB*HE-ALB*HO+GLB*ME-GLB*MO
C
      A(11)=EXP(-PA/(RO*(TE+PC))*EXP(-PB*ME))*(EXP(-PB*ME)*(-PA/(RO*(TE+
     ¬PC)**2)))
      A(12)=0.
      A(13)=EXP(-PA/(RO*(TE+PC))*EXP(-PB*ME))*(-PA/(RO*(TE+PC))*EXP(-PB*
     ¬ME)*(-PB))
      A(14)=-1.
C
C   CHUNG PFOST EQUILIBRIUM RELATIVE HUMIDITY EQUATION
C
      A(15)=EXP(-PA/(RO*(TE+PC))*EXP(-PB*ME))-ERH
C
      CALL PARTF4(PF4TE,1)
      A(16)=PF4TE
      A(17)=1.
      A(18)=0.
      CALL PARTF4(PF4ERH,2)
      A(19)=PF4ERH
C
C   PSYCHROMETRIC CHART CHART EQUATION
C
      A(20)=HE-((.6219*(ERH*PS))/(  ATM -(ERH*PS)))
C
      RETURN
      END
```

```
      SUBROUTINE PARTF4(ANS,N)                                          DRYR6190
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS                            DRYR6200
      COMMON/LAYRC  /TO,HO,MO,RHA,TE,HE,ME,ERH,TG,ALB,GLB,ATM,LAYR      DRYR6210
      GO TO (1,2) ,N                                                    DRYR6220
C   PARTIAL OF PSYCHRCMETRIC EQUATION WITH RESPECT TO  TE               DRYR6230
  1   B1=F*TR-G*TR*TR                                                   DRYR6240
      B2=PS                                                             DRYR6250
      B3=A1+TR*(B+TR*(C+TR*(D+TR*E)))                                   DRYR6260
      B4=B+TR*(2.*C+TR*(3.*D+TR*(4.*E)))                                DRYR6270
      B5=B1*B1                                                          DRYR6280
      B6=F-2.*G*TR                                                      DRYR6290
      PPS=B2*(B1*B4-B3*B6)/B5                                           DRYR6300
      IF(TE.LE.32.) PPS=((11286.6/(TR*TR))-(.46057/TR))*PS              DRYR6310
      ANS=((  ATM -ERH*PS)*(-.6219*ERH*PPS)-(-.6219*ERH*PS)*(-ERH*PPS))/DRYR6320
     1((  ATM -ERH*PS)*(  ATM -ERH*PS))                                 DRYR6330
      RETURN                                                            DRYR6340
C   PARTIAL CF PSYCHROMETRIC EQUATION WITH RESPECT TO ERH               DRYR6350
  2   ANS=((  ATM -ERH*PS)*(-.6219*PS)-(.6219*ERH*PS)*PS)/((  ATM -ERH*PDRYR6360
     1S)*(  ATM -ERH*PS))                                               DRYR6370
      RETURN                                                            DRYR6380
      END                                                               DRYR6390
```

```
      SUBROUTINE GAUSS                                                  DRYR6400
      COMMON/ JORDAN/ A(20),DELTA(4),N                                  DRYR6410
      DIMENSION ID(4)                                                   DRYR6420
  1   FORMAT(' ','DETERMINANT = 0.0')                                   DRYR6430
  2   FORMAT(' ',12F10.5)                                               DRYR6440
  4   FORMAT(' ',5E16.8)                                                DRYR6450
      DO 5 I=1,N                                                        DRYR6460
  5   ID(I)=I                                                           DRYR6470
      EPS=1.0 E-6                                                       DRYR6480
      N1=N+1                                                            DRYR6490
      DO 120 M=1,N                                                      DRYR6500
      IP=(M-1)*N1                                                       DRYR6510
      IC=M                                                              DRYR6520
      IR=M                                                              DRYR6530
      PIVOT=A(IP+M)                                                     DRYR6540
      AMAX=ABS(PIVOT)                                                   DRYR6550
      DO 20 I=M,N                                                       DRYR6560
      IS=(I-1)*N1                                                       DRYR6570
      DO 10 J=M,N                                                       DRYR6580
      IF(ABS(A(IS+J)).LE.AMAX ) GO TO 10                                DRYR6590
      PIVOT=A(IS+J)                                                     DRYR6600
      AMAX=ABS(PIVOT)                                                   DRYR6610
      IC=J                                                              DRYR6620
      IR=I                                                              DRYR6630
  10  CONTINUE                                                          DRYR6640
  20  CONTINUE                                                          DRYR6650
      IF(IR.EQ.M) GO TO 40                                              DRYR6660
C  INTERCHANGE IRTH ROW (ROW WITH PIVOT) WITH MTH ROW (ROW WITH PIVOT LODRYR6670
      IS=(IR-1)*N1                                                      DRYR6680
      DO 30 JJ=1,N1                                                     DRYR6690
      DUMMY=A(IP+JJ)                                                    DRYR6700
      A(IP+JJ)=A(IS+JJ)                                                 DRYR6710
      A(IS+JJ)=DUMMY                                                    DRYR6720
  30  CONTINUE                                                          DRYR6730
  40  CONTINUE                                                          DRYR6740
      IF(IC.EQ.M) GO TO 60                                              DRYR6750
C  INTERCHANGE ICTH COLUMN (COLUMN WITH PIVOT) WITH MTH COLUMN (COLUMN ODRYR6760
      DO 50 II=1,N                                                      DRYR6770
      IS=(II-1)*N1                                                      DRYR6780
      DUMMY=A(IS+M)                                                     DRYR6790
      A(IS+M)=A(IS+IC)                                                  DRYR6800
      A(IS+IC)=DUMMY                                                    DRYR6810
  50  CONTINUE                                                          DRYR6820
C  INTERCHANGE ROW INDICATORS FOR DELTA VALUES ACCORDING TO COLUMN CHANGDRYR6830
      IDUMMY=ID(M)                                                      DRYR6840
      ID(M)=ID(IC)                                                      DRYR6850
      ID(IC)=IDUMMY                                                     DRYR6860
  60  CONTINUE                                                          DRYR6870
C  ABSOLUTE VALUE OF THE PIVOT MEANS THAT MATRIX IS SINGULAR AND DETERMIDRYR6880
      IF(ABS(PIVOT).GT.EPS) GO TO 80                                    DRYR6890
      WRITE(6,1)                                                        DRYR6900
      DO 70 I=1,N                                                       DRYR6910
      IS=(I-1)*N1                                                       DRYR6920
  70  WRITE(6,2) (A(IS+J),J=1,N1)                                       DRYR6930
      RETURN                                                            DRYR6940
  80  CONTINUE                                                          DRYR6950
      DIV=1./PIVOT                                                      DRYR6960
C  DIVIDE THE MTH ROW BY THE PIVOT ELEMENT SARTING WITH THE PIVOT LOCATIDRYR6970
      DO 90 J=M,N1                                                      DRYR6980
      A(IP+J)=A(IP+J)*DIV                                               DRYR6990
```

```
  90  CONTINUE                                                          DRYR7000
C  ELIMINATE ALL ROWS I = 1 TO N EXCEPT THE MTH ROW                     DRYR7010
      DO 110 I=1,N                                                      DRYR7020
      IS=(I-1)*N1                                                       DRYR7030
      IF(I.EQ.M) GO TO 110                                              DRYR7040
      AIM=-A(IS+M)                                                      DRYR7050
      DO 100 J=M,N1                                                     DRYR7060
      A(IS+J)=A(IS+J)+AIM*A(IP+J)                                       DRYR7070
 100  CONTINUE                                                          DRYR7080
 110  CONTINUE                                                          DRYR7090
 120  CONTINUE                                                          DRYR7100
C  END OF GAUSS-JORDAN REDUCTION LOOP                                   DRYR7110
C        MATRIX A NOW IS IN THE FORM :  (A) = (I|D)                     DRYR7120
C                  '|' MEANS AUGMENTED BY                               DRYR7130
C                  (D) = DELTA COLUMN VECTOR EQUIVALENT TO (A-INVERSE)*(DRYR7140
C                                                                       DRYR7150
      DO 130 I=1,N                                                      DRYR7160
C                                                                       DRYR7170
C  PUT THE APPROPRIATE VALUES OF A(ID(I),N1) INTO THE DELTA(I)  ACCORDINDRYR7180
C                  PREVIOUS COLUMN INTERCHANGES RECORDED IN THE ID ARRAYDRYR7190
C                                                                       DRYR7200
      IDEL=(I-1)*N1                                                     DRYR7210
      DELTA(ID(I))=A(IDEL+N1)                                           DRYR7220
 130  CONTINUE                                                          DRYR7230
      RETURN                                                            DRYR7240
      END                                                               DRYR7250
```

```
FUNCTION EQCO2(T,WB,PD,DB)                                         DRYR7260
RM=.103*(EXP(455./ (DB*100.)**1.53)-.845*DB+1.558)                 DRYR7270
IF(WB.LE..19)  WB=.19                                              DRYR7280
IF(WB.GT..28) WB=.28                                               DRYR7290
RT=32.3*EXP(-3.48*(T/60.))+(WB-.19)*EXP(.61*(T-60.)/60.)           DRYR7300
IF(T.LT.60.) RT=128.76*EXP(-.081*T)                                DRYR7310
RD=2.08*EXP(-.0239*PD)                                             DRYR7320
EQCO2=RT*RM*RD                                                     DRYR7330
RETURN                                                             DRYR7340
END                                                                DRYR7350
```

```
      FUNCTION SATPS(T)                                                 DRYR7360
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS                            DRYR7370
      TR=T+459.69                                                       DRYR7380
      SATPS=EXP((A1+TR*(B+TR*(C+TR*(D+TR*E))))/(TR*(F-G*TR)))*R         DRYR7390
      IF(T.LE.32.) SATPS=EXP(23.3924-(11286.6/TR)-.46057*ALOG(TR))      DRYR7400
      RETURN                                                            DRYR7410
      END                                                               DRYR7420
```

```
      BLOCK DATA
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS
      COMMON/GRAIN/ EMC(27),SPHEAT(18),DEN(18),DCS(9),GRAINS(9)
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,DC,DEN1,DEN2
      COMMON/NEWTON/ICODE(10),KCODE(10)
      COMPLEX*16 GRAINS
C
C           BROOKER SATURATION PREESURE EQUATION CONSTANTS
C
      DATA R,A1,B,C,D /3206.18,-27405.5,54.1896,-.045137,.215321E-4/
      DATA E,F,G /-.462027E-8, 2.41613 ,.121547E-2 /
C
C           GRAIN (IG) WHICH MODEL IS APLICABLE TO
C
      DATA GRAINS/              'YELLOW DENT CORN',  '    ROUGH RICE   ',
     ¬   '  GRAIN SORGHUM ',    '  SOYBEAN SEED  ',  '    MILLET SEED  ',
     ¬   ' CHICK-PEA SEED ',    '    SESAME SEED  ', 'GROUNDNUT IN POD',
     ¬   '   WHEAT SEED    ' /
C
C           DENSITY EQUATION CONSTANTS FOR GRAIN (IG) DEN=B0+B1*MW
C
      DATA DEN/49.35405,-27.82596,49.35405,-27.82596,49.35405,-27.82596,
     ¬        49.35405,-27.82596,49.35405,-27.82596,49.35405,-27.82596,
     ¬        49.35405,-27.82596,49.35405,-27.82596,49.35405,-27.82596/
C
C           DIFFUSSION COEFFICIENTS FOR GRAIN(IG)
C
      DATA DCS / .02, .02, .02, .02, .02, .02, .02, .02, .02 /

C
C           CHUNG-PFOST EMC EQUATION CONSTANTS FOR GRAIN (IG)
C                 A(IG), B(IG), C(IG)
C
      DATA RO /1.987/
      DATA EMC/1110.4268,16.9534,21.8947,   1975.6600,19.6650,40.4100,
     ¬         1110.4268,16.9534,21.8947,   1110.4268,16.9534,21.8947,
     ¬         1110.4268,16.9534,21.8947,   1110.4268,16.9534,21.8947,
     ¬         1110.4268,16.9534,21.8947,   1110.4268,16.9534,21.8947,
     ¬         2793.2200,23.6036,57.6554    /
C
C           KAZARIAN-HALL(65) SPECIFIC HEAT CCNSTANTS FOR GRAIN (IG)
C
      DATA SPHEAT/.35,.851,  .35,.851,  .35,.851,  .35,.851,  .35,.851,
     ¬ .35,.851, .35,.851,  .35,.851,  .35,.851  /
      DATA ICCDE,KCODE/20*0/
      END
/*
```

APPENDIX

E

EMC - DATA

E-1

YELLOW DENT
CORN EMC

```
              CHUNG - PFOST EMC EQUATION   CORN PROBLEM



 1       RODR       1       0.0809       0.1400        4.4400
 2       RODR       1       0.1171       0.3460        4.4400
 3       RODR       1       0.1227       0.3700        4.4400
 4       RODR       1       0.1500       0.5340        4.4400
 5       RODR       1       0.1635       0.5930        4.4400
 6       RODR       1       0.2114       0.7590        4.4400
 7       RODR       1       0.2051       0.7590        4.4400
 8       RODR       1       0.1051       0.3240       15.5600
 9       RODR       1       0.1052       0.3390       15.5600
10       RODR       1       0.1140       0.3750       15.5600
11       RODR       1       0.1120       0.3750       15.5600
12       RODR       1       0.1138       0.3750       15.5600
13       RODR       1       0.1108       0.3750       15.5600
14       RODR       1       0.1377       0.5660       15.5600
15       RODR       1       0.1823       0.7590       15.5600
16       RODR       1       0.2870       0.9440       15.5600
17       RODR       1       0.0486       0.1120       30.0000
18       RODR       1       0.0810       0.2740       30.0000
19       RODR       1       0.0796       0.2740       30.0000
20       RODR       1       0.0902       0.3240       30.0000
21       RODR       1       0.0890       0.3240       30.0000
22       RODR       1       0.0874       0.3240       30.0000
23       RODR       1       0.0897       0.3240       30.0000
24       RODR       1       0.1032       0.4000       30.0000
25       RODR       1       0.0960       0.4000       30.0000
26       RODR       1       0.0987       0.4000       30.0000
27       RODR       1       0.1050       0.4350       30.0000
28       RODR       1       0.1190       0.5310       30.0000
29       RODR       1       0.1148       0.5310       30.0000
30       RODR       1       0.1193       0.5310       30.0000
31       RODR       1       0.1188       0.5310       30.0000
32       RODR       1       0.1190       0.5310       30.0000
33       RODR       1       0.1238       0.5630       30.0000
34       RODR       1       0.1364       0.6330       30.0000
35       RODR       1       0.1357       0.6330       30.0000
36       RODR       1       0.1489       0.6830       30.0000
37       RODR       1       0.1452       0.6830       30.0000
38       RODR       1       0.1583       0.7520       30.0000
39       RODR       1       0.1583       0.7520       30.0000
40       RODR       1       0.1928       0.8630       30.0000
41       RODR       1       0.0478       0.1110       37.7800
42       RODR       1       0.0846       0.3190       37.7800
43       RODR       1       0.0995       0.4340       37.7800
```

```
 44     RODR    1    0.1086     0.5000    37.7800
 45     RODR    1    0.1278     0.6180    37.7800
 46     RODR    1    0.1528     0.7510    37.7800
 47     RODR    1    0.1535     0.7510    37.7800
 48     RODR    1    0.1688     0.7910    37.7800
 49     RODR    1    0.2481     0.9630    37.7800
 50     RODR    1    0.0393     0.1140    50.0000
 51     RODR    1    0.0383     0.1140    50.0000
 52     RODR    1    0.0412     0.1140    50.0000
 53     RODR    1    0.0597     0.2040    50.0000
 54     RODR    1    0.0748     0.2840    50.0000
 55     RODR    1    0.0988     0.4710    50.0000
 56     RODR    1    0.1165     0.5980    50.0000
 57     RODR    1    0.1331     0.6870    50.0000
 58     RODR    1    0.1478     0.7470    50.0000
 59     RODR    1    0.1774     0.8500    50.0000
 60     RODR    1    0.1779     0.8500    50.0000
 61     RODR    1    0.1733     0.8500    50.0000
 62     RODR    1    0.0339     0.1120    60.0000
 63     RODR    1    0.0521     0.2100    60.0000
 64     RODR    1    0.0612     0.2530    60.0000
 65     RODR    1    0.0859     0.4990    60.0000
 66     RODR    1    0.0892     0.5520    60.0000
 67     RODR    1    0.0965     0.5520    60.0000
 68     RODR    1    0.0975     0.5930    60.0000
 69     RODR    1    0.1078     0.6750    60.0000
 70     RODR    1    0.1243     0.7490    60.0000
 71     RODR    1    0.1371     0.8070    60.0000
 72     RODR    1    0.1403     0.8070    60.0000
 73     GUST    1    0.0749     0.1330    10.0000
 74     GUST    1    0.1092     0.3420    10.0000
 75     GUST    1    0.1480     0.5780    10.0000
 76     GUST    1    0.1966     0.7540    10.0000
 77     GUST    1    0.2076     0.8180    10.0000
 78     GUST    1    0.3373     0.9550    10.0000
 79     GUST    1    0.0556     0.1190    32.2200
 80     GUST    1    0.0914     0.3260    32.2200
 81     GUST    1    0.1169     0.5190    32.2200
 82     GUST    1    0.1712     0.7560    32.2200
 83     GUST    1    0.1844     0.8000    32.2200
 84     GUST    1    0.2438     0.9000    32.2200
 85     GUST    1    0.0392     0.1150    48.8900
 86     GUST    1    0.0814     0.3160    48.8900
 87     GUST    1    0.0985     0.4730    48.8900
 88     GUST    1    0.1584     0.7480    48.8900
 89     GUST    1    0.1697     0.7910    48.8900
 90     GUST    1    0.2002     0.8530    48.8900
 91     GUST    1    0.0340     0.1110    68.3300
 92     GUST    1    0.0610     0.3030    68.3300
 93     GUST    1    0.0671     0.4220    68.3300
 94     GUST    1    0.1317     0.7320    68.3300
 95     GUST    1    0.1362     0.7800    68.3300
 96     GUST    1    0.1342     0.7870    68.3300
 97     CHUN    1    0.2422     0.8860    22.0000
 98     CHUN    1    0.1909     0.7290    22.0000
 99     CHUN    1    0.1605     0.6760    22.0000
100     CHUN    1    0.1438     0.5730    22.0000
101     CHUN    1    0.1292     0.4650    22.0000
102     CHUN    1    0.1166     0.3580    22.0000
103     CHUN    1    0.0979     0.2580    22.0000
```

```
104     CHUN    1     0.0848     0.1670    22.0000
105     CHUN    1     0.0700     0.0940    22.0000
106     CHUN    1     0.2308     0.8890    50.0000
107     CHUN    1     0.1494     0.6810    50.0000
108     CHUN    1     0.1291     0.5830    50.0000
109     CHUN    1     0.1115     0.4830    50.0000
110     CHUN    1     0.0965     0.3780    50.0000
111     CHUN    1     0.0857     0.2810    50.0000
112     CHUN    1     0.0706     0.1890    50.0000
113     CHUN    1     0.0564     0.1100    50.0000
114     PIXE    1     0.1060     0.2800     5.0000
115     PIXE    1     0.1550     0.5370     5.0000
116     PIXE    1     0.1980     0.7200     5.0000
117     PIXE    1     0.2360     0.8420     5.0000
118     PIXE    1     0.3090     0.9240     5.0000
119     PIXE    1     0.1060     0.3070    15.0000
120     PIXE    1     0.1550     0.5720    15.0000
121     PIXE    1     0.1980     0.7530    15.0000
122     PIXE    1     0.2360     0.8550    15.0000
123     PIXE    1     0.3090     0.9390    15.0000
124     PIXE    1     0.1060     0.3430    25.0000
125     PIXE    1     0.1550     0.6280    25.0000
126     PIXE    1     0.1980     0.7820    25.0000
127     PIXE    1     0.2360     0.8740    25.0000
128     PIXE    1     0.3090     0.9450    25.0000
129     PIXA    1     0.0990     0.2740     5.0000
130     PIXA    1     0.1560     0.5940     5.0000
131     PIXA    1     0.2120     0.8170     5.0000
132     PIXA    1     0.2500     0.8990     5.0000
133     PIXA    1     0.3290     0.9820     5.0000
134     PIXA    1     0.0990     0.3060    15.0000
135     PIXA    1     0.1560     0.6280    15.0000
136     PIXA    1     0.2120     0.8350    15.0000
137     PIXA    1     0.2500     0.9080    15.0000
138     PIXA    1     0.3290     0.9620    15.0000
139     PIXA    1     0.0990     0.3470    25.0000
140     PIXA    1     0.1560     0.6730    25.0000
141     PIXA    1     0.2120     0.8600    25.0000
142     PIXA    1     0.2500     0.9160    25.0000
143     PIXA    1     0.3290     0.9700    25.0000
144     END     1   999.0000   999.0000   999.0000
```

E-2

YELLOW DENT
CORN (RODR & RODI)

Chung-Pfost EMC Euqation   Corn Problem   Actual Versus Interpolated

```
 1     RODR     1     0.0809     0.1400      4.4400
 2     RODR     1     0.1171     0.3460      4.4400
 3     RODR     1     0.1227     0.3700      4.4400
 4     RODR     1     0.1500     0.5340      4.4400
 5     RODR     1     0.1635     0.5930      4.4400
 6     RODR     1     0.2114     0.7590      4.4400
 7     RODR     1     0.2051     0.7590      4.4400
 8     RODR     1     0.1051     0.3240     15.5600
 9     RODR     1     0.1052     0.3390     15.5600
10     RODR     1     0.1140     0.3750     15.5600
11     RODR     1     0.1120     0.3750     15.5600
12     RODR     1     0.1138     0.3750     15.5600
13     RODR     1     0.1108     0.3750     15.5600
14     RODR     1     0.1377     0.5660     15.5600
15     RODR     1     0.1823     0.7590     15.5600
16     RODR     1     0.2870     0.9440     15.5600
17     RODR     1     0.0486     0.1120     30.0000
18     RODR     1     0.0810     0.2740     30.0000
19     RODR     1     0.0796     0.2740     30.0000
20     RODR     1     0.0902     0.3240     30.0000
21     RODR     1     0.0890     0.3240     30.0000
22     RODR     1     0.0874     0.3240     30.0000
23     RODR     1     0.0397     0.3240     30.0000
24     RODR     1     0.1032     0.4000     30.0000
25     RODR     1     0.0960     0.4000     30.0000
26     RODR     1     0.0987     0.4000     30.0000
27     RODR     1     0.1050     0.4350     30.0000
28     RODR     1     0.1190     0.5310     30.0000
29     RODR     1     0.1148     0.5310     30.0000
30     RODR     1     0.1193     0.5310     30.0000
31     RODR     1     0.1198     0.5310     30.0000
32     RODR     1     0.1190     0.5310     30.0000
33     RODR     1     0.1238     0.5630     30.0000
34     RODR     1     0.1364     0.6330     30.0000
35     RODR     1     0.1357     0.6330     30.0000
36     RODR     1     0.1489     0.6830     30.0000
37     RODR     1     0.1452     0.6830     30.0000
38     RODR     1     0.1583     0.7520     30.0000
39     RODR     1     0.1583     0.7520     30.0000
40     RODR     1     0.1928     0.8630     30.0000
41     RODR     1     0.0478     0.1110     37.7800
42     RODR     1     0.0846     0.3190     37.7800
43     RODR     1     0.0995     0.4340     37.7800
```

```
 44     RODR     1     0.1086     0.5000     37.7800
 45     RODR     1     0.1278     0.6190     37.7800
 46     RODR     1     0.1528     0.7510     37.7800
 47     RODR     1     0.1535     0.7510     37.7800
 48     RODR     1     0.1688     0.7910     37.7800
 49     RODR     1     0.2481     0.9630     37.7800
 50     RODR     1     0.0393     0.1140     50.0000
 51     RODR     1     0.0383     0.1140     50.0000
 52     RODR     1     0.0412     0.1140     50.0000
 53     RODR     1     0.0597     0.2040     50.0000
 54     RODR     1     0.0748     0.2840     50.0000
 55     RODR     1     0.0938     0.4710     50.0000
 56     RODR     1     0.1165     0.5980     50.0000
 57     RODR     1     0.1331     0.6870     50.0000
 58     RODR     1     0.1473     0.7470     50.0000
 59     RODR     1     0.1774     0.8500     50.0000
 60     RODR     1     0.1779     0.8500     50.0000
 61     RODR     1     0.1733     0.8500     50.0000
 62     RODR     1     0.0339     0.1120     60.0000
 63     RODR     1     0.0521     0.2100     60.0000
 64     RODR     1     0.0612     0.2530     60.0000
 65     RODR     1     0.0859     0.4990     60.0000
 66     RODR     1     0.0892     0.5520     60.0000
 67     RODR     1     0.0965     0.5520     60.0000
 68     RODR     1     0.0975     0.5930     60.0000
 69     RODR     1     0.1078     0.6750     60.0000
 70     RODR     1     0.1243     0.7490     60.0000
 71     RODR     1     0.1371     0.8070     60.0000
 72     RODR     1     0.1403     0.8070     60.0000
 73     RODI     1     0.0672     0.1000      4.4400
 74     RODI     1     0.0941     0.2000      4.4400
 75     RODI     1     0.1036     0.3000      4.4400
 76     RODI     1     0.1236     0.4000      4.4400
 77     RODI     1     0.1416     0.5000      4.4400
 78     RODI     1     0.1601     0.6000      4.4400
 79     RODI     1     0.1862     0.7000      4.4400
 80     RODI     1     0.2136     0.8000      4.4400
 81     RODI     1     0.2739     0.9000      4.4400
 82     RODI     1     0.0811     0.1000     15.5600
 83     RODI     1     0.0846     0.2000     15.5600
 84     RODI     1     0.0989     0.3000     15.5600
 85     RODI     1     0.1148     0.4000     15.5600
 86     RODI     1     0.1274     0.5000     15.5600
 87     RODI     1     0.1416     0.6000     15.5600
 88     RODI     1     0.1614     0.7000     15.5600
 89     RODI     1     0.1947     0.8000     15.5600
 90     RODI     1     0.2469     0.9000     15.5600
 91     RODI     1     0.0460     0.1000     30.0000
 92     RODI     1     0.0799     0.2000     30.0000
 93     RODI     1     0.0893     0.3000     30.0000
 94     RODI     1     0.0989     0.4000     30.0000
 95     RODI     1     0.1136     0.5000     30.0000
 96     RODI     1     0.1287     0.6000     30.0000
 97     RODI     1     0.1481     0.7000     30.0000
 98     RODI     1     0.1737     0.8000     30.0000
 99     RODI     1     0.2107     0.9000     30.0000
100     RODI     1     0.0417     0.1000     37.7800
101     RODI     1     0.0638     0.2000     37.7800
102     RODI     1     0.0787     0.3000     37.7800
103     RODI     1     0.0953     0.4000     37.7800
```

```
104       RODI     1     0.0989     0.5000     37.7800
105       RODI     1     0.1236     0.6000     37.7800
106       RODI     1     0.1429     0.7000     37.7800
107       RODI     1     0.1655     0.8000     37.7800
108       RODI     1     0.2005     0.9000     37.7800
109       RODI     1     0.0373     0.1000     50.0000
110       RODI     1     0.0582     0.2000     50.0000
111       RODI     1     0.0718     0.3000     50.0000
112       RODI     1     0.0870     0.4000     50.0000
113       RODI     1     0.1013     0.5000     50.0000
114       RODI     1     0.1161     0.6000     50.0000
115       RCDI     1     0.1364     0.7000     50.0000
116       RODI     1     0.1574     0.8000     50.0000
117       RODI     1     0.1919     0.9000     50.0000
118       RODI     1     0.0309     0.1000     60.0000
119       RODI     1     0.0526     0.2000     60.0000
120       RODI     1     0.0638     0.3000     60.0000
121       RODI     1     0.0753     0.4000     60.0000
122       RODI     1     0.0858     0.5000     60.0000
123       RODI     1     0.0965     0.6000     60.0000
124       RODI     1     0.1148     0.7000     60.0000
125       RODI     1     0.1377     0.8000     60.0000
126       RODI     1     0.1710     0.9000     60.0000
127       END      1   999.0000   999.0000    999.0000
```

E-3

ALL OTHER EMC DATA

```
HENDERSON-THOMPSON EMC        SOYBEANS PROBLEM



  1        KOS       1       0.0634      0.3000      38.0000
  2        KOS       1       0.0731      0.4500      38.0000
  3        KOS       1       0.0857      0.6000      38.0000
  4        KOS       1       0.1346      0.7500      38.0000
  5        KOS       1       0.2016      0.9000      38.0000
  6        KOS       1       0.0685      0.3000      30.0000
  7        KOS       1       0.0781      0.4500      30.0000
  8        KOS       1       0.0982      0.6000      30.0000
  9        KOS       1       0.1391      0.7500      30.0000
 10        KOS       1       0.2130      0.9000      30.0000
 11        KOS       1       0.0734      0.3000      25.0000
 12        KOS       1       0.0826      0.4500      25.0000
 13        KOS       1       0.1008      0.6000      25.0000
 14        KOS       1       0.1590      0.7500      25.0000
 15        KOS       1       0.2252      0.9000      25.0000
 16        KOS       1       0.0753      0.3000      20.0000
 17        KOS       1       0.0872      0.4500      20.0000
 18        KOS       1       0.1109      0.6000      20.0000
 19        KOS       1       0.1692      0.7500      20.0000
 20        KOS       1       0.2385      0.9000      20.0000
 21        KOS       1       0.0846      0.3000      15.0000
 22        KOS       1       0.0918      0.4500      15.0000
 23        KOS       1       0.1222      0.6000      15.0000
 24        KOS       1       0.1805      0.7500      15.0000
 25        KOS       1       0.2536      0.9000      15.0000
 26        KOS       1       0.0896      0.3000      10.0000
 27        KOS       1       0.0993      0.4500      10.0000
 28        KOS       1       0.1293      0.6000      10.0000
 29        KOS       1       0.2008      0.7500      10.0000
 30        KOS       1       0.2666      0.9000      10.0000
 31        KOS       1       0.0636      0.3000      38.0000
 32        KOS       1       0.0811      0.4500      38.0000
 33        KOS       1       0.1102      0.6000      38.0000
 34        KOS       1       0.1592      0.7500      38.0000
 35        KOS       1       0.2189      0.9000      38.0000
 36        KOS       1       0.0693      0.3000      30.0000
 37        KOS       1       0.0858      0.4500      30.0000
 38        KOS       1       0.1145      0.6000      30.0000
 39        KOS       1       0.1666      0.7500      30.0000
 40        KOS       1       0.2268      0.9000      30.0000
 41        KOS       1       0.0735      0.3000      25.0000
 42        KOS       1       0.0887      0.4500      25.0000
 43        KOS       1       0.1181      0.6000      25.0000
```

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 44     KOS     1     0.1758     0.7500     25.0000
 45     KOS     1     0.2488     0.9000     25.0000
 46     KOS     1     0.0760     0.3000     20.0000
 47     KOS     1     0.0928     0.4500     20.0000
 48     KOS     1     0.1211     0.6000     20.0000
 49     KOS     1     0.1848     0.7500     20.0000
 50     KOS     1     0.2587     0.9000     20.0000
 51     KOS     1     0.0815     0.3000     15.0000
 52     KOS     1     0.0952     0.4500     15.0000
 53     KOS     1     0.1245     0.6000     15.0000
 54     KOS     1     0.1950     0.7500     15.0000
 55     KOS     1     0.2663     0.9000     15.0000
 56     KOS     1     0.0896     0.3000     10.0000
 57     KOS     1     0.0995     0.4500     10.0000
 58     KOS     1     0.1364     0.6000     10.0000
 59     KOS     1     0.2021     0.7500     10.0000
 60     KOS     1     0.2910     0.9000     10.0000
 61     BROK    1     0.0550     0.2000     25.0000
 62     BROK    1     0.0650     0.3000     25.0000
 63     BROK    1     0.0710     0.4000     25.0000
 64     BROK    1     0.0800     0.5000     25.0000
 65     BROK    1     0.0930     0.6000     25.0000
 66     BROK    1     0.1150     0.7000     25.0000
 67     BROK    1     0.1480     0.8000     25.0000
 68     BROK    1     0.1880     0.9000     25.0000
 69     BROK    1     0.0700     0.4000     25.0000
 70     BROK    1     0.0800     0.5000     25.0000
 71     BROK    1     0.1010     0.6000     25.0000
 72     BROK    1     0.1220     0.7000     25.0000
 73     BROK    1     0.1600     0.8000     25.0000
 74     BROK    1     0.2070     0.9000     25.0000
 75     PIXE    1     0.0580     0.2680     15.0000
 76     PIXE    1     0.0830     0.5150     15.0000
 77     PIXE    1     0.1170     0.6810     15.0000
 78     PIXE    1     0.1380     0.7510     15.0000
 79     PIXE    1     0.1690     0.8200     15.0000
 80     PIXE    1     0.0580     0.2970     25.0000
 81     PIXE    1     0.0830     0.5380     25.0000
 82     PIXE    1     0.1170     0.6970     25.0000
 83     PIXE    1     0.1380     0.7610     25.0000
 84     PIXE    1     0.1690     0.8290     25.0000
 85     PIXE    1     0.0580     0.3310     35.0000
 86     PIXE    1     0.0830     0.5540     35.0000
 87     PIXE    1     0.1170     0.7010     35.0000
 88     PIXE    1     0.1380     0.7650     35.0000
 89     PIXE    1     0.1690     0.8320     35.0000
 90     PIXE    1     0.0500     0.2100     15.0000
 91     PIXE    1     0.0780     0.4790     15.0000
 92     PIXE    1     0.1060     0.6590     15.0000
 93     PIXE    1     0.1330     0.7560     15.0000
 94     PIXE    1     0.1680     0.8380     15.0000
 95     PIXE    1     0.0500     0.2360     25.0000
 96     PIXE    1     0.0780     0.5030     25.0000
 97     PIXE    1     0.1060     0.6730     25.0000
 98     PIXE    1     0.1330     0.7630     25.0000
 99     PIXE    1     0.1680     0.8420     25.0000
100     PIXE    1     0.0500     0.2600     35.0000
101     PIXE    1     0.0780     0.5170     35.0000
102     PIXE    1     0.1060     0.6750     35.0000
103     PIXE    1     0.1330     0.7640     35.0000
```

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104       PIXE     1     0.1680     0.8390    35.0000
105       END      1   999.0000   999.0000   999.0000
```

```
HENDERSON-THOMPSON EMC          ROUGH RICE PROBLEM


  1        KOS        1      0.0997       0.3000       38.0000
  2        KOS        1      0.1049       0.4500       38.0000
  3        KOS        1      0.1169       0.6000       38.0000
  4        KOS        1      0.1366       0.7500       38.0000
  5        KOS        1      0.1772       0.9000       38.0000
  6        KOS        1      0.1012       0.3000       30.0000
  7        KOS        1      0.1136       0.4500       30.0000
  8        KOS        1      0.1260       0.6000       30.0000
  9        KOS        1      0.1457       0.7500       30.0000
 10        KOS        1      0.1879       0.9000       30.0000
 11        KOS        1      0.1016       0.3000       25.0000
 12        KOS        1      0.1188       0.4500       25.0000
 13        KOS        1      0.1275       0.6000       25.0000
 14        KOS        1      0.1481       0.7500       25.0000
 15        KOS        1      0.1910       0.9000       25.0000
 16        KOS        1      0.1075       0.3000       20.0000
 17        KOS        1      0.1218       0.4500       20.0000
 18        KOS        1      0.1324       0.6000       20.0000
 19        KOS        1      0.1507       0.7500       20.0000
 20        KOS        1      0.2066       0.9000       20.0000
 21        KOS        1      0.1109       0.3000       15.0000
 22        KOS        1      0.1236       0.4500       15.0000
 23        KOS        1      0.1370       0.6000       15.0000
 24        KOS        1      0.1555       0.7500       15.0000
 25        KOS        1      0.2229       0.9000       15.0000
 26        KOS        1      0.1159       0.3000       10.0000
 27        KOS        1      0.1358       0.4500       10.0000
 28        KOS        1      0.1476       0.6000       10.0000
 29        KOS        1      0.1712       0.7500       10.0000
 30        KOS        1      0.2422       0.9000       10.0000
 31        KOS        1      0.0918       0.3000       38.0000
 32        KOS        1      0.1067       0.4500       38.0000
 33        KOS        1      0.1204       0.6000       38.0000
 34        KOS        1      0.1386       0.7500       38.0000
 35        KOS        1      0.1822       0.9000       38.0000
 36        KOS        1      0.1061       0.3000       30.0000
 37        KOS        1      0.1216       0.4500       30.0000
 38        KOS        1      0.1342       0.6000       30.0000
 39        KOS        1      0.1507       0.7500       30.0000
 40        KOS        1      0.1937       0.9000       30.0000
 41        KOS        1      0.1074       0.3000       25.0000
 42        KOS        1      0.1231       0.4500       25.0000
 43        KOS        1      0.1368       0.6000       25.0000
```

44	KOS	1	0.1601	0.7500	25.0000
45	KOS	1	0.2050	0.9000	25.0000
46	KOS	1	0.1095	0.3000	20.0000
47	KOS	1	0.1249	0.4500	20.0000
48	KOS	1	0.1387	0.6000	20.0000
49	KOS	1	0.1680	0.7500	20.0000
50	KOS	1	0.2183	0.9000	20.0000
51	KOS	1	0.1164	0.3000	15.0000
52	KOS	1	0.1254	0.4500	15.0000
53	KOS	1	0.1393	0.6000	15.0000
54	KOS	1	0.1751	0.7500	15.0000
55	KOS	1	0.2333	0.9000	15.0000
56	KOS	1	0.1285	0.3000	10.0000
57	KOS	1	0.1382	0.4500	10.0000
58	KOS	1	0.1559	0.6000	10.0000
59	KOS	1	0.1885	0.7500	10.0000
60	BROK	1	0.1013	0.4000	26.6700
61	BROK	1	0.1161	0.5000	26.6700
62	BROK	1	0.1325	0.6000	26.6700
63	BROK	1	0.1521	0.7000	26.6700
64	BROK	1	0.1765	0.8000	26.6700
65	BROK	1	0.2063	0.9000	26.6700
66	BROK	1	0.1148	0.6000	43.8900
67	BROK	1	0.1403	0.7000	43.8900
68	BROK	1	0.1669	0.8000	43.8900
69	BROK	1	0.1976	0.9000	43.8900
70	BROK	1	0.0893	0.2000	0.0
71	BROK	1	0.1099	0.3000	0.0
72	BROK	1	0.1249	0.4000	0.0
73	BROK	1	0.1403	0.5000	0.0
74	BROK	1	0.1534	0.6000	0.0
75	BROK	1	0.1696	0.7000	0.0
76	BROK	1	0.1990	0.8000	0.0
77	BROK	1	0.2376	0.9000	0.0
78	BROK	1	0.0811	0.2000	20.0000
79	BROK	1	0.1001	0.3000	20.0000
80	BROK	1	0.1161	0.4000	20.0000
81	BROK	1	0.1249	0.5000	20.0000
82	BROK	1	0.1429	0.6000	20.0000
83	BROK	1	0.1587	0.7000	20.0000
84	BROK	1	0.1792	0.8000	20.0000
85	BROK	1	0.2136	0.9000	20.0000
86	BROK	1	0.0764	0.2000	30.0000
87	BROK	1	0.0929	0.3000	30.0000
88	BROK	1	0.1111	0.4000	30.0000
89	BROK	1	0.1223	0.5000	30.0000
90	BROK	1	0.1351	0.6000	30.0000
91	BROK	1	0.1507	0.7000	30.0000
92	BROK	1	0.1723	0.8000	30.0000
93	BROK	1	0.2063	0.9000	30.0000
94	BROK	1	0.0482	0.1000	25.0000
95	BROK	1	0.0695	0.2000	25.0000
96	BROK	1	0.0858	0.3000	25.0000
97	BROK	1	0.1038	0.4000	25.0000
98	BROK	1	0.1211	0.5000	25.0000
99	BROK	1	0.1390	0.6000	25.0000
100	BROK	1	0.1547	0.7000	25.0000
101	BROK	1	0.1737	0.8000	25.5000
102	BROK	1	0.2005	0.9000	25.0000
103	BROK	1	0.0515	0.1000	22.7800

```
104      BROK    1    0.0787    0.2000    22.7800
105      BROK    1    0.0953    0.3000    22.7800
106      BROK    1    0.1086    0.4000    22.7800
107      BROK    1    0.1223    0.5000    22.7800
108      BROK    1    0.1416    0.6000    22.7800
109      BROK    1    0.1561    0.7000    22.7800
110      BROK    1    0.1891    0.8000    22.7800
111      BROK    1    0.2346    0.9000    22.7800
112      HITO    1    0.0858    0.2300    30.0000
113      HITO    1    0.1050    0.3500    30.0000
114      HITO    1    0.1236    0.4400    30.0000
115      HITO    1    0.1351    0.5500    30.0000
116      HITO    1    0.1521    0.6400    30.0000
117      HITO    1    0.1792    0.7400    30.0000
118      HITO    1    0.2195    0.8700    30.0000
119      END     1  999.0000  999.0000   999.0000
```

```
HENDERSON-THOMPSON EMC          SORGHUM PROBLEM



  1       DUNS        1       0.0643       0.0500       26.6700
  2       DUNS        1       0.1217       0.3120       26.6700
  3       DUNS        1       0.1537       0.5370       26.6700
  4       DUNS        1       0.0459       0.0240       37.7800
  5       DUNS        1       0.0552       0.0500       37.7800
  6       DUNS        1       0.0679       0.1190       37.7800
  7       DUNS        1       0.0951       0.2130       37.7800
  8       DUNS        1       0.1127       0.3140       37.7800
  9       DUNS        1       0.1292       0.4320       37.7800
 10       DUNS        1       0.1446       0.5360       37.7800
 11       DUNS        1       0.1707       0.6730       37.7800
 12       DUNS        1       0.1855       0.7860       37.7800
 13       BROK        1       0.0893       0.2000       -1.1000
 14       BROK        1       0.1123       0.3000       -1.1000
 15       BROK        1       0.1261       0.4000       -1.1000
 16       BROK        1       0.1403       0.5000       -1.1000
 17       BROK        1       0.1561       0.6000       -1.1000
 18       BROK        1       0.1696       0.7000       -1.1000
 19       BROK        1       0.1876       0.8000       -1.1000
 20       BROK        1       0.0811       0.2000       15.6000
 21       BROK        1       0.1050       0.3000       15.6000
 22       BROK        1       0.1198       0.4000       15.6000
 23       BROK        1       0.1338       0.5000       15.6000
 24       BROK        1       0.1481       0.6000       15.6000
 25       BROK        1       0.1628       0.7000       15.6000
 26       BROK        1       0.1834       0.8000       15.6000
 27       BROK        1       0.0460       0.1000       25.0000
 28       BROK        1       0.0787       0.2000       25.0000
 29       BROK        1       0.0941       0.3000       25.0000
 30       BROK        1       0.1086       0.4000       25.0000
 31       BROK        1       0.1236       0.5000       25.0000
 32       BROK        1       0.1364       0.6000       25.0000
 33       BROK        1       0.1601       0.7000       25.0000
 34       BROK        1       0.1876       0.8000       25.0000
 35       BROK        1       0.2315       0.9000       25.0000
 36       BROK        1       0.0753       0.2000       32.2000
 37       BROK        1       0.0953       0.3000       32.2000
 38       BROK        1       0.1136       0.4000       32.2000
 39       BROK        1       0.1338       0.5000       32.2000
 40       BROK        1       0.1390       0.6000       32.2000
 41       BROK        1       0.1507       0.7000       32.2000
 42       BROK        1       0.1737       0.8000       32.2000
 43       BROK        1       0.0707       0.2000       48.9000
```

```
44      BROK     1     0.0870     0.3000    48.9000
45      BROK     1     0.1038     0.4000    48.9000
46      BROK     1     0.1198     0.5000    48.9000
47      BROK     1     0.1312     0.6000    48.9000
48      BROK     1     0.1455     0.7000    48.9000
49      BROK     1     0.1669     0.8000    48.9000
50      BROK     1     0.0730     0.1000     4.4000
51      BROK     1     0.0929     0.2000     4.4000
52      BROK     1     0.1074     0.3000     4.4000
53      BROK     1     0.1236     0.4000     4.4000
54      BROK     1     0.1403     0.5000     4.4000
55      BROK     1     0.1587     0.6000     4.4000
56      BROK     1     0.1806     0.7000     4.4000
57      BROK     1     0.2092     0.8000     4.4000
58      BROK     1     0.0638     0.1000    21.1000
59      BROK     1     0.0834     0.2000    21.1000
60      BROK     1     0.1001     0.3000    21.1000
61      BROK     1     0.1274     0.4000    21.1000
62      BROK     1     0.1299     0.5000    21.1000
63      BROK     1     0.1468     0.6000    21.1000
64      BROK     1     0.1655     0.7000    21.1000
65      BROK     1     0.1905     0.8000    21.1000
66      BROK     1     0.2346     0.9000    21.1000
67      BROK     1     0.0526     0.1000    32.2000
68      BROK     1     0.0753     0.2000    32.2000
69      BROK     1     0.0917     0.3000    32.2000
70      BROK     1     0.1062     0.4000    32.2000
71      BROK     1     0.1211     0.5000    32.2000
72      BROK     1     0.1364     0.6000    32.2000
73      BROK     1     0.1521     0.7000    32.2000
74      BROK     1     0.1723     0.8000    32.2000
75      BROK     1     0.2048     0.9000    32.2000
76      END      1   999.0000   999.0000   999.0000
```

```
HENDERSON-THOMPSON EMC          BARLEY PROBLEM




 1        PIXE     1      0.0770      0.1780      5.0000
 2        PIXE     1      0.1190      0.4350      5.0000
 3        PIXE     1      0.1500      0.6320      5.0000
 4        PIXE     1      0.1950      0.8490      5.0000
 5        PIXE     1      0.2400      0.9500      5.0000
 6        PIXE     1      0.0770      0.2080     15.0000
 7        PIXE     1      0.1190      0.4650     15.0000
 8        PIXE     1      0.1500      0.6700     15.0000
 9        PIXE     1      0.1950      0.8610     15.0000
10        PIXE     1      0.2400      0.9390     15.0000
11        PIXE     1      0.0770      0.2380     25.0000
12        PIXE     1      0.1190      0.5150     25.0000
13        PIXE     1      0.1500      0.7170     25.0000
14        PIXE     1      0.1950      0.8820     25.0000
15        PIXE     1      0.2400      0.9480     25.0000
16        PIXE     1      0.0940      0.3280      5.0000
17        PIXE     1      0.1320      0.5830      5.0000
18        PIXE     1      0.1770      0.7830      5.0000
19        PIXE     1      0.2150      0.9020      5.0000
20        PIXE     1      0.2650      0.9590      5.0000
21        PIXE     1      0.0940      0.3550     15.0000
22        PIXE     1      0.1320      0.6180     15.0000
23        PIXE     1      0.1770      0.8070     15.0000
24        PIXE     1      0.2150      0.9080     15.0000
25        PIXE     1      0.2650      0.9570     15.0000
26        PIXE     1      0.0940      0.3870     25.0000
27        PIXE     1      0.1320      0.6620     25.0000
28        PIXE     1      0.1770      0.8360     25.0000
29        PIXE     1      0.2150      0.9240     25.0000
30        PIXE     1      0.2650      0.9570     25.0000
31        END      1    999.0000    999.0000    999.0000
```

```
       HENDERSON-THOMPSON EMC        PEANUT KERNEL PROBLEM


   1       KOS       1      0.0423      0.3000      38.0000
   2       KOS       1      0.0472      0.4500      38.0000
   3       KOS       1      0.0580      0.6000      38.0000
   4       KOS       1      0.0651      0.7500      38.0000
   5       KOS       1      0.1152      0.9000      38.0000
   6       KOS       1      0.0443      0.3000      30.0000
   7       KOS       1      0.0488      0.4500      30.0000
   8       KOS       1      0.0630      0.6000      30.0000
   9       KOS       1      0.0733      0.7500      30.0000
  10       KOS       1      0.1238      0.9000      30.0000
  11       KOS       1      0.0457      0.3000      25.0000
  12       KOS       1      0.0537      0.4500      25.0000
  13       KOS       1      0.0661      0.6000      25.0000
  14       KOS       1      0.0771      0.7500      25.0000
  15       KOS       1      0.1369      0.9000      25.0000
  16       KOS       1      0.0496      0.3000      20.0000
  17       KOS       1      0.0574      0.4500      20.0000
  18       KOS       1      0.0666      0.6000      20.0000
  19       KOS       1      0.0904      0.7500      20.0000
  20       KOS       1      0.1492      0.9000      20.0000
  21       KOS       1      0.0516      0.3000      15.0000
  22       KOS       1      0.0618      0.4500      15.0000
  23       KOS       1      0.0695      0.6000      15.0000
  24       KOS       1      0.0976      0.7500      15.0000
  25       KOS       1      0.1557      0.9000      15.0000
  26       KOS       1      0.0559      0.3000      10.0000
  27       KOS       1      0.0673      0.4500      10.0000
  28       KOS       1      0.0741      0.6000      10.0000
  29       KOS       1      0.1029      0.7500      10.0000
  30       KOS       1      0.1658      0.9000      10.0000
  31       KOS       1      0.0422      0.3000      38.0000
  32       KOS       1      0.0487      0.4500      38.0000
  33       KOS       1      0.0612      0.6000      38.0000
  34       KOS       1      0.0844      0.7500      38.0000
  35       KOS       1      0.1212      0.9000      38.0000
  36       KOS       1      0.0452      0.3000      30.0000
  37       KOS       1      0.0535      0.4500      30.0000
  38       KOS       1      0.0639      0.6000      30.0000
  39       KOS       1      0.0857      0.7500      30.0000
  40       KOS       1      0.1256      0.9000      30.0000
  41       KOS       1      0.0473      0.3000      25.0000
  42       KOS       1      0.0578      0.4500      25.0000
  43       KOS       1      0.0664      0.6000      25.0000
```

44	KOS	1	0.0884	0.7500	25.0000
45	KOS	1	0.1373	0.9000	25.0000
46	KOS	1	0.0503	0.3000	20.0000
47	KOS	1	0.0611	0.4500	20.0000
48	KOS	1	0.0677	0.6000	20.0000
49	KOS	1	0.0904	0.7500	20.0000
50	KOS	1	0.1492	0.9000	20.0000
51	KOS	1	0.0540	0.3000	15.0000
52	KOS	1	0.0629	0.4500	15.0000
53	KOS	1	0.0697	0.6000	15.0000
54	KOS	1	0.0976	0.7500	15.0000
55	KOS	1	0.1618	0.9000	15.0000
56	KOS	1	0.0627	0.3000	10.0000
57	KOS	1	0.0675	0.4500	10.0000
58	KOS	1	0.0752	0.6000	10.0000
59	KOS	1	0.1079	0.7500	10.0000
60	KOS	1	0.1662	0.9000	10.0000
61	PIXE	1	0.0530	0.5250	15.0000
62	PIXE	1	0.0780	0.7190	15.0000
63	PIXE	1	0.0990	0.8300	15.0000
64	PIXE	1	0.1270	0.8810	15.0000
65	PIXE	1	0.1660	0.9300	15.0000
66	PIXE	1	0.0530	0.5460	25.0000
67	PIXE	1	0.0780	0.7350	25.0000
68	PIXE	1	0.0990	0.8370	25.0000
69	PIXE	1	0.1270	0.8870	25.0000
70	PIXE	1	0.1660	0.9380	25.0000
71	PIXE	1	0.0530	0.5670	35.0000
72	PIXE	1	0.0780	0.7410	35.0000
73	PIXE	1	0.0990	0.8380	35.0000
74	PIXE	1	0.1270	0.8890	35.0000
75	PIXE	1	0.1660	0.9320	35.0000
76	PIXE	1	0.0390	0.3190	15.0000
77	PIXE	1	0.0560	0.5730	15.0000
78	PIXE	1	0.0840	0.7680	15.0000
79	PIXE	1	0.1120	0.8630	15.0000
80	PIXE	1	0.1550	0.9160	15.0000
81	PIXE	1	0.0390	0.3470	25.0000
82	PIXE	1	0.0560	0.5960	25.0000
83	PIXE	1	0.0840	0.7760	25.0000
84	PIXE	1	0.1120	0.8660	25.0000
85	PIXE	1	0.1550	0.9260	25.0000
86	PIXE	1	0.0390	0.3690	35.0000
87	PIXE	1	0.0560	0.6060	35.0000
88	PIXE	1	0.0840	0.7780	35.0000
89	PIXE	1	0.1120	0.8680	35.0000
90	PIXE	1	0.1550	0.9190	35.0000
91	TROG	1	0.0376	0.3700	44.4400
92	TROG	1	0.0184	0.0400	45.5600
93	TROG	1	0.0707	0.5800	52.2200
94	TROG	1	0.0799	0.6900	51.1100
95	TROG	1	0.0226	0.0300	45.5600
96	TROG	1	0.0454	0.3200	43.8900
97	TROG	1	0.1008	0.8200	32.2200
98	TROG	1	0.0651	0.6500	32.2200
99	TROG	1	0.0313	0.2000	31.6700
100	TROG	1	0.0443	0.5900	30.5600
101	TROG	1	0.0351	0.0800	21.1100
102	TROG	1	0.0579	0.4000	20.5600
103	TROG	1	0.1328	0.8700	20.5600

```
 104        TROG      1     0.0437     0.2000     21.6700
 105        TROG      1     0.0744     0.4700     22.7800
 106        TROG      1     0.0264     0.3700     44.4400
 107        TROG      1     0.0170     0.0400     45.5600
 108        TROG      1     0.0590     0.5800     52.2200
 109        TROG      1     0.0556     0.6900     51.1100
 110        TROG      1     0.0200     0.0300     45.5600
 111        TROG      1     0.0430     0.3200     43.8900
 112        TROG      1     0.0204     0.1000     44.4400
 113        TROG      1     0.0493     0.4300     46.6700
 114        TROG      1     0.0363     0.7800     31.6700
 115        TROG      1     0.0546     0.7100     31.6700
 116        TROG      1     0.0245     0.1200     31.1100
 117        TROG      1     0.0490     0.4000     32.7800
 118        TROG      1     0.0970     0.6600     32.7800
 119        TROG      1     0.0250     0.1300     30.5600
 120        TROG      1     0.0530     0.4900     31.1100
 121        TROG      1     0.1150     0.8300     33.3300
 122        TRCG      1     0.0263     0.2000     31.6700
 123        TROG      1     0.0301     0.5900     30.5600
 124        TROG      1     0.0350     0.0800     21.1100
 125        TROG      1     0.0568     0.4000     20.5600
 126        TROG      1     0.1182     0.8700     20.5600
 127        TROG      1     0.0399     0.2000     21.6700
 128        TROG      1     0.0695     0.4700     22.7800
 129        TROG      1     0.0288     0.3700     44.4400
 130        TROG      1     0.0148     0.0400     45.5600
 131        TROG      1     0.0603     0.5800     52.2200
 132        TROG      1     0.0649     0.6900     51.1100
 133        TROG      1     0.0205     0.0300     45.5600
 134        TROG      1     0.0435     0.3200     43.8900
 135        TROG      1     0.0302     0.2000     31.6700
 136        TROG      1     0.0647     0.5900     30.5600
 137        TROG      1     0.0333     0.0800     21.1100
 138        TROG      1     0.0548     0.4000     20.5600
 139        TROG      1     0.1067     0.8700     20.5600
 140        TROG      1     0.0383     0.2000     21.6700
 141        TROG      1     0.0660     0.4700     22.7800
 142        END       1   999.0000   999.0000    999.0000
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HENDERSON-THOMPSON EMC          PEANUT POD PROBLEM


 1      TROG      1      0.0234      0.0400      45.0000
 2      TROG      1      0.0957      0.5900      51.1100
 3      TROG      1      0.0464      0.3700      44.4400
 4      TROG      1      0.0240      0.0400      45.0000
 5      TROG      1      0.0787      0.5900      51.1100
 6      TROG      1      0.1040      0.6900      51.1100
 7      TROG      1      0.0241      0.0300      45.5600
 8      TROG      1      0.0537      0.3200      43.8900
 9      TROG      1      0.0706      0.6900      51.1100
10      TROG      1      0.0232      0.0300      45.5600
11      TROG      1      0.0532      0.3200      43.8900
12      TROG      1      0.0430      0.7800      31.6700
13      TROG      1      0.0660      0.7100      31.6700
14      TROG      1      0.2000      0.7000      30.5600
15      TROG      1      0.2087      0.9400      33.3300
16      TROG      1      0.1203      0.7000      30.5600
17      TROG      1      0.1205      0.8200      32.2200
18      TROG      1      0.0930      0.6500      32.2200
19      TROG      1      0.0372      0.7200      36.6700
20      TROG      1      0.1008      0.5400      31.6700
21      TROG      1      0.1621      0.9600      28.3300
22      TROG      1      0.0423      0.2100      31.6700
23      TROG      1      0.0819      0.6100      30.5600
24      TROG      1      0.0340      0.1900      28.8900
25      TROG      1      0.0968      0.6100      30.5600
26      TROG      1      0.0374      0.0900      21.1100
27      TROG      1      0.0807      0.3900      20.5600
28      TROG      1      0.0570      0.3900      20.5600
29      TROG      1      0.0592      0.7700      22.2200
30      TROG      1      0.1758      0.5200      22.7800
31      TROG      1      0.1471      0.2700      22.7800
32      TROG      1      0.0057      0.1700      22.2200
33      TROG      1      0.0876      0.5200      22.7800
34      TROG      1      0.0343      0.2100      31.6700
35      TROG      1      0.0762      0.6100      30.5600
36      TROG      1      0.0342      0.1900      31.6700
37      TROG      1      0.0886      0.6400      30.5600
38      TROG      1      0.0369      0.0900      21.1100
39      TROG      1      0.0562      0.3900      20.5600
40      TROG      1      0.1364      0.9990      21.1100
41      TROG      1      0.0334      0.0900      21.1100
42      TROG      1      0.0673      0.3900      20.5600
43      TROG      1      0.0814      0.1700      22.2200
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 44      TROG      1      0.1832      0.5200     22.7800
 45      TROG      1      0.1290      0.7700     22.7800
 46      TROG      1      0.0251      0.1700     22.2200
 47      TROG      1      0.0764      0.5200     22.7800
 48      TROG      1      0.0505      0.3700     44.4400
 49      TROG      1      0.0222      0.0400     45.0000
 50      TROG      1      0.0866      0.5900     51.1100
 51      TROG      1      0.0465      0.3700     44.4400
 52      TROG      1      0.0189      0.0400     45.0000
 53      TROG      1      0.0704      0.5900     51.1100
 54      TROG      1      0.0844      0.6900     51.1100
 55      TROG      1      0.0218      0.0300     45.5600
 56      TROG      1      0.0510      0.3200     43.8900
 57      TROG      1      0.0716      0.6900     51.1100
 58      TROG      1      0.0209      0.0300     45.5600
 59      TROG      1      0.0465      0.3200     43.8900
 60      TROG      1      0.0218      0.1000     44.4400
 61      TROG      1      0.0590      0.4300     46.6700
 62      TROG      1      0.0283      0.7800     31.6700
 63      TROG      1      0.0677      0.7100     31.6700
 64      TROG      1      0.0265      0.1200     31.1100
 65      TROG      1      0.0600      0.4000     32.7800
 66      TROG      1      0.1260      0.6600     32.7800
 67      TROG      1      0.0290      0.1300     30.5600
 68      TROG      1      0.0646      0.4900     31.1100
 69      TROG      1      0.1450      0.8300     33.3300
 70      TROG      1      0.1444      0.7200     36.6700
 71      TROG      1      0.1118      0.5400     31.6700
 72      TROG      1      0.1505      0.9600     28.3300
 73      TROG      1      0.0469      0.3700     44.4400
 74      TROG      1      0.0208      0.0400     45.0000
 75      TROG      1      0.0857      0.5900     51.1100
 76      TROG      1      0.0466      0.3700     44.4400
 77      TROG      1      0.0189      0.0400     45.0000
 78      TROG      1      0.0711      0.5900     51.1100
 79      TROG      1      0.0738      0.6900     51.1100
 80      TROG      1      0.0215      0.0300     45.5600
 81      TROG      1      0.0487      0.3200     43.8900
 82      TROG      1      0.0694      0.6900     51.1100
 83      TROG      1      0.0215      0.0300     45.5600
 84      TROG      1      0.0458      0.3200     43.8900
 85      TROG      1      0.1620      0.8200     32.2200
 86      TROG      1      0.1071      0.6500     32.2200
 87      TROG      1      0.1636      0.9400     33.3300
 88      TROG      1      0.1092      0.7000     30.5600
 89      TROG      1      0.1516      0.9600     28.3300
 90      TROG      1      0.0324      0.2100     31.6700
 91      TROG      1      0.0758      0.6100     30.5600
 92      TROG      1      0.0317      0.1900     31.6700
 93      TROG      1      0.0892      0.6100     30.5600
 94      TROG      1      0.0348      0.0900     21.1100
 95      TROG      1      0.0691      0.3900     20.5600
 96      TROG      1      0.0314      0.0900     21.1100
 97      TROG      1      0.0543      0.3900     20.5600
 98      TROG      1      0.0464      0.1700     22.2200
 99      TROG      1      0.1482      0.5200     22.7800
100      TROG      1      0.1252      0.7900     22.7800
101      TROG      1      0.0479      0.1700     22.2200
102      TROG      1      0.0742      0.5200     22.7800
103      END       1    999.0000    999.0000    999.0000
```

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              HENDERSON-THOMPSON EMC        EDIBLE BEANS PROBLEM



     1        KOS        1        0.0797        0.3000        38.0000
     2        KOS        1        0.0917        0.4500        38.0000
     3        KOS        1        0.1137        0.6000        38.0000
     4        KOS        1        0.1547        0.7500        38.0000
     5        KOS        1        0.2231        0.9000        38.0000
     6        KOS        1        0.0853        0.3000        30.0000
     7        KOS        1        0.1005        0.4500        30.0000
     8        KOS        1        0.1227        0.6000        30.0000
     9        KOS        1        0.1597        0.7500        30.0000
    10        KOS        1        0.2413        0.9000        30.0000
    11        KOS        1        0.0885        0.3000        25.0000
    12        KOS        1        0.1044        0.4500        25.0000
    13        KOS        1        0.1245        0.6000        25.0000
    14        KOS        1        0.1618        0.7500        25.0000
    15        KOS        1        0.2549        0.9000        25.0000
    16        KOS        1        0.0948        0.3000        20.0000
    17        KOS        1        0.1123        0.4500        20.0000
    18        KOS        1        0.1348        0.6000        20.0000
    19        KOS        1        0.1662        0.7500        20.0000
    20        KOS        1        0.2682        0.9000        20.0000
    21        KOS        1        0.1011        0.3000        15.0000
    22        KOS        1        0.1216        0.4500        15.0000
    23        KOS        1        0.1383        0.6000        15.0000
    24        KOS        1        0.1765        0.7500        15.0000
    25        KOS        1        0.2902        0.9000        15.0000
    26        KOS        1        0.1115        0.3000        10.0000
    27        KOS        1        0.1264        0.4500        10.0000
    28        KOS        1        0.1551        0.6000        10.0000
    29        KOS        1        0.1915        0.7500        10.0000
    30        KOS        1        0.2995        0.9000        10.0000
    31        KOS        1        0.0808        0.3000        38.0000
    32        KOS        1        0.1011        0.4500        38.0000
    33        KOS        1        0.1306        0.6000        38.0000
    34        KOS        1        0.1555        0.7500        38.0000
    35        KOS        1        0.2563        0.9000        38.0000
    36        KOS        1        0.0885        0.3000        30.0000
    37        KOS        1        0.1099        0.4500        30.0000
    38        KOS        1        0.1380        0.6000        30.0000
    39        KOS        1        0.1732        0.7500        30.0000
    40        KOS        1        0.2700        0.9000        30.0000
    41        KOS        1        0.0943        0.3000        25.0000
    42        KOS        1        0.1148        0.4500        25.0000
    43        KOS        1        0.1526        0.6000        25.0000
```

```
 44      KOS     1    0.1860    0.7500    25.0000
 45      KOS     1    0.2958    0.9000    25.0000
 46      KOS     1    0.0981    0.3000    20.0000
 47      KOS     1    0.1186    0.4500    20.0000
 48      KOS     1    0.1628    0.6000    20.0000
 49      KOS     1    0.2044    0.7500    20.0000
 50      KOS     1    0.3104    0.9000    20.0000
 51      KOS     1    0.1062    0.3000    15.0000
 52      KOS     1    0.1233    0.4500    15.0000
 53      KOS     1    0.1762    0.6000    15.0000
 54      KOS     1    0.2174    0.7500    15.0000
 55      KOS     1    0.1109    0.3000    10.0000
 56      KOS     1    0.1322    0.4500    10.0000
 57      KOS     1    0.1891    0.6000    10.0000
 58      KOS     1    0.2238    0.7500    10.0000
 59      PIXE    1    0.1040    0.3730     5.0000
 60      PIXE    1    0.1390    0.5970     5.0000
 61      PIXE    1    0.1890    0.8000     5.0000
 62      PIXE    1    0.2210    0.8750     5.0000
 63      PIXE    1    0.2470    0.9130     5.0000
 64      PIXE    1    0.1040    0.3980    15.0000
 65      PIXE    1    0.1390    0.6130    15.0000
 66      PIXE    1    0.1890    0.8100    15.0000
 67      PIXE    1    0.2210    0.8760    15.0000
 68      PIXE    1    0.2470    0.9140    15.0000
 69      PIXE    1    0.1040    0.4330    25.0000
 70      PIXE    1    0.1390    0.6470    25.0000
 71      PIXE    1    0.1890    0.8330    25.0000
 72      PIXE    1    0.2210    0.8850    25.0000
 73      PIXE    1    0.2470    0.9220    25.0000
 74      PIXE    1    0.0960    0.3200     5.0000
 75      PIXE    1    0.1370    0.5870     5.0000
 76      PIXE    1    0.1750    0.7680     5.0000
 77      PIXE    1    0.2100    0.8660     5.0000
 78      PIXE    1    0.2540    0.9200     5.0000
 79      PIXE    1    0.0960    0.3430    15.0000
 80      PIXE    1    0.1370    0.6170    15.0000
 81      PIXE    1    0.1750    0.7820    15.0000
 82      PIXE    1    0.2100    0.8660    15.0000
 83      PIXE    1    0.2540    0.9210    15.0000
 84      PIXE    1    0.0960    0.3680    25.0000
 85      PIXE    1    0.1370    0.6250    25.0000
 86      PIXE    1    0.1750    0.7980    25.0000
 87      PIXE    1    0.2100    0.8770    25.0000
 88      PIXE    1    0.2540    0.9250    25.0000
 89      GUIO    1    0.2323    0.7920    21.1100
 90      GUIO    1    0.1870    0.6950    21.1100
 91      GUIO    1    0.1561    0.5910    21.1100
 92      GUIO    1    0.1293    0.4860    21.1100
 93      GUIO    1    0.1168    0.3890    21.1100
 94      GUIO    1    0.0938    0.3010    21.1100
 95      GUIO    1    0.0861    0.2040    21.1100
 96      GUIO    1    0.0773    0.1160    21.1100
 97      GUIO    1    0.1846    0.6900    26.6700
 98      GUIO    1    0.1506    0.5900    26.6700
 99      GUIO    1    0.1243    0.4860    26.6700
100      GUIO    1    0.1032    0.3900    26.6700
101      GUIO    1    0.0904    0.3020    26.6700
102      GUIO    1    0.0786    0.2070    26.6700
103      GUIO    1    0.0689    0.1210    26.6700
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104	GUIO	1	0.1833	0.6940	32.2200
105	GUIO	1	0.1496	0.5930	32.2200
106	GUIO	1	0.1200	0.4900	32.2200
107	GUIO	1	0.1023	0.3940	32.2200
108	GUIO	1	0.0894	0.3060	32.2200
109	GUIO	1	0.0773	0.2120	32.2200
110	GUIO	1	0.0674	0.1230	32.2200
111	GUIO	1	0.1829	0.6980	37.7800
112	GUIO	1	0.1440	0.5980	37.7800
113	GUIO	1	0.1184	0.4960	37.7800
114	GUIO	1	0.1016	0.4010	37.7800
115	GUIO	1	0.0880	0.3120	37.7800
116	GUIO	1	0.0765	0.2170	37.7800
117	GUIO	1	0.0629	0.1270	37.7800
118	GUIO	1	0.2295	0.7920	21.1100
119	GUIO	1	0.1777	0.6950	21.1100
120	GUIO	1	0.1412	0.5910	21.1100
121	GUIO	1	0.1161	0.4860	21.1100
122	GUIO	1	0.1022	0.3890	21.1100
123	GUIO	1	0.0838	0.3010	21.1100
124	GUIO	1	0.0732	0.2040	21.1100
125	GUIO	1	0.2269	0.7860	26.6700
126	GUIO	1	0.1760	0.6900	26.6700
127	GUIO	1	0.1408	0.5900	26.6700
128	GUIO	1	0.1151	0.4860	26.6700
129	GUIO	1	0.1012	0.3900	26.6700
130	GUIO	1	0.0827	0.3020	26.6700
131	GUIO	1	0.0728	0.2070	26.6700
132	GUIO	1	0.2253	0.7900	32.2200
133	GUIO	1	0.1729	0.6940	32.2200
134	GUIO	1	0.1400	0.5930	32.2200
135	GUIO	1	0.1144	0.4900	32.2200
136	GUIO	1	0.1008	0.3940	32.2200
137	GUIO	1	0.0817	0.3060	32.2200
138	GUIO	1	0.2208	0.7920	37.7800
139	GUIO	1	0.1716	0.6980	37.7800
140	GUIO	1	0.1400	0.5980	37.7800
141	GUIO	1	0.1135	0.4960	37.7800
142	GUIO	1	0.0943	0.4010	37.7800
143	GUIO	1	0.0807	0.3120	37.7800
144	GUIO	1	0.0705	0.2170	37.7800
145	GUIO	1	0.2235	0.7920	21.1100
146	GUIO	1	0.1888	0.6950	21.1100
147	GUIO	1	0.1405	0.5910	21.1100
148	GUIO	1	0.1279	0.4860	21.1100
149	GUIO	1	0.1076	0.3890	21.1100
150	GUIO	1	0.0991	0.3010	21.1100
151	GUIO	1	0.0866	0.2040	21.1100
152	GUIO	1	0.0753	0.1160	21.1100
153	GUIO	1	0.1759	0.6900	26.6700
154	GUIO	1	0.1429	0.5900	26.6700
155	GUIO	1	0.1206	0.4860	26.6700
156	GUIO	1	0.1000	0.3900	26.6700
157	GUIO	1	0.0869	0.3020	26.6700
158	GUIO	1	0.0778	0.2070	26.6700
159	GUIO	1	0.0653	0.1210	26.6700
160	GUIO	1	0.1828	0.6940	32.2200
161	GUIO	1	0.1433	0.5930	32.2200
162	GUIO	1	0.1166	0.4900	32.2200
163	GUIO	1	0.1011	0.3940	32.2200

```
164      GUIO     1     0.0881     0.3060     32.2200
165      GUIO     1     0.0733     0.2120     32.2200
166      GUIO     1     0.0643     0.1230     32.2200
167      GUIO     1     0.1837     0.6980     37.7800
168      GUIO     1     0.1424     0.5980     37.7800
169      GUIO     1     0.1195     0.4960     37.7800
170      GUIO     1     0.0944     0.4010     37.7800
171      GUIO     1     0.0891     0.3120     37.7800
172      GUIO     1     0.0639     0.2170     37.7800
173      GUIO     1     0.0559     0.1270     37.7800
174      GUIO     1     0.1778     0.6980     37.7800
175      GUIO     1     0.1339     0.5980     37.7800
176      GUIO     1     0.1148     0.4960     37.7800
177      GUIO     1     0.0935     0.4010     37.7800
178      GUIO     1     0.0774     0.2170     37.7800
179      GUIO     1     0.2150     0.7920     21.1100
180      GUIO     1     0.1750     0.6950     21.1100
181      GUIO     1     0.1365     0.5910     21.1100
182      GUIO     1     0.1100     0.4860     21.1100
183      GUIO     1     0.0935     0.3890     21.1100
184      GUIO     1     0.0889     0.3010     21.1100
185      GUIO     1     0.0750     0.2040     21.1100
186      GUIO     1     0.1952     0.7860     26.6700
187      GUIO     1     0.1693     0.6900     26.6700
188      GUIO     1     0.1361     0.5900     26.6700
189      GUIO     1     0.1106     0.4860     26.6700
190      GUIO     1     0.0968     0.3900     26.6700
191      GUIO     1     0.0835     0.3020     26.6700
192      GUIO     1     0.0714     0.2070     26.6700
193      GUIO     1     0.2177     0.7900     32.2200
194      GUIO     1     0.1790     0.6940     32.2200
195      GUIO     1     0.1404     0.5930     32.2200
196      GUIO     1     0.1156     0.4900     32.2200
197      GUIO     1     0.1007     0.3940     32.2200
198      GUIO     1     0.0846     0.3060     32.2200
199      GUIO     1     0.0719     0.2120     32.2200
200      GUIO     1     0.0815     0.3120     37.7800
201      END      1   999.0000   999.0000    999.0000
```

```
          HENDERSON-THOMPSON EMC        DURHAM WHEAT PROBLEM




   1      HUBB     1     0.0613      0.1180     30.0000
   2      HUBB     1     0.0830      0.2200     30.0000
   3      HUBB     1     0.1010      0.3280     30.0000
   4      HUBB     1     0.1181      0.4350     30.0000
   5      HUBB     1     0.1387      0.5630     30.0000
   6      HUBB     1     0.1539      0.6460     30.0000
   7      HUBB     1     0.1747      0.7560     30.0000
   8      HUBB     1     0.0653      0.1200     25.0000
   9      HUBB     1     0.0877      0.2260     25.0000
  10      HUBB     1     0.1045      0.3320     25.0000
  11      HUBB     1     0.1218      0.4380     25.0000
  12      HUBB     1     0.1440      0.5700     25.0000
  13      HUBB     1     0.1586      0.6600     25.0000
  14      HUBB     1     0.1805      0.7580     25.0000
  15      HUBB     1     0.0580      0.1170     35.0000
  16      HUBB     1     0.0764      0.2100     35.0000
  17      HUBB     1     0.0946      0.3250     35.0000
  18      HUBB     1     0.1122      0.4340     35.0000
  19      HUBB     1     0.1293      0.5460     35.0000
  20      HUBB     1     0.1430      0.6320     35.0000
  21      HUBB     1     0.1632      0.7550     35.0000
  22      COLE     1     0.0537      0.1000     25.0000
  23      COLE     1     0.0799      0.2000     25.0000
  24      COLE     1     0.0929      0.3000     25.0000
  25      COLE     1     0.1038      0.4000     25.0000
  26      COLE     1     0.1173      0.5000     25.0000
  27      COLE     1     0.1299      0.6000     25.0000
  28      COLE     1     0.1507      0.7000     25.0000
  29      COLE     1     0.1820      0.8000     25.0000
  30      COLE     1     0.2392      0.9000     25.0000
  31      END      1   999.0000    999.0000    999.0000
```

```
 44      COLE      1     [illegible]
 45      COLE      1     [illegible]
 46      COLE      1     [illegible]
 47      COLE      1     [illegible]
 48      COLE      1     [illegible]
 49
 50
 51
 52 HENDERSON-THOMPSON EMC        SOFT WHEAT PROBLEM
 53
 54
 55
 56
 57
 58
  1      GANE      1     0.0770      0.1000     10.0000
  2      GANE      1     0.1200      0.3000     10.0000
  3      GANE      1     0.1530      0.5000     10.0000
  4      GANE      1     0.1800      0.7000     10.0000
  5      GANE      1     0.2050      0.8000     10.0000
  6      HUBB      1     0.0661      0.1180     30.0000
  7      HUBB      1     0.0893      0.2200     30.0000
  8      HUBB      1     0.1074      0.3280     30.0000
  9      HUBB      1     0.1244      0.4350     30.0000
 10      HUBB      1     0.1446      0.5630     30.0000
 11      HUBB      1     0.1625      0.6460     30.0000
 12      HUBB      1     0.1837      0.7560     30.0000
 13      HUBB      1     0.0701      0.1200     25.0000
 14      HUBB      1     0.0936      0.2260     25.0000
 15      HUBB      1     0.1098      0.3320     25.0000
 16      HUBB      1     0.1268      0.4380     25.0000
 17      HUBB      1     0.1504      0.5700     25.0000
 18      HUBB      1     0.1673      0.6600     25.0000
 19      HUBB      1     0.1874      0.7580     25.0000
 20      THOM      1     0.1274      0.4000     -6.6600
 21      THOM      1     0.1468      0.5000     -6.6600
 22      THOM      1     0.1641      0.6000     -6.6600
 23      THOM      1     0.1806      0.7000     -6.6600
 24      THOM      1     0.2048      0.8000     -6.6600
 25      THOM      1     0.1236      0.4000      0.0
 26      THOM      1     0.1390      0.5000      0.0
 27      THOM      1     0.1561      0.6000      0.0
 28      THOM      1     0.1723      0.7000      0.0
 29      THOM      1     0.1933      0.8000      0.0
 30      THOM      1     0.1136      0.4000     10.0000
 31      THOM      1     0.1325      0.5000     10.0000
 32      THOM      1     0.1507      0.6000     10.0000
 33      THOM      1     0.1682      0.7000     10.0000
 34      THOM      1     0.1905      0.8000     10.0000
 35      THOM      1     0.1074      0.4000     21.1100
 36      THOM      1     0.1236      0.5000     21.1100
 37      THOM      1     0.1416      0.6000     21.1100
 38      THOM      1     0.1628      0.7000     21.1100
 39      COLE      1     0.0430      0.1000     25.0000
 40      COLE      1     0.0720      0.2000     25.0000
 41      COLE      1     0.0860      0.3000     25.0000
 42      COLE      1     0.0970      0.4000     25.0000
 43      COLE      1     0.1090      0.5000     25.0000
```

```
44      COLE     1      0.1190      0.6000      25.0000
45      COLE     1      0.1360      0.7000      25.0000
46      COLE     1      0.1570      0.8000      25.0000
47      COLE     1      0.1970      0.9000      25.0000
48      COLE     1      0.2560      0.9900      25.0000
49      COLE     1      0.0520      0.1000      25.0000
50      COLE     1      0.0750      0.2000      25.0000
51      COLE     1      0.0860      0.3000      25.0000
52      COLE     1      0.0940      0.4000      25.0000
53      COLE     1      0.1050      0.5000      25.0000
54      COLE     1      0.1180      0.6000      25.0000
55      COLE     1      0.1370      0.7000      25.0000
56      COLE     1      0.1600      0.8000      25.0000
57      COLE     1      0.1970      0.9000      25.0000
58      END      1    999.0000    999.0000     999.0000
```

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        HENDERSON-THOMPSON EMC        HARD WHEAT PROBLEM



  1      HUBB      1      0.0609      0.1170      35.0000
  2      HUBB      1      0.0798      0.2100      35.0000
  3      HUBB      1      0.0984      0.3250      35.0000
  4      HUBB      1      0.1184      0.4340      35.0000
  5      HUBB      1      0.1307      0.5460      35.0000
  6      HUBB      1      0.1448      0.6320      35.0000
  7      HUBB      1      0.1681      0.7550      35.0000
  8      GANE      1      0.0730      0.1000      10.0000
  9      GANE      1      0.1190      0.3000      10.0000
 10      GANE      1      0.1520      0.5000      10.0000
 11      GANE      1      0.1670      0.7000      10.0000
 12      GANE      1      0.1990      0.8000      10.0000
 13      GANE      1      0.0720      0.1000      20.0000
 14      GANE      1      0.1110      0.3000      20.0000
 15      GANE      1      0.1430      0.5000      20.0000
 16      GANE      1      0.1970      0.8000      20.0000
 17      HUBB      1      0.0677      0.1200      25.0000
 18      HUBB      1      0.0905      0.2260      25.0000
 19      HUBB      1      0.1079      0.3320      25.0000
 20      HUBB      1      0.1251      0.4380      25.0000
 21      HUBB      1      0.1476      0.5700      25.0000
 22      HUBB      1      0.1655      0.6600      25.0000
 23      HUBB      1      0.1834      0.7580      25.0000
 24      COLE      1      0.0460      0.1000      25.0000
 25      COLE      1      0.0776      0.2000      25.0000
 26      COLE      1      0.0929      0.3000      25.0000
 27      COLE      1      0.1086      0.4000      25.0000
 28      COLE      1      0.1249      0.5000      25.0000
 29      COLE      1      0.1429      0.6000      25.0000
 30      COLE      1      0.1614      0.7000      25.0000
 31      COLE      1      0.1891      0.8000      25.0000
 32      COLE      1      0.2453      0.9000      25.0000
 33      BECK      1      0.0421      0.0450      25.0000
 34      BECK      1      0.0602      0.0900      25.0000
 35      BECK      1      0.0646      0.1110      25.0000
 36      BECK      1      0.0830      0.2030      25.0000
 37      BECK      1      0.1068      0.3280      25.0000
 38      BECK      1      0.1395      0.5200      25.0000
 39      BECK      1      0.1660      0.6830      25.0000
 40      BECK      1      0.1852      0.7470      25.0000
 41      COLE      1      0.0460      0.1000      25.0000
 42      COLE      1      0.0776      0.2000      25.0000
 43      COLE      1      0.0929      0.3000      25.0000
```

```
44        COLE     1       0.1074       0.4000       25.0000
45        COLE     1       0.1223       0.5000       25.0000
46        COLE     1       0.1429       0.6000       25.0000
47        COLE     1       0.1614       0.7000       25.0000
48        COLE     1       0.1876       0.8000       25.0000
49        COLE     1       0.2453       0.9000       25.0000
50        BECK     1       0.0471       0.1270       50.0000
51        BECK     1       0.0609       0.2060       50.0000
52        BECK     1       0.0698       0.2860       50.0000
53        BECK     1       0.0907       0.3900       50.0000
54        HUBB     1       0.0655       0.1180       30.0000
55        HUBB     1       0.0889       0.2200       30.0000
56        HUBB     1       0.1068       0.3280       30.0000
57        HUBB     1       0.1235       0.4350       30.0000
58        HUBB     1       0.1400       0.5630       30.0000
59        HUBB     1       0.1515       0.6460       30.0000
60        HUBB     1       0.1722       0.7560       30.0000
61        HUBB     1       0.0636       0.1180       30.0000
62        HUBB     1       0.0873       0.2200       30.0000
63        HUBB     1       0.1057       0.3280       30.0000
64        HUBB     1       0.1242       0.4350       30.0000
65        HUBB     1       0.1414       0.5630       30.0000
66        HUBB     1       0.1549       0.6460       30.0000
67        HUBB     1       0.1699       0.7560       30.0000
68        HUBB     1       0.0652       0.1180       30.0000
69        HUBB     1       0.0912       0.2200       30.0000
70        HUBB     1       0.1066       0.3280       30.0000
71        HUBB     1       0.1238       0.4350       30.0000
72        HUBB     1       0.1439       0.5630       30.0000
73        HUBB     1       0.1610       0.6460       30.0000
74        HUBB     1       0.1809       0.7560       30.0000
75        HUBB     1       0.0644       0.1180       30.0000
76        HUBB     1       0.0875       0.2200       30.0000
77        HUBB     1       0.1050       0.3280       30.0000
78        HUBB     1       0.1215       0.4350       30.0000
79        HUBB     1       0.1416       0.5630       30.0000
80        HUBB     1       0.1585       0.6460       30.0000
81        HUBB     1       0.1790       0.7560       30.0000
82        HUBB     1       0.0647       0.1180       30.0000
83        HUBB     1       0.0865       0.2200       30.0000
84        HUBB     1       0.1044       0.3280       30.0000
85        HUBB     1       0.1222       0.4350       30.0000
86        HUBB     1       0.1423       0.5630       30.0000
87        HUBB     1       0.1585       0.6460       30.0000
88        HUBB     1       0.1781       0.7560       30.0000
89        END      1     999.0000     999.0000      999.0000
```

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NATURAL - AIR GRAIN DRYING: MODELING AND VALIDATION

by

SAMUEL GWINN MAURER

B. S. Kansas State University, 1974

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1977

Rising energy costs have prompted extensive research in natural-air grain drying. This investigation into cost savings is time consuming because of the many uncontrollable factors, ie. weather conditions, grain moisture content, or harvest date. Modeling this drying system allows the experimenter control of these variables and yields the desired results at a reasonable cost. However, model accuracy must first be determined.

The objectives of this study were:

1) to compare natural-air grain drying experimental results with equilibrium model predictions,
2) to develop a statistical method for validation of model accuracy, and
3) to make reasonable modifications to the model as indicated by the results of 1 and 2.

Statistical hypotheses were stated about the ideal model accuracy, and tested with the analysis of variance procedure. This stated analysis of variance 'model' can be extended to choose the best grain drying model from multiple model comparison studies for a particular test. The Bartlett's test for homogeneity of variance is used to test experimental consistency.

A published equilibrium model was tested for accuracy using drying data supplied by the USDA, ARS. The model overpredicted the actual drying rate. A new equilibrium model was developed and another series of drying tests were conducted. The results were that the new equilibrium model was the best of the equilibrium models tested, but it was not an accurate model.

Drying models were then considered as a possible means of accuracy improvement. The new equilibrium model was modified by the addition of the moisture ratio drying rate equation. This model significantly improved the prediction accuracy. Then a new mass diffusion drying model was developed. These three models were tested as a group. We conclude that the mass diffusion model was the most accurate and efficient of the models tested. This model should be used for future energy studies, such as energy conservation or solar energy adaptation.

When the mass diffusion model was developed, equilibrium moisture constants were required. Several authors submitted data for analysis. We found that significant differences exist between varieties of yellow dent corn and author-technique.

As a result of our experience in this work we have also given a definite procedure for natural-air grain drying experiments such that a maximum amount of information will be acquired for model validation purposes.