PARAMETER ESTIMATION METHODOLOGY
IN SELECTED MOISTURE DESORPTION MODELS

By

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ABSTRACT

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Nonlinear data analysis techniques were used to obtain parameter estimates in moisture desorption models for parboiled rice. A model for equilibrium moisture content, EMC, was combined with a thin layer model for moisture content over time and with an Arrhenius form for the drying constant to form a single model of moisture content as a function of time, temperature, relative humidity and initial moisture content.

Moisture loss data were collected at twelve combinations of relative humidity and temperature ranging from 17.3 Celsius to 40.6 Celsius and from 0.24 to 0.53 relative humidity. Two samples of approximately 100 grams dry matter content and initial moisture content of between 0.50 and 0.18 dry basis were studied, simultaneously.

The dry bulb temperature was maintained to within 0.2 degrees Celsius and the relative humidity to about one-half of one percent of the mean value during each test.

The data sets were studied individually, comparing models with from one to four decaying exponential terms, Page's equation, and the diffusion equation for spherical and infinite cylinder geometry. While Page's equation fits the data well, the equation is inadequate. The spherical and infinite cylinder models did not produce acceptable models. The three term exponential was able to predict the data with an error mean square of 0.3 E-6, which was believed to be the approximate accuracy of the data. In the best sets of data the four term exponential was required to explain the measured variation.

Data were selected from the complete data sets on an exponentially increasing time interval, over the first 37 hours. The parameter estimates obtained from subsets of 98 data points, following an algorithm described in this dissertation, predicted the complete data sets of over 2400 data points as well as the parameters estimated using the entire data set. These subsets, with constant temperature and relative humidity, were combined and analyzed to produce the final model covering the initial moisture content, from 0.18 to 0.30. The resulting model, with a residual mean square of 11 E-6, was found to fit the data better than a model with parameters estimated by linear techniques.

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To Patricia

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NOMENCLATURE

A,B,C,F,G,H,I,J = constant parameters

a,b,c,d,g = constant parameters

D = diffusion coefficient, $length^2/time$

Db = dry bulb temperature, Celsius

DS = change in setting of controller

DM = change in moisture content, dry basis, decimal

e = random errors, Gaussian distribution

E[1],E[2],E[3],E[4] = error history at uniform time intervals

EMC = equilibrium moisture content, dry basis, decimal

K = drying constant, 1/time

L = typical length

M = final moisture content of sample, dry basis, decimal

MCd = moisture content, dry basis, decimal

MR = moisture ratio, decimal

Mi = initial moisture content, time=0, dry basis, decimal

M(t) = moisture content at time=t, dry basis, decimal

P1,P2,P3 . . . = parameters fit by regression

R = universal gas constant

R_n	=	roots of Bessel Function of order Ø
R^2	=	coefficient of determination
RH	=	relative humidity, decimal (unless specified)
RHn	=	most recently calculated relative humidity, percent
RHo	=	previously calculated relative humidity, percent
r	=	correlation coefficient
T	=	temperature, degrees C
TK	=	completeness of drying
TMP	=	drying air temperature, degrees K
t	=	time, hours
W	=	residual weight
WCf	=	final weight of can, grams
WCi	=	initial weight of can, grams
WSCf	=	final weight of can and sample, grams
WSCi	=	initial weight of can and sample, grams
WT	=	water temperature, Celsius
Wdm	=	weight of sample dry matter, grams
Ws	=	total weight of the sample, grams
X	=	independent variable
Y	=	dependent variable

1. INTRODUCTION

The advent in recent years of the microcomputer has provided researchers with a tool both to conduct experiments with closer control of important parameters and to collect far more data than was previously possible. The digital computer, while not really new, has also provided researchers with a powerful tool to analyze data in detail and to evaluate models of biological phenomena with which previously it was not practical to work. In addition, more powerful statistical computer programs are available to analyze data, particularly when the models are nonlinear. Modern electronics can provide another valuable tool in the study of the drying of agricultural products.

Drying is one of the oldest methods man has used to preserve food. Most of the drying is and has been solar drying, but due to weather and other factors artificial drying has been of increasing interest. Engineers have become involved in the design and construction of dryers of agricultural products and have been able to improve the artificial drying process in terms of energy efficiency, product quality, operator time and equipment use. There continues to be a great deal of interest in improving the artificial drying process.

Engineers need a mathematical model of the drying process to predict a product's response to different drying conditions. With such a model of the product and a compatible model of the equipment being designed, the engineer can evaluate the design of drying equipment and the response of the product-equipment combination. Engineers have found that the evaluation of alternative designs by testing computer simulation models requires far less time and money than building and testing of the actual equipment. The parameters of the product drying model include product moisture content, product maturity, product type, ambient conditions, and time.

Much agricultural drying research centers on the drying of cereal grains, which are of extreme importance to mankind as a food source and as feed for animals. In fact the storage of dry grain is our best hedge against famine. Of all the cereal grains, rice is the most important single crop. Rice produces more carbohydrates and calories per hectare than wheat, maize (corn), barley, oats or millet. In terms of protein produced per hectare rice is second only to oats (Luh, 1980).

Parboiling is an irreversible hydrothermal process which has been used, since ancient times, to improve the nutritional content of polished rice and to increase the percentage of whole grains after milling. The exact process varies, and in many cases is a trade secret of the processor. Parboiling can be described, in general terms, as occurring in six steps: preparation of the grain, soaking the grain, cooking, drying, tempering, and milling.

The first step in parboiling is to remove foreign material and to sort the grain by size so that only rice of uniform size is parboiled in a given batch. Because the soaking, cooking and drying involve moisture diffusion and heat transfer, the shape and size of the grains affect the process. The goal of the second step is to increase the moisture content of the grains of the rough rice and is usually carried out in large vats of warm water. After the rice contains sufficient water it is heated, usually with steam, to gelatinize the starch. After starch gelatinization the product is dried, often in a series of dryers and then allowed to temper, or rest, for several days. Finally the rice, which up to this point still has the husks attached, is milled (Luh 1980). Little information is available on the modeling of drying of parboiled rice.

The goal of this research project was to improve upon current techniques of thin layer drying data acquisition and modeling. The specific objectives detailed in section 3.3.

2. LITERATURE REVIEW

The data analysis in this study will utilize several statistical computer programs including nonlinear regression programs. An introduction to the nonlinear regression concepts used in this dissertation is included in section 2.1 along with a discussion of several statistics which are useful in comparing regression analyses.

The mathematical relationship between the parameters and the independent variables is referred to, in the regression literature and in this work, as the model. Any model may be used in regression but if the results are to have maximum meaning the model should be related to the physical phenomena involved. Section 2.2 reviews appropriate models in the literature which are related to the underlying phenomena, of drying, and which other researchers have successfully used. Special emphasis is placed on the models and parameters used by other researchers pertaining to the thin layer drying of rice and parboiled rice.

The objectives of this study include the design and construction of equipment. Section 2.3 is devoted to a review of the literature pertaining to the thin layer drying study equipment. The equipment in this study is controlled by a microcomputer. Therefore, in section 2.4 the subject of direct digital control is reviewed.

2.1 Statistics

The information contained in this section was obtained largely from Draper and Smith (1981). They provide an excellent presentation of linear regression and an introduction to nonlinear regression. Their book has been invaluable during the data analysis portion of this investigation.

There are two main uses for statistics in this dissertation. The first is to fit various nonlinear models to sets of data. The second is to compare the prediction power of different models to the same set of data.

2.1.1 Linear Least Squares Regression

One of the simplest regression problems involves two variables, the independent variable and the dependent variable, and two parameters. Several pairs of numbers, representing the independent variable and dependent variable, are collected and combined into one data set. What is desired is to obtain an equation of the form:

$$Y=P1*X+P2 \qquad 2.1$$

where: Y = the dependent variable
X = the independent variable
P1,P2 = the parameters to be estimated.

Any two numbers may be used for P1 and P2, but some combinations of values for P1 and P2 will predict the measured values of the dependent variable much better than others. The most common way to measure how well an equation using a particular set of parameters predicts the data is to calculate the residual at each value of X. The residual is simply the observed value minus the predicted value. The residuals comprise, therefore, a set of signed numbers.

In a least squares approach to minimizing the residuals each individual residual is squared and the squares are then summed producing the residual, or error, sum of squares. The "best" set of parameters is considered to be the set which produces the lowest possible value for the error sum of squares. The error, or residual, mean square is obtained by dividing the error sum of squares by the degrees of freedom and represents a weighted average of the square of the residuals. The square root of the mean square error, often referred to as the standard error of the estimate, or standard deviation, represents the weighted average residual.

The corrected total sum of squares is obtained by considering the mean value of Y to be the predicted value and then calculating the error sum of squares. The sum of squares due to regression can be calculated by subtracting the error sum of squares calculated for the regression equation from the corrected total sum of squares.

Based on the relationship of the paramaters, not the variables, models are divided into three categories: linear, intrinsically linear, and intrinsically nonlinear. The three categories indicate the ease of determining the parameters and do not indicate the complexity of the relationship among the variables. For instance, for two independent variables, X1 and X2, and three parameters, P1, P2 and P3, the following forms are both linear in the parameters:

$$Y=P1*X1+P2*X2+P3 \qquad 2.2$$

$$Y=P1*X1*X2+P2*X1^2+P3*X2. \qquad 2.3$$

Equation 2.2 is linear in both the parameters and the variables while equation 2.3 is linear in the parameters but not the variables.

The category, intrinsically linear, refers to models which appear to be nonlinear in the parameters but which can be transformed into linear form, or linearized. The commonly used model:

$$Z=P3*\exp(P2*X) \qquad 2.4$$

is an equation of this type. If the logarithm is taken of both sides:

$$\ln(Z)=\ln(P3)+P2*X \qquad 2.5$$

and two substitutions made:

$$Y=\ln(Z)$$
$$P1=\ln(P3)$$

the equation takes the form:

$$Y=P1+P2*X \qquad 2.6$$

which is linear. Transformations of the dependent variable must be used with caution. The assumption is made in linear regression that the error associated with the dependent variable has a mean of zero and a uniform variance. In the case where these two assumptions hold for the measured dependent variable, Z in equation 2.4, they are violated in the transformed dependent variable, Y in equation 2.6. In this case a nonlinear analysis using equation 2.4 would be more useful than a linear analysis of equation 2.6.

The final type, intrinsically nonlinear, includes models which cannot be transformed into models which are linear in the parameters. One example of an intrinsically nonlinear model which will be seen later is:

$$Y=(P1+P2*\ln(P3*X1))*(P4*\exp(P5*X2)+(1.0-P4)*\exp(P6*X2)). \qquad 2.7$$

There are simpler models which are nonlinear such as:

$$Y=(P1+P2*X)/(1.0+P3*X). \qquad 2.8$$

In the case of linear models, or intrinsically linear models after transformation, there is one unique set of parameters which will produce a unique minimum value for the residual mean square. In addition these parameters, at least in principle, can be determined in closed form.

2.1.2 Nonlinear Least Squares

In the case of nonlinear regression the residual sum of squares is again minimized. Most computer programs for nonlinear regression include the provision for weighting the residuals other than by frequency of occurrence. If in the measurement of the variables the researcher feels that some sets of variables are measured more accurately than others, then residuals resulting from them can be weighted more heavily. The algorithm will attempt to reduce the residuals which have the most meaning at the expense of not reducing residuals which have less meaning. If there is no reason to believe that some data are better than other data all weights are unity. The formula for calculating the residuals squared is:

$$RS=W*(Y-f(X,P))^2 \qquad 2.9$$

where: RS = the weighted residual squared
W = the weight for that particular point
Y = the dependent variable at that point
f(X,P) = the predicted value for the dependent variable using the nonlinear model, the measured values for the independent variables and the current estimate for the parameters.

The residual sum of squares is obtained by summing the RS terms.

Choosing parameters which minimize the residual sum of squares when the model is nonlinear is much more difficult than in the linear case. The parameters cannot generally be determined in closed form and therefore must be obtained by iteration. In addition there may be more than one set of parameters which will produce the same minimum residual sum of squares. In other situations there may exist a local minimum residual sum of squares with the absolute minimum lying some distance away.

If a slight change in any of the parameters increases the residual sum of squares, then that set of parameters is the solution, only if there exists no other set which produces a smaller residual sum of squares. If one or more sets exist which produce a smaller or equal residual sum of squares, then a local minimum is said to exist. If local minimums are present, they may be found by an iterative algorithm to be the solution, when they usually are not the solution sought by the researcher. If local minimums are suspected, alternative starting values for the parameters will often reveal them and certain starting values will lead to the absolute minimum residual mean square. Because the nonlinear functions dealt with in this study are monotonic, continuous and have monotonic, continuous derivatives local minimums are not likely to be a problem.

2.1.2.1 Nonlinear Regression With Derivatives

There exist several algorithms which search for increasingly better sets of parameters. Many of them involve the use of the partial derivatives of the model with respect to each of the parameters. The computer program BMDP3R (Dixon 1981) makes use of derivatives and employs a modified Gauss-Newton algorithm. This algorithm (page 673, Dixon, 1981 and page 462, Draper and Smith, 1981) consists of first carrying out a Taylor series expansion about the point defined by the most recently calculated set of parameters. If the expansion is limited to the first two terms, the result is:

$$Y=f(X,Pr)+\Sigma Z_i*(Ps_i-Pr_i) \qquad 2.10$$

where: Pr = the most recently calculated set of parameters

Ps = the solution set of parameters

f(X,Pr) = the model evaluated at X,Pr

Z_i = the partial derivative with respect to the ith parameter evaluated at the most recent set of parameters.

Equation 2.10 is then considered to be a linear regression problem and solved for the terms (Ps_i-Pr_i) as the parameters. When the linear regression problem is solved the new estimate for the parameters is the old estimate adjusted as indicated by the results of the linear regression. This process is repeated until either the convergence criterion is met or the maximum number of iterations is reached.

The convergence criterion is specified by the user of the program as the relative change in the residual sum of squares from iteration to iteration. The maximum number of iterations is also specified by the user, generally to avoid wasted calculations in cases where the algorithm may not converge.

2.1.2.2 Nonlinear Regression Without Derivatives

A second computer program, BMDPAR (Dixon, 1981) searches for improved sets of parameters but does not use the derivative of the model. This program uses a pseudo-Gauss-Newton algorithm. It calculates a linear function L(X,P) equal to f(X,P) at the most recently calculated set of parameters. Because the function is linear the solution is obtained by linear methods. A new linear function is created which is equal to f(X,P) at the improved set of parameters. This algorithm is repeated until convergence or the specified number of iterations is reached.

BMDPAR allows the user to eliminate certain of the input data specifying acceptable ranges or identification numbers and allows the user to specify how small the change in the residual mean square is before ending the program. The program informs the user of simple statistics about the input variables comprising the data points which were used in the analysis and the residual sum of squares at each step in the algorithm. The statistics include:

1) the total number of data points
2) the number of data points included in the analysis
3) the mean of each variable
4) the standard deviation of each variable
5) the minimum and maximum value for each variable.

When the program ends, the best set of parameters which have been encountered is printed along with the estimated mean square error, the statistic used to compare the various models. The program prints the estimated asymptotic correlation matrix which gives an indication of whether the parameters are independent of each other. It also prints the estimated standard deviation for each parameter, useful in estimating the confidence interval for each parameter.

The program prints the estimated value and observed value at each data point if desired and can construct simple graphs of the predicted values and the residuals. The use of these graphs will be discussed under residual analysis. When there are several independent variables a close scrutiny of the list of residuals can be helpful.

The term "best fit parameters" refers to the estimate of the parameters which produces the smallest residual sum of squares when that particular set of parameter estimates is used in a prediction equation and the predicted values are compared with the observed values. There is no guarantee that some other set of parameter estimates, which was not tested, might not produce a smaller residual sum of squares. Using the asymptotic standard deviations listed for each parameter estimate, confidence intervals can be calculated so that a range containing the true parameters producing the smallest residual sum of squares is known.

2.1.3 Analysis of Fit

As stated earlier any model can be used in a regression analysis but only certain models are of real interest. One question which must be asked during a regression analysis is whether the model was appropriate. The first answer to this question is provided by the analysis of variance table for the regression. This table is an organized way of presenting the significant statistics regarding the regression analysis. The goal is to calculate the error mean square for the regression and determine the significance of the error mean square. If the regression analysis fails the test, then the model is not appropriate. If it passes there are many steps left before accepting the model.

A statistic is needed in this work to compare the fit of different models to the same set of data and also to compare the fit of a model to a set of data in general. In the linear case the R^2 value is often used. The R^2 statistic may be defined in different ways. The most useful definition is that it is the square of the correlation coefficient between the predicted and observed values of the dependent variable. However, this statistic is not of great value when comparing the fit of a linear model to different sets of data (Draper and Smith 1981, pages 89-93) and is of less value in the nonlinear case. The statistic that will be used whenever possible is the residual, or error, mean square. This statistic is similar to the average residual squared and is usable for linear and nonlinear models. It is useful when there are few or many data points in the analysis and is the best estimate of the variance, if the model is correct.

Before the advent of digital computers most of the grain drying regression was done graphically so there was neither a reliable estimate of the goodness of fit to the data nor of what was the probable range on the parameters in the equation (e.g. Hall and Rodriguez-Arias, 1958; Chu and Hustrulid, 1968; and Henderson, 1974). When researchers began using the digital computer in regression, parameter estimates appeared in the literature to four to six significant digits with no indication of the probable confidence interval on the parameter estimates (e.g. Rowe and Gunkel, 1972; Husain, Chen and Clayton, 1973; Zuritz et al., 1979; Fortes, Okos and Barrett, 1981; and ASAE, 1982). Too frequently, no measure of the goodness of fit was published or if any was it was an R^2 value (e.g. Hussain, Chen and Clayton, 1973; Sharaf-Eldeen, Hamdy and Blaisdell, 1979b; Fortes, Okos and Barrett, 1981; and Sharma, Kunze and Tolley, 1982). This statistic is of limited value in comparing the fit when different sets of data are being considered and does not give much of an indication of the magnitude of the difference between the predicted and observed values.

The nonlinear regression techniques do not necessarily produce the best set of parameter estimates in the sense that there exists no set which will result in a lower residual mean square. They can only choose the set which was used in the algorithm and produced the lowest residual mean square. What can be done in addition to choosing the best set which has been tested is to place a confidence interval around the set chosen to give researchers an idea of the range of the true parameters. Usually the parameter estimates with the wider confidence interval are the less reliable parameter estimates in the sense that in varying them a given amount a smaller change in residual mean square results than when the other parameter estimates are varied.

A reasonable confidence interval is plus or minus two standard deviations from the estimated value, although in the nonlinear case the exact probability that the actual value will lie within this range is not known. When the regression problem is viewed as an n-dimensional geometric space the confidence intervals are seen as a confidence region (Draper and Smith, 1981 p. 489). This approach can help clarify the nonlinear regression problem.

2.1.3.1 Residual Analysis

An examination of the residuals should always be carried out in a regression analysis. If the model sum of squares passed the F test, the residual analysis can still show that the model is not adequate. If the model sum of squares failed the F test, the residuals can provide guidance in selecting a better model. The assumption is made for the rest of this section that the regression analysis was significant.

The residuals are the variation of the measured dependent variable which the model fails to explain. If the model is correct then these are the errors and the residuals provide the best estimate of the error in the data. In the statistical analysis the assumptions about the residuals usually include that they: are independent, have zero mean, have a constant variance and follow a normal distribution. In the examination of the residuals any evidence that these assumptions are not correct is sought.

The residuals are examined graphically by plotting each residual against all reasonable variables. The most likely to plot against include the predicted value, time, (whether or not it is a variable) and each independent variable. Any pattern other than a uniform band about zero for any of these plots is an indication that one or more of the assumptions are violated and may be an indication of inadequacy in the model. A normal plot of the residuals, that is plotted on normal probability paper, will produce a straight line if the variance is constant.

2.1.3.2 Correlation Matrix

One of the aids in working with nonlinear regression is the asymptotic correlation matrix. This is a set of numbers which has been normalized and indicates how independent the parameters are from one another. If the correlation between two parameters is large, near 1 or -1, it indicates that a model with one of these parameters removed may produce a residual mean square almost as low as the present model. It does not indicate that the model is necessarily inappropriate only that the present set of data may not support one of the parameters.

2.1.4 Examples

The first example is intended to show how residual analysis is used and that R^2 values can be misleading if not used with caution. For this example, data were created by using the integers from 1 to 15 as the values for the independent variable and calculating values for the dependent variable from the formula:

$$Y = 8.000+4.000*X+0.100*X^2+e \qquad 2.11$$

where e are errors randomly chosen from a normally distributed population with mean 0.000 and standard deviation 0.100. (The assumption is commonly made that errors in measurement are of this type, but the magnitude of the standard deviation depends on the situation). The data are shown in Table 2.1.

Table 2.1 Data for Example One

Independent Variable	Error	Dependent Variable
1.0	0.1007	12.2007
2.0	-0.1816	16.2184
3.0	-0.0730	20.8270
4.0	-0.2726	25.3274
5.0	0.0354	30.5354
6.0	0.1161	35.7161
7.0	-0.0454	40.8546
8.0	0.0391	46.4391
9.0	-0.0762	52.0238
10.0	0.0456	58.0456
11.0	0.0370	64.1370
12.0	-0.0292	70.3708
13.0	-0.1086	76.7914
14.0	-0.0641	83.5359
15.0	0.0782	90.5782

These data were fit to a model of the form:

$$Y = P1+P2*X \qquad 2.12$$

and it was determined by linear regression that P1=3.4 and P2=5.6 produces the best fit. The resulting fit is plotted in Figure 2.1. The model seems to work fairly well with an R^2 value of 0.995, a value which in most cases is quite acceptable. It might be tempting to stop the analysis at this point and accept the model. However, when the residuals are plotted, as in Figure 2.2, a clear pattern can be seen in them, i.e. the residuals are a function of a variable.

The pattern suggests that the model of the form 2.12 is not adequate and another model should be sought. If a model of the form:

$$Y = P1+P2*X+P3*X^2 \qquad 2.13$$

is fit to the data the resulting plot of the predicted and the observed values is as shown in Figure 2.3. In this case it was determined that P1=7.9, P2=4.0 and P3=0.100 produced the lowest sum of squares. It should be noted that the R^2 value is 0.99998, higher than before. This is one case where the R^2 statistic is of value, in comparing the fit of different models to the same set of data. Viewing the previous R^2 value in isolation and not in

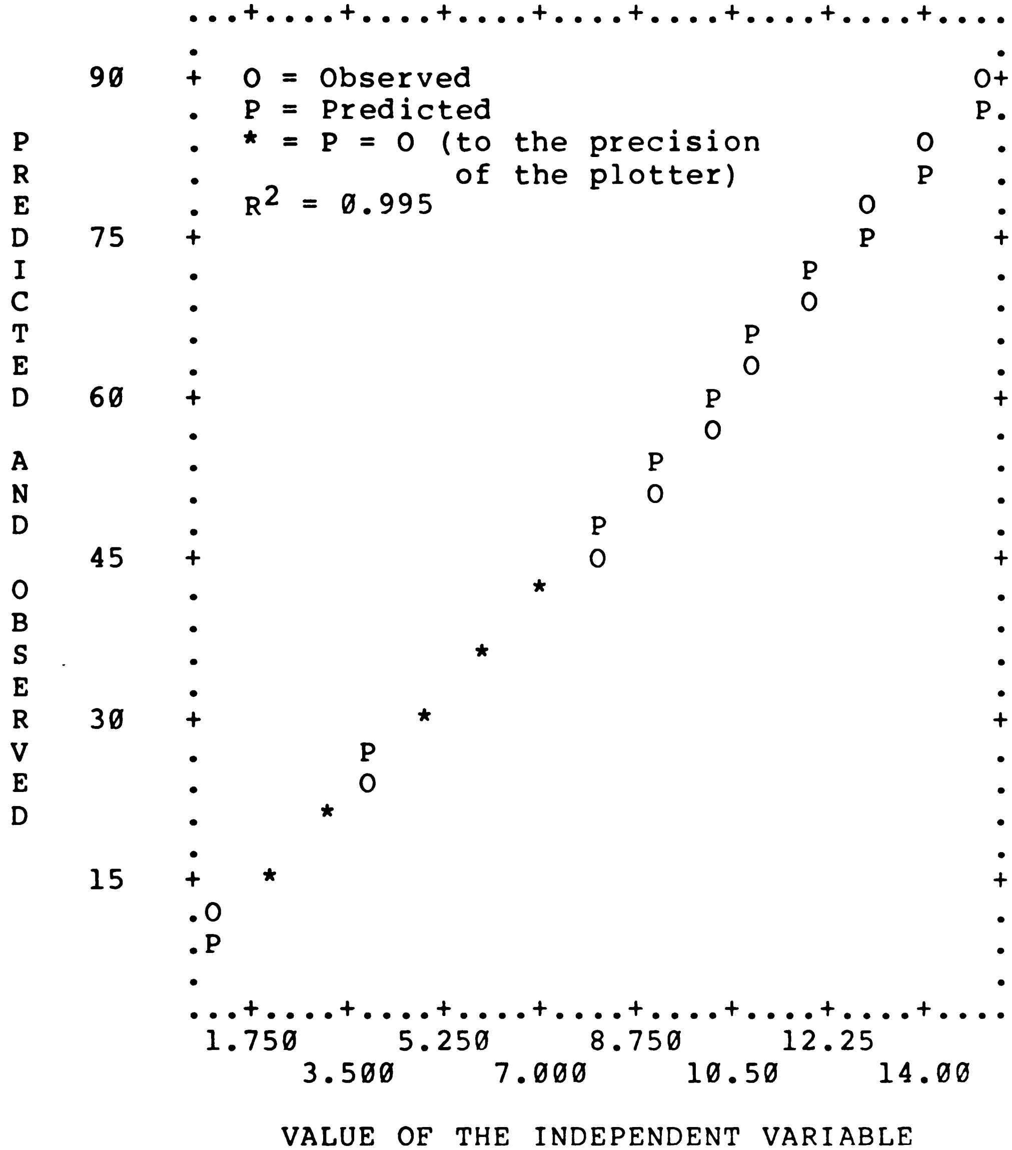

Figure 2.1 Predicted and Observed Values of Example Data, Eq. 2.12

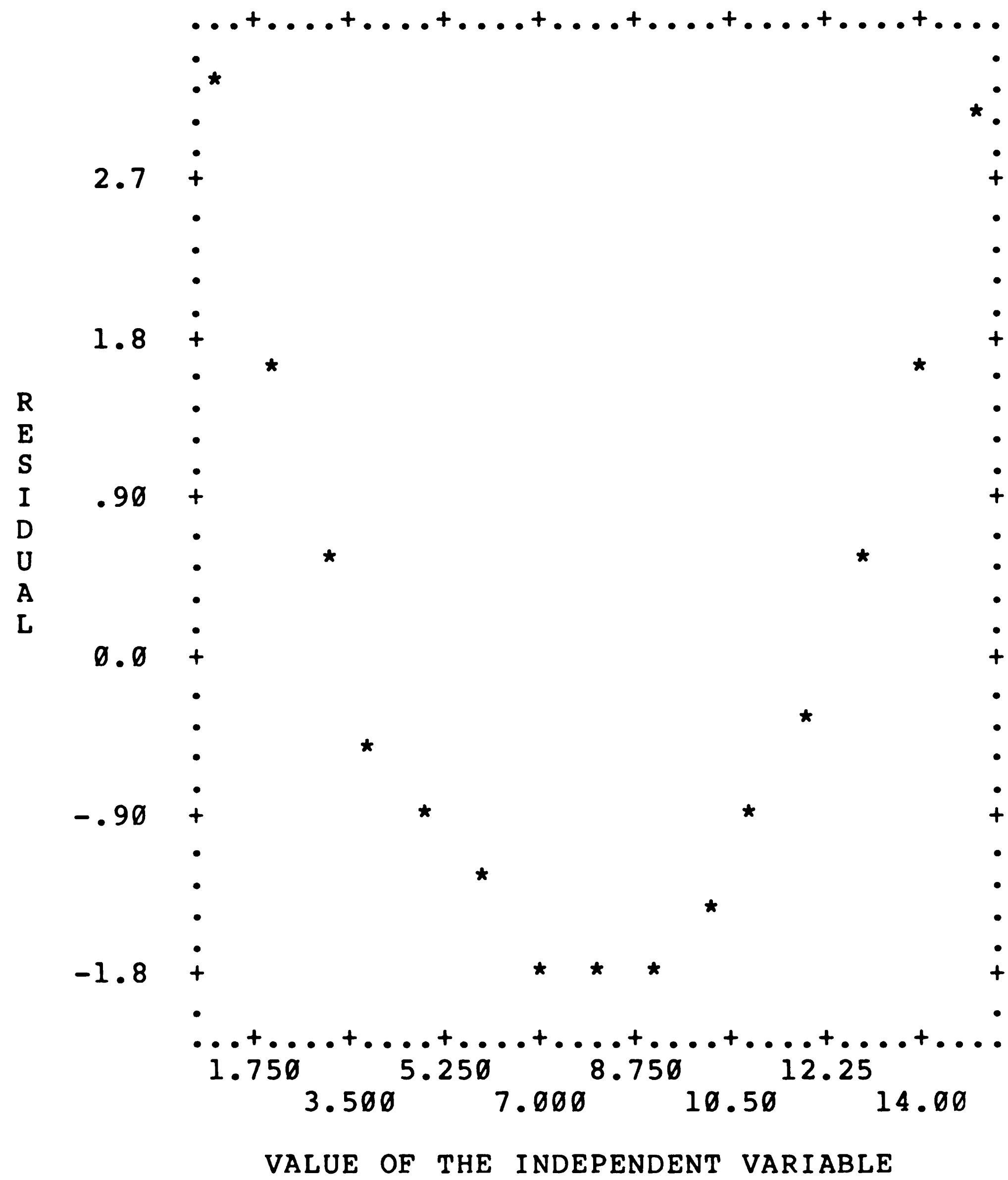

Figure 2.2 Residuals of Example Data, Eq. 2.12

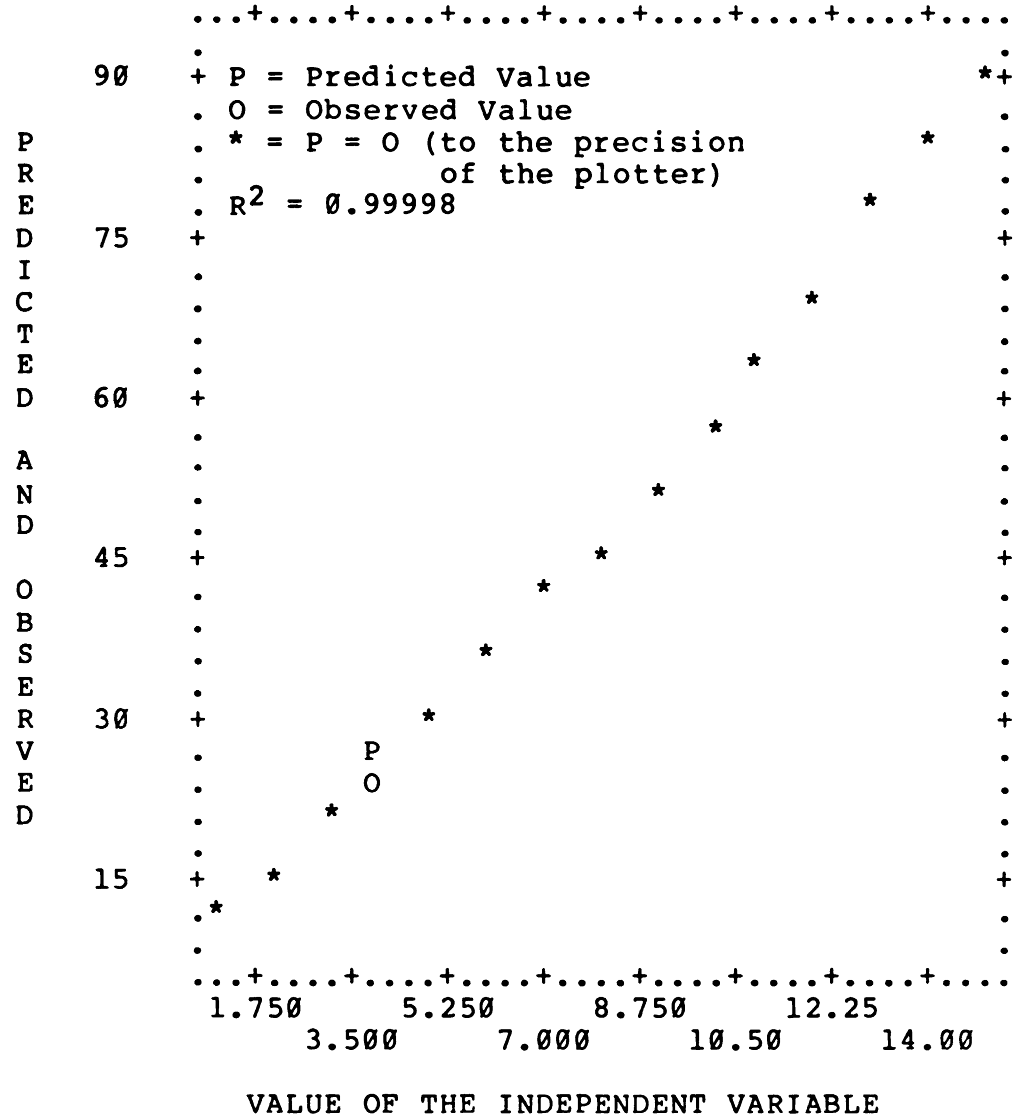

Figure 2.3 Predicted and Observed Values, Example Data, Eq. 2.13

comparison to other R^2 values for models fit to the same set of data would have been misusing the statistic. The plot of the residuals from the model 2.13 is shown in Figure 2.4. There is no clear pattern in these residuals and a plot of data which is known to be random, such as this, can give a idea of how random data should look.

As mentioned earlier, those models which are intrinsically linear can be transformed to make the relationship linear in the parameters. One important additional concern when transformations are used, however, is the effect that the transformations have on the errors in the data. The second example should help clarify the weakness of using transformations and show the use of residual analysis at the same time.

A second set of data was created using the integers from 1 to 15 as the values for the independent variable and the dependent variable was calculated from the formula:

$$Y = 8.000*\exp(-0.300*X)+e \qquad 2.14$$

where e are random errors introduced from a normal distribution with mean 0.000 and standard deviation 0.100. The data are shown in Table 2.2.

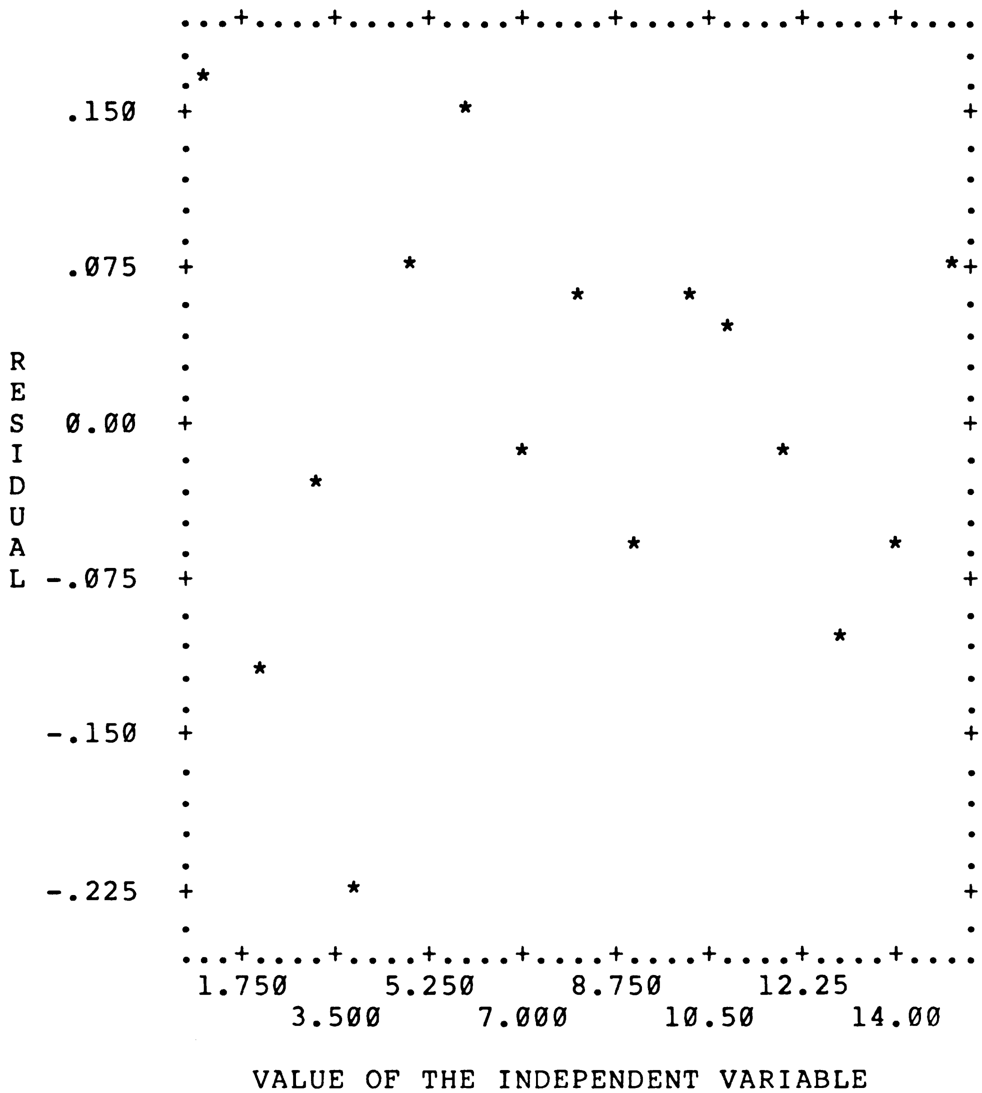

Figure 2.4 Residuals of Example Data, Eq. 2.13

Table 2.2 Data for Example Two

Independent Variable	Error	Dependent Variable
1.0	0.1007	6.0272
2.0	-0.1816	4.2089
3.0	-0.0730	3.1796
4.0	-0.2726	2.1370
5.0	0.0354	1.8204
6.0	0.1161	1.4385
7.0	-0.0454	0.9343
8.0	0.0391	0.7648
9.0	-0.0762	0.4614
10.0	0.0456	0.4439
11.0	0.0370	0.3321
12.0	-0.0292	0.1894
13.0	-0.1086	0.0533
14.0	-0.0641	0.0559
15.0	0.0782	0.1671

The data were analyzed by two methods, linear through the transformation used with equation 2.4 and nonlinear with the use of BMDPAR. For the linear analysis, the logarithm was taken of the values of the dependent variable and the resulting transformed data were fit to a linear model. A plot of the predicted and observed values is shown in Figure 2.5. The resulting prediction equation is:

$$\ln(Y) = 2.14-0.32*X \qquad 2.15$$

which when transformed back to the original form produces:

$$Y = 8.5*\exp(-0.32*X) \qquad 2.16$$

The estimated parameter values are observed to be different from those in the equation which was used to generate the data. The reason for this is that one of the basic

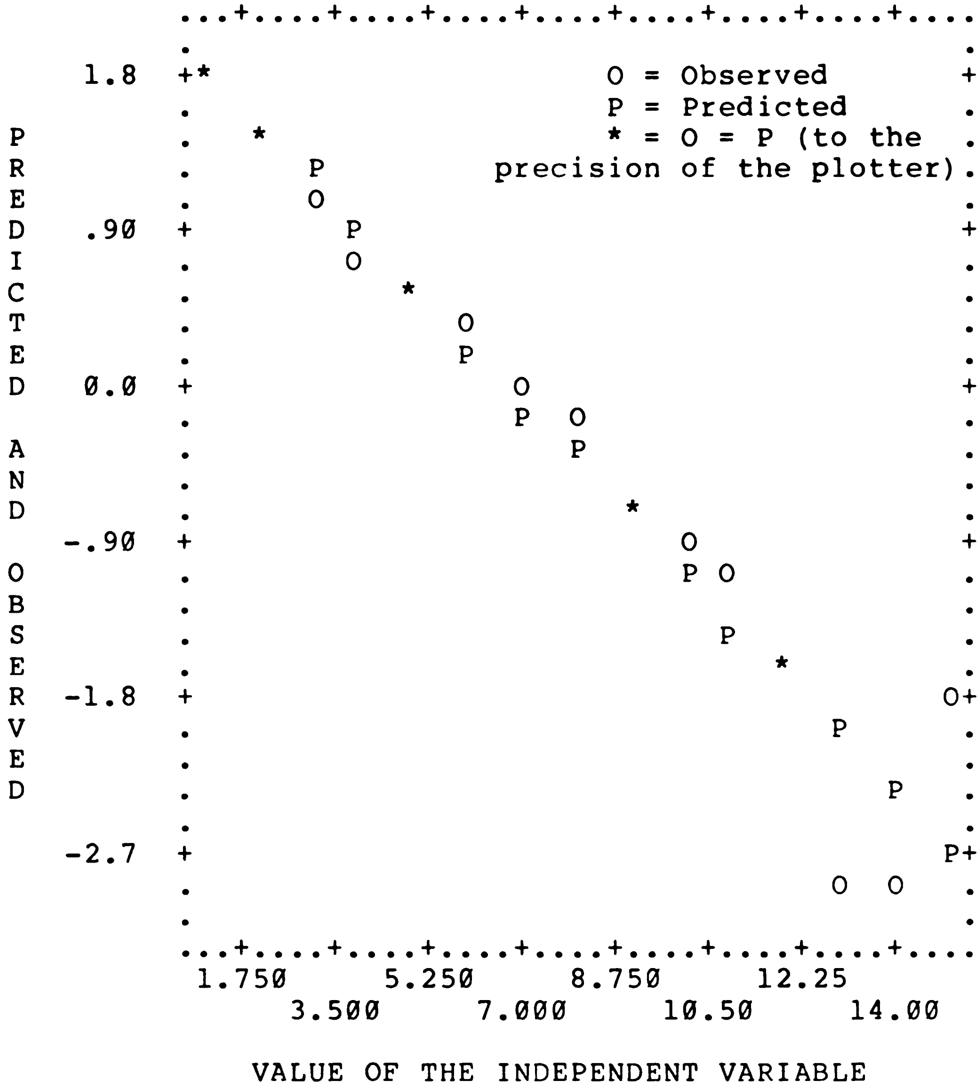

Figure 2.5 Predicted and Observed Values, Example Data, Eq. 2.15

assumptions of linear regression was violated when the transformation was made.

If the residuals are examined, Figure 2.6, they are again observed to lie in a pattern with much lower variance at low values for the independent variable and higher variance at larger values for X. Because the errors which were used to generate the data were randomly distributed they represented a larger proportion of the dependent variable as the independent variable increased. Therefore, the transformation did not affect all of the errors equally and the regression could not properly handle the transformed errors. Because the pattern in the residuals shows that one of the basic assumptions of regression has been violated this analysis should be rejected.

The same data were then analyzed with nonlinear methods. A model of the form:

$$Y = P1*\exp(P2*X) \qquad 2.17$$

was used to fit the data. The resulting predicted and observed data are shown in Figure 2.7. The fit does not appear to be much better than before but if the residuals are plotted, Figure 2.8, there is no clear pattern in them. The resulting model with parameter values is:

$$Y = 8.0*\exp(-0.308*X) \qquad 2.18$$

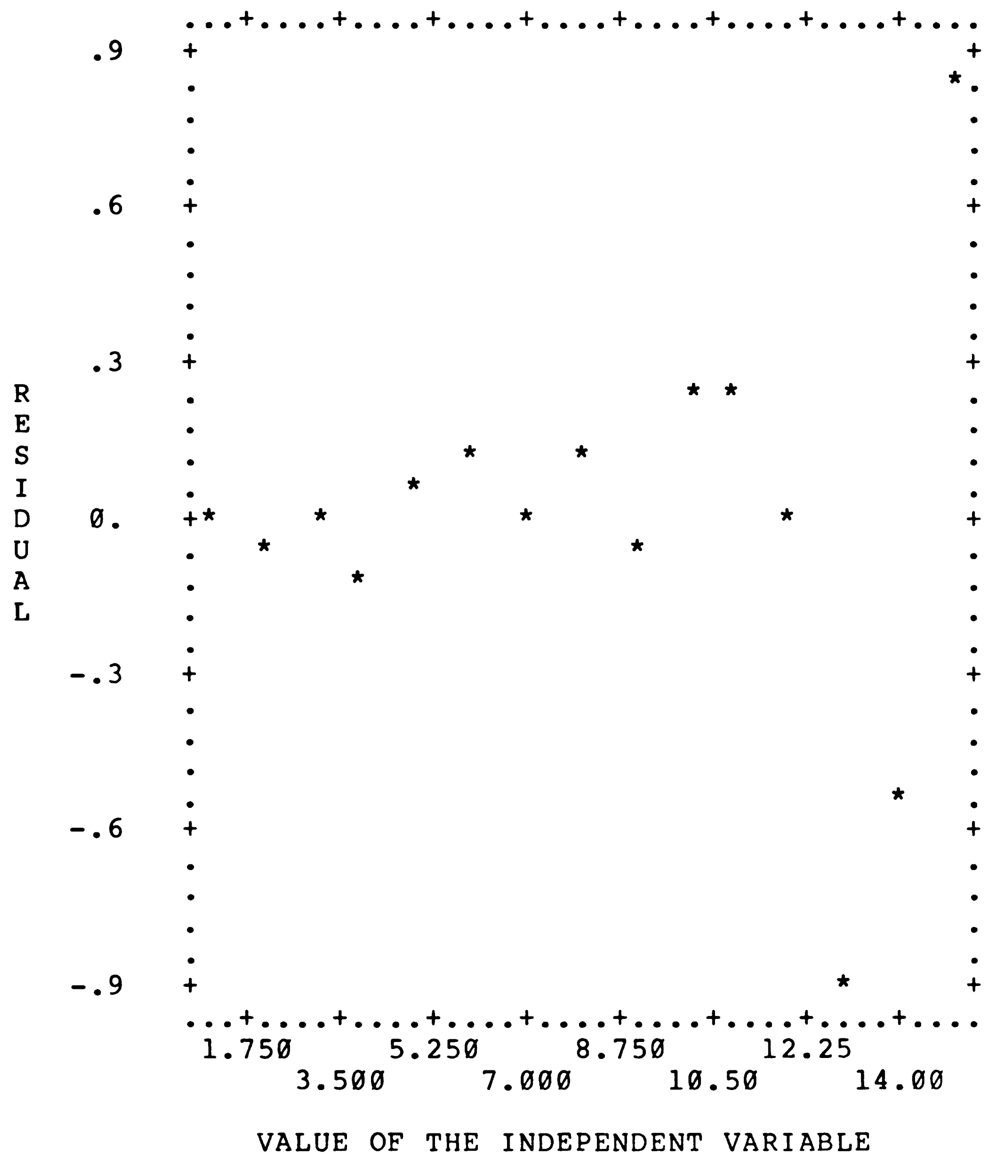

Figure 2.6 Residuals, Example Data, Eq. 2.15

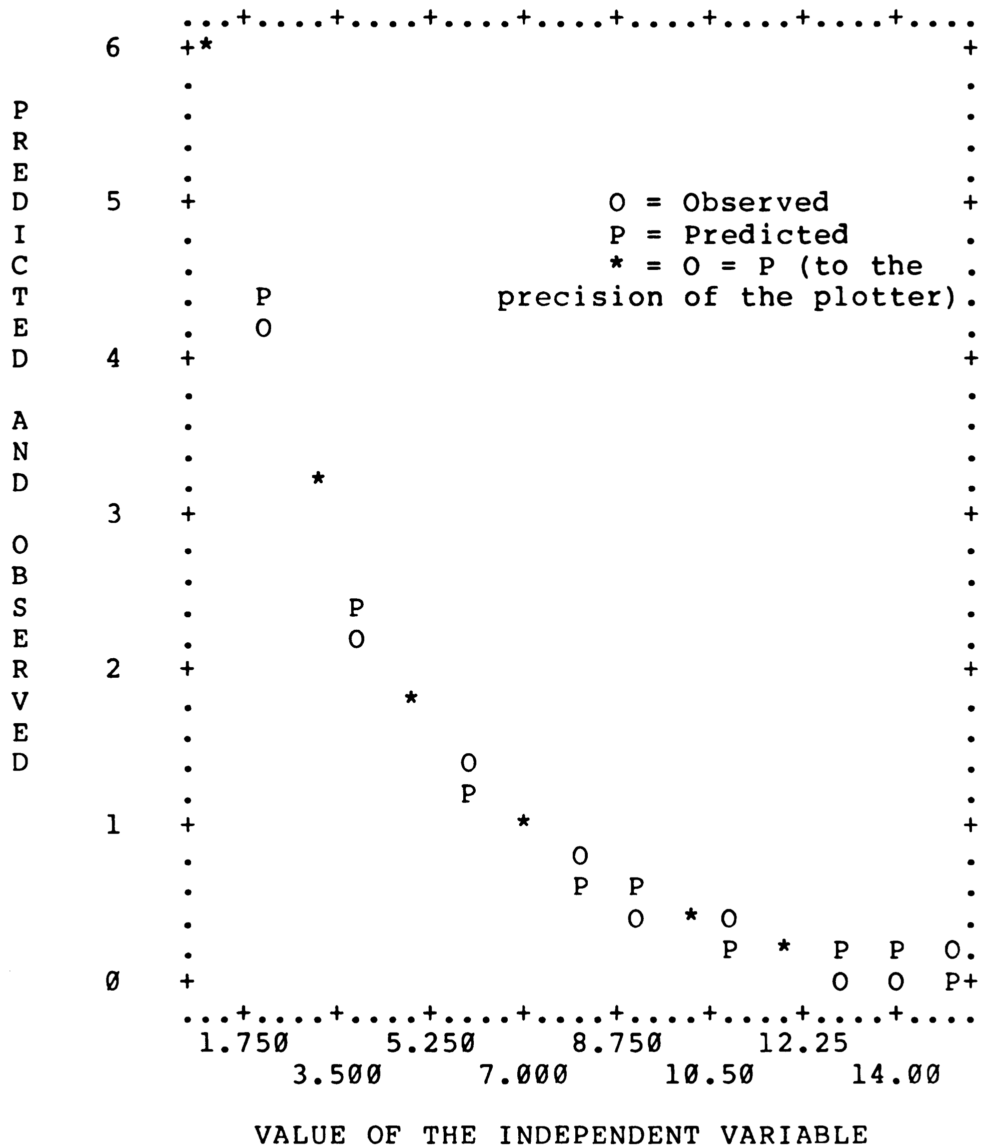

Figure 2.7 Predicted and Observed Values, Example Data, Eq. 2.17

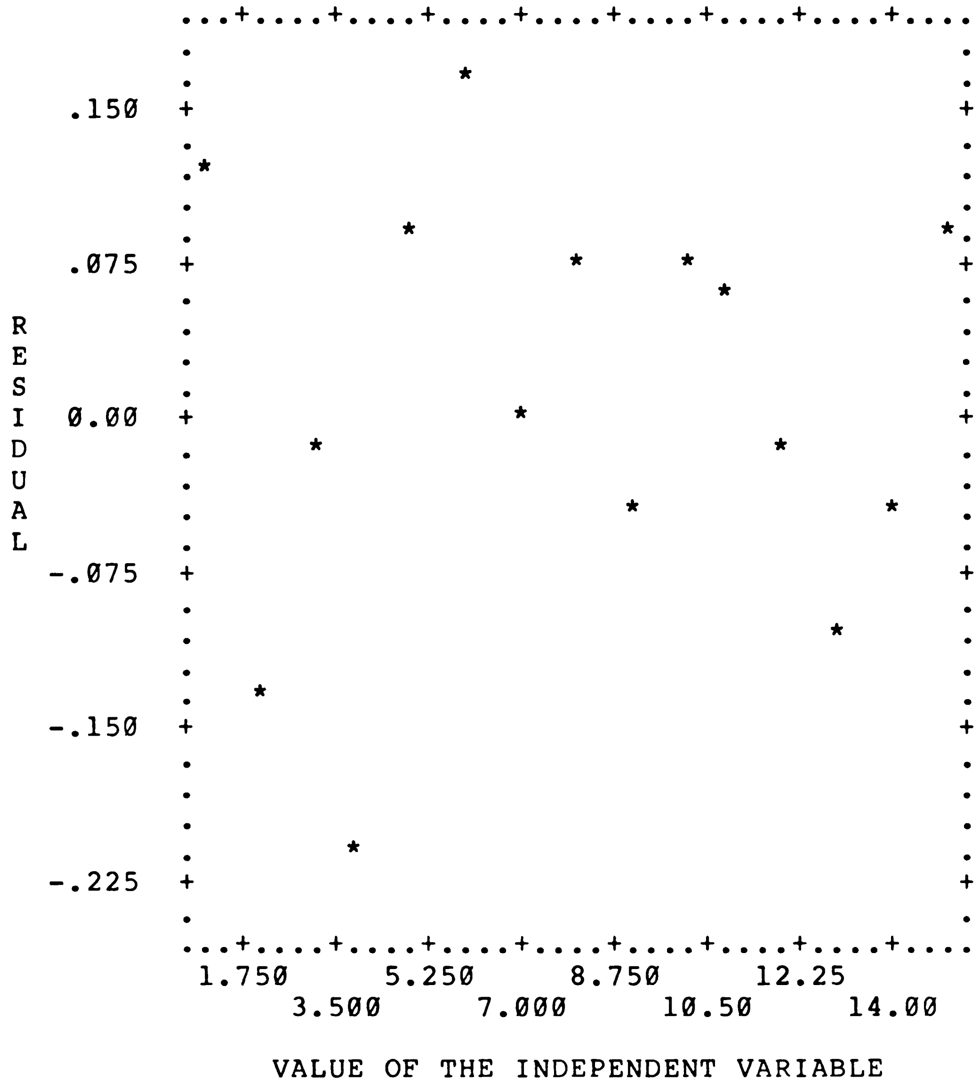

Figure 2.8 Residuals, Example Data, Eq. 2.17

which is observed to be much better than that obtained from the previous method. In addition the estimated standard deviation, from the nonlinear analysis, is 0.108 which compares favorably with the population standard deviation of 0.100. The estimated standard deviation for P1 is 0.17 and for P2 is 0.008. The true parameters are observed to be within one standard deviation of the parameter estimates. From this example, it can be seen that nonlinear analysis may be preferable even when the model can be transformed and analyzed with linear methods.

2.2 Grain Drying

The drying of agricultural products is and has been of great importance to mankind. It has been the subject of numerous papers, reports and theses over the past fifty years with over one hundred additions to the scientific literature during 1981. Despite much effort, progress has been slow in understanding the phenomena involved. Many models of agricultural product moisture content have been used with varying success. Average differences between the predicted and observed moisture contents of 0.004 to 0.03 (decimal dry basis) are common.

What is desired by engineers is a model which predicts the moisture content of a bed of grain many grain thicknesses deep given the air conditions and the duration of exposure of the grain to those conditions. This problem is referred to as the modeling of deep bed drying.

One approach to deep bed modeling which has seen increasing use is to divide the volume of grain to be dried into thin layers and model the whole volume by treating each layer separately. The digital computer can then combine the layers into a total picture of the process. The modeling of the moisture content of these thin layers of grain is referred to as thin layer modeling. For this approach to work the thin layer model for each layer must be accurate over a range of drying temperatures, product moisture contents and air moisture contents. There are generally two approaches to obtaining the thin layer equation: one utilizing moisture diffusion principles and based on an individual particle of grain, and the other obtained from a study of the response of an actual thin layer of grain (Brooker, Bakker-Arkema and Hall, 1974).

The process of drying agricultural products of high initial moisture content can be divided into two periods depending on the drying rate-time relation (Newman, 1932a). The first, at moisture contents of about 0.70 dry basis and above, is called the constant rate period where the drying rate does not change with time. In the second, the falling rate period, the drying rate decreases with time. Grain drying usually occurs only in the falling-rate drying period (Brooker, Bakker-Arkema and Hall, 1974).

In the development of thin layer models for moisture relationships in agricultural products several physical parameters have emerged as highly important. The two most important of these parameters are the equilibrium moisture content and the diffusion constant. Each of these parameters has been modeled separately and in general researchers have focused on only one of these parameters at a time. The attempt has been to try to obtain the most useful overall model by obtaining the best model for each of the parameters and then combining the parameters in an overall thin layer model.

In this dissertation the moisture contents will be calculated in decimal dry basis. When referring to the work by others the moisture contents will be expressed in decimal dry basis except in formulas which will be kept as published. If the literature refers to the moisture content wet basis the values will not be converted to dry basis.

Many models considered here use the variable, moisture ratio, MR, defined as:

$$MR = (M(t)-EMC)/(Mi-EMC) \qquad 2.19$$

where:

M(t) = the moisture content, dry basis decimal, at time t

EMC = the equilibrium moisture content, dry basis decimal

Mi = the initial moisture content, dry basis decimal.

The evaporation of moisture requires energy and that energy must come from the air. In addition, the air and the product under study are usually at different temperatures at the beginning of the testing period. These two factors have led to concern over what is the appropriate temperature to use in modeling. Sets of coupled differential equations can be written and solved digitally to determine the relative effect of the temperature and moisture gradients on the drying. Several researchers have done this and then measured the temperature of the product. Rowe and Gunkel (1972) measured the surface temperature of chopped alfalfa during moisture removal and showed that the product was nearly at the air temperature within 6 to 15 minutes.

Husain, Chen and Clayton (1973) measured the center temperature of grains of Bluebelle rough rice with a thermocouple and found that the center temperature had changed from the initial grain temperature of 22 C to within 2.5 C of the drying air temperature of 50 C within 15 minutes. Fortes, Okos, and Barrett (1981) measured, with a thermocouple, the center temperature of wheat as it dried. They found that the product changed from the initial temperature of 26.7 C to virtually the drying air temperature of 47.0 C within 3 minutes. They also found that the actual temperature change was faster than the change predicted by a theoretical model.

Both studies presented the data in graphic form so it is difficult to make exact conclusions from their data. They assumed particle geometry and created models based on that geometry. In neither case did the researchers defend the validity of their geometric assumptions.

2.2.1 Equilibrium Moisture Content

All products display a characteristic water vapor pressure dependent on their moisture content, temperature and physical characteristics. In grain the physical characteristics include the species and variety of the grain and the moisture history of the grain. The driving force in drying is considered to be the difference in vapor pressure of the air surrounding the grain and the vapor pressure within the grain. As a result of these two relationships the final moisture content of the grain depends on the water vapor pressure of the drying air.

Unfortunately, the vapor pressure within the grain cannot be measured directly. The vapor pressure within the grain is inferred by measuring the vapor pressure of air at which no net moisture exchange takes place. The moisture content of the grain at which there is no net moisture exchange at a given temperature and vapor pressure of the surrounding air is referred to as the equilibrium moisture content (Brooker, Bakker-Arkema and Hall, 1974).

The equilibrium moisture content, EMC, is usually determined by measuring the moisture content of grain which has been held in a constant environment for a long period of time. In practice, the grain is held under constant conditions for varying lengths of time from less than a day to over a year (Neuber, 1980). In some studies with rice, the product was placed in containers with saturated salt solutions, the rice being held above the salt solution by wire mesh. The weight of the rice was checked periodically until the moisture content stabilized (Karon and Adams, 1949; Breese, 1955; Hogan and Karon, 1955; Zuritz et al., 1979). This moisture content is known as the static equilibrium moisture content.

Allen (1960) discussed the static EMC and a dynamic EMC which is obtained from moisture content vs. time plots. These two equilibrium moisture contents have been observed to be different and Allen proposed that the static EMC should be used in situations involving long term storage but that the dynamic EMC should be used in dynamic situations such as grain drying.

Because the dynamic EMC is obtained from graphic or mathematical regression, for which assumptions about the form of the moisture content vs. time relationship must be made, the difference between the static EMC and the dynamic EMC could be a result of either the inadequacy of the model or a result of real physical phenomena. Considering the limited evidence in support of the adequacy of the models available in the literature the simplest explanation, and thus the preferred explanation, is that the models were inadequate.

Equilibrium moisture content is not an easily calculated variable but depends on many factors. Neuber (1980) in his review of equilibrium moisture content included the following variables related to shelled corn:

1) Air relative humidity
2) Temperature of both the product and the air
3) Desorption vs. sorption
4) Description of the grain
   (species, maturity, processing, dimensions, etc.)
5) Composition of the grain
   (ash, protein, fat, N.F.E)
6) Pre-treatment of the grain
   (storage time, MR history)
7) Method of determination of moisture content
8) Air-conditioning method, measurement of air moisture content
9) Differential vs. integral test procedure
10) Moisture equilibrium - definition, frequency of testing

While conducting research many variables which are difficult to measure can be included in a model but what is needed for design is an equation of the form:

EMC = f(easily measured variables)

Pfost et al. (1976) reported on the static equilibrium moisture content of yellow dent corn from the data of five researchers. They compared five of the most commonly used models:

Henderson-Thompson

$$RH = 1-\exp(-A*(T+C)*EMC^{1/B}) \qquad 2.20$$

Chung-Pfost

$$RH = \exp(-A/R/(T+C)*\exp(-B*EMC)) \qquad 2.21$$

Day-Nelson

$$RH = 1-\exp(F*EMC^{G}) \qquad 2.22$$

$$F = A*T^{B}$$

$$G = C/T^{H}$$

Chen-Clayton

$$RH = \exp(-F*\exp(-G*EMC)) \qquad 2.23$$

$$F = A/T^{B}$$

$$G = C*T^{H}$$

Strohman-Yoerger

$$RH = \exp(A*\exp(-B*EMC)*\ln(PS)-C*\exp(-H*EMC)) \qquad 2.24$$

where:

A,B,C,H	=	empirical constants
T	=	temperature
R	=	universal gas constant
RH	=	relative humidity
EMC	=	equilibrium moisture content, dry basis.
PS	=	saturation pressure of water vapor at T

They found all of the equations to be acceptable, but for the equations with three variables (Henderson-Thompson and Chung-Pfost) the standard error of estimate, the square root of the mean square error, was not appreciably higher than for the other equations. Since these two equations used only three parameters, while the other equations employed more parameters, these two equations were preferred.

These two equations have limited theoretical bases. Henderson (1952) proposed the form of the Henderson-Thompson equation and presented some theoretical arguments for the equation with C set to zero. Thompson

(1972) found that the addition of C to the equation improved the fit of the equation to the experimental data. Thompson's change resulted in biasing the temperature upwards from absolute zero and weakened the theoretical justification for the equation. Chung and Pfost (1967) proposed the Chung-Pfost equation as a two coefficient equation and included theoretical justification for it but the arbitrary addition of an offset from absolute zero improved the fit to the data with this equation also.

2.2.2 Drying or Diffusion Coefficient

In all of the diffusion based equations there is a variable concerning the resistance of the grain to moisture diffusion. This variable is the flow rate (mass per time) per unit area ($length^{-2}$) with a unit concentration gradient (mass per volume per length). The units reduce to $length^2$ per time (Newman 1932b). This variable is referred to as the diffusion coefficient or the diffusivity. Another variable, the drying constant, is closely related but is used in different equations (Brooker, Bakker-Arkema and Hall, 1974). The values of these variables depend on the product and the product temperature. The Arrhenius form is often used for the relationship (Henderson 1974) and is of the form:

$$D = A*\exp(B/T) \text{ or } K=C*\exp(H/T) \qquad 2.25$$

where:

D = the diffusion coefficient ($length^2/time$)
K = the drying constant (1/time)
T = the absolute temperature
A,B,C,H = empirical constants.

The diffusion coefficient and the drying constant are related to each other by the geometry of the product. If assumptions are made about the geometry of the particles and about the moisture time relationship, then values for the diffusion coefficient can be obtained for irregular solids, such as agricultural products, from experimental data of moisture content over time. If no assumptions are made about the geometry of the particles then only the drying constant can be obtained from the data.

Some researchers have found it necessary to include a relationship between the drying constant and variables in addition to the product temperature. White, Ross, and Poneleit (1981) modeled the drying constant of popcorn with:

$$K = 0.13+0.0023*\exp(0.08*T)-0.0551/DM +0.00235*T/DM \qquad 2.26$$

where:

K = the drying constant
T = temperature degrees C
DM = the change in moisture content from original to final

Several researchers have reported evidence that diffusion in agricultural products is concentration dependent (Chu and Hustrulid, 1968a; Husain, Chen and

Clayton, 1973). In both studies the researchers assumed that the moisture dependence followed the relationship:

$$D(t) = A*\exp((B*T-C)*M(t)-H/T) \qquad 2.27$$

where: A,B,C,H = regression coefficients
M(t) = the moisture content at time t
T = the temperature absolute
D(t) = the diffusivity at time t

However, in neither study did the researchers report on how well the equation fit the data nor the confidence intervals on the parameters. Neither paper included a theoretical justification for the form of the concentration dependent diffusion so the form is empirical. In both studies assumptions were made about particle geometry but no evidence was presented to show that the assumptions were not invalid. (It is not possible to show that the assumptions are valid only that they are invalid).

Diffusivity is measured by collecting data on the moisture-time relationship and then fitting the data to a model by some regression technique. The inclusion of variables other than temperature in the model has little theoretical basis and the inclusion of parameters such as initial moisture content of the product, current moisture content or drying air relative humidity could result from using drying models of incorrect form, instead of from such variables' actual effect on the drying being modeled.

2.2.3 Moisture Versus Time

There have been many mathematical models proposed for the falling-rate period of grain drying which can be divided into three categories:

1) Theoretically derived equations,
2) Semitheoretical equations, and
3) Empirical equations.

2.2.3.1 Theoretical Thin Layer Equations.

Equations based on theoretical considerations have been derived. Brooker, Bakker-Arkema and Hall (1974) describe a set of general equations developed by Luikov (page 188) and show that they can be reduced to two differential equations in three dimensions relating the product moisture and temperature change with time. Assuming that the temperature of the product does not change, a reasonable assumption in some cases, will result in a single differential equation in three dimensions. If it is further assumed that 1) drying is a diffusion process, 2) moisture moves as a vapor, 3) the product is of homogeneous composition, and 4) the product is a regular geometric shape, then the moisture ratio-time ralationship can be solved.

Newman (1932a,b) considered three basic shapes, a slab with the edges coated to prevent evaporation except in two opposite faces, a sphere, and a cylinder with no diffusion through the ends. He assumed that the product was homogeneous and of regular geometric shape. He also assumed that drying is a diffusion process, that for falling rate drying the initial concentration in the product is uniform, and there is no resistance to evaporation at the air-product interface. He demonstrated that the solution to the problem of diffusion in a porous solid where the diffusivity is constant results in an infinite series of the form:

```
MR = A*exp(-a*D*t)+B*exp(-b*D*t)
                   +C*exp(-c*D*t)+...       2.28
```

where:

```
     t          = time in convenient dimensions
     D          = diffusivity, length**2/time
     A,B,C...,
     a,b,c...   = Constants related to geometry of the
                  product
```

Some numerical values are, from Newman:

	slab thickness=2*L	sphere radius=L	cylinder radius=L
A =	0.81057	0.60793	0.69167
B =	0.09006	0.15198	0.13127
C =	0.03242	0.06755	0.05341
a =	$2.4674/L^2$	$9.8696/L^2$	$5.7831/L^2$
b =	$22.207/L^2$	$39.48/L^2$	$30.472/L^2$
c =	$61.685/L^2$	$88.83/L^2$	$74.892/L^2$

The desired form for the equations for the current study is moisture at time t as a function of the other variables. Rearranging this equation produces:

$$M(t) = (Mi-EMC)*(A*\exp(-a*D*t)+B*\exp(-b*D*t) +C*\exp(-c*D*t)+...)+EMC \qquad 2.29$$

where: M(t) = the moisture content at time t, dry basis
Mi = the initial moisture content, dry basis
EMC = the equilibrium moisture content, dry basis
D = the diffusivity, length**2/time
The other parameters are as defined above.

Newman observed that the first term of the equation should model the diffusion process adequately after sufficient time but that for the initial time, t=0, all of the terms are needed. For the equation to be correct at t=0, the sum of the terms A,B,C,... must be one. It can readily be seen that at t=0 the sum of A, B, and C is 0.933 for the slab, 0.827 for the sphere and 0.876 for the cylinder of infinite length. However, depending on the relative values of D and L, the effect of the terms past the first one diminishes rapidly due to the exponential decay of the terms.

Crank (1975) showed that a series of exponentials of this form is a solution to the general diffusion problem (Crank, 1975 section 2.3). Unfortunately, for these closed form solutions to be directly applicable, the material in which the diffusion takes place must be homogenous and of regular geometry. Although the closed form solution for any regular solid might be obtained by the proper change of coordinate system, only the simplest shapes have yielded to this approach. Clearly most of the biological materials of interest do not fit the standard shapes exactly.

Moon and Spencer (1961) showed that the solution in time to the Helmholtz equation (which includes the diffusion equation) is always of the form of a series of decaying exponentials. The solution in space, however, depends on the shape of the particle and the boundary conditions.

2.2.3.2 Semitheoretical Thin Layer Equations

Lewis (1921) proposed a relationship considered to be analogous to Newton's law of cooling to describe the diffusion phenomenon. He theorized that the rate of drying is proportional to the driving force, the difference between the air moisture content and the product equilibrium moisture content. This relationship is integrated over time to give:

$$MR = \exp(-Kt) \qquad 2.30$$

where:
K = drying parameter or constant, 1/hour.

Rewriting this equation for moisture content as a function of time and diffusion constant produces:

$$M(t) = (Mi-EMC)*\exp(-Kt)+EMC \qquad 2.31$$

In the development of this model the assumption is made that the resistance to moisture flow is concentrated in a layer at the surface of the product; therefore, the geometry of the product particles is irrelevant. The equation is commonly called the exponential or logarithmic model and is probably the most commonly used thin layer drying equation.

Sharaf-Eldeen, Hamdy and Blaisdell (1979a) reviewed the literature on the falling rate drying of fully exposed materials and found that many investigators have used the logarithmic model, but many did not have good success in describing the complete drying curve with such a relationship. They state that the experimental evidence shows that the model underestimates the drying rate over the first part of the curve and overestimates it over the last part of the curve.

Comparing this equation with Newman's (1932b) equation it is seen that the logarithmic model is the first term of Newman's equation with A=1. If Newman's equations were correct, the logarithmic model would be expected to underestimate the drying rate at small time. Also, because regression is used in obtaining the coefficients in the logarithmic model, that model would be expected to overestimate the drying constant at large time. In addition, because of regression, the final moisture content would be predicted to be higher than the observed final moisture content, producing differences between the static EMC and dynamic EMC.

Several modifications of the logarithmic equation have been used to compensate for the discrepancy between the observed moisture content and the moisture content predicted by the logarithmic model. Several researchers (Misra and Brooker, 1980; Wang and Singh, 1978a; Agrawal and Singh, 1977; Bakshi, 1979; White, Ross and Poneleit, 1981) have used an equation first proposed by Page, adding an empirical exponent to time in the equation producing:

$$MR = \exp(-Kt^a) \qquad 2.32$$

where:
a = an additional empirical constant.

Rewriting this equation with moisture content as a function of time produces:

$$M(t) = (Mi-EMC)*\exp(-Kt^a)+EMC. \qquad 2.33$$

Researchers who have used Page's equation have found that it generally fits the data better than the logarithmic model. Misra and Brooker (1980) examined selected data from ten different researchers on the thin layer drying of shelled corn and found Page's equation to fit the data well. They used a sophisticated model for EMC, developed by Bakker-Arkema et al. (1974) and used a five-parameter model of Page's form. They found that the R^2 of the curve fit varied from 0.973 down to 0.801 for the individual data sets with an overall R^2 of 0.967. Because R^2 is not of great value when comparing the fit of an equation to different sets of data the mean square error was calculated from the data Misra and Brooker reported. This statistic varied from 1.5 to 8.0 with a value of 2.15 for the combined data. This mean square error was calculated from the moisture ratio in percent not the moisture at time t, as will be done later in this work.

Comparing Page's equation with the logarithmic equation, Page's equation should be able to fit the data better because the exponent on time can cause the exponential decay to curve slightly, increasing the slope at small time and decreasing the slope at larger time. If the moisture ratio could be measured over time, then Page's equation could be linearized and for that reason the regression required to choose the parameters with Page's equation would be much simpler mathematically than with Newman's form of the equation.

Henderson (1974), Henderson and Henderson (1968), Rowe and Gunkel (1972) and Sharaf-Eldeen, Hamdy, and Blaisdell (1979b) found that a two or three term exponential model produced good results. This model has the strongest theoretical base. Henderson (1974) used graphical methods of regression and thus did not report the goodness of fit of his data.

Sharaf-Eldeen, Hamdy, and Blaisdell (1979b) modeled the parts of the total moisture equation separately and obtained regression fits to three equations: EMC, overall two term exponential decay, and drying constant. For the EMC equation they reported an R^2 greater than 0.99. For the individual drying curves they reported an R^2 "consistently" greater than 0.98. Finally, for the drying constant they reported that both the initial moisture and the temperature were important variables but that the R^2 was 0.67. This R^2 value is low indicating that the drying constant was not well predicted by their model. They used the same model for the drying constant, equation 2.4, that was used by Chu and Hustrulid (1968a) and by Husain, Chen and Clayton (1973). Unfortunately, they did not report any details of the nature of the lack of fit of this equation to their data nor the technique used in approximating the parameters.

2.2.3.3 Empirical Models

Numerous empirical models have been introduced to the literature. However, because in this study it is desired to use a model with some theoretical basis they will not be reviewed here. Theoretically based equations have the advantage that there is some hope of extrapolating the results from one study to wider ranges of variables and even to other products. There is no justification for the extrapolation of purely empirical equations.

2.2.4 Studies of Rice Drying

Allen (1960) studied the deep bed drying of rice and corn (maize). He developed prediction equations of the grain temperature and moisture content over time. Because he concentrated on the deep bed relationships, however, his work is of limited use in this investigation despite the fact that the ultimate goal of thin layer drying studies is to predict the behavior of the grain in a deeper bed.

Agrawal and Singh (1977) studied short grain rough rice drying with the relative humidity held constant at 0.26 and varied the temperature from 32 C to 51 C. They also conducted studies with the temperature held constant at 51 C and varied the relative humidity from 0.1875 to 0.85. They used Page's equation for the form of the thin layer equation and the Chung-Pfost equation to calculate equilibrium moisture content. They reported that the error mean square comparing the predicted moisture ratio to the observed moisture ratio was 0.0007665.

Wang and Singh (1978a) used one set of data from a thin layer study of rice to try to find a suitable prediction equation. They concluded that the theoretical diffusion model did not predict values which agreed well with their experimental values but did not report any statistics.

Wang and Singh (1978b) tested one variety of medium grain rough rice at thirty different drying air temperatures and humidities. They compared four equations and chose an equation quadratic in time as the best, partially based on the residual mean square from a nonlinear regression and partially based on practical application. They reported that the three semitheoretical equations: a one term exponential decay with six parameters, Page's equation with six parameters, and a quadratic equation with six parameters all fit the data equally well with an error mean square of about 0.00045 when comparing the predicted moisture ratio to the observed moisture ratio. They also used a theoretical diffusion model based on spherical product geometry and found that the theoretical model was not as good as the other models with an error mean square of 0.000971. Because the focus of their study was to obtain models applicable to drying for short periods of time, only data covering the first forty minutes of drying were included.

Sharma, Kunze and Tolley (1982) reported on a "two compartment model" for the moisture relationship in long grain rough rice. They argue that each material in the product displays an independent moisture-time relationship and that each is modeled by one term exponential decay. Noting that there are three parts to rough rice, hull, bran, and endosperm, they proposed a three term exponential model. This is the same form suggested by strictly diffusion arguments for uniform products.

Twelve experiments, containing 6 replications, were conducted on samples of grain at three temperatures, 24 C, 43 C and 56 C. At the end of 2, 10, 18 and 24 hours they determined the moisture content. They then used nonlinear regression techniques to determine the parameters in a logarithmic model and a two term exponential model. They did not report the relative humidity of the drying air and did not control the relative humidity of the drying air, although they show that it was constant over time. They did not report any measure of how well the curves fit the data but did show graphically the confidence interval on the data. The confidence intervals appeared to be about 0.01 to 0.02 moisture content dry basis. They reported six equations:

for drying temperature of 24 C

$$M(t)=15.13+3.60*\exp(-0.310*t) \quad (2.34)$$

$$M(t)=12.01+3.01*\exp(-0.0006*t) +3.97*\exp(-0.4*t) \quad (2.35)$$

for drying temperature of 43 C

$$M(t)=8.23+12.38*\exp(-0.426*t) \quad (2.36)$$

$$M(t)=4.99+3.54*\exp(-0.0048*t) +12.08*\exp(-0.4387*t) \quad (2.37)$$

for drying temperature of 56 C

$$M(t)=6.18+13.71*\exp(-0.528) \quad (2.38)$$

$$M(t)=3.66+3.73*\exp(-0.0223t) +12.52*\exp(-0.6095*t) \quad (2.39)$$

Bhattacharya and Swamy (1967) studied the drying of parboiled rice as it related to breakage of the rice. They presented several plots of moisture content vs. time but did not attempt to describe the drying mathematically. In addition, the drying of the parboiled rice was not well controlled but rather was done by spreading the product in a thin layer and exposing it to ambient conditions. They concluded that drying methods have a substantial impact on the quality of the finished parboiled rice.

Only one study of the drying of parboiled rice was found in the literature where a mathematical model of the drying was attempted. In this study (Bakshi 1979), the emphasis was on the parboiling process itself and not on the drying aspects. He dried one variety of short grain rice which had been parboiled in a laboratory parboiling apparatus. He concluded that parboiled rice dries at about the same rate as brown rice and considerably faster than rough rice. He theorized that the husk, which offers considerable resistance to drying in rough rice (Steffe and Singh 1980a) offers little resistance in parboiled rice.

Bakshi used a form of Page's equation (2.32) to model the drying of parboiled short grain rice. His study included both parboiled rough rice and parboiled brown rice. He reported that for parboiled rough rice:

$$K = 0.503265+0.0002734*T-0.0001760*RH \qquad 2.40$$
$$a = 0.064445+0.0046369*T-0.0147194*RH \qquad 2.41$$

and for parboiled brown rice:

$$K = 0.016538+0.000173684*T+0.0064722*RH \qquad 2.42$$
$$a = -.7766099+0.001417332*T+0.07367*RH \qquad 2.43$$

where:
T = Temperature C
RH = relative humidity, percent.

Bakshi reported a residual sum of squares for the regression of the parboiled rough rice data to be 0.331 and the residual sum of squares for the regression of the parboiled brown rice data to be 0.174 when the predicted moisture ratio was compared with the measured moisture ratio and 66 degrees of freedom in each case.

Singh has continued the work begun by Bakshi on the thin layer modeling of parboiled rice.* He and P. K. Chandra assumed that the long grain rice behaved as infinite cylinders. They determined the diffusion constant D as a function of temperature. The equation they used for diffusion in an infinite cylinder was:

$$MR = \Sigma\, 4/(a^2 * R_n{}^2) * \exp(-D * R_n{}^2 * t) \qquad 2.44$$

where: t = time, hours

R_n = roots of the Bessel Function

a = radius of infinite cylinder

Their model for the diffusion coefficient was:

$$D = 0.0149668 * \exp(-3748.60/T) \qquad 2.45$$

where: T = the air temperature, absolute

D = diffusion coefficient, meters^2/hr.

For the EMC model they used a model developed by Kachru and Matthes (1976) for long grain rough rice. This model was:

---

* R. P. Singh 1983: personal communication.

$$EMC = 4.510+0.069*RH+8.837*RH^{0.5}-0.015*T*RH^{0.5} \qquad 2.46$$

where: T = temperature, Rankine
RH = relative humidity, percent
EMC = equilibrium moisture content, percent, d. b.

The equilibrium moisture content of rice has been studied by several researchers. Karon and Adams (1949) studied the hygroscopic equilibria of rice using different salt solutions to maintain the environment for the rice. Their tests lasted for forty days. They presented their results in graphic form and did not publish an equation.

Hogan and Karon (1955) studied the equilibria of rough rice at three temperatures and several relative humidities. They concluded that the moisture is adsorbed in three different modes, the first from 0.0 to about 0.07 (dry basis) considered to be unilayer adsorption, the second from 0.07 to about 0.14 considered to be a second layer of adsorption, and the third above 0.14 considered to be multilayer adsorption. They did not publish a mathematical model of their data. Juliano (1964) found that the EMC varies considerably with the variety of the rice. He studied four varieties at two temperatures and five relative humidities. He also published his data in tables only.

Zuritz et al. (1979) published a study of the EMC values of rough rice in the temperature range from 10 C to 40 C and relative humidity from 0.112 to 0.863. The air moisture content was maintained by salt solutions. They used three equations: Day-Nelson, Chung-Pfost and a semi-empirical equation they originated. They concluded that there was no difference among the predictions of the three equations. They reported an average root mean square error of from 0.24 to 0.31 of the EMC when expressed as whole percent dry basis.

Pfost et al. (1976) and ASAE (1982) reported the equilibrium moisture content parameters for eleven products for the two preferred equations. They reported the standard error (root mean square error) to be 0.0097 dry basis for the Henderson-Thompson equation and 0.0096 for the Chung-Pfost equation for rough rice. The equation for rough rice from data collected from five researchers for the Henderson-Thompson equation is:

$$EMC = (\ln(1-RH)/-1.9187/(T+51.161))^{(1/2.4451)}/100 \quad 2.47$$

and the Chung-Pfost equation is:

$$EMC = 0.29394-0.046015*\ln(-(T+35.703)*\ln(RH)) \quad 2.48$$

where: T = temperature in Celsius

No information was found in the literature on the modeling of the equilibrium moisture content of parboiled rice. Bakshi (1979) calculated moisture ratios and therefore used EMC values, when working with parboiled short grain rice, but did not include a prediction equation for the EMC. For the EMC value, he used the moisture content of the product at the end of the data collection period, usually about twelve hours.*

Bakshi (1979) in his study of parboiled short grain rice also assumed a spherical particle shape and found the following relationships for the diffusivity over the temperature range from 40.6 C to 56.1 C:

raw rough	$D = 33029. * \exp(-8624.3/T)$	$R^2 = 0.99$
raw brown	$D = 0.7979 * \exp(-4933.3/T)$	$R^2 = 0.91$
parboiled rough	$D = 411.86 * \exp(-6977.7/T)$	$R^2 = 0.98$
parboiled brown	$D = 401.62 * \exp(-6743.6/T)$	$R^2 = 0.97$

Bakshi found that both parboiled rough and parboiled brown rice behaved about the same and at temperatures in the range of 305 K to 320 K both kinds of parboiled rice responded nearly the same as the brown rice. He concluded that the resistance to moisture movement in rough rice was mostly in the hull and that in parboiling, the hulls were split so that the parboiled rice behaved much like brown raw rice.

In his conclusions, he stated that there is no constant rate drying in parboiled rice even at moisture contents as high as 0.60 and that the Arrhenius relationship was found to be valid in parboiled rice.

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* Amarjit Bakshi 1983: personal communication.

Steffe and Singh (1980a and 1982) studied the diffusivity of short grain rice endosperm, bran and hulls. They assumed a spherical shape for the rice and found the diffusion coefficient to depend only on the product temperature, thus obtaining the following Arrhenius relationships for rice components over the temperature range of 35 to 55 C:

endosperm	$D = 0.00257 * \exp(-2880/T)$	
bran	$D = 0.797 * \exp(-5110/T)$	
hull	$D = 484. * \exp(-7380/T)$	
whole rough	$D = 33.6 * \exp(-6420/T)$	$R^2 = 0.93$
whole brown	$D = 0.141 * \exp(-4350/T)$	$R^2 = 0.85$

where:
T = temperature deg. Kelvin

The slopes of the diffusivity-temperature relationships are similar but the diffusivities vary greatly. The hull has the greatest resistance to moisture movement, the bran has an intermediate resistance and the endosperm displays the least. They did not find that the diffusion was concentration dependent in the range of moisture contents studied (0.33 to 0.14).

Husain, Chen and Clayton (1973) applied coupled heat and mass diffusion models to the moisture loss in rough rice. They concluded that diffusion depends upon both the temperature of the rice and the concentration of the moisture in the grain. Their model with parameters was:

D=Pl*exp(P2/T)*exp((P3*T+P4)*M(t)) 2.49

where:
P1 = 94.8787
P2 = -7730.65
P3 = 8.833 E-4
P4 = -0.3788
T = product temperature, K
M(t) = moisture content, dry basis percent
D = the diffusion coefficient, cal/g F

2.3 Thin Layer Drying Laboratory Equipment

Relatively few researchers have described the equipment used in their studies of thin layer drying in any detail. Among those who have are Young and Whittaker (1971), Ross and White (1972), Rowe and Gunkel (1972), Henderson (1974), Agrawal and Singh (1977), and Stone and Kranzler (1981). These researchers used equipment of varying levels of sophistication and described what they used in varying detail. None of them provided much information on how to design thin layer drying study equipment.

Rugumayo (1979) described equipment with which he obtained thin layer drying data for shelled corn. His equipment used an Aminco-Aire unit to control drying conditions. The equipment monitored the drying conditions and the weight of the product as it dried and stored the data on paper tape at hourly intervals. His tests ran for 16 to 32 hours and did not reach equilibrium. It was difficult to control the temperature and relative humidity with his equipment and the analysis of his data by Misra and Brooker (1980) showed that the resulting data did not fit Page's equation as well as had previous data.

Solvason and Hutcheon (1965) provided an excellent introduction to the problems encountered in the design of the drying study chamber. They emphasized the psychrometrics involved, as well as the choice of enclosure and conditioning equipment in the construction of controlled environment cabinets, chambers of less than room size. They noted that mass and energy balances can be written which describe the product, the cabinet, the conditioning equipment and the environment. These balances will often give rough estimates of the important parameters to be considered in the chamber design. From these equations one can conclude that the conditions throughout the chamber can never be uniform as long as there is heat and/or moisture transfer, and that the degree of nonuniformity will depend on the rate of heat and moisture transfer and the air flow rate between the chamber and conditioning equipment.

Solvason and Hutcheon discussed the problem of mixing the conditioned air with the stale air around the product, the problems due to radiation if there are significant differences in temperature between the chamber and environment, and the problem of control. They stated that often a simple on/off controller is sufficient. They stated that the simultaneous control of temperature and relative humidity, as is desired in this study, presents special problems. These two parameters are associated through psychrometrics and one cannot be simply controlled independently of the other.

An additional problem is that it is impossible to accurately control a parameter which cannot be accurately measured either directly or indirectly. Fisher, Lillevik, and Jones (1981) discussed the measurement of relative humidity and the inherent problems in measuring it. Because the water vapor pressure cannot be measured directly some secondary parameter must be used. Wet and dry bulb temperatures or vapor saturation temperature (dew point) are commonly used.

Considering a psychrometric chart and the effect of temperature measurement errors on the calculated relative humidity, it can quickly be determined that the error in relative humidity due to a temperature measurement error depends upon the section of the chart in which the error is made. For example, consider a case where the dew point is 5 C and a one degree error in dry bulb temperature is made; the resulting error in relative humidity is approximately 0.08 if the air were nearly saturated and only about 0.01 if the air were rather dry. However, for any dry bulb temperature in the range 0 to 40 C, an error in dew point of one degree will result in an error in relative humidity of about 0.08 for any degree of saturation of the air.

2.4 Direct Digital Control

Man has long striven to control the processes about him. A major portion of engineering has been devoted to control of processes and machines. For many years the more complicated processes required a human to operate the controls and as engineering progressed the human controller became more powerful. Analog computers were and are able to perform well as controllers, but digital computers are more flexible and easily programmed. However, until recent years the digital computer was too expensive to devote solely to control. The microprocessor, an inexpensive digital computer, has provided engineers a powerful tool in direct digital control.

A considerable body of literature and terminology has grown around the branch of engineering concerned with control. Much of this discipline requires an extensive knowledge and complete mathematical description of the process which is to be controlled. Sometimes the expense in time and money is justified but in many cases the mathematical description of the process is too expensive to obtain.

In the control literature a process, referred to as the "plant", for which the basic differential equations are not known is considered to be an "unknown plant". The literature applied to the problem, direct digital control of an unknown plant, is much scarcer than the literature applied to digital control of a known plant. Johnson (1977) provided a good introduction to the field of digital control.

The first step in control is to define a desired reaction in the plant to be controlled. For example, it may be desired to maintain a water bath at a constant temperature. Ideally, the pertinent variable is measured, either directly or indirectly. In this example, a thermometer may measure the water temperature. The controller then compares the desired output, the water temperature, with the actual output and obtains an error. This error is used to adjust a control element, in this example, a water heater. The controller is designed to maintain nearly zero error.

In a digital controller the value of the variable, or variables, is represented by a digital code. The controller compares the code with the desired code, operates on the difference using the control algorithm and then adjusts the control element. The digital controller cannot follow the process continually but must make a measurement of the process, do the necessary computations with that reading, then make the necessary adjustment on the control element. The entire process is repeated, leading to the use of difference equations instead of differential equations.

Bibbero (page 161, 1977) described the proportional-integral-differential, PID, algorithm in difference form. If E(1) is the most recently measured error, E(2) the previous error, etc., and I, J, and H are the gains in the proportional, integral, and differential portions of the controller, respectively; the algorithm takes on the form:

```
DS = I*(E(1)-E(2))+J*E(1)
                       +H*(E(1)-2*E(2)+E(3))     2.50
```

where:
DS = the change in setting of the control element.

This algorithm, referred to as a velocity PID algorithm, has several advantages over other possible algorithms. It is relatively simple computationally; the terms have physical significance and are therefore easier to understand than some other algorithms; it is "bumpless" which means that it responds smoothly to step changes in the measured variable; and it is usable with an unknown plant. A relatively simple method can be used to adjust the gain coefficients until nearly optimal response of the system is obtained (Smith 1979).

3. OBSERVATIONS AND OBJECTIVES

The goal of this research project is to improve upon current techniques of thin layer drying data acquisition and modeling. Because the effects of temperature and relative humidity on drying are nonlinear, nonlinear data analysis and regression techniques will be used. Transformations on the data, which make the data analysis simpler but distort the effects of the error inherent in all data, will not be used. Rather the relationship of the variables will be used directly to avoid distorting the effects of errors. The parameters resulting from proper data treatment should predict the observed data better than the parameters resulting from the traditional methods.

The form of the model under which all thin layer data is collected is:

$$M(t) = f(t, T, Mi, RH) \tag{3.1}$$

where: $M(t)$ = the moisture content at time t
t = the time
T = the temperature
Mi = the initial moisture content of the product
RH = the relative humidity of the drying air.

The researcher measures the moisture content of the product at a known time after it has been subjected to a known relative humidity and temperature. The moisture content data are collected differently by different researchers. The form of the model, however, is the same whether the moisture content is estimated from a weight measured as the drying test is running, or if the weight is measured by removing the sample momentarily from the drying apparatus, or if the moisture content is estimated by removing subsamples periodically from the sample and measuring their moisture content.

Usually the relative humidity and temperature are held constant while one sample is dried and then the procedure is repeated at a different relative humidity and temperature. In this case the model for each individual test may be rewritten as:

$$M(t)_{T,RH} = f(t, Mi, EMC_{T,RH}) \qquad 3.2$$

where: $EMC_{T,RH}$ = the equilibrium moisture content.

The subscripts emphasize that the model is useful only at one combination of relative humidity and temperature. The subscripts will not be repeated further but the equation should be understood to apply to only one combination of relative humidity and temperature.

3.1 Constant Relative Humidity and Temperature

Two of the simpler models for the relationship between the factors in equation 3.2 which have received much attention in the grain drying literature are the logarithmic model and Page's model. The logarithmic model produces:

$$M(t) = (Mi-EMC)*\exp(-K*t)+EMC \qquad 3.3$$

where: K = the diffusion constant.

Some researchers treat EMC as a known constant and others treat it as a parameter to be estimated by regression. Likewise, the quantity (Mi-EMC) is treated as a known constant by some and an unknown parameter by others. If both EMC and (Mi-EMC) are treated as known constants the equation may be rewritten by the transformation:

$$Y = \ln((M(t)-EMC)/(Mi-EMC)) \qquad 3.4$$

where: Y = the transformed dependent variable.

The quantity of which the logarithm is taken in equation 3.4 is observed to be the moisture ratio. Using eqution 3.4, equation 3.3 is transformed to:

$$Y = -K*t \qquad 3.5$$

Equation 3.5 is linear and a value for K can easily be obtained from a set of data. However, as observed in section 2.1, transformations on the dependent variable such as equation 3.4 must be done carefully, i.e. examine the residuals for evidence of nonuniform variance. The assumption that the errors in the measured values for M(t) are normally distributed and constant over the range of the independent variable, time, is more reasonable than the assumption that the errors in Y after the transformation 3.4 are normally distributed and constant over the range of the independent variable. The more reasonable approach, therefore, is to not transform the data but to analyze the data by nonlinear methods assuming a model of the form of 3.3. In either case, whether model 3.3 or 3.5 is used the residuals should be carefully examined before anything is said about the suitability of the model.

If EMC in equation 3.3 is considered to be an unknown parameter, the equation is intrinsically nonlinear and must be treated by nonlinear methods. Therefore, when the logarithmic model is used the use of nonlinear regression techniques is preferable to the use of transformations. Moreover, if EMC is unknown, nonlinear regression techniques must be used.

The next model to be considered is Page's equation. Inserting this model in equation 3.2 produces:

$$M(t) = (Mi-EMC)*\exp(-K*t^{a})+EMC \qquad 3.6$$

where: a = the parameter added by Page.

In the case of equation 3.6, if either Mi or EMC is unknown the model is intrinsically nonlinear and must be treated by nonlinear regression techniques.

In the case where Mi and EMC are considered to be known constants for the particular temperature and relative humidity of the test, a transformation will simplify the estimation of parameter values. First the known Mi and EMC are moved to the same side of the equation as M(t):

$$(M(t)-EMC)/(Mi-EMC) = \exp(-K*t^{a}) \qquad 3.7$$

If the logarithm is taken twice and the substitution made:

$$Y = \ln(-\ln((M(t)-EMC)/(Mi-EMC))) \qquad 3.8$$

equation 3.7 becomes:

$$Y = \ln(K)+a*\ln(t) \qquad 3.9$$

Given the data of the value of Y at different times t, the values for K and a may easily be determined. Of course the same comments apply to the model incorporating Page's equation as in the model incorporating the logarithmic model, with regard to the errors of the measured dependent variable, M(t), compared with the errors of the transformed dependent variable Y. In fact, because the logarithm of the moisture ratio is taken twice it is even more unlikely that the errors about Y will be normally distributed and uniform over the range of the independent variable, now transformed to ln(t).

In the case of Page's equation, as in the case of the logarithmic equation, the use of the measured dependent variable is desirable in regression. In the case where either Mi or EMC is to be determined along with the other parameters the use of nonlinear regression techniques is required.

The more complex models such as the two term exponential model, equation 3.10, or the even more complex three term exponential model are intrinsically nonlinear and cannot be treated except by nonlinear regression techniques.

$$M(t) = (Mi-EMC)*(P1*exp(P2*t)+P3*exp(P4*t)) + EMC \qquad 3.10$$

where: P1,P2,P3,P4
= the parameters to be estimated

3.2 Relative Humidity and Temperature Variable

In modeling the drying curves obtained at a constant relative humidity and temperature, nonlinear regression techniques are desirable and in many cases required for proper treatment of the data. Curves of moisture content vs. time are obtained at discrete values of temperature and relative humidity over the range of temperature and relative humidity of interest. The intent is to create a model which will be useful at any combination of relative humidity and temperature within the range for which the data were collected.

The method common to much of the recent drying literature is for the researcher to have a model for EMC and another model for diffusion constant which is to be inserted in the model for moisture content vs. time. Assuming that the model for EMC is the Chung-Pfost equation (although the argument is the same for any of the currently popular models of EMC) and that the Arrhenius model is to be used for the drying constant, the logarithmic moisture content vs. time model takes the form:

$$M(t) = (Mi-P1+P2*\ln(-(T+P3)*\ln(RH))) *\exp(-P4*\exp(P5/T)*t) +P1-P2*\ln(-(T+P3)*\ln(RH)) \qquad 3.11$$

where: P1,P2,P3,P4,P5
= parameters to be estimated.

Equation 3.11 is nonlinear in both the variables, RH, T, t, and Mi, and the parameters. Statistically, the most desirable approach is to use the data to fit the parameters P1-P5 with nonlinear regression.

The researcher may be working with a product which has a model of EMC where P1, P2 and P3 are known. The effect of temperature on the drying constant as well as the moisture content at time t may be obtained by linear regression. The EMC model and Mi are combined with M(t) to produce the moisture ratio and logarithms are taken of both sides producing:

$$\ln(MR) = -P4*\exp(P5/T)*t \qquad 3.12$$

Taking logarithms of both sides again and using the substitution:

$$Y = \ln(-\ln(MR))$$

produces:

$$Y = \ln(P4)+P5/T+\ln(t). \quad 3.13$$

If the same treatment is used with Page's equation, the Arrhenius form may be substituted into equation 3.9 producing:

$$Y = \ln(P4)+P5/T+a*\ln(t). \quad 3.14$$

After the transformations the parameters in equations 3.13 and 3.14 may easily be estimated by linear regression. The only questions about the process are whether, because of the transformations, the assumptions on which linear regression is based are violated, and if they are, in what way the results of the regression are affected. These questions remain unanswered in the grain drying literature.

A more important question involves what effect moving the model for EMC (containing the variables temperature and relative humidity) from an unknown parameter to a known variable has on the overall model. There is no reason to assume that the model for EMC produces errors which are significantly lower than the errors elsewhere in the model. In fact, models for EMC for eleven agricultural products have standard errors associated with them from 0.006 to 0.03 (ASAE 1982). With final moisture contents of 0.10 the error is 30 percent.

The best way to determine the effect these errors have on the overall model is to collect data of moisture content vs. time for a range of temperatures and relative humidities. Nonlinear regression techniques should then be used to analyze all of the parameters involved even in the cases where it would be mathematically possible to use linear regression.

The most reasonable assumptions about the errors in the dependent variable in thin layer moisture relationships of agricultural products require starting with an equation of the form of 3.1. The appropriate substitutions are then made producing an equation such as 3.11 containing only variables which can be measured and the parameters which will be estimated by nonlinear regression techniques. A series of tests are conducted controlling the variables and varying them as appropriate. Finally the data are fit to the nonlinear equation.

Following the approach described in the previous paragraph allows much more to be concluded about the model than could be concluded if the traditional approach were used. When the observed data are regressed against a model such as equation 3.11, the model as a whole can be tested for adequacy. In addition, each parameter can be tested to determine its significance and the parameters, if any, which are not significant can be removed from the model. Also, the relative importance of each variable can be observed more easily and possible interactions between the parameters in the model can be observed. The preceding method of experimentation coupled with computer programs for nonlinear regression constitute an improvement over the method of researchers who have had to limit themselves to mathematically simple models, make dubious transformations and make dubious assumptions about errors.

All of the currently popular thin layer models are nonlinear in the variables and all are also nonlinear in the parameters if EMC is not known. The errors associated with EMC indicate that (when it is obtained from a model) EMC is a significant source of error and should not be treated as a constant with zero error. In addition, the theoretical diffusion-based model, assuming the resistance to diffusion is not simply located at the surface of the particles, is nonlinear in form. Despite these facts, no study of the thin layer drying of an agricultural product has been published in which the observed data has been regressed against the complete model, including EMC and drying constant with nonlinear methods.

3.3 Obectives

In order to accomplish the overall goal of improving current thin layer drying study techniques these specific objectives were formulated.

A) Design and construct equipment capable of measuring, controlling and recording the air temperature and relative humidity over time and measuring and recording the moisture content of an agricultural product over time.

B) Collect data at small time intervals on an agricultural product, parboiled rice, at several constant relative humidities and temperatures and analyze the data to:

1) determine the most appropriate form for the thin layer equation at a constant relative humidity and constant temperature. Four forms will be considered:

   a) the logarithmic model, i.e. the resistance to moisture movement is at the particle surface,

   b) a series of decaying exponentials, i.e. the resistance to moisture movement is distributed throughout the particles,

   c) Page's empirical equation, and

   d) models based on regular particle geometry and distributed resistance to moisture movement.

2) determine if the results are affected by collecting thin layer data at different intervals and for different lengths of time. There are two questions:

   a) how frequently should data be collected to obtain parameter estimates and at what times should the observations be made?

   b) How long should data be collected to obtain reasonable estimates of EMC?

3) obtain a complete model of the product in the form:

$$M(t) = f(t, T, RH, Mi) \qquad 3.1$$

   This model will contain implicitly an EMC model, an Arrhenius equation for the drying constant, and a model of moisture content vs. time.

4. EQUIPMENT

The first objective was to build equipment with which thin layer drying studies could be made. This equipment must be able to control the main independent variables, the drying air temperature and relative humidity. It also must be able to measure the main dependent variable, the moisture content of the product. All of these variables must be recorded over time.

4.1 Organization of Equipment

Figure 4.1 shows the air flow in the equipment. The air entered the Aminco-Aire unit (Aminco-Aire, 1967) and was saturated by a mist of water. The water temperature was controlled by a refrigeration unit or an electric heater as needed. Next, the air passed into a chamber where it was heated (without adding moisture) by another electric heater. Thus, the air temperature and relative humidity were controlled as the air left the Aminco-Aire unit. The air next passed through a circulation fan and then into the study chamber. After the air left the chamber it recirculated through the Aminco-Aire unit.

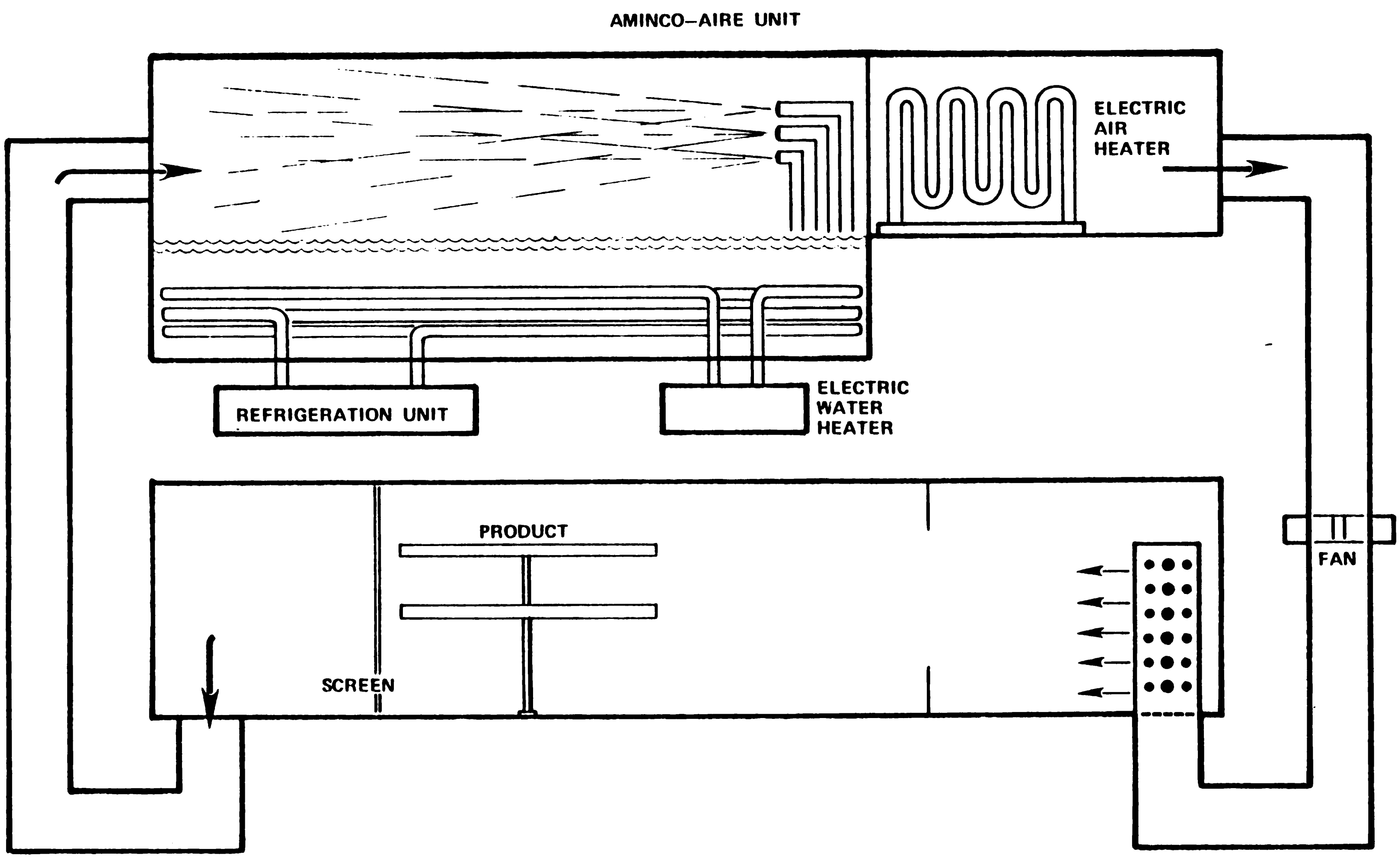

Figure 4.1 Air Flow in System

Figure 4.2 shows the information flow in the data acquisition and process control equipment. There were two types of sensors in the system, weight sensors and temperature sensors. Temperature sensors were located in the water bath, near the electric air heater, in the air stream as it entered the study chamber and near the sample in the chamber. These sensors monitored the drying conditions for the product. The product was located in the chamber on trays which were attached to load cells so that the weight of the sample and trays could be monitored. Each type of sensor required different signal conditioning before the information could be converted from an analog signal to a digital one. The microcomputer contained instructions to 1) store the data on digital tape, 2) display the data on paper through the line printer and, 3) use the information to control the air conditioning unit.

4.2 Microcomputer

The microcomputer consisted of 4 boards interconnected by an S-100, IEEE (Institute of Electrical and Electronic Engineers) standard 696, bus. The IEEE-696 standard had not been written when some of the boards used in this system were designed so not all of the boards would meet the standard but this particular set of boards worked well

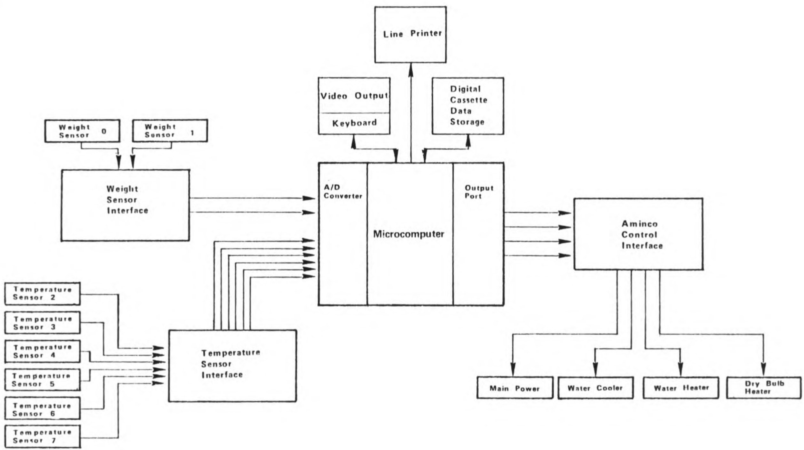

Figure 4.2 Block Diagram of Process Controller

together. The heart of the microcomputer was a Z-80 microprocessor on a Cromemco Single Card Computer, SCC, (Cromemco, 1980) which also contained 8K of read only memory, ROM, and 1K of random access memory, RAM. Other functions contained on the Cromemco SCC were a serial port (for communication with the printer or video terminal), a parallel port (for control of the air conditioning unit), another parallel port (for communication with the digital cassette deck), and one status port (for control of the communication with the digital tape deck).

A second board in the system was a California Computer Systems 16K RAM board (California Computer Systems, undated), providing additional RAM. A third board was a Vector Graphics 12K-ROM/RAM board which has 1K of RAM and up to 12K of ROM (Vector Graphics, undated).

The final part of the system was the TecMar analog to digital, A/D, converter unit (TecMar, 1980). This two board set contained a Data Translation 5712 module which provided software controlled gain, multiplexing of 16 input channels and 12-bit analog-to-digital conversion. Because the A/D converter was multiplexed, the eight transducer signals could be connected directly to the module after signal conditioning. The 12-bit A/D converter provided a precision of 1 part in 4096, adequate for the range of values encountered in this study. This unit also contained an Advanced Micro Devices Am9513 timing controller chip, which was used as a "real-time" clock providing time in days, hours, and seconds as well as providing an interrupt to the microprocessor every 40 milliseconds, mS, as required by the control and data acquisition software.

4.3 Transducers and Microcomputer Interface

Because only temperatures and weights were measured there were only two types of sensors and two signal conditioning circuits to consider. After the signal conditioning equipment was constructed and the transducers connected to the microcomputer system the transducers were calibrated.

4.3.1 Temperature Transducer

The temperature sensor used was the National Semiconductor precision temperature sensor LM335 (National Semiconductor 1980). This is a solid state integrated circuit device which operates as an improved zener diode. The voltage output has a linear relationship with absolute temperature of about +10mV/K. The device operating temperature range is -10 C to +100 C and the corresponding typical nonlinearity over that range is 0.3 C (National Semiconductor 1980).

Because the design temperature range for the laboratory equipment was at most 50 C and the majority of the expected nonlinearity is at elevated temperatures (National Semiconductor 1980) the expected nonlinearity in the range 5 C to 50 C was no more than 0.15 C.

After the temperature sensor circuits were assembled they were tested against a laboratory mercury thermometer marked in 0.1 C. The sensors were used in a temperature control algorithm during calibration to hold the temperature as constant as possible by controlling the air conditioning unit. The water temperature sensors were calibrated in water and the air temperature sensor calibrations were conducted in air. No nonlinearities were detected in any of the six sensors used. Table 4.1 shows the results of the calibration. In all cases the correlation coefficient, r, was greater than 0.9999.

Table 4.1 Conversion Factors from Digital to Temperature

Sensor Number	A	B
2	0.00393	-18.85
3	0.00399	-19.00
4*	0.32	-15.9
5	0.00392	-19.05
6	0.00392	-18.79
7	0.00399	-18.52

* Approximate

Predicted Temperature = A*(digital value) + B

The conversion factors for sensor 4 are only approximate because its conversion factors were not checked after the initial equipment was set up. Sensor 4 was used to measure the temperature of the air heater and its exact temperature was unimportant. The control algorithm depended on sensor 3 for the chamber temperature control and adjusted the heater temperature as needed to obtain the desired chamber temperature. The conversion factors did not change during the testing.

Six temperature transducers were chosen to allow for three to be used in the control algorithm leaving three to measure the air temperature around the samples. Three sensors allowed the temperature to be averaged among the sensors and also provided backup sensors in case of sensor failure. The sensors were inexpensive but the calibration time which was required before their use added considerably to the expense of each data point.

4.3.2 Temperature Transducer Signal Conditioning

Figure 4.3 shows the circuit used with the temperature sensors. Because the sensors produce 0V output at 0 K (nominal) and have a slope of 0.01V/K (nominal) they produce at least 2.5V at normal drying temperatures. If a constant voltage of 2.5V is subtracted from the output of the sensors before the signal is converted to a digital signal, the gain of the A/D converter can be higher, producing a correspondingly higher precision. This idea was implemented with a National Semiconductor LM336 integrated circuit voltage reference (National Semiconductor 1980) producing approximately -2.5V to add to the voltage output of the temperature sensors. A small RC

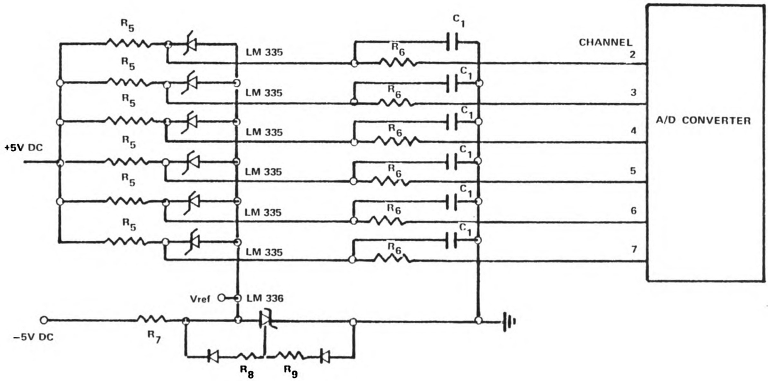

Figure 4.3 Circuit Diagram for the Temperature Transducers

passive filter, with a time constant of 2.2 ms, was used between the temperature sensors and the A/D converter to reduce noise.

4.3.3 Weight Transducer

The weight transducer used in this equipment was the 2 pound model 4850 built by GSE Inc (GSE, 1982). This device is a strain gauge device with 2 pound full scale capacity. Its rated nonlinearity is 0.02% of full scale or 0.2 grams, with half of that being typical. The operating temperature range was -18 C to 93 C (0-200 F); the temperature effect on rated output was 0.0004%/C (0.0008%/F) and the temperature effect on zero was 0.0008%/C (0.0015%/F). Two of the devices were used, one labeled weight transducer 0 and the other weight transducer 1 to allow two samples to be studied simultaneously. The transducers were located outside the chamber to minimize temperature effects. They would be expected to be affected to some extent by chamber temperature changes, even when located outside the chamber, but should be free of most of the temperature effect. In the case of high humidity conditions within the chamber the weight transducers would also be isolated somewhat from the moisture. The product was placed on trays made of aluminum screen attached to a rod which passed through the bottom of the chamber. There were two trays and one rod attached to each weight transducer.

The transducers were designed to be insensitive to moments and forces other than in the one direction of desired loading. The rated error per inch of off-center loading at 1/2 capacity was 0.004% of full scale or 0.04g. The transducers were loaded with a 100g. mass alternately at each of the corners and at the center of the screen tray. No discernible correlation between the mass location and the number in the computer was noted. The sample holder was designed so that the sample center of gravity was above the mounting for the support rods.

The weight transducers were loaded with known masses and the corresponding number in the microcomputer was noted. Since the relationship between the weight and the number in the microcomputer should be linear (according to the manufacturer's literature) a linear least squares curve fit was run to obtain the conversion factors from the number in the microcomputer to the actual weight, in grams. In all cases the correlation coefficient, r, was greater then 0.9999. Table 4.2 shows the conversion factors for transducer 0 and 1. Although the weight transducer measures force the calculations were made in grams, the unit of mass. Since all data were collected in the same room gravitational effects were constant.

Table 4.2 Conversion Factors from Digital to Weight

	Sensor Number 0	Sensor Number 1
A1	0.0366	0.0353
B1	-145.5	-156.8
A2	0.0364	0.0350
B2	-143.8	-155.8
A3	0.0360	0.0348
A3	-140.6	-152.3
A4	0.01627	0.01574
B4	-20.6	-52.9

Sample Weight = A*(digital value) + B

There were four sets of conversion factors used for the weight transducers. The first covered tests 3 and 4, the second tests 5 through 10, the third tests 11 to 17 and the last tests 18 through 21. In all cases the change in calibration was caused by changes in the system. The numbers associated with A and B refer to the order in time in which the different values were used.

The temperature measurement system was adequate from the beginning. At first the weight measurement system was not as accurate as was desired. The change between tests 4 and 5 was due to a change in the sample holder; the change between tests 10 and 11 was again due to a change in the sample holder; and the change between tests 17 and 18 was due to a change to a better excitation source for the weight transducer. At the end, tests 18 through 21, the weight measurements were more accurate than those at the beginning of the testing.

The equipment needed at least one half hour to warm-up properly before any reliable weight data could be collected. It was observed that calibrations completed before adequate warm-up were different than calibrations done after warm-up. However, the conversion factors after warm-up were stable. Because of this warm-up time the equipment was left with the power on for most of the testing period.

4.3.4 Weight Transducer Signal Conditioning

Due to the relatively low level signal obtained from strain gauge type sensors, an Analog Devices, model 2B31J, strain gauge signal conditioner was used as shown in Figure 4.4. This device includes an instrumentation amplifier with gain from 1 to 2000 and a low pass filter with a time constant of 0.5s. The excitation of the strain gauge bridge was regulated, at 6.9V, with a National Semiconductor LM399, a temperature stabilized integrated circuit precision voltage reference. A second LM399 was used with a voltage divider to provide an offset voltage which produced nearly 0V out of the strain gauge signal conditioner when there was no sample load on the weight transducer.

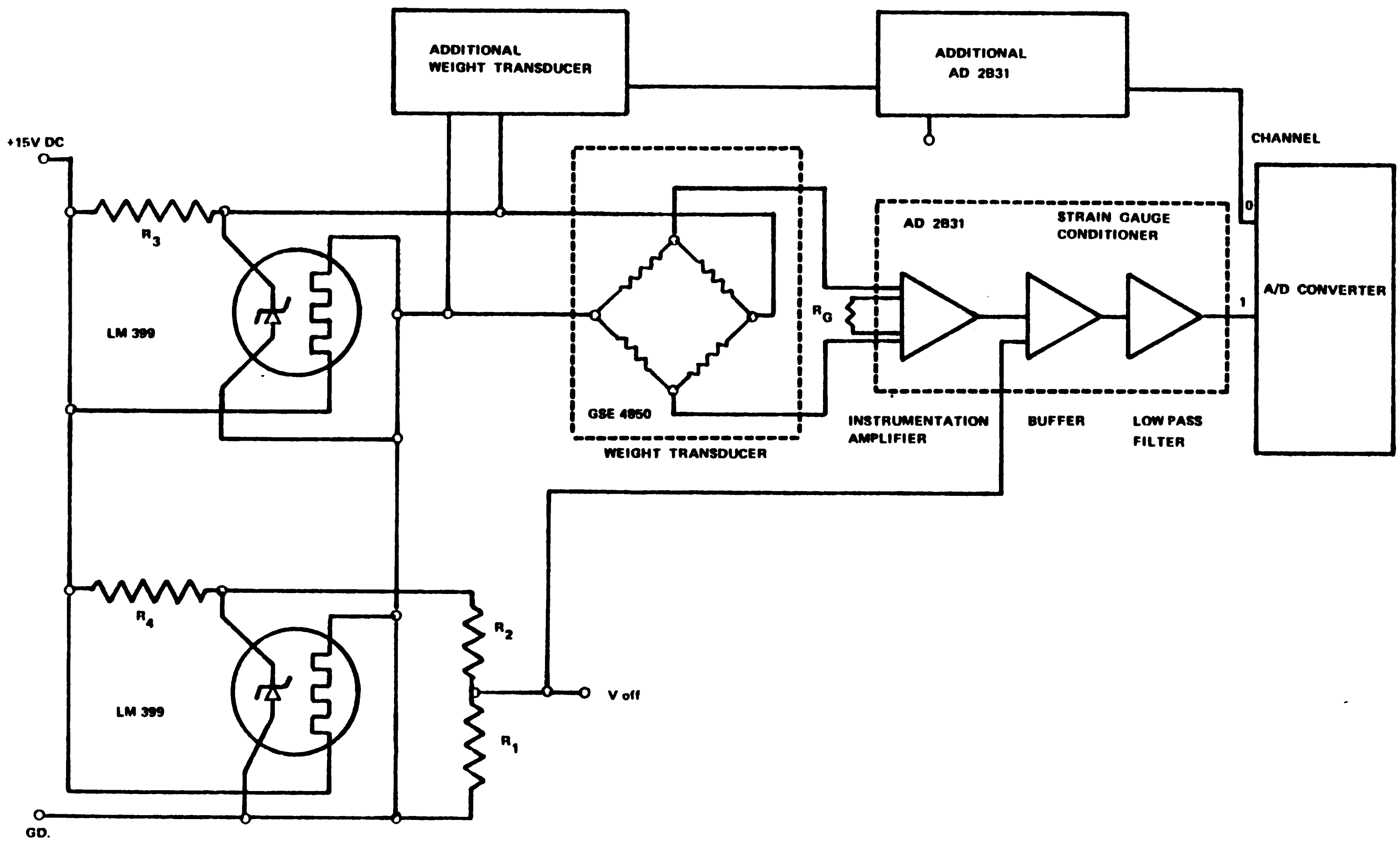

Figure 4.4 Circuit Diagram for Weight Transducer

A metal film resister was used to set the gain on the strain gauge signal conditioner at approximately 1880. This gain was near the maximum allowable on the unit and produced a precision of about 0.016 grams; while the transducer itself had a worst case precision of 0.26 grams. The total range with a gain of 1880 was about 65 grams which was adequate for the testing of grain. This range may not be adequate, however, for the study of products containing more than 50% moisture in which case the gain should be reduced.

4.4 Air Conditioning Unit

The unit which was used to condition the air was an Aminco-Aire model J4-5460 which can condition up to 8.5 cubic meters per minute (300 cubic feet per minute). This unit was designed to condition relatively small chambers of less than 1.1 cubic meters (40 cubic feet). The chamber used in this test had a volume of approximately 0.24 cubic meters and about 2.5 cubic meters per minute of conditioned air were circulated through it.

In the Aminco-Aire unit, the air moisture and temperature control are achieved in two steps. First the air passes into the larger chamber where there is a mist of water droplets spraying into the air. The droplets fall into a water bath the temperature of which is maintained by a refrigeration unit and electric resistance heater. Each water droplet is surrounded by air and thus heat and moisture transfer occur between the air and water droplet. The air then passes into a second chamber where it is heated by electric heaters. The air finally passes through the test chamber and is recirculated into the first chamber. The microprocessor based circuitry controls the temperature of the water bath and the duty cycle of the electric heaters which heat the air. Because the relative humidity is not measured, errors often encountered in measuring humidity are avoided.

There is a unique correlation between the Aminco water temperature, air dry bulb temperature and the relative humidity of the air. A chart of this relationship was provided by the manufacturer and a formula obtained by regression was calculated from the chart:

$$DB=P1+P2*\ln(RH)+P3*WT*\ln(RH)+P4/RH+P5*WT \qquad 4.1$$

where: DB = the dry bulb temperature, Celsius
RH = the relative humidity, percent
WT = the temperature of the water bath, Celsius
P1 = 77.4
P2 = -16.98
P3 = -0.0821
P4 = 73.7
P5 = 1.377

Once steady state conditions are reached the test chamber conditions should change very little because the load produced by the drying grain is very slight. A much greater load is the heat loss to the environment. This load does change during the test as the room temperature changes, but the change is relatively minor. By far the greatest load within the air conditioning system is the cooling and saturating of the air followed by the reheating of the air.

The Aminco-Aire operates on 208VAC three phase power and so voltage and power amplification were necessary from the 5VDC control signals coming from the microcomputer. The circuit is shown in Figure 4.5. When the equipment was first built the opto-isolated solid state relays were not readily available so regular opto-isolators, for noise and voltage isolation, were used with relays for power amplification and voltage translation. Later when additional control was desired solid state relays were used. They are much smaller and simpler to use than the series of relays. The switches were operated from an eight bit parallel output port available on the microprocessor board. An additional safety feature was added to turn off all power to the Aminco-Aire if a signal was not received from the microprocessor every 100 mS. This circuitry was a resettable, retriggerable monostable multivibrator attached to a solid state relay.

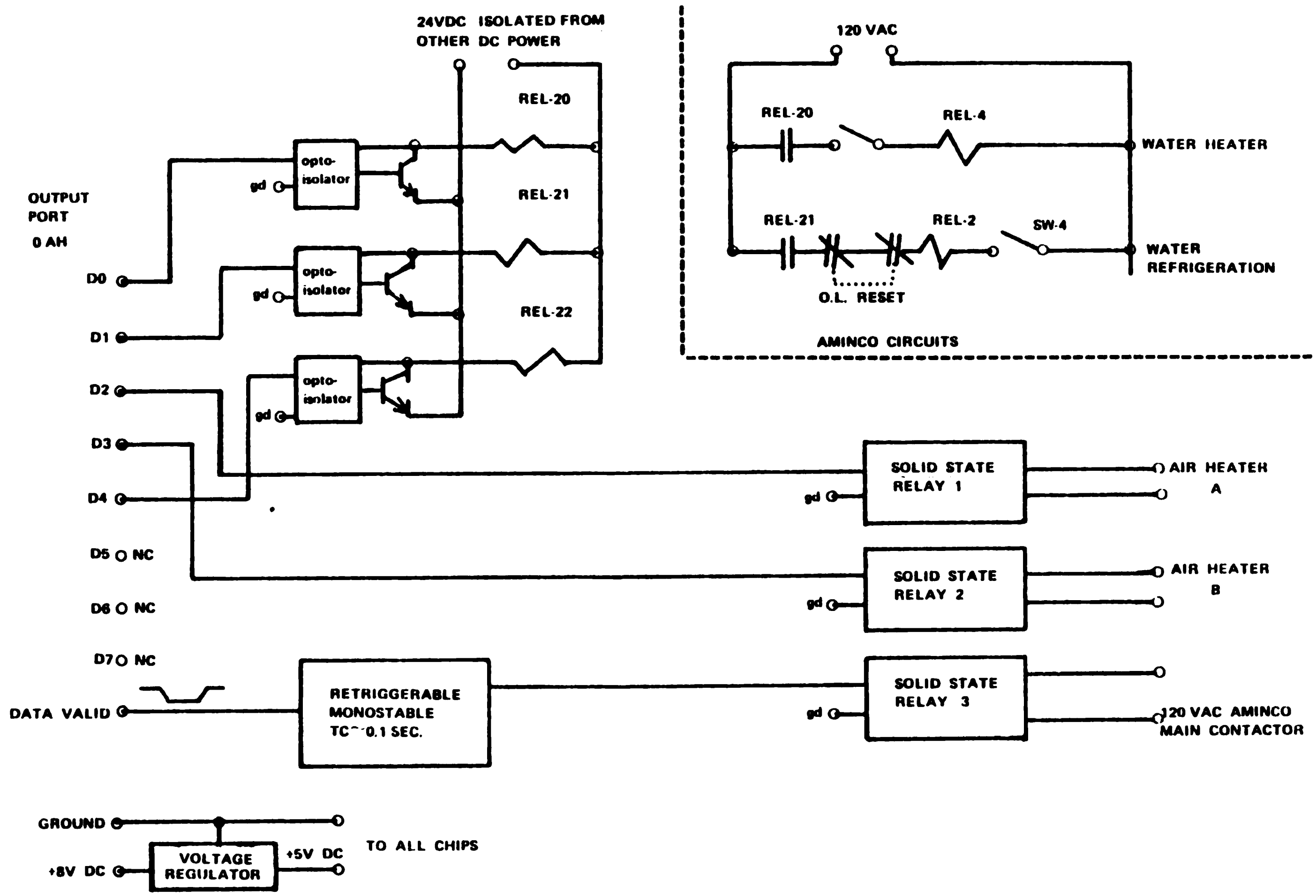

Figure 4.5 Circuit Diagram for Air Conditioner Control

4.5 Study Chamber

A sketch of the study chamber is shown in Figure 4.6. The chamber was 0.50m by 0.30m by 1.60m and was constructed mostly of plywood. The wood was painted with several coats of shellac to reduce moisture absorption and was lined in all but the viewing area with 0.25m (1 inch) of rigid foam insulation. A section of top and sides, 1.04m long, was removable for access to the chamber. In this removable section was a piece of clear plastic 0.39m long and extending across the top and down both sides to serve as a viewing area. The test chamber was connected to the air conditioning unit by ducts 0.127m (5 inches) in diameter and about 1 meter long. The duct from the air conditioning unit to the test chamber was insulated with foil-faced fiberglass insulation approximately 30mm thick while the return duct from the chamber to the air conditioning unit was uninsulated.

The center of the load cells was located 1.05m from the front of the chamber and 0.29m behind the center of the load cells was a honey-comb shaped metal grid. This grid acted as a "flow straightener" which made the airflow more uniform around the sample holder. The airflow was found to be parallel to the sides of the chamber in the vicinity of

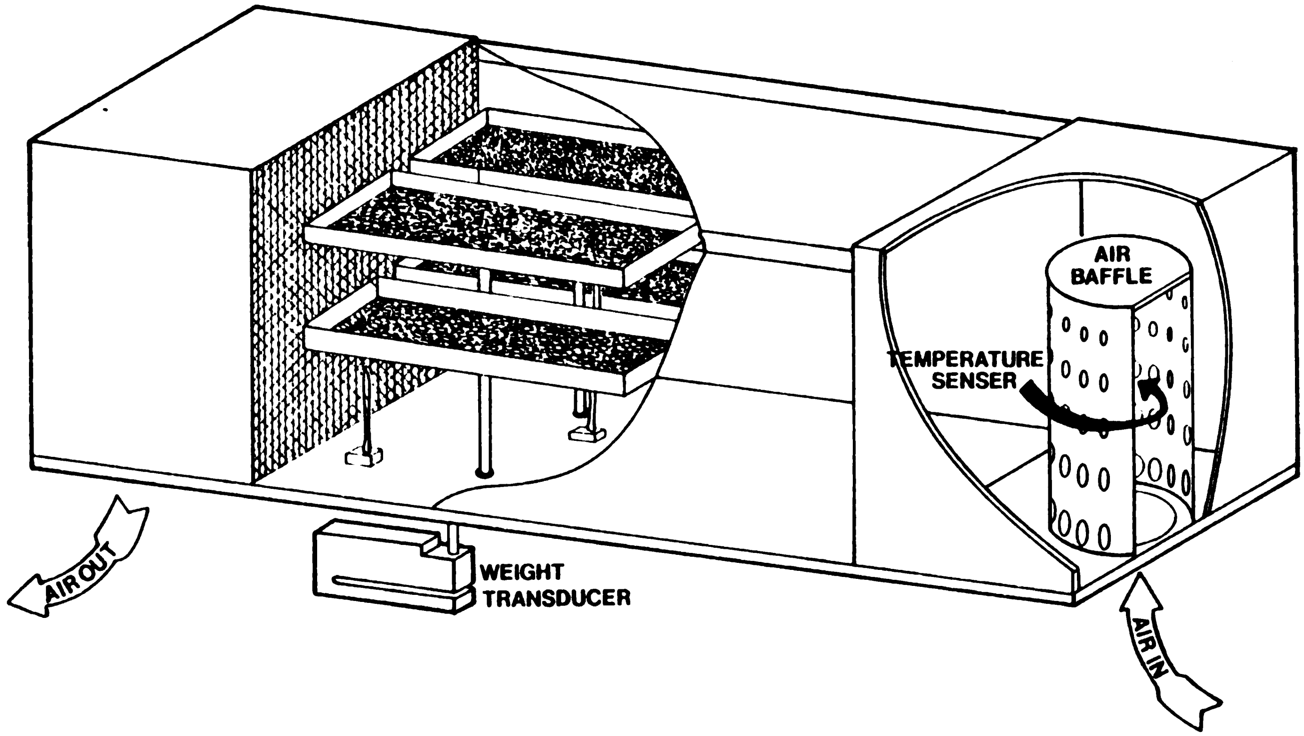

Figure 4.6 Study Chamber

the grain sample and its velocity was measured with a hot-wire anemometer at 21 points in a plane normal to the sides and bottom of the chamber at the rear of the sample holders. The velocity was observed to vary from a minimum of 0.10 m/s to a maximum of 0.70m/s with an average of 0.28 m/s. Henderson and Pabis (1962) found that, in this range, variations in airflow have an "insignificant" effect on the rate of drying.

The weight transducers were fastened to a concrete block 0.18m by 0.30m by 0.35m in order to reduce mechanical vibrations and were located 0.25m apart. This block was insufficient to damp out the vibrations and additional filtering was necessary. The vibrations adversely affected the weight measurements. The filtering was included in the strain gauge amplifier described in Section 4.3.4.

The sample holders consisted of two trays 0.20m by 0.30m made of aluminum screen with a lip of about 10 mm around the edge to hold the sample on the tray. There were two trays attached by an aluminum rod to each weight transducer. The bottom tray was about 0.10m from the bottom of the chamber and the trays were about 0.10m apart resulting in the top tray being located about 0.10m from the top of the chamber.

4.6 Software

A considerable amount of software was required for this project. Copies of the programs used in data acquisition and control may be found in the Appendix. The software may be divided into three categories, two of which will be discussed here: the data acquisition software and the digital control software. The software used in data analysis will be discussed in chapter 5.

The software for data acquisition and digital control was written in three languages: Z-80 assembly language, BASIC, and Pascal. The microprocessor used was a Z-80 so a few of the most primitive routines, those which were used often and were critical to the timing, were written in Z-80 assembly language. The instructions for data display and storage and the overall control of the equipment were written in integer BASIC. The data acquisition and air conditioning control software was written in Pascal and compiled into Z-80 code. The code written in Pascal was called by an interrupt while programs written in BASIC were running. This made it appear that data storage and control were occurring simultaneously but actually the data acquisition and control functions had priority over data storage and display.

4.6.1 Data Acquisition

The data acquisition software was written in Pascal and called several Z-80 code subroutines. The Pascal program was called every 40 mS. The code contained a variable which counted the number of times it had been called. After this counter reached the value of 5000, which occurs after 200 seconds, it was reset to 0. This time base was originally provided for the control of the refrigeration unit but was not needed with the simple on/off control algorithm which proved adequate.

A second timing loop was based on 250 40 mS calls or 10 seconds. At the end of each second for the first 9 seconds, each of the 8 analog input lines was sampled and converted to digital form. After the 9 values for each of the 8 input lines were obtained they were averaged and the average stored in memory by the end of the tenth second. Also before the end of the tenth second the average values representing the water temperature, heater temperature and air temperature at the entrance to the test chamber were converted to engineering terms for use by the control algorithms.

The average of the digital representation of the eight transducer values was placed in memory at the end of the ten second period and a flag was set in memory. Software in BASIC responded to this flag and reset it before moving the averages to other memory and subsequently calculating averages over a one minute period.

The one minute averages were stored on cassette tape and printed at the terminal. The shortest period covered in the recorded data was one minute, with each data point representing an average of 54 observations. The averages of the weight on each transducer, the water temperature, and the five other temperatures were recorded. The reading of the clock in days, hours, minutes and seconds was recorded with the other data. From the sample weights and the sample dry matter content the moisture content of the product on each sample holder could be calculated. From the Aminco water temperatures and the air temperatures near the product the drying air relative humidity could be calculated.

4.6.2 Digital Control

The water temperature was controlled by a simple on/off control algorithm. A dead band of 0.16 C was used because that was the minimum dead band which did not induce oscillations. At the end of each ten second period the actual water temperature was compared with the desired water temperature. If the actual temperature was more than 0.08 C warmer than the set temperature, the refrigeration unit was activated. If the actual temperature was more than 0.08 C cooler than the set temperature, the water heater was activated. If the actual temperature was within the 0.16 C deadband, then both the refrigeration unit and the water heater were turned off.

The heating and cooling of the water was observed to overshoot the goal, especially when large changes in the setting were requested. Therefore, in addition to the previous control algorithm, the set temperature was compared to the actual water temperature at the end of each second. If the two temperatures were within 0.05 C of each other, the heater or cooler was turned off for the remainder of the 10 second period. This adjustment allowed a narrower dead band without undesirable oscillations between the heater and cooler.

The control algorithm for the air temperature was first designed as a simple velocity PID controller. Initially the temperature sensors in the chamber were used as the basis of the controller. It became immediately obvious that the heater would be activated and because of the considerable lag in getting heated air to the sensors would become very warm. The thermal masses stored considerable energy. The algorithm continuously reduced the duty cycle to the heater, when the chamber was too warm, but because of the thermal storage would reduce the setting much too far. When the air in the chamber was too cool the reverse action was taken producing undesirable cycling of the chamber temperature.

A simple solution to this problem was to base the control on a sensor located near the heater. It was assumed that under steady state conditions the heat losses would be relatively constant between the heater and the product so that the chamber conditions, while not directly controlled, would be constant.

A PID velocity algorithm, equation 3.8, was implemented:

DS = I*(E(1)-E(2))+J*E(1)
+H*(E(1)-2*E(2)+E(3)). 3.8

One disadvantage of this algorithm is that the derivative term contains what is essentially the second derivative of the input signal. Taking derivatives of variables tends to greatly amplify any noise in the signal so that the derivative action can be badly masked in the noise. A smoothing formulation of the second derivative was used:

(3*E(1)-4*E(2)-E(3)+2*E(4)). 4.2

This formula was substituted for

(E(1)-2*E(2)+E(3)) 4.3

resulting in the formula:

DS = I*(E(1)-E(2))+J*E(1)
+H*(3*E(1)-4*E(2)-E(3)+2*E(4)) 4.4

where: DS = the change in the duty cycle of the heaters.

In order to use this algorithm, values for the constant coefficients I, J, H must be chosen. There are several methods of choosing the values for these coefficients when control of an unknown plant is desired. All methods involve choosing a particular set of values for the coefficients and then testing the system to see how it will react to changes in the controlled variable. Smith (1979) suggests the following steps:

1) Remove all reset and derivative action, i.e. J=H=0, and tune the proportional mode, I, to give the desired response characteristics, ignoring any offset.
2) Increase the proportional gain, and attempt to restore the response characteristics by adjusting the derivative term, H. Repeat until the proportional gain is as large as possible.
3) Adjust the reset time, J, to remove the offset.

He adds that the adjustment of H is by far the most difficult and the derivative action is probably not justified in most cases.

An algorithm in the form of equation 4.4 was adjusted using the method described by Smith (1979). Controlling the heater temperature did not allow the operator to choose the temperature in the chamber directly but a guess as to the temperature drop from the heater to the chamber would allow the chamber temperature to be set close enough for most applications. Locating the sensor near the source of the energy, the electric heater, made the control reasonably simple. The derivative action of the PID controller was observed to be erratic, due to noise in the temperature signal. Attempts were made to filter the signal both with analog filters of various orders and with digital filters. A simple RC analog filter, with a time constant of 2.2 ms, was finally chosen with the smoothing formula described above acting as a digital filter.

At the end of each 10 second period the updated error, in air temperature, was computed and an adjustment to the duty cycle for the heater was calculated. During each interrupt, occurring every 40 ms, the current duty cycle was checked to see if the heater should be turned off or on. The appropriate code was then sent to the interface circuit along with data to control the water temperature. The duty cycle was based on 100 of the interrupts so that if the duty cycle were 46%, for example, the heater would be on for 1.84 seconds and off for 2.16 seconds. This period of 4 seconds is short enough so that the heater does not change measurably in temperature due to thermal masses.

This algorithm had two main weaknesses: it was difficult to repeat an experiment because it was difficult to obtain a given chamber temperature, and the load in the room was not constant so the chamber temperature tended to drift. Therefore, an addition to the control algorithm was added between test 9 and test 10.

Instead of the operator trying to guess what the heater temperature should be to achieve a desired temperature in the chamber, the additional software adjusted the heater temperature setting. This process is sometimes referred to as cascade control. For this second level of control an integral controller was used. The goal of the original PID controller was adjusted by 0.02 times the difference between the actual temperature at the entrance of the chamber and the desired temperature. This additional controller makes the system much slower to respond to changes in the setting but the variation of temperature within the chamber was significantly reduced and the actual temperature within the chamber was usually within 0.5 C of the set temperature.

5. EXPERIMENTAL INVESTIGATION

5.1 Product

The parboiled rice which was tested had been processed and collected from a commercial parboiling plant on October 12, 1982 and stored in sealed plastic bags and glass containers at a temperature of 5 C until needed for testing. The rice variety was LaBonnet, a long grain variety, often used in commercial parboiling plants. This particular processing plant had a series of commercial dryers which were used after gelatinization. The first two in this series were rotary dryers operating in the temperature range of 260-320 C.

The product was obtained from three places in the material stream in the plant, just before the rotary dryer (initial moisture content from 0.47 to 0.57 dry basis) just after the first dryer (initial moisture from 0.20 to 0.30 dry basis) and after the second dryer (moisture content from 0.17 to 0.18 dry basis). Most of the rice tested was taken from the exit from the first dryer.

Each sample taken from the material stream was about 300 g. Several samples of similar moisture content were combined and stored in sealed glass containers for at least one week before testing.

5.2 Laboratory Methods

The laboratory methods will be described in the order in which they were performed during an individual test. The method was as uniform as possible over the testing of the rice, October 20, 1982 to February 8, 1983.

The tests were numbered consecutively from 1 to 21. Several of the tests were not analyzed completely, for various reasons. Tests 1 and 2 were not analyzed at all but were considered to be "warm-up" tests.

5.2.1 Equipment Initialization and Initial Data

If the equipment had been turned off previous to the individual test, it was turned on and the water temperature goal and dry bulb temperature goal were set. The equipment was given at least one hour to warm-up and stabilize at the new setting. Before loading the rice on the weight transducers, the data collection computer program was begun. Several initial measurements were taken with known masses placed on the transducers to check the weight conversion factors.

All weights, other than those obtained from the weight transducers, were measured with a Mettler, type B5, balance and recorded to the nearest 0.001 g. The rice used in the test was removed from storage and weighed in a container with a lid. The initial product weight was over 100 g. for each weight transducer. The product was then spread over the trays, first on the bottom tray then on the top tray for an individual weight transducer. Any surplus parboiled rice was weighed with the container for a determination of the weight of grain on the transducer. The surplus rice was then returned to storage.

Weight transducer 0, also referred to as tray A, was loaded first and transducer 1, tray B, was loaded second. The chamber was left open for one to two minutes while each transducer was loaded and closed for approximately four minutes between the loading of the two transducers. After the product was loaded onto the weight transducers, additional samples were taken from storage to determine the initial moisture content of the grain.

The samples for the moisture content determination weighed at least 15 grams and were placed in numbered cans with numbered lids which had been previously oven dried and weighed. The cans and samples were weighed and then placed in an oven at 103 C, with the lids in the oven also but not on the can. The samples were dried for approximately 80 hours. Several prior tests of the moisture determination method showed that the required sample drying time was at least 72 hours. After the samples were dried in the oven the lids were placed on the cans, the samples were cooled in a dessicator, and then weighed again. The rice was removed from the containers and the container and lids were reweighed. The formula used to calculate the moisture content was:

$$MCd = (WSCi-WCi-WSCf+WCf)/(WSCf-WCf) \qquad 5.1$$

where: MCd = the moisture content, dry basis
WCi = weight of the can, initial
WCf = weight of the can, final
WSCi = weight of the can and sample, initial
WSCf = weight of the can and sample, final.

5.2.2 Treatment During Test

The microcomputer controlled the drying conditions during each test. The data representing the weight on each transducer, the temperature at three places near the samples, the temperature at the entrance of the chamber, the temperature at the air heater, and the temperature of the water were recorded each minute along with the time of recording of the data. Each test was allowed to run for between 23 and 54 hours with most being at least 40 hours.

Table 5.1 shows the various tests which were run. The Aminco-Aire water temperature setting as well as the calculated relative humidity and observed chamber temperature and the product moisture content before the test was started are included in this table.

Table 5.1 Test Conditions for Parboiled Rice

Test Number		Water Temperature Celsius	Relative Humidity	Chamber Temperature Celsius	Sample Initial Moisture Content*
test 3	A	15.0	0.38	34.0	0.276
	B				0.229
test 4	A	15.0	0.32	37.8	0.228
	B				0.276
test 5	A	7.2	0.24	34.8	0.284
	B				0.242
test 6	A	5.2	0.25	31.5	0.505
	B				0.286
test 7	A	15.1	0.41	32.5	0.566
	B				0.292
test 8	A	20.0	0.51	33.4	0.292
	B				0.568
test 9	A	25.0	0.47	40.2	0.576
	B				0.294
test 10	A	15.0	0.27	40.6	0.225
	B				0.278
test 12	A	12.0	0.50	25.2	0.295
	B				0.278
test 13	A	5.0	0.51	17.3	0.302
	B				0.296
test 14	A	8.0	0.40	25.0	0.299
	B				0.258
test 15	A	15.0	0.40	32.6	0.325**
	B				0.297
test 16	A	27.0	0.53	39.8	0.324**
	B				0.299
test 17	A	15.0	0.27	40.6	0.186
	B				0.296
test 18	A	14.0	0.27	39.8	0.259
	B				0.181
test 19	A	15.0	0.31	38.0	0.252
	B				0.183
test 20	A	12.0	0.47	26.3	0.254
	B				0.260
test 21	A	12.0	0.47	26.1	0.255
	B				0.262

* Moisture content determined by oven method of separate samples taken from the stored grain

** Rewetted long grain rough rice, tests not included in this analysis

5.2.3 Sample Post-treatment and Final Data

At the end of a test, the rice on the two trays of an individual transducer was combined and weighed. A sample was then drawn from this rice, separate samples representing the separate transducers, to determine the final moisture content of the rice. The same procedure was used as was described for determining the initial moisture content of the rice. Since the final moisture content was used to calculate the dry matter weight on each transducer and the dry matter weight affected the results substantially, a duplicate sample was taken for determining the final moisture content starting with test 14. The dry matter weight determined from the duplicate samples agreed to Ø.1 g. in all tests and generally agreed to within Ø.Ø2g.

5.3 Data Reduction

In order to proceed with the data analysis and the determination of the proper thin layer model, the moisture content of the rice must be determined. Also the drying air conditions, temperature and relative humidity must be calculated for the same period of time.

The most important variable for the determination of the moisture content of the sample was the weight of the dry matter in the sample. This value was calculated from the product weight in grams, averaged over the last five minutes of the test, and the moisture content which had been measured at the end of the test using the following formula:

$$Wdm = Ws*(1.0-M/(M+1.0)) \qquad 5.2$$

where: Wdm = weight of the dry matter in grams
Ws = weight of the sample in grams
M = final moisture content dry basis decimal

In tests 1-13 only one sample was taken from the rice on each of the weight transducers. Therefore there was only one final dry matter weight to be used. In tests 14-21 duplicate samples were taken from the rice on each of the weight transducers. The dry matter content of the rice on each transducer was calculated separately and the two dry matter weights were averaged for each transducer.

The data were then converted from integers to engineering terms. The data reduction program converted the time from days, hours, minutes, and seconds, to the hours and seconds since the beginning of the test. It also converted the numbers representing the weights on transducers 0 and 1 to moisture content dry basis, and converted the numbers representing the temperatures in the system to temperature in Celsius. After the temperatures of the air and water in the Aminco-Aire were known the relative humidity was calculated by the iterative formula, rewritten from equation 4.1:

$$RHn = RHo+P1+P2*WT-DB+Ln(RHo)*(P3+P4*WT)+P5/RHo \qquad 5.3$$

where: RHn = the most recent estimate of the relative humidity, percent
RHo = the previous estimate of the relative humidity, percent
WT = the water temperature in Celsius
DB = the dry bulb temperature of the air in Celsius
P1 = 77.4
P2 = 1.377
P3 = -16.98
P4 = -0.0821
P5 = 73.7

The iteration started at the relative humidity which was calculated for the previous time period and ended when the absolute value of (RHo-RHn) was less than 0.0004.

After carefully examining the data and physical arrangement of the temperature sensors, it was decided that for tests 3 through 14 the temperatures measured by sensors 5 and 6 best represented the actual temperature of the drying air near the product. Therefore, the average of the values from these two sensors was used in the calculations of relative humidity for the tests 3 through 14 and was also recorded as the chamber temperature for these tests. Between tests 14 and 15 the distribution of the airflow was improved and temperature sensors 5, 6, and 7 were in the airstream which surrounded the rice. For tests 15 through 21 the average of the temperature readings from sensors 5, 6 and 7 was used as the true air temperature.

The calculations were performed with floating point arithmetic, but the results were stored as integers. The moisture contents and the relative humidities were rounded to the nearest 0.001. Temperatures were rounded to the nearest 0.1 degree Celsius. The moisture contents and relative humidities were multiplied by 1000 and the temperatures by 10 to obtain suitable integers for storage. These integer values were converted to ASCII for transmission to the mainframe computer for the data analysis. The data sets were transmitted to the mainframe computer over telephone lines and stored as separate files.

5.4 Variables and Errors

In this investigation four variables were important. The first was the temperature of the drying air. Averages for temperature were used in the analysis. The second and third were the other two independent variables, time and relative humidity. The fourth was the dependent variable, the moisture content of the parboiled rice.

The temperatures used in the analysis had been rounded to the nearest 0.1 C. The temperature conversion data, calibrated against a laboratory thermometer marked in 0.1 C, was analyzed to obtain the conversion factors in Table 4.1. The estimate of the standard deviation on the predicted temperature is 0.09, so a reasonable estimate of the error in the temperature data is 0.2 C.

The time was truncated to a second and was recorded in hours, so the error in time due to truncation could be as large as 0.028%. The clock was controlled by a crystal and was measured to be about 0.0123% too slow. Over a 48 hour test the time would be about 21 seconds too small.

When errors in temperature of 0.2 C are entered into the iterative formula for relative humidity (equation 5.3) the resulting uncertainty in the relative humidity is 0.006, in the temperature ranges used in this study. The relative humidities were calculated to a precision of 0.005, but the accuracy was no better than 0.03 because a more accurate standard was not available with which to calibrate the equipment. The formula was tested by measuring the actual moisture content of the air in the chamber and comparing it to the calculated moisture content. Three methods were used to measure the moisture content of the air: a chilled mirror instrument, wet-bulb dry-bulb temperature sensor combination, and a commercial moisture sensor accurate to 0.03. The moisture content of the air from the formula agreed to within the accuracies of the instruments against which it was checked.

The largest error in the moisture content measurement calculations came from the weight transducers. The moisture content data for each test were all based on the dry matter content of the samples taken at the end of that test. The errors in the moisture content oven tests were in the range of 0.0004 moisture content dry basis. However, the errors in the sample moisture content calculations, before test 18, were in the range of 0.002

because of the weight transducer error. After the hardware changes between tests 17 and 18 the error due to the transducers dropped to the range of 0.0008. The moisture contents of the product were rounded to the nearest 0.001, moisture content dry basis, before the data analysis was begun. Therefore, in the data analysis the error in the moisture content data due to the rounding may be as much as 0.0005 moisture content, dry basis. The error due to transducer error is in the same range for test 18 to 21.

One possible source of error was in the determination of exactly when time=0 occurred and what the moisture content of the samples was at that point. Since the equations and models are nonlinear in time the concern over this error is not trivial. In this study time=0 was considered to occur halfway through the loading of each tray, so this time is not the same for the two trays. The difference was about five minutes. The initial moisture contents were estimated graphically from the data taken at times of less than fifteen minutes.

6. DATA ANALYSIS AND RESULTS

The remaining objectives involved determining how well the variables in the drying process had been controlled and the use of available equations to determine appropriate models for the drying relationships. The data analysis consisted of choosing appropriate subsets of data and the examination of data with statistical software packages. Four BMDP packages (Dixon 1981) were used in the statistical analyses. BMDPAR and BMDP3R were used to fit various nonlinear models to the data, BMDP6D was used to create plots of the data and residuals, and BMDP2D was used to analyze how much variation there was in the temperature and relative humidity data.

The data sets were contained on several files which were analyzed. The original data sets contained data on the moisture content of the samples from every minute for the individual tests, in addition to the temperature and relative humidity data for each minute. Separate files had combined sets of data, with a range of relative humidities and temperatures, but with samples of data at intervals greater than one minute.

The first step in the analysis of the moisture loss data was to plot the moisture content vs. time for each curve. Visual examination of these plots indicated poor data sets and poor data points. Since all of the plots were at the same scale the different data sets were also compared visually.

The moisture content data from the eleventh data set were observed to vary considerably more than the other data sets. The data from this test had sudden changes in the moisture content of 0.03 while the other tests had sudden changes of no more than 0.01. The water level in the Aminco Aire unit had become low during this test, the only instance where this problem was encountered. Therefore, data from test eleven was not analyzed further.

Upon examination, data from tests three and four were observed to have irregularities in them. These occurred as a result of the sample holders hitting the side of the chamber. This problem was eliminated after the fourth test by pinning the sample trays to the supporting rod.

The remaining sixteen data sets were kept for further analysis. These sixteen tests on each of the two trays covered a total of 1308 hours of data with one data point every minute. This amounts to over 78,500 data points of moisture content vs. time. Since each data point represented an average of 54 observations the data sets resulted from over 4 million observations of moisture over time. In contrast, Misra and Brooker (1980) combined data from seven researchers for a total of 15,353 data points.

As will be shown later, sheer quantities of data are not an adequate goal and collecting data every minute about a process which does not change measurably for half an hour is not always needed. However, in order to demonstrate the necessary frequency and duration of data collection some researcher must collect too much data for too long and demonstrate what the limits are. In this study the plan was to collect more data than necessary for longer than necessary to give future researchers some guidance in this matter.

6.1 Analysis of Operation of Equipment

The thin layer study equipment maintained conditions as shown in Table 6.1. The distribution of the temperatures and calculated relative humidities did not follow a Gaussian distribution because these two variables were controlled by the digital equipment. The control algorithm requires measurable errors to occur. But after they occur substantially larger errors are unlikely to occur because of the feedback control. Therefore the usual statistic of central tendency, standard deviation, is misleading.

What is presented instead is the mean value and the range which includes at least 90% of the data points. The temperature and relative humidity each minute, after the first half hour of the test, was included in this analysis for the remaining period of the run. For most of the tests there were at least 2400 data points in this analysis. During the first half hour the opening of the chamber affected the drying conditions and the results of an analysis including all data would not indicate the effectiveness of the control for the majority of the time.

Table 6.1 Variation in Chamber Conditions

	Relative Humidity			Average Chamber Temperature Degrees Celsius		
Percentile	5	50	95	5	50	95
test 5	0.23	0.24	0.24	34.4	34.8	35.3
test 6	0.24	0.25	0.26	30.9	31.5	32.2
test 7	0.39	0.41	0.42	32.0	32.5	33.0
test 8	0.50	0.51	0.52	32.9	33.4	33.6
test 9	0.46	0.47	0.49	39.5	40.2	40.7
test 10	0.27	0.27	0.28	40.3	40.6	40.8
test 12	0.49	0.50	0.50	24.9	25.2	25.4
test 13	0.50	0.51	0.52	17.1	17.3	17.6
test 14	0.40	0.40	0.41	24.8	25.0	25.3
test 15	0.40	0.40	0.41	32.3	32.6	32.9
test 16	0.51	0.53	0.54	39.5	39.8	40.4
test 17	0.27	0.27	0.28	40.2	40.6	41.0
test 18	0.26	0.27	0.27	39.5	39.8	40.2
test 19	0.31	0.31	0.31	37.8	38.0	38.2
test 20	0.46	0.47	0.47	26.1	26.3	26.5
test 21	0.47	0.47	0.48	25.8	26.1	26.4

The improvement due to the cascade control introduced between tests 9 and 10 can be seen. Before the inclusion of the cascade control algorithm, the range of chamber temperatures was about 1.0 C and after the change was about 0.5 C.

When the chamber temperature distribution for each test is examined, the tests conducted before the addition of the cascade control algorithm show a marked bimodal pattern in time. That is, there were apparently two temperatures about which the temperatures varied. One possible explanation for this could be that diurnal temperature changes in the laboratory affected the chamber temperature.

After the control algorithm was improved the temperature-frequency distribution was much more square with a relatively even distribution of several tenths of a degree about the mean and a very rapid decrease in the number of observations at higher and lower temperatures.

The water temperature was less variable than the other temperatures, the range including over 90% of the water temperature values generally was 0.1 C. Therefore the variations in the chamber temperature affected the relative humidity in the chamber. The average range of relative humidities before the algorithm change was 0.021 and after the change was 0.010. Because the water temperature was virtually unchanged, the saturation vapor pressure did not change during the tests.

The real question about the adequacy of control was whether the variations in the independent variables significantly affected the drying behavior of the product. The best measure of the effect of uncontrolled variation in the independent variables is to study the data from repeat tests. This approach is discussed in Section 6.5.1.

The control of the independent variables, air temperature and relative humidity, was more than adequate for all tests. The control after the improvement in the algorithm between tests 9 and 10 was closer than the control previous to the improvement and removed the bimodal distribution in the air temperature noted in some of the tests.

6.2 Exponential Models

In this section the relative humidity and temperature are considered to be constant. Comparisons between tests where relative humidity and temperature have been changed will be covered in later sections. The relative humidity during the test was constant after the first half hour but because of the opening of the chamber varied by as much as 0.15 during the first few minutes. After the chamber had been closed for five minutes the chamber was generally within 0.03 of the mean value. The temperature was constant after the first half hour but was up to 15 C from the mean at the first minute after the chamber was closed. After five minutes had passed the temperature was within 1 C of the mean value for the rest of the test period. The grain temperature was not measured but can be expected to be near the air temperature in the temperature range of this study after the first 10 minutes (Husain, Chen and Clayton, 1973; Fortes, Okos and Barrett, 1981).

One of the findings of the literature review was that one or more decaying exponentials have been used to model the drying process. If the resistance to diffusion lies on the surface of the particle, one term should be sufficient. If the resistance is spread throughout the particle then several terms should be required. The set of data with the least error should be used in evaluating the appropriateness of any model. Tests 18, 19 and 20 were used to determine which of the models were most appropriate for thin layer drying modeling of parboiled rice because they had the lowest expected error. Because test 21 was an exact repeat of test 20 it was used only for comparison with test 20.

The one term model, also called the logarithmic model was:

$$M(t) = P1*\exp(P2*t)+P3 \tag{6.1}$$

The two term exponential model was:

$$M(t) = P1*\exp(P2*t)+P3*\exp(P4*t)+P5 \tag{6.2}$$

The three term exponential model was:

$$M(t) = P1*\exp(P2*t)+P3*\exp(P4*t)+P5*\exp(P6*t)+P7 \tag{6.3}$$

The four term exponential model was:

$$M(t) = P1*\exp(P2*t)+P3*\exp(P4*t)+P5*\exp(P6*t) +P7*\exp(P8*t)+P9 \tag{6.4}$$

The statistical package BMDP3R has a series of exponentials built into it as one of the possible nonlinear models for use in regression. It was, therefore, relatively simple to fit varying numbers of exponential terms to the data.

6.2.1 One Term Exponential Model

The one term exponential model was fit with the resulting parameter estimates listed in Table 6.2. The residual mean square, the statistic which will be used for a measure of "goodness of fit," for each data set is also listed.

Table 6.2 One Term Exponential Fit to Data Sets

Test	18 A	18 B	19 A	19 B	20 A	20 B
P1	0.118	0.067	0.120	0.067	0.107	0.113
P2	-0.215	-0.161	-0.224	-0.150	-0.161	-0.180
P3	0.078	0.077	0.083	0.081	0.111	0.111
Residual Mean Square	14.3 E-6	5.0 E-6	19.1 E-6	6.3 E-6	10.6 E-6	12.7 E-6

The data sets for these six tests comprise over 2500 data points each, and were believed to be accurate to nearly 0.0005, the roundoff error. Therefore, the expected best case residual mean square should be about 0.25 E-6. The residuals were examined and a very clear pattern was seen in all cases indicating that something was measured in the data which was not accounted for in the model. In other words the model is inadequate.

The figures in the tables in this chapter do not necessarily reflect the significant digits in the data. The parameters which represent the moisture content of the grain directly are rounded to the nearest 0.001. The parameters which are in the exponents are listed to three places. The asymptotic standard deviations are known for all parameters in this study but only listed for the final model. Generally the asymptotic standard deviations showed that the parameters directly associated with moisture contents are estimated to 0.001 or better but the parameters in the exponents are only estimated to one or two places. The residual mean square values have six significant digits, but because the intended use of the values is to estimate the variance they are listed to only two or three significant digits.

Figure 6.1 shows the residuals in test 19 B plotted against time and Figure 6.2 shows the same residuals plotted against the predicted moisture content.* In this case the two plots show basically the same thing but in some cases one plot may show a pattern which is not obvious

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* Because so many nonlinear regressions were completed and so much data was available only a few of the residual plots will be included in the dissertation.

in the other plot. Figure 6.3 shows the residuals from test 20 B plotted against time.

In the plots the numbers refer to the number of data points which should be plotted at the same place on the paper. If more than nine are to be plotted in the same place, the letters of the alphabet are used. If more than 35 points lie on the same place on the plot, the symbol * is used. If any points lie off the plot the symbol * is used at the border of the plot.

6.2.2 Two Term Exponential Model

Because the one term exponential model was inadequate and the theory shows that a series of exponentials may be the best model for thin layer drying the two term exponential model was fit to the data. Table 6.3 shows the results from the nonlinear regression of the six data sets to the two term exponential (equation 6.2).

Table 6.3 Two Term Exponential Fit to Data Sets

Test	18 A	18 B	19 A	19 B	20 A	20 B
P1	0.096	0.043	0.102	0.047	0.074	0.074
P2	-0.647	-0.691	-0.584	-0.510	-0.448	-0.448
P3	0.059	0.045	0.052	0.040	0.058	0.058
P4	-0.102	-0.098	-0.081	-0.070	-0.078	-0.078
P5	0.074	0.075	0.077	0.077	0.106	0.106
Residual Mean Square	0.39 E-6	0.38 E-6	0.80 E-6	0.44 E-6	0.57 E-6	0.57 E-6

```
         .*....+....+....+....+....+....+....+....+....+...
    .0125 +                                                +
         .2                                                .
         .2              Explanation of symbols, p. 126   .
         .                                                 .
         .1                                                .
    .0100 +2                                               +
         .2                                                .
         .2                                                .
         .1                                                .
         .1                                                .
    .0075 +11                                              +
         .12                                               .
         . 1                                               .
         . 3                                               .
         . 4                                               .
    .0050 + 2                                              +
         . 2                                               .
         . 2                                               .
         . 3               52   1                          .
         . 7           23BB9AS29                           .
    .0025 + 4          359JUUNHW9EH  2                     +
R        . 4         1LJWKGCMCBTU *U                       .
E        . 4       15KNQD93433F7E*1 *J2                    .
S        . 2       5IKD611     51 CU  6G2                  .
I        . 6       FKB 12           7**                    .
D  0.000 + 6      9NC8                6***71               +
U        . 33    2GG5                 A    BRA13           .
A        . 48   17K                    1IN*R               .
L        .  9  17EF                        3W**PK6362      .
         .  6   EL                        8I               .
  -.0025 +  6  8LE                          14KV*****Z     +
         .  A 5QB2                                         .
         .  76BJ4                              23C35D      .
         .  6QH42                                          .
         .  5MJ1                                           .
  -.0050 +   68                                            +
         .                                                 .
         .                                                 .
         .                                                 .
         .                                                 .
  -.0075 +                                                 +
         .+....+....+....+....+....+....+....+....+....+...
               5.        15        25        35        45
         0.        10        20        30        40

                            TIME, hour
```

Figure 6.1 Residuals 19 B vs. Time, 1 Term Exp. Model

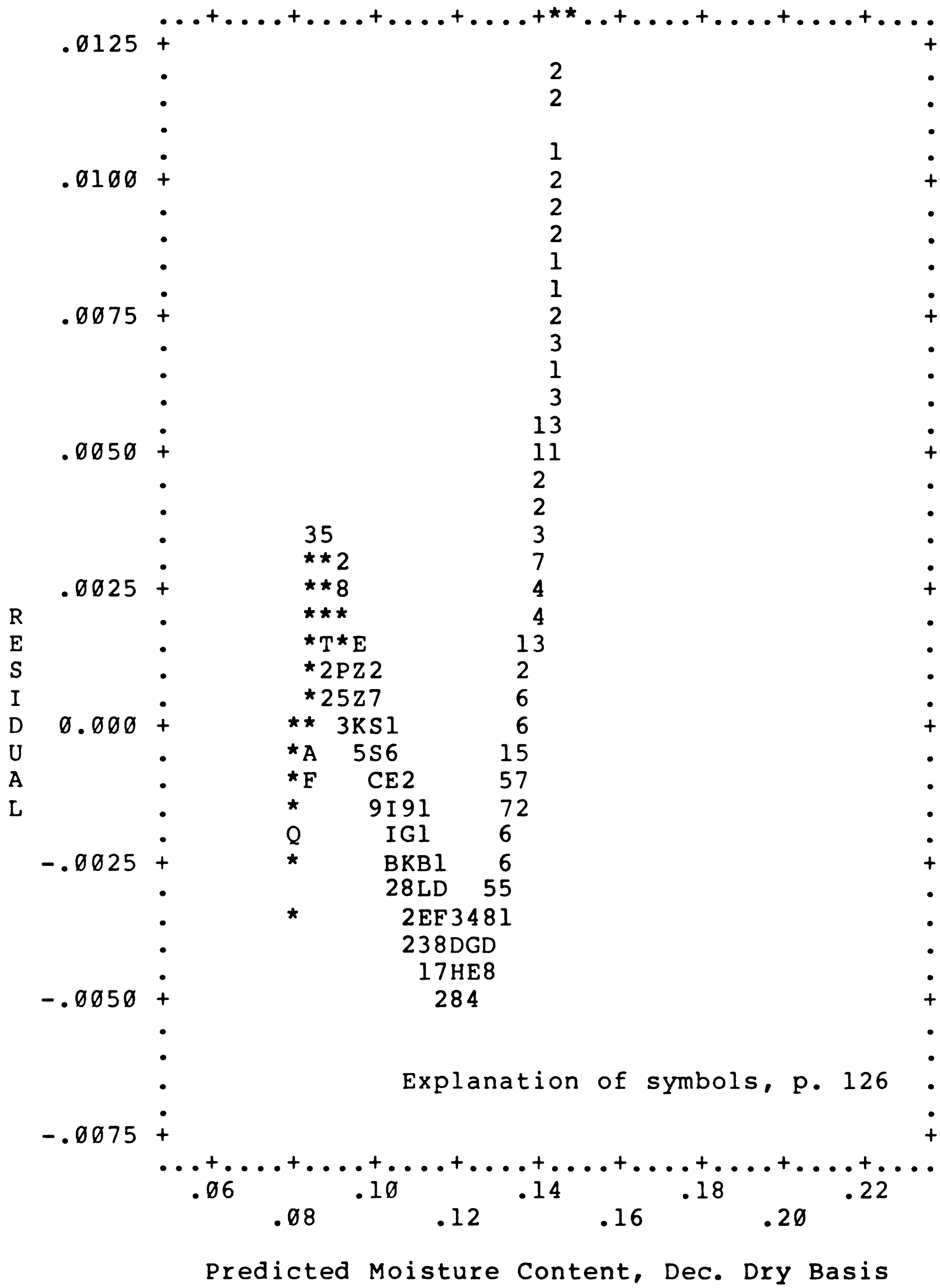

Figure 6.2 Residuals 19 B vs. Predicted, 1 Term Exp. Model

```
         .*....+....+....+....+....+....+....+....+....+....+..
   .0125 +1                                              +
         .                                               .
         .1                                              .
         .2         Explanation of symbols, p. 126       .
         .1                                              .
   .0100 +1                                              +
         . 1                                             .
         .11                                             .
         .                                               .
         .                                               .
   .0075 + 1                                             +
         . 2                                             .
         . 3                                             .
         . 3                                             .
         . 2                                             .
   .0050 + 2           3   772                           +
         . 3           CF42LM82                          .
         .            3JRD6NUL93                         .
         . 1         3PGBTS5 OYHG3                       .
         . 3        1PO97EJ 15C*O4P1                     .
   .0025 + 3        6P81  44  22G* 1F                    +
R        . 3       5K7    1    24 Z*                     .
E        . 2       CO            6 3**9                  .
S        . 3      4J9              C   SD1               .
I        . 5      BJ                 B*7                 .
D  0.000 + 4      H5                   P**K5             +
U        . 3      K                   2                  .
A        . 3    1A6                     L**Y8            .
L        . 4    4O1                           L6G        .
         . 31   6M                        1P**A          .
  -.0025 + 33   84                            O**Z**J2  +
         . 35  1H                          19M5          .
         .  8  7H                                2POC****.
         .  C  C7                                        .
         .  8  I                                     219I.
  -.0050 +  215D                                         +
         .  7BH7                                         .
         .  5PP2                                         .
         .   JC                                          .
         .   41                                          .
  -.0075 +                                               +
         .+....+....+....+....+....+....+....+....+....+..
               5.        15        25        35        45
          0.        10        20        30        40

                           TIME, hour
```

Figure 6.3 Residuals 20 B vs. Time, 1 Term Exp. Model

This model fits the data significantly better than the one term model with the residual mean square at least an order of magnitude lower for the two term exponential than for the one term exponential. In addition the residual mean square values are reasonably near the estimated lower limit of 0.25 E-6.

The plots of the residuals were examined for evidence that the model was not adequate. Figure 6.4 shows the residuals from test 19 B plotted vs. time. The plot shows a much improved distribution but there are points within the first several hours which are not satisfactorily modeled. If the residuals are plotted against the predicted values, Figure 6.5, the pattern was even more clear. Figure 6.6 shows the residuals from test 20 B plotted against time. In all six cases the residuals showed patterns such as these and the model must be considered to be inadequate.

6.2.3 Three Term Exponential Model

Because the two term exponential was not adequate a three term model (equation 6.3) was regressed against the six sets of data. Table 6.4 shows the results of the regression.

```
         .+....+....+....+....+....+....+....+....+....+...
   .0100 +                                                +
         .                                                .
         .          Explanation of symbols, p. 126        .
         .                                                .
         .                                                .
   .0075 +                                                +
         .1                                               .
         .1                                               .
         .                                                .
         .                                                .
   .0050 +1                                               +
         .                                                .
         .2                                               .
         .1                                               .
         .                                                .
   .0025 +2                                               +
R        .2    2                                          .
E        .1   5E4               11 7222        1          .
S        .2  4HMJ6231      1242A3GHNFH G2271 712  162     .
I        .2 7NNGNBDF5 533669AYI8*GVG*9* MZ IR3 7K62  F    .
D  0.000 +4 JND3AOQLJLIA9JPUOEPT8R4E4W *H2*K O*I  X**K    +
U        .4DN9223EHHOIKRSMMFL6B79 8 3 G3CL 6WM B**C  9    .
A        .2P91  15246CHFHB743245        6 8F  KK  B354    .
L        .1J2       59 312 1           1    14  231       .
         . 3           12                                 .
  -.0025 +                                                +
         .                                                .
         .                                                .
         .                                                .
         .                                                .
  -.0050 +                                                +
         .                                                .
         .                                                .
         .                                                .
         .                                                .
  -.0075 +                                                +
         .+....+....+....+....+....+....+....+....+....+...
               5.        15        25        35        45
          0.        10        20        30        40

                             TIME, hours
```

Figure 6.4 Residuals 19 B vs. Time, 2 Term Exp. Model

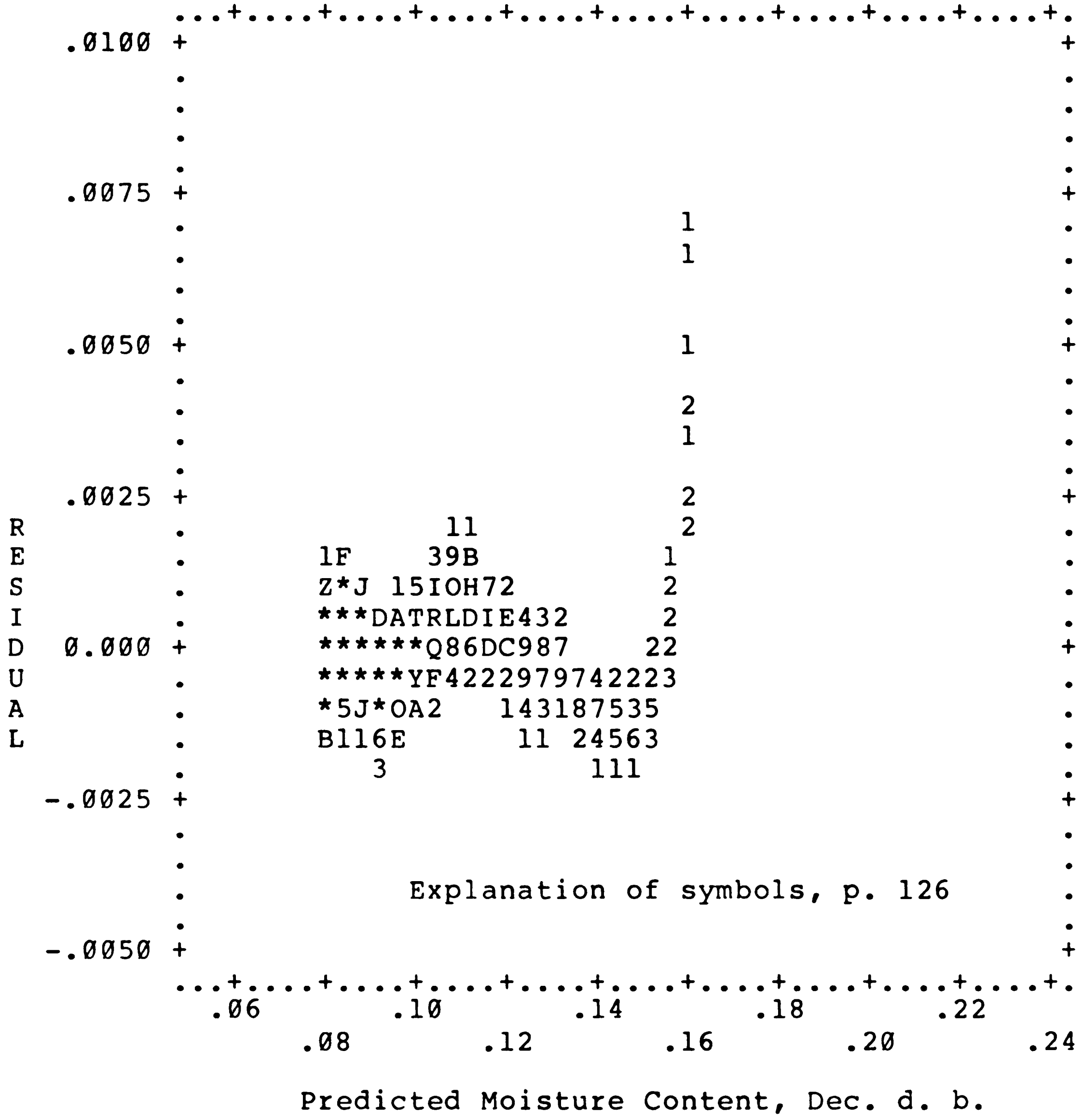

Figure 6.5 Residuals 19 B vs. Predicted, 2 Term Exp. Model

```
         .+....+....+....+....+....+....+....+....+....+...
   .Ø15Ø +                                                +
         .                                                .
         .          Explanation of symbols, p. 126        .
         .                                                .
         .                                                .
   .Ø125 +                                                +
         .1                                               .
         .                                                .
         .                                                .
         .1                                               .
   .Ø1ØØ +                                                +
         .1                                               .
         .                                                .
         .                                                .
         .1                                               .
   .ØØ75 +                                                +
         .                                                .
         .1                                               .
         .                                                .
         .2                                               .
   .ØØ5Ø +1                                               +
         .                                                .
         .                                                .
         .1                                               .
         .1                                               .
   .ØØ25 +2                                               +
R        .1    13                                         .
E        .1  2AD711          11  3 16 6  1                .
S        .1 3DORIA3    3   244216 PB9X3ED1K5 8   C        .
I        .3 9PKGOJI823  3  GUKGJYXEXSGULN* *Y 1V64 1*J2   .
D  Ø.ØØØ +3 HI528JNN7EALG43NONWYGIKFH6IJO3*I **  YZZ   U*R+
U        .3 B211 9CJTQRNREAE2884461  526 I 1P22T*8 3C**L  .
A        .236    22AIELA7VR1 4 2             9K  2PL   3I8.
L        .184       43237BG4                1        216  .
         . O1             4                              1.
  -.ØØ25 + K                                              +
         . 6                                              .
         .                                                .
         .                                                .
         .                                                .
  -.ØØ5Ø +                                                +
         .+....+....+....+....+....+....+....+....+....+...
               5.        15        25        35        45
          Ø.        1Ø        2Ø        3Ø        4Ø

                             TIME, hours
```

Figure 6.6 Residuals 2Ø B vs. Time, 2 Term Exp. Model

Table 6.4 Three Term Exponential Fit to Data Sets

Test	18 A	18 B	19 A	19 B	20 A	20 B
P1	0.028	0.019	0.032	0.019	0.021	0.026
P2	-2.67	-2.60	-2.39	-1.81	-2.68	-2.75
P3	0.087	0.037	0.091	0.042	0.072	0.080
P4	-0.535	-0.459	-0.447	-0.321	-0.359	-0.345
P5	0.054	0.040	0.045	0.034	0.052	0.046
P6	-0.095	-0.088	-0.067	-0.052	-0.069	-0.063
P7	0.074	0.074	0.076	0.075	0.106	0.104
Residual Mean Square	0.28 E-6	0.29 E-6	0.45 E-6	0.27 E-6	0.38 E-6	0.25 E-6

This model fits the data somewhat better than the two term exponential with the residual mean square lower in every case. However, the degree of improvement is not great and the difference in residual mean square is not statistically significant. In several cases the residual mean square is approaching the expected minimum of 0.25 E-6.

The plots of the residuals were again examimed. Figure 6.7 shows the residuals from the fit to test 18 A plotted vs. time and Figure 6.8 shows the same residuals plotted against the predicted value. In neither case is there any pattern which was significant. The small dips could easily be ascribed to transducer drift. At time greater than 35 hours the roundoff error can be seen as stripes in the residuals, in Figure 6.7. In Figure 6.8 the slightly triangular distribution is caused because there are far more observations at the lower predicted moisture

```
         .+....+....+....+....+....+....+....+....+....+...
   .0075 +                                                 +
         .                                                 .
         .          Explanation of symbols, p. 126         .
         .                                                 .
         .                                                 .
   .0050 +                                                 +
         .                                                 .
         .                                                 .
         .                                                 .
         .                                                 .
   .0025 +                                                 +
R        .                                                 .
E        .  1  1 2          2C42   3        1     2        .
S        .285 25899212 2131EGH86315 1 1  3A2  GFB1       IH.
I        .3AH5ELNITHBA83874FRNXF5M2U J32E3 J**7  P**N82    .
D  0.000 +6JOQNLKNINPJFKJTRFD8DVW6* *7T* J*X  U**S    V**O+
U        .5JCMH9773DELQMQHMD2 26GS1R1VL2*Y 1LN5  3BM**L    .
A        .14 733211568AC5453    335 832I  55  22 2   3G    .
L        .  1       2 111               3 11         32    .
         .                               1                 .
  -.0025 +                                                 +
         .                                                 .
         .                                                 .
         .                                                 .
         .                                                 .
  -.0050 +                                                 +
         .                                                 .
         .                                                 .
         .                                                 .
         .                                                 .
  -.0075 +                                                 +
         .+....+....+....+....+....+....+....+....+....+...
              5.        15        25        35        45
          0.        10        20        30        40

                              TIME, hours
```

Figure 6.7 Residuals 18 A vs. Time, 3 Term Exp. Model

```
          .+....+....+....+....+....+....+....+....+....+..
   .0075 +                                                 +
         .                                                 .
         .          Explanation of symbols, p. 126         .
         .                                                 .
         .                                                 .
   .0050 +                                                 +
         .                                                 .
         .                                                 .
         .                                                 .
         .                                                 .
   .0025 +                                                 +
R        .                                                 .
E        .     36H   21         1                          .
S        .     *K*44AA752    1121 31211   1 1              .
I        .     ***JR*QOD87 345353221 12 1 111              .
D  0.000 +     ******TIHCEA8A65544233123 411               +
U        .     *****C968B8B7345123242311411 1              .
A        .     Z*BPJ41322143    11   1 1   1               .
L        .     64 32        1                              .
         .      1                                          .
  -.0025 +                                                 +
         .                                                 .
         .                                                 .
         .                                                 .
         .                                                 .
  -.0050 +                                                 +
         .                                                 .
         .                                                 .
         .                                                 .
         .                                                 .
  -.0075 +                                                 +
          .+....+....+....+....+....+....+....+....+....+..
               .075      .125      .175      .225      .275
          .050      .100      .150      .200      .250

                Predicted Moisture Content, dec. d. b.
```

Figure 6.8 Residuals 18 A vs. Predicted, 3 Term Exp. Model contents and therefore it is likely to have a few observations further from the mean than at the higher moisture contents.

In Figure 6.9 the residuals from test 18 B are plotted against time and in Figure 6.10 they are plotted against the predicted value. Figure 6.9 looks much like Figure 6.7 with no pattern which could not easily result from transducer drift. However, in Figure 6.10 there appears to be a slight pattern for the first 40 data points. The residuals for test 19 A are much like those for test 18 B and those for 20 A appear much like those for 18 A and are not included.

The residuals from test 19 B plotted vs. time are shown in Figure 6.11 and plotted against the predicted value in Figure 6.12. Figure 6.11 shows no real pattern, but, in Figure 6.12 a pattern is seen similar to that seen in Figure 6.10 only more pronounced. The residuals from 20 B are plotted vs. time in Figure 6.13 and vs. the predicted value in Figure 6.14. Again there is no clear pattern in Figure 6.13 but the pattern seen in Figure 6.10 and 6.12 is repeated in Figure 6.14.

On the basis of the pattern in the residuals it was concluded that something was measured during the first half hour of some of the tests which was not accounted for by the three term exponential model. Actually the residuals are all quite low. The roundoff error was 0.00005 and the

```
          .+....+....+....+....+....+....+....+....+....+...
    .0075 +                                                 +
          .                                                 .
          .          Explanation of symbols, p. 126         .
          .                                                 .
          .                                                 .
    .0050 +                                                 +
          .                                                 .
          .                                                 .
          .                                                 .
          .                                                 .
    .0025 +                                                 +
R         .1                     1                          .
E         . 1   1     2         2371 1                11    .
S         .253 231765135  11 12 4IR36 77  92    34       5C.
I         .1IB4EHAMMH7S88E543C18HYC* *K YU1 HLA1   MV***M   .
D   0.000 +6MMNORSNLNTIPUGMGHMTBZ2E7*6M*9 **9  V**K1    3*M+
U         .8CJQGBJ8BBE9HIDQSYGD* 1 A 3B GU3 M**A   YT1FEW   .
A         .5256312  47 54G6869E 2      41 1JC  GB6*3    3B .
L         .1  1      1   1 2  12            152             .
          .                                                 .
   -.0025 +                                                 +
          .                                                 .
          .                                                 .
          .                                                 .
          .                                                 .
   -.0050 +                                                 +
          .                                                 .
          .                                                 .
          .                                                 .
          .                                                 .
   -.0075 +                                                 +
          .+....+....+....+....+....+....+....+....+....+...
                5.        15        25        35        45
           0.        10        20        30        40

                              TIME, hours
```

Figure 6.9 Residuals 18 B vs. Time, 3 Term Exp. Model

```
         .+....+....+....+....+....+....+....+....+....+....+...
   .0075 +                                                 +
         .                                                 .
         .           Explanation of symbols, p. 126        .
         .                                                 .
         .                                                 .
   .0050 +                                                 +
         .                                                 .
         .                                                 .
         .                                                 .
         .                                                 .
   .0025 +                                                 +
R        .      1                1                         .
E        .     2E 2  1      1                              .
S        .     Z*39C831 12131   11                         .
I        .     *****PL944646631                            .
D  0.000 +     ******YLHC99655312                          +
U        .     ****OPCJHC873 3332                          .
A        .     *L*G42143431 1 221                          .
L        .     8331    1       1                           .
         .                                                 .
  -.0025 +                                                 +
         .                                                 .
         .                                                 .
         .                                                 .
         .                                                 .
  -.0050 +                                                 +
         .                                                 .
         .                                                 .
         .                                                 .
         .                                                 .
  -.0075 +                                                 +
         .+....+....+....+....+....+....+....+....+....+....+...
              .075      .125      .175      .225      .275
        .050      .100      .150      .200      .250

               Predicted Moisture Content, dec. d. b.
```

Figure 6.10 Residuals 18 B vs. Predicted, 3 Term Exp. Model

```
         .+....+....+....+....+....+....+....+....+....+...
   .0075 +                                                +
         .                                                .
         .          Explanation of symbols, p. 126        .
         .                                                .
         .                                                .
   .0050 +                                                +
         .                                                .
         .                                                .
         .                                                .
         .                                                .
   .0025 +2                                               +
R        .                                                .
E        .  1  1    1           1   1 1        1   22     .
S        .267 266328  21 1 12 1  8 J19132 11 112 334      .
I        .1KH16MMAMKLDE54C88AU8II9*B*AED W6 P9 9K3 6*Z    .
D  0.000 +1KILKMJNNNKMMKMMVWKFZIQWCQFSSA*5I*2E*G K**      +
U        .8BARM6AHB9BDMQPFHEPC6IEB846DCX LR TW E*V  5D    .
A        .9369A1372 7B 6794523A51 4 1 4 I28L3 KH  C3      .
L        .3 12 1     1 121  1          1    14  23        .
         .                                                .
  -.0025 +                                                +
         .                                                .
         .                                                .
         .                                                .
         .                                                .
  -.0050 +                                                +
         .                                                .
         .                                                .
         .                                                .
         .                                                .
  -.0075 +                                                +
         .+....+....+....+....+....+....+....+....+....+...
               5.        15        25        35        45
          0.        10        20        30        40

                            TIME, hours
```

Figure 6.11 Residuals 19 B vs. Time, 3 Term Exp. Model

```
        .+....+....+....+....+....+....+....+....+....+...
  .0075 +                                                 +
        .                                                 .
        .          Explanation of symbols, p. 126         .
        .                                                 .
        .                                                 .
  .0050 +                                                 +
        .                                                 .
        .                                                 .
        .                                                 .
        .                                                 .
  .0025 +                        2                        +
R       .                                                 .
E       .     53  1 1   1                                 .
S       .     L*43C78   643     2                         .
I       .     *****PR312C9A31  1                          .
D 0.000 +     ******RHGB88572 1                           +
U       .     ****MO7OJE22 45341                          .
A       .     *PUO661B68   1353                           .
L       .     A142  1 21    12                            .
        .                                                 .
 -.0025 +                                                 +
        .                                                 .
        .                                                 .
        .                                                 .
        .                                                 .
 -.0050 +                                                 +
        .                                                 .
        .                                                 .
        .                                                 .
        .                                                 .
 -.0075 +                                                 +
        .+....+....+....+....+....+....+....+....+....+...
             .075      .125      .175      .225      .275
        .050      .100      .150      .200      .250

            Predicted Moisture Content, dec. d. b.
```

Figure 6.12 Residuals 19 B vs. Predicted, 3 Term Exp. Model

```
         .+....+....+....+....+....+....+....+....+....+...
   .0050 +                                                +
         .                                                .
         .                                                .
         .                                                .
         .                                                .
   .0025 +                                                +
R        .                                                .
E        .     15 3    3     21  2 13 4  1                .
S        .145  AA65311     4832131I5CL58D G5 8  1G   22   .
I        .7GC7HMMLJG3C8GB 1KULFJZRC*KSLRC*4VY 5V5  Z*H   3.
D  0.000 +6LJQQKLMMSPPLNMA4MLPXVGOSBP6REZ *N *W C*Z1 2***O+
U        .7FELE529ABQHP9KKM915875624 52B L 1P18T*  IC*   5.
A        .451632 2 255697RK1 4 21           9E  2P6  19I3.
L        .2              3B4                1        2   1.
         .                2                               .
  -.0025 +                                                +
         .                                                .
         .                                                .
         .                                                .
         .            Explanation of symbols, p. 126      .
  -.0050 +                                                +
         .+....+....+....+....+....+....+....+....+....+...
               5.        15        25        35        45
          0.        10        20        30        40

                          TIME, hours
```

Figure 6.13 Residuals 20 B vs. Time, 3 Term Exp. Model

```
          ....+....+....+....+....+....+....+....+....+....+
    .0050 +                                                +
          .                                                .
          .                                                .
          .                                                .
          .                                                .
    .0025 +                                                +
R         .                                                .
E         .           95 3  3 33                           .
S         .           **LF 13548942     131     22       1 .
I         .          ****RKANKJGC7962212532122333142  1  1 .
D   0.000 +          *******XNGBDABC9875533346421213    2  +
U         .          **T*****AA21384577761144421112 33 1   .
A         .          * 7VWC7 2  131 2221   4     1   121   .
L         .          4  F3                           1 1   .
          .             2                                  .
   -.0025 +                                                +
          .                                                .
          .                                                .
          .                                                .
          .             Explanation of symbols, p. 126     .
   -.0050 +                                                +
          ....+....+....+....+....+....+....+....+....+....+
                  .10       .14       .18       .22
             .08       .12       .16       .20       .24
```

Predicted Moisture Content, dec. d. b.

Figure 6.14 Residuals 20 B vs. Predicted, 3 Term Exp. Model

transducer error was believed to be in the range of 0.001. Fewer than 2% of the data points in test 19 B, for example, lie outside the band -0.00125 to +0.00125. Therefore, the three term exponential model fits well for all the tests and is adequate for tests 18 A and 20 A, but does not adequately explain all observations in tests 18 B, 19 A, 19 B and 20 B.

6.2.4 Four Term Exponential Model

The curves which show the clearest pattern in the residual with the three term exponential, 19 B and 20 B, are also the ones with the lowest estimated error. The effect measured is the fourth exponential term. The fourth term is smaller than the previous terms, so the measurement error must be lower in order to see the effect of this term. Another observation is that the patterns appear mostly with test B and not with test A. The explanation for this is that the fourth term of the exponential dies away rapidly in time. Test B was always loaded second and none of the data were used until the test chamber had been closed. Therefore, the major effect of the fourth term had died away before the data collection was begun for test A. The delays from the time the trays were loaded until the first data point are shown in Table 6.5 rounded to the nearest half minute.

Table 6.5 Tray Loading Delays

Test	Delay (hours)	Test	Delay (hours)
5 A	0.117	14 A	0.100
5 B	0.033	14 B	0.033
6 A	0.150	15 A	0.133
6 B	0.033	15 B	0.050
7 A	0.117	16 A	0.100
7 B	0.033	16 B	0.033
8 A	0.117	17 A	0.083
8 B	0.033	17 B	0.017
9 A	0.117	18 A	0.133
9 B	0.033	18 B	0.017
10 A	0.133	19 A	0.117
10 B	0.017	19 B	0.067
12 A	0.183	20 A	0.133
12 B	0.050	20 B	0.050
13 A	0.100	21 A	0.133
13 B	0.017	21 B	0.067

The four tests in which a pattern in the residuals had been noted were fit to a four term exponential (equation 6.4). The other two tests were not fit to a four term exponential because there was no valid reason to do so and the residual mean square had not been reduced significantly by the three term exponential compared to the two term exponential. The results of the fit to a four term exponential model are presented in Table 6.6.

Table 6.6 Four Term Exponential Fit to Data Sets

Test	18 B	19 A	19 B	20 B
P1	0.019	0.023	0.013	0.021
P2	-8.47	-4.66	-8.37	-5.11
P3	0.026	0.034	0.020	0.027
P4	-0.934	-0.982	-0.986	-0.788
P5	0.026	0.075	0.038	0.068
P6	-0.283	-0.386	-0.272	-0.277
P7	0.035	0.044	0.032	0.041
P8	-0.079	-0.063	-0.047	-0.055
P9	0.074	0.075	0.074	0.103
Residual Mean Square	0.27 E-6	0.44 E-6	0.25 E-6	0.23 E-6

The residual mean square was reduced in every case compared to the three term exponential, but not significantly. There was no expectation that the residual mean square would be reduced significantly since the residual due to the points which were not fit well with the three term exponential was very small compared to the total number of data points. However, the pattern in the residuals had been removed by the additional two parameters. Figure 6.15 and Figure 6.16 show the residuals vs. the predicted moisture content for tests 19 B and 20 B respectively. There is no discernible pattern in these plots.

A series of decaying exponentials modeled the six data sets adequately. In some of the tests it was possible to support a four term exponential model. In the other cases only a three term exponential model was supportable.

```
         ...+....+....+....+....+....+....+....+....+....+.
   .0075 +                                                +
         .                                                .
         .                                                .
         .                                                .
         .                                                .
   .0050 +                                                +
         .                                                .
         .                                                .
         .                                                .
         .                                                .
   .0025 +                                                +
R        .                                                .
E        .       73  1  1     1                           .
S        .       I*E467757   32 1     1                   .
I        .       *****YNMJ662785522222 1                  .
D  0.000 +       ******UMFHIB89975653121                  +
U        .       ****TNJB8GAB5 4253322 1                  .
A        .       *ELFH56533151   1    1                   .
L        .       91 41                                    .
         .                                                .
  -.0025 +                                                +
         .                                                .
         .                                                .
         .                                                .
         .                                                .
  -.0050 +                                                +
         .          Explanation of symbols, p. 126        .
         .                                                .
         .                                                .
         .                                                .
  -.0075 +                                                +
         ...+....+....+....+....+....+....+....+....+....+.
           .06       .10       .14       .18       .22
                .08       .12       .16       .20
```

Predicted Moisture Content, dec. d. b.

Figure 6.15 Residuals 19 B vs. Predicted, 4 Term Exp. Model

```
            ....+....+....+....+....+....+....+....+....+....
      .0075 +                                                +
            .                                                .
            .                                                .
            .                                                .
            .                                                .
      .0050 +                                                +
            .                                                .
            .                                                .
            .                                                .
            .                                                .
      .0025 +                                                +
R           .                                                .
E           .             4 3  2 22        2                 .
S           .          **BOB757 6131  111342     21 21  1    .
I           .          *****ZJNIDD96873454632222123123    1 *
D     0.000 +          *******SOHJE9CD997522725443222 43  1 +
U           .          *****QQBBA589447543  14334112    22  .
A           .          *48QD14 5  152        3     1  1  1  .
L           .          5  9                                  .
            .             1                                  .
     -.0025 +                                                +
            .                                                .
            .                                                .
            .                                                .
            .                                                .
     -.0050 +                                                +
            .             Explanation of symbols, p. 126     .
            .                                                .
            .                                                .
            .                                                .
     -.0075 +                                                +
            ....+....+....+....+....+....+....+....+....+....
                     .10       .14       .18       .22
                .08       .12       .16       .20       .24

                  Predicted Moisture Content, dec. d. b.
```

Figure 6.16 Residuals 20 B vs. Predicted, 4 Term Exp. Model

Because these six data sets had the lowest expected error, there is no reason to assume that a four term exponential could be supported by the other data sets with greater errors. Therefore, while the four term exponential model has been shown to be useful in some cases, it will not be used when data for different data sets are combined.

6.3 Reduced Data Sets

One of the objectives of this study was to obtain guidelines of how often data on thin layer drying should be collected and at what times. The 32 data sets with one data point every minute were too large to fit into the mainframe computer for analysis. Nonlinear regression would have been prohibitively expensive if all of the data had fit in.

Parameters may be determined accurately with few data points if a proper model is used and the data are measured with small errors. Of course, variables cannot be measured with zero error and the models do not fit the data exactly. The determination of a reasonable number of observations which are required is always subjective until the errors in each of the variables are known. Three to five observations per parameter are often used providing the observations cover the range of interest. The individual curves and the three term exponential model of seven parameters would require a minumum of 20 to 40 points well spaced in time.

6.3.1 Maximum Time

If the moisture content model fits the data well it should not be necessary to measure the moisture content of the product at equilibrium but the value for EMC should be obtainable from the model as the moisture content approaches equilibrium. In order to get an indication of the maximum time which is necessary for data collection three of the data sets (18 A, 18 B, and 19 A) were regressed to a three term exponential (equation 6.3) with the last included data point at 24, 30, and 36 hours.

The resulting parameter estimates were used to calculate the residual mean square for the entire data set. The value for the residual mean square from the parameter estimates resulting from the regression of all of the data was taken as the "best" answer. In comparing the residual mean square some guideline had to be chosen as to what was a good fit. When the error mean square was more than doubled the fit was considered to be significantly worse. Tables 6.7, 6.8, and 6.9 show the results of this study.

Table 6.7 Time Maximum for Test 18 A

Time max. (hours)	24	30	36	47.2
P1	0.07	0.031	0.028	0.028
P2	-3.48	-2.17	-2.68	-2.67
P3	0.086	0.085	0.087	0.087
P4	-0.589	-0.499	-0.535	-0.535
P5	0.058	0.052	0.054	0.054
P6	-0.1086	-0.0884	-0.0944	-0.0946
P7	0.076	0.074	0.074	0.074
Residual Mean Square (of total data set)	0.56 E-6	0.31 E-6	0.28 E-6	0.28 E-6

Table 6.8 Time Maximum for Test 18 B

Time max. (hours)	24	30	36	47.1
P1	0.018	0.017	0.022	0.019
P2	-6.98	-4.96	-1.97	-2.60
P3	0.035	0.037	0.036	0.037
P4	-0.733	-0.622	-0.385	-0.459
P5	0.048	0.045	0.037	0.040
P6	-0.121	-0.106	-0.080	-0.088
P7	0.077	0.076	0.074	0.075
Residual Mean Square (of total data set)	1.06 E-6	0.47 E-6	0.29 E-6	0.29 E-6

Table 6.9 Time Maximum for Test 19 A

Time max. (hours)	24	30	36	43.3
P1	0.027	0.034	0.040	0.033
P2	-3.57	-2.14	-1.71	-2.39
P3	0.086	0.090	0.088	0.091
P4	-0.553	-0.429	-0.382	-0.447
P5	0.053	0.044	0.042	0.046
P6	-0.109	-0.065	-0.051	-0.067
P7	0.082	0.076	0.073	0.076
Residual Mean Square (of total data set)	2.50 E-6	0.46 E-6	0.56 E-6	0.45 E-6

The entries in the column headed by the maximum time of over 40 hours are the same as those in Table 6.4. From these tables it is clear that 24 hours of data is not enough, that 30 hours may be enough and that 36 hours certainly is long enough. Therefore, the maximum time for the reduced data set was chosen to be 37 hours, in order to be certain that the maximum time chosen would be large enough for all data sets.

6.3.2 Data Acquisition Interval

A series of tests were performed on data sets 18 A, 20 A and 20 B to determine how often data should be collected during a study. Traditionally most researchers have collected data on a constant time interval. It would seem logical to collect data only when a measurable change in the independent variable is expected. Because the moisture content may be approximated by exponential decay, an exponentially increasing time interval was used.

Subsets of 44, 66, 100 and 150 data points were constructed from the original data sets with evenly spaced points on the predicted moisture ratio (using the logarithmic model and P2 set to -0.10). The value of -0.1 was used because that value was a low estimate of the drying rate. The subsets of data were fit to a three term exponential and the model was compared to the original set of data for the residual mean square calculation. The results of this study are included in Tables 6.10, 6.11, and 6.12.

Table 6.10 Time Intervals, Test 18 A

Number of Points	44	66	100	150	2810
P1	0.034	0.035	0.020	0.024	0.028
P2	-3.15	-1.54	-3.35	-2.75	-2.67
P3	0.088	0.078	0.088	0.087	0.087
P4	-0.526	-0.459	-0.611	-0.570	-0.535
P5	0.054	0.051	0.059	0.057	0.054
P6	-0.093	-0.086	-0.106	-0.100	-0.095
P7	0.074	0.074	0.075	0.075	0.074
Residual Mean Square (of total data set)	0.29 E-6	0.33 E-6	0.33 E-6	0.30 E-6	0.28 E-6

Table 6.11 Time Intervals, Test 20 A

Number of Points	44	66	100	150	2810
P1	0.016	0.022	0.026	0.020	0.021
P2	-2.12	-3.76	-4.31	-2.97	-2.68
P3	0.067	0.069	0.069	0.069	0.072
P4	-0.385	-0.407	-0.412	-0.392	-0.359
P5	0.055	0.057	0.057	0.055	0.052
P6	-0.079	-0.078	-0.080	-0.078	-0.069
P7	0.107	0.107	0.107	0.107	0.106
Residual Mean Square (of total data set)	0.50 E-6	0.42 E-6	0.46 E-6	0.43 E-6	0.38 E-6

Table 6.12 Time Intervals, Test 20 B

Number of Points	44	66	100	150	2810
P1	0.024	0.022	0.022	0.024	0.026
P2	-1.44	-2.80	-2.82	-3.09	-2.75
P3	0.073	0.076	0.078	0.076	0.080
P4	-0.323	-0.378	-0.371	-0.388	-0.345
P5	0.045	0.049	0.049	0.051	0.046
P6	-0.072	-0.078	-0.072	-0.078	-0.063
Residual Mean Square (of total data set)	0.55 E-6	0.47 E-6	0.29 E-6	0.35 E-6	0.25 E-6

The indications are that 44 points are not enough but that 66 points are enough. It would be prudent to include more than 66 points because of the results shown in table 6.12 where the residual mean square is not double the value for 2810 points but is nearly so with 66 data points. There is no significant difference between 100, 150 and 2810 points with these subsets of data.

The serial correlation was between 0.3 and 0.5 when the total data set was fit to the three term exponential model. This coefficient measures whether or not the error at one observation is independent of the error at the previous point. Ideally the coefficient should be near 0.0. If the value is large it means that the estimated errors on the predicted values are probably too low. The reduced data sets produced a serial correlation coefficient of between 0.0 and 0.3.

The coefficients were high when all of the data was included in the regression because there were many observations for which there was no reasonable expectation of a measurable change in the observed value, particularly after 24 hours of drying time. Another factor was that the roundoff error, 0.0005, was a significant error in the data and this error is not random when the variable is slowly decreasing.

6.3.3 The Reduced Data Set

The logarithmic model provides a good first estimate of the moisture relationship and was used as the base for the data collection interval. It is desirable to base the data collection on a reasonable value of the drying rate so that adequate coverage is given the faster drying tests. A value of -0.16 was used as an estimate for the drying rate, Table 6.2 shows this to be a reasonable estimate. Data points were selected from the original data sets based on the time at which 80 evenly spaced moisture ratios varying from 0.995 to 0.024 would occur with a P2 value of -0.16. These two values of moisture ratio were chosen because they occur at the approximate beginning of the data collection at 37 hours.

When this algorithm is followed strictly the time interval at the beginning of the test is 5 minutes and at the end is 4 hours. It seemed undesirable to allow the interval to be too large, so one hour was the greatest time interval used. The maximum time included was 37 hours.

After these adjustments, each subset contained 98 data points. Thus these subsets met both the requirements of including data for the first 37 hours and including more than 66 data points based on an exponentially increasing time interval.

To check whether these data subsets represented the entire data set from which they were drawn the six data subsets were regressed against the three term exponential model. Then the parameter estimates were used to calculate the residual mean square for predicting the entire data set. The results are presented in Table 6.13.

Table 6.13 Reduced Data Sets Fit to Three Term Exponential

Test	18 A	18 B	19 A	19 B	20 A	20 B
P1	0.028	0.017	0.031	0.015	0.020	0.025
P2	-3.59	-6.11	-2.63	-5.70	-2.94	-3.64
P3	0.088	0.039	0.094	0.043	0.069	0.079
P4	-0.580	-0.653	-0.464	-0.480	-0.385	-0.385
P5	0.057	0.045	0.047	0.040	0.055	0.050
P6	-0.101	-0.100	-0.065	-0.074	-0.076	-0.071
P7	0.075	0.075	0.075	0.077	0.106	0.105
Residual Mean Square (of total data set)	0.30 E-6	0.32 E-6	0.54 E-6	0.36 E-6	0.39 E-6	0.24 E-6
Residual Mean Square (from Table 6.4)	0.28 E-6	0.29 E-6	0.45 E-6	0.27 E-6	0.38 E-6	0.25 E-6

This table shows that the subsets do represent the original data sets well. In most cases the fit from the subset of data was not quite as good as when all of the data was used but in no case could the fit be considered significantly worse. The greatest difference between the fits is for test 19 B where the residual mean square was increased by one third. Even in this case the standard error was 0.0006 which compares favorably with the roundoff error of 0.0005.

The measured moisture content for test 19 A at time greater than 41 hours actually increased slightly which accounts for the relatively poor fit for both the full set of data and the subset of data. It also explains why the fit with the subsample was worse than with the full set of data, since no data was included in the subset after 37 hours.

6.4 Other Thin Layer Models

The objectives included analyzing the data to determine if Page's equation and models based on particle geometry were adequate in the thin layer modeling of parboiled rice. The reduced data sets were used in the analyses of the spherical model and the cylindrical model because these data sets had been found to represent the complete data sets well. Page's model was tested with the total data sets.

6.4.1 Page's Model

The model referred to as Page's equation has been used by many researchers to model the thin layer drying of different agricultural products. The model in its complete form has parameters which are dependent on the drying air temperature and relative humidity. In this section only data with constant relative humidity and temperature will be used so these variables will not enter into the formulation of the equation. The model which was fit to the data by nonlinear regression was:

$$M(t) = P1*\exp(P2*\exp(P3*\ln(t)))+P4 \qquad 6.5$$

The same six sets of data were used to test this model which were used to test the exponential models. The results of these regressions are shown in Table 6.14.

Table 6.14 Page's Equation Fit to Data Sets

Test	18 A	18 B	19 A	19 B	20 A	20 B
P1	0.230	0.110	0.228	0.115	0.165	0.170
P2	-0.810	-0.549	-0.811	-0.546	-0.504	-0.533
P3	0.455	0.507	0.439	0.464	0.537	0.539
P4	0.073	0.073	0.076	0.074	0.105	0.105
Residual Mean Square	0.50 E-6	0.29 E-6	1.25 E-6	0.37 E-6	0.61 E-6	0.62 E-6

As can be seen from the residual mean square values this model works fairly well at predicting the observed data. In no case is the fit better than with the three term exponential but the fit of 18 B is as good with one model as with the other. Only in the case of 19 A is the three term exponential model clearly better than Page's equation.

When the plots of the residuals for test 18 B were examined no clear pattern was found. However, in all other data sets a clear pattern in the plotted residuals indicated that the model was inadequate. Figure 6.17 shows the residuals from test 19 B plotted against time and Figure 6.18 shows them plotted against the predicted values. Figures 6.19 and 6.20 show the residuals from test 20 B plotted against time and the predicted values, respectively. The other three sets of residuals were similar to these two.

The conclusion is that Page's empirical model is a good model in the sense of predicting the data well. However, this model is inadequate in explaining the variation seen in the moisture content over time and, based on the pattern in the residuals, must be rejected as a model.

6.4.2 Spherical Model

Several researchers have assumed that the grain particles being studied behaved as spheres. The spherical model is (Newman 1932a):

$$M(t) = P1 * \sum (6.0/PS/n^2 * \exp(P2 * t * PS * n^2)) + P3 \qquad 6.6$$

where: $PS = 3.14159*3.14159$

```
          .+....+....+....+....+....+....+....+....+....+..
   .0050 +                                                 +
         .                                                 .
         .                                                 .
         .                                                 .
         .                                                 .
   .0025 +                                                 +
R        . 11                   1                          .
E        . EA              11    5 A2 2                    .
S        . NH  1   11 21 5459P7IBCOKEJ A2 31  13   62      .
I        .1HFD7E522A82D7AJMRHKXFXPOH*4*69*4 QA  E63  J     .
D  0.000 +44APJMNALKHQKOTKNLSC7LEI6D4* YU U*1 *P6 G**G     +
U        .516HOFKMNLMIPMGBB543D31 6 3 G97NF T*  Y*T  A     .
A        .7 1595AHC87D 435 11  2       B 8L3 KV4 A353      .
L        .3   12292 51 12             1    14  232         .
         .5                                                .
  -.0025 +                                                 +
         .1                                                .
         .                                                 .
         .                                                 .
         .          Explanation of symbols, p. 126         .
  -.0050 +                                                 +
          .+....+....+....+....+....+....+....+....+....+..
               5.        15        25        35        45
          0.        10        20        30        40

                              TIME, hours
```

Figure 6.17 Residuals 19 B vs. Time, Page's Equation

```
             ...+....+....+....+....+....+....+....+....+..
     .0050 +                                             +
           .                                             .
           .                                             .
           .                                             .
           .                                             .
     .0025 +                                             +
R          .        1          1  1                      .
E          .        J2         46671                     .
S          .       I**731 l   18B8642                    .
I          .       ****IC58D397943 652                   .
D   0.000  +       *****ZPNNDFD3   134                   +
U          .       ******SMFKA9      24                  .
A          .       *22CKKKB4921       241                .
L          .       Cl 362941           2 1               .
           .                            311              .
    -.0025 +                                             +
           .                              1              .
           .                                             .
           .                                             .
           .                                             .
    -.0050 +                                             +
           .                                             .
           .        Explanation of symbols, p. 126       .
           .                                             .
           .                                             .
    -.0075 +                                             +
             ...+....+....+....+....+....+....+....+....+..
               .06       .10       .14       .18       .22
                    .08       .12       .16       .20
```

Predicted Moisture Content, dec. d. b.

Figure 6.18 Residuals 19 B vs. Predicted, Page's Equation

```
         .+....+....+....+....+....+....+....+....+....+...
   .0075 +                                                +
         .                                                .
         .                                                .
         .                                                .
         .                                                .
   .0050 +                                                +
         .                                                .
         .                                                .
         .                                                .
         .                                                .
   .0025 + 15                                             +
R        . 6L                21  2 1                      .
E        . OD1         3   6D42131F D 6  1                .
S        . I7B          6 1LUNKJZMAX2*3ED 75              .
I        . 35L3 2 1  45LH74KGQXYETQB*4*LC*D3Y8  6G   82   .
D  0.000 +35 LG741573KNNSJO91334769F57BIZ ** 7*V  B**B   A+
U        .63 6NLFDKLPPQA6VI  2 21    427 L4 P*  **O  G***H.
A        .11  BNPQKORA6333B4               1 3MT1 GOCM   6.
L        .5   78EEC851    2                 16   29   19I2.
         .2    1 61                                  2   1.
  -.0025 +5                                               +
         .4                                               .
         .1                                               .
         .                                                .
         .                                                .
  -.0050 +                                                +
         .                                                .
         .                                                .
         .          Explanation of symbols, p. 126        .
         .                                                .
  -.0075 +                                                +
         .+....+....+....+....+....+....+....+....+....+...
               5.        15        25        35        45
          0.        10        20        30        40

                            TIME, hours
```

Figure 6.19 Residuals 20 B vs. Time, Page's Equation

```
         ...+....+....+....+....+....+....+....+....+....
   .0075 +                                              +
         .                                              .
         .                                              .
         .                                              .
         .                                              .
   .0050 +                                              +
         .                                              .
         .                                              .
         .                                              .
         .                                              .
   .0025 +                           32  1              +
R        .          15              15835 41            .
E        .          ZBJ3            24424554431         .
S        .         3***6          1763  3313432         .
I        .         *****9  111  147881   1    1 1       .
D  0.000 +         **L***B6432439CA51        1133       +
U        .         **5ZU**MEH9DCB94           12141     .
A        .         *  I5HXTKMLED4              1     1  .
L        .         *  2 17EF8A554                 32    .
         .         3      16  1                    11   .
  -.0025 +                                         1211 +
         .                                            2 *
         .                                              *
         .                                              .
         .                                              .
  -.0050 +                                              +
         .                                              .
         .                                              .
         .          Explanation of symbols, p. 126      .
         .                                              .
  -.0075 +                                              +
         ...+....+....+....+....+....+....+....+....+....
                .10       .14       .18       .22
           .08       .12       .16       .20       .24

                Predicted Moisture Content, dec. d. b.
```

Figure 6.20 Residuals 20 B vs. Predicted, Page's Equation

There is no clear indication of the number of terms needed to adequately model the drying of grain. The terms become smaller as n increases and the time period over which they are important decreases as n increases. For example, the coefficient on the eighth term is 0.009 and the coefficient on the tenth term is 0.006. Since these coefficients are multiplied by P1, the total moisture loss from initial time to equilibrium, which is typically in the range of 0.2, the tenth term would not be expected to have much effect.

The fit to this model of several data sets was poor and the only conclusion which can be drawn is that the spherical model is not adequate for parboiled long grain rice. Tables 6.15 and 6.16 show some of the results indicating that even with 12 terms in the model, the fit is not good. The residual mean square using the three term exponential was 0.5 E-6 or less while the residual with this model was at least four times as large. In addition the fit is not improved significantly with the added terms.

Table 6.15 Test 19 B With Spherical Model

n	4	6	8	12
P1	0.095	0.094	0.094	0.093
P2	-0.0159	-0.0154	-0.0152	-0.0151
P3	0.083	0.083	0.083	0.083
Residual Mean Square (of subset)	2.9 E-6	2.3 E-6	2.1 E-6	2.0 E-6

Table 6.16 Test 20 B With Spherical Model

n	4	6	8	12
P1	0.157	0.156	0.155	0.155
P2	-0.0182	-0.0177	-0.0175	-0.0174
P3	0.113	0.112	0.112	0.112
Residual Mean Square (of subset)	4.2 E-6	3.2 E-6	3.0 E-6	2.9 E-6

Figure 6.21 shows the residuals from test 19 B vs. time for the four term case. All plots of the residuals showed a similar clear pattern. With more terms the fit was slightly better for small time but substantially unchanged in shape.

6.4.3 Infinite Cylinder Model

It would seem more reasonable to assume that the particles of long grain rice behave as infinitely long cylinders than as spheres. The exact radius of the cylinder which would work best should be less than half the maximum grain thickness. The cylindrical model is (Newman 1932a,b):

Figure 6.21 Residuals 19 B vs. Time, 4 Term Sphere Model

$$M(t) = P1 * \Sigma 4.0/R_n^2 * \exp(P2 * time * R_n^2) + P3 \quad 6.7$$

where:

n	R_n
1	2.4048
2	5.5201
3	8.6537
4	11.9715
5	14.9309
6	18.0711
7	21.212
8	24.352

(The R constants are the roots of the Bessel Function)

There is again no clear indication of how many terms should be included in the series. The terms approach zero faster than in the case of the sphere because the R constants grow faster than n. Several data sets were fit to this model with various numbers of terms included. The results of the regression study on the cylindrical model are shown in Tables 6.17 and 6.18.

Table 6.17 Test 18 A With Cylindrical Model

n	4	6	8
P1	0.169	0.169	0.169
P2	-0.0452	-0.0450	-0.0450
P3	0.082	0.082	0.082
Residual Mean Square (of subset)	13.3 E-6	13.2 E-6	13.2 E-6

Table 6.18 Test 19 A With Cylindrical Model

n	4	6	8
P1	Ø.168	Ø.167	Ø.167
P2	-Ø.Ø453	-Ø.Ø450	-Ø.Ø449
P3	Ø.Ø87	Ø.Ø86	Ø.Ø86
Residual Mean Square (of subset)	13.8 E-6	13.4 E-6	13.4 E-6

The results of the regression showed that the model did not work well, i.e. produce residual mean square values near those produced by the three term exponential. The residuals were examined and clear patterns were seen in all of the data sets examined. One example, Figure 6.22, is included to show the basic shape of the residual vs. time plot. All plots for the other data sets and number of terms resembled this plot.

The two most commonly used particle geometries, spherical and infinite cylinder, have been shown to be inadequate. In order to calculate a diffusivity, as is often done by other researchers, assumptions must be made about the geometry of the particles. In this study, these assumptions have been shown to be invalid for long grain parboiled rice. It is unfortunate that there are many researchers who have made assumptions about particle geometry and have not included in their published results evidence that there was no reason to reject the assumption they made about particle geometry. Usually there is no

```
                       .+....+....+....+....+....+....+....+....+....+...
                 .0100 +                                                +
                       .                                                .
                       .                                                .
                       .                                                .
                       .                                                .
                 .0075 +                                                +
                       .1                                               .
                       .1                                               .
                       .         235                                    .
                       .2      29HH95                                   .
                 .0050 +2      5TNNJ83                                  +
                       .3      9GDDLNB31                                .
                       .       H4536LQH2                                .
                       .5     8D2   3JHP1                               .
                       .      D8     1M8C 2                             .
                 .0025 + 1   1D6       LAT                              +
              R        .31   3E       13W XF                            .
              E        . 3   99         1VB 1                           .
              S        . 5   C2         3 E*8                           .
              I        . 6   C1             X8                          .
              D  0.000 + 2  1D             6E                           +
              U        . 5  77              4*81                        .
              A        . 8  93                                          .
              L        . 7  K                6*S63                      .
                       . 71 F                     1                     .
                -.0025 + 7875                  3V*U                     +
                       . 5DH1                     2*Q4                  .
                       . 2NO1                    5P                     .
                       . 1AB                      8Y**E6A21             .
                       .  41                                            .
                -.0050 +  1                          5K******NFB12      +
                       .                                                .
                       .                              11156LNZ*****N82 IH.
                       .                                                .
                       .                                    22 5BM*****O.
                -.0075 +                                                +
                       .                                           35G  .
                       .                                                .
                       .                                                .
                       .         Explanation of symbols, p. 126         .
                -.0100 +                                                +
                       .+....+....+....+....+....+....+....+....+....+...
                             5.        15        25        35        45
                        0.        10        20        30        40

                                        TIME, hours
```

Figure 6.22 Residuals 18 A vs. Time, 4 Term Inf. Cyl.

indication that the validity of the assumptions was even examined. It is not possible to prove that a particular model is correct but it is possible to look at the evidence of whether it should be rejected.

6.5 Combined Data Sets

After the individual data sets were examined the process of combining the data sets was begun. The analysis of the individual data sets has produced estimates of the error in the data within the individual data sets. There were several repeat data sets in this study which were used to determine the error between data sets. After the between data set error was better understood a subset of the data was formed by combining data from sets of different relative humidity and temperature.

6.5.1 Error Between Data Sets

There were a number of repeated data sets in the study. Only two sets had every variable repeated as nearly as possible, tests 20 and 21. In those tests grain from the same container was placed on the same tray and all settings of the equipment were the same. Every test had two samples which were subjected to the same relative humidity and temperature, except for the first 5 to 10 minutes of the approximately 40 hour test. These can be considered to be repeat points for the variables temperature and relative humidity. In addition test 7 and

15 were nearly repeat points with the control algorithm improvement between them. Also, tests 10, 17 and 18 were nearly repeat points, with the same average relative humidity while the average temperatures were 0.8 C apart.

Tests 20 A and B were combined first. These were two of the sets with the lowest residual mean square when fit with the three term exponential. They had parboiled rice of nearly the same initial moisture content, 0.254 and 0.260. A three term exponential model was written containing eight parameters, one additional parameter to allow for the fact that the initial moisture contents were different. The two dummy variables, DA and DB, had the value of 0 or 1 depending on whether the data point of consideration was from set A or B. If the model fits the data the sum of the coefficients on the exponential terms must be equal to the difference between the initial moisture content and the final moisture content. The complete model before combining was:

$$M(t)_A = DA*(P1*\exp(P2*t)+P3*\exp(P4*t)+P5*\exp(P6*t)+P7) \quad 6.8$$

$$M(t)_B = DB*(P8*\exp(P9*t)+P10*\exp(P11*t)+P12*\exp(P13*t)+P14) \quad 6.9$$

Combining 6.8 and 6.9 and considering all similar parameters except initial moisture content to be equal produces:

```
M(t) = (DA*P1+DB*P2)*((1-P4-P6)*exp(P3*t)
          +P4*exp(P5*t)+P6*exp(P7))+P8          6.10
```

This model was fit to the data of test 20 A and B. The resulting residual mean square was 1.3 E-6, considerably higher than the residual mean square from the individual data sets.

The model was then returned to the form of 6.8 and 6.9 with none of the parameters combined and the parameters were combined one by one. The two EMC parameters P7 and P14 were easily combined producing a residual mean square of 0.29 E-6, as low as with the separate data sets. Next P6 was combined with P13 and P4 was combined with P11. The resulting residual mean square was still 0.29 E-6 with 11 parameters. Then P9 and P2 were combined for a model of 10 parameters and a residual mean square of 0.30 E-6.

This meant that the drying constant and EMC values were the same for the two sets of data, as they should have been. The estimated standard deviations on the remaining parameters indicated that P3 and P10 should be combined next. The residual mean square was 0.35 E-6, still not substantially higher for the model with 9 parameters. The combining of the next two parameters produced a residual mean square of 1.3 E-6. The square root of the residual mean square is an estimate of the errors in the data. The square root of 1.3 E-6 is 0.0011 or only slightly higher than the error which was estimated to be in the moisture content data for this test, 0.0008 (Section 5.4).

There are several possible explanations for this result including transducer drift and initial condition effects. It may have been that the errors in the individual curves were underestimated because of serial correlation. The most likely explanation was that the error in the data was such that it was constant from point to point within a curve but not constant between sets.

If the equations which have been used in this work are rewritten to separate the moisture variables from the other variables the result is:

$$M(t) = (MI-EMC)*f(t,T,RH)+EMC \qquad 6.11$$

where: t = time
T = temperature
RH = relative humidity
ME = initial moisture content
EMC = equilibrium moisture content.

The formula used to calculate the moisture content data from the weight data was:

$$M(t) = (W(t)-WDM)/WDM \qquad 6.12$$

where: W(t) = weight from the weight transducer
WDM = weight of the dry matter

If 6.12 is entered in 6.11 and the equation simplified the weight of the dry matter drops out. So for an individual curve the weight of the dry matter does not matter in determining the parameters and the fit to the data. However, when the individual curves were combined the weight of the dry matter was important. Errors in the weight of the dry matter may have been the reason that the errors between the curves were much higher than the errors within the curves. In any case, the residual mean square of 1.3 E-6 was believed to be a more reliable estimate of the actual error in the data for tests 18 through 21 than the residual mean square obtained from the individual data sets.

The analysis of the data from 20 A and 20 B gave an estimate of the error in the data with temperature and relative humidity the same, so this error resulted from the experimental method or differences in the weight transducers. The next comparisons were with the transducers and initial moisture content constant, but from different tests with the same settings of relative humidity and temperature. The resulting error will give an indication of how the uncontrolled variations in these variables affect the results.

The data from test 20 A and 21 A were combined and fit to a three term exponential. Because all conditions, including initial moisture content, were to have been the same for these two tests a seven parameter model was used. The residual mean square from this analysis was 1.45 E-6. The same treatment was given to test 20 B and 21 B with the resulting residual mean square of 1.19 E-6. The individual curves from test 21 were earlier fit to the three term exponential with a residual mean square for test 21 A of Ø.34 E-6 and for test 21 B of Ø.24 E-6.

The residuals of the three combinations were nearly the same so the source of the error was neither the difference between the weight transducers nor the uncontrolled differences in relative humidity or temperature. Therefore, the best estimate of the expected mean square error in the data for tests 18 through 21 is then between 1.2 and 1.45 E-6. This will be considered to be unavoidable error, called inherent error, caused by the error of measurement in these sets of data.

The inherent error in the tests 1 through 17 was expected to be greater than that for the later tests. To get an estimate of this error, tests as nearly the same as possible were combined. There were two good sets to combine, test 7 B with test 15 B and test 1Ø B with test 17 B. These combinations were made with an eight parameter fit, the seven parameters of the three term exponential model plus one additional parameter to allow for the initial moisture content to be different. The residual mean square resulting from the combination of test 7 B with 15 B was 3.6 E-6 and for the combination of tests 1Ø B and 17 B was 2.7 E-6. In both cases the residual mean square was higher than for the later tests as expected.

6.5.2 Nonlinear Combined Approach

In this section the nonlinear approach was used for the data analysis. The data were selected from the full set of data on an exponentially increasing time interval but with a maximum interval of one hour as explained in Section 6.3.3. Eleven data sets were used (6 B, 8 A, 9 B, 12 B, 13 A, 14 B, 18 A, 18 B, 19 A, 19 B, and 20 B) with 98 points from each data set for a total of 1078 data points. The relative humidity of the drying air ranged from 0.25 to 0.51 and the temperature of the drying air ranged from 17.3 to 40.2 C.

The initial moisture content data, as determined from the data plots, were also entered into the data set. The initial moisture content, for each test, which was used in the regression analysis is shown in Table 6.19.

Originally the data set had included data from tests with the high moisture rice, initial moisture content greater than 0.45. However, these tests clearly stood out in the plots of the residuals indicating that the product was different than the lower moisture content product. The explanation for this is that the high moisture samples were removed from the material stream at the parboiling plant before entering the first 300 C rotary dryer and the lower moisture samples were removed after the first rotary dryer. The product was evidently changed by the high temperature rotary dryer. There was relatively little data for the high moisture rice, four tests at two temperatures and three relative humidities. Only data from the rice which had been dried in the high temperature rotary dryer was included for the estimation of the parameters in the model.

Table 6.19 Moisture Content at Time Zero

Test	Initial Moisture Content	Test	Initial Moistue Content
5 A	0.268	14 A	0.298
5 B	0.233	14 B	0.255
6 A	0.500	15 A	0.305
6 B	0.283	15 B	0.292
7 A	0.530	16 A	0.322
7 B	0.293	16 B	0.289
8 A	0.281	17 A	0.174
8 B	0.576	17 B	0.292
9 A	0.572	18 A	0.241
9 B	0.300	18 B	0.178
10 A	0.210	19 A	0.242
10 B	0.277	19 B	0.172
12 A	0.292	20 A	0.253
12 B	0.294	20 B	0.258
13 A	0.309	21 A	0.253
13 B	0.299	21 B	0.260

A general three term exponential form was used as described in Section 6.2.3 with the Chung-Pfost form for EMC and an Arrhenius form for drying constant. The form for the EMC was:

$$EMC = P1-P2*\ln(-(T+P3)*\ln(RH)) \qquad 6.13$$

The form for drying constant was:

$$Z = \exp(P4/(T+273.2)) \qquad 6.14$$

The three term exponential form was:

$$M(t) = (Mi-EMC)*((1-P6-P8)*exp(P5*Z*t)+P6*exp(P7*Z*t) +P8*exp(P9*Z*t))+EMC \qquad 6.15$$

These equations, with the partial derivatives with respect to each of the parameters, were entered into the nonlinear regression package BMDP3R.

The parameter values which were estimated for the model from equations 6.13, 6.14 and 6.15 are shown in Table 6.20.

Table 6.20 Parameter Values, 9 Parameter Model

Parameter	Value	Asymptotic Standard Deviation
1	0.170	0.003
2	0.0247	0.0006
3	-8.4	0.7
4	-3160	70
5	-120000	30000
6	0.589	0.009
7	-13000	3000
8	0.27	0.01
9	-2100	500

Residual Mean Square 10.7 E-6

The next step in the regression study was to see what effect the removal of one parameter had on the model. The choice was to either try a two term exponential model or to remove P3. P3 was removed first and the results are shown in Table 6.21.

Table 6.21 Parameter Values, 8 Parameter Model

Parameter	Value	Asymptotic Standard Deviation
1	0.187	0.002
2	0.0274	0.0005
4	-3590	60
5	-500000	100000
6	0.586	0.008
7	-50000	10000
8	0.28	0.01
9	-8000	2000

Residual Mean Square 11.4 E-6

The next model with a reduced number of parameters which was fit to the data was the two term exponential model with P3 in the model. The results are shown in Table 6.22.

Table 6.22 Parameter Values, 7 Parameter Model

Parameter	Value	Asymptotic Standard Deviation
1	0.182	0.002
2	0.0268	0.0006
3	-9.5	0.6
4	-2730	80
5	-8000	2000
6	0.57	0.01
7	-1200	300

Residual Mean Square 15.5 E-6

The next model was the two term exponential with P3 removed. The results of the regression are shown in Table 6.23.

Table 6.23 Parameter Values, 6 Parameter Model

Parameter	Value	Asymptotic Standard Deviation
1	0.204	0.002
2	0.0305	0.0005
4	-3310	70
5	-50000	10000
6	0.53	0.01
7	-7000	2000

Residual Mean Square 17.0 E-6

These alternative models should be compared by the residual mean square values but the F statistic cannot be depended on entirely in the nonlinear case. When the residual mean square values are compared with and without P3 the conclusion can be made that P3 does not improve the fit enough to keep it in the model.

When the results from the two term and three term models are compared the three term model is seen to be better than the two term model. The evidence from the study of the individual curves was that the three term model was required to adequately model the data. Therefore, the 8 parameter model was chosen as the appropriate model for the thin layer drying of parboiled rice.

The residual mean square value for this model, 11.4 E-6, is considerably higher than was expected from the estimate of the inherent error, between 1.2 E-6 and 3.5 E-6, from Section 6.3.2. There are two values which were considered to be parameters in Section 6.3.2 and were considered to be variables in this part of the study. One was the initial moisture content and the other was the EMC. Comments have already been made about the difficulty of estimating the initial moisture content and determining the initial time. The initial moisture content was estimated graphically and probably was no more accurate than within 0.003. Published EMC models, the form of which was used in this study, produce estimates no better than within 0.005 (ASAE 1982).

The residuals from the regression are shown plotted in Figure 6.23 against time. This figure shows that the errors at small time, due to the initial moisture content variable, and those at large time, due to EMC values, are higher than the errors at intermediate times. The conclusion is then that the larger value for the residual mean square is due to the problem of obtaining the proper initial moisture content and obtaining suitable values for EMC. The large values are not due to the fact that the three term exponential model is inappropriate. The errors due to the initial moisture variable and the EMC values should be relatively constant for either the two term or the three term exponential, so the error due to these two parts of the equation tends to overshadow the errors due to the difference between the number of terms.

Figure 6.23 does show that the regression produced a reasonably good fit to the data with fairly constant

```
            .+....+....+....+....+....+....+....+....+.
       .020 +                                         +
            .                                         .
            .                                         .
            .                                         .
            .                                         .
       .015 +                                         +
            .                                         .
            .                                         .
            .                                         .
            .                                         .
       .010 +    1                                1   +
            .    1                                    .
            .  11                                     .
            .2125431                      2  1 1 1    .
            .2 533331   1                1      1     .
       .005 +88311 531              111   1 1 21 1    +
R           .93274725321111  11 2  2131221 12211111   .
E           .3G573148645311114211 2321 1  1 1    1 2  .
S           .4GA 46A5235321 1131221 3 112 11 1 11     .
I           .6FN9BB1336534423  3 1   11111131 1  11   .
D      0.00 +3DHKF8585443444222l 2 11 112 1  1 1112   +
U           .4929A886331 2122  111 211   11 11 11 1   .
A           .3G443766341122 1 11 221112221   11       .
L           .8D454432346427331224121ll 121132311 22   .
            .CA58542412424114211 112223 112 1 32412   .
      -.005 +2877211121     1111  1    2 2211 12 1    +
            . 34 1111  1         1      1  112  111   .
            . 12131111       1                        .
            .  11212    1                             .
            .  1    1       1                         .
      -.010 +  1                                      +
            .                                         .
            .                                         .
            .                                         .
            .      Explanation of symbols, p. 126     .
      -.015 +                                         +
            .+....+....+....+....+....+....+....+....+.
                  5.        15        25        35
             0.        10        20        30        40

                         TIME, hours
```

Figure 6.23 Residuals of Fit to Total Data Set variance and few points unreasonable far from zero. The slightly hourglass shape has a reasonable physical explanation.

A control data set was constructed from data sets which were not used in the determination of the parameters. This data set was created from 9 tests (5 A, 10 A, 10 B, 13 B, 15 B, 16 B, 17 B, 21 A, and 21 B). The same algorithm which was used to choose the data points to include in the data set for estimating the parameters was used to choose the data points for this set.

The complete model, obtained by combining equations 6.13, 6.14, 6.15 and the parameters in Table 6.21 was:

$$EMC = 0.187-0.0274*\ln(-T*\ln(RH)) \tag{6.16}$$

$$Z = \exp(-3590/(273.2+T)) \tag{6.17}$$

$$\begin{aligned} M(t) = {} & (Mi-EMC)*((1-0.589-0.27)*\exp(-120000*Z*t) \\ & +0.589*\exp(-13000*Z*t)+0.27*\exp(-2100*Z*t)) \\ & +EMC. \end{aligned} \tag{6.18}$$

The model was used to predict the data of the control data set. The resulting residuals are shown in Figure 6.24 plotted against time. This plot has more scatter than the residuals from the data from which the parameters were determined, as it should have. The initial moisture content variable seems to be even worse for this data set than for the data set from which the parameters were determined. The EMC values do not seem to be as much of a

```
         .+....+....+....+....+....+....+....+....+....+.
   .020  +                                              +
         .                                              .
         .                                              .
         .                                              .
         .                                              .
   .015  +                                              +
         .                                              .
         . 1                                            .
         .                                              .
         . 1                                            .
   .010  +12                                            +
         .341                                           .
         . 2 1                                          .
R        .11                                            .
E        .12211               1 1 1                     .
S  .005  + 2613111                                      +
I        .32552441 1  1        1                        .
D        .2523442442232421   1       1                  .
U        .357B73A3122     1 1    1  1  1     1          .
A        .523245142221   1 2111    2  1   1 1 121       .
L  0.00  +66123621522122122  1 1  111 1 2211 2212       +
         .452641  1 2332   11 1111  11121 122712        .
         .676    2434   1 1     2222111111 1 61 1       .
         .521   1212 11    1  12111 1211 1  21          .
         .52   4322 2 1212112311 11   121332  111       .
  -.005  +46  32222211231  211222211 1  2 1 1 1 1       +
         .4F764243333411  2 2 1 1   1 1                 .
         .1EBBC754321 1121 1 111   1      11 112        .
         . 8533532122  1 111 1       1     111  1       .
         . 4441221211121111 1    1111  111              .
  -.010  + 51252  1  121        1   111                 +
         . 5B411 1   1                                  .
         .  452 11213                                   .
         .  13111111 1                                  .
         .  11112111                                    .
  -.015  +   1231                                       +
         .                                              .
         .                                              .
         .                                              .
         .         Explanation of symbols, p. 126       .
  -.020  +                                              +
         .+....+....+....+....+....+....+....+....+....+.
               5.        15        25        35        45
          0.        10        20        30        40
```

TIME, hours

Figure 6.24 Residuals, Complete Model on Control Data problem with this data set as they were with the other data set. The residual mean square from this analysis was 26.4 E-6.

6.5.3 Traditional Combined Approach

Realizing that this study included equipment which was believed to produce more accurate data than has been previously avaliable as well as methods of analysis which should produce models with lower overall error, a method was sought which would fairly compare the methodology covered in this dissertation with traditional methods. There were two alternatives, either analyze the data from other researchers with complete nonlinear methods or analyze the data from this study with the linearization techniques. The second approach was taken.

Page's equation had proven to be good at fitting the data in previous studies as well as this study. Therefore a model similar to that of Misra and Brooker (1980) was used:

$$M(t) = (Mi-EMC)*\exp(-K*t^{n})+EMC \qquad 6.19$$

where:
$K = \exp(P1+P2*\ln(T)+P5*V)$
$n = P3*\ln(RH)+P4*Mi$
V = the velocity of the air

In this study the velocity of the air was constant so P1 and P5*V were combined into one parameter P1. The Chung-Pfost EMC equation for rough rice was used (ASAE 1982):

$$EMC = 0.294-0.0460*\ln(-(T+35.7)*\ln(RH)) \qquad 6.20$$

Equation 6.19 was solved for moisture ratio and logarithms taken twice, as shown in Section 3.1, producing:

$$\ln(-\ln(MR)) = P1+P2*\ln(T)+\ln(t)*(P3*\ln(RH)+P4*Mi) \qquad 6.21$$

New variables were created for ln(t)*ln(RH) and ln(t)*Mi producing an equation linear in the parameters. Data were then obtained from the same tests which were used to estimate the parameters with the nonlinear method (6 B, 8 A, 9 B, 12 B, 13 A, 14 B, 18 A, 18 B, 19 A, 19 B, and 20 B). Data points were taken starting at one half hour into the test and at one half hour intervals for the first 12 hours, similar to traditional methods of data treatment. The data set consisted of 264 data points with a temperature range of 17.2 to 40.8 C and a relative humidity range from 0.24 to 0.52. The initial moisture variable was obtained from Table 6.19.

The resulting equations for n and K were:

$$n = 2.22*Mi-0.0872*\ln(RH) \qquad 6.22$$

$$K = \exp(-3.74+0.879*\ln(T)) \qquad 6.23$$

Although the statistical package which was used to obtain the parameters included information of the fit to the data, the statistics which were included lose their physical significance when transformations such as those required to obtain equation 6.21 are performed. The model, from equations 6.21, 6.22 and 6.23, was used to predict the same data set used to test the model from the nonlinear method. The residuals which resulted are plotted in Figure 6.25. The residual mean square was 67.8 E-6.

6.5.4 Comparisons of Data and Models

In this section the model which was obtained by nonlinear methods will be compared with the model obtained by traditional methods. In addition data from an independent source will be compared with the data obtained in this study.

6.5.4.1 Traditional vs. Nonlinear

The parameters for the traditional and nonlinear models were estimated by using selected data from the same tests in this study. They were then compared with selected data from different data sets from this study. The plots of the residuals are shown in Figures 6.24 and 6.25. The fit to the test data by the model resulting from the nonlinear methods is observed to be better than the fit to the same data set by the model resulting from traditional methods. In addition the residual mean square was calculated for the fit by the two models to the test data set. For the model by traditional methods it was 68 E-6 while for the model by nonlinear methods it was 26 E-6.

```
         .+....+....+....+....+....+....+....+....+....+.
         .                                              .
         .             Explanation of symbols, p. 126   .
   .020  + 11                                           +
         . 1 1                                          .
         . 2 11       1                                 .
         . 52 211211 1                                  .
         .  3323  1 11  21                              .
   .015  + 111  4 1 1         1                         +
         . 12221 2 2  1         1                       .
         .41   1    1    1   1 1  1                     .
         .1       2       111                           .
         . 1    12321                                   .
   .010  +1    132 11 1          1                      +
         .22   21   1 1                                 .
         .12  33     2 2           111                  .
R        .33 14         1                               .
E        .   1  11       1 1          11                .
S  .005  +2154 33211      1                             +
I        .62347212122              1    111             .
D        .34C72152511311    111                         .
U        .296323223221221         1 1 111111    1       .
A        .6A664623231 1  1     111   1     11111        .
L  0.00  +2C45114   21 3212      111                    +
         .461 3211  112  11211 11   11 1                .
         .831153 121        1 21      1                 .
         .54654211  222211 112111                       .
         .3A98 1 12231 2112 11   1      111             .
  -.005  +1B1321   21 12 1 21122 111  1    1 211        +
         . 9  5344  133 1  11 11 1 111 1    21111       .
         . 25  21 111     1     32421 11111121221       .
         . 124    421           1   121 31 11   1       .
         . 2234112 1         1      1 12123211211       .
  -.010  + 11125411                1 111 11     1       +
         . 13 1  12                  1     1   1        .
         .  1                1      1        1          .
         .  3          1   11   1                       .
         .   111 111 12 1      1                        .
  -.015  +  152 22213  1 1    1  1           1          +
         .   111  11      1                  71         .
         .   12131   1                       4 11       .
         .    13                                        .
         .                                              .
  -.020  +                                              +
         .+....+....+....+....+....+....+....+....+....+.
               5.        15        25        35        45
          0.        10        20        30        40
```

TIME, hours

Figure 6.25 Residuals vs. Time, Page's Model on Control Data

Neither fit is very good at low time indicating that the initial moisture variable was in error in several of the tests.

The difference in residual mean square was large enough to be considered different. Therefore, the nonlinear method produced a model which fit the data better than the model produced by one of the traditional methods from the same original data.

The difference in researcher effort and computer expense was also considerable, with the traditional method much less expensive. If only a good estimate of the moisture content of the product of study is desired, with no intent to use the parameters for anything other than predicting moisture contents, then the traditional method could be used. However, if the researcher desires to base further studies on the results of the analysis, or wishes to learn about the drying process rather than merely modeling it then the nonlinear method must be used, whether or not it produces a better fit to the data.

6.5.4.2 Comparison With Independent Data

In this section the data collected in this study are to be compared with the data published by Bakshi (1979) for short grain parboiled rice. As discussed in Chapter 2 Bakshi is the only researcher to have published data on the thin layer drying of parboiled rice. His data were published as time and moisture ratio pairs with 12 data points in the first 1.2 hours. No data at later times were published. He collected two sets of data on the drying of parboiled rough rice at three temperatures for a total of six sets of data and seventy-two data points. The three temperatures he used were 56.1, 51.0 and 40.6 C. The last temperature was near enough to temperatures covered in this study that comparisons could be made. This data set was obtained at 0.79 relative humidity, a wet bulb temperature of 36.7 C, higher than any test in this study. The initial moisture content for the two sets of data was 0.6375.

The high moisture rice in this study had been noted to behave differently than the lower moisture rice. The reason for the difference was due to the difference in treatment at the parboiling plant. The wettest rice had not been subjected to the 300 C rotary dryer to which the drier rice had been subjected. The model in this study was developed from data excluding the parboiled rice which had not been partially dried at this high temperature. The EMC values for the rice were not changed substantially but certain of the other parameters had been changed.

The data set from this study which most closely resembles Bakshi's with respect to product pretreatment and drying conditions was test 9 A. The temperature in this test was 40.2 and the relative humidity 0.47. Because this data set was from the first sets and therefore contained higher errors it was fit to only a two term exponential. The resulting parameters are shown in Table 6.24.

Table 6.24 Two Term Exponential Fit to Test 9 A

Parameter	Value	Asymptotic Standard Deviation
1	0.445	0.004
2	-0.636	0.007
3	0.044	0.003
4	-0.10	0.01
5	0.105	0.001

Residual Mean Square 4.5 E-6

This model was transformed into the form:

$$M(t) = DM*(P1*\exp(P2*t)+P3*\exp(P4*t))+P5 \qquad 6.24$$

so that it could be used with a different initial moisture content and EMC. The parameters P1 through P4 in equation 6.24 were used to model Bakshi's data and are shown in Table 6.25. P5 is, of course, the EMC.

Table 6.25 Parameters For Model 6.24

Parameter	Value
1	0.910
2	-0.636
3	0.090
4	-0.0966

The model which was used for EMC was the model developed by the nonlinear technique in this study:

$$EMC = 0.187-0.0274*\ln(-T*\ln(RH)) \qquad 6.25$$

This model, equation 6.24 and 6.25, was used to predict Bakshi's data and the residuals resulting from the prediction to data set 1 are shown in Figure 6.26.

The model predicts the data fairly well and is approaching the data at 1.2 hours when the data ends. The shape of the residual plot appears to be similar to that obtained using the two term exponential model with the data from this study, such as Figure 6.4. It is interesting to note that the predicted value is greater than the observed value, the short grain rice in Bakshi's study appears to dry slightly more rapidly than the long grain rice in this study. Caution must be used in drawing conclusions from this comparison since the study conditions are different, the product different and his data rather limited.

A similar comparison was made to Bakshi's second set of data. The residuals are shown plotted in Figure 6.27. Because the conditions were the same the residuals should have been the same, however, the moisture content at 0.25 hours appears to differ by about 0.008 in the two tests.

The model again predicts Bakshi's data fairly well supporting the premise that the data from this study were basically similar in the time-moisture content relationship to the data that he collected. If these particular two sets of data are a good measure then his data were less repeatable than the data from this study.

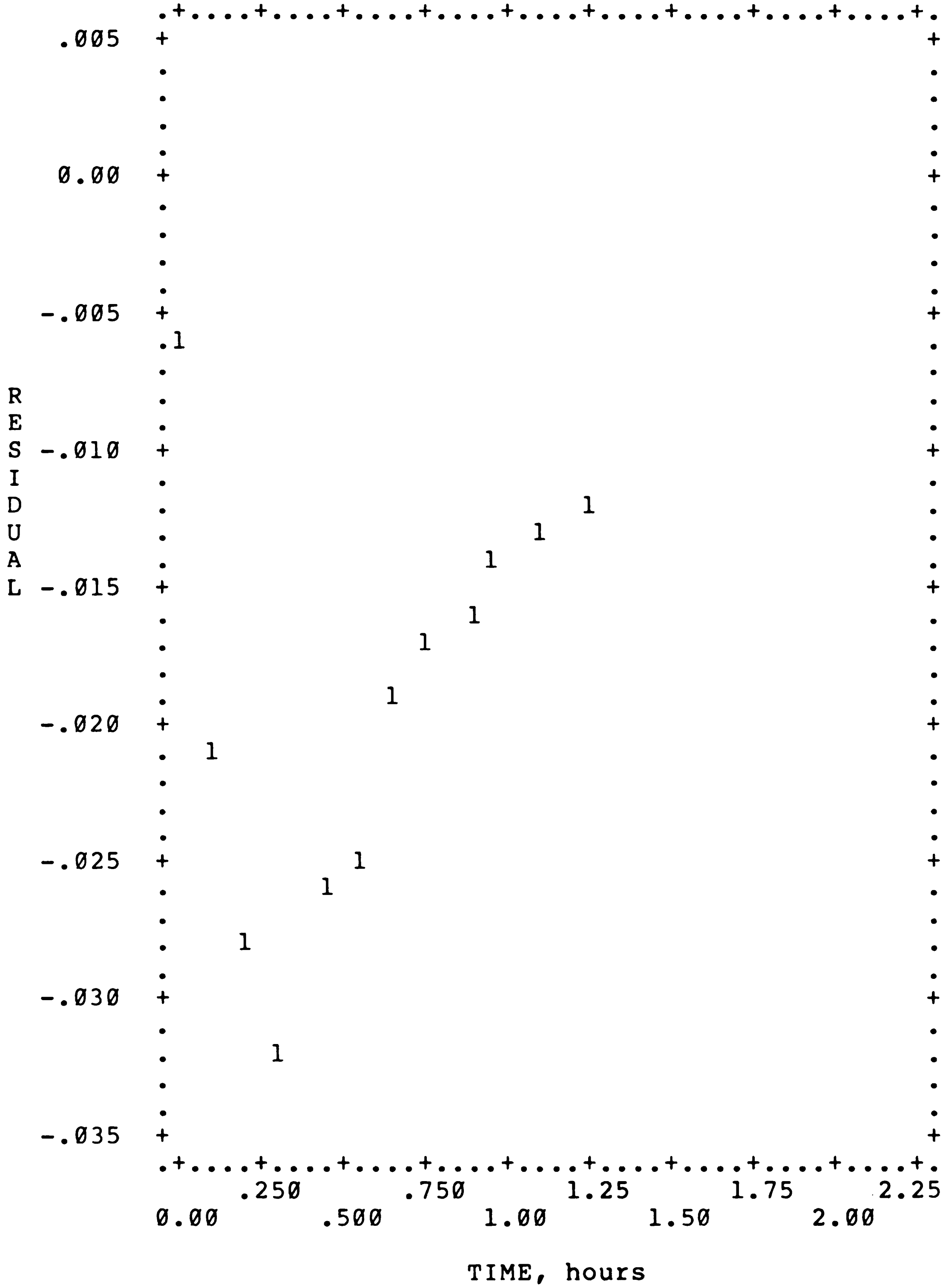

Figure 6.26 Residuals, Bakshi's Data Set 1 vs. Model

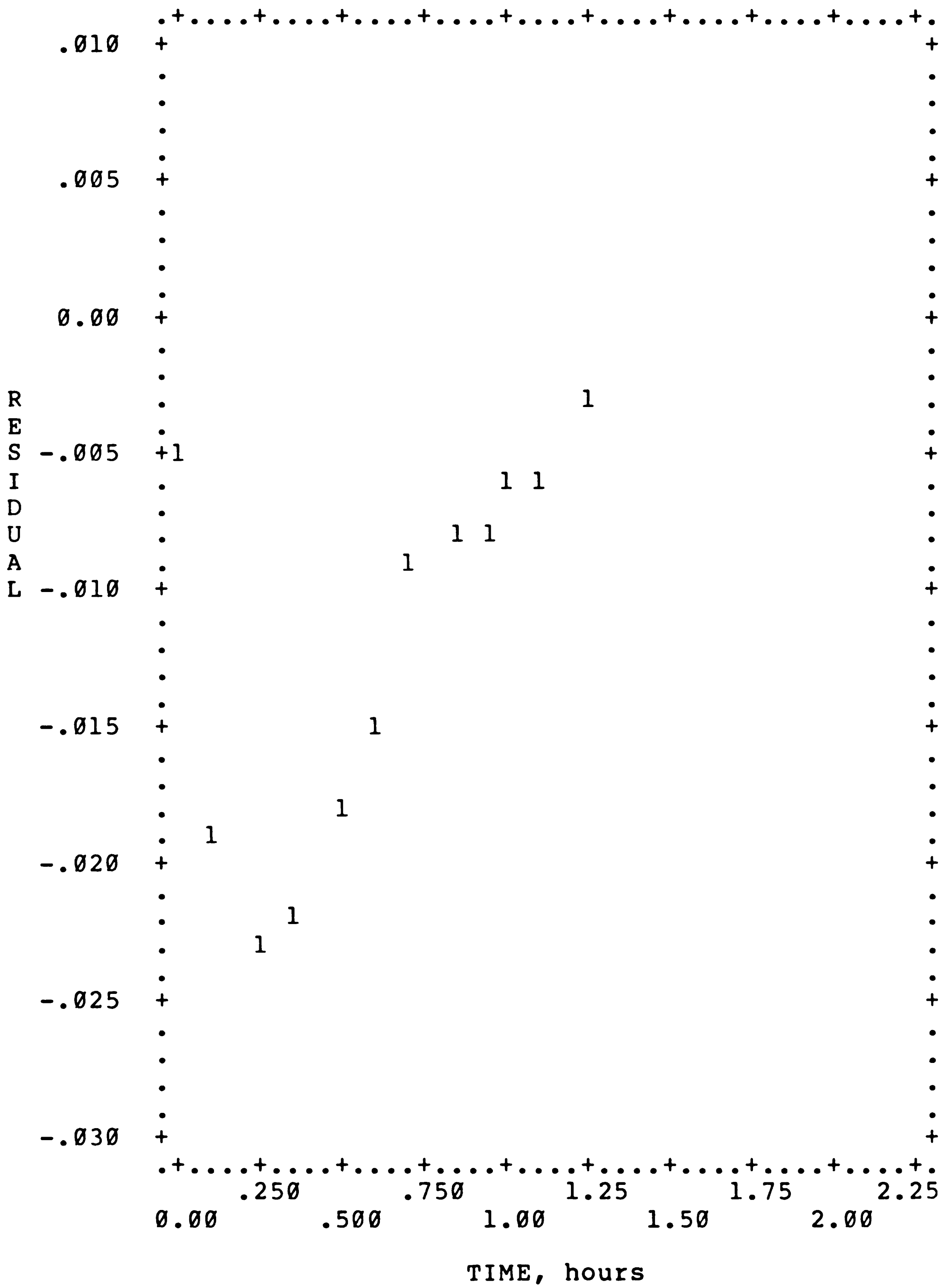

Figure 6.27 Residuals, Bakshi's Data Set 2 vs. Model

7. CONCLUSIONS

In thin layer drying studies nonlinear regression techniques should be used to obtain the parameter estimates because all of the models used are nonlinear in the parameters. For agricultural products EMC is not a known constant. Even when EMC values can be estimated with established models, the errors are in the range 0.005 to 0.03 (ASAE 1982, page 318). The errors in the moisture content data in this study were in the range of 0.001 so the EMC models produce significantly more error than is in the data. The method used in this study was to fit the data to the complete model for moisture content over time, a model which included a model for EMC. This method produced a model with lower total error and allowed the removal of parameters which could not be supported by the data. In addition, this method allowed confidence intervals to be attached to the parameters so that other researchers who may want to use the model can have a better understanding of the parameters in the model.

The equipment, which was constructed for use in this study, was operated in the range of 0.24 to 0.53 relative humidity and in the temperature range of 17.3 to 40.6 Celsius. The dry bulb temperature was maintained to within

0.3 C of the mean value for over 90% of the observations (after the initial half hour) during each testing period of over 40 hours. The relative humidity was calculated to have been maintained to within 0.005 of the mean value for over 90% of the observations during the same periods.

Models with varying numbers of decaying exponential terms were fit to the data sets believed to have the lowest inherent error. It was concluded that three or four terms were required to adequately model the observations. In reaching this conclusion, plots of the residuals were examined. These plots showed that the errors in models with fewer terms were correlated with the independent variable. The value of the residual mean square alone was not sufficient to show that a two term exponential was an inadequate model. With the three and four term exponential models the weight data of individual curves was predicted with a standard error of 0.0005. Equilibrium moisture content, EMC, was considered to be an unchanging parameter in these curves.

Page's empirical equation was found to fit the weight data well, with standard errors as low as 0.0005. In most cases, however, this model does not explain all of the variation in the dependent variable (sample weight) and was rejected as a model for thin layer drying of parboiled rice.

Two models based on particle geometry, spherical and infinite cylinder, did not fit the observed data adequately even when the radius of the particle was a parameter. While assumptions about particle geometry cannot be proven to be correct, the evidence from this research showed that these two assumptions were incorrect for parboiled rice. Whenever studies are based on assumptions about particle geometry the validity of the assumptions should be examined.

The minimum length of time for data collection was found to be 36 hours for thin layer studies of long grain parboiled rice in the temperature range of 20 to 40 C and the relative humidity range of 0.25 to 0.50. The parameter estimates which result from including data to this maximum time predicted the whole data set (with maximum time of 43 to 47 hours) as well as when the entire data set was used. The model predicts that the EMC value would have been reached in 74 hours.

An examination of several data sets was undertaken to determine the minimum number of observations which were necessary to represent the entire data set. A scheme using exponentially increasing time intervals between data points was examined and found to be useful. The one term exponential model, with a rough estimate of drying rate, was used to choose the time at which data were selected. Data subsets of 98 points for constant relative humidity and temperature were used to estimate the parameters of a three term exponential. The resulting estimates predicted the data as well as estimates obtained from the entire data set of over 2400 data points.

The preferred thin layer model which was obtained from this study for parboiled long grain rice in the temperature range of 17 to 40 C, the relative humidity range of 0.25 to 0.51, and initial moisture content from 0.18 to 0.30 was:

$$EMC = P1-P2*\ln(-T*\ln(RH)) \qquad 7.1$$

$$Z = \exp(P3/(T+273.2)) \qquad 7.2$$

$$M(t) = (Mi-EMC)*((1-P5-P7)*\exp(P4*Z*t) + P5*\exp(P6*Z*t)+P7*\exp(P8*Z*t))+EMC \qquad 7.3$$

where: t = time, hours
T = temperature, celsius
RH = relative humidity, decimal
Mi = initial moisture content, decimal d. b.
M(t) = moisture content at time t, decimal d. b.
EMC = equilibrium moisture content, decimal

and:

Parameter	Value	Asymptotic Standard Deviation
1	0.187	0.002
2	0.0274	0.0005
3	-3590	60
4	-500000	100000
5	0.586	0.009
6	-50000	10000
7	0.28	0.01
8	-8000	2000

8. SUGGESTIONS FOR FUTURE STUDY

1. The data from other thin layer studies, which has been analyzed with linearization techniques, should be reanalyzed with nonlinear techniques, when the quality of the data warrants further study. This further study would not only clarify the value of the nonlinear approach but could also examine the assumptions of particle geometry made in other studies.

2. There are many products of economic importance which are normally dried or stored at temperatures attainable in the chamber for which there is either no model of the moisture relationships or only limited data from which a model has been constructed. These products should be studied.

3. The closed form solution to diffusion in an ellipsoid would make a much better model for the particle geometry of long grain rice than the infinite cylinder or sphere which were considered in this study. The infinite cylinder and spherical models had to be rejected because of the distinct pattern in the residuals. A solution to diffusion in an ellipsoid was searched for in the mathematical and physics literature and was not found.

4. In this study the individual curves are modeled quite well, but the models used for the combined data do not work nearly as well. This discrepancy is due to problems in measuring the initial moisture content and problems with the form of the EMC equation. Perhaps different experimental techniques could reduce the error in determining the conditions at the initial time. A more theoretically based model may produce a better EMC model. In this study it has been shown that basing the temperature dependence of EMC on the freezing point of water was statistically sound. Further studies of EMC should consider this finding because the form of the model for EMC considered in this study was developed based on perfect gas laws. Considering that the models are nonlinear, the question of initial conditions is not trivial.

5. Further studies of the time interval between data points and the length of data collection in a thin layer drying study with products of vastly different drying rates should be done. The results of these studies would produce guidelines about the length of time and time interval suitable for the study of any agricultural product.

6. Moisture transfer from the air to the product is important in grain drying. Studies of this process, using nonlinear data analysis, should be undertaken.

7. The range of temperature and relative humidity could be expanded for some applications. If the

temperature sensor located at the air heater were replaced with a sensor which can operate at temperatures greater than 100 C the present equipment and algorithms should be capable of maintaining at least 60 C in the chamber. A substantial increase in the relative humidity of the test would require that the study chamber be redesigned because of condensation problems.

APPENDICES

APPENDIX A

This software is for data acquisition and digital control of the Aminco-Aire unit. This software is interrupt driven.

```
PROGRAM TRY60; (*$E+,I+,S-,C-*)
{ JAN 4, 1983  Byler}
{  to be assembled with MAINNEW }
{  and linked with IPUT IGET LIBRKB }
CONST STAT=208;
      LBYTE=210;
      HBYTE=212;
       DBSENS=4;
       WATSENS=2;
      CHTMP=3;
VAR TIME:INTEGER;
    DBHEAT,WATHEAT,WATCOOL:BOOLEAN;
    DBDC,LTIME,I1T,JUNK1:INTEGER;
    ISUM:ARRAY[0..15]OF INTEGER;
    AVINI:ARRAY[0..15] OF INTEGER;
    ENGV:ARRAY[0..15] OF REAL;
  THIST:ARRAY[1..4] OF REAL;
  DBGOAL,DBSET,WATGOAL,K1,K2,K3:INTEGER;
  DDC,PVAL,IVAL,DVAL,ADJUST:REAL;
    d1,d2,d3,d4:integer;

PROCEDURE PUT(HBYTE,LBYTE,DATA:INTEGER);EXTERNAL;
FUNCTION GET(HBYTE,LBYTE:INTEGER):INTEGER;EXTERNAL;
PROCEDURE OUTPUT(VAL,PORT:INTEGER);EXTERNAL;
FUNCTION INPUT(PORT:INTEGER):INTEGER;EXTERNAL;
FUNCTION ATOD(DEV,GAIN,T1,T2:INTEGER):INTEGER;EXTERNAL;
PROCEDURE IPUT(HBYTE,LBYTE,DATA:INTEGER);EXTERNAL;
FUNCTION IGET(HBYTE,LBYTE:INTEGER):INTEGER;EXTERNAL;

{converts the integers from the A/D converter to
engineering terms}
FUNCTION ITOE(IVAL,ADDR:INTEGER):REAL;
  BEGIN
  if addr=4 then itoe:=iget(161,8)/10.0*ival-iget(161,40)
    else ITOE:=(iget(161,(2*addr))/1000.0*IVAL
                         -iget(161,(2*addr+32)))/10.0;
  END;
```

```
{sets the output bits to control the Aminco}
PROCEDURE SWITCHES;
VAR SWITCH:INTEGER;
BEGIN
  IF (TIME MOD 100)<DBDC THEN
    DBHEAT:=TRUE
    ELSE DBHEAT:=FALSE;
  IF WATCOOL THEN SWITCH:=2
    ELSE IF WATHEAT THEN SWITCH:=1
        ELSE SWITCH:=3;
  IF DBHEAT THEN SWITCH:=SWITCH+12;
  OUTPUT(SWITCH,11);
END;

{calls the A/D code and turns off the water heater/cooler
if necessary}
PROCEDURE GETDATA;
  VAR IIN,JUNK:INTEGER;
     T1,T2,GAIN,DIG,VAL:INTEGER;
  BEGIN
  JUNK:=INPUT(HBYTE);
  FOR IIN:=0 TO 8 DO
    BEGIN
    if (iin<2) OR (IIN=4) then GAIN:=0 else gain:=1;
    VAL:=ATOD(IIN,GAIN,T1,T2);
    IF (IIN=WATSENS) AND (ABS(ITOE(VAL,WATSENS)-WATGOAL)<5)
                                                         THEN
      BEGIN
      WATCOOL:=FALSE;
      WATHEAT:=FALSE;
      END;
    IF (I1T)=25 THEN ISUM[IIN]:=VAL
      ELSE ISUM[IIN]:=ISUM[IIN]+VAL;
    END
  END;

{averages the 9 integers representing the data}
PROCEDURE AVDATA;
VAR IIN:INTEGER;
    FVAL:REAL;
BEGIN
  IIN:=(I1T)-226;
  FVAL:=ISUM[IIN]/9.0;
  AVINI[IIN]:=ROUND(FVAL);
  IPUT(160,IIN*2,avini[iin]);
END;
```

```
{reads the RAM values put there in BASIC}
PROCEDURE PASSVAL;
  BEGIN
  DBSET:=IGET(32,2);
  if abs(dbSET-4000)>3800 then dbSET:=2500;
  WATGOAL:=IGET(32,0);
  if abs(watgoal-2600)>2400 then watgoal:=2000;
  END;

{calls conversion to engineering terms of necessary
variables and does water temperature control}
PROCEDURE GTENGV;
  VAR I:INTEGER;
  BEGIN
  FOR I:=2 TO 4 DO
    BEGIN
    ENGV[I]:=ITOE(AVINI[I],I);
    IPUT(160,(48+I*2),ROUND(ENGV[I]));
    END;
  WATCOOL:=FALSE;
  WATHEAT:=FALSE;
  IF ENGV[WATSENS]<(WATGOAL-8)THEN WATHEAT:=TRUE;
  IF ENGV[WATSENS]>(WATGOAL+8) THEN WATCOOL:=TRUE;
  END;

{stores the current errors in RAM, accessible in BASIC, for
debugging of the control algorithms and setting the gains}
PROCEDURE PSERR;
  BEGIN
  IPUT(161,112,ROUND(WATGOAL-ENGV[WATSENS]));
  IPUT(161,114,ROUND(DBGOAL-ENGV[DBSENS]));
  IPUT(32,08,DBGOAL);
  END;

{integral part of cascade control and first part of the PID
algorithm}
PROCEDURE PID1;
  BEGIN
  DBGOAL:=DBGOAL+ROUND(0.02*(DBSET-ENGV[CHTMP]));
  THIST[4]:=THIST[3];
  THIST[3]:=THIST[2];
  THIST[2]:=THIST[1];
  THIST[1]:=DBGOAL-ENGV[DBSENS];
  DDC:=DDC+7.25*THIST[1]-8.0*THIST[2]-THIST[3]
                                      +2.0*THIST[4];
  END;
```

```
{second part of the PID control}
PROCEDURE PID3;
  BEGIN
  IF DDC>15000.0 THEN DDC:=15000.0;
  IF DDC<-5000.0 THEN DDC:=-5000.0;
  IF DDC>=0.0 THEN DBDC:=ROUND(DDC/100.0)
    ELSE DBDC:=0;
  PUT(161,84,DBDC);
  PUT(161,104,255);
  END;

{main program}
BEGIN
  if iget(161,116)<0 then
    begin
    PASSVAL;
    DBGOAL:=DBSET+ROUND(0.6*(DBSET-2000));
    put(161,117,0);
    thist[3]:=0.0;
    thist[2]:=0.0;
    thist[1]:=0.0;
    end;
  IF ((TIME<0) OR (TIME>4999)) THEN TIME:=0;
  TIME:=TIME+1;
  SWITCHES;
  IlT:=TIME MOD 250;
  if (ilt<226) and (ilt mod 25 =0) then getdata;
  if (ilt>225) and (ilt<235) then avdata;
  if ilt>241 then
    case (ilt-241) of
     1: PASSVAL;
     2: GTENGV;
     3: PSERR;
     5: PID1;
     7: PID3
     END
END.
```

APPENDIX B

This software is for data storage, temperature selection, setting of clock, and initialization of equipment on power up. The most important routines are %4Ø and %5Ø.

```
LO.%4Ø

>OK
>L.
   1 REM THIS IS THE MAIN DATA ACQUISITION SOFTWARE
   5 FOR S=1Ø TO 138;@(S)=Ø;NEXT S
   6 IF CØ<5Ø CØ=5Ø
  1Ø FOR T=Ø TO 224 STEP 32
  2Ø FOR U=Ø TO 5
  25 IF GET(%A168)<1 G.25
  3Ø FOR S=Ø TO 7
  35 PUT(%2Ø32)=GET(%AØØØ+S*2)
  4Ø PUT(%2Ø33)=GET(%AØØ1+2*S)
  45 @(1Ø+S+T/2)=@(1Ø+S/2)+Z
  5Ø NEXT S
  52 PUT(%A168)=Ø
  55 NEXT U
  6Ø RUN%46
  7Ø FOR S=Ø TO 9
  8Ø &(42+T+S)=GET(%2Ø14+S)
  9Ø NEXT S
 11Ø P.#%,M,':',L,':',K,' ',O,N,
 15Ø FOR S=1Ø TO 17
 151 P.@(S+T/2),
 152 NEXT S
 153 P.E
 155 IF D<2 G.21Ø
 16Ø FOR S=1 TO (D-1)*6
 17Ø IF GET(%A168)<1 G.17Ø
 18Ø PUT(%A168)=Ø
 19Ø NEXT S
 21Ø NEXT T
 22Ø RUN%52
 3ØØ G.5

>OK
```

```
>LO.%44

>OK
>L.
   1 REM SETS THE TIME
   2 Q=%DC;R=%DE;OUT(R)=255;OUT(R)=23
   3 OUT(Q)=255;OUT(Q)=138;OUT(R)=1;OUT(Q)=57
   4 OUT(Q)=15;OUT(Q)=Ø
   5 INPUT'SECONDS'B;OUT(Q)=B
   6 O(Q)=Ø
   7 INPUT'MINUTES'B;OUT(Q)=B
   8 INPUT'HOURS'B;OUT(Q)=B
   9 OUT(R)=3;OUT(Q)=57;OUT(Q)=Ø
  2Ø INPUT'DAYS-TENSONES'B;OUT(Q)=B
  3Ø INPUT'DAYS-THOUSANDSHUNDREDS'B;OUT(Q)=B
  32 OUT(R)=5;OUT(Q)=%31
  33 OUT(Q)=%1C;OUT(Q)=Ø;OUT(Q)=%4Ø
  4Ø OUT((R)=9;OUT(Q)=Ø
  5Ø OUT(Q)=Ø;OUT(R)=1Ø;OUT(Q)=Ø
  6Ø OUT(Q)=Ø;OUT(R)=68;OUT(R)=39
  62 OUT(R)=%7Ø
  9Ø STOP

>OK
>LO.%46

>OK
>L.
   1 REM GET THE TIME
   2 Q=%DC;R=%DE;OUT(R)=167;OUT(R)=17
   3 J=IN(Q);K=IN(Q)
   4 IF(J#Ø)+(K#Ø) G.6
   5 OUT(R)=166
   6 OUT(R)=18;L=IN(Q);M=IN(Q)
   7 OUT(R)=19;N=IN(Q);O=IN(Q)
   9 STOP

>OK
>LO.%47

>OK
>L.
   1 REM PRINTS THE TIME
   2 RUN%46
   5 P.#%,'DATE: ',O,N,' TIME: ',M,':',L,':',K,'.',J
   6 STOP

>OK
```

```
>LO.%48

>OK
>L.
   1 REM INITIALIZE
   2 REM SET ALL DUTY CYCLES TO Ø% ON
   3 H=Ø;HØ=Ø;WØ=Ø
   4 REM CLEAR A/D CONVERTER
   5 B=IN(%DØ)
   6 OUT(2)=8;REM SETUP FOR TIMER
   9 RUN%44;REM SET CLOCK AND START 4Ø MS TIM SETUP
                                                   FOR TIMER
  1Ø OUT(3)=4;REM SETUP FOR TIMER
  11 OUT(%DØ)=%1Ø;REM SETUP FOR TIMER
  14 REM CLEAR RAM
  15 FOR I=Ø TO 512;PUT(%AØØØ+I)=%FF;PUT(%DDAØ+I)=%FF;
                                                        NEXT I
  2Ø PUT(%21FE)=%28;REM LOCK 4Ø ROOM FOR @()
  3Ø RUN%5Ø;REM RESET TAPE DECK
  9Ø STOP

>OK
>LO.%4A

>OK
>L.
   1 REM INITIALIZE
   2 REM SET ALL DUTY CYCLES TO Ø% ON
   3 H=Ø;HØ=Ø;WØ=Ø
   4 REM CLEAR A/D CONVERTER
   5 B=IN(%DØ)
   6 OUT(2)=8;REM SETUP FOR TIMER
  1Ø OUT(3)=4;REM SETUP FOR TIMER
  11 OUT(%DØ)=%1Ø;REM SETUP FOR TIMER
  9Ø STOP

>OK
>LO.%4C

>OK
>L.
   1 REM SAVES VARIABLES ON TAPE
  1Ø FOR I=Ø TO 63;&(2Ø+I)=GET(%A1ØØ+I);NEXT I
  4Ø @(5Ø)=C;@(51)=D;@(52)=E
  5Ø CØ=1Ø;DØ=Ø
  6Ø RUN%52
  7Ø CØ=1
  9Ø STOP

>OK
```

```
>LO.%4D

>OK
>L.
    1 REM GETS VARIABLES FROM TAPE
   10 C0=10;D0=0;RUN%5E
   20 FOR I=0 TO 63;PUT(%A100+I)=&(20+I);NEXT I
   30 C=@(50);D=@(51);E=@(52)
   40 C0=1
   90 STOP

>OK
>LO.%4E

>OK
>L.
    1 REM INPUTS CONVERSION FACTORS ON TAPE
   10 FOR I=0 TO 15
   20 P.'FOR CHANNEL NUMBER',I,'   ',
   30 INPUT'A='@(0),'  B='@(1)
   35 PUT(%A100+2*I)=&(0)
   36 PUT(%A101+2*I)=&(1)
   37 PUT(%A120+2*I)=&(2)
   38 PUT(%A121+2*I)=&(3)
   40 NEXT I
   50 RUN%4C
   90 STOP

>OK
>LO.%50

>OK
>L.
    1 REM INITIALIZATION OF TAPE
    4 FOR I=0 TO 5;I0=IN(10);NEXT I
    6 OUT(4)=0;OUT(4)=1;RUN%56
    8 H=%18;RUN%54;RUN%56
   10 H=%14;RUN%54
   12 H=%30;C.%5880;H=%0D;C.%5880
   16 RUN%55;RUN%56
   20 H=%1A;RUN%54
   22 H=%0D;C.%5880;RUN%55;RUN%56
   30 ST.

>OK
```

```
>LO.%52

>OK
>L.
  10 REM SAVES @(10)-@(137) ON TAPE TR=D0,BL=C0
  15 RUN%57
  20 H=%14;RUN%54;H=(%30+D0);C.%5880
  22 H=%0D;C.%5880;RUN%55;RUN%56
  24 RUN%5A;H=%17;RUN%54
  26 FOR I=0 TO 2;H=(%30+@(I));C.%5880;NEXT I
  32 H=%2C;C.%5880;H=%30;C.%5880;H=%0D;C.%5880
  38 RUN%55
  40 FOR I=0 TO 255
  42 H=&(20+I);C.%5880
  44 NEXT I
  50 RUN%56
  52 C0=C0+1
  54 P.C0,D0;IF C01000 G.99
  56 C0=0;D0=2
  99 ST.

>OK
>LO.%54

>OK
>L.
   1 REM OUTPUT CONTROL BYTE TO TAPE DECK
   2 C.%5800;OUT(10)=H
   3 C.%5840;P=IN(10);IFP=94G.6
   4 P.'ERROR NO CTRL ECHOED';G.9
   6 C.%5840;P=IN(10);IFP=(H+64)G.9
   8 P.#%,'ERROR, BE SENT=',H,'BYTE RCVD=',P
   9 ST.

>OK
>LO.%55

>OK
>L.
   1 REM GET 0D-0A
   4 C.%5840;P=IN(10);IFP=13G.6
   5 P.#%,P,' RCVD. OD EXPECTED';G.9
   6 C.%5840;P=IN(10);IFP=10G.9
   7 P.#%,P,' RCVD. 0A EXPECTED'
   9 ST.

>OK
```

```
>LO.%56

>OK
>L.
   1 REM GET Ø7-ØD-ØA
   2 C.%584Ø;P=IN(1Ø);IFP=7 G.4
   3 P.#%,P,' RCVD. 7 EXPECTED';G.9
   4 RUN%55
   9 ST.

>OK
>LO.%57

>OK
>L.
   5 REM CLEAR COMM. FROM TD.
  1Ø GOS.99
  2Ø OUT(1Ø)=27;GOS.99
  3Ø OUT(1Ø)=Ø;GOS.99
  4Ø H=24;RUN%54
  5Ø RUN%56
  9Ø ST.
  99 F.P=1TO9;Q=IN(1Ø);NE.P;R.

>OK
>LO.%5A

>OK
>L.
   1 REM CONVERTS A BINARY NUMBER CØ TO 3 INTEGERS
   4 @(Ø)=CØ/1ØØ
   6 @(1)=CØ/1Ø-@(Ø)*1Ø
   8 @(2)=CØ-1Ø*@(1)-1ØØ*@(Ø)
   9 ST.

>OK
>LO.%5B

>OK
>L.
   1 REM INPUTS CONVERSION FACTORS, STORES ON TAPE
  1Ø FOR I=Ø TO 15
  2Ø P.'FOR CHANNEL NUMBER',I,'   ',
  3Ø INPUT'A='@(Ø),'  B='@(1)
  35 PUT(%A1ØØ+2*I)=&(Ø)
  36 PUT(%A1Ø1+2*I)=&(1)
  37 PUT(%A12Ø+2*I)=&(2)
  38 PUT(%A121+2*I)=&(3)
  4Ø NEXT I
  5Ø RUN%1E
  9Ø STOP

>OK
```

```
>LO.%5C

>OK
>L.
   1 REM READ/WRITE TR=DØ,BL=CØ CODE STARTING=EØ
   2 IF FØ=1 G.7
   3 RUN%5E
   4 FOR I=ØTO255;PUT(EØ+I)=&(2Ø+I);NEXT I
   6 STOP
   7 P.'WARNING THIS SUBROUTINE WILL ERASE WHAT IS
                                              CURRENTLY'
   8 P.'ON THE TAPE.  ENTER 1 TO CONTINUE'
   9 INPUT FØ
  1Ø IF FØ#1G.2Ø
  12 FOR I=ØTO255;&(2Ø+I)=GET(EØ+I);NE.I
  14 RUN%52
  2Ø STOP

>OK
>LO.%5E

>OK
>L.
   1 REM READS @(1Ø)-@(137) FROM TAPE FROM TRDØ,BLCØ
   4 RUN%5A;H=%14;RUN%54
   6 H=(%3Ø+DØ);C.%588Ø
   8 H=%ØD;C.%588Ø;RUN%55;RUN%56
  12 H=%12;RUN%54
  14 FOR I=Ø TO 2;H=(%3Ø+@(I));C.%588Ø;NEXT I
  2Ø H=%2C;C.%588Ø;H=%3Ø;C.%588Ø;H=%ØD;C.%588Ø;RUN%55
  3Ø FOR I=Ø TO 255
  32 C.%584Ø;H=IN(1Ø);IFH#7G.4Ø
  36 C.%584Ø;P=IN(1Ø);IFP=7G.4Ø
  38 P.'ERROR CODE DETECTED =',P;G.99
  4Ø &(2Ø+I)=H
  42 NEXT I
  44 RUN%56
  99 ST.

>OK
>
```

APPENDIX C

Listing of Selected Data

t = time, hours
T = temperature of air, Celsius
RH = relative humidity, decimal
Mi = initial moisture content, decimal d. b.
ID = (test number)*2 + tray number

	t	M(t)	T	RH	Mi	ID
Test 6 A						
	.158333	.467	30.1	.266	.500	12.
	.175278	.465	30.5	.261	.500	12.
	.192222	.460	30.9	.257	.500	12.
	.259722	.449	31.3	.251	.500	12.
	.343333	.429	31.5	.250	.500	12.
	.427500	.416	31.6	.248	.500	12.
	.511389	.398	31.7	.246	.500	12.
	.594722	.393	31.6	.249	.500	12.
	.678889	.379	31.7	.248	.500	12.
	.763056	.368	31.6	.247	.500	12.
	.846944	.358	31.7	.246	.500	12.
	.930556	.347	31.7	.247	.500	12.
	1.014167	.335	31.7	.246	.500	12.
	1.114722	.327	31.7	.247	.500	12.
	1.198056	.317	31.7	.247	.500	12.
	1.298889	.307	31.7	.247	.500	12.
	1.381667	.301	31.7	.248	.500	12.
	1.481667	.287	31.8	.246	.500	12.
	1.582500	.279	31.7	.247	.500	12.
	1.683333	.273	31.8	.247	.500	12.
	1.784167	.260	31.8	.245	.500	12.
	1.885000	.256	31.8	.246	.500	12.
	1.985833	.253	31.8	.248	.500	12.
	2.086111	.244	31.8	.247	.500	12.
	2.203611	.236	31.8	.247	.500	12.
	2.303611	.231	31.8	.246	.500	12.
	2.421944	.223	31.7	.248	.500	12.
	2.523611	.219	31.7	.247	.500	12.
	2.640833	.215	31.6	.248	.500	12.
	2.757222	.209	31.6	.247	.500	12.
	2.874722	.204	31.7	.247	.500	12.
	2.992222	.199	31.6	.250	.500	12.
	3.126667	.195	31.6	.247	.500	12.
	3.244444	.193	31.6	.247	.500	12.
	3.377500	.186	31.6	.248	.500	12.
	3.511944	.184	31.7	.249	.500	12.
	3.646111	.180	31.6	.248	.500	12.
	3.780833	.176	31.6	.249	.500	12.
	3.915556	.177	31.6	.248	.500	12.

4.066944	.173	31.6	.248	.500	12.
4.218333	.169	31.6	.248	.500	12.
4.368611	.163	31.6	.247	.500	12.
4.517500	.161	31.6	.248	.500	12.
4.669722	.162	31.6	.248	.500	12.
4.837222	.159	31.6	.248	.500	12.
5.005556	.158	31.6	.247	.500	12.
5.173333	.150	31.6	.248	.500	12.
5.357778	.150	31.5	.249	.500	12.
5.541944	.147	31.6	.249	.500	12.
5.726111	.147	31.6	.249	.500	12.
5.910833	.140	31.6	.248	.500	12.
6.111944	.142	31.6	.247	.500	12.
6.314167	.143	31.6	.249	.500	12.
6.532500	.138	31.6	.249	.500	12.
6.750278	.137	31.6	.248	.500	12.
6.983889	.136	31.6	.249	.500	12.
7.219444	.134	31.6	.247	.500	12.
7.455556	.133	31.6	.249	.500	12.
7.722500	.130	31.6	.248	.500	12.
7.974722	.131	31.7	.247	.500	12.
8.261111	.126	31.6	.248	.500	12.
8.545833	.126	31.8	.246	.500	12.
8.849444	.126	31.7	.246	.500	12.
9.169167	.124	31.9	.247	.500	12.
9.521111	.123	31.8	.246	.500	12.
9.873889	.125	31.8	.245	.500	12.
10.257778	.117	31.8	.245	.500	12.
10.662222	.120	31.8	.245	.500	12.
11.080833	.122	31.9	.244	.500	12.
11.549167	.117	32.0	.242	.500	12.
12.054167	.119	31.9	.244	.500	12.
12.590556	.116	32.0	.244	.500	12.
13.196389	.112	31.9	.245	.500	12.
13.853333	.115	31.9	.244	.500	12.
14.589167	.109	32.0	.244	.500	12.
15.429722	.106	32.0	.245	.500	12.
16.388611	.110	31.9	.244	.500	12.
17.394167	.110	32.1	.243	.500	12.
18.403333	.108	32.1	.242	.500	12.
19.397222	.104	32.1	.244	.500	12.
20.391667	.104	32.2	.242	.500	12.
21.391111	.103	32.3	.239	.500	12.
22.402222	.108	32.3	.240	.500	12.
23.395000	.102	32.3	.240	.500	12.
24.402500	.099	32.2	.243	.500	12.
25.394167	.101	31.6	.250	.500	12.
26.401667	.098	31.5	.249	.500	12.
27.388889	.099	31.4	.251	.500	12.
28.396111	.094	31.4	.251	.500	12.
29.401944	.096	31.4	.249	.500	12.
30.391111	.096	31.4	.251	.500	12.
31.397500	.096	31.3	.252	.500	12.

32.403611	.094	31.3	.252	.500	12.
33.393611	.092	31.2	.254	.500	12.
34.401667	.092	31.2	.253	.500	12.
35.395000	.092	31.2	.253	.500	12.
36.405000	.092	31.2	.252	.500	12.
37.399167	.093	31.3	.251	.500	12.

Test 6 B

.041666	.276	30.1	.266	.283	13.
.109166	.267	31.2	.255	.283	13.
.193611	.256	31.4	.250	.283	13.
.260277	.249	31.5	.250	.283	13.
.344166	.243	31.6	.250	.283	13.
.428055	.238	31.6	.250	.283	13.
.511666	.234	31.7	.248	.283	13.
.595833	.228	31.8	.249	.283	13.
.680277	.224	31.6	.248	.283	13.
.764166	.221	31.7	.246	.283	13.
.847500	.217	31.8	.246	.283	13.
.931111	.214	31.7	.248	.283	13.
1.014722	.212	31.8	.248	.283	13.
1.115000	.208	31.7	.247	.283	13.
1.198611	.204	31.7	.246	.283	13.
1.298333	.201	31.8	.247	.283	13.
1.381944	.198	31.8	.246	.283	13.
1.482500	.197	31.8	.245	.283	13.
1.583611	.194	31.9	.245	.283	13.
1.684444	.192	31.9	.246	.283	13.
1.785000	.189	31.7	.248	.283	13.
1.886111	.185	31.8	.246	.283	13.
1.985833	.184	31.7	.246	.283	13.
2.086944	.181	31.8	.247	.283	13.
2.203889	.179	31.7	.248	.283	13.
2.305277	.175	31.7	.248	.283	13.
2.423611	.175	31.7	.247	.283	13.
2.524166	.172	31.6	.248	.283	13.
2.640555	.170	31.6	.247	.283	13.
2.758055	.168	31.7	.247	.283	13.
2.875555	.166	31.6	.250	.283	13.
2.993055	.164	31.7	.247	.283	13.
3.127777	.162	31.6	.247	.283	13.
3.244166	.160	31.6	.248	.283	13.
3.378333	.157	31.7	.249	.283	13.
3.512500	.157	31.6	.247	.283	13.
3.647500	.154	31.6	.248	.283	13.
3.782222	.153	31.6	.247	.283	13.
3.916389	.151	31.6	.248	.283	13.
4.068333	.150	31.6	.248	.283	13.
4.218333	.148	31.6	.247	.283	13.
4.366944	.147	31.6	.248	.283	13.
4.519166	.144	31.6	.247	.283	13.
4.670277	.144	31.6	.249	.283	13.
4.838333	.142	31.7	.249	.283	13.

5.006389	.141	31.5	.249	.283	13.
5.174166	.140	31.6	.248	.283	13.
5.358333	.138	31.5	.250	.283	13.
5.541944	.137	31.6	.250	.283	13.
5.727500	.135	31.6	.247	.283	13.
5.911389	.134	31.6	.247	.283	13.
6.113611	.133	31.6	.248	.283	13.
6.314444	.132	31.6	.247	.283	13.
6.532777	.130	31.6	.249	.283	13.
6.750555	.130	31.6	.247	.283	13.
6.984722	.127	31.6	.248	.283	13.
7.220277	.126	31.7	.248	.283	13.
7.456389	.126	31.7	.247	.283	13.
7.706944	.124	31.6	.248	.283	13.
7.975833	.123	31.6	.248	.283	13.
8.260555	.121	31.7	.246	.283	13.
8.547777	.120	31.7	.246	.283	13.
8.850833	.119	31.7	.246	.283	13.
9.168611	.120	31.8	.246	.283	13.
9.522500	.118	31.9	.246	.283	13.
9.873889	.116	31.8	.246	.283	13.
10.259166	.114	31.8	.245	.283	13.
10.663055	.118	32.0	.244	.283	13.
11.081389	.114	31.9	.245	.283	13.
11.550555	.112	31.9	.244	.283	13.
12.055277	.110	31.9	.245	.283	13.
12.591944	.110	31.9	.245	.283	13.
13.197500	.108	31.9	.244	.283	13.
13.854444	.106	31.9	.244	.283	13.
14.590277	.107	31.9	.245	.283	13.
15.430833	.105	31.9	.244	.283	13.
16.389722	.104	32.1	.244	.283	13.
17.395555	.103	32.0	.242	.283	13.
18.403333	.101	32.2	.242	.283	13.
19.398889	.101	32.1	.244	.283	13.
20.393333	.099	32.1	.242	.283	13.
21.392222	.099	32.2	.241	.283	13.
22.402222	.098	32.4	.238	.283	13.
23.395555	.097	32.2	.241	.283	13.
24.403611	.095	32.1	.243	.283	13.
25.394444	.095	31.6	.249	.283	13.
26.402222	.094	31.4	.249	.283	13.
27.389722	.092	31.5	.249	.283	13.
28.396944	.093	31.3	.251	.283	13.
29.402500	.094	31.5	.251	.283	13.
30.391666	.093	31.4	.251	.283	13.
31.397777	.091	31.3	.252	.283	13.
32.403611	.090	31.3	.254	.283	13.
33.394166	.089	31.2	.254	.283	13.
34.402777	.091	31.2	.253	.283	13.
35.396111	.090	31.2	.252	.283	13.
36.390277	.091	31.3	.253	.283	13.
37.400277	.088	31.3	.252	.283	13.

Test 8 A

.125000	.266	31.6	.551	.281	16.
.141667	.268	32.1	.543	.281	16.
.192222	.263	32.5	.531	.281	16.
.259444	.260	32.7	.522	.281	16.
.343056	.249	32.9	.520	.281	16.
.426944	.249	33.0	.516	.281	16.
.511389	.240	33.0	.516	.281	16.
.595833	.234	33.0	.513	.281	16.
.680278	.232	33.1	.512	.281	16.
.765000	.224	33.1	.512	.281	16.
.849444	.224	33.1	.512	.281	16.
.933611	.219	33.1	.513	.281	16.
1.018056	.214	33.1	.512	.281	16.
1.102500	.209	33.1	.512	.281	16.
1.203889	.209	33.1	.513	.281	16.
1.288333	.206	33.1	.512	.281	16.
1.389722	.204	33.2	.511	.281	16.
1.491111	.197	33.1	.512	.281	16.
1.575556	.195	33.1	.510	.281	16.
1.676667	.195	33.1	.510	.281	16.
1.777778	.189	33.1	.510	.281	16.
1.879167	.185	33.2	.510	.281	16.
1.980278	.183	33.2	.511	.281	16.
2.081667	.182	33.1	.510	.281	16.
2.199722	.178	33.1	.511	.281	16.
2.301389	.174	33.1	.511	.281	16.
2.419722	.172	33.2	.512	.281	16.
2.521389	.173	33.1	.510	.281	16.
2.639167	.173	33.2	.512	.281	16.
2.757500	.170	33.2	.510	.281	16.
2.875278	.169	33.4	.504	.281	16.
2.993333	.167	33.3	.506	.281	16.
3.127778	.165	33.3	.505	.281	16.
3.246111	.164	33.3	.507	.281	16.
3.381111	.158	33.2	.510	.281	16.
3.516389	.159	33.2	.510	.281	16.
3.651111	.155	33.2	.509	.281	16.
3.786111	.154	33.2	.508	.281	16.
3.921389	.153	33.1	.509	.281	16.
4.073056	.150	33.2	.511	.281	16.
4.208056	.151	33.1	.511	.281	16.
4.359722	.148	33.1	.510	.281	16.
4.511389	.150	33.1	.510	.281	16.
4.680278	.147	33.1	.511	.281	16.
4.848611	.146	33.1	.511	.281	16.
5.000000	.142	33.1	.514	.281	16.
5.185833	.142	33.1	.512	.281	16.
5.354444	.143	33.1	.510	.281	16.
5.540000	.138	33.1	.513	.281	16.
5.725278	.139	33.0	.512	.281	16.
5.910556	.139	33.1	.512	.281	16.

6.113056	.135	33.1	.510	.281	16.
6.315000	.135	33.1	.513	.281	16.
6.534167	.139	33.1	.511	.281	16.
6.753056	.133	33.0	.512	.281	16.
6.971667	.135	33.0	.514	.281	16.
7.208056	.132	33.0	.515	.281	16.
7.460833	.128	32.9	.516	.281	16.
7.713611	.131	32.9	.515	.281	16.
7.983333	.130	33.0	.515	.281	16.
8.253611	.128	32.9	.516	.281	16.
8.556667	.129	33.0	.514	.281	16.
8.860556	.128	33.0	.513	.281	16.
9.180556	.127	33.0	.513	.281	16.
9.517222	.127	33.1	.512	.281	16.
9.871111	.126	33.0	.513	.281	16.
10.259722	.123	32.9	.516	.281	16.
10.647778	.126	33.0	.515	.281	16.
11.086111	.120	32.9	.517	.281	16.
11.558056	.124	33.1	.515	.281	16.
12.046944	.122	33.1	.512	.281	16.
12.603889	.122	32.9	.516	.281	16.
13.195000	.121	32.9	.517	.281	16.
13.854167	.119	32.8	.517	.281	16.
14.597778	.119	32.9	.514	.281	16.
15.425278	.120	32.9	.516	.281	16.
16.400833	.122	33.0	.514	.281	16.
17.394722	.122	33.1	.513	.281	16.
18.389722	.120	33.2	.510	.281	16.
19.401667	.115	33.3	.507	.281	16.
20.396667	.116	33.4	.505	.281	16.
21.401389	.110	33.5	.502	.281	16.
22.391111	.112	33.5	.500	.281	16.
23.396944	.113	33.6	.501	.281	16.
24.403889	.110	33.6	.498	.281	16.
25.394167	.111	33.7	.498	.281	16.
26.399167	.109	33.7	.500	.281	16.
27.388611	.109	33.7	.497	.281	16.
28.393611	.114	33.7	.498	.281	16.
29.400000	.110	33.6	.501	.281	16.
30.405000	.108	33.8	.495	.281	16.
31.392500	.110	33.7	.497	.281	16.
32.393611	.110	33.7	.497	.281	16.
33.395833	.106	33.8	.495	.281	16.
34.399722	.112	33.7	.497	.281	16.
35.403333	.109	33.6	.501	.281	16.
36.390833	.109	33.6	.500	.281	16.
37.395278	.109	33.7	.498	.281	16.

Test 8 B

.041666	.572	31.6	.551	.576	17.
.108889	.550	32.5	.531	.576	17.
.192500	.528	32.7	.522	.576	17.
.259722	.512	32.9	.520	.576	17.

.343611	.497	33.0	.516	.576	17.
.428055	.479	33.0	.516	.576	17.
.512500	.464	33.0	.513	.576	17.
.596944	.448	33.1	.512	.576	17.
.681666	.433	33.1	.512	.576	17.
.766111	.419	33.1	.512	.576	17.
.850277	.406	33.1	.513	.576	17.
.934722	.394	33.1	.512	.576	17.
1.019166	.383	33.1	.512	.576	17.
1.103611	.370	33.1	.512	.576	17.
1.205000	.357	33.1	.512	.576	17.
1.289444	.347	33.2	.511	.576	17.
1.391111	.336	33.1	.511	.576	17.
1.492222	.326	33.1	.510	.576	17.
1.576389	.316	33.2	.510	.576	17.
1.677777	.306	33.2	.511	.576	17.
1.779166	.296	33.2	.511	.576	17.
1.880277	.288	33.2	.510	.576	17.
1.981389	.280	33.2	.510	.576	17.
2.082777	.273	33.1	.511	.576	17.
2.201111	.265	33.1	.511	.576	17.
2.302500	.256	33.2	.512	.576	17.
2.421111	.249	33.2	.511	.576	17.
2.522500	.244	33.1	.512	.576	17.
2.640277	.237	33.2	.510	.576	17.
2.758055	.233	33.2	.509	.576	17.
2.876389	.229	33.3	.507	.576	17.
2.994166	.224	33.3	.507	.576	17.
3.128889	.217	33.2	.508	.576	17.
3.246944	.213	33.3	.508	.576	17.
3.382222	.205	33.2	.509	.576	17.
3.517500	.201	33.2	.509	.576	17.
3.652222	.196	33.2	.509	.576	17.
3.787222	.193	33.2	.508	.576	17.
3.922222	.188	33.2	.510	.576	17.
4.074166	.185	33.2	.509	.576	17.
4.208889	.180	33.2	.510	.576	17.
4.360555	.176	33.2	.509	.576	17.
4.512222	.175	33.1	.512	.576	17.
4.681111	.170	33.1	.511	.576	17.
4.832777	.167	33.1	.510	.576	17.
5.001111	.165	33.1	.511	.576	17.
5.170277	.162	33.2	.510	.576	17.
5.355555	.160	33.1	.512	.576	17.
5.540833	.158	33.1	.513	.576	17.
5.726111	.155	33.0	.514	.576	17.
5.911666	.154	33.1	.514	.576	17.
6.113611	.152	33.1	.511	.576	17.
6.316111	.148	33.0	.513	.576	17.
6.534722	.147	33.0	.514	.576	17.
6.753889	.145	33.1	.513	.576	17.
6.972777	.145	33.0	.513	.576	17.
7.209166	.143	32.9	.517	.576	17.

7.461666	.141	33.0	.516	.576	17.
7.714444	.139	33.0	.518	.576	17.
7.984444	.138	32.9	.516	.576	17.
8.254444	.136	33.0	.515	.576	17.
8.557777	.135	33.0	.516	.576	17.
8.861666	.135	33.0	.514	.576	17.
9.181389	.133	33.0	.516	.576	17.
9.518055	.133	33.0	.514	.576	17.
9.872222	.132	33.0	.515	.576	17.
10.243889	.129	33.0	.515	.576	17.
10.649166	.128	33.0	.515	.576	17.
11.087222	.127	32.9	.517	.576	17.
11.558889	.126	33.1	.511	.576	17.
12.048055	.125	33.1	.513	.576	17.
12.605000	.125	33.0	.513	.576	17.
13.196389	.124	32.9	.517	.576	17.
13.855000	.124	32.9	.520	.576	17.
14.598889	.122	32.9	.516	.576	17.
15.426666	.123	32.9	.517	.576	17.
16.401944	.122	33.0	.514	.576	17.
17.395833	.122	33.1	.511	.576	17.
18.390555	.124	33.1	.512	.576	17.
19.402500	.120	33.3	.509	.576	17.
20.396389	.118	33.3	.507	.576	17.
21.401944	.119	33.4	.503	.576	17.
22.391666	.117	33.6	.501	.576	17.
23.398333	.116	33.5	.501	.576	17.
24.404722	.116	33.7	.500	.576	17.
25.394444	.116	33.7	.497	.576	17.
26.399444	.116	33.7	.498	.576	17.
27.389444	.115	33.7	.498	.576	17.
28.393055	.115	33.6	.501	.576	17.
29.400555	.116	33.6	.501	.576	17.
30.405000	.116	33.7	.496	.576	17.
31.392500	.114	33.7	.497	.576	17.
32.393055	.114	33.8	.496	.576	17.
33.395555	.115	33.7	.500	.576	17.
34.400555	.113	33.7	.499	.576	17.
35.403055	.114	33.6	.501	.576	17.
36.391389	.112	33.6	.499	.576	17.
37.395277	.115	33.6	.500	.576	17.

Test 9 A

.125000	.551	35.7	.585	.572	18.
.141944	.550	37.4	.538	.572	18.
.191389	.540	38.7	.505	.572	18.
.258333	.527	39.2	.494	.572	18.
.342500	.509	39.4	.489	.572	18.
.426667	.485	39.6	.484	.572	18.
.510556	.468	39.8	.478	.572	18.
.595000	.453	39.9	.476	.572	18.
.679167	.435	39.9	.475	.572	18.
.763333	.424	40.0	.474	.572	18.

.847778	.407	40.1	.473	.572	18.
.931944	.394	40.1	.469	.572	18.
1.016389	.378	40.2	.469	.572	18.
1.117500	.364	40.2	.468	.572	18.
1.201944	.353	40.2	.468	.572	18.
1.286389	.342	40.2	.467	.572	18.
1.387500	.327	40.2	.467	.572	18.
1.488889	.315	40.2	.467	.572	18.
1.573056	.306	40.4	.466	.572	18.
1.674444	.298	40.3	.465	.572	18.
1.775278	.284	40.3	.465	.572	18.
1.876389	.274	40.3	.465	.572	18.
1.977778	.267	40.4	.464	.572	18.
2.095833	.255	40.4	.463	.572	18.
2.196944	.247	40.3	.464	.572	18.
2.298056	.243	40.4	.463	.572	18.
2.416389	.233	40.4	.464	.572	18.
2.534444	.225	40.4	.463	.572	18.
2.635833	.221	40.4	.462	.572	18.
2.753889	.216	40.4	.466	.572	18.
2.871944	.206	40.3	.465	.572	18.
3.006944	.202	40.4	.466	.572	18.
3.124722	.196	40.3	.466	.572	18.
3.242500	.192	40.4	.464	.572	18.
3.377500	.189	40.5	.461	.572	18.
3.512500	.182	40.6	.461	.572	18.
3.647500	.178	40.5	.462	.572	18.
3.781944	.175	40.5	.462	.572	18.
3.917222	.174	40.6	.461	.572	18.
4.069444	.169	40.5	.460	.572	18.
4.221389	.164	40.5	.463	.572	18.
4.373333	.160	40.6	.459	.572	18.
4.525278	.159	40.5	.461	.572	18.
4.676944	.158	40.5	.462	.572	18.
4.845833	.152	40.5	.462	.572	18.
5.014167	.151	40.4	.465	.572	18.
5.183056	.148	40.4	.464	.572	18.
5.351944	.144	40.5	.463	.572	18.
5.536944	.143	40.5	.460	.572	18.
5.722500	.142	40.5	.462	.572	18.
5.908056	.141	40.5	.461	.572	18.
6.110556	.140	40.4	.463	.572	18.
6.313056	.139	40.5	.461	.572	18.
6.532778	.137	40.5	.462	.572	18.
6.751944	.134	40.5	.462	.572	18.
6.971389	.131	40.5	.460	.572	18.
7.207778	.130	40.6	.462	.572	18.
7.461389	.132	40.6	.458	.572	18.
7.714722	.128	40.6	.460	.572	18.
7.984722	.128	40.6	.458	.572	18.
8.254722	.126	40.6	.457	.572	18.
8.557500	.126	40.6	.459	.572	18.
8.860833	.126	40.6	.459	.572	18.

9.181944	.128	40.6	.458	.572	18.
9.520278	.125	40.5	.461	.572	18.
9.874444	.126	40.6	.460	.572	18.
10.245278	.126	40.7	.458	.572	18.
10.649722	.123	40.8	.453	.572	18.
11.088056	.120	40.7	.457	.572	18.
11.543611	.122	40.7	.457	.572	18.
12.049722	.120	40.6	.460	.572	18.
12.589444	.116	40.6	.459	.572	18.
13.195278	.114	40.5	.460	.572	18.
13.852778	.116	40.1	.471	.572	18.
14.595556	.116	40.1	.473	.572	18.
15.438333	.112	40.1	.473	.572	18.
16.397500	.113	40.0	.471	.572	18.
17.393056	.111	40.0	.471	.572	18.
18.402778	.112	40.1	.470	.572	18.
19.394722	.110	40.2	.468	.572	18.
20.405000	.109	40.4	.464	.572	18.
21.399722	.110	40.4	.462	.572	18.
22.395000	.109	40.6	.460	.572	18.
23.390556	.110	40.6	.459	.572	18.
24.402222	.108	40.4	.463	.572	18.
25.397222	.107	40.3	.467	.572	18.
26.391944	.106	40.2	.470	.572	18.
27.403889	.109	40.0	.472	.572	18.
28.396944	.107	40.0	.476	.572	18.
29.393056	.107	39.9	.475	.572	18.
30.405000	.110	39.9	.477	.572	18.
31.400833	.108	39.7	.481	.572	18.
32.395000	.108	39.8	.478	.572	18.
33.390556	.108	39.6	.481	.572	18.
34.402778	.105	39.6	.479	.572	18.
35.396389	.108	39.7	.482	.572	18.
36.391389	.106	39.5	.485	.572	18.
37.402222	.110	39.5	.485	.572	18.

Test 9 B

.041667	.296	35.7	.585	.300	19.
.108056	.286	38.7	.505	.300	19.
.191944	.275	39.2	.493	.300	19.
.259167	.267	39.4	.489	.300	19.
.343333	.258	39.6	.484	.300	19.
.427222	.252	39.8	.478	.300	19.
.511667	.248	39.9	.476	.300	19.
.595833	.241	39.9	.475	.300	19.
.680000	.235	40.0	.474	.300	19.
.764444	.230	40.1	.473	.300	19.
.848611	.225	40.1	.469	.300	19.
.933056	.221	40.2	.469	.300	19.
1.017500	.217	40.2	.468	.300	19.
1.118611	.211	40.2	.468	.300	19.
1.203056	.209	40.2	.467	.300	19.
1.287222	.206	40.2	.467	.300	19.

1.388611	.201	40.2	.467	.300	19.
1.489722	.199	40.4	.466	.300	19.
1.574167	.194	40.3	.465	.300	19.
1.675000	.191	40.3	.466	.300	19.
1.776389	.188	40.3	.464	.300	19.
1.877500	.185	40.4	.464	.300	19.
1.978889	.183	40.4	.465	.300	19.
2.096667	.178	40.3	.464	.300	19.
2.198056	.177	40.4	.462	.300	19.
2.299167	.174	40.4	.462	.300	19.
2.417500	.171	40.4	.464	.300	19.
2.535556	.168	40.4	.462	.300	19.
2.636944	.167	40.4	.464	.300	19.
2.755000	.164	40.4	.465	.300	19.
2.873056	.161	40.4	.464	.300	19.
3.007778	.159	40.4	.464	.300	19.
3.125556	.157	40.4	.466	.300	19.
3.243611	.155	40.4	.464	.300	19.
3.378611	.152	40.5	.463	.300	19.
3.513333	.152	40.5	.462	.300	19.
3.648056	.150	40.5	.461	.300	19.
3.783056	.149	40.5	.459	.300	19.
3.918333	.146	40.5	.459	.300	19.
4.070556	.144	40.5	.461	.300	19.
4.222778	.144	40.5	.460	.300	19.
4.357500	.142	40.6	.460	.300	19.
4.526111	.140	40.5	.462	.300	19.
4.678056	.140	40.5	.462	.300	19.
4.846389	.137	40.4	.463	.300	19.
5.015000	.137	40.4	.462	.300	19.
5.184167	.136	40.4	.464	.300	19.
5.352500	.134	40.5	.462	.300	19.
5.537778	.133	40.5	.461	.300	19.
5.723611	.132	40.5	.460	.300	19.
5.909167	.130	40.5	.462	.300	19.
6.111389	.129	40.5	.460	.300	19.
6.314167	.128	40.5	.462	.300	19.
6.533333	.128	40.5	.462	.300	19.
6.753333	.127	40.6	.461	.300	19.
6.972500	.126	40.5	.461	.300	19.
7.208889	.125	40.6	.459	.300	19.
7.462500	.124	40.5	.462	.300	19.
7.715833	.123	40.6	.459	.300	19.
7.985556	.122	40.6	.458	.300	19.
8.255833	.121	40.7	.458	.300	19.
8.558333	.120	40.7	.457	.300	19.
8.861944	.120	40.6	.457	.300	19.
9.183333	.120	40.6	.458	.300	19.
9.521389	.119	40.7	.459	.300	19.
9.875556	.119	40.6	.458	.300	19.
10.246389	.118	40.7	.456	.300	19.
10.650278	.118	40.7	.455	.300	19.
11.088889	.118	40.7	.457	.300	19.

11.544722	.115	40.7	.457	.300	19.
12.050556	.114	40.6	.457	.300	19.
12.590000	.114	40.6	.460	.300	19.
13.196111	.112	40.2	.468	.300	19.
13.853889	.111	40.1	.470	.300	19.
14.596389	.110	40.1	.470	.300	19.
15.422500	.110	40.1	.469	.300	19.
16.398611	.108	40.0	.477	.300	19.
17.393889	.109	40.0	.475	.300	19.
18.402778	.107	40.1	.474	.300	19.
19.395833	.108	40.2	.470	.300	19.
20.388889	.106	40.3	.466	.300	19.
21.400833	.105	40.3	.464	.300	19.
22.395833	.104	40.5	.461	.300	19.
23.391667	.104	40.7	.459	.300	19.
24.403333	.104	40.3	.464	.300	19.
25.398333	.104	40.3	.467	.300	19.
26.393056	.103	40.2	.469	.300	19.
27.404722	.103	40.1	.472	.300	19.
28.398056	.103	40.0	.474	.300	19.
29.393889	.104	39.9	.477	.300	19.
30.389167	.102	39.8	.477	.300	19.
31.401389	.103	39.7	.479	.300	19.
32.396111	.102	39.8	.476	.300	19.
33.391389	.102	39.6	.482	.300	19.
34.403889	.102	39.7	.482	.300	19.
35.397222	.101	39.6	.482	.300	19.
36.392500	.103	39.5	.486	.300	19.
37.403056	.101	39.5	.484	.300	19.

Test 12 B

.058333	.286	24.8	.508	.294	25.
.107778	.280	24.8	.510	.294	25.
.191389	.272	24.9	.505	.294	25.
.258611	.268	24.9	.505	.294	25.
.342500	.262	24.9	.505	.294	25.
.426389	.258	25.0	.505	.294	25.
.510556	.254	24.9	.505	.294	25.
.594444	.250	24.9	.505	.294	25.
.678056	.246	24.9	.504	.294	25.
.762222	.242	24.9	.505	.294	25.
.845833	.240	24.9	.504	.294	25.
.929722	.238	24.9	.502	.294	25.
1.013333	.234	24.9	.503	.294	25.
1.114167	.233	24.9	.504	.294	25.
1.198056	.231	24.9	.504	.294	25.
1.298889	.226	25.0	.503	.294	25.
1.382500	.225	25.0	.503	.294	25.
1.483333	.222	24.9	.504	.294	25.
1.584167	.219	24.9	.504	.294	25.
1.685000	.216	25.0	.503	.294	25.
1.785556	.216	25.0	.502	.294	25.
1.886389	.214	25.0	.502	.294	25.

1.986667	.211	25.0	.504	.294	25.
2.087222	.207	25.0	.504	.294	25.
2.204722	.206	25.0	.502	.294	25.
2.305556	.205	24.9	.503	.294	25.
2.423056	.202	24.9	.503	.294	25.
2.523889	.201	25.0	.503	.294	25.
2.641389	.198	25.0	.503	.294	25.
2.758889	.197	24.9	.504	.294	25.
2.876667	.195	25.0	.502	.294	25.
2.993889	.192	25.0	.503	.294	25.
3.128333	.191	24.9	.503	.294	25.
3.245833	.190	25.0	.503	.294	25.
3.380278	.188	25.0	.503	.294	25.
3.514444	.186	25.0	.504	.294	25.
3.648611	.184	25.0	.504	.294	25.
3.782778	.183	25.0	.503	.294	25.
3.916944	.181	25.0	.503	.294	25.
4.068056	.179	25.0	.502	.294	25.
4.218889	.179	25.0	.504	.294	25.
4.370000	.176	25.0	.503	.294	25.
4.520833	.175	25.0	.502	.294	25.
4.671667	.172	25.0	.503	.294	25.
4.839444	.172	25.0	.503	.294	25.
5.007500	.170	25.0	.502	.294	25.
5.175278	.169	25.0	.502	.294	25.
5.360000	.167	25.0	.502	.294	25.
5.544444	.165	25.0	.501	.294	25.
5.729167	.164	25.0	.500	.294	25.
5.913889	.163	25.0	.502	.294	25.
6.115556	.162	25.0	.503	.294	25.
6.316667	.161	25.0	.502	.294	25.
6.534722	.160	25.0	.503	.294	25.
6.752778	.159	25.0	.503	.294	25.
6.970833	.157	25.0	.502	.294	25.
7.205833	.155	25.0	.503	.294	25.
7.457778	.155	25.0	.502	.294	25.
7.709167	.154	25.0	.502	.294	25.
7.977500	.152	25.0	.502	.294	25.
8.262500	.152	25.0	.504	.294	25.
8.547222	.150	25.0	.503	.294	25.
8.849167	.149	24.9	.503	.294	25.
9.168056	.148	25.0	.502	.294	25.
9.520833	.146	24.9	.504	.294	25.
9.873333	.146	25.0	.503	.294	25.
10.258889	.145	25.0	.501	.294	25.
10.661389	.144	25.0	.501	.294	25.
11.080833	.143	25.1	.502	.294	25.
11.551111	.143	25.1	.501	.294	25.
12.052500	.140	25.2	.498	.294	25.
12.606111	.139	25.2	.498	.294	25.
13.193333	.137	25.3	.496	.294	25.
13.847500	.137	25.4	.493	.294	25.
14.585833	.137	25.5	.491	.294	25.

15.424722	.136	25.5	.491	.294	25.
16.398333	.135	25.4	.491	.294	25.
17.388611	.132	25.5	.491	.294	25.
18.395278	.130	25.4	.493	.294	25.
19.403056	.130	25.4	.493	.294	25.
20.393056	.130	25.4	.492	.294	25.
21.400000	.128	25.5	.491	.294	25.
22.389444	.129	25.4	.493	.294	25.
23.393611	.129	25.4	.491	.294	25.
24.399167	.128	25.4	.492	.294	25.
25.388611	.128	25.3	.493	.294	25.
26.395278	.126	25.3	.494	.294	25.
27.402778	.124	25.4	.494	.294	25.
28.393611	.124	25.3	.492	.294	25.
29.400000	.127	25.4	.492	.294	25.
30.390278	.124	25.4	.494	.294	25.
31.396389	.124	25.3	.495	.294	25.
32.403333	.126	25.3	.495	.294	25.
33.394167	.124	25.2	.496	.294	25.
34.401944	.123	25.2	.497	.294	25.
35.391944	.124	25.2	.497	.294	25.
36.398611	.124	25.3	.495	.294	25.
37.405278	.126	25.3	.494	.294	25.

Test 13 A

.108333	.300	20.0	.445	.309	26.
.125000	.297	18.5	.480	.309	26.
.191389	.292	17.5	.509	.309	26.
.257778	.286	17.4	.511	.309	26.
.340833	.282	17.3	.513	.309	26.
.424722	.284	17.2	.516	.309	26.
.508056	.276	17.3	.514	.309	26.
.591389	.274	17.3	.512	.309	26.
.674167	.270	17.4	.511	.309	26.
.758056	.266	17.4	.509	.309	26.
.841944	.263	17.4	.511	.309	26.
.925556	.260	17.4	.509	.309	26.
1.025278	.257	17.4	.508	.309	26.
1.107778	.258	17.5	.512	.309	26.
1.208611	.255	17.4	.510	.309	26.
1.292500	.252	17.4	.510	.309	26.
1.393333	.253	17.3	.511	.309	26.
1.477222	.251	17.2	.515	.309	26.
1.578056	.251	17.3	.511	.309	26.
1.678611	.250	17.3	.513	.309	26.
1.779444	.249	17.3	.512	.309	26.
1.880278	.245	17.2	.514	.309	26.
1.981111	.244	17.2	.514	.309	26.
2.081944	.240	17.2	.513	.309	26.
2.199444	.238	17.3	.513	.309	26.
2.300278	.242	17.3	.512	.309	26.
2.417778	.236	17.2	.513	.309	26.
2.535278	.234	17.2	.513	.309	26.

2.635833	.234	17.2	.513	.309	26.
2.753056	.231	17.3	.512	.309	26.
2.870833	.229	17.2	.513	.309	26.
3.005000	.227	17.3	.513	.309	26.
3.122500	.226	17.3	.512	.309	26.
3.256667	.224	17.2	.512	.309	26.
3.374167	.226	17.3	.513	.309	26.
3.508333	.226	17.3	.511	.309	26.
3.642500	.224	17.3	.512	.309	26.
3.776944	.215	17.3	.511	.309	26.
3.927778	.210	17.4	.509	.309	26.
4.061944	.211	17.5	.507	.309	26.
4.213333	.208	17.4	.508	.309	26.
4.364444	.210	17.5	.506	.309	26.
4.515278	.206	17.5	.507	.309	26.
4.683333	.203	17.4	.507	.309	26.
4.834444	.201	17.5	.506	.309	26.
5.002222	.200	17.5	.506	.309	26.
5.186667	.198	17.5	.505	.309	26.
5.354444	.199	17.6	.503	.309	26.
5.538889	.198	17.6	.504	.309	26.
5.723889	.198	17.6	.503	.309	26.
5.908056	.195	17.6	.503	.309	26.
6.109444	.194	17.6	.503	.309	26.
6.310833	.194	17.6	.501	.309	26.
6.528889	.188	17.6	.503	.309	26.
6.746667	.186	17.7	.501	.309	26.
6.981667	.188	17.6	.503	.309	26.
7.216389	.186	17.6	.502	.309	26.
7.451389	.182	17.7	.503	.309	26.
7.719444	.181	17.6	.503	.309	26.
7.987778	.179	17.7	.502	.309	26.
8.256389	.179	17.7	.501	.309	26.
8.558611	.175	17.6	.504	.309	26.
8.860556	.172	17.5	.506	.309	26.
9.179444	.172	17.5	.505	.309	26.
9.514722	.171	17.5	.506	.309	26.
9.866944	.168	17.4	.508	.309	26.
10.253056	.168	17.4	.508	.309	26.
10.656111	.165	17.4	.508	.309	26.
11.092500	.164	17.4	.510	.309	26.
11.544722	.162	17.3	.510	.309	26.
12.047500	.161	17.4	.509	.309	26.
12.600556	.158	17.4	.508	.309	26.
13.187778	.156	17.3	.510	.309	26.
13.859167	.156	17.3	.511	.309	26.
14.597222	.152	17.3	.512	.309	26.
15.436389	.145	17.3	.512	.309	26.
16.392222	.146	17.2	.515	.309	26.
17.397778	.146	17.1	.515	.309	26.
18.404167	.145	17.1	.515	.309	26.
19.394444	.148	17.2	.514	.309	26.
20.401389	.141	17.2	.515	.309	26.

21.391111	.145	17.4	.508	.309	26.
22.396667	.142	17.6	.501	.309	26.
23.402778	.144	17.7	.500	.309	26.
24.393056	.146	17.7	.501	.309	26.
25.399444	.143	17.6	.503	.309	26.
26.403889	.142	17.6	.505	.309	26.
27.392778	.143	17.5	.506	.309	26.
28.399167	.138	17.5	.506	.309	26.
29.404167	.145	17.5	.505	.309	26.
30.393611	.139	17.5	.507	.309	26.
31.399722	.138	17.5	.507	.309	26.
32.389444	.138	17.5	.506	.309	26.
33.395556	.140	17.5	.505	.309	26.
34.402500	.137	17.4	.508	.309	26.
35.391944	.136	17.5	.507	.309	26.
36.398611	.134	17.4	.508	.309	26.
37.404444	.137	17.4	.508	.309	26.

Test 14 B

.041667	.254	25.3	.400	.255	29.
.107500	.247	25.3	.399	.255	29.
.190556	.240	25.2	.399	.255	29.
.256667	.235	25.3	.400	.255	29.
.338889	.232	25.3	.397	.255	29.
.421667	.226	25.3	.400	.255	29.
.505833	.224	25.3	.397	.255	29.
.589444	.222	25.2	.399	.255	29.
.673611	.220	25.3	.397	.255	29.
.757500	.218	25.3	.398	.255	29.
.841389	.214	25.3	.397	.255	29.
.925278	.213	25.3	.398	.255	29.
1.026111	.210	25.3	.397	.255	29.
1.109444	.208	25.3	.398	.255	29.
1.210000	.204	25.3	.397	.255	29.
1.294167	.203	25.3	.398	.255	29.
1.395000	.201	25.3	.398	.255	29.
1.478889	.198	25.3	.397	.255	29.
1.579444	.196	25.3	.399	.255	29.
1.680278	.194	25.2	.399	.255	29.
1.781111	.193	25.2	.399	.255	29.
1.881667	.191	25.2	.401	.255	29.
1.982222	.189	25.2	.400	.255	29.
2.082778	.187	25.1	.401	.255	29.
2.200278	.187	25.2	.400	.255	29.
2.301111	.185	25.1	.401	.255	29.
2.418611	.182	25.1	.400	.255	29.
2.536111	.180	25.1	.401	.255	29.
2.636389	.178	25.1	.402	.255	29.
2.753889	.178	25.0	.403	.255	29.
2.871111	.176	25.0	.405	.255	29.
3.005278	.173	25.0	.404	.255	29.
3.123056	.172	24.9	.405	.255	29.
3.256944	.170	25.0	.405	.255	29.

3.374444	.169	24.9	.406	.255	29.
3.508611	.169	25.0	.404	.255	29.
3.642778	.166	24.9	.405	.255	29.
3.776944	.165	24.9	.405	.255	29.
3.927778	.163	25.0	.404	.255	29.
4.061944	.162	25.0	.403	.255	29.
4.212778	.161	25.0	.403	.255	29.
4.363611	.161	25.0	.403	.255	29.
4.514444	.160	25.1	.402	.255	29.
4.682222	.158	25.1	.402	.255	29.
4.833333	.156	25.0	.403	.255	29.
5.001111	.155	25.1	.402	.255	29.
5.185278	.154	25.1	.401	.255	29.
5.352778	.152	25.1	.402	.255	29.
5.537222	.152	25.0	.403	.255	29.
5.721944	.151	25.0	.403	.255	29.
5.923333	.151	25.0	.403	.255	29.
6.108056	.149	25.0	.403	.255	29.
6.326111	.147	25.1	.402	.255	29.
6.527778	.148	25.0	.403	.255	29.
6.746111	.146	25.0	.404	.255	29.
6.980833	.144	24.9	.405	.255	29.
7.215556	.143	25.0	.404	.255	29.
7.467500	.144	24.9	.406	.255	29.
7.719444	.142	24.9	.405	.255	29.
7.987778	.142	24.9	.405	.255	29.
8.256389	.139	25.0	.404	.255	29.
8.558611	.138	25.0	.404	.255	29.
8.860278	.138	25.0	.405	.255	29.
9.179167	.137	25.0	.404	.255	29.
9.514722	.136	25.0	.404	.255	29.
9.867222	.135	25.0	.404	.255	29.
10.252778	.135	25.0	.403	.255	29.
10.655833	.134	24.9	.406	.255	29.
11.091944	.132	25.0	.404	.255	29.
11.545000	.133	24.9	.405	.255	29.
12.047222	.131	24.8	.406	.255	29.
12.601111	.130	25.0	.403	.255	29.
13.188611	.128	25.2	.401	.255	29.
13.859722	.127	25.2	.400	.255	29.
14.598889	.126	25.2	.400	.255	29.
15.436111	.125	25.2	.400	.255	29.
16.391944	.125	25.2	.400	.255	29.
17.398333	.123	25.2	.400	.255	29.
18.395000	.121	25.2	.401	.255	29.
19.397500	.122	25.1	.403	.255	29.
20.404722	.119	25.1	.401	.255	29.
21.394167	.120	25.1	.401	.255	29.
22.401667	.119	25.3	.397	.255	29.
23.392500	.117	25.5	.394	.255	29.
24.398611	.117	25.5	.395	.255	29.
25.404722	.116	25.2	.399	.255	29.
26.392500	.115	25.0	.404	.255	29.

27.399444	.115	24.9	.405	.255	29.
28.389444	.114	24.9	.406	.255	29.
29.396389	.111	24.9	.405	.255	29.
30.402778	.112	25.1	.403	.255	29.
31.393056	.111	24.9	.406	.255	29.
32.400278	.110	24.9	.406	.255	29.
33.389167	.110	25.0	.405	.255	29.
34.395833	.109	24.9	.406	.255	29.
35.402778	.109	24.9	.405	.255	29.
36.392778	.109	25.0	.403	.255	29.
37.399444	.109	25.0	.402	.255	29.

Test 18 A

.219722	.221	37.5	.299	.241	36.
.236389	.220	37.8	.295	.241	36.
.253055	.217	38.0	.291	.241	36.
.269722	.216	38.2	.289	.241	36.
.336666	.211	38.7	.282	.241	36.
.423055	.205	39.1	.276	.241	36.
.506666	.199	39.3	.275	.241	36.
.590000	.194	39.4	.272	.241	36.
.673611	.191	39.5	.272	.241	36.
.757500	.186	39.6	.269	.241	36.
.840833	.183	39.6	.269	.241	36.
.924722	.179	39.7	.269	.241	36.
1.025000	.176	39.8	.267	.241	36.
1.108611	.172	39.8	.267	.241	36.
1.208889	.170	39.7	.269	.241	36.
1.292500	.167	39.8	.269	.241	36.
1.392777	.163	39.8	.267	.241	36.
1.476389	.162	39.8	.267	.241	36.
1.576389	.159	39.9	.266	.241	36.
1.676944	.157	39.9	.268	.241	36.
1.777222	.154	39.8	.267	.241	36.
1.877222	.152	39.8	.268	.241	36.
1.977500	.149	39.8	.268	.241	36.
2.094722	.148	39.7	.268	.241	36.
2.195000	.145	39.8	.266	.241	36.
2.312222	.143	39.9	.266	.241	36.
2.412222	.142	39.8	.267	.241	36.
2.529444	.139	39.9	.267	.241	36.
2.646389	.138	39.8	.268	.241	36.
2.763333	.135	39.8	.268	.241	36.
2.880000	.134	39.8	.267	.241	36.
2.997222	.133	39.8	.268	.241	36.
3.131111	.131	39.7	.268	.241	36.
3.248055	.129	39.8	.268	.241	36.
3.381666	.128	39.9	.267	.241	36.
3.515555	.126	39.7	.268	.241	36.
3.649444	.124	39.8	.268	.241	36.
3.783333	.124	39.8	.267	.241	36.
3.916944	.122	39.8	.267	.241	36.
4.067500	.122	39.8	.268	.241	36.

4.217777	.119	39.8	.268	.241	36.
4.368055	.119	39.8	.266	.241	36.
4.518611	.118	39.8	.267	.241	36.
4.685833	.116	39.8	.267	.241	36.
4.836389	.115	39.8	.268	.241	36.
5.003611	.114	39.9	.267	.241	36.
5.170833	.114	39.8	.267	.241	36.
5.354444	.112	39.9	.266	.241	36.
5.538333	.112	39.8	.268	.241	36.
5.722500	.109	39.7	.268	.241	36.
5.922777	.109	39.8	.268	.241	36.
6.106389	.109	39.8	.267	.241	36.
6.323611	.108	39.8	.267	.241	36.
6.524166	.107	39.7	.270	.241	36.
6.758055	.106	39.7	.270	.241	36.
6.975000	.105	39.6	.271	.241	36.
7.209166	.104	39.6	.270	.241	36.
7.459444	.104	39.8	.268	.241	36.
7.710555	.102	39.8	.268	.241	36.
7.978055	.101	39.8	.269	.241	36.
8.262500	.100	39.8	.268	.241	36.
8.546666	.100	39.8	.268	.241	36.
8.847500	.099	39.8	.267	.241	36.
9.181666	.098	39.7	.268	.241	36.
9.516111	.097	39.8	.268	.241	36.
9.866666	.096	39.8	.269	.241	36.
10.251389	.095	39.8	.268	.241	36.
10.652500	.094	39.8	.268	.241	36.
11.087222	.093	39.7	.268	.241	36.
11.555277	.092	39.8	.267	.241	36.
12.056666	.092	39.8	.268	.241	36.
12.591666	.090	39.7	.269	.241	36.
13.193333	.090	39.7	.268	.241	36.
13.861666	.089	39.8	.267	.241	36.
14.597222	.088	39.8	.269	.241	36.
15.432222	.086	39.6	.270	.241	36.
16.401389	.086	39.4	.272	.241	36.
17.404166	.086	39.6	.270	.241	36.
18.390555	.085	39.6	.271	.241	36.
19.393889	.084	39.8	.268	.241	36.
20.396666	.083	40.0	.265	.241	36.
21.399166	.082	40.0	.266	.241	36.
22.401389	.081	40.2	.263	.241	36.
23.404166	.081	40.1	.264	.241	36.
24.389444	.080	39.8	.266	.241	36.
25.392222	.080	39.8	.268	.241	36.
26.395277	.078	39.9	.267	.241	36.
27.397500	.079	39.8	.267	.241	36.
28.401389	.078	39.7	.269	.241	36.
29.404166	.077	39.8	.268	.241	36.
30.390000	.077	39.9	.266	.241	36.
31.392777	.077	39.8	.266	.241	36.
32.395000	.078	39.9	.266	.241	36.

33.397777	.077	39.9	.268	.241	36.
34.401389	.076	39.9	.267	.241	36.
35.404722	.077	39.8	.268	.241	36.
36.391389	.077	39.9	.267	.241	36.
37.394722	.076	39.9	.266	.241	36.

Test 18 B

.103056	.166	37.5	.299	.178	37.
.119722	.164	37.8	.295	.178	37.
.186667	.159	38.5	.284	.178	37.
.256389	.156	38.9	.279	.178	37.
.340000	.152	39.1	.277	.178	37.
.423611	.150	39.3	.274	.178	37.
.506944	.147	39.4	.272	.178	37.
.590556	.145	39.5	.270	.178	37.
.674167	.143	39.6	.270	.178	37.
.757778	.141	39.6	.271	.178	37.
.841389	.139	39.7	.269	.178	37.
.925000	.138	39.7	.268	.178	37.
1.025278	.136	39.8	.268	.178	37.
1.109167	.135	39.8	.269	.178	37.
1.209167	.133	39.8	.267	.178	37.
1.292778	.131	39.8	.268	.178	37.
1.393056	.130	39.9	.266	.178	37.
1.476667	.129	39.9	.267	.178	37.
1.576944	.128	39.8	.266	.178	37.
1.677222	.126	39.9	.267	.178	37.
1.777222	.125	39.8	.266	.178	37.
1.877778	.123	39.8	.269	.178	37.
1.978056	.123	39.7	.268	.178	37.
2.095278	.121	39.8	.268	.178	37.
2.195556	.121	39.9	.266	.178	37.
2.312500	.120	39.9	.267	.178	37.
2.412778	.119	39.9	.267	.178	37.
2.529722	.118	39.8	.268	.178	37.
2.646667	.117	39.8	.268	.178	37.
2.763333	.116	39.8	.267	.178	37.
2.880556	.115	39.8	.268	.178	37.
2.997500	.114	39.7	.268	.178	37.
3.131389	.114	39.8	.268	.178	37.
3.248333	.112	39.9	.267	.178	37.
3.382222	.112	39.8	.268	.178	37.
3.516111	.111	39.7	.268	.178	37.
3.649722	.110	39.8	.268	.178	37.
3.783611	.110	39.8	.268	.178	37.
3.917500	.109	39.8	.268	.178	37.
4.067500	.108	39.8	.267	.178	37.
4.217778	.107	39.8	.268	.178	37.
4.368333	.107	39.8	.269	.178	37.
4.518889	.106	39.8	.267	.178	37.
4.686111	.105	39.8	.266	.178	37.
4.836944	.105	39.8	.268	.178	37.
5.003889	.104	39.8	.266	.178	37.

5.171111	.104	39.8	.267	.178	37.
5.354722	.103	39.8	.266	.178	37.
5.538889	.102	39.8	.267	.178	37.
5.722222	.101	39.9	.267	.178	37.
5.922778	.101	39.7	.269	.178	37.
6.106667	.100	39.8	.268	.178	37.
6.323889	.099	39.7	.269	.178	37.
6.524444	.099	39.6	.269	.178	37.
6.758333	.099	39.7	.270	.178	37.
6.975556	.098	39.6	.271	.178	37.
7.209444	.097	39.7	.269	.178	37.
7.460000	.097	39.7	.268	.178	37.
7.710833	.097	39.8	.267	.178	37.
7.978611	.096	39.8	.267	.178	37.
8.262778	.095	39.7	.269	.178	37.
8.547222	.094	39.8	.268	.178	37.
8.848056	.093	39.8	.268	.178	37.
9.181944	.093	39.8	.269	.178	37.
9.516389	.093	39.8	.268	.178	37.
9.866944	.092	39.8	.267	.178	37.
10.251944	.091	39.7	.269	.178	37.
10.652778	.091	39.7	.269	.178	37.
11.087500	.091	39.8	.268	.178	37.
11.555556	.089	39.7	.269	.178	37.
12.056944	.088	39.7	.268	.178	37.
12.591944	.088	39.8	.268	.178	37.
13.193611	.087	39.7	.269	.178	37.
13.861667	.086	39.7	.269	.178	37.
14.597500	.086	39.7	.268	.178	37.
15.432778	.084	39.7	.269	.178	37.
16.401944	.083	39.5	.272	.178	37.
17.404722	.083	39.5	.272	.178	37.
18.390833	.082	39.7	.268	.178	37.
19.394167	.081	39.8	.269	.178	37.
20.396944	.081	40.0	.265	.178	37.
21.399444	.081	40.0	.265	.178	37.
22.401944	.081	40.1	.263	.178	37.
23.404444	.080	40.1	.263	.178	37.
24.389722	.080	39.8	.268	.178	37.
25.392500	.079	39.9	.266	.178	37.
26.395278	.079	39.9	.268	.178	37.
27.398056	.078	39.8	.268	.178	37.
28.401944	.079	39.8	.267	.178	37.
29.404722	.078	39.8	.268	.178	37.
30.390278	.077	39.9	.266	.178	37.
31.393333	.077	39.9	.266	.178	37.
32.395556	.077	39.9	.267	.178	37.
33.398056	.076	39.8	.266	.178	37.
34.401667	.076	39.9	.268	.178	37.
35.388611	.076	39.8	.268	.178	37.
36.391944	.075	39.8	.268	.178	37.
37.395278	.076	39.9	.266	.178	37.

Test 19 A

.125000	.232	33.9	.380	.242	38.
.141389	.230	34.8	.360	.242	38.
.190556	.226	36.1	.339	.242	38.
.256667	.219	36.9	.327	.242	38.
.340556	.213	37.3	.318	.242	38.
.424167	.207	37.7	.313	.242	38.
.507222	.202	37.8	.309	.242	38.
.590833	.197	37.9	.309	.242	38.
.674722	.194	38.0	.309	.242	38.
.758333	.190	38.0	.308	.242	38.
.841944	.186	38.0	.307	.242	38.
.925278	.183	38.0	.306	.242	38.
1.025556	.180	38.1	.307	.242	38.
1.109167	.176	38.1	.307	.242	38.
1.209167	.173	38.1	.307	.242	38.
1.292500	.170	38.1	.305	.242	38.
1.392778	.168	38.1	.307	.242	38.
1.476389	.165	38.1	.306	.242	38.
1.576111	.164	38.1	.306	.242	38.
1.676389	.160	38.1	.306	.242	38.
1.776944	.158	38.1	.305	.242	38.
1.877222	.156	38.2	.305	.242	38.
1.977778	.154	38.1	.307	.242	38.
2.094722	.151	38.2	.305	.242	38.
2.194722	.149	38.2	.306	.242	38.
2.311667	.147	38.1	.307	.242	38.
2.411944	.146	38.0	.307	.242	38.
2.528611	.142	38.0	.308	.242	38.
2.645556	.142	38.1	.307	.242	38.
2.762500	.140	38.1	.306	.242	38.
2.879444	.138	38.1	.307	.242	38.
2.996389	.137	38.1	.306	.242	38.
3.130000	.135	38.1	.306	.242	38.
3.246667	.133	38.2	.306	.242	38.
3.380278	.132	38.1	.305	.242	38.
3.513611	.131	38.1	.306	.242	38.
3.647222	.129	38.1	.305	.242	38.
3.780556	.127	38.2	.305	.242	38.
3.930833	.126	38.0	.307	.242	38.
4.064722	.125	38.1	.307	.242	38.
4.215000	.124	37.9	.309	.242	38.
4.365556	.123	38.0	.307	.242	38.
4.515556	.122	38.0	.308	.242	38.
4.682778	.121	38.0	.308	.242	38.
4.833333	.119	38.0	.307	.242	38.
5.000000	.119	38.0	.308	.242	38.
5.183889	.117	38.0	.306	.242	38.
5.350833	.116	38.1	.307	.242	38.
5.534722	.115	38.2	.306	.242	38.
5.718333	.114	38.1	.307	.242	38.
5.918889	.113	38.1	.305	.242	38.

6.119444	.113	38.0	.307	.242	38.
6.320278	.112	38.2	.306	.242	38.
6.537500	.110	38.1	.306	.242	38.
6.755000	.110	38.0	.307	.242	38.
6.971944	.109	38.0	.308	.242	38.
7.206111	.107	38.0	.309	.242	38.
7.456667	.107	38.1	.306	.242	38.
7.707222	.106	38.1	.305	.242	38.
7.975000	.105	38.1	.306	.242	38.
8.258611	.103	38.1	.307	.242	38.
8.542778	.103	38.1	.307	.242	38.
8.859444	.103	38.2	.306	.242	38.
9.176389	.102	38.0	.307	.242	38.
9.510278	.101	38.0	.308	.242	38.
9.877778	.100	38.1	.307	.242	38.
10.244722	.100	38.1	.305	.242	38.
10.661944	.099	38.1	.306	.242	38.
11.079722	.098	38.0	.307	.242	38.
11.547222	.097	38.0	.307	.242	38.
12.048333	.096	38.0	.308	.242	38.
12.599722	.096	38.0	.308	.242	38.
13.201111	.095	38.1	.306	.242	38.
13.852222	.094	38.1	.307	.242	38.
14.587222	.094	38.1	.306	.242	38.
15.422222	.092	38.0	.308	.242	38.
16.391389	.091	38.1	.305	.242	38.
17.392500	.090	38.0	.306	.242	38.
18.394722	.089	38.0	.307	.242	38.
19.396667	.089	38.1	.307	.242	38.
20.398611	.088	38.0	.308	.242	38.
21.401111	.086	38.0	.307	.242	38.
22.404167	.086	38.1	.306	.242	38.
23.389444	.086	38.1	.307	.242	38.
24.401111	.086	38.0	.306	.242	38.
25.404722	.084	38.1	.306	.242	38.
26.390833	.083	38.0	.306	.242	38.
27.392222	.082	38.0	.308	.242	38.
28.394167	.083	37.8	.310	.242	38.
29.396944	.083	37.7	.311	.242	38.
30.400000	.081	37.8	.311	.242	38.
31.403056	.081	37.9	.309	.242	38.
32.388889	.081	37.5	.315	.242	38.
33.391667	.081	38.2	.305	.242	38.
34.394167	.080	38.1	.306	.242	38.
35.395833	.079	38.0	.306	.242	38.
36.398333	.079	38.0	.309	.242	38.
37.400556	.079	38.0	.308	.242	38.

Test 19 B

.075000	.169	33.9	.380	.172	39.
.107778	.166	35.3	.351	.172	39.
.190278	.161	36.7	.330	.172	39.
.256944	.158	37.3	.320	.172	39.

.340556	.155	37.6	.314	.172	39.
.424167	.153	37.7	.311	.172	39.
.507500	.151	37.8	.309	.172	39.
.591111	.149	38.0	.309	.172	39.
.674722	.147	38.1	.308	.172	39.
.758611	.145	38.1	.308	.172	39.
.842222	.144	38.0	.307	.172	39.
.925278	.143	38.1	.306	.172	39.
1.025833	.141	38.0	.308	.172	39.
1.109167	.140	38.1	.306	.172	39.
1.209167	.138	38.1	.306	.172	39.
1.292778	.137	38.1	.306	.172	39.
1.392778	.135	38.1	.306	.172	39.
1.476389	.134	38.1	.306	.172	39.
1.576389	.133	38.1	.307	.172	39.
1.676667	.132	38.1	.307	.172	39.
1.777222	.132	38.1	.306	.172	39.
1.877500	.130	38.2	.306	.172	39.
1.977778	.128	38.1	.307	.172	39.
2.094722	.128	38.1	.306	.172	39.
2.194722	.126	38.1	.307	.172	39.
2.311944	.125	38.0	.306	.172	39.
2.412222	.124	38.0	.308	.172	39.
2.528889	.123	38.0	.307	.172	39.
2.645556	.122	38.0	.308	.172	39.
2.762778	.122	38.1	.306	.172	39.
2.879444	.121	38.1	.307	.172	39.
2.996389	.120	38.1	.307	.172	39.
3.130000	.119	38.2	.305	.172	39.
3.246944	.118	38.1	.306	.172	39.
3.380278	.117	38.1	.306	.172	39.
3.513611	.116	38.2	.304	.172	39.
3.647222	.116	38.2	.305	.172	39.
3.780556	.115	38.2	.305	.172	39.
3.931111	.114	38.0	.307	.172	39.
4.064722	.113	38.1	.308	.172	39.
4.215000	.113	38.1	.307	.172	39.
4.365556	.113	38.1	.307	.172	39.
4.515833	.112	38.0	.308	.172	39.
4.683056	.111	38.1	.306	.172	39.
4.833611	.110	38.0	.307	.172	39.
5.000278	.110	38.0	.306	.172	39.
5.183889	.109	38.0	.306	.172	39.
5.350833	.108	38.0	.307	.172	39.
5.535000	.107	38.1	.306	.172	39.
5.718611	.107	38.1	.307	.172	39.
5.919167	.105	38.0	.306	.172	39.
6.119722	.106	38.1	.307	.172	39.
6.320278	.105	38.1	.307	.172	39.
6.537778	.104	38.1	.306	.172	39.
6.755000	.103	38.0	.308	.172	39.
6.972222	.103	38.0	.308	.172	39.
7.206111	.103	38.1	.307	.172	39.

7.456944	.102	38.0	.308	.172	39.
7.707500	.101	38.1	.306	.172	39.
7.975000	.100	38.0	.307	.172	39.
8.258611	.100	38.2	.305	.172	39.
8.542778	.100	38.1	.307	.172	39.
8.859722	.099	38.1	.305	.172	39.
9.176389	.098	38.1	.305	.172	39.
9.510000	.098	38.1	.308	.172	39.
9.877500	.097	38.1	.307	.172	39.
10.245000	.097	38.1	.306	.172	39.
10.662222	.095	38.1	.307	.172	39.
11.079722	.095	38.1	.306	.172	39.
11.547500	.094	38.0	.307	.172	39.
12.048333	.094	38.0	.309	.172	39.
12.600000	.093	38.0	.307	.172	39.
13.200833	.092	38.1	.305	.172	39.
13.852222	.092	38.0	.308	.172	39.
14.587500	.092	38.0	.307	.172	39.
15.422500	.090	38.0	.308	.172	39.
16.391389	.089	38.0	.306	.172	39.
17.392500	.089	38.0	.307	.172	39.
18.394722	.088	38.0	.307	.172	39.
19.396944	.087	38.1	.307	.172	39.
20.398889	.087	38.0	.309	.172	39.
21.401111	.085	38.1	.306	.172	39.
22.404444	.085	38.2	.304	.172	39.
23.389444	.085	38.2	.305	.172	39.
24.401111	.085	38.1	.306	.172	39.
25.404722	.084	38.0	.307	.172	39.
26.391111	.084	38.0	.306	.172	39.
27.392500	.083	38.0	.310	.172	39.
28.394444	.082	37.9	.310	.172	39.
29.396944	.082	37.8	.310	.172	39.
30.400278	.082	37.8	.311	.172	39.
31.403056	.082	37.9	.308	.172	39.
32.389167	.080	37.5	.314	.172	39.
33.391667	.080	38.2	.305	.172	39.
34.394167	.080	38.1	.306	.172	39.
35.396111	.080	38.0	.308	.172	39.
36.398333	.080	38.0	.309	.172	39.
37.400556	.080	38.0	.308	.172	39.

Test 20 B

.058333	.253	25.4	.494	.258	41.
.107778	.247	25.8	.486	.258	41.
.189722	.239	25.9	.481	.258	41.
.271389	.234	26.0	.478	.258	41.
.337500	.230	25.9	.479	.258	41.
.420278	.226	26.0	.477	.258	41.
.503611	.223	26.0	.478	.258	41.
.587222	.219	26.0	.478	.258	41.
.670833	.217	26.1	.476	.258	41.
.753611	.214	26.1	.476	.258	41.

.836389	.211	26.0	.477	.258	41.
.935556	.208	26.1	.476	.258	41.
1.018333	.205	26.0	.476	.258	41.
1.117778	.203	26.1	.476	.258	41.
1.201111	.201	26.0	.476	.258	41.
1.300278	.198	26.0	.476	.258	41.
1.383056	.196	26.1	.476	.258	41.
1.482500	.194	25.9	.481	.258	41.
1.582778	.192	26.0	.478	.258	41.
1.816944	.188	26.1	.475	.258	41.
1.833889	.188	26.1	.475	.258	41.
1.883889	.187	26.2	.473	.258	41.
1.984444	.185	26.3	.470	.258	41.
2.084722	.184	26.3	.469	.258	41.
2.201667	.182	26.4	.467	.258	41.
2.301944	.180	26.4	.467	.258	41.
2.418611	.179	26.5	.464	.258	41.
2.535556	.176	26.4	.468	.258	41.
2.636111	.175	26.3	.469	.258	41.
2.752778	.173	26.4	.469	.258	41.
2.886111	.172	26.3	.468	.258	41.
3.003056	.170	26.3	.471	.258	41.
3.120000	.169	26.3	.469	.258	41.
3.253889	.167	26.3	.468	.258	41.
3.387500	.165	26.4	.469	.258	41.
3.504722	.164	26.3	.470	.258	41.
3.638333	.163	26.3	.470	.258	41.
3.788611	.162	26.5	.465	.258	41.
3.922222	.160	26.5	.466	.258	41.
4.072778	.159	26.4	.466	.258	41.
4.206667	.157	26.4	.468	.258	41.
4.356944	.156	26.3	.468	.258	41.
4.523889	.155	26.4	.468	.258	41.
4.673889	.154	26.5	.465	.258	41.
4.841111	.153	26.4	.468	.258	41.
5.008333	.152	26.2	.471	.258	41.
5.175556	.151	26.4	.469	.258	41.
5.359444	.150	26.5	.465	.258	41.
5.543333	.148	26.4	.467	.258	41.
5.727222	.147	26.4	.467	.258	41.
5.911111	.146	26.3	.469	.258	41.
6.111389	.145	26.1	.474	.258	41.
6.311944	.144	26.1	.475	.258	41.
6.529444	.143	26.1	.473	.258	41.
6.746944	.142	26.2	.474	.258	41.
6.980556	.141	26.1	.475	.258	41.
7.214167	.139	26.1	.474	.258	41.
7.464722	.139	26.1	.474	.258	41.
7.715000	.139	26.5	.464	.258	41.
7.982500	.137	26.3	.469	.258	41.
8.266944	.136	26.2	.472	.258	41.
8.550833	.135	26.3	.471	.258	41.
8.851944	.134	26.3	.471	.258	41.

9.169444	.134	26.3	.471	.258	41.
9.520278	.132	26.1	.473	.258	41.
9.871389	.131	26.2	.472	.258	41.
10.255556	.130	26.1	.474	.258	41.
10.656667	.130	26.3	.470	.258	41.
11.090833	.128	26.2	.473	.258	41.
11.558333	.128	26.4	.467	.258	41.
12.059167	.126	26.3	.468	.258	41.
12.594444	.126	26.4	.468	.258	41.
13.195278	.125	26.3	.469	.258	41.
13.846944	.124	26.3	.468	.258	41.
14.599444	.122	26.3	.469	.258	41.
15.432778	.121	26.4	.467	.258	41.
16.393889	.120	26.4	.470	.258	41.
17.393333	.120	26.4	.468	.258	41.
18.396389	.119	26.3	.469	.258	41.
19.398889	.118	26.5	.466	.258	41.
20.401944	.118	26.3	.468	.258	41.
21.404444	.116	26.3	.470	.258	41.
22.390278	.115	26.4	.467	.258	41.
23.392500	.114	26.3	.469	.258	41.
24.393056	.114	26.2	.471	.258	41.
25.395556	.113	26.3	.470	.258	41.
26.398333	.113	26.3	.468	.258	41.
27.398611	.113	26.6	.462	.258	41.
28.400000	.112	26.4	.468	.258	41.
29.402222	.111	26.2	.472	.258	41.
30.388889	.111	26.3	.470	.258	41.
31.391389	.110	26.3	.469	.258	41.
32.394167	.110	26.5	.465	.258	41.
33.394444	.110	26.4	.466	.258	41.
34.395278	.109	26.4	.469	.258	41.
35.398611	.108	26.3	.468	.258	41.
36.400000	.109	26.4	.468	.258	41.
37.402778	.108	26.4	.467	.258	41.

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