25

MODELING FOR DRYER SELECTION AND SIMULATION OF NATURAL AIR DRYING OF ROUGH RICE

by

DONG IL CHANG

B.S., Seoul National University, 1972

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1978

Approved by:

Do Sup Chung
Major Professor

TABLE OF CONTENTS

Page

CHAPTER 1 MODELING FOR DRYER SELECTION

CHAPTER 2 SIMULATION OF NATURAL AIR DRYING OF ROUGH RICE

LIST OF FIGURES

LIST OF TABLES

Chapter 1

MODELING FOR DRYER SELECTION

1.1 Introduction

Grain drying is an energy intensive agricultural operation that will be increasingly affected by the growing fossil fuel shortage. Most of the recent studies on artificial drying of grain have been devoted toward increasing capacity or output of dryers. Little effort has been extended toward the optimization of drying procedures to conserve energy or capital. The present energy crisis has served to emphasize our lack of attention to energy conservation in the past and to serve notice that our drying research efforts should be reoriented toward the optimization of the total drying process.

The cost of operation of a grain dryer is the sum of the operating costs plus the fixed costs. In the past, when energy costs were relatively low, the thermal efficiency was not an important factor in dryer design, so fixed costs had a more important role in dryer design. Though current energy costs have not risen more rapidly than fixed costs, predictions of the future indicate that energy costs will be a larger proportional part of the total costs of drying grain. Previously, the typical midwest corn drying installation had fixed costs per bushel about equal to the operating costs per bushel, according to McKenzie (1966). Therefore, the analysis of thermal efficiency of grain dryers is valuable for economic drying systems as well as energy conservation.

Increased production, combined with increased field shelling and harvesting at high moisture levels, has increased the need for conditioning and storage. Grain handling facilities have been expanded on the farm as well as at commercial sites. According to Schwart and Hill (1977), by 1965, 53.5 per cent of the acreage harvested for corn was field shelled; by 1975, this had increased to 87 per cent in Illinois. In 1965, 225 million bushels, or about one-half of the shelled corn harvested, was stored in bins on farms. By 1975, this had increased to 533 million bushels. The pressure on time and labor associated with field loss encouraged early corn harvesting. As a result, shelled corn is harvested with a moisture content above safe storage levels, and most of it must be dried.

The decision to purchase on-farm drying and storage facilities requires an economic analysis of drying systems. Many factors influence the choice of equipment, but a comparison of drying costs and performance generally has the most effect on the decision. Because many alternative systems and combinations of equipment are available, a systematic procedure for comparison of optimized drying cost is needed to enable farmers to select the facilities best suited to their needs. For this purpose, mathematical modeling would give benefits of control of input variables and allow testing of many proposed designs and drying conditions.

The approach proposed in this study is to collect the specifications of dryers which are manufactured in the U.S.A. for the purpose of determining the relations of dryer capacity and dependent variables of cost functions in drying systems.

1.2 Review of Literature

1.2.1 Drying System Selection

Brooker et al. (1974) described the following drying system selection method: "The two most important considerations in selecting a grain dryer are: (1) drying capacity and (2) the investment necessary to get that capacity. These two items overshadow other factors such as airflow, labor requirements, operating cost, management and feed or market value of the dried grain. Other factors may become major considerations. For example, if grain is dried for seed, the quality (germination) is the most important requirement. Anti-pollution laws directed against dust and chaff in the atmosphere or against noise, as well as availability of fuel, may force operators to select certain types of system."

McKenzie (1966) evaluated estimated cost and performance relationships of grain dryers on shelled corn dryed from 25 per cent to 13.5 per cent (wet basis) and suggested volume ranges for alternative drying methods based primarily on drying capacity and management considerations in graphical figure.

1.2.2 Method of Evaluating Drying Costs

Young and Dickens (1975) discussed a method for evaluating drying costs and the effects that various drying parameters had on these costs. They used Hukill's analysis for deep-bed drying in batch or continuous cross-flow dryers to predict fuel costs, fan-operating costs, fixed costs, and total drying costs for shelled corn. They made the following general conclusions:

1. Costs per bushel for fuel tend to peak and then decrease as drying temperature is increased at a fixed airflow rate; and for certain environmental conditions, any increase in drying temperature reduces fuel costs per bushel.

2. Costs per bushel for fuel increased with airflow rate at all drying temperatures.

3. Costs per bushel for fan operation decrease with an increase in drying temperature or a decrease in airflow rate.

4. Fixed costs per bushel decrease to some minimum level with an increase in either drying temperature or airflow rate (increased initial cost for higher fan capacity was neglected).

5. Total drying costs per bushel are generally lower for the highest permissible drying temperature.

6. The airflow rate which results in minimum total cost per bushel depends upon a number of factors. For a given initial moisture content, optimum airflow rate decreases with an increase in drying temperature. If initial moisture content is increased, optimum airflow rate increases for a given drying temperature.

7. Although costs may be reduced by using low airflow rates and high drying temperatures, consideration should be given to the effects on grain quality. Moisture gradients within the layer of grain increase with an increase in drying temperature and with a decrease in airflow rate. These gradients may result in considerable overdrying of some grain while other grain is not dry enough to prevent spoilage. High drying temperatures may also cause heat damage or stress cracks in the grain.

Schwart and Hill (1977) illustrated an approach for comparing costs of drying and storage for several alternatives by comparing the total costs of the systems in Illinois. They made the following summary: "No one conditioning and storage system can be recommended as the most economical. The choice of a system depends upon annual volume, the marketing pattern, the type of farm, and the kind and capacity of existing facilities. Drying and storage services of commercial elevators may be the most economical for small volumes of corn production. In-bin dryers provide the lowest cost across the greatest range of annual volumes. At volumes above 20,000 bushels, the addition of a stirring device reduces the cost per bushel by providing greater drying capacity with any given size of heating components. The automatic batch and continuous flow dryers are very similar in their characteristics and become competitive with the other systems at 60,000 bushels or more per year. Low temperature drying reduces the requirement for supplemental heat sources, but this saving is offset by the electricity used to meet the high airflow requirements. The height of the bin is also restricted by airflow requirements."

Foster and Peart (1976) reported that typical high-temperature corn drying costs in 1975 were 15 cents per bushel for 10 percentage points moisture removal.

1.2.3 Simulation Model for Corn Drying

Morey and Peart (1971) studied the optimum design of a natural air corn drying system with two different filling procedures. They obtained optimal combinations of horsepower and depth for several sets of costs and capacities. They indicated sensitivity of the solution to various parameter changes, especially to the bed depth.

Bloome and Shove (1972) simulated low temperatures drying of shelled corn leading to optimization. Low temperature drying of shelled corn is dependent upon the airflow, the harvest mositure content, the harvest date, the amount of heat added to the drying air and the variability of weather. They determined the effects of each of these variables and developed a least cost optimization of low temperature drying. Recommendations were presented for design parameters of best systems for drying shelled corn having specific harvest moisture contents.

Carpenter and Brooker (1972) presented a simulation model to analyse costs associated with harvesting, drying and storing systems for shelled corn. The model provided a means of evaluating the effect of the size and type of equipment used in system. This system used weather data for 20 harvesting seasons from 1946 to 1965 and cost data were obtained by averaging the computed yearly costs for the 20-year period.

1.2.4 Heat Required to Vaporize Moisture

Evaluation of systems and design of equipment for processing operations such as artificial drying of grain usually requires information on three aspects of the basic process: (a) the amount of energy required, (b) the rate at which the process may be made to proceed, and (c) the equilibrium moisture. Johnson and Dale (1954) described a method of measuring the heat of vaporization, and the results obtained in drying tests on wheat and shelled corn. He concluded the following:

1. The heat required for evaporation of moisture in wheat and shelled corn may be greater than the heat required for evaporation of free water depending on the magnitude of the hygroscopic effect at lower moisture contents.

2. The heat requirement is primarily a function of grain moisture content and is not significantly dependent upon drying temperature and initial moisture.

3. Over the range of moistures encountered in most actual drying systems for wheat and shelled corn, above 14 per cent dry basis, the heat required for vaporization is between 1.00 and 1.06 times that for vaporization of free water.

4. If drying is carried to moisture contents below 14 per cent, the heat requirement is further increased; at moisture content of 10 per cent dry basis, it is aobut 1.15 to 1.20 times that for free water.

Chung and Pfost (1967) investigated the heat and free energy changes of adsorption and desorption. Adsorption and desorption isotherms were obtained for corn, corn starch, corn germ, corn hull, and corn gluten at 22, 25, and 50 ^{o}C and at relative humidity in the range of 8.9 to 88.9 per cent. They described the heat of adsorption and desorption as the following: When water vapor is adsorbed on a surface, a quantity of heat, the heat of adsorption is released. When adsorbed water vapor is desorbed, a quantity of heat is taken up, the heat of desorption, and is a measure of the heat or energy that must be added to adsorbed gas to break the intermolecular force. The heat of adsorption or desorption indicated the binding energy of the intermolecular force between the molecules of water vapor and the surface of adsorbent. They presented the following equation for evaluating the isosteric heats of adsorption and desorption of the materials investigated by assuming that ΔH_{st} was invariant with temperature.

$$\Delta H_{st} = R \left[\frac{T_1 \cdot T_2}{T_2 - T_1} \right] \ln \frac{P_2}{P_1}$$

where ΔH_{st} = the isosteric heat of sorption (BTU/lb-mole)

R = universal gas constant (1.987 BTU/lb-mole-^{o}R)

P_1, P_2= equilibrium vapor pressures at temperatures at T_1 and T_2, respectively (psia)

T_1, T_2= absolute temperature (^{o}R)

The calculation values of isosteric heats of adsorption and desorption ranged from 16 Kcal/g-mole to 10.5 Kcal/g-mole. They concluded that isosteric heats and free energy changes of adsorption and desorption decreased continually with increasing moisture content, and isosteric heats and free energy changes of desorption were consistently greater than those of adsorption.

1.2.5 Efficiency of Drying System

Peart and Lien (1975) defined fuel efficiency and drying efficiency by the following:

1. Fuel efficiency is defined as the ratio of the theoretical energy required to evaporate the water to the amount of energy supplied by the fuel used to heat the air. Fan energy is usually not included in the denominator for high temperature dryers.

2. Drying efficiency is defined as the ratio of the theoretical energy required to vaporize the moisture to the heat available for drying in the drying air.

They showed that fuel efficiency for high speed dryers, 140-284 ^{o}F and 45-125 cfm per bushel, increased with temperature and increased as airflow rates decreased; and for low-speed drying systems, 50-90 ^{o}F and 0.9-4.5 cfm per bushel, increased as drying air temperature decreased with the same ambient air state.

Agricultural Engineering (1975) showed the energy efficiencies of various drying techniques. In that report, drying efficiency (bushel per gallon of L.P. gas) of drying techniques are as follows:

1. Batch or continuous flow with cooling in dryer (180 ^{o}F to 220 ^{o}F); 6.5 bushel per gallon.

2. Batch or continuous flow with dryeration (180 ^{o}F to 220 ^{o}F); 8.1 bushel per gallon.

3. Bin drying without stirring device (10 ^{o}F rise with 55 per cent

relative humidity humidistat control); 9.2 bushel per gallon.

4. Bin drying with stirring device (110 °F to 140 °F); 9.2 bushel per gallon.

5. Bin batch-drying cooling in bin (120 °F to 140 °F); 9.2 bushel per gallon.

6. Electric bin drying (2 °F to 7 °F rise); 7.7 bushel per gallon.

7. Combination system, 5 per cent with batch or continuous flow drying, 2 per cent with dryeration, 3 per cent with aeration; 12.6 bushel per gallon.

Foster and Peart (1976) presented the overall efficiency in drying tests with both batch and continuous flow operation of a typical dryer was near 40 per cent. Modification in heated air drying procedures (dryeration) increased efficiency to about 60 per cent (Sinha and Muir, 1973).

Morey et al. (1976) attempted to define and evaluate some of the commonly proposed alternatives for saving energy in drying. Some of the conclusions made by them are:

1. Reducing the airflow rate on high-airflow dryers (90-120 cmm/m^3) down to 60-90 cmm/m^3 will produce energy savings. However, reducing airflow may be difficult to accomplish on some dryers and may cause problems with nonuniformity of drying at high initial moisture contents.

2. Increasing drying air temperature should be considered if acceptable quality can be maintained. Grain quality must be monitored closely if drying air temperature is increased.

3. Drying air temperature should not be lowered in an attempt to reduce energy requirements.

4. If airflow rates have been lowered, care should be exercised in increasing drying air temperatures.

5. Partial drying in a high-temperature dryer followed by cooling and drying in a bin at lower airflows will save significant amount of energy without reducing quality or yield and may actually improve quality.

6. Drying air temperature can be increased to provide additional energy savings with acceptable quality if grain is only partially dried in the high temperature system.

1.2.6 Timeliness Loss Factors

Timliness of a field operation must be considered to have an economic value. Timeliness costs arise because of the inability to complete a drying operation in a reasonably short time. Delay in harvesting or drying due to low capacity of dryer is a cost that should be borne by the dryer. Hunt (1977) described some typical timeliness loss factors (K) for most machine operations. From his data, K is 0.003 for corn and 0.004 for sorghum.

1.3 Objectives of Study

The broad objective of this study was to develop a simple dryer selection model for on-farm drying facilities in order to select the drying system in optimum cost.

The specific objectives were as follows:

1. To analyse the thermal efficiencies of several drying systems.
2. To discuss the mathematical modeling method for dryer selection.
3. To suggest optimized drying systems for shelled corn drying.

1.4 Mathematical Modeling for Costs of Shelled Corn Drying

Dryer selection should be based on anticipated performance and anticipated costs. Since these future values can never be known exactly, selection must proceed with a liberal or flexible view toward some of the relationships among the pertinent variables. Some of the rigid relationships may have to be relaxed in the interest of arriving at a general, workable method for selection. In dryer selection, the most pertinent variable is capacity of the dryer.

1.4.1 Method of Arriving at Total System Cost

Based on the above philosophy, the method of arriving at the approximate total system cost is described schematically in Figure 1.1.

The steps taken in this study are: (a) collecting more than 100 different dryer specifications obtained from 22 dryer manufacturers in the U.S.A., (b) mathematical modeling of the dependent variables as the functions of the independent variables, (c) development of the dependent cost functions, and (d) optimization of the drying system requirements.

1.4.2 Cost Components in Drying Systems

Machinery costs are divided into two categories, fixed costs and operating costs. Operating costs increase proportionally with the amount of operational use given the machine, while fixed costs are independent of use.

(a) Fixed Costs

Fixed costs make up the major share of the total cost of drying systems. Depreciation, interest, taxes, and insurance are commonly referred to as fixed costs (Hunt, 1977).

1. Depreciation measures the amount by which the value of a dryer decreases with the passage of time whether used or not. The following expected life of a dryer was assumed: continuous flow dryer is 10 years;

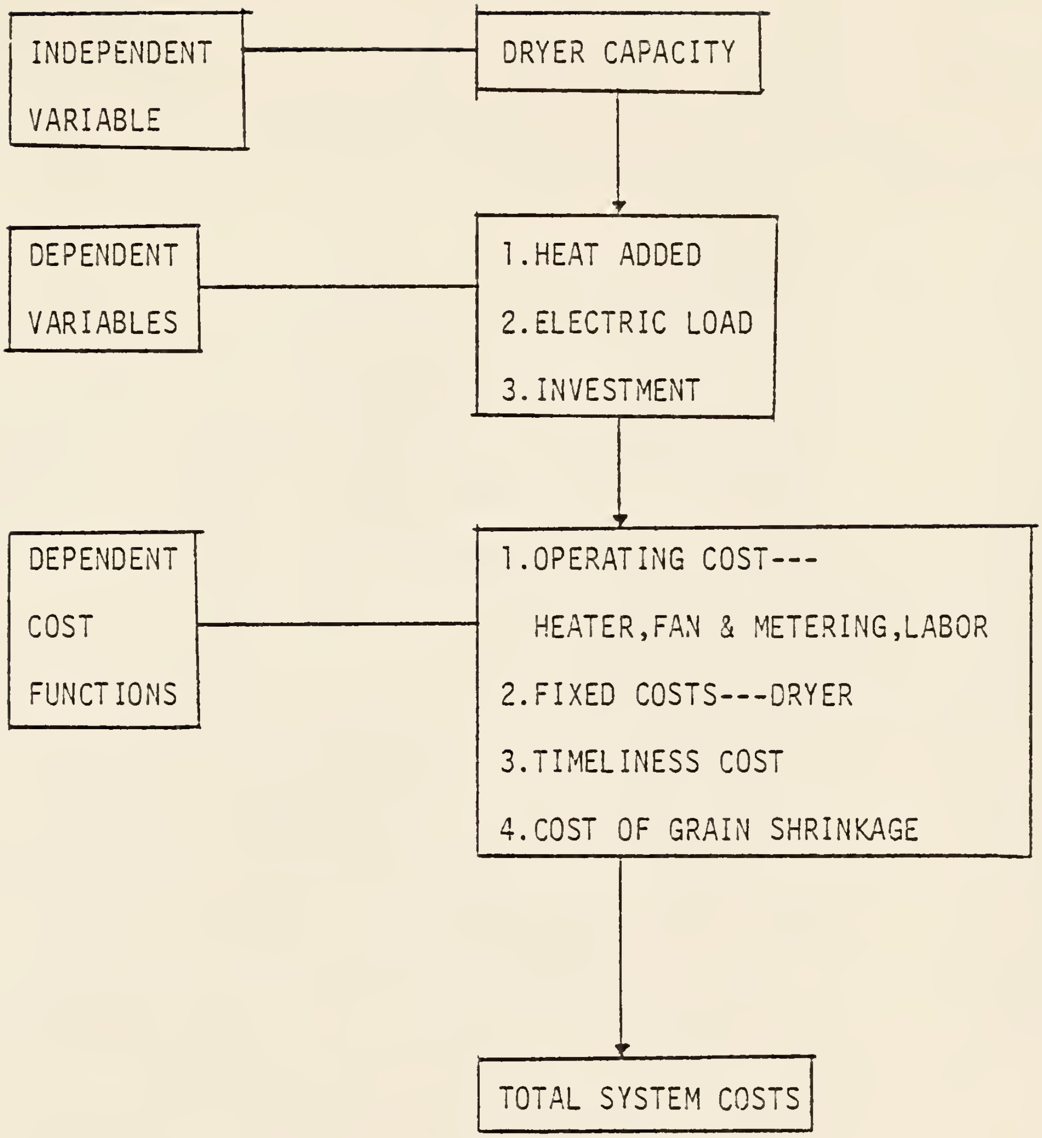


Figure 1.1 Method of Arriving at Total System Costs

portable batch dryer, 10 years; batch-in-bin dryer, 15 years; natural air dryer and natural air dryer with supplemental heat, 20 years. In this study, the straight line method was used for calculating depreciation.

2. Interest cost was calculated at an annual rate of 8 per cent of the average value over the life of investment or at 4 per cent of the new cost of the dryers.

3. Taxes were calculated at 1.5 per cent of the new cost of the dryers.

4. Insurance costs were computed at 0.3 per cent of the cost of the new dryers.

Cost figures were based on dryer, storage, and equipment prices of the representative dealers and manufacturers in the U.S.A. (1977).

The annual fixes costs were computed by multiplying the component prices by the following percentages: continuous flow dryer and portable batch dryer, 15 per cent; batch-in-bin dryer, 13 per cent; natural air dryer with supplemental heat and natural air dryer, 12 per cent.

(b) Operating Costs

Operating costs include costs of liquefied petroleum gas, electricity, and labor. The following prices were used in calculating costs: L. P. gas, 36 cents per gallon; electricity, 4 cents per KWH; supervisory labor, 84 cents per hour.

In most hot-air drying systems, the labor to operate these dryers was assumed to be about one-sixth of the operating time, or about three hours per day. In low-temperature drying systems, labor was required for only occational checking of bins. Therefore, labor costs could be neglected in these systems (Schwart and Hill, 1977).

(c) Miscellaneous Costs

These costs include the shrinkage of dry matter during drying, the loss of dry matter during fermentation, cost of over- or under-drying and the cost of grain spoilage. But only shrinkage of corn is considered as 0.5 per cent in this study.

1.4.3 Analysis of Dryer Specifications for Modeling

The systems for drying shelled corn included in this study are continuous flow dryers, portable batch dryers (automatic batch dryers), batch-in-bin dryers, natural air dryers with supplemental heat (low-temperature dryers), and natural air dryers.

(a) Regression Analysis

For the purpose of mathematical modeling of the dependent variables as the functions of the independent variable (dryer capacity), more than 100 dryer specifications which had been obtained from 22 manufacturers were analyzed in terms of the following factors:

1. Grain: shelled corn.
2. Moisture content: 25 per cent to 15 per cent (wet basis)
3. Kind of dryer.
4. Holding capacity (bushel per unit).
5. Dryer capacity (bushel per hour).
6. Heat (BTU per hour).
7. Electric load (Hp and KWH).
8. Airflow rate (cfm per bushel).
9. Drying temperature (^{o}F).
10. Dryer price (dollar per unit).

Since the dependent variables which are heat, electric load, and dryer price (investment) depend on dryer capacity, all of these dependent variables were expressed in terms of dryer capacity by using a regression analysis of a digital computer program. These analyses included only the following drying system:

1. Continuous flow dryers
2. Portable batch dryers
3. Batch-in-bin dryers
4. Prices of grain bins for natural drying systems

Since there were no dryer specifications for natural air dryers or low temperature drying systems available, design parameters of the best system for drying shelled corn proposed by Bloome and Shove (1972) were used for design of natural air dryers and low temperature dryers. Table 1.1 showed the results of regression analyses. Figure 1.2 through 1.5 showed a few typical results of regression analyses. The results of regression analyses were well fitted to the linear, first-order model by least squares, and there was no reason to doubt the adequacy of the model at $\alpha = 0.05$ level.

(a) Drying Methods

Processes used to dry cereal grain for storage are divided into two broad categories: those that dry grain in batches and those that dry grain as it flows continuously through the equipment. All grain drying systems include an air-moving device, a means of introducing the air into the grain mass, and a chamber to hold the grain. A heater to increase the temperature of the drying air may or may not be a part of the system (Brooker et al., 1974). A heater was included in the drying systems in this study. The following is the summary of analysis of specifications:

Table I.1. Results of Regression Analyses

Relationship / Systems	Heat(BTU/hr,Y) vs DC(bu/hr,X)	Electric Load(Hp,Y) vs DC(bu/hr,X)	Investment($/unit,Y) vs DC(bu/hr,X)
	Y=aX + b	Y=cX + d	Y=eX + f
Continuous Flow Dryer $70 \leq DC^{*} \leq 1200$	a = 20855.30 b = -313197.0 R^2 = 0.806 SD = 2.167	c = 0.1072 d = 5.6179 R^2 = 0.816 SD = 11.839	e = 37.6000 f = 5645.27 R^2 = 0.971 SD = 1054.6
Portable Batch Dryer $40 \leq DC \leq 420$	a = 20575.90 b = -309002.4 R^2 = 0.968 SD = 0.306	c = 0.1058 d = 5.5427 R^2 = 0.979 SD = 1.181	e = 18.3974 f = 4928.701 R^2 = 0.947 SD = 474.7
Batch-In-Bin Dryer $40 \leq DC \leq 250$	a = 19928.80 b = -299248.8 R^2 = 0.825 SD = 0.956	c = 0.1024 d = 5.3684 R^2 = 0.954 SD = 1.358	e = 39.6805 f = 2099.035 R^2 = 0.937 SD = 517.6
Natural Air Dryer with Supplemental Heat $3.6 \leq DC \leq 44.6$	a = 5159.16 b = 0.0 ———— ————	c = 0.605 d = 0.0 ———— ————	e = 119.952 f = 2173.0 R^2 = 0.955 SD = 367.3
Natural Air Dryer $1.3 \leq DC \leq 16.7$	———— ———— ———— ————	c = 0.780 d = 0.0 ———— ————	e = 350.520 f = 1423.0 R^2 = 0.955 SD = 367.3

* DC = Dryer Capacity(bu/hr)

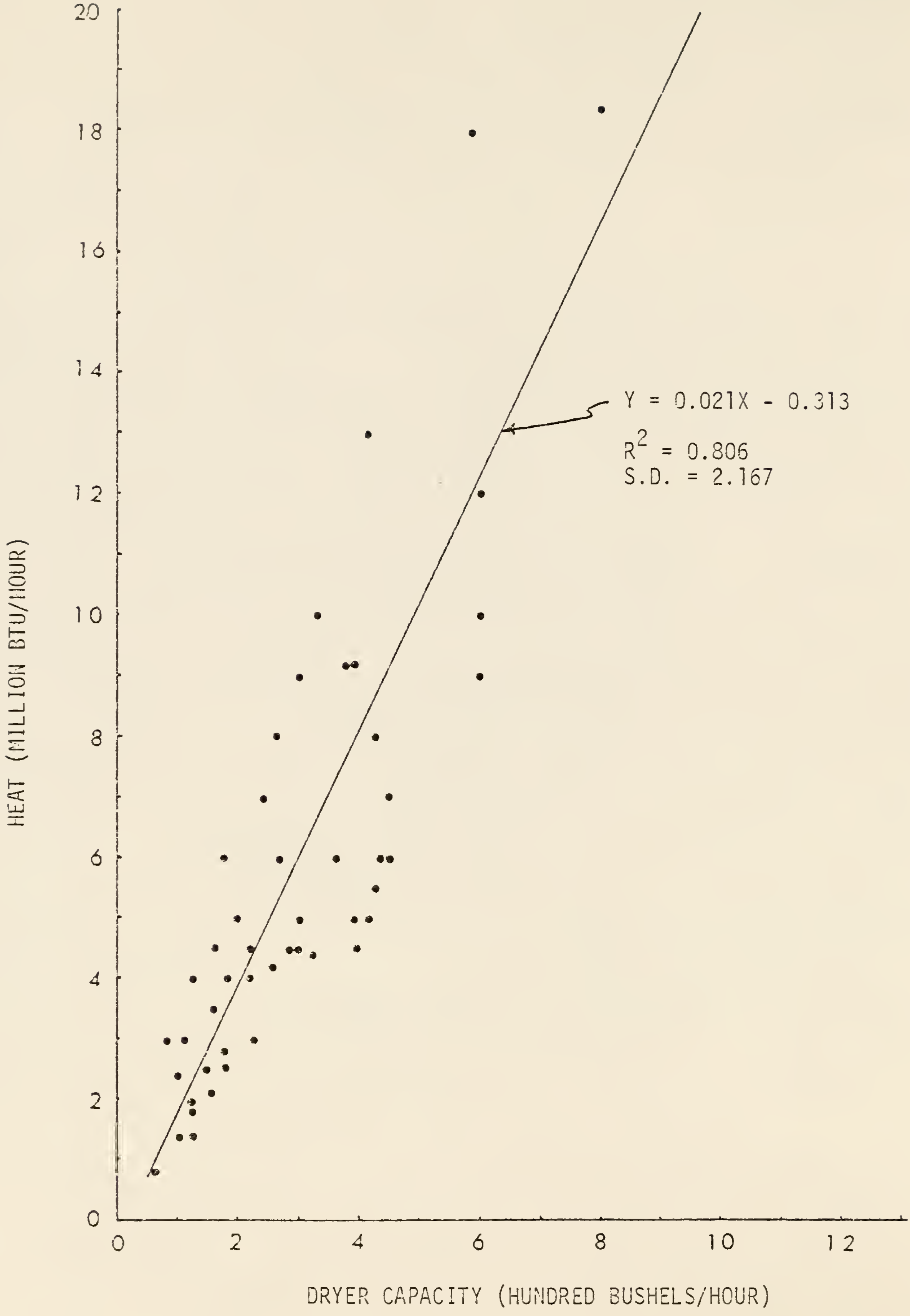


Figure 1.2. Dryer Capacity vs Heat (Continuous Flow Dryer)

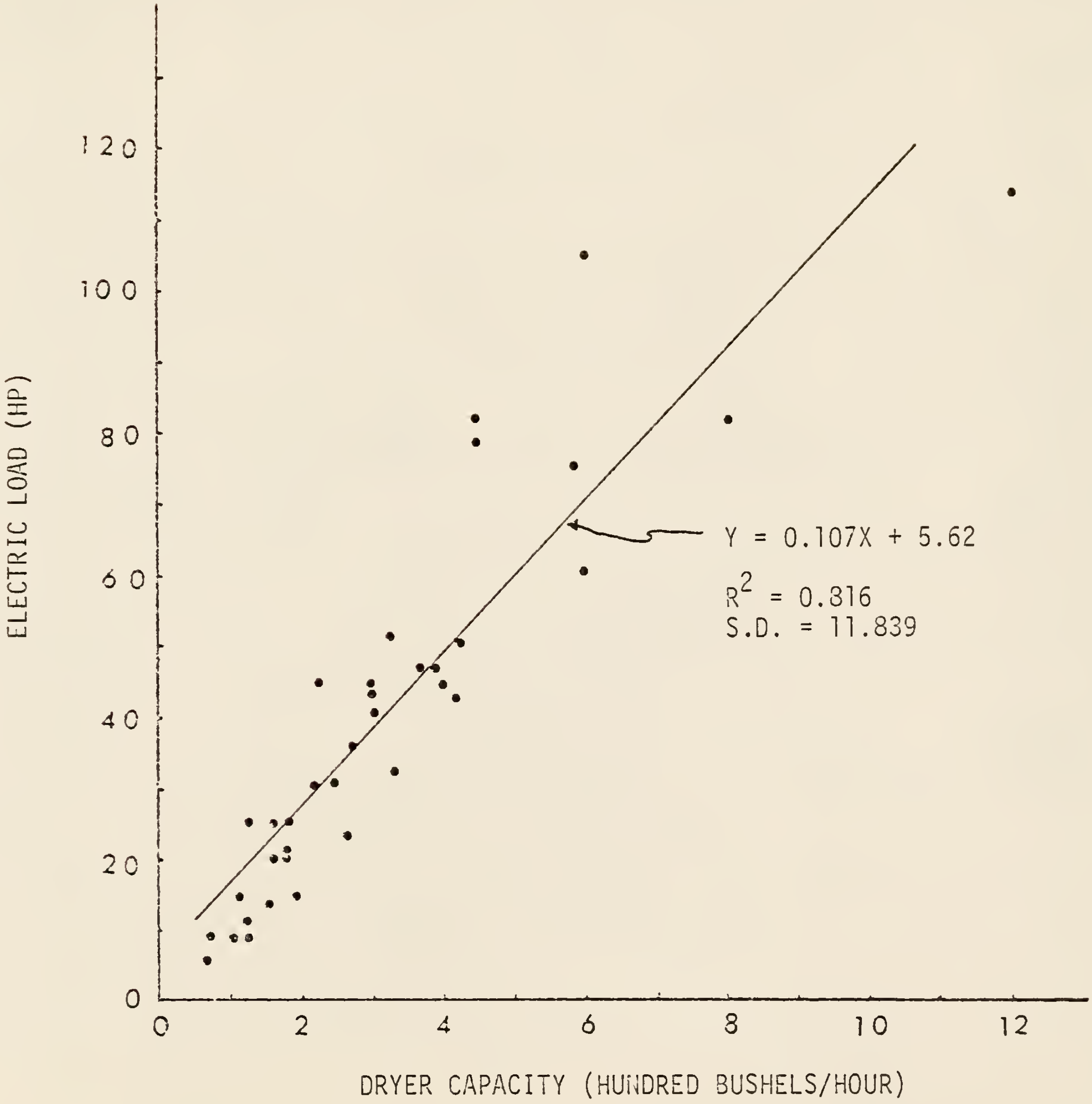


Figure 1.3. Dryer Capacity vs Electric Load (Continuous Flow Dryer)

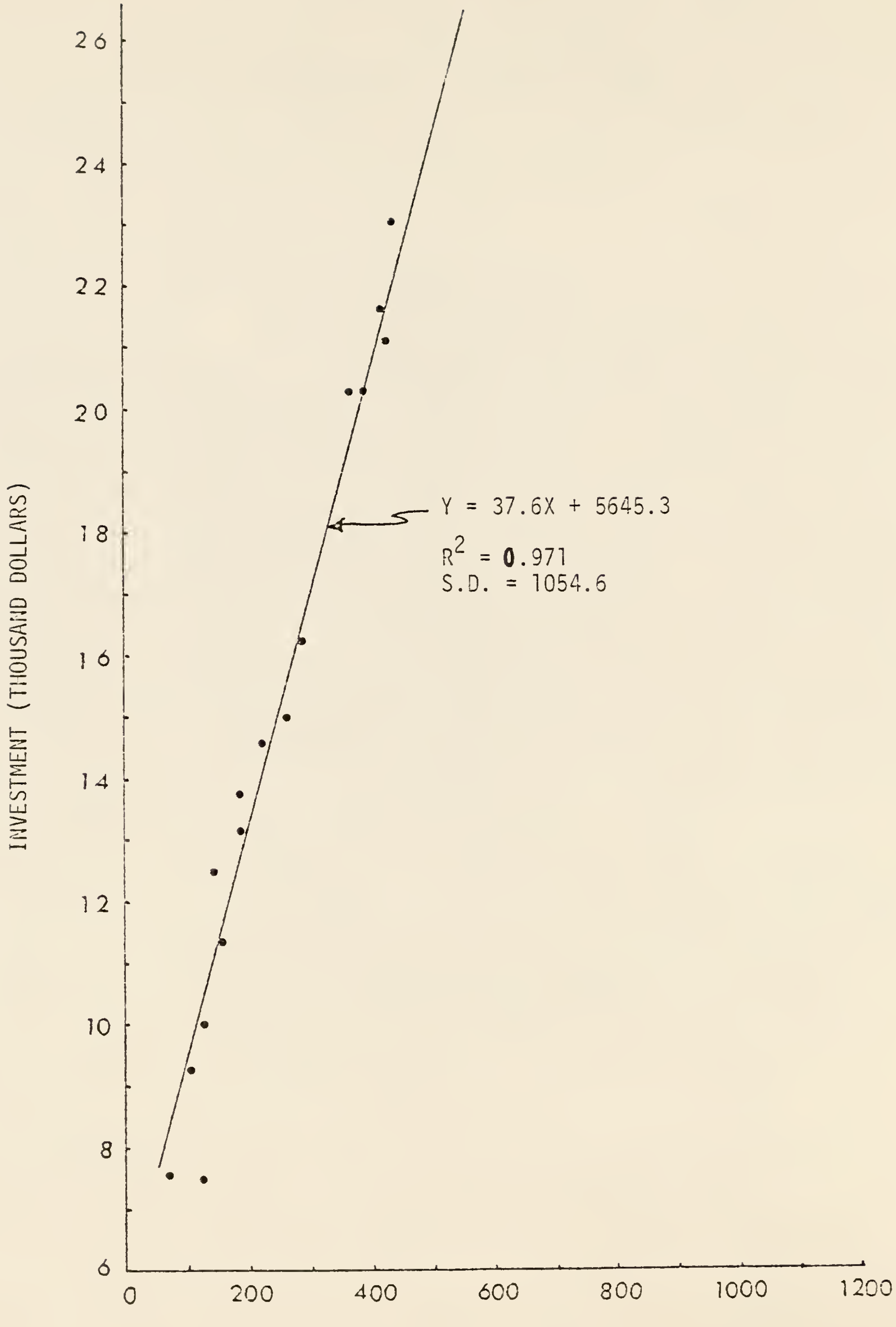


Figure 1.4. Dryer Capacity vs Investment (Continuous Flow Dryer)

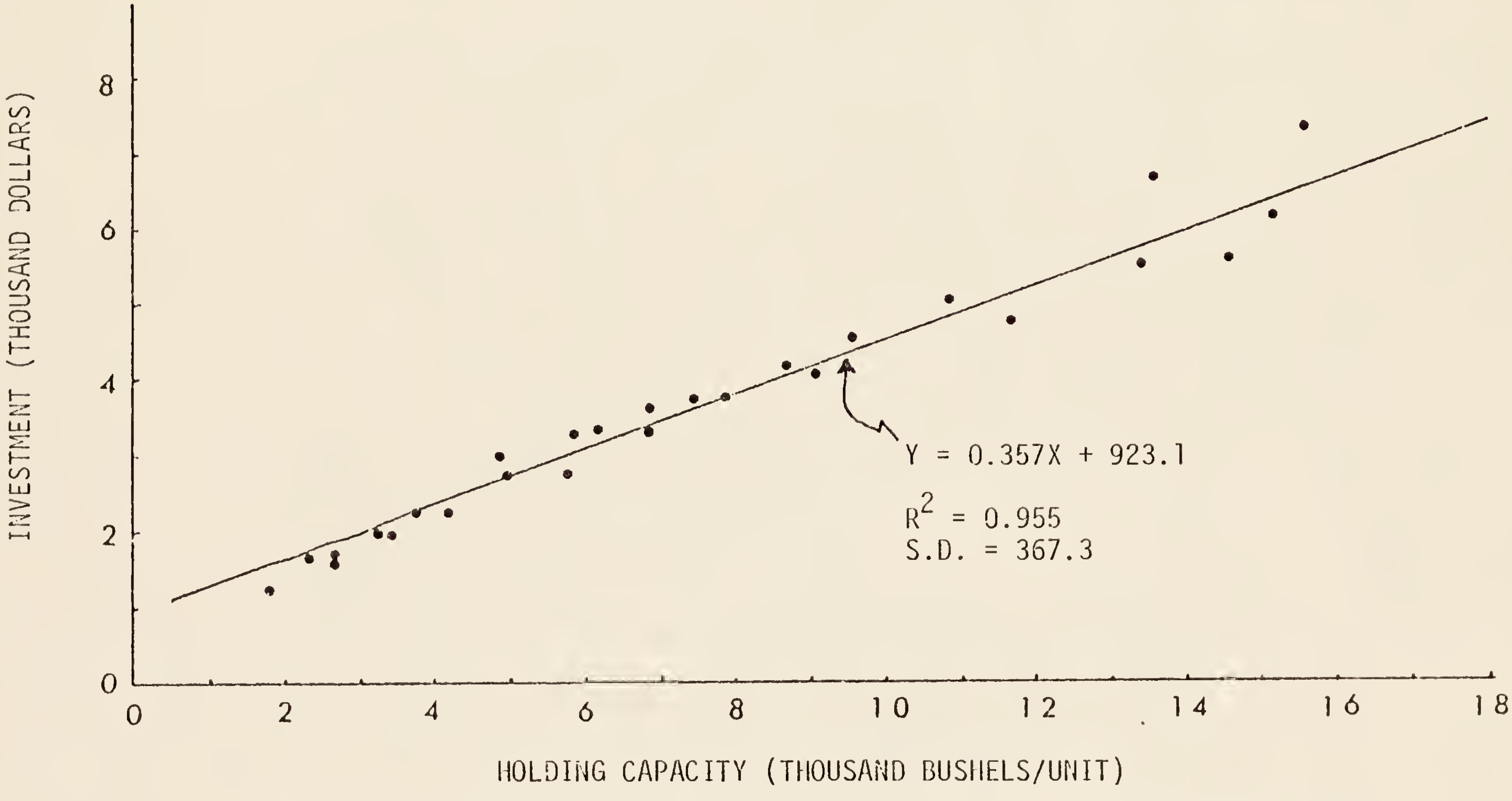


Figure 1.5. Grain Bin Holding Capacity vs Investment (Natural Air Dryer)

1. Continuous flow dryer: Continuous flow dryers are usually operated 16 hours a day or more and require careful management. The high air temperature demands that careful attention to be given to safety devices. There is usually considerable handling equipment in the complete system as well as expensive harvesting equipment that causes dryer shutdown time to be costly. Holding capacity ranges from 100 bushels to 1600 bushels; dryer capacity, 70 to 1200 bushels per hour; heat, 1 to 25.0 million BTU per hour; electric load, 13 to 135 horsepower; approximate airflow rate, 20 to 100 cfm per bushel; approximate drying temperature, 180 ^{o}F to 220 ^{o}F; estimated investment, $8,000 to $50,765 per unit.

2. Portable batch dryer (automatic batch dryer): Portable batch dryers are often equipped to operate automatically. Timers and temperature sensors are used to control drying time, cooling time, and transfer of the grain to and from the dryer and from one part of the dryer to another. This drying system differs from the in-bin systems in that: (a) the bed thickness is less, columns are usually 12 to 18 inches wide; (b) the airflow rate is higher, airflow rates of 50 to 100 cfm per bushel are commonly used; and (c) the grain column is vertical and air passes through it from side to side. Holding capacity ranges from 100 bushels to 1,000 bushels; dryer capacity, 40 to 420 bushels per hour; heat, 1.0 to 8.4 million BTU per hour; electric load, 10 to 50 horsepower; approximate airflow rate, 50 to 120 cfm per bushel; approximate drying temperature, 160 ^{o}F to 200 ^{o}F; estimated investment, $5,700 to $12,600 per unit.

3. Batch-in-bin dryer: Drying grain in batches within a bin and subsequently moving the dried grain to storage is a popular drying method. Batch-in-bin drying becomes feasible when large diameter bins become available. The grain surface must be leveled to assure even drying over the entire bin floor. Sweep augers and under-bin augers are employed to unload

the bin in a reasonable length of time. Holding capacity ranges from 500 bushels to 1500 bushels; dryer capacity, 40 to 250 bushels per hour; heat, 1.0 to 4.0 million BTU per hour; electric load, 10 to 30 horsepower; approximate airflow rate, 10 to 30 cfm per bushel; approximate drying temperature, 120 ^{o}F to 140 ^{o}F; estimated investment, $4,500 to $12,000 per unit.

4. Natural air dryer with supplemental heat: Drying a full bin of grain as a single batch is a slow process. The grain bed is usually deep (up to 16 feet) and a relatively low airflow rate is provided. A heater may be used in conjunction with the fan; in this case a humidistat is located in the plenum to serve as a sensing device for the heater control. The purpose of the heaters is to decrease the relative humidity of the inlet air when it is higher than some preselected value. In this study, design parameters of optimum system proposed by Bloome and Shove (1972) were used. These parameters were: heater size (electric heater) is 4.5 KW per 1,000 bushels per 14 days; electric load, 1.8 horsepower per 1,000 bushels per 14 days; airflow rate, 2.0 cfm per bushel; grain depth, 12 feet. Using electric heater, air temperature is increased 2 to 10 ^{o}F. Bin holding capacity ranges from 1,200 to 20,000 bushel; estimated investment, $2,600 to $7,530 per unit.

5. Natural air dryer: When natural air (unheated) is used with the full bin system, the fan is turned on as soon as a few inches of grain cover the false floor or the duct system. The fan runs continuously until the drying zone moves through the entire bin of grain. The grain is warmed by the drying air during daytime fan operation, and the heated grain serves as a heat source for the cooler air during nighttime operation. The design parameters were as the follows: Fan size is 0.87 horsepower per 1,000

bushels per 38 days; airflow rate is 1.88 cfm per bushel; grain depth is 12 feet. Holding capacity ranges from 1,200 to 15,000 bushels and estimated investment is from $1,900 to $7,300 per unit.

1.4.4 Mathematical Modeling

Cost calculations for drying systems are based on several assumptions about drying practices and characteristics of drying systems. The following assumptions or relationships were used in the development of the mathematical model:

(a) Assumptions

1. The average corn farm size is 636 acres, but corn production per farm ranges from 1,000 bushels to 300,000 bushels (Kansas Agriculture, 1976).

2. The optimum number of days for corn harvest is considered to be 20 to 25. This number of days refers to harvesting, not calendar days (Brooker et al., 1974).

3. Ambient air conditions read from the Schmidt and Waite maps for the corn belt are: mean wet bulb temperature, 47 ^{O}F; mean wet bulb depression, 8 ^{O}F $\pm$ 2.0; relative humidity, 50 per cent.

4. Shelled corn is dried from 25 per cent to 15 per cent moisture content, wet basis.

5. Cost components of drying system include fuel cost (L.P. gas), electric costs, supervisory labor costs, timeliness costs, fixed costs, and shrinkage costs.

6. Prices of dryers are based on dryer specifications of 1977. L.P. gas price is 36 cents per gallon; electricity, 4 cents per KWH; supervisory labor, 84 cents per hour; and price of yellow dent corn, $2.30 per bushel.

7. Heat of combustion of L.P. gas is 91,400 BTU per gallon and efficiency is 0.9 (Yound and Dickens, 1975). Overall efficiency of fan and motor

system is 0.5, and efficiency of heat exchange system (efficiency of generation) is 0.3 (Pfost et al., 1977).

8. Operating hours per day for continuous flow and portable batch systems are 16 for batch-in-bin; natural air with supplemental heat and natural air dry systems are 24.

9. Timeliness loss factor (TF) is 0.003 for corn and 0.004 for sorghum (Hunt, 1977).

10. Shrinkage in dry matter during drying is 0.5 per cent (Schwart and Hill, 1977).

(b) Analysis of the Problem and Modeling

A number of different costs are involved in the drying of grain. These include energy to heat the air, energy to force the air through the grain, energy to operate metering equipment, labor, maintenance, depreciation, interest, taxes, insurance, and miscellaneous costs.

In this analysis, costs for heating the drying air, costs for electric load, costs for supervisory labor, and fixed costs were considered. Also for the optimum drying cost systems, timeliness costs and cost of shrinkage were considered.

1. Total annual drying cost was calcualted by:

$$C_T = (C_1 + C_2 + C_3 + C_4) \frac{TQ}{DC} + C_5 + C_6 \qquad (1\text{-}1)$$

where C_T = total drying cost (dollar per year)

C_1 = fuel cost for drying (dollar per hour)

C_2 = electric cost for drying (dollar per hour)

C_3 = cost of supervisory labor (dollar per hour)

C_4 = timeliness cost (dollar per hour)

C_5 = fixed cost (dollar per year)

C_6 = cost of shrinkage (dollar per year)

TQ = total quantity to be dried (bushel per year)

DC = dryer capacity (bushel per hour)

2. Fuel cost for drying is directly proportional to the energy to heat the air. It was calculated from equation 1-2:

$$C_1 = \frac{H \times P_1}{E_1 \times HC} \qquad (1\text{-}2)$$

where C_1 = fuel cost for drying (dollar per hour)

H = energy to heat the air (BTU per hour)

P_1 = price of fuel (dollar per gallon)

E_1 = efficiency of fuel combustion (decimal)

HC = heat of fuel combustion (BTU per gallon)

3. Electric cost for drying is also directly proportional to the electric load. It was calculated from equation 1-3:

$$C_2 = \frac{0.7457 \times HP \times P_2}{E_2} \qquad (1\text{-}3)$$

where C_2 = electric cost for drying (dollar per hour)

HP = fan and metering horsepower (Hp)

P_2 = price of electricity (dollar per KWH)

E_2 = overall efficiency of fan and motor system (decimal)

4. Cost of supervisory labor for dryer operation is a function of drying time. It is constant.

$$C_3 = P_3 \qquad (1\text{-}4)$$

where P_3 = cost of labor (dollar per hour)

5. Timeliness costs of a field operation must be considered to have an economic value. These costs arise because of the inability to complete a field operation in a reasonable short time. These are not out-of-pocket costs but reductions in potential return, as when the yield and quality of

a crop are reduced because of delays in harvesting (Hunt, 1977). Delays due to bad weather cannot be charged to the dryer, but delay in harvesting the last part of the field because the dryer has low capacity is a cost that should be charged to the dryer. Therefore, timeliness costs are so important in the dryer selection process that they must be evaluated quantitatively and considered as a valid cost of dryer operation.

Total timeliness costs for an operation depend on the scheduling of operations with respect to the optimum time and on the duration of the operation. There are three types of scheduling: premature scheduling, delayed scheduling, and balanced scheduling. In this analysis, scheduling was assumed as balanced scheduling. Timeliness costs were determined by the following expression (Hunt, 1977):

$$C_4 = \frac{TF \times P_4 \times TQ}{FS \times HR} \tag{1-5}$$

where C_4 = timeliness costs (dollar per hour)

TF = timeliness loss factor (one per day)

P_4 = price of crop (dollar per bushel)

TQ = total quantity to be dried (bushel per year)

FS = factor of scheduling of operations

premature scheduling, 2.0

delayed scheduling, 2.0

balanced scheduling, 4.0

HR = hours of dryer operation (hours per day)

6. Fixed costs were expressed by the following equation:

$$C_5 = F \times P_5 \tag{1-6}$$

where C_5 = fixed costs (dollars per year)

F = estimated total annual fixed cost percentage of new investment (decimal)

P_5 = cost of new investment (dollars per unit)

7. Cost of shrinkage was calculated from equation 1-7:

$$C_6 = SK \times P_4 \times TQ \tag{1-7}$$

where C_6 = cost of shrinkage (dollars per year)

SK = percentage of shrinkage (decimal)

P_4 = price of crop (dollars per bushel)

TQ = total quantity to be dried (bushel per year)

Since heat, electric load, and the price of a dryer could be expressed in terms of dryer capacity using the results of analysis of dryer specifications (Table 1.1), equation 1-2, 1-3, and 1-6 can be expressed by:

$$C_1 = \frac{P_1}{E_1 \times HC} (a \times DC + b) \tag{1-8}$$

$$C_2 = \frac{0.7457 \times P_2}{E_2} (c \times DC + d) \tag{1-9}$$

$$C_5 = F (e \times DC + f) \tag{1-10}$$

When all these cost functions were substituted in equation 1-1, the total cost function was expressed by the following equation:

$$C_T = \Big[\frac{P_1}{E_1 \times HC} (a \times DC + b) + \frac{0.7457 \times P_2}{E_2} (c \times DC + d) + P_3 + \frac{TF \times P_4 \times TQ}{FS \times HR} \Big] \frac{TQ}{DC} + F (e \times DC + f) + (SK \times P_4 \times TQ) \tag{1-11}$$

1.5 Analysis of Thermal Efficiency

Thermal efficiency is defined as the ratio of the theoretical energy required to evaporate the water from the grain to the amount of energy supplied to the drying systems.

The amount of energy supplied usually includes energy to heat the air and the electric load. Thermal efficiency was determined as the following equation:

$$TE = \frac{DM \times DC \times HVP \times (GM1 - GM2)}{\frac{H}{E_1} + \frac{CONT \times HP}{E_2 \times E_3}} \qquad (1\text{-}12)$$

where TE = thermal efficiency (decimal)

DM = dry matter content (pounds per bushel)

corn: 47.32 (pounds per bushel)

sorghum: 48.16 (pounds per bushel)

DC = dryer capacity (bushels per hour)

HVP = heat of vaporization of water from grain (BTUs per pound)

GM1, GM2 = initial and final moisture content of grain (dry basis, decimal)

H = energy to heat the air (BTUs per hour)

E_1 = efficiency of fuel combustion (decimal)

CONT = constant of conversion factor (0.7457 x 3412.4)

HP = fan and metering horsepower (Hp)

E_2 = overall efficiency of fan and motor system (decimal)

E_3 = efficiency of heat exchange system (efficiency of generation, decimal)

The heat of vaporization of cereal grain is defined as the energy required to vaporize moisture from the product. Equilibrium moisture content curves furnish the data necessary to calculate it. It is dependent upon its moisture content and temperature. The lower the moisture content and the temperature, the higher the heat of vaporization.

In this study, the heat of vaporization for corn was estimated from the data of Johnson and Dale (1954) and Haynes (1961):

Drying Temperature (^{o}F)	Heat of Vaporization (BTU/lb.)*
180 - 220	1045.0
160 - 200	1060.0
120 - 140	1092.0
60 - 70	1133.0
50 - 60	1138.0

*Moisture content: 25 per cent to 15 per cent (wet basis)

The results of the analysis of thermal efficiency are shown in Figure 1.6. The thermal efficiencies of continuous flow dryers ranged from 31.3 to 36.3 per cent; portable batch dryer, 32.7 to 42.7 per cent; batch-in-bin dryer, 35.4 to 44.8 per cent; natural air dryer with supplemental heat, 52.6 per cent; and natural air dryer, 63.8 per cent.

In this analysis, thermal efficiencies of natural air drying systems were higher than those of heated air drying systems, and continuous flow drying systems have the lowest thermal efficiency. Since the heated air leaves the column (drying zone) before it is saturated, continuous flow drying systems have the lowest thermal efficiency.

1.6 Drying Systems Leading to Optimum Cost

In order to determine the optimum drying system for corn drying, the annual drying costs and optimum drying costs of five different drying systems were compared. Also estimated cost and performance relationships were analyzed, and volume ranges of optimum costs were suggested.

1.6.1 Comparison of Annual and Optimum Drying Costs

Annual drying costs were calculated by using equation 1-11. Figure 1.7

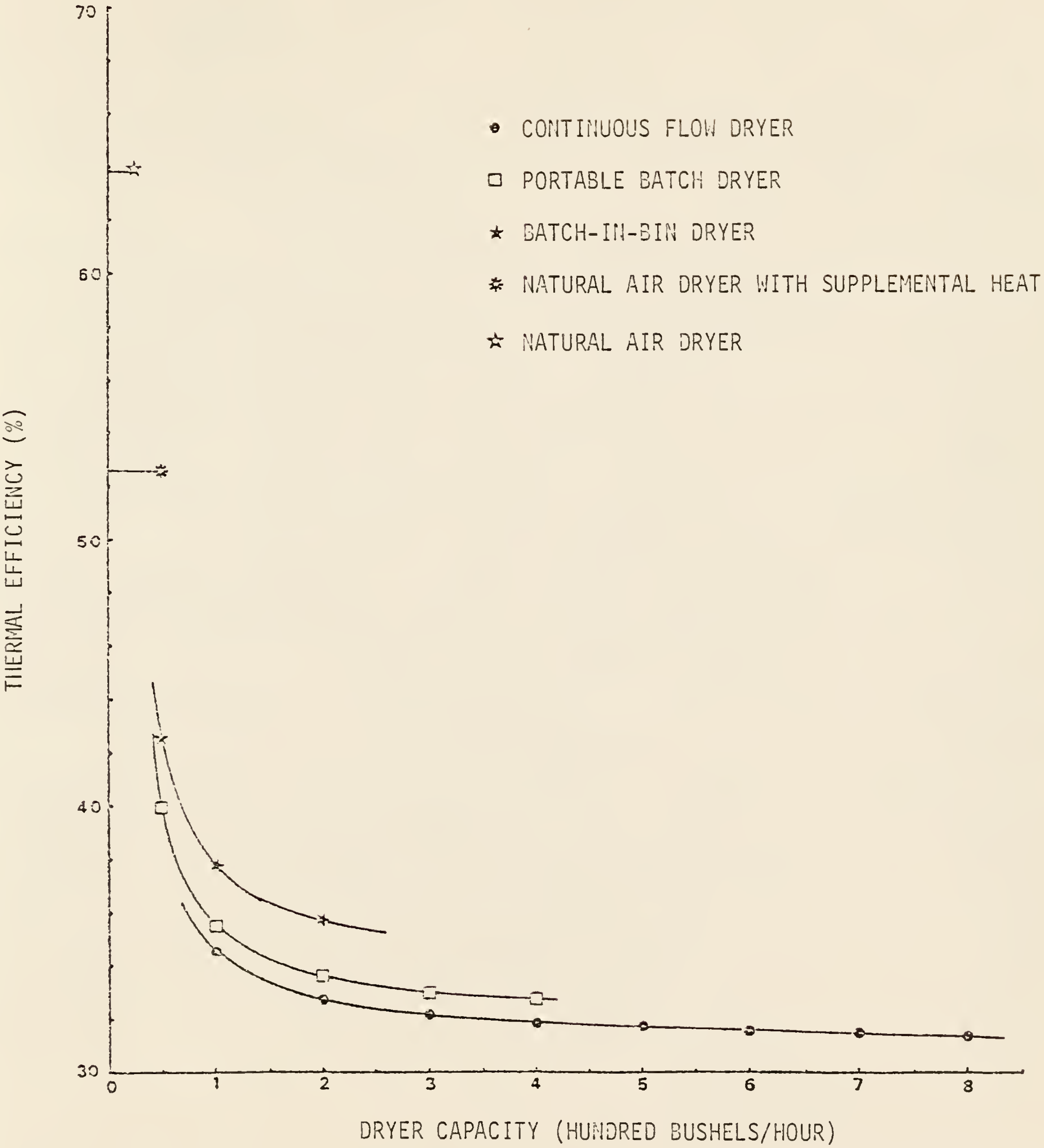


Figure 1.6. Comparison of Thermal Efficiencies

and Figure 1.8 show the annual drying costs of volumes to be dried from 2,000 bushels to 100,000 bushels. The dryer capacities for optimum costs increase, and annual drying costs of lower dryer capacities are higher than those of higher dryer capacity as the volume to dried increases in general. But each system has its own dryer capacity for optimum cost.

Therefore, it is desirable to determine the optimum dryer capacity for selecting the optimum drying system, instead of comparing annual drying costs.

When the objective function of a design problem can be written in terms of a single independent variable, the differential calculus may often be used to determine the optimum, then the derivative of the objective function [equation (1-11)] should be 0 at the optimum.

$$\frac{dC_T}{dDC} = 0 \qquad (1\text{-}13)$$

The optimum dryer capacity was:

$$DCOP = \sqrt{\frac{TQ}{e \times F}\left(\frac{b \times P_1}{E_1 \times HC} + \frac{0.7457d \times P_2}{E_2} + P_3 + \frac{TF \times P_4 \times TQ}{FS \times HR}\right)} \qquad (1\text{-}14)$$

DCOP = optimum dryer capacity (bushels per hour)

From equation 1-14, optimum dryer capacity can be determined, which is necessary to calculate the optimum drying cost.

Figure 1.9 shows optimum dryer costs of five different drying systems in terms of dollar per year and dollar per bushel. Optimum drying costs were described within dryer capacities for each drying system. The natural air drying system can dry the shelled corn economically for volumes from 1,000 bushels to 2,700 bushels and natural air drying systems with supplemental heat is the most economical system for volumes from 2,700 bushels to 20,000 bushels. The hot-air drying systems, which permit the greatest flexibility at harvest time, are the most optimum systems above 20,000 bushels. The batch-in-bin dryer is the most economical hot-air drying system for

ANNUAL DRYING COST (THOUSAND DOLLARS/YEAR)

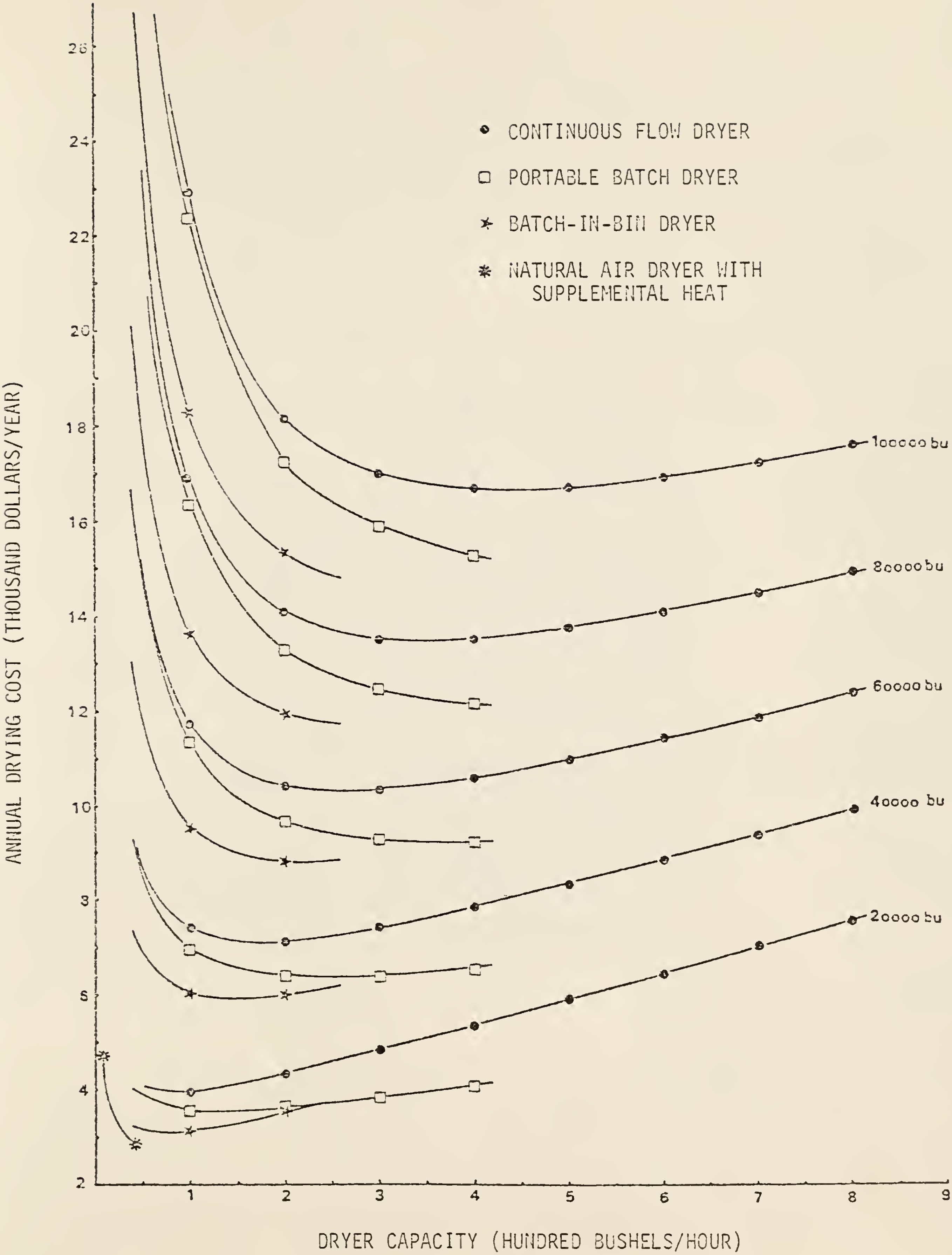


Figure 1.7. Comparison of Annual Drying Cost

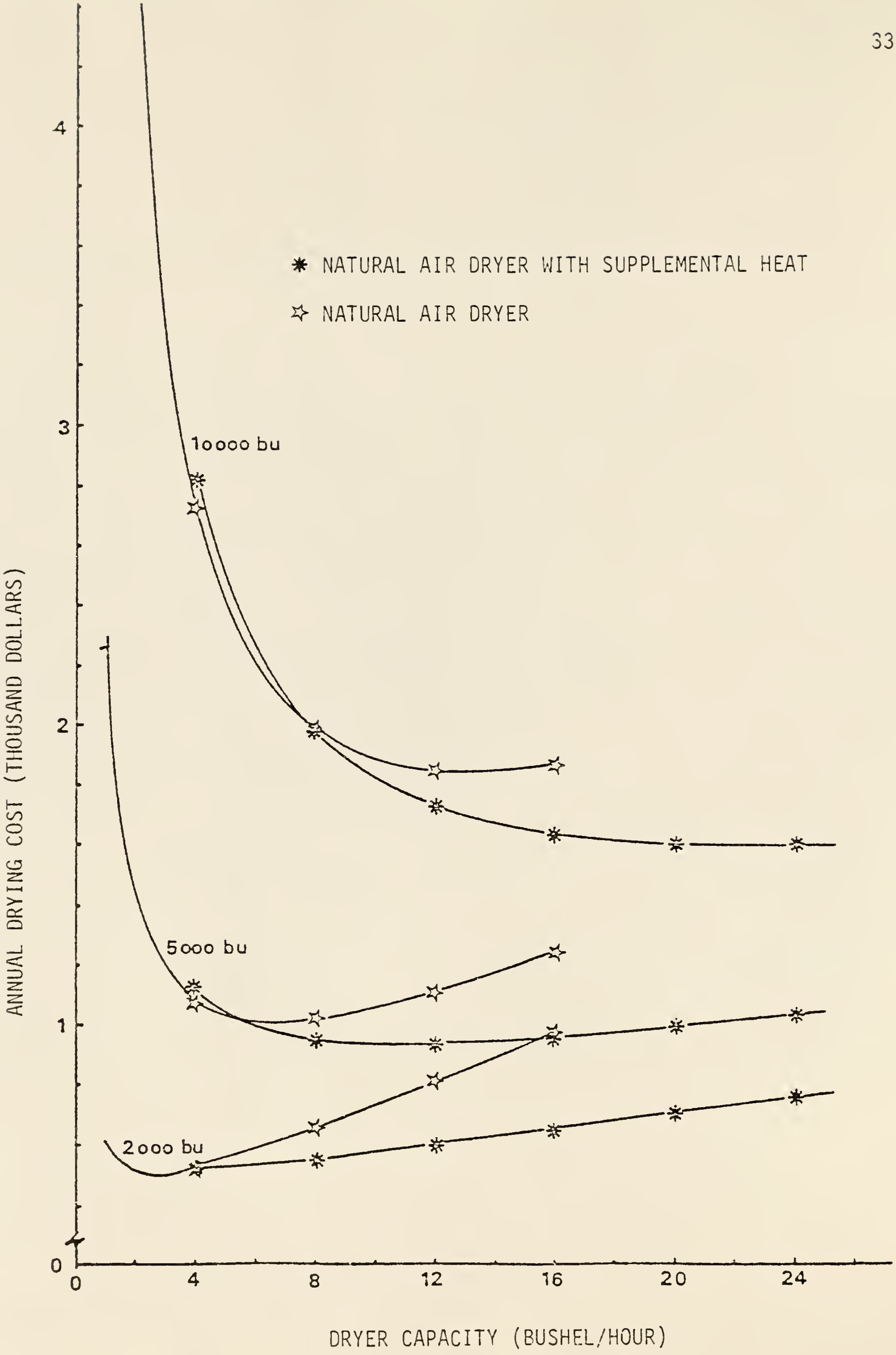


Figure 1.8. Comparison of Annual Drying Cost

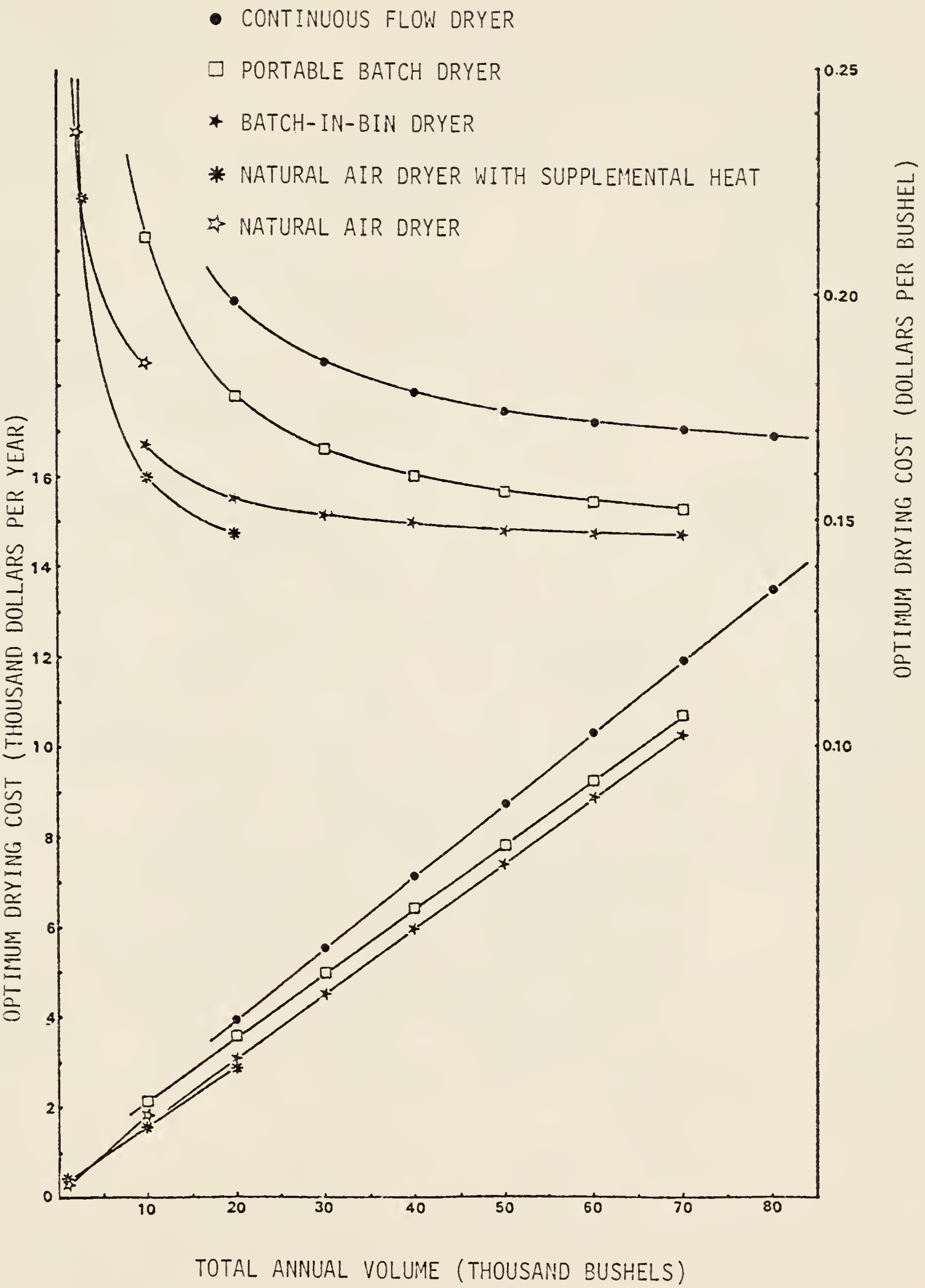


Figure 1.9. Comparison of Optimum Drying Cost

volumes from 20,000 bushels to 70,000 bushels. The portable batch and continuous flow drying systems are not competitive with the batch-in-bin drying system in the optimum drying cost per bushel at volumes below 70,000 bushels per year; at 70,000 bushels or above, they can be compared favorably with other drying and storage systems.

In comparison of optimum drying cost per bushel, the estimated costs range 16.3 to 20.6 cents per bushel for the continuous flow drying system; 15.3 to 32.1 cents per bushel for the portable batch drying system; 14.7 to 16.3 cents per bushel for batch-in-bin drying system; 14.8 to 39.5 cents per bushel for natural air drying system with supplemental heat; 18.1 to 33.9 cents per bushel for natural air drying system.

The relationships between the optimum drying costs and the thermal efficiencies of different drying systems are that the higher the thermal efficiency, the lower the optimum drying cost in general.

1.6.2 Estimated Cost and Performance Relationships

Table 1.2 shows the estimated cost and performance relationships of grain dryers for shelled corn in reducing the moisture content from 25 per cent to 15 per cent, wet basis.

This table was based on the following assumptions:

1. Optimum number of days for harvesting was considered to be approximately 20.

2. Design parameter for drying capacity of natural air dryer with supplemental heat was 1,000 bushels per 14 days, and drying could be done twice.

3. Drying and storage days for natural air dryers was 40.

In this table, all drying systems were classified by their holding capacities into small, medium, and large sizes. Labor costs, timeliness

Table 1.2. Estimated Cost and Performance Relationship of Grain Dryer, Shelled Corn 25%-15% (w.b.)

Drying System / Contents	Continuous Flow Dryer			Portable Batch Dryer			Batch-In-Bin Dryer			Natural Air Dryer with Supplemental Heat			Natural Air Dryer		
	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large
Holding Capacity(bu)	100-400	450-800	1000-1600	100-200	300-500	700-1000	500-600	700-1000	1200-1500	1200-4000	5000-8000	10000 — 20000	1200-4000	5000-8000	10000 — 15000
Estimated Drying Capacity(bu/hr)	70-300	200-500	400-1200	40-90	100-130	150-420	40-110	90-180	110-250	3.6-11.9	14.9-23.8	29.8-44.6	1.3-4.5	5.6-8.9	11.1-16.7
Heat (BTU/hr)	1.0-6.0 mil.	4.0-10.2 mil.	8.0-25.0 mil.	0.5-1.5 mil.	1.7-2.4 mil.	2.8-8.4 mil.	0.5-1.7 mil.	1.3-3.0 mil.	1.7-4.1 mil.	18420 — 61400	76770 — 122840	153540 — 230300	—	—	—
Fan & Metering(Hp)	13-38	27-60	48-135	10-15	16-19	21-50	8-15	13-21	15-28	2.2-7.2	9.0-14.4	18.0-27.0	1.0-3.5	4.5-7.0	8.5-13.0
Approx. Air Flow(cfm/bu)	75-100	70-90	20-45	100-120	80-100	50-70	10-20	10-20	15-30	2.0	2.0	2.0	1.88	1.88	1.88
Approx. Drying Temp.(°F)	180-220	180-220	180-220	160-200	160-200	160-200	120-140	120-140	120-140	65	65	65	57	57	57
Estimated Investment($)	8000 — 17000	13000 — 24000	21000 — 50765	5700-6600	6800-7200	7700 — 12600	3690-6500	5600-9300	6500 — 12000	2600-3600	3960-5030	5740-7530	1900-3000	3400-4500	5400-7500
Drying Capacity vs Investment (bu/$1000)	15	20	20	10	15	25	15	20	20	2.5	4.3	5.6	1.2	1.8	2.2
Thermal Efficiency(%)	32.1-36.3	31.7-32.7	31.3-31.8	36.0-42.7	34.6-35.5	32.7-14.2	37.4-44.8	36.0-38.2	35.4-37.4	52.6	52.6	52.6	63.8	63.8	63.8
Estimated Annual Fixed Cost(Newcost %)	15 %	15 %	15 %	15 %	15 %	15 %	13 %	13 %	13 %	12 %	12 %	12 %	12 %	12 %	12 %
Annual Fixed Cost($/unit)	1200-2550	1950-3600	3150-7615	855-990	1020-1080	1155-1890	480-845	728-1209	845-1560	312-432	689-904	475-604	228-360	408-540	648-876
Estimated Operating Cost($/hr)	5.99 — 29.37	19.96 — 49.06	38.71 — 117.46	3.62 — 8.30	9.23 — 12.48	14.35 — 39.74	2.67 — 9.17	7.30 — 15.22	9.17 — 19.61	0.21-0.70	0.87-1.40	1.75-2.62	0.06-0.21	0.27-0.42	0.51-0.78
Estimated Fixed Cost(¢/bu) 5,000 bu	24.0-51.0	39.0-72.0	63.0-152.	17.1-19.8	20.4-21.6	23.1-37.8	9.6-16.9	14.6-24.2	16.9-31.2	6.2-8.6	9.5-12.1	13.8-18.1	4.6-7.2	8.2-10.8	13.0-17.5
10,000 bu	12.0-25.5	19.5-36.0	31.5-76.2	85.5-99.0	10.2-10.8	11.6-18.9	4.8-8.5	7.3-12.1	8.5-15.6	6.2-8.6 (2units)	4.6-6.0	6.9-9.0	4.6-7.2 (3units)	8.2-10.8 (2units)	6.5-8.8
15,000 bu	8.0-17.0	13.0-24.0	21.0-50.8	5.7-6.6	6.8-7.2	7.7-12.6	3.2-5.6	4.9-8.1	5.6-10.4	6.2-8.6 (3units)	4.8-6.0 (2units)	4.6-6.0	4.6-7.2 (4units)	8.2-10.8 (3units)	6.5-8.8 (2units)
25,000 bu	4.8-10.2	7.8-14.4	12.6-30.5	3.4-4.0	4.1-4.3	4.6-7.6	1.9-3.4	2.9-4.8	3.4-6.2	6.2-8.6 (5units)	4.8-6.0 (2units)	2.8-3.6	4.6-7.2 (6units)	8.2-10.8 (4units)	6.5-8.8 (2units)
50,000 bu	2.4-5.1	3.9-7.2	6.3-15.2	3.4-4.0 (2units)	2.0-2.2	2.3-3.8	1.9-3.4 (2units)	1.5-2.4	1.7-3.1	6.2-8.6 (10units)	4.8-6.0 (4units)	2.8-3.6 (2units)	4.6-7.2 (12units)	8.2-10.8 (8units)	6.5-8.8 (4units)
100,000 bu	2.4-5.1 (2units)	2.0-3.6	3.2-7.6	3.4-4.0 (4units)	2.0-2.2 (2units)	1.2-1.9	1.9-3.4 (3units)	1.5-2.4 (2units)	1.7-3.1 (2units)	—	—	—	—	—	—
150,000 bu	2.4-5.1 (2units)	1.3-2.4	2.1-5.1	3.4-4.0 (5units)	2.0-2.2 (3units)	1.2-1.9 (2units)	1.9-3.4 (4units)	1.5-2.4 (3units)	1.7-3.1 (2units)	—	—	—	—	—	—
200,000 bu	2.4-5.1 (3units)	1.3-2.4 (2units)	1.6-3.8	3.4-4.0 (7units)	2.0-2.2 (4units)	1.2-1.9 (2units)	1.9-3.4 (5units)	1.5-2.4 (4units)	1.7-3.1 (3units)	—	—	—	—	—	—
250,000 bu	2.4-5.1 (3units)	1.3-2.4 (2units)	1.3-3.0	3.4-4.0 (9units)	2.0-2.2 (5units)	1.2-1.9 (3units)	1.9-3.4 (7units)	1.5-2.4 (5units)	1.7-3.1 (4units)	—	—	—	—	—	—
300,000 bu	2.4-5.1 (4units)	1.3-2.4 (2units)	1.3-3.0 (2units)	3.4-4.0 (10units)	2.0-2.2 (6units)	1.2-1.9 (3units)	1.9-3.4 (8units)	1.5-2.4 (5units)	1.7-3.1 (4units)	—	—	—	—	—	—
350,000 bu	2.4-5.1 (4units)	1.3-2.4 (3units)	1.3-3.0 (2units)	3.4-4.0 (12units)	2.0-2.2 (7units)	1.2-1.9 (3units)	1.9-3.4 (9units)	1.5-2.4 (6units)	1.7-3.1 (5units)	—	—	—	—	—	—

cost and shrinkage loss were not included in operating costs and fixed costs. Estimated fixed costs were compared according to the volumes to be dried in order to give some idea about alternative drying systems. Drying capacity per investment is approximately 20 bushels per $1,000 in heated-air drying systems.

1.6.3 Suggested Volume Ranges

Solving for an optimum dryer capacity in equation 1-14 will produce a very precise mathematical answer. The practicability of this precision will depend on the degree of sharpness of the annual cost curve at its optimum point. The range in allowable dryer capacity of optimum cost for a preselected difference in annual costs was given by equation 1-15 and illustrated in Figure 1.10.

$$DC_{1,\,2} = DCOP + \frac{DAC}{2\ e \times F} \pm \sqrt{4\ e \times F \times DAC\left(DCOP + \frac{DAC}{4\ e \times F}\right)} \qquad (1\text{-}15)$$

where $DC_{1,\,2}$ = allowable ranges of optimum dryer capacity (bushels per hour)
DAC = preselected difference in annual cost (dollars per year)
DCOP = optimum dryer capacity (bushels per hour)
e, F = constants

In Figure 1.10, if the annual drying costs were allowed to vary as much as $200 above the optimum cost point which was $5,000 and 340 bushels per hour (DAC = $200), the resulting ranges in optimum drying capacity might be 230 and 460 bushels per hour instead of being 340 bushels per hour.

The volume ranges of grain were presented graphically in Figure 1.11 in relation to the drying methods. The volume limits of a given method were not, by any means, absolutely fixed but were rather the suggested ranges for the drying method. The range indicated was based on the analysis of optimum drying cost and management considerations.

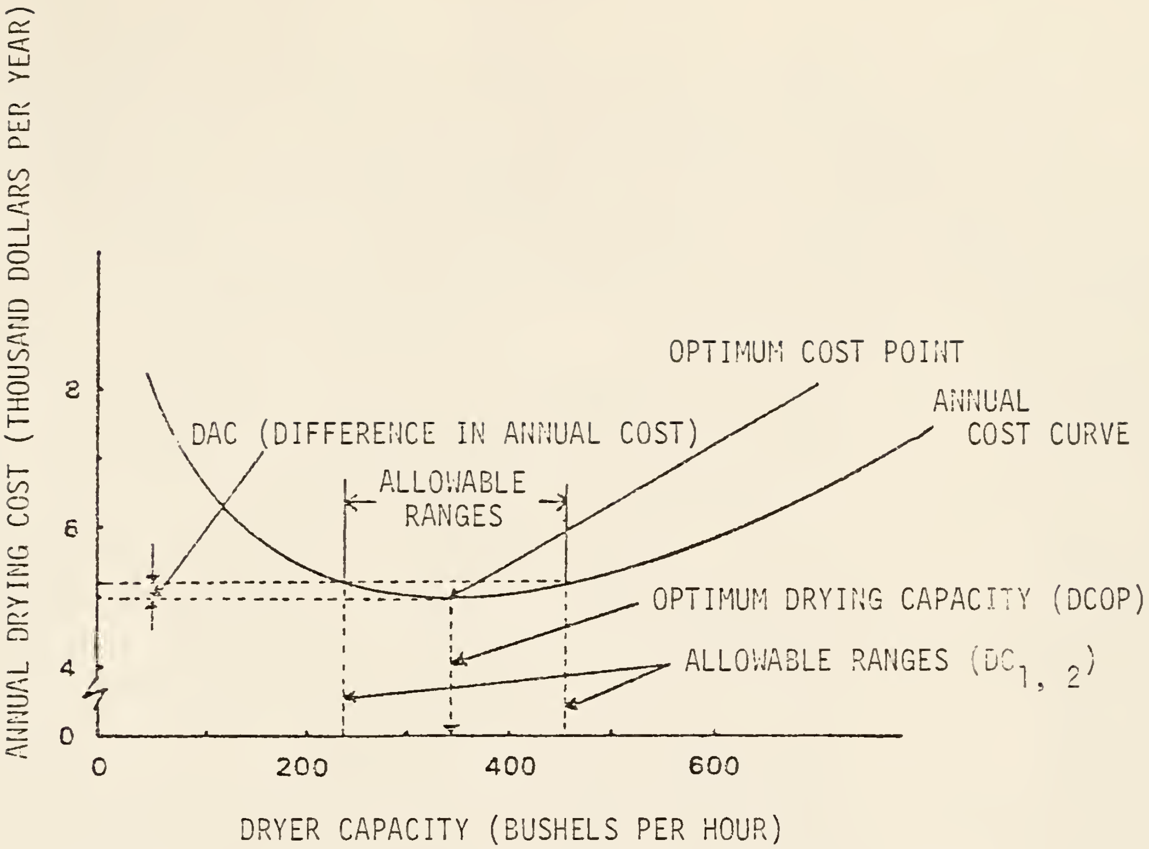


Figure 1.10. Optimum Dryer Capacity and Allowable Ranges

1.7 Other Considerations Affecting the Selection of Drying and Storage Systems

Besides the cost relationships, there may be operational and managerial requirements that should be considered in selecting a dryer. Some advantages and disadvantages are listed below for each system.

1.7.1 Continuous Flow Drying System

Advantages:

1. This system is usually operated automatically.
2. It is the most acceptable device for large capacities and long seasonal use.
3. Generally, grain is dried uniformly.

Disadvantages:

1. Operates automatically, this system requires careful management.

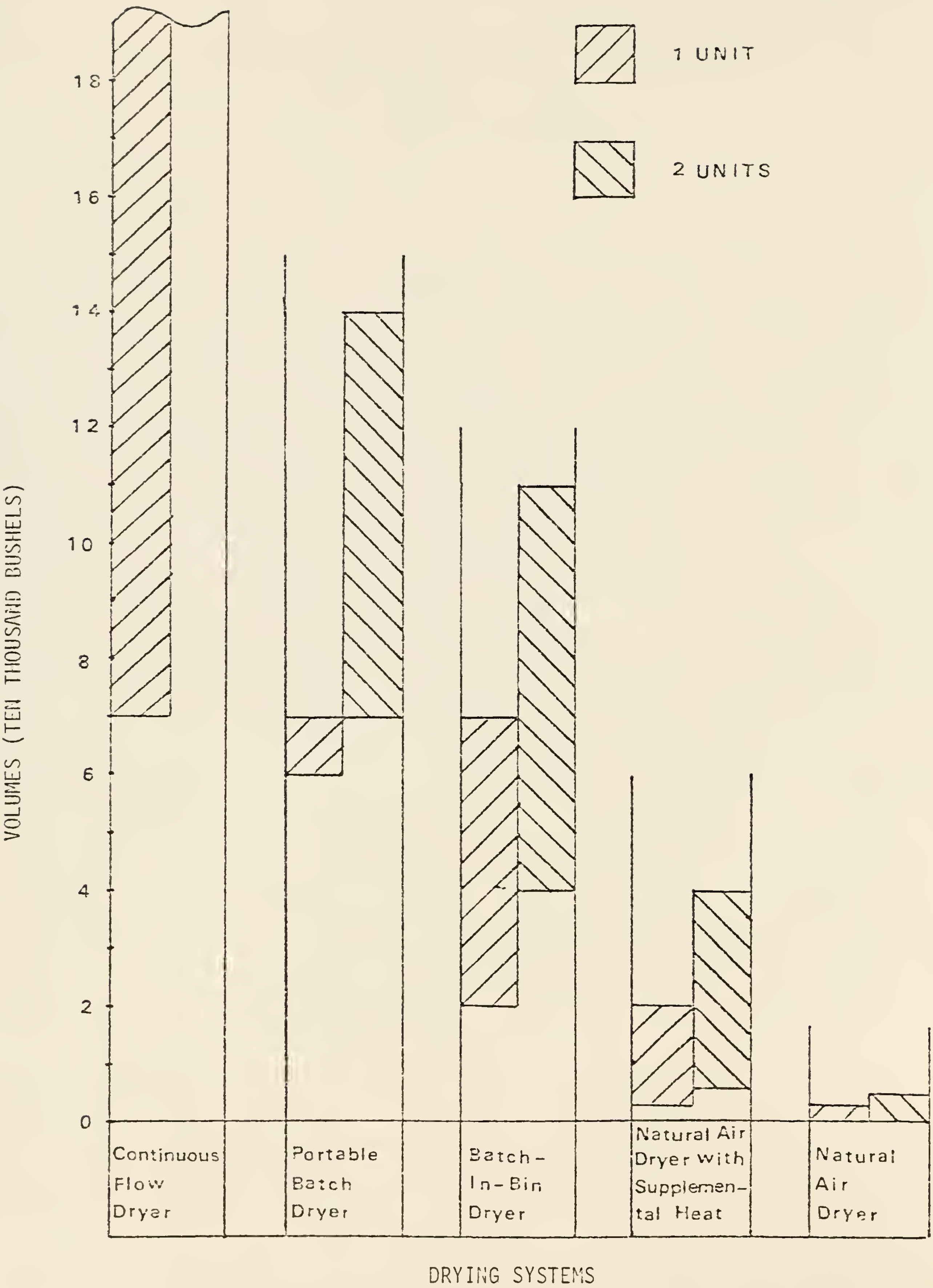


Figure 1.11. Suggested Volume Ranges for Drying Systems

2. The high air temperature required demands that careful attention be given to the safety devices.

1.7.2 Portable Batch Drying System

Advantages:

1. Units can be obtained to process a wide range of batch sizes.

2. Units can be moved from one location to another when they are not filled with grain.

3. The dryers can be driven and operated by a tractor, independent of all other electrical sources.

4. The dryers can be automated.

Disadvantages:

1. Some portion of the grain is over-dried; high- and low-moisture grain are blended to obtain an acceptable average moisture content.

2. Units that dry and cool with the same fan require considerable time per batch for cooling, unloading, and loading.

3. The heat available in the drying air is not used as efficiently as it is in deep-bed drying.

1.7.3 Batch-In-Bin Drying System

Advantages:

1. A wide range of dryer selection exists.

2. The depth of drying can be varied from day to day to give flexibility to the harvesting schedule.

3. The batch-drying bin can be filled at the end of the harvest season by using the layer-drying technique.

Disadvantages:

1. There is a large moisture gradient from the bottom to the top of the batch.

2. The grain must be handled at least twice. The second handling, that of unloading the bin, can cause considerable damage to the portion of grain that is over-dried.

3. Time is spent in cooling and unloading the dried grain.

1.7.4 Natural Air Drying System

Advantages:

1. The grain can be harvested at any rate desired.

2. The management is relatively simple.

3. Grain handling is held to a minimum.

4. The heat in the drying air that is available for drying is efficiently used.

5. Grain is not over-dried.

6. The low-temperature air cuases high quality grain with not stress cracks from heating and cooling.

7. Reliance on restricted supplies of L.P. gas or natural gas is eliminated.

Disadvantages:

1. Harvesting cannot take place when the grain is high in moisture content.

2. The drying process is continued over an extended period of time, prolonging the management period.

3. Each bin must have a drying unit since the drying period may extend for a month or more.

4. Drying process is influenced much by weather conditions.

1.8 Future Grain Drying Systems

Increasing costs of energy, decreasing supplies of fossil fuels and an increasing trend of field shelling (corn production) may require major changes in present practices of harvesting, conditioning, and storing corn. Therefore, field drying, even at the cost of high field losses, can be economical if fuel costs become too great. Figures 1.12 and 1.13 show the increasing trends of energy costs and on-farm corn drying. The use of alternative energy sources is also receiving increasing attention. Substitution of electricity for natural gas or L.P. gas does not reduce total energy consumption but may have short-term advantages where electricity is generated from energy sources in greater abundance than gas. The use of solar energy for drying has been deomonstrated to be technically feasible. Investment costs appear to be too high for rapid adoption at the present time, but some units are currently being operated on farms. As energy costs rise and collector designs are refined to reduce costs per unit of heat collected, the cost of solar energy relative to other fuels will improve (Foster and Peart, 1976).

1.9 Summary and Conclusion

Mathematical modeling for dryer selection was discussed and thermal efficiencies of drying systems were analysed. In the process of formulating a model, more than 100 dryer specifications, which had been obtained from 22 manufacturers and dealers in the U.S.A., were used and were examined. Not one of these drying methods is superior to all others when considering the entire range of circumstances that exist in on-farm grain drying. The choice depends upon the annual volume, the marketing pattern, the type of farm, the cost, and the kind and capacity of existing facilities.

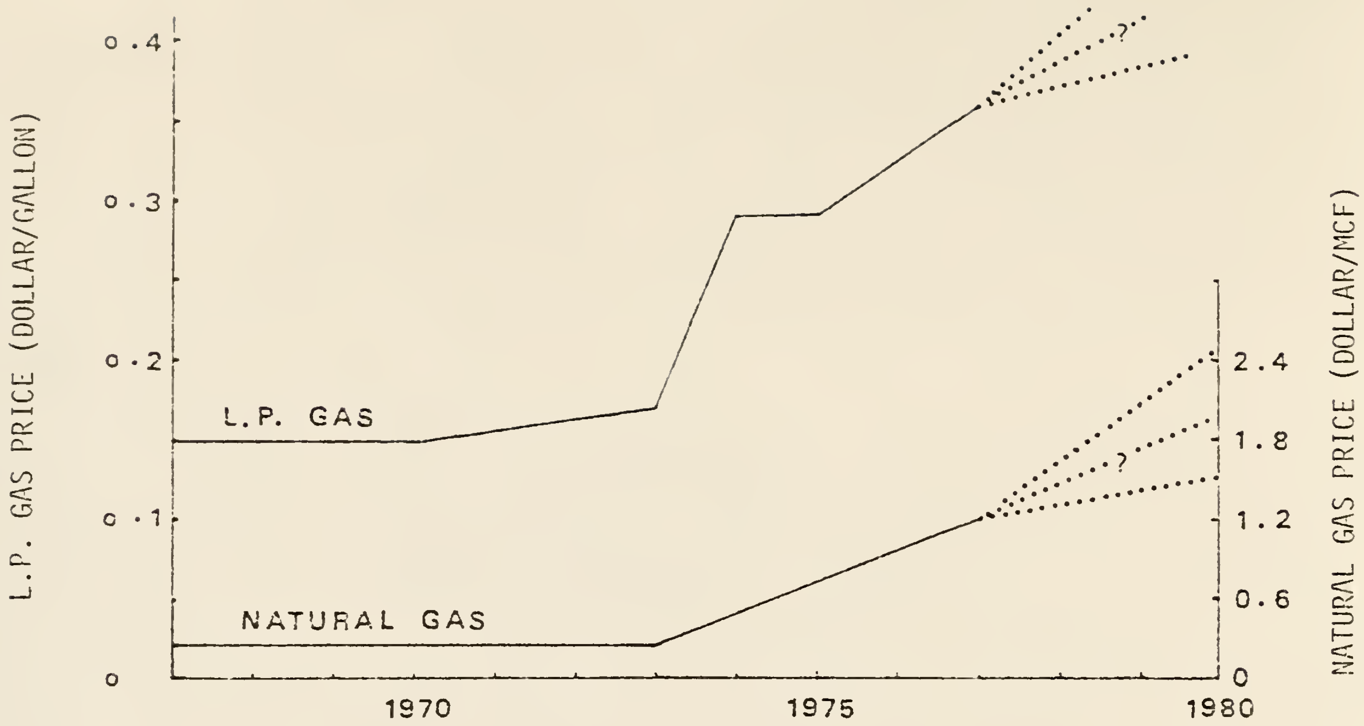


Figure 1.12. Fuel Prices for Grain Drying

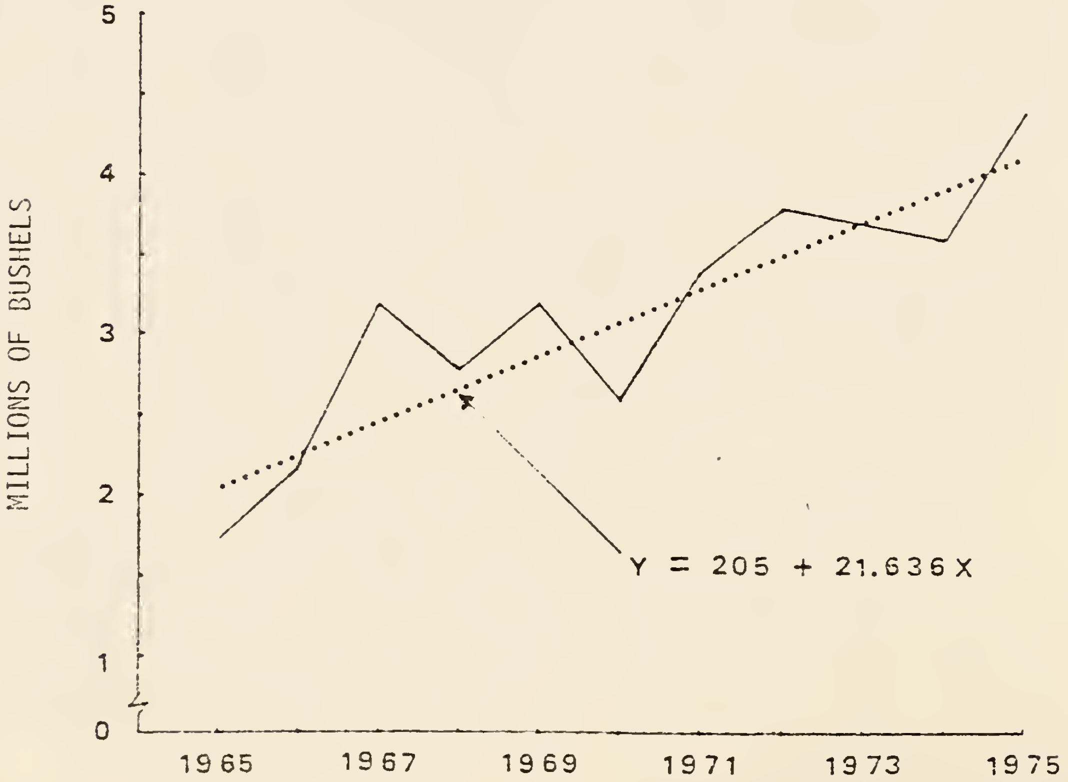


Figure 1.13. Trends in On-Farm Corn Drying in Illinois, 1965-1975 (Schwart and Hill, 1977)

The following general conclusions may be drawn from the study:

1. The thermal efficiency of natural air drying systems is better than any other system, and that of the continuous flow drying system is the lowest of the drying systems.

2. The thermal efficiencies of drying systems have a close relationship with the annual drying costs which are usually low when the thermal efficiencies are high.

3. Natural air dryers are economical drying systems at volumes below 2,700 bushels; natural air dryers with supplemental heat are economical at volumes from 2,700 to 20,000 bushels; and batch-in-bin dryers, from 20,000 to 70,000 bushels. Portable batch and continuous flow dryers, which are very similar in their characteristics, become economically competitive only at volumes of 70,000 bushels or more per year.

4. Future grain drying systems may include field drying or a system which uses alternative energy sources such as natural air or solor energy.

1.10 Suggestions for Further Research

In order to develop a more accurate model, a field survey of grain drying methods is desirable. The mathematical model should be developed into the model associated with harvesting, drying, handling, and storing systems not only for shelled corn but also for other cereal grains.

Simulation leading to optimum cost for combination drying systems may be a good study for economical drying and fuel conservation.

1.11 References

1. ASAE. 1975. Energy efficiencies of various drying techniques. Agr. Eng. May, 1975.

2. ASAE. 1977. Agricultural Engineerers Yearbook. ASAE. St. Joseph, Michigan.

3. Bloome, P. D. and Shove, G. C. 1972. Simulation of low temperature drying of shelled corn leading to optimization. ASAE Transaction 15(1): 310-316.

4. Brooker, D. B., Bakker-Arkema, F. W., Hall, C. W. 1974. Drying cereal grains. AVI Publishing Co., Westport, Conn.

5. Carpenter, M. L. and Brooker, D. B. 1972. Minimum cost machinery systems for harvesting, drying and storing shelled corn. ASAE Transaction 15(2): 515-519.

6. Christensen, C. M. 1974. Storage of cereal grains and their products. American Association of Cereal Chemists.

7. Chung, D. S. and Pfost, H. B. 1967. Asorption and desorption of water vapor by cereal grains and their products, Part I: Heat and free energy changes of adsorption and desorption. ASAE Transaction 10(4): 549-551, 555.

8. Fan, L. T., Erickson, L. E., Hwang, C. L. 1971. Unconstrained optimization and the differential calculus. Institute for System Design and Optimization, Kansas State University.

9. Foster, G. H. and Peart, R. M. 1976. Solar grain drying progresses and potential. Agricultural Information Bulletin No. 401. ARS, USDA.

10. Henderson, S. M. and Perry, R. L. 1976. Agricultural process engineering. Third Edition. AVI Publishing Co., Inc., Westport, Conn.

11. Hunt, D. 1977. Farm power and machinery management. Seventh edition. Iowa State University Press.

12. Johnson, H. K. and Dale, A. C. 1954. Heat required to vaporize moisture. Agr. Eng. 35(10): 705-709, 714.

13. Kansas State Board of Agriculture. 1976. 60th annual report with farm facts.

14. McKenzie, B. A. 1966. Selecting a grain drying method. AE-67, Cooperative Extension Service, Purdue University.

15. Morey, R. V. and Peart, R. M. 1971. Optimimum horsepower and depth for a natural air corn drying system. ASAE Transaction 14(5): 930-934.

16. Morey, R. V. and Cloud, H. A. 1973. Simulation and evaluation of a multiple column crossflow grain dryer. ASAE Transaction 16(5): 984-987.

17. Morey, R. V., Cloud, H. A., Lueschen, W. E. 1976. Practices for the efficient utilization of energy for drying corn. ASAE Transaction 19(1): 151-155.

18. Morey, R. V., Gustafson, R. J., Cloud, H. A. 1976. Energy requirements for high-low temperature drying. ASAE Paper No. 76-3522, ASAE. St. Joseph, Michigan.

19. Peart, R. M. and Lien, R. M. 1975. Grain dryer energy requirement. ASAE Paper No. 75-3019, ASAE. St. Joseph, Michigan.

20. Pfost, H. B., Maurer, S. G., Chung, D. S., Milliken, G. A. 1976. Summarizing and reporting equilibrium moisture data for grains. ASAE Paper No. 76-3520, ASAE. St. Joseph, Michigan.

21. Pfost, H. B., Maurer, S. G., Grosh, L. E., Chung, D. S., Foster, G. H. 1977. Fan management systems for natural air dryers. ASAE Paper No. 77-35267. ASAE, St. Joseph, Michigan.

22. Pierce, R. O. and Thompson, T. L. 1975. Energy utilization and efficiency of crossflow grain dryers. ASAE Paper No. 75-3020. ASAE, St. Joseph, Michigan.

23. Schwart, R. B. and Hill, L. D. 1977. Comparative costs of conditioning and storing corn. Circular 1141, Cooperative Extension Service, University of Illinois.

24. Sinha, R. N. and Muir, W. E. 1973. Grain storage part of a system. AVI Publishing Co., Inc., Westport, Conn.

25. Young, J. H. and Dickens, J. W. 1975. Evaluation of costs for drying grains in batch or cross-flow systems. ASAE Transaction 18(4): 734-739.

Chapter 2

SIMULATION OF NATURAL AIR DRYING OF ROUGH RICE

2.1 Introduction

In the past, the drying characteristics of other grains such as corn have been extensively investigated. However, relatively little research has been performed on drying of rough rice.

Rice production in the United States is a highly mechanized operation. This includes harvesting by combines at a time when the kernels are mature, but still at a high moisture content. Drying is necessary before the rice is suitable for storage in bulk bins. Most of the rice is custom-dried at commercial dryers by exposure to heated air; however, some of the rice crop is dried on the farm in bins designed for grain drying (Calderwood and Webb, 1971).

Rough rice must be dried to approximately 13.5 per cent (wet basis) which is an acceptable market delivery moisture content (Henderson, 1955). The problems encountered in drying rough rice are similar to those in drying other cereal crops, but rice requires a more careful drying treatment than what is needed for most other grain crops. This is because a premium is placed on merchandising milled rice as whole kernels. Improper drying causes internal stresses in kernels of rough rice that result in breakage when the rice is milled (Calderwood, 1966).

Heated air is not recommended for drying deep depths of rice, since it results in overdrying the bottom part and may cause spoilage in the upper layers of the rice (Sorenson and Crane, 1960).

Now, we are experiencing renewed interest in unheated air drying of cereal grains. Two factors seem to be contributing to this interest:

1. The expense and complexity of high capacity heated air drying systems.
2. The farmers' desire for drying systems capable of accepting wet grain as rapidly as it can be harvested.

The effectiveness of unheated air drying is, of course, dependent upon the weather. It is the uncertainty of the weather that prompts us to set the limits of operation for these systems.

A list of factors affecting the operation of unheated air drying systems must include: airflow rate, rice moisture content,grain depth, and harvest date. The evaluation of these factors as well as the effect of year-to-year weather variations would require the operation of a large number of field or laboratory systems for several years. Such an approach seems prohibitive in time and funds required. Therefore, a computer simulation was suggested for a feasibility study over several years of weather data, harvest moisture contents and dryer designs. This simulation would give benefits by the control of input variables, and allow testing of many proposed designs and management methods.

During the past years, there have been several actual experiments of natural air drying of rough rice in rice growing areas, but this interest has now been expended by the possibility of drying rice in storage in the Gulf Coast area. The humid weather conditions existing in that area and the differences in the harvesting dates and the handling practices make it necessary to develop the design parameters for natural air rough rice drying in order to have a good quality and minimum costs.

2.2 Review of Literature

2.2.1 Rough Rice Drying by Natural Air

There were several experiments for rough rice drying with unheated air, which gave reasonable test data and recommendations for natural air drying systems in the rice growing area.

Morrison (1954) made tests to determine the practicability of drying rice in storage bins at Beaumont, Texas. His test results indicate that rough rice can be dried using unheated air under weather conditions in the Texas rice belt. The following recommendations were made on the basis of the tests conducted at Beaumont:

1. Fill bins to a maximum depth of 10 feet if the rice contains less than 18 per cent moisture and 8 feet if the moisture content is above 18 per cent.

2. Select ventilation equipment which will provide an air-flow rate of 9.0 cfm per barrel.

3. Start the blower as soon as possible after the air ducts are uniformly covered with rice.

4. Push air through the rice continuously, except when a period of extremely high humidity lasts longer than 24 hours. During such periods, operate the blower two to three hours each day to prevent heating until the weather clears. Continue with this procedure until the moisture content of the top foot of the rice is reduced to about 16 per cent. Then push air only when the outside relative humidity is 75 per cent or less.

Henderson (1955) conducted studies to find the optimum air rate for deep bed unheated air rice dryers for California installations to determine the effect of various performance features upon final rice quality and to apply the findings to other rice producing areas. He made conclusions that deep bed, unheated air rice dryers would produce good quality rice in California if the proper airflow rate through the mass was applied.

Sorensor and Crane (1960) made tests at Beaumont, Texas, during seven crop years (1952-53 through 1958-59) to determine the practicability of drying rough rice in storage in Texas. Their results, with small-scale and full-scale bins, emphasized the importance of the time-temperature-initial moisture relationship in reducing the moisture content of rice below 16 per cent. In unheated air and supplemental heat drying applications under Texas conditions, the moisture in the wettest layer of rice at temperatures of 70 to 75 ^{o}F must be reduced below 16 per cent in 15 days or less to prevent grade loss from discolored kernels. Further reduction in moisture to a safe storage level of 12.5 per cent was accomplished over a period of several weeks in the Beaumont area without grade loss. Tests conducted for the past seven years indicate a minimum airflow rate of 9.0 cfm per barrel (2.5 cfm per bushel) for 20 per cent moisture content and 8 feet bed depth to insure drying without loss in grade and milling yields under the different weather and moisture conditions occuring within a season or from year to year.

2.2.2 Simulation Model of Natural Air Drying

Maurer (1977) tested three basic natural air drying models against six actual drying tests; the three models were equilibrium, moisture ratio, and mass diffusion models. He developed a statistical method for validation of model accuracy and made reasonable modifications to the model. He concluded that the mass diffusion model was the most accurate and efficient of the models tested and developed natural-air grain drying simulation model. His simulation model is applicable to nine different grains, but there are some problems in modifying and applying. The mass diffusion model was then used to evaluate the performance of ten different fan management systems (Pfost et al., 1977). Following conclusions were made from the study:

1. Equilibrium model of natural air drying systems perform best with long time increments, i.e. 24 hours.

2. Computer models need to be tested against actual drying tests to ascertain their accuracy and usefulness.

3. Improved equations to determine moisture transfer rates from grain to air are needed.

4. When conducting drying studies, data need to be taken frequently during the first part of the test to test computer models.

5. Accurate computer models can aid in evaluating fan management systems.

6. Well tested computer models can be used to evaluate the likelihood of success of natural air drying systems under a wide variety of weather conditions, i.e. locations, years, and seasons.

Thompson et al. (1968) developed a mathematical procedure whereby grain drying predictions could be made with many sets of drying conditions and with nonconventional as well as conventional grain drying methods.

Bloome (1971) developed near equilibrium simulation of shelled corn drying, and Bloome and Shove (1972) determined the effects of independent variables of low temperature drying of shelled corn and a least cost optimization of low temperature drying.

Flood et al. (1972) evaluated a natural air corn drying system by simulation. And the following basic requirements for a natural air drying simulation were suggested:

1. Data for a thin-layer equation for drying under typical fall conditions in the Midwest.

2. Data for a thin-layer equation for rewetting under typical fall conditions in the Midwest.

3. Hourly weather data for the years and geographical location of interest.

4. means of evaluating the success or failure of a given simulation.

Thompson (1972) described and demonstrated the effect of factors, which are date of harvest, initial moisture content, grain temperature and weather conditions, on the temporary storage of high moisture shelled corn with weather data of Lincoln, Nebraska. In this study, he simplified Bloome's model to use at near equilibrium drying situations, or more specifically low-temperature, low-airflow conditions.

Paulsen and Thompson (1973) investigated the drying characteristics or grain sorghum at various drying air temperatures and developed a drying simulation model to predict drying results in a deep bed.

2.2.3 Fan Model

Morey and Peart (1971) determined the best combinations of fan horsepower and grain depth for a natural or unheated-air drying system. One level of corn moisture, 25 per cent, was considered and input air conditions were considered constant. From these conditions, the time for 0.5 per cent dry matter loss was calculated from Steele's equations. Any combination of horsepower and grain depth requiring a greater time for drying was discarded. The combination of fan horsepower and grain depth which had the lowest total cost while not exceeding the time limit was determined as the best combination. In their study, the following fan models were presented for single fill:

The static pressure drop (P) through a bed of grain x-feet deep as described by data from Shedd (1953) is:

$$P = x \left[\frac{Q}{cA} \right]^{d}$$

where Q = airflow rate (cfm)

A = area (square feet)

c, d = constants

The horsepower (HP) required to provide an airflow (Q, cfm) against a static pressure (P) for a fan operating at an efficiency (E) is given by:

$$HP = \frac{0.0001575PQ}{E}$$

2.2.4 Physical and Thermal Properties of Rough Rice

Wratten et al. (1969) determined the physical characteristics such as length, width, thickness, volume, specific gravity, density, porosity, and surface area of medium grain (Saturn) and long grain (Bluebonnet) rough rice as a function of moisture content, and determined the thermal characteristics such as specific heat, bulk thermal conductivity, and bulk thermal diffusivity of rough rice as a function of moisture content. Bulk density was determined by the following:

$$P_M = 31.195 + 0.52M \qquad r^2 = 0.99$$

$$P_L = 32.425 + 0.33M \qquad r^2 = 0.94$$

where P_M = bulk density (pounds per cubic foot) of medium grain

P_L = bulk density (pounds per cubic foot) of long grain

M = moisture content in per cent, wet basis

Haswell (1954) found that the specific heat of rough rice was well fitted by a straight line, he used a modified Bunsen Ice Colorimeter for his experiments and from his tests on rough rice, he determined the following equation:

$$C = 0.0107M + 0.265$$

where C = specific heat (BTU per pound deg F)

M = moisture content in per cent, wet basis

2.2.5 Equilibrium Moisture Content of Rough Rice

Pfost et al. (1976) tested five equilibirum moisture-relative humidity models using extensive experimental data. In this study, constants were determined for various important grains for the Henderson-Thompson and Chung-Pfost equations. The following constants of Chung-Pfost equation were determined for rough rice:

$$ERH = \exp\left[-PA / \left(RO\ (TG + PC)\ \right) \exp\left(-PB \times M_{db}\right)\right]$$

where PA = constant of Chung-Pfost equation (2126.826)

PB = constant of Chung-Pfost equation (21.733)

PC = constant of Chung-Pfost equation (32.2654)

ERH = equilibrium relative humidity of the grain at TG and M_{db} (decimal)

TG = initial grain temperature (^{o}F)

M_{db} = initial grain moisture content (dry basis, decimal)

2.2.6 Dry Matter Loss of Grain

Steele et al. (1969) measured carbon dioxide production from shelled corn held under various conditions and related this to the dry matter decomposition of the shelled corn. Families of curves were presented to permit calculation of permissible storage times as a function of the temperature, moisture content, and mechanical damage of the corn kernels.

Saul (1970) updated Steele's curves and reported that the deterioration rate of moist shelled corn at low temperature is approximately one-half of that reported earlier.

2.3 Objectives of Study

1. To make reasonable modifications of a drying simulation model (Maurer, 1977) to predict the drying results of rough rice by natural air.
2. To investigate the drying characteristics of rough rice at various drying conditions.
3. To suggest the design parameters of natural-air drying systems of rough rice.

2.4 Drying Simulation Model -KSUDRYER

Maurer (1977) tested three basic natural air models against six actual drying tests and developed a simulation model for natural air grain drying.

To give a background for understanding the model behavior, the equations and assumptions of the model will be clearly described, and for application purposes, there will be some descriptions about digital computer simulation programming. This simulation model will be referred to as the KSUDRYER throughout this study.

2.4.1 Assumptions

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

This system is simplified by assuming a one-foot square column of grain will be arbitrarily selected within the bin. We assume that the changes within this theoretical column will reflect the fluctuations throughout the drying bin. Since the thickness of these layers will change with moisture content, they are calculated on an equal dry weight basis (Maurer, 1977).

There are five initial known values in this system:

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

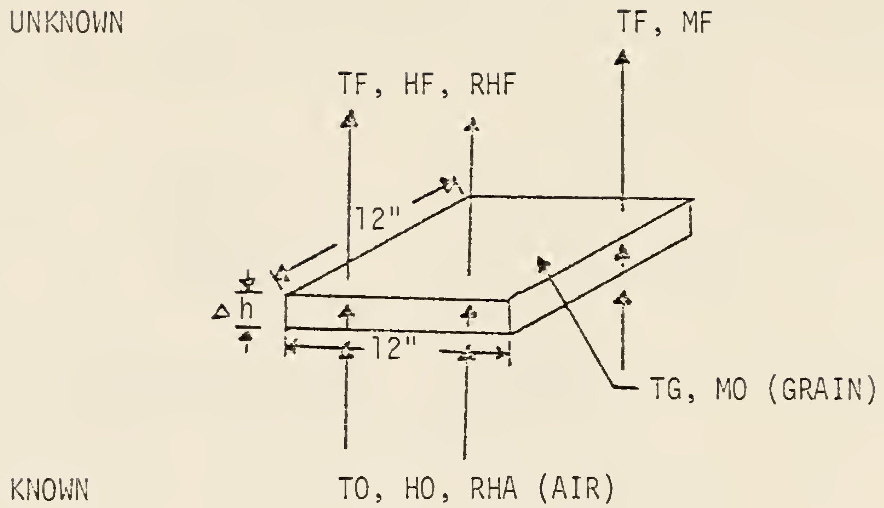
The airflow is assumed to be, from bottom to top, that of the exhaust air of the i^{th} layer being the input air to the $(i + 1)^{th}$ layer, at any given time (j) and layer (i).

A schematic diagram of basic simulation approach is shown in Figure 2.1.

The following assumptions were used in the development of the mathematical model.

Assumptions:

1. Mass diffusion is assumed to be the governing process for the natural air drying system.
2. No temperature or moisture gradients are assumed to exist within each grain particle.
3. Heat transfer is implicitly defined by the mass transfer.
4. Final air temperature is equal to final grain temperature.
5. Airflow is plug type which means that the total weight of air for a time increment Δt is considered present at time tj.



LAYER = i

TIME = j

Figure 2.1. The Visualization of a Modeled Layer

6. Heat transfer is adiabatic with no conduction losses laterally from the layer.

7. The total mass of the system remains constant within the time interval and mixing does not occur between the layer.

8. The bin is assumed to be air tight with atmospheric pressure or site elevation given.

9. Density fluctuations do exist over time and are given as functions of moisture content only.

2.4.2 Equations of Simulation Model

$$MF = MO - Kg \ast NTINC \ast (ERH \ast PSTG - RHA \ast PSA) \qquad (2\text{-}1)$$

where MF, MO = final and initial grain moisture content, dry basis
Kg = mass transfer coefficient (decimal dry basis per hour·psia)
NTINC = small time increment (hour)
ERH = equilibrium relative humidity, decimal
PSTG = saturation vapor pressure at the temperature of the grain (psia)
RHA = relative humidity of air, decimal
PSA = saturation vapor pressure of water at initial air temperature (psia)

The equilibrium relative humidity for the grain is calculated from the Chung-Pfost equilibrium relative humidity equations as follows (Chung-Pfost, 1967):

$$ERH = \exp\ (-PA/RO \ast (TG + PC)\ ) \ast \exp\ (-PB \ast M)\ ) \qquad (2\text{-}2)$$

where ERH = equilibrium relative humidity of the grain at TG, MO
PA, PB, PC = fitted constants for a particular grain
RO = universal gas constant (1.987 Kcal/Kg-mole-^{O}K)

Saturation pressure is given by the following equation (Brooker, 1974):

If $491.69 \leq T \leq 959.69$,

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

If $459.69 \leq T \leq 491.69$,

$$PS = \exp(23.3924 - \frac{11286.65}{T} - 0.46057*\ln(T)) \qquad (2\text{-}4)$$

where PS = saturation pressure at temperature T (psia)

R_o = universal gas constant (3206.1822 ft-lb)

T = absolute temperature (°R)

Constants:

A = -0.274055E 05

B = 0.541896E 02

C = -0.451370E-01

D = 0.215321E-04

E = -0.462027E-08

F = 0.241613E 01

G = 0.121547E-02

Double precision constants are given in Brooker et al. (1974).

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

$$HF = HO + (MO - MF)*GLB/ALB \qquad (2\text{-}5)$$

where HF, HO = final and initial absolute humidity of the air (lb H_2O/lb dry air)

GLB = pounds of dry grain per $ft^2\cdot NTINC\cdot layer$

ALB = pounds of dry air per $ft^2\cdot NTINC$

The final grain temperature is assumed to be equal to the final air temperature. And this value is calculated from the heat balance equation for final temperature (Thompson, 1972).

$$TF = \{.24*ALB*TO + ALB*HO*(1060.8 + .45*TO) - ALB*HF*1060.8 + GLB*(MO + 1.)*[.35 + .851*(MO/(1. + MO))]*TG\}/[.24*ALB + ALB*HF*.45 + GLB*(MF + 1.)*(.35 + .851*MF/(1. + MF))] \tag{2-6}$$

Relative humidity of the exit air is found by the following equation (Brooker, 1974):

$$RHF = (ATM*HF)/PS_{TF}*(.6219 + HF) \tag{2-7}$$

where ATM = atmospheric pressure (psia)

PS_{TF} = partial pressure of water vapor at saturation (psia)

2.4.3 Success Criterion of Simulation

In this simulation model, dry matter loss (0.5 per cent) is used to indicate drying system success. Steele et al. (1969) used carbon dioxide production as an index of deterioration in shelled corn stored under various storage conditions. A series of equations was presented for use in calculating deterioration during storage or slow drying.

The equations for dry matter loss which are taken from Steele (1969) were given in FORTRAN as follows:

$$DML_i = 0.0883* [\exp (.006*EQST_i) -1] + 0.00102*EQST_i \tag{2-8}$$

$$EQST_i = \sum_{j=1}^{i} NTINC/(M_{M_j} \cdot M_{T_j} \cdot M_D) \tag{2-9}$$

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

$$M_{M_j} = 0.103* [\exp (455./M_{db_j}**1.53] - 0.00845*M_{db_j} + 1.558 \quad (2\text{-}10)$$

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

$$M_{T_j} = 32.3*\exp(-3.48*(T_{G_j}/60.)) \quad (2\text{-}11)$$

If $T_{G_j} > 60\ ^oF$ and 19 per cent $< M_{wb_j} \leq 28$ per cent

$$M_{T_j} = 32.3*\exp [-3.48*(T_{G_j}/60.)] + (M_{wb_j} - 19.)/100.* \exp\{0.61*[(T_{G_j}-60.)/60.]\} \quad (2\text{-}12)$$

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

$$M_{T_j} = 32.3*\exp [-3.48*(T_{G_j}/60.)] + .09*\exp \{0.61*[(T_{G_j}-60.)/60.]\} \quad (2\text{-}13)$$

Damage multiplier (M_D): for 0.5 per cent dry matter loss

$$M_D = 2.08*\exp(-0.0239*PD) \quad (2\text{-}14)$$

Saul (1970) reported that the temperature multiplier at low temperature was more closely approximated by:

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

$$M_{T_j} = 128.76*\exp(-4.68*(T_{G_j}/60.)) \quad (2\text{-}15)$$

where DML_i = total dry matter loss up to time i (per cent)

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

NTINC = time increment of drying model (hours)

M_{M_j} = moisture multiplier for time j

M_{T_j} = temperature multiplier for time j

M_b = damage multiplier

M_{db_j} = grain moisture per cent dry basis at time j

M_{wb_j} = grain moisture per cent wet basis at time j

T_{G_j} = grain temperature at time j (^{O}F)

PD = per cent kernel damage as defined in Steele (1969)

2.4.4 Digital Computer Simulation Program

The drying simulation program consisted of the following (Appendix A):

1. Main Program
2. DATAIN Subroutine: transfer weather data as input data
3. USSATM Subroutine: correcting of atmospheric pressure
4. LAGRNG Subroutine: data interpolation
5. WEATHER Subroutine: arrange weather data for input
6. DESIGN Subroutine: read all conditions of grain and dryer
7. TABLE Subroutine: format of computer output
8. TIME Subroutine: write the status of iteration counters
9. OUTPUT Subroutine: format and statement of output
10. AIRFLO Subroutine: fan management and bin enhancement logic
11. BIN Subroutine: calculate dry matter loss
12. DEWPT Subroutine: calculate dew point
13. DRYER Subroutine: calculate the initial and final conditions of each layer
14. EQLBRM Subroutine: calculate equilibrium value
15. PARTAL Subroutine: solve heat and mass balance equation
16. PARTF4 Subroutine: calculate partial pressure
17. GAUSS Subroutine: calculate the inverse matrix
18. EQCO2 Function: calculate storage time for each layer
19. SATPS Function: calculate saturation pressure

20. BLOCK DATA: constants of all equations

Input data to the simulator consisted of:

1. Drying time interval
2. Mass transfer coefficient
3. Initial grain moisture content (wet basis)
4. Initial grain temperature
5. Total airflow rate
6. Total weight of grain
7. Diameter of bin
8. Stain-test damage per cent
9. Number of modeled layers
10. Grain number (kind of grains were expressed in numbers)
11. Number of weather points
12. Elevation of location of bin
13. Hourly weather data (dry bulb temperature and relative humidity)
14. Equilibrium moisture equation
15. Specific heat equation
16. Density equation

2.4.5 Computer Output

Information printed as a result of a completion of a simulation consisted of weather data as calculated by weather subroutine and communicated to the time subroutine, status of iteration counters, grain initial conditions, aeration bin configuration, mathematical model attributes and moisture content at each layer with bed height.

If this program is used for the model validation purpose, actual test data should be added to input data. Then difference table for validation between the actual and the predicted data, and the results of statistical analysis of differences are printed on the computer output in addition.

2.4.6 Discussion of Simulation Model

The equations for the drying rate can be written as follows:

$$\frac{dM}{d\theta} = -Kg\ (Pg - Pa)\ \text{(Rodriguez-Arias (1956))} \qquad (2\text{-}16)$$

where $\frac{dM}{d\theta}$ = drying rate (pounds of water evaporated per hour)

Kg = mass transfer coefficient (decimal db/hour·psia)

Pg = water vapor pressure of grain (psia)

Pa = water vapor pressure of air (psia)

Equation 2-1 is an approximated form of equation 2-16. Therefore, equation 2-1 cannot predict the drying rate precisely and Kg should be mass transfer coefficient instead of diffusion coefficient.

Equation 2-2 is the Chung-Pfost equation for calculating equilibrium relative humidity, which can predict ERH more accurately than any other Equilibrium Moisture Content Model (Pfost et al., 1976).

Equations 2-3 and 2-4 came from FORTRAN PSYCHROMETRIC MODEL (SYCHART) which was programmed by Lerew (1972).

Equation 2-5 is the statement of the mass balance. This equation states that the moisture picked up by air is equal to the moisture lost by the grain mass in a given layer.

Equation 2-6 is the heat balance equation which simply states that the initial heat content of the system is equal to the final heat content.

Equation 2-7 can be used for calculating relative humidity of the exit air. But, in the simulation model (Maurer, 1977), it was written as the following:

$$RHF = (ATM*HF*PS_{TF})/(.6219 + HF) \qquad (2\text{-}17)$$

But equation 2-17 should be corrected as equation 2-7.

From equation 2-8 to 2-15 which are for dry matter loss calculation, there are several erros and misquotations in the simulation on model by Maurer (1977). All of these errors were corrected in this study.

2.5 Simulation Model Modification and Validation

Originally, KSUDRYER was written as the simulation program for corn drying by natural air. Therefore, this program should be modified and validated for rough rice drying before it is used to simulate rough rice drying by natural air.

2.5.1 Model Modification

To simulate rough rice drying by natural air, several modifications were made to the KSUDRYER. The following information was needed for the modifications: equation for equilibrium moisture content of rough rice, the specific heat of rough rice, the density of rough rice, the appropriate mass transfer coefficient, and equation for calculating dry matter loss of rough rice. The following information was used in the modification. Equilibrium Moisture Content Equation: Pfost et al. (1976).

$$ERH = \exp(-PA/(RO*(TG + PC))*\exp(-PB*M_{db}))$$

where PA = 2126.826

PB = 21.733

PC = 32.2654

ERH = equilibrium relative humidity of the grain at TG and M_{db} (decimal)

TG = initial grain temperature (^{o}F)

M_{db} = initial grain moisture content (dry basis, decimal)

Specific Heat Equation: Haswell (1954)

$$C = 1.07M_{wb} + 0.265 \qquad (2\text{-}19)$$

where C = specific heat (BTU/lb dry air·^{o}F)

M_{wb} = moisture content (wet basis, decimal)

Bulk Density Equation: Wratten et al. (1969)

for long grain;

$$DENSY = 32.425 + 33.0\ M_{wb}$$

for medium grain;

$$DENSY = 31.195 + 52.0\ M_{wb}$$

where DENSY = bulk density of rough rice (pounds per cubic foot)

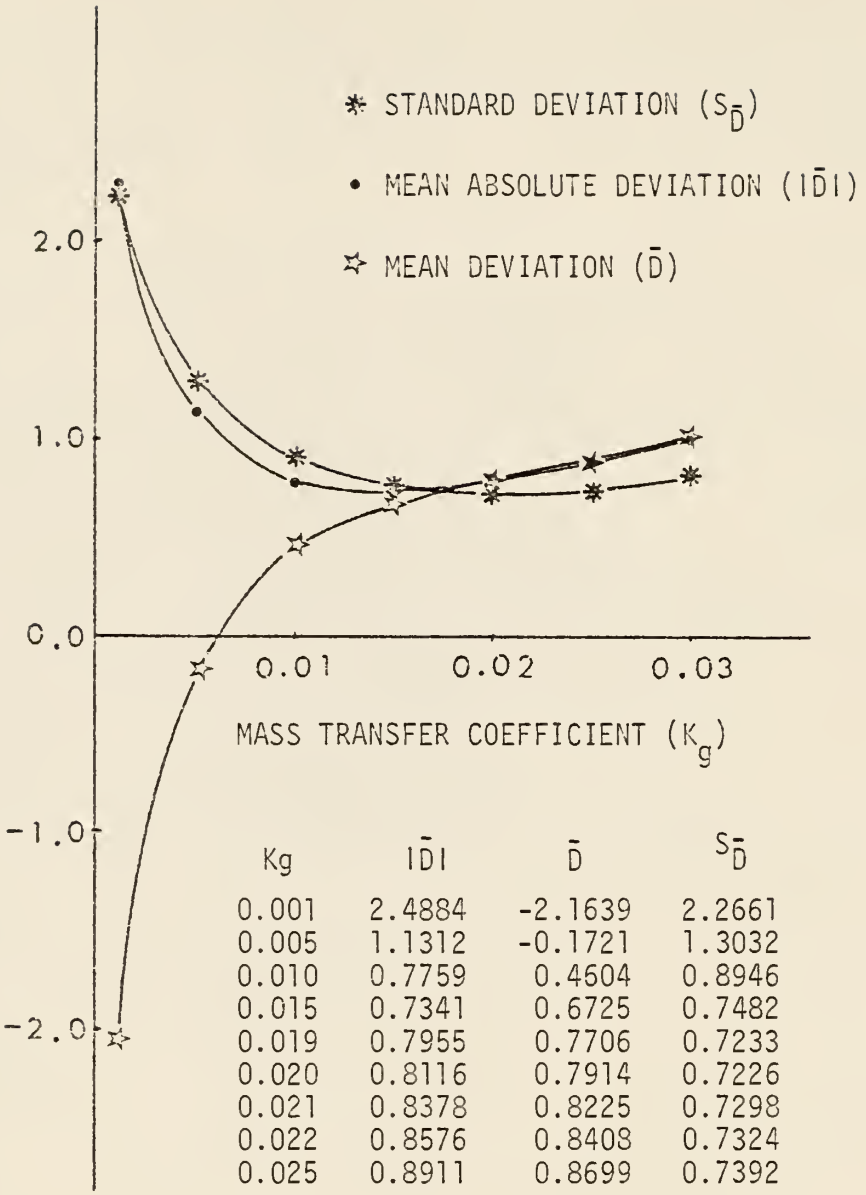
Mass Transfer Coefficient: 0.020 (decimal db/hour·psia)

Mass transfer coefficient was calculated from actual experimental data which was available from the Rice-Pasture Experiment Station near Beaumont, Texas. When it was evaluated, equation 2-16 and the evaluation methods in Rodriguez-Arias (1965) were used (Figure 2.2).

Dry Matter Loss Equation: Steele et al. (1969)

As far as the dry matter loss equation is concerned, only Steele's data are available, which are for corn storage. Therefore, Steele's equations were used in calculating dry matter loss as a reference index in this study.

The preceeding information was used to modify the KSUDRYER. Since the KSUDRYER has OUTPUT Subroutine and BLOCK DATA, it is easy to modify the program. OUTPUT Subroutine and BLOCK DATA include all variable components which are varied according to grain. In addition, write-statement of dry matter loss was added to OUTPUT Subroutine in the procedure of modification (Apendix A, B, and C).



Kg	$\lvert\bar{D}\rvert$	$\bar{D}$	$S_{\bar{D}}$
0.001	2.4884	-2.1639	2.2661
0.005	1.1312	-0.1721	1.3032
0.010	0.7759	0.4604	0.8946
0.015	0.7341	0.6725	0.7482
0.019	0.7955	0.7706	0.7233
0.020	0.8116	0.7914	0.7226
0.021	0.8378	0.8225	0.7298
0.022	0.8576	0.8408	0.7324
0.025	0.8911	0.8699	0.7392

Figure 2.2. Effect of Mass Transfer Coefficent on Accuracy of Simulated Moisture Content

2.5.2 Model Validation

Before applying the KSUDRYER to rough rice drying simulation, model validation is necessary.

Many statistical and graphical techniques have been proposed and used in attempting to validate the output of computer models (Bowersox et al, 1972). In order to determine which of these techniques is most suitable for this validation of grain drying simulation, consideration should be given to the nature of the techniques and chose an appropriate technique for our specific problem.

In this validation study, actual drying test data were used, which was conducted during 1976 and available from Mr. D. L. Calderwood, Agricultural Engineer, USDA, ARS at Beaumont, Texas.

An actual drying test of rough rice was conducted from August 19, 1976, to September 11, 1976, at Beaumont, Texas. The dryer was 9 feet in diameter, corrugated steel tanks having a wall height of approximately 11 feet. A perforated steel floor was installed at a level of 1.5 feet above the base. The nominal drying capacity at 8 feet depth was 8.8 tonne of rice. Centrifugal fans with backward curved, 15 inches diameter wheels provided air delivery to plenum chamber below the floor. Initial moisture content was 19.6 per cent wet basis and airflow rate was 1006 cfm. Initial drying bed depth was 8.3 feet. Samples were probed at daily intervals except for some non-work days. Mositure content and temperature of grain were recorded at the bottom, center, and top of the bed height. The bottom sample was removed at a depth of 14 inches above the floor. The center sample was taken at approximately 51 inches above the floor, and the top sample came from 6 inches below the top surface. The fan connected to the dryer plenum chamber was operated continuously until rice near the top surface was dried to less than 16 per cent moisture content. During the remainder of the dryer operation, the fan moving unheated air was actuated by a humidistat, set for operation at ambient air relative humidities of 65 per cent and lower. The average moisture content for a given drying time was listed on Table 2.1.

Moisture content of rough rice was simulated by simulation model in order to compare with actual test data. Input data for this simulation were:

1. Drying time interval: 3 hours
2. Mass transfer coefficient: 0.02 (decimal db/hour·psia)
3. Initial moisture content of rough rice: 19.6 per cent (wet basis)
4. Initial grain temperature: 90 ^{o}F
5. Total airflow rate: 1006 cfm
6. Total weight of grain: 20,413 pounds
7. Diameter of bin: 9 feet
8. Stain-test damage per cent: 20 per cent
9. Number of modeled layers: 10
10. Grain number: 2 (rough rice)
11. Number of weather points: 111
12. Elevation of location of bin: 30 feet
13. Hourly weather data: 3-hour basis dry bulb temperature and relative humidity

Fan was operated continuously until the moisture content of top layer reached 16 per cent and then operated only when relative humidity was 65 per cent and lower. The predicted average moisture content was listed in Table 2.1.

Table 2.1 and Figure 2.3 show the comparisons of the actual and predicted average moisture content of rough rice in the bin. Table 2.2 shows the difference of moisture content at each layer. The bottom, center, and top layers were 14 inches, 51 inches, and 94 inches from the bin floor, respectively. These comparisons showed good agreement of the shape of moisture content.

Table 2.1. Difference Table of Average Moisture Content*

Drying Time (Hours)	Actual Moisture Content (w.b., percent)	Predicted Moisture Content (w.b., percent)	Difference (Actual - Predicted)
23	19.1	18.7	0.4
75	17.7	17.3	0.4
115	16.4	16.1	0.3
140	15.8	15.5	0.3
163	15.6	15.2	0.4
188	14.8	14.5	0.3
216	14.2	14.2	0.0
231	14.0	13.8	0.2
247	13.5	13.7	-0.2
256	13.6	13.7	-0.1
266	13.5	13.7	-0.2
280	13.2	13.5	-0.3
294	12.8	12.8	0.0
306	12.7	12.4	0.3
319	12.5	12.3	0.2
327	12.3	12.1	0.2
336	11.9	11.8	0.1

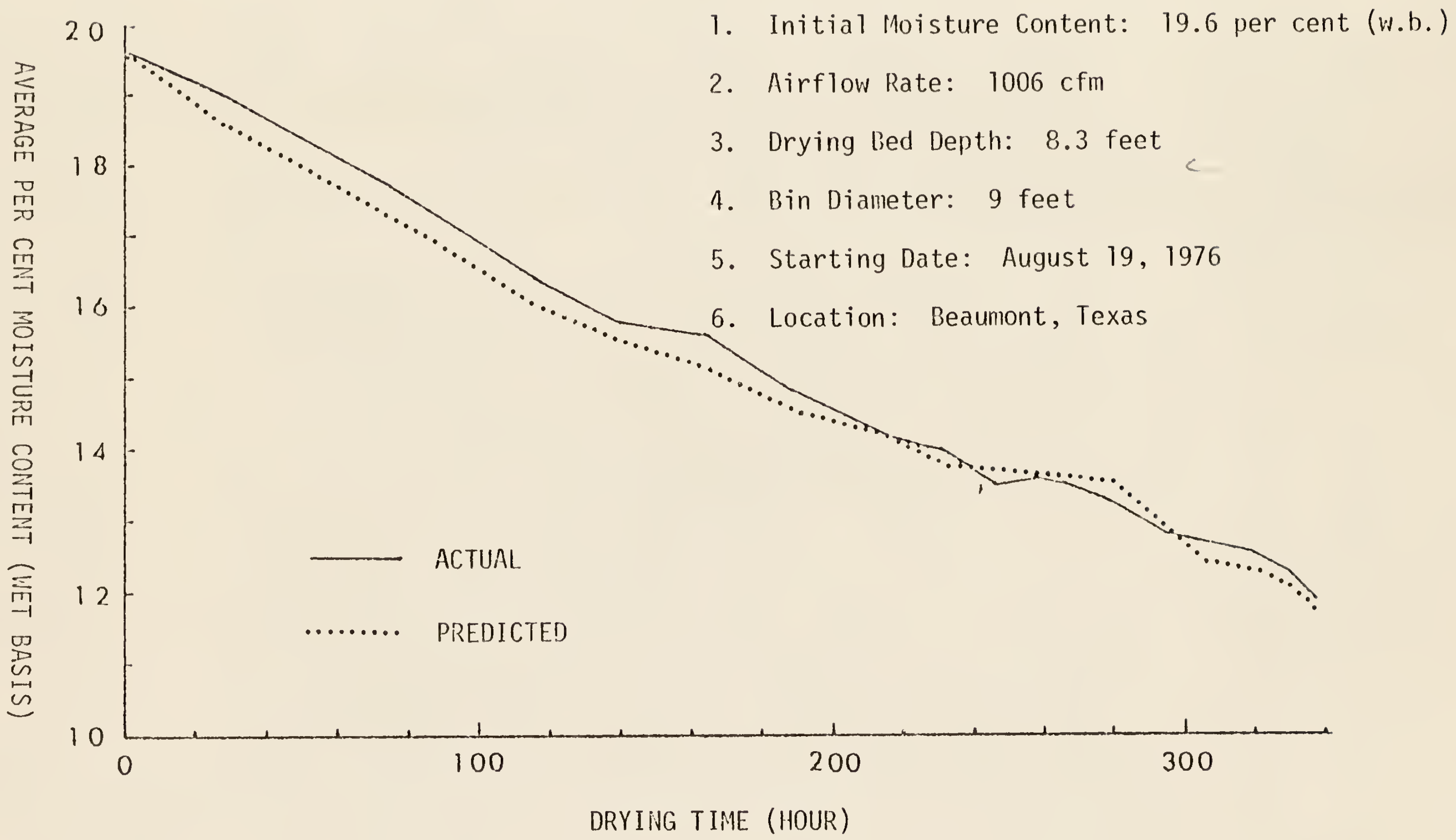
*Actual test data had the drying conditions as the following:

1. Initial Moisture Content: 19.6 percent (wet basis)
2. Airflow Rate: 1006 cfm
3. Drying Bed Depth: 8.3 ft
4. Bin Diameter: 9 ft
5. Starting Date: August 19, 1976
6. Location: Beaumont, Texas

Table 2.2. Difference Table of Moisture Content at Each Layer

Drying Time (Hours)	Bottom Layer (14 in.)			Center Layer (51 in.)			Top Layer (94 in.)		
	A*	P*	D*	A	P	D	A	P	D
23	18.5	18.1	0.4	19.2	18.8	0.4	19.6	19.2	0.4
75	14.3	14.2	0.1	19.2	18.7	0.5	19.5	19.0	0.5
115	13.5	13.4	0.1	16.0	15.9	0.1	19.6	19.0	0.6
140	13.3	13.2	0.1	15.7	15.1	0.6	18.5	18.2	0.3
163	13.2	13.1	0.1	14.3	14.2	0.1	19.2	18.3	0.9
188	13.6	13.0	0.6	13.6	13.6	0.0	17.3	16.9	0.4
216	13.7	13.7	0.0	13.9	13.5	0.4	15.1	15.4	-0.3
231	13.2	13.0	0.2	14.0	13.3	0.7	14.7	15.0	-0.3
247	13.1	13.3	-0.2	13.2	13.4	-0.2	14.2	14.5	-0.3
256	13.0	13.3	-0.3	13.5	13.4	0.1	14.2	15.3	-0.1
266	12.9	13.4	-0.5	13.4	13.5	-0.1	14.2	14.2	0.0
280	12.7	13.2	-0.5	13.0	13.4	-0.4	13.9	14.0	-0.1
294	12.5	11.9	0.6	12.7	12.9	-0.2	13.2	13.5	-0.3
306	12.0	11.1	0.9	13.0	12.5	0.5	13.7	13.3	0.4
319	11.8	11.5	0.3	13.5	12.3	1.2	13.2	13.2	0.0
327	11.8	11.3	0.5	12.3	12.1	0.2	12.9	13.0	-0.1
336	11.6	11.1	0.5	11.7	11.7	0.0	12.4	12.5	-0.1

*A: Actual Moisture Content (w.b., per cent)
P: Predicted Moisture Content (w.b., per cent)
D: Difference (Actual - Predicted)



1. Initial Moisture Content: 19.6 per cent (w.b.)
2. Airflow Rate: 1006 cfm
3. Drying Bed Depth: 8.3 feet
4. Bin Diameter: 9 feet
5. Starting Date: August 19, 1976
6. Location: Beaumont, Texas

Figure 2.3. Comparison of the Actual and Predicted Average Moisture Content

Results of statistical analysis provide no evidence to reject the null hypothesis as the following:

Null Hypothesis: The Actual = The Predicted

Mean Deviation ($\bar{D}$): 0.14

Standard Deviation ($S_{\bar{D}}$): 0.22

$$t = \frac{\bar{D}}{S_{\bar{D}}} = 0.636 \qquad t_{0.05} = 2.120 \qquad \text{d.f.} = 16$$

Therefore, the null hypothesis is accepted, and this model is considered to be valid for the simulation of rough rice by natural air.

2.6 Results of Simulations and Discussion

2.6.1 Input and Output of Simulation Program

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

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

These factors as discussed in Thompson (1972), and Bloome and Shove (1971) were found to be the major contributing components of the natural aeration system studied (Maurer, 1977).

In this study, initial moisture content of rough rice, airflow rate of the system and harvest date were considered as the inputs to the simulation model.

Hourly weather data for Beaumont, Texas, from 1962 through 1976 was obtained from the National Weather Bureau Center, Asheville, North Carolina. This official weather data was used as input data to the simulation model. This data contained hourly dry bulb temperature, relative humidity and elevation in addition to other data. Figure 2.4 shows average hourly temperatures and relative humidity during August, September, and October at the Beaumont area from 1962 to 1976 (15 years).

Table 2.3 represents the combination of system performance factors used in simulation.

The following assumptions and drying systems were made in this simulation:

1. Stain-test damage of rough rice was 20 per cent.
2. The number of modeled layers were 10.
3. Final acceptable moisture content was 13.5 per cent, wet basis.
4. Bin elevation was 30 feet.
5. Fan was operated continuously for 10 days and then operated only when the relative humidity was less than 75 per cent until the average moisture content of the rough rice was reduced to 13.5 per cent, wet basis.
6. Filling procedure was a single fill procedure in which drying started only after the bin was full and air was pushed up through the rice when the fan was operated.

Moisture content and dry matter loss at each drying bed height was printed in the output of simulation. From these outputs, the success or failure of a given simulation was determined by using the following means of evaluation:

1. Allowable storage time is based on a criterion of 0.5 per cent dry matter loss (Steele et al., 1969).
2. In unheated air and supplemental heat drying applications under Texas conditions, the moisture in the wettest layer of rice was to be reduced

Table 2.3. Combinations of System Performance Factors

Initial Moisture Content, percent w.b.	Airflow Rate (cfm/bu)									Harvest Date		
	6.0	5.0	4.5	4.0	3.0	2.5	2.0	1.0	0.5	Aug. 15	Sept. 1	Sept. 15
24	X	X	X	X						X	X	X
22		X		X	X	X	X			X	X	X
20				X	X		X	X		X	X	X
18					X		X	X	X	X	X	X

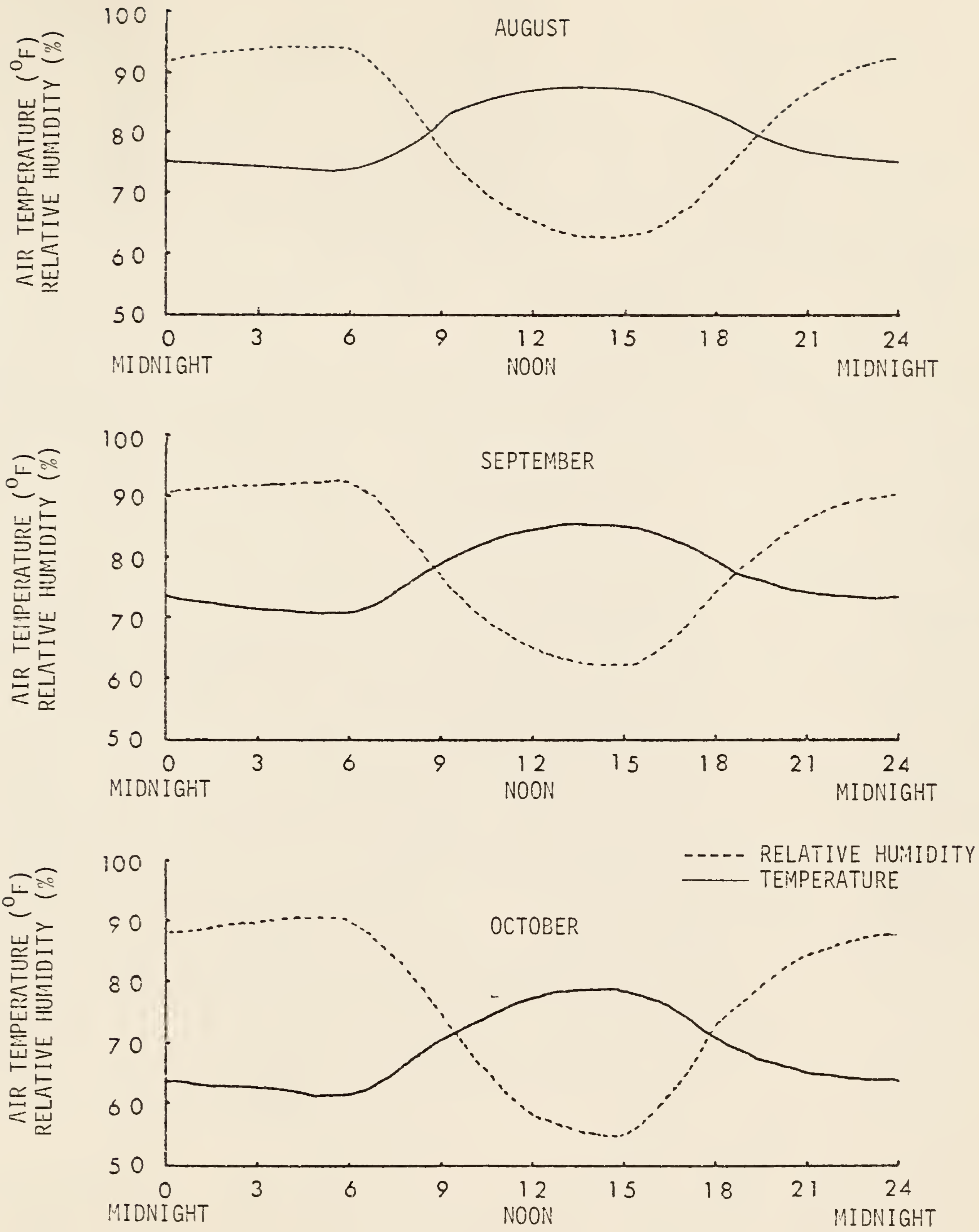


Figure 2.4. Average hourly temperatures and relative humidity during August, September, and October at Beaumont area, 1962-1976

Table 2.4. Minimum Airflow Rate for Rough Rice Drying by Natural Air(Final Moisture Content 13.5 %,Wet Basis)

Initial M.C. (%,w.b.)	Harvest Date	Airflow Rate (cfm/bu)	Drying Time (hour)	Dry Matter Loss(%)	Top-Layer M.C. (%,w.b.)	Airflow Rate (cfm/bu)	Drying Time (hour)	Dry Matter Loss(%)	Top-Layer M.C. (%,w.b.)	Airflow Rate (cfm/bu)	Drying Time (hour)	Dry Matter Loss(%)	Top-Layer M.C. (%,w.b.)
24	Aug.15	5.0	300	0.497	14.46	4.5	303	0.559	14.82	---	---	---	---
	Sept. 1	5.0	294	0.495	14.65	4.5	300	0.554	14.99	---	---	---	---
	Sept.15	5.0	291	0.450	15.08	4.5	297	0.493	15.51	4.0	309	0.529	15.68
22	Aug.15	3.0	327	0.434	15.17	2.5	354	0.515	15.41	---	---	---	---
	Sept. 1	3.0	321	0.422	15.43	2.5	354	0.485	15.82	2.0	384	0.607	16.25
	Sept.15	3.0	318	0.356	15.79	2.5	342	0.408	16.24	2.0	381	0.503	16.71
20	Aug.15	3.0	315	0.209	14.68	2.0	366	0.302	15.17	1.0	522	0.584	16.62
	Sept. 1	3.0	312	0.205	14.71	2.0	357	0.286	15.40	1.0	504	0.476	16.92
	Sept.15	3.0	303	0.184	14.96	2.0	351	0.246	15.83	1.0	501	0.393	17.13
18	Aug.15	2.0	336	0.129	14.80	1.0	468	0.225	15.58	0.5	639	0.324	16.69
	Sept. 1	2.0	333	0.123	14.88	1.0	447	0.190	15.81	0.5	630	0.267	16.58
	Sept.15	2.0	324	0.107	15.12	1.0	444	0.163	16.01	0.5	624	0.218	16.87

below 16 per cent in 15 days or less to prevent loss in grade from discolored kernels (Sorenson and Crane, 1960).

Using the above means of evaluation, simulation results were analyzed, and the minimum airflow rates of natural air rough rice drying systems were shown in Table 2.4. In general, minimum airflow rates for 24, 22, 20, and 18 per cent initial moisture content are 5.0, 3.0, 2.0, and 1.0 cfm per bushel, respectively.

2.6.2 Economical Design Parameters for Natural Air Rough Rice Drying

The drying capacity, total cost per bushel and the final quality of the grain are the primary factors to consider in designing any grain drying system. In a natural air system, these factors are affected by two design variables: airflow rate and bed depth (Morey and Peart, 1971).

Since airflow rate is primarily a function of the fan horsepower and depth of the grain, fan horsepower and bed depth can be considered the independent variables.

Fan Models

In case of the single fill procedure, the fan operates at one airflow rate for the drying time. The static pressure drop through a grain bed described by data from Shedd (1953) is:

$$P = X\left(\frac{Q}{cA}\right)^{d} \tag{2-22}$$

where P = static pressure drop (inches of water)

X = bed height (feet)

Q = airflow rate (cfm)

A = area (square feet)

c, d = constants

Table 2.5. Constants of Equation (2-24)

Airflow Rate (cfm/bu)	c	d
6	75.1506	0.5078
5	74.4580	0.5387
4	69.9234	0.5830
3	171.3980	0.4230
2	12,880.60	0.2003
1	5.3559×10^{10}	0.0872

Table 2.6. Recommended Rough Rice Drying Systems by Natural Air

Initial Moisture Content (percent, w.b.)	Fan Model		USDA Recommendation*	
	Airflow Rate (cfm/bu)	Bed Depth (ft)	Min. Airflow Rate (cfm/bu)	Max. Depth (ft)
24	5	3		
22	3	5	4	6
20	2	7	3	8
18	1	8	2	8

* Sorenson and Crane (1960)

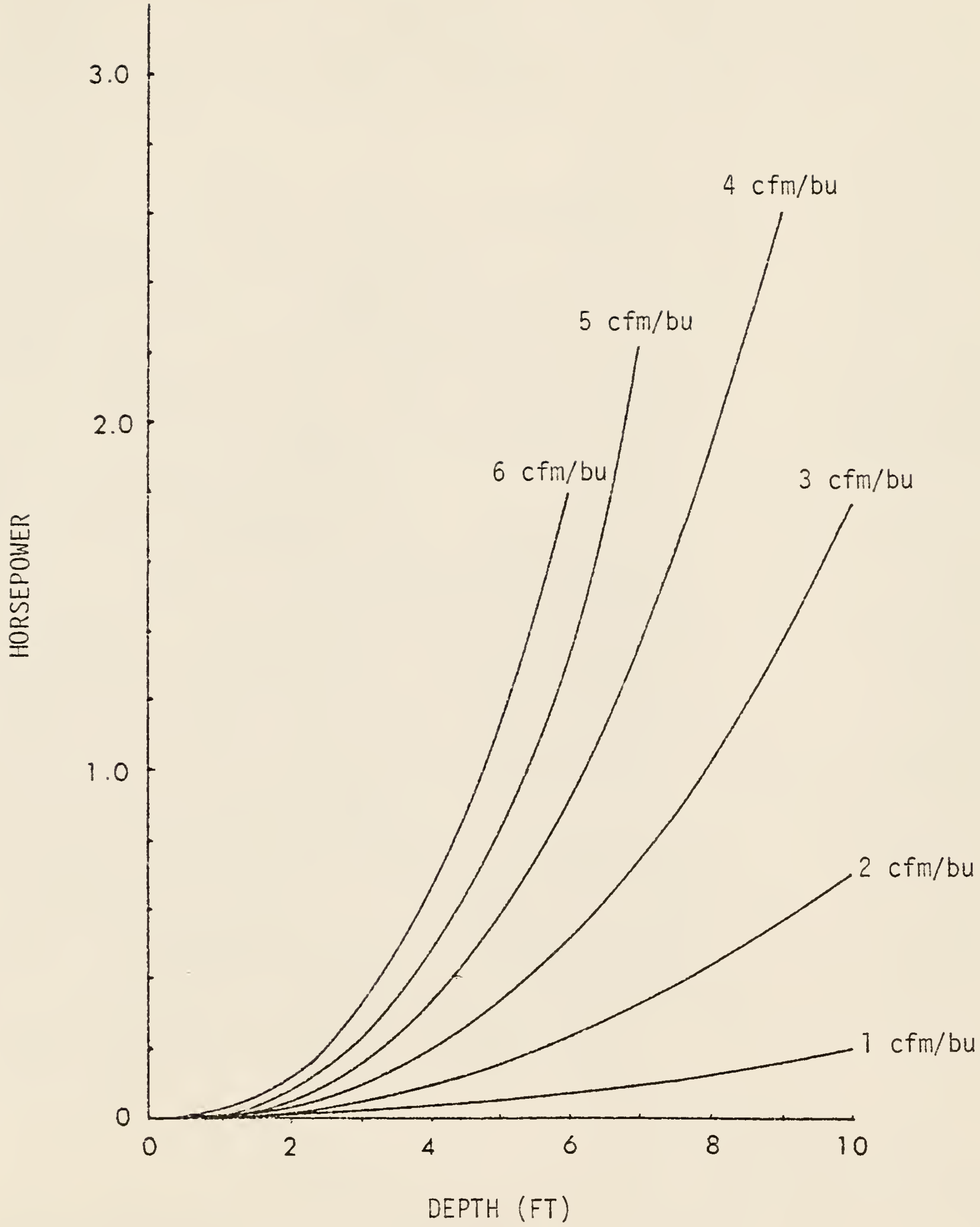


Figure 2.5. Effect of Airflow Rate on Fan Horsepower and Bed Depth

Based on the results of Table 2.4 and Figure 2.5, economical airflow rate and bed depth, which have minimum energy costs, can be recommended as the Table 2.6. The results are similar to the USDA recommendation (Sorenson and Crane, 1960).

Fan model leading to optimum drying system should be studied more in the future.

2.6.3. Results from Simulations

A series of natural air rough rice drying tests was simulated to demonstrated the effect of airflow rate, harvest date, initial moisture content, and moisture content distributions. The simulated tests were made using official weather data from Beaumont, Texas, as an input to the simulation model. The assumption was made that the rough rice was dried in the bin immediately after harvest.

Effect on Airflow Rate

Figure 2.6 presents the effect of airflow rate on time required to dry rough rice. In this figure per cent moisture content of the top layer is described in two cases. One is the continuous fan operation and the other is the fan operation only when relative humidity is below 75 per cent. Intermittent fan operation was started at 250 hours of drying time. Generally, the higher the airflow rate, the less the drying time required; and the higher the airflow rate, the higher the effect of the intermittent fan operation on drying time.

Figure 2.7 shows the results from the same simulation describing the effect of airflow rate on dry matter loss of rough rice. This dry matter loss is a measure or indication of grain deterioration. According to Saul's studies (U.S. Department of Agriculture, 1968), 0.5 per cent dry matter

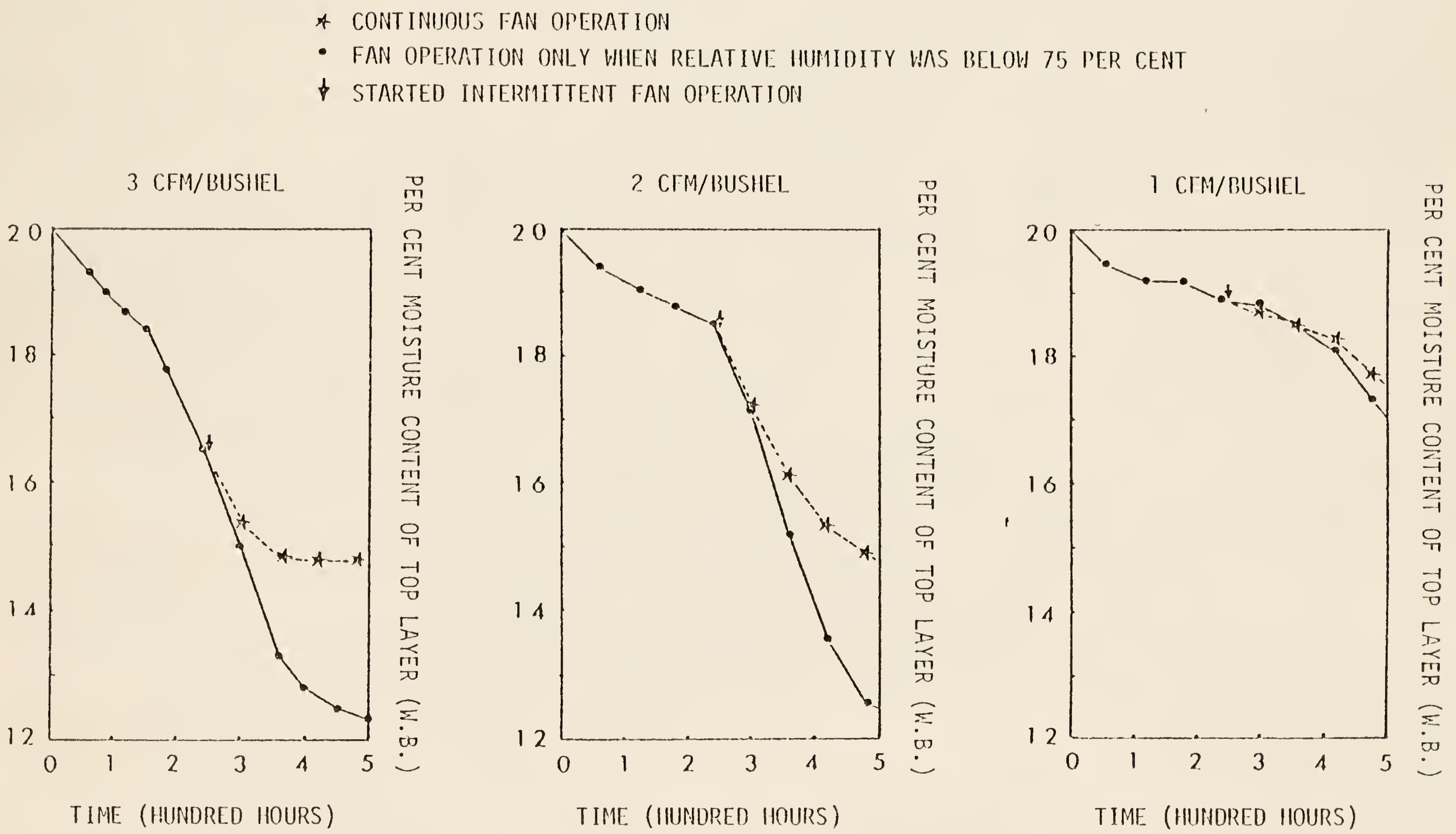


Figure 2.6. Effect of airflow rate on the time required to dry rough rice which has an initial moisture content of 20 per cent (wet basis) and a bed depth of 6-feet. It was dried by natural air on September 1.

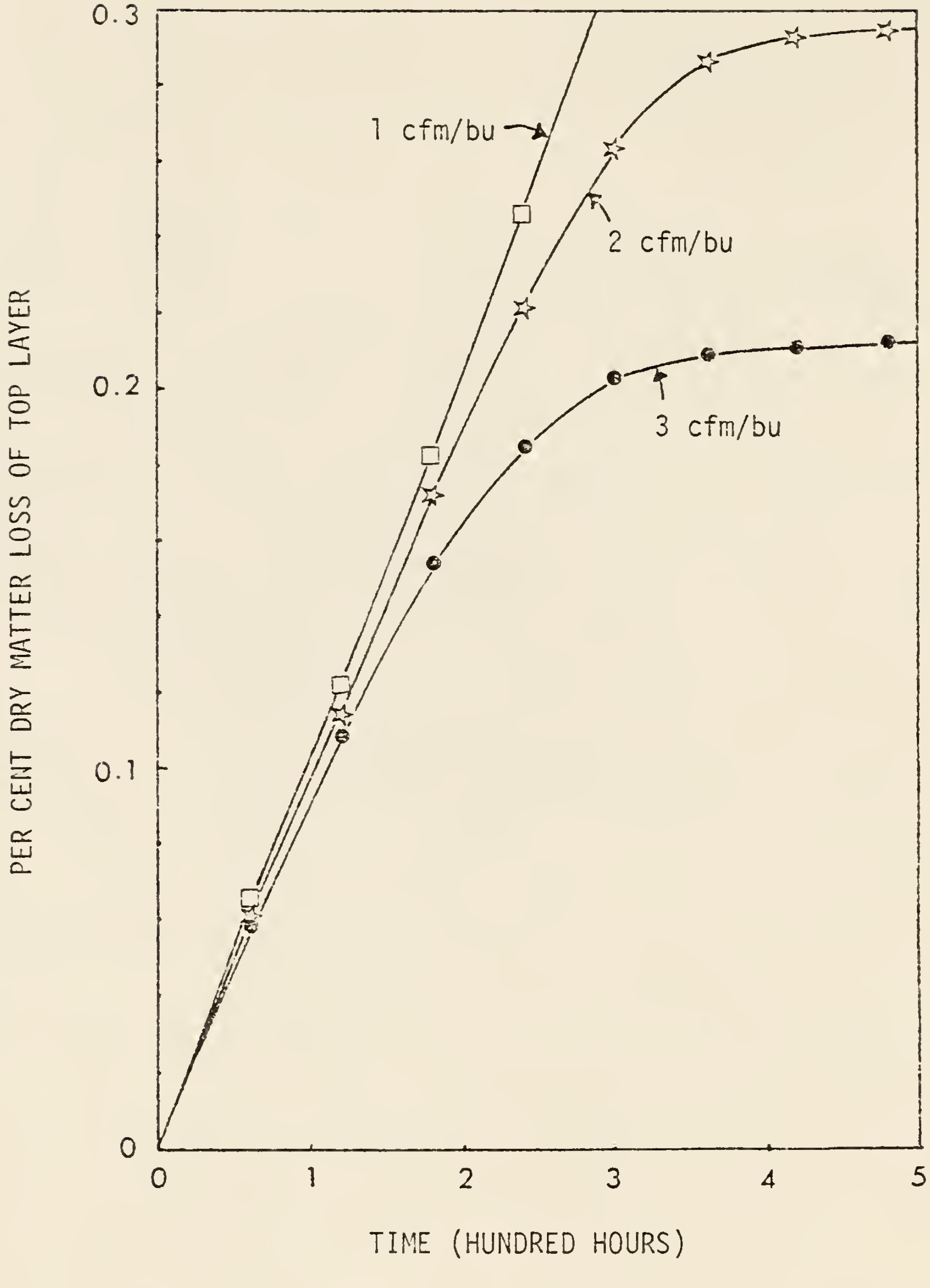


Figure 2.7. Effect of airflow rate on dry matter loss of rough rice which was 20 per cent (wet basis) initial moisture content, 6-feet bed depth and was dried from September 1 on.

decomposition makes the corn lose some quality but keeps its market grade. Thus, 0.5 per cent decomposition is about the limit without a reduction in grade. Since the moisture content of top layer is usually higher than any other part, top layer's dry matter loss is presented. There is not so much difference of per cent dry matter loss until 5 days of drying time among different airflow rates, in general. But after 5 days, the difference becomes larger than before. In general, the higher the airflow rate, the lower the dry matter loss.

Effect of Harvesting Date

Figure 2.8 shows the results of simulation of the effect of harvesting date on per cent dry matter loss of rough rice. These three simulations have the same drying conditions except for the harvesting date. Here a 15-day delay in harvesting, from August 15 to September 15, shows that the amount of rough rice deterioration has decreased. Even though there is the effect of the harvesting date on dry matter loss between August 15 and September 1, the effect is not so much. While comparing with the effect of these harvesting dates, the one on September 15 is much more than others. This means that the weather conditions of the latter part of September and October are more favorable to rice drying (Figure 2.4). This also means that weather conditions can also drastically change the results. Practically, the effect of harvest date on grain storability is considerably greater than that reported in Figure 2.8 (Thompson, 1972).

Figure 2.9 shows the effect of the harvesting date on the drying time. The results presented do not show much of an effect of the harvesting date on the drying time, but the drying rate harvested on August 15 is faster than others during a continuous fan operation and lower than others during

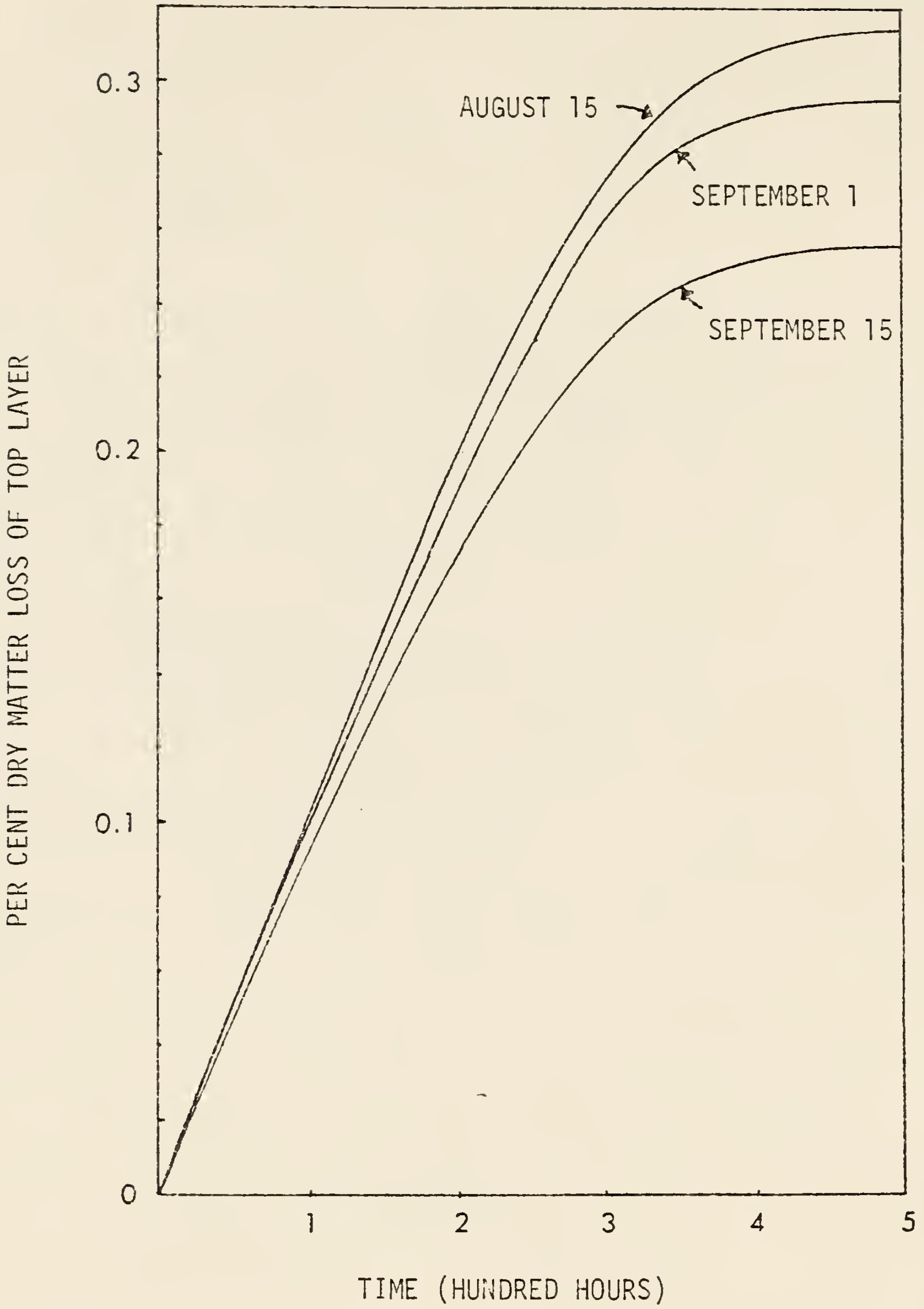


Figure 2.8. Effect of harvesting date on per cent dry matter loss of rough rice which was 20 per cent (wet basis) initial moisture content, 6-feet bed depth and dried with 2.0 cfm/bushel.

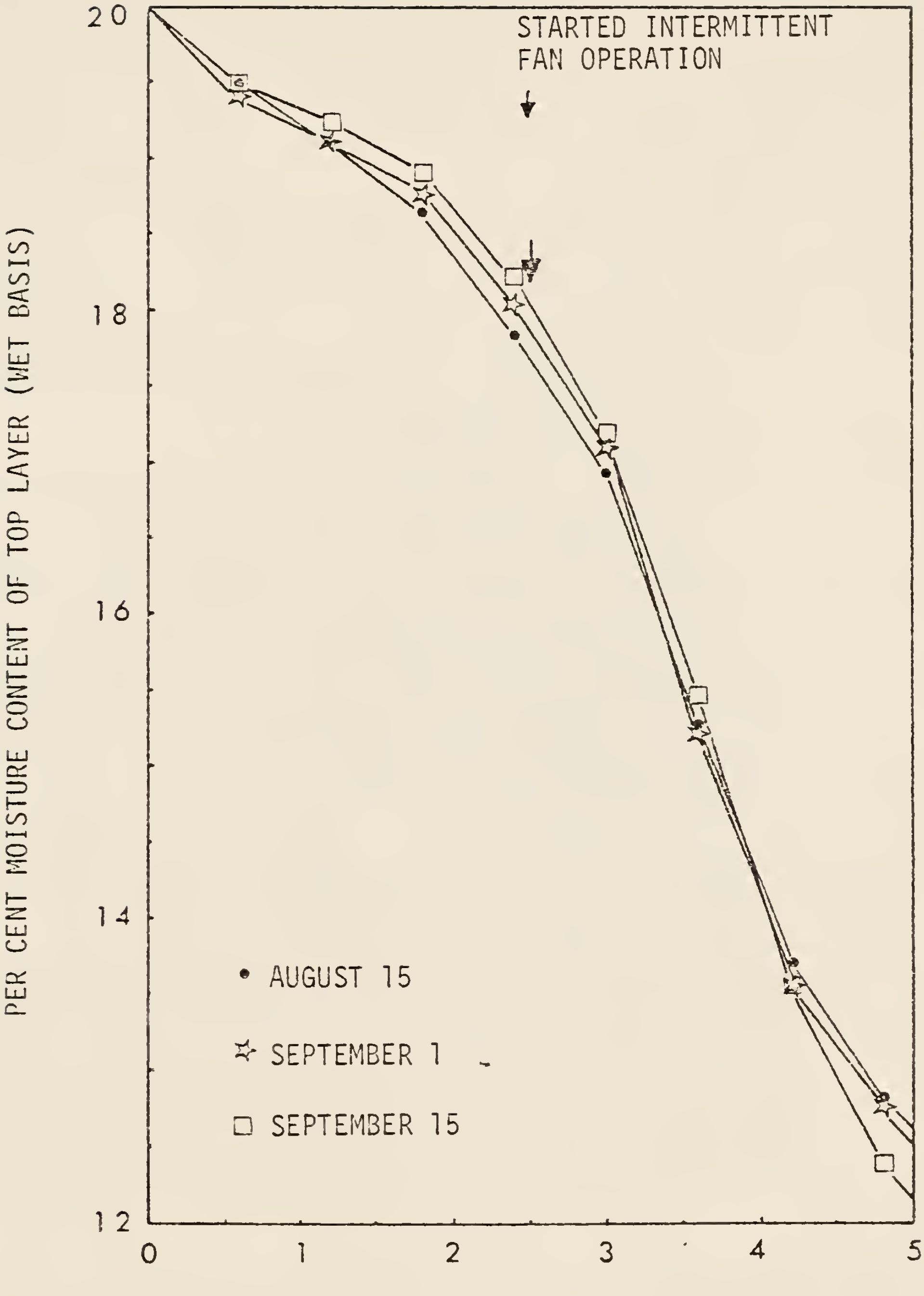


Figure 2.9. Effect of the harvesting date on the time required to dry rough rice which was an initial moisture content of 20 per cent (wet basis), airflow rate of 2 cfm per bushel, and bed depth of 6-feet.

an intermittent fan operation. These results are caused by the fact that the temperature and humidity during August are higher than during September or October (Figure 2.4).

Effect of Initial Moisture Content

Figure 2.10 shows the results of four simulations, each simulation starting with a different initial moisture content of rough rice and dried under the same conditions. Per cent dry matter losses in the bottom layer of each initial moisture content is from 0.03 to 0.09, but there are wide differences in the top layer during a 300 hour drying period. In other words, initial moisture content affects the per cent dry matter loss of rough rice greatly; and the higher the initial moisture content, the more the gradient of the dry matter loss within the bed depth.

Figure 2.11 shows the moisture content distributions in a bed depth during a 300 hour drying time according to different initial moisture contents. This simulation result shows that different initial moisture content of rough rice in the lower layer; but in the top layer, the higher the initial moisture content, the higher the moisture content of the rough rice, in general.

Effect of Weather Conditions

Figure 2.12 presents the results of three simulations which show the variation of moisture content of each layer. In this simulation, the moisture content of bottom layer is very sensitive to the weather conditions. Though the general tendency is that the moisture content is decreased continuously, it can be increased and decreased during drying process. But comparing with the bottom layer, the center layer and top layer are less sensitive to weather conditions. Moisture content of those layers is decreased continuously without fluctuation.

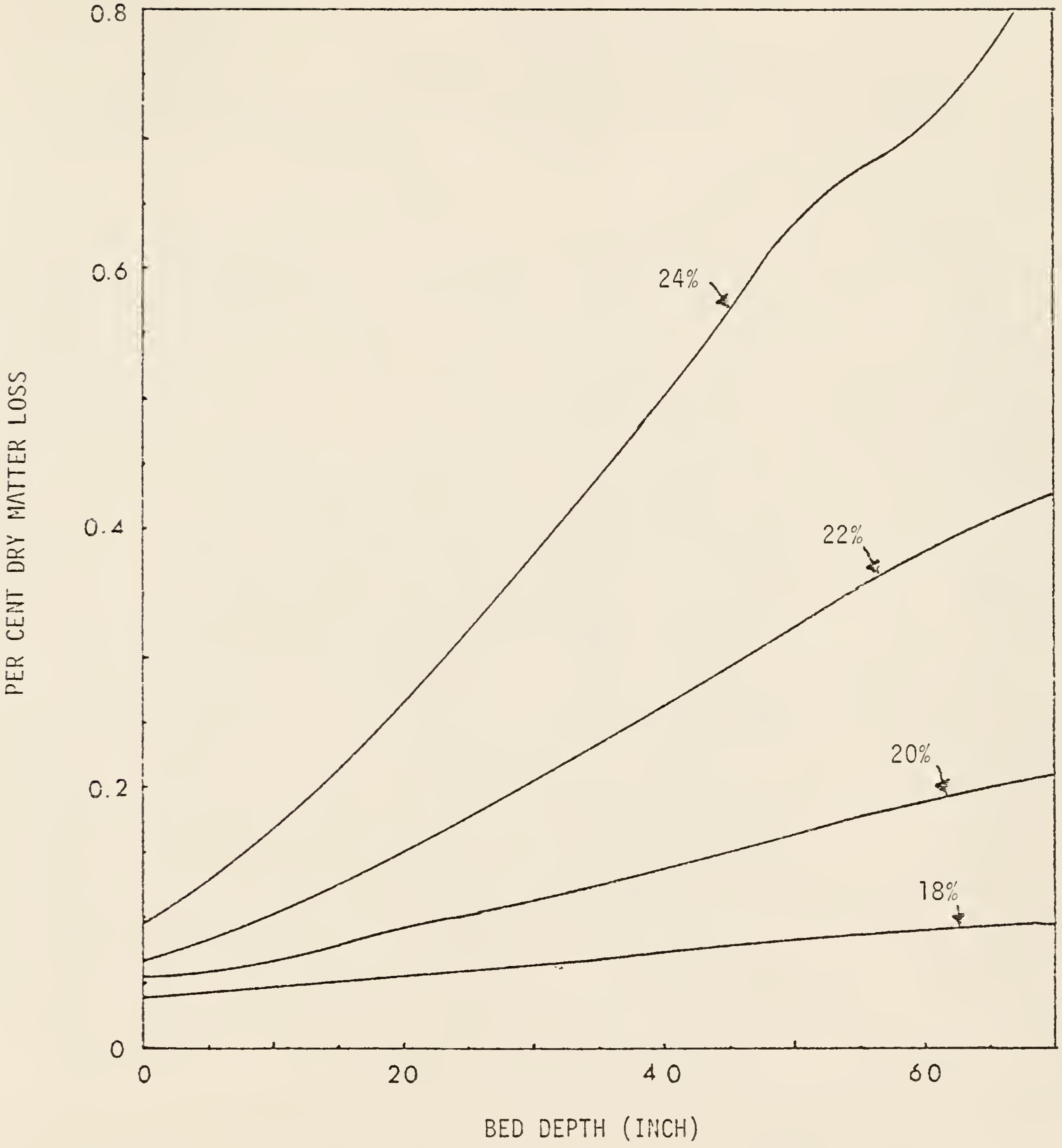


Figure 2.10. Effect of initial moisture content on dry matter loss of rough rice which was dried by 3 cfm per bushel airflow rate with a 6-feet bed depth at 300 hours drying period. Drying was started on September 1.

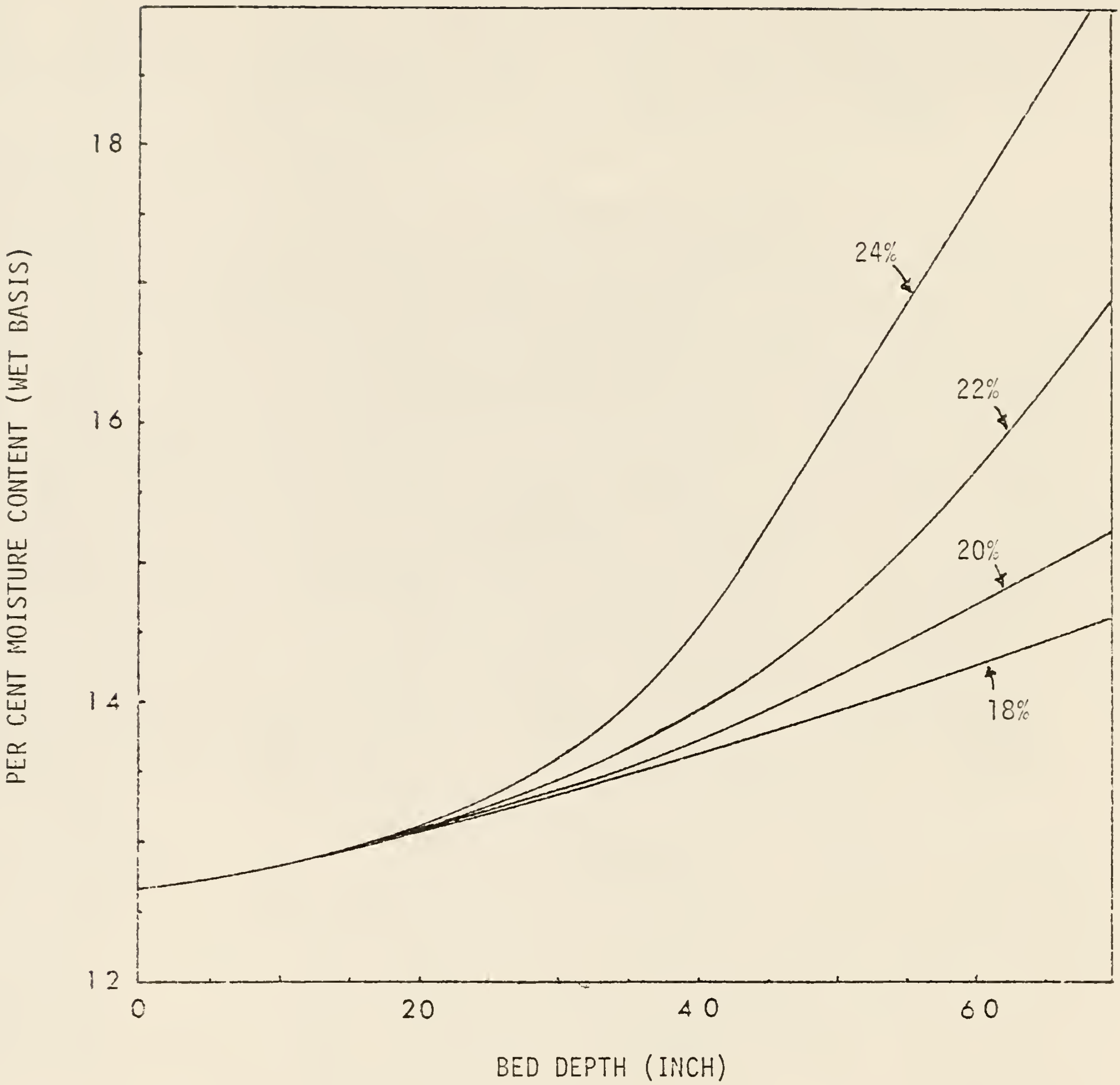


Figure 2.11. Moisture content distribution on bed depth at 300 hours drying time according to initial moisture content when rough rice was dried with 3 cfm per bushel airflow rate, bed depth 6-feet. Drying was started on September 1.

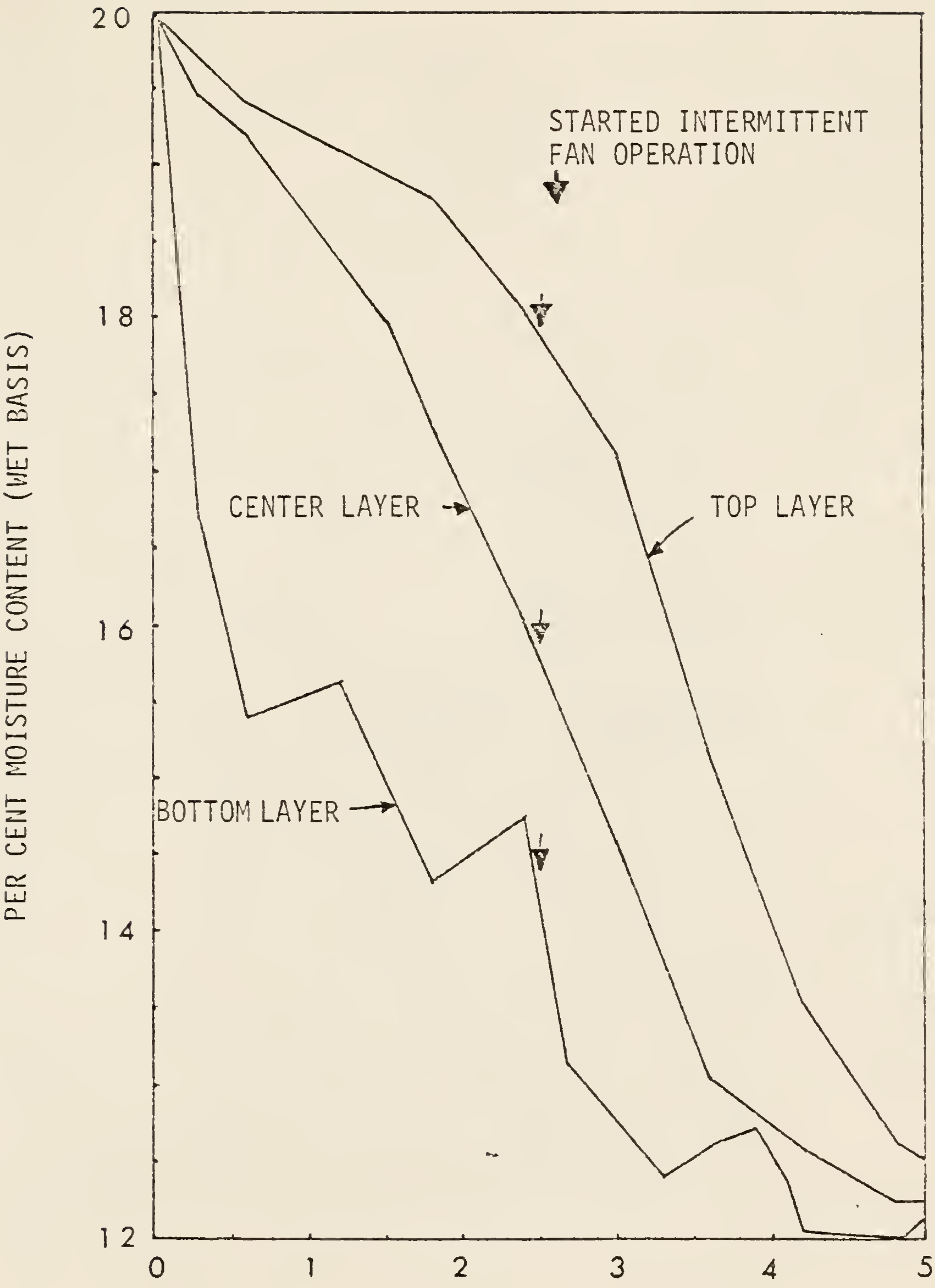


Figure 2.12. Moisture content of each layer of rough rice dried by 2 cfm per bushel airflow rate from September 1. Bed depth was 6-feet, and the initial moisture content was 20 per cent (wet basis).

2.7 Summary and Conclusions

Simulation model of natural air grain drying (KSUDRYER) was discussed and modified to predict the changes of grain moisture content and dry matter loss of rough rice drying. Then the modified simulation model was validated using actual test data.

A series of simulated drying tests using official weather data for 15 years from Beaumont, Texas, was taken and fan models were developed to make minimum airflow rate and maximum bed depth of rough rice drying by natural air. And characteristics of rough rice drying by natural air were discussed.

From the results of this study, the following conclusions were drawn:

1. Simulation model of natural air grain drying (KSUDRYER) can be applicable to rough rice once the properties of specific heat, equilibirum relative humidity (ERH), density (DENSY), the appropriate mass transfer coefficient, and the dry matter loss equations are known.

2. Model validation results showed that the modified model could predict the changes of moisture content of rough rice drying by natural air accurately.

3. In general, natural air drying can be applicable to rice drying under Texas weather conditions using the following parameters: minimum airflow rates for 24, 22, 20, and 18 per cent initial moisture content are 5.0, 3.0, 2.0, and 1.0 cfm per bushel, respectively. Maximum bed depths of 24, 22, 20, and 18 per cent initial moisture content are 3, 5, 7, and 8 feet, respectively. These results show the good agreement with Morrison (1954) and Sorenson and Crane (1960).

4. The higher the airflow rate, the less the drying time required and the lower the dry matter loss.

5. Harvesting data can drastically change the natural air drying results.

6. The higher the initial moisture content, the more the gradient of

the dry matter loss within bed depth.

7. The changes of moisture content of bottom layer is very much sensitive to the weather conditions while the ones of center layer and top layer are less sensitive.

2.8 Suggestions for Further Research

The following suggestions are recommended for the further studies:

1. Study the mass transfer coefficient (Kg) of rough rice to develop the functional relationship with moisture content, grain temperature and airflow rate.

2. Develop the dry matter loss equations for rough rice for the success criterion of simulation.

3. Study optimum horsepower and bed depth for a natural air rough rice drying system having objective function which includes the yearly fixed cost of fan and motor, the cost of electrical energy, and the yearly fixed cost of the drying and storage structure.

2.9 References

✓ 1. ASAE. 1977. *Agricultural Engineers Yearbook*. ASAE, St. Joseph, Michigan.

2. Bloome, P. D. and Shove, G. C. 1971. Near equilibrium simulation of shelled corn drying. ASAE Transaction 14(4): 709-712.

3. Bowersox, D. et al. 1972. *Dynamic simulation of physical distribution systems*. MSU Business Studies, East Lansing, Michigan.

✓ 4. Bloome, P. D. and Shove, G. C. 1972. Simulation of low temperature drying of shelled corn leading to optimization. ASAE Transaction 15(1): 310-316.

✓ 5. Brooker, D. B., Bakker-Arkema, F. W., Hall, C. W. 1974. *Drying Cereal Grains*. AVI Publishing Co., Westport, Conn.

6. Calderwood, D. L. 1966. Use of aeration to aid rice drying. ASAE Transaction 9(6): 893-895.

7. ______________________ 1973. Resistance to airflow of rough, brown, and milled rice. ASAE Transaction 16(3): 525-527.

✓ 8. Christensen, C. M. 1974. *Storage of cereal grains and their products*. American Association of Cereal Chemists.

9. Flood, C. A., Sabbah, M. A., Meeker, D., Peart, R. M. 1972. Simulation of a natural-air corn drying system. ASAE Transaction 15(1): 156-162.

10. Foster, G. H. 1953. Minimum air flow requirements for drying grain with unheated air. Agricultural Engineering 34: 681-684.

11. Haswell, G. H. 1954. A note on the specific heat of rice, oats, and their products. Cereal Chemistry 31: 341-343.

12. Henderson, S. M. 1955. Deep-bed rice drier performance. Agricultural Engineering 36: 817-820.

13. Louisiana State University Agricultural Experiment Station. 1947. Rice drying and storage in Louisiana. Louisiana Bul. 416.

14. Maurer, S. G. 1977. Natural-air grain drying modeling and validation. Unpublished MS thesis, Kansas State University, Manhattan, Kansas.

✓ 15. Morey, R. V. and Peart, R. M. 1971. Optimum horsepower and depth for a natural air corn drying system. ASAE Transaction 14(5): 930-934.

16. Morrison, S. 1954. Drying rice with unheated air. Agricultural Engineering 35: 735-736.

17. Paulsen, M. R., Thompson, T. L. 1973. Drying analysis of grain sorghum. ASAE Transaction 16: 537-540.

18. ✓ Pfost, H. B., Maurer, S. G., Chung, D. S., Milliken, G. A. 1976. Summarizing and reporting equilibrium moisture data for grains. ASAE Paper No. 76-3520. ASAE, St. Joseph, Michigan.

19. ✓ Pfost, H. B., Maurer, S. G., Grosh, L. E., Chung, D. S., Foster, G. H. 1977. Fan management systems for natural air drying. ASAE Paper No. 77-35267. ASAE, St. Joseph, Michigan.

20. Robayo, J. F. 1973. Rice drying rates. Unpublished MS thesis, Kansas State University, Manhattan, Kansas.

21. Saul, R. A. 1970. Deterioration rate of moist shelled corn at low temperature. ASAE Paper No. 70-302. ASAE, St. Joseph, Michigan.

22. Sorenson, J. W., Jr., and Crane, L. E. 1960. Drying rough rice in storage. Texas Agr. Exp. Sta. Bul. B-952.

23. Steele, J. L., Saul, R. A. 1969. Deterioration of shelled corn as measured by carbon dioxide production. ASAE Transaction 12(5): 685-689.

24. Teter, N. C. and Roane, C. W. 1958. Molds impose limitations in grain drying. Agricultural Engineering 39: 24-27.

25. Thompson, T. L., Peart, R. M., Foster, G. H. 1968. Mathematical simulation of corn drying - a new model. ASAE Transaction 11(4): 582-586.

26. Thompson, T. L. 1972. Temporary storage of high moisture shelled corn using continuous aeration. ASAE Transaction 15(2): 333-337.

27. Wratten, F. T., Poole, W. D., Chesness, J. L., Bal, S., Ramarao, V. 1969.; Physical and thermal properties of rough rice. ASAE Transaction 12: 801-803.

APPENDIX

A

KSUDRYER MAIN PROGRAM

```
//RICEDRY  JOB (510755721,BHA3SKN7,,20),DONG IL CHANG',TIME=(,29)       DRYR0010
/*ROUTE  PUNCH DUMMY                                                    DRYR0020
/*TAPE9                                                                 DRYR0030
// EXEC RINGWTR,PARM=9939SM                                             DRYR0040
// EXEC FORTGCLG                                                        DRYR0050
//FORT.SYSIN DD *                                                       DRYR0060
      COMMON/DESAIR/CFMTOT,AREA,ELEVTN,T(20),IG                         DRYR0070
   1  FORMAT(20A4)                                                      DRYR0080
   2  FORMAT(' ',20A4)                                                  DRYR0090
      CALL DATAIN                                                       DRYR0100
  10  READ(5,1,END=100) T                                               DRYR0110
      WRITE(8) T                                                        DRYR0120
C                                                                       DRYR0130
C     IF(NVALID.NE.0) WRITE(NVALID) T                                   DRYR0140
C                                                                       DRYR0150
      WRITE( 6,2) T                                                     DRYR0160
      CALL WEATHR                                                       DRYR0170
      CALL DESIGN                                                       DRYR0180
      CALL TIME                                                         DRYR0190
      GO TO 10                                                          DRYR0200
 100  CONTINUE                                                          DRYR0210
      RETURN                                                            DRYR0220
      END                                                               DRYR0230
```

```
      SUBROUTINE DATAIN
      COMMON/WTRDAT/  NT,NPS,IDT,IDB(720),IRH(720),PATM(720),ITIME(720)
      COMMON/WTRLGE/ ELEV,A0,A1,A2,A3,FACTOR,C0,C1,C2,C3,AB(10)
      COMMON/DESAIR/CFMTOT,AREA,ELEVTN,T(20),IG
    1 FORMAT(7(I3,I2,F5.2),10X)
    2 FORMAT((' ',7(I3,I2,F5.2),10X))
    3 FORMAT((' ',6(2I3,1X,F6.3,1X,I3,5X)))
    4 FORMAT('0',5X,'LIST OF WEATHER DATA CARD DECK',/)
    5 FORMAT('1','NUMBER OF DATA POINTS FOUND =',I5,'  NUMBER OF POINTS
     -SPECIFIED (NPS) =',I5)
    6 FORMAT('0',5X,'LISTING OF WEATHER DATA WITH THE TIME POINTER',/)
      N=1
      NT=0
   10 READ (3,1,END=30) NPS,IDT,ELEV, (IDB(NT+I),IRH(NT+I),PATM(NT+I),I=
     11,NPS)
      WRITE(6,4)
      WRITE(6,2) NPS,IDT,ELEV,(IDB(NT+I).IRH(NT+I),PATM(NT+I),I=1,NPS)
      ITIME(1)= 0
      DO 20 I=1,NPS
   20 ITIME(N+I)=IDT+ITIME(N+I-1)
      N= N+NPS
      NT=NT+NPS
      GO TO 10
   30 CONTINUE
      IF(I.LT.NPS) WRITE(6,5) I,NPS
C               IF THERE HAS BEEN AN ERROR  ON INPUT OF WEATHER DATA STOP
      IF(I.LT.NPS) STOP
      ELEVTN=ELEV*1000.
C
      CALL USSATM
C
      IF(ELEV.NE.1.0) GO TO 50
      DO 40 I=1,NT
   40 PATM(I)=PATM(I)-.4912*ELEV
      WRITE(6,6)
      WRITE(6,3) (IDB(I),IRH(I),PATM(I),ITIME(I),I=1,NT)
      RETURN
   50 CONTINUE
      DO 60 I=1,NT
   60 PATM(I)=29.9186-.4912*ELEV
      WRITE(6,6)
      WRITE(6,3) (IDB(I),IRH(I),PATM(I),ITIME(I),I=1,NT)
      RETURN
      END
```

```
      SUBROUTINE USSATM
      COMMON/WTRLGE/ ELEV,A0,A1,A2,A3,FACTOR,C0,C1,C2,C3,AB(10)
      DIMENSION ALT(11),CONV(11)
      DATA ALT/0.,1.,2.,3.,4.,5.,6.,7.,8.,9.,10./
      DATA CONV /1.,.9653,.9318,.8991,.8674,.8370,.8072,.7785,.7504,.723
     14,.6970 /
      IF(ELEV.GT.0.) GO TO 10
      ELEV=1.0
      RETURN
   10 IF(ELEV.GT.10.) ELEV=ELEV/1000.
      N1=ELEV
      IF(N1 .LE. 2) N1=2
      IF (N1.GE. 10)  N1=9
      A0=ALT(N1-1)
      A1=ALT( N1 )
      A2=ALT(N1+1)
      A3=ALT(N1+2)
      C0=CONV(N1-1)
      C1=CONV( N1 )
      C2=CONV(N1+1)
      C3=CONV(N1+2)
      DO 20 I=1,10
   20 AB(I)=0.0
C
      CALL LAGRNG
C
      ELEV=FACTOR
      RETURN
      END
```

```
      SUBROUTINE LAGRNG                                                 DRYR0970
      COMMON /WTRLGE/ T,T0,T1,T2,T3,X,X0,X1,X2,X3,Y,Y0,Y1,Y2,Y3,Z,Z0,Z1,DRYR0980
     1Z2,Z3                                                             DRYR0990
      DT0= T -T0                                                        DRYR1000
      DT1= T -T1                                                        DRYR1010
      DT2= T -T2                                                        DRYR1020
      DT3= T -T3                                                        DRYR1030
      D01= T0-T1                                                        DRYR1040
      D02= T0-T2                                                        DRYR1050
      D03= T0-T3                                                        DRYR1060
      D10= T1-T0                                                        DRYR1070
      D12= T1-T2                                                        DRYR1080
      D13= T1-T3                                                        DRYR1090
      D20= T2-T0                                                        DRYR1100
      D21= T2-T1                                                        DRYR1110
      D23= T2-T3                                                        DRYR1120
      D30= T3-T0                                                        DRYR1130
      D31= T3-T1                                                        DRYR1140
      D32= T3-T2                                                        DRYR1150
      F0=(DT1*DT2*DT3)/(D01*D02*D03)                                    DRYR1160
      F1=(DT0*DT2*DT3)/(D10*D12*D13)                                    DRYR1170
      F2=(DT0*DT1*DT3)/(D20*D21*D23)                                    DRYR1180
      F3=(DT0*DT1*DT2)/(D30*D31*D32)                                    DRYR1190
      X=F0*X0+F1*X1+F2*X2+F3*X3                                         DRYR1200
      Y=F0*Y0+F1*Y1+F2*Y2+F3*Y3                                         DRYR1210
      Z=F0*Z0+F1*Z1+F2*Z2+F3*Z3                                         DRYR1220
      RETURN                                                            DRYR1230
      END                                                               DRYR1240
```

```
      SUBROUTINE WEATHR                                                 DRYR1250
      COMMON/WTRDAT/  NT,NPS,IDT,IDB(720),IRH(720),PATM(720),ITIME(720) DRYR1260
      COMMON/WRTME/ITCALC,NTPS,DB(720),RH(720),PTM(720),AH(720),APD(720)DRYR1270
      COMMON /WTRLGE/ T,T0,T1,T2,T3,X,X0,X1,X2,X3,Y,Y0,Y1,Y2,Y3,Z,Z0,Z1,DRYR1280
     1Z2,Z3                                                             DRYR1290
      COMMON/RING/GT(30),GM(30),DGLB(30),EQST(30),NLAYRS,NTINC,NTIME,PD DRYR1300
      COMMON /DRY/ RO,PA,PB,PC,CA,C3,DC,DEN1,DEN2                       DRYR1310
    1 FORMAT(I10,F10.4)                                                 DRYR1320
    2 FORMAT('1',5X,'WEATHER DATA AS CALCULATED BY WEATHER SUBROUTINE ANDRYR1330
     ¬D COMMUNICATED TO THE TIME SUBROUTINE',/)                         DRYR1340
    3 FORMAT((' ',5(F5.2,1X,F6.4,1X,F5.2,4X)))                          DRYR1350
C                                                                       DRYR1360
   10 READ(4,1,END=80) ITCALC,DC                                        DRYR1370
C                                                                       DRYR1380
      WRITE(6,1) ITCALC,DC                                              DRYR1390
      DO 20 I=1,NT                                                      DRYR1400
      DB(I)=IDB(I)                                                      DRYR1410
      RH(I)=IRH(I)                                                      DRYR1420
      PTM(I)=PATM(I)                                                    DRYR1430
      IF(NT.NE.NPS    .OR.  ITCALC.NE.IDT)  GO TO 30                    DRYR1440
   20 CONTINUE                                                          DRYR1450
      NTPS=NT                                                           DRYR1460
      GO TO 65                                                          DRYR1470
   30 K=2                                                               DRYR1480
      DO 60 I=2,NT                                                      DRYR1490
C                                                                       DRYR1500
C             ITPTR = CURRENT TIME POINTER                              DRYR1510
C                                                                       DRYR1520
   40 ITPTR=(K-1)*ITCALC                                                DRYR1530
      IF(ITIME(I) .NE. ITPTR)  GO TO 50                                 DRYR1540
      DB(K)=IDB(I)                                                      DRYR1550
      RH(K)=IRH(I)                                                      DRYR1560
      PTM(K)=PATM(I)                                                    DRYR1570
      GO TO 55                                                          DRYR1580
   50 IF(ITIME(I+1) .LT. ITPTR) GO TO 60                                DRYR1590
      J=I                                                               DRYR1600
      IF(I+2 .GT. NT) J=NT-2                                            DRYR1610
C                                                                       DRYR1620
C             T = THE DESIRED BASE POINT WERE DEPENDENT VARIABLES ARE   DRYR1630
C                 TO BE CALCULATED FOR THE WEATHER VARIABLES X, Y AND Z DRYR1640
C                                                                       DRYR1650
      T =ITPTR                                                          DRYR1660
C                                                                       DRYR1670
C             CURRENT BASE POINTS FOR LAGRANGIAN INTERPOLATION TO TIME TDRYR1680
C                                                                       DRYR1690
      T0=ITIME(J-1)                                                     DRYR1700
      T1=ITIME( J )                                                     DRYR1710
      T2=ITIME(J+1)                                                     DRYR1720
      T3=ITIME(J+2)                                                     DRYR1730
      X0=IDB(J-1)                                                       DRYR1740
      X1=IDB( J )                                                       DRYR1750
      X2=IDB(J+1)                                                       DRYR1760
      X3=IDB(J+2)                                                       DRYR1770
      Y0=IRH(J-1)                                                       DRYR1780
      Y1=IRH(  J)                                                       DRYR1790
      Y2=IRH(J+1)                                                       DRYR1800
      Y3=IRH(J+2)                                                       DRYR1810
      Z0=PATM(J-1)                                                      DRYR1820
      Z1=PATM( J )                                                      DRYR1830
      Z2=PATM(J+1)                                                      DRYR1840
```

```
      Z3=PATH(J+2)                                                      DRYR1850
C                                                                       DRYR1860
      CALL LAGRNG                                                       DRYR1870
C                                                                       DRYR1880
C             LAGRANGIAN INTERPOLATED VALUES                            DRYR1890
C                                                                       DRYR1900
      DB(K)=X                                                           DRYR1910
      RH(K)=Y                                                           DRYR1920
      PTH(K)=Z                                                          DRYR1930
C                                                                       DRYR1940
   55 K=K+1                                                             DRYR1950
      GO TO 40                                                          DRYR1960
   60 CONTINUE                                                          DRYR1970
      NTPS=K                                                            DRYR1980
      IF(ITPTR .GT. ITIME(NT)) NTPS=(ITIME(NT)/ITCALC)+1                DRYR1990
   65 CONTINUE                                                          DRYR2000
      DO 70 I=1,NTPS                                                    DRYR2010
      IF(RH(I) .GT. 1.) RH(I)=RH(I) *.01                                DRYR2020
   70 CONTINUE                                                          DRYR2030
      WRITE(6,2)                                                        DRYR2040
      WRITE(6,3) (DB(I),RH(I),PTH(I),I=1,NTPS)                          DRYR2050
      NTINC=ITCALC                                                      DRYR2060
      RETURN                                                            DRYR2070
   80 STOP                                                              DRYR2080
      END                                                               DRYR2090
```

```
      SUBROUTINE DESIGN                                                 DRYR2100
      COMMON/DESAIR/CFMTOT,AREA,ELEVTN,T(20),IG                         DRYR2110
      COMMON/GRAIN/ EMC(27),SPHEAT(18),DEN(19),DCS(9),GRAINS(9)         DRYR2120
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,DC,DEN1,DEN2                       DRYR2130
      COMMON/BINC/GT(30),GM(30),DGLB(30),EOST(30),NLAYRS,NTINC,NTIME,PD DRYR2140
      COMMON/LAYRC  /TO,HO,MO,RHA,TE,HE,ME,ERH,TG,ALB,GLB,ATM,LAYR      DRYR2150
      REAL MO,ME,MW                                                     DRYR2160
      COMPLEX*16 GRAINS                                                 DRYR2170
    1 FORMAT(6F10.0,2I5,10X)                                            DRYR2180
      READ(5,1) MW,TG,CFMTOT,WTGRN,DIA,PD,NLAYRS,IG                     DRYR2190
      ME=MW                                                             DRYR2200
      IF(IG.EQ.0) IG=1                                                  DRYR2210
      IF(IG.GT.9) IG=9                                                  DRYR2220
      IF(MW.GT..5) MW=MW*.01                                            DRYR2230
      MO=MW/(1.-MW)                                                     DRYR2240
      AREA=(3.14159*DIA*DIA)/4.                                         DRYR2250
C                                                                       DRYR2260
      PA=EMC(IG*3-2)                                                    DRYR2270
      PB=EMC(IG*3-1)                                                    DRYR2280
      PC=EMC(IG*3)                                                      DRYR2290
C                                                                       DRYR2300
      CA=SPHEAT(IG*2-1)                                                 DRYR2310
      CB=SPHEAT(IG*2)                                                   DRYR2320
C                                                                       DRYR2330
      DEN1=DEN(IG*2-1)                                                  DRYR2340
      DEN2=DEN(IG*2)                                                    DRYR2350
C                                                                       DRYR2360
      IF(DC.EQ.0.0) DC=DCS(IG)                                          DRYR2370
C                                                                       DRYR2380
      DENSY=DEN1+DEN2*MW                                                DRYR2390
      WGLB=WTGRN/(NLAYRS*AREA)                                          DRYR2400
      GLB=WGLB*(1.-MW)                                                  DRYR2410
      CFMFT2=CFMTOT/AREA                                                DRYR2420
      DEPTH=WTGRN/(DENSY*AREA)                                          DRYR2430
      CALL TABLE(WTGRN,NTINC,ME,DIA,NLAYRS,TG,CFMFT2,DEPTH,PD,WGLB)     DRYR2440
      DO 90 I=1,NLAYRS                                                  DRYR2450
      GT(I)=TG                                                          DRYR2460
      DGLB(I)=GLB                                                       DRYR2470
      EOST(I)=0.0                                                       DRYR2480
   90 GM(I)=MO                                                          DRYR2490
C  FAN MANAGEMENT AND BIN ENHANCEMENT LOGIC GOES HERE                   DRYR2500
      RETURN                                                            DRYR2510
      END                                                               DRYR2520
```

```
      SUBROUTINETABLE(WTGRN,NTINC,ME,DIA,NLAYRS,TG,CFMFT2,DEPTH,PD,WGLB)DRYR2530
      COMMON/DESAIR/CFMTOT,AREA,ELEVTN,T(20),IG                         DRYR2540
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,DC,DEN1,DEN2                       DRYR2550
      COMMON/GRAIN/ EMC(27),SPHEAT(13),DEN(13),DCS(9),GRAINS(9)         DRYR2560
      COMPLEX*16 JBNAME,PARM(2)                                         DRYR2570
      COMPLEX*16 GRAINS                                                 DRYR2580
      REAL*8 CLASS,ACCT                                                 DRYR2590
      LOGICAL*1 OVLY(32)                                                DRYR2600
      EQUIVALENCE (OVLY(1),CLASS),(OVLY(9),ACCT),(OVLY(17),JBNAME),     DRYR2610
     X (PARM(1),OVLY(1))                                                DRYR2620
1     FORMAT('0',4X,'T', T34,'DRYING BED HEIGHT ABOVE BIN FLOOR (INCHES)DRYR2630
     ¬',/,5X,'I',T56,'GRAIN MOISTURES (WB) AT EACH SENSING LOCATION',/, DRYR2640
     15X,'M',/,5X,'E',T15, '1-11-21   2-12-22   3-13-23   4-14-24   5-15DRYR2650
     ¬-25   6-16-26   7-17-27   8-18-28   9-19-29  10-20-30'/)          DRYR2660
2     FORMAT(' ',120('*'))                                              DRYR2670
3     FORMAT(' SIMULATION OF NATURAL-AIR GRAIN CONDITIONING  **  KANSAS DRYR2680
     ¬STATE UNIVERSITY  **   DEPARTMENT OF AGRICULTURAL ENGINEERING  ') CHANG001
4     FORMAT('  ',2A8,2X,'INITAL CONDITIONS',T41,'****',T49,'AERATION BIDRYR2700
     ¬N CONFIGURATION',T80,'**',T87,'MATHEMATICAL MODEL ATTRIBUTES')    DRYR2710
5     FORMAT(' TOTAL WEIGHT OF GRAIN =',F8.0,' LBS.',T41,'****',T47,'TOTDRYR2720
     ¬AL AIRFLOW   =',F6.0,' CFM',T80,'**',T84,'MODELED TIME INTERVAL   DRYR2730
     ¬   =',I7,' HR')                                                   DRYR2740
6     FORMAT(' MOISTURE CONTENT      =',F8.1,' %W.B.',T41,'****',T47,'DIDRYR2750
     ¬AMETER OF BIN =',F6.0,' FT',T80,'**',T84,'NUMBER OF MODELED LAYERSDRYR2760
     ¬   =',I7)                                                         DRYR2770
7     FORMAT(' GRAIN TEMPERATURE     =',F8.1,' DEG F',T41,'****',T47,'AIDRYR2780
     ¬RFLOW IN BIN  =',F6.1,' CFM/FT2',T80,'**',T84,'DEPTH OF GRAIN IN BDRYR2790
     ¬IN        =',F7.1,' FT')                                          DRYR2800
8     FORMAT(' STAIN-TEST DAMAGE     =',F8.0,' %',T41,'****',T47,'BIN ELDRYR2810
     ¬EVATION   =',F6.0,' FT',T80,'**',T84,'WEIGHT OF GRAIN PER LAYER  =DRYR2820
     ¬',F7.1,' LB')                                                     DRYR2830
9     FORMAT(' ',T37,'MATHEMATICAL MODEL EMPIRICAL GRAIN PARAMETERS')   DRYR2840
 10   FORMAT(' CHUNG-PFOST EQUILIBRIUM MOISTURE EQUATION ***  HASWELL,G.CHANG002
     ¬A., SPECIFIC-HEAT EQUATION ** DENSITY EQUATION* DRYING CONSTANT') CHANG003
11    FORMAT('  A=',F10.4,'   B=',F8.4,'   C=',F8.4,'    ***',9X,'CA=', DRYR2870
     ¬F6.3,4X,'CB=',F6.3,8X,'**  B0=',F6.2,'  B1=',F6.2,'  DC=',F6.3)   DRYR2880
12    FORMAT(' ',120('-'))                                              DRYR2890
13    FORMAT(' ',T47,'****',T76,'****')                                 DRYR2900
14    FORMAT(' TITLE: ',20A4,5X,'INVESTIGATOR: ',A8,A6)                 DRYR2910
15    FORMAT(' ')                                                       DRYR2920
      NPRINT=13                                                         DRYR2930
      WRITE(NPRINT,2)                                                   DRYR2940
      WRITE(NPRINT,13)                                                  DRYR2950
      WRITE(NPRINT,3)                                                   DRYR2960
      WRITE(NPRINT,13)                                                  DRYR2970
      WRITE(NPRINT,2)                                                   DRYR2980
      WRITE(NPRINT,4) GRAINS(IG)                                        DRYR2990
      WRITE(NPRINT,2)                                                   DRYR3000
      WRITE(NPRINT,5)  WTGRN,CFMTOT,NTINC                               DRYR3010
      WRITE(NPRINT,6)  ME,DIA,NLAYRS                                    DRYR3020
      WRITE(NPRINT,7)  TG,CFMFT2,DEPTH                                  DRYR3030
      WRITE(NPRINT,8)  PD,ELEVTN,WGLB                                   DRYR3040
      WRITE(NPRINT,15)                                                  DRYR3050
      WRITE(NPRINT,12)                                                  DRYR3060
C     CALL KSUACT(PARM)                                                 DRYR3070
C     WRITE(NPRINT,14) T,JBNAME                                         DRYR3080
      ACCT=0.0                                                          DRYR3090
      WRITE(NPRINT,12)                                                  DRYR3100
      WRITE(NPRINT,15)                                                  DRYR3110
      WRITE(NPRINT,9)                                                   DRYR3120
```

```
      WRITE(NPRINT,2)
      WRITE(NPRINT,10)
      WRITE(NPRINT,11)  PA,PB,PC,CA,CB,DEN1,DEN2,DC
      WRITE(NPRINT,12)
      WRITE(NPRINT,1)
      RETURN
      END
```

```
      SUBROUTINE TIME                                                   DRYR3200
      COMMON/WRTME/ITCALC,NTPS,DB(720),RH(720),PTM(720),AH(720),APD(720)DRYR3210
      COMMON/BINC/GT(30),GM(30),DGLB(30),EQST(30),NLAYRS,NTINC,NTIME,PD DRYR3220
      COMMON/LAYRC  /TO,HO,MO,RHA,TE,HE,ME,ERH,TG,ALB,GLB,ATM,LAYR      DRYR3230
      COMMON/NEWTON/ ICODE(10),KCODE(10)                                DRYR3240
      REAL MO,ME,MW                                                     DRYR3250
    1 FORMAT('0',T24,'****     STATUS OF INTERATION COUNTERS     ****') DRYR3260
    2 FORMAT(' NUMBER OF ITERATIONS',6X,'1',4X,'2',4X,'3',4X,'4',4X,'5',DRYR3270
     -4X,'6',4X,'7',4X,'8',4X,'9',3X,'10')                              DRYR3280
    3 FORMAT(' DEWPT  SUBROUTINE',5X,10I5)                              DRYR3290
    4 FORMAT(' EQLBRH SUBROUTINE',5X,10I5)                              DRYR3300
    5 FORMAT(' ',72('-'))                                               DRYR3310
C                                                                       DRYR3320
C     IF(NVALID.NE.0) WRITE(NVALID) NTPS,NLAYRS                         DRYR3330
      WRITE(8) NTPS,NLAYRS                                              DRYR3340
C                                                                       DRYR3350
      CALL AIRFLO                                                       DRYR3360
C                                                                       DRYR3370
      NTIME=0                                                           DRYR3380
      DO 90 I=1,NTPS                                                    DRYR3390
      TO=DB(I)                                                          DRYR3400
      HO=AH(I)                                                          DRYR3410
      RHA=RH(I)                                                         DRYR3420
      ALB=APD(I)                                                        DRYR3430
      ATM=PTM(I)                                                        DRYR3440
C                                                                       DRYR3450
      CALL BIN                                                          DRYR3460
C                                                                       DRYR3470
      NTIME=NTIME+NTINC                                                 DRYR3480
C                                                                       DRYR3490
      CALL OUTPUT                                                       DRYR3500
C                                                                       DRYR3510
   90 CONTINUE                                                          DRYR3520
      WRITE(6,1)                                                        DRYR3530
      WRITE(6,2)                                                        DRYR3540
      WRITE(6,5)                                                        DRYR3550
      WRITE(6,3) KCODE                                                  DRYR3560
      WRITE(6,4) ICODE                                                  DRYR3570
      RETURN                                                            DRYR3580
      END                                                               DRYR3590
```

```
      SUBROUTINE OUTPUT                                                 DRYR3600
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,DC,DEN1,DEN2                       DRYR3610
      COMMON/BINC/GT(30),GM(30),DGLB(30),EQST(30),NLAYRS,NTINC,NTIME,PD DRYR3620
      DIMENSION DEPS(30),GMW(30),DML(30)                                DRYR3630
      DATA DML /30*0.0/                                                 DRYR3640
    2 FORMAT('0',I5,5X,10F11.3)                                         DRYR3650
    3 FORMAT(' ',10X,10F11.3)                                           DRYR3660
    9 FORMAT(' ',10X,10F11.4)                                           DRYR3670
   11 FORMAT(' ',10X,10F11.4)                                           CHANG004
      NPRINT=13                                                         DRYR3680
      DEPTH=0.                                                          DRYR3690
      DO 30 I=1,NLAYRS                                                  DRYR3700
      GMW(I)=GM(I)/(1.+GM(I))                                           DRYR3710
      WGLB=DGLB(I)/(1.-GMW(I))                                          DRYR3720
      DMLOSS=.0533*(EXP(.006*EQST(I))-1.)+.00102*EQST(I)                DRYR3730
      DML(I)=DMLOSS                                                     DRYR3740
      DENSY=32.4250+33.0*GMW(I)                                         CHANG005
      THICK=WGLB*12./DENSY                                              DRYR3760
      DEPTH=DEPTH+THICK                                                 DRYR3770
      DEPS(I)=DEPTH-.5*THICK                                            DRYR3780
   30 CONTINUE                                                          DRYR3790
      N1=1                                                              DRYR3800
   40 N2=(N1-1)+10                                                      DRYR3810
      IF(N2.GT.NLAYRS) N2=NLAYRS                                        DRYR3820
      IF(N1.EQ.1) WRITE(NPRINT,2) NTIME,(DEPS(I),I=N1,N2)               DRYR3830
      IF(N1.EQ.2) WRITE(NPRINT,3)  (DEPS(I),I=N1,N2)                    DRYR3840
      WRITE(NPRINT,9)(GMW(I),I=N1,N2)                                   DRYR3850
      WRITE(NPRINT,11)(DML(I),I=N1,N2)                                  CHANG006
      N1=N1+10                                                          DRYR3860
      IF(N2.LT.NLAYRS) GO TO 40                                         DRYR3870
      WRITE(8) NTIME,DEPS,GMW,GT,DML                                    DRYR3880
C                                                                       DRYR3890
C     IF(NVALID.NE.0) WRITE(NVALID) NTIME,DEPS,GMW,GT,DML               DRYR3900
C                                                                       DRYR3910
      RETURN                                                            DRYR3920
      END                                                               DRYR3930
```

```
      SUBROUTINE AIRFLO
      COMMON/WRTME/ITCALC,NTPS,DB(720),RH(720),PTM(720),AH(720),APD(720)
      COMMON/DESAIR/CFMTOT,AREA,ELEVTN,T(20),IG
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS
      RWV=85.78
      DO 90 I=1,NTPS
      TA=DB(I)
      RHA=RH(I)
      PS=SATPS(TA)
      PV=RHA*PS
      AHM=(.6219*PV)/(PTM(I)-PV)
      VSA=(AHM*RWV*TR)/(144.*PV)
      APD(I)=(CFMTOT*(1.-AHM)*60.*ITCALC)/(VSA*AREA)
      AH(I)=AHM
   90 CONTINUE
C  FAN MANAGEMENT AND BIN ENHANCEMENT LOGIC GOES HERE
      RETURN
      END
```

```
      SUBROUTINE BIN                                                    DRYR4120
      COMMON/BINC/GT(30),GM(30),DGLB(30),EQST(30),NLAYRS,NTINC,NTIME,PD DRYR4130
      COMMON/LAYRC  /TO,HO,MO,RHA,TE,HE,ME,ERH,TG,ALB,GLB,ATM,LAYR      DRYR4140
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS                            DRYR4150
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,UC,DEN1,DEN2                       DRYR4160
      DIMENSION X(4),EQ(4)                                              DRYR4170
      EQUIVALENCE (TO,X(1)),(TE,EQ(1))                                  DRYR4180
      EQUIVALENCE (TE,TF),(HE,HF),(ME,MF),(ERH,RHF)                     DRYR4190
      REAL MO,ME,MW,MF                                                  DRYR4200
      DO 20 LAYR=1,NLAYRS                                               DRYR4210
      TG=GT(LAYR)                                                       DRYR4220
      MO=GM(LAYR)                                                       DRYR4230
      MW=MO/(1.+MO)                                                     DRYR4240
C                                                                       DRYR4250
C               CALCULATE DRY MARTER LOSS                               DRYR4260
C                                                                       DRYR4270
C DEQST  = DELTA EQUIVALENT STORAGE TIMES                               DRYR4280
C EQST   = EQUIVALENT STORAGE TIMES CUMULATIVE                          DRYR4290
C DMLOSS = DRYMATTER LOSS EXPRESSED AS A PERCENT                        DRYR4300
C PD     = PERCENT DAMAGE AS DEFINED BY STEELE(67)                      DRYR4310
C                                                                       DRYR4320
      DEQST=NTINC/EQCO2(TG,MW,PD,MO)                                    DRYR4330
      EQST(LAYR)=EQST(LAYR)+DEQST                                       DRYR4340
      DMLOSS=.0383*(EXP(.006*DEQST)-1.)+.00102*DEQST                    DRYR4350
      WGLB=GLB/(1.-MW)                                                  DRYR4360
      CC=CA+CB*MW                                                       DRYR4370
C                                                                       DRYR4380
C  HEAT OF COMBUSTION OF CORN = 6771.57 BTU/LB.                         DRYR4390
C DGLB = ARRAY CONTAINING DRY MATTER OF EACH LAYER                      DRYR4400
C                                                                       DRYR4410
      TG=TG+(DMLOSS*.01*GLB*6771.57)/(WGLB*CC)                          DRYR4420
      GLB=DGLB(LAYR)*(1.-.01*DMLOSS)                                    DRYR4430
      DGLB(LAYR)=GLB                                                    DRYR4440
      MO=(MO+.006*DMLOSS)/(1.-.01*DMLOSS)                               DRYR4450
      CALL DEWPT(DP,TO,RHA)                                             DRYR4460
      IF(TG.LE.DP) GO TO 10                                             DRYR4470
C                                                                       DRYR4480
      CALL DRYER(NTINC)                                                 DRYR4490
C                                                                       DRYR4500
      GT(LAYR)=TF                                                       DRYR4510
      GM(LAYR)=MF                                                       DRYR4520
      TO =TF                                                            DRYR4530
      HO=HF                                                             DRYR4540
      RHA=RHF                                                           DRYR4550
      GO TO 20                                                          DRYR4560
C                                                                       DRYR4570
   10 CALL EQLBRM                                                       DRYR4580
C                                                                       DRYR4590
      GT(LAYR)=TE                                                       DRYR4600
      GM(LAYR)=ME                                                       DRYR4610
      TO=TE                                                             DRYR4620
      HO=HE                                                             DRYR4630
      RHA=ERH                                                           DRYR4640
C                                                                       DRYR4650
   20 CONTINUE                                                          DRYR4660
      RETURN                                                            DRYR4670
      END                                                               DRYR4680
```

```
      SUBROUTINE DEWPT(DP,DB,RH)                                        DRYR4690
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS                            DRYR4700
      COMMON/NEWTON/ ICODE(10),KCODE(10)                                DRYR4710
      T=DB+459.69                                                       DRYR4720
      PS=R*EXP((A1+T*(B+T*(C+T*(D+T*E))))/(T*(F-T*G)))                  DRYR4730
      IF(DB.LE.32.) PS=EXP(23.3924-11286.6/T-.46057*ALOG(T))            DRYR4740
      PV=RH*PS                                                          DRYR4750
      N=0                                                               DRYR4760
      CK=1.                                                             DRYR4770
   10 PVDP=R*EXP((A1+T*(B+T*(C+T*(D+T*E))))/(T*(F-T*G)))                DRYR4780
      N=N+1                                                             DRYR4790
      IF(T.LE.491.69) PVDP=EXP(23.3924-11286.6/T-.46057*ALOG(T))        DRYR4800
      FY=PV-PVDP                                                        DRYR4810
      D1=F*T-G*T*T                                                      DRYR4820
      D2=R*EXP((A1+T*(B+T*(C+T*(D+T*E))))/(T*(F-T*G)))                  DRYR4830
      IF(DB.LE.32.) D2=EXP(23.3924-11286.6/T-.46057*ALOG(T))            DRYR4840
      D3=A1+T*(B+T*(C+T*(D+T*E)))                                       DRYR4850
      D4=B+T*(2.*C+T*(3.*D+T*4.*E))                                     DRYR4860
      D5=D1*D1                                                          DRYR4870
      D6=F-2.*G*T                                                       DRYR4880
      DPVDP=D2*(D1*D4-D3*D6)/D5                                         DRYR4890
      IF(T.LE.491.69)DPVDP=(11286.6/(T*T)-(.46057/T))*D2                DRYR4900
      DFY=-DPVDP                                                        DRYR4910
      DELTA=FY/DFY                                                      DRYR4920
      IF(N.GE.5) CK=.5*CK                                               DRYR4930
      T=T-DELTA*CK                                                      DRYR4940
      IF(ABS(DELTA).GT..001 .AND. N.LE.9) GO TO 10                      DRYR4950
      DP=T-459.69                                                       DRYR4960
      KCODE(N)=KCODE(N)+1                                               DRYR4970
      RETURN                                                            DRYR4980
      END                                                               DRYR4990
```

```
      SUBROUTINE DRYER(NTINC)                                           DRYR5000
      COMMON/LAYRC  /TO,HO,MO,RHA,TF,HF,MF,RHF,TG,ALB,GLB,ATM,LAYR      DRYR5010
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS                            DRYR5020
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,DC,DEN1,DEN2                       DRYR5030
      REAL*4 MO,MF                                                      DRYR5040
      PSTG=SATPS(TG)                                                    DRYR5050
      PSA=SATPS(TO)                                                     DRYR5060
      ERH=EXP(-PA/(RO*(TG+PC))*EXP(-PB*MO))                             DRYR5070
C                                                                       DRYR5080
C             MASS DIFFUSION EQUATION                                   DRYR5090
C                                                                       DRYR5100
      MF=MO-NTINC*DC*(ERH*PSTG-RHA*PSA)                                 DRYR5110
C                                                                       DRYR5120
      HF=HO+(GLB/ALB)*(MO-MF)                                           DRYR5130
      TF=(.24*ALB*TO+.45*ALB*HO*TO+1060.8*ALB*(HO-HF)+CA *GLB*(MO+1.)*TGDRYR5140
     *+CB  *GLB*TG*MO)/(.24*ALB+.45*ALB*HF+CB  *GLB*MF+CA *GLB*(MF+1.)) DRYR5150
      PS=SATPS(TF)                                                      DRYR5160
      RHF=(HF*ATM)/(.6219*PS+HF*PS)                                     DRYR5170
      RETURN                                                            DRYR5180
      END                                                               DRYR5190
```

```
      SUBROUTINE EQLBRM                                                 DRYR5200
      COMMON/LAYRC  /TO,HO,MO,RHA,TE,HE,ME,ERH,TG,ALB,CLB,ATM,LAYR      DRYR5210
      COMMON/ JORDAN/ A(20),DELTA(4),N                                  DRYR5220
      COMMON/NEWTON/ ICODE(10),KCODE(10)                                DRYR5230
      EQUIVALENCE (TO,X(1)),(TE,EQ(1))                                  DRYR5240
      DIMENSION X(4),EQ(4)                                              DRYR5250
      REAL*4 MO,ME                                                      DRYR5260
      N=4                                                               DRYR5270
      IOBS=0                                                            DRYR5280
      DMC=1.                                                            DRYR5290
C                                                                       DRYR5300
C              MAKE INITIAL GUESSES OF EQUILIBRIUM                      DRYR5310
C                                                                       DRYR5320
      DO 10 I=1,N                                                       DRYR5330
   10 EQ(I)=X(I)                                                        DRYR5340
C                                                                       DRYR5350
C              CALCULATE THE NEWTON RAPHSON AUGMENTED MATRIX ( A )      DRYR5360
C                                                                       DRYR5370
   20 CALL PARTAL                                                       DRYR5380
C                                                                       DRYR5390
C              SOLVE FOR DELTA BY GAUSS-JORDAN REDUCTION OF ( A )       DRYR5400
C                                                                       DRYR5410
      CALL GAUSS                                                        DRYR5420
C                                                                       DRYR5430
C              NEWTON-RAPHSON ITERATION COUNTER                         DRYR5440
C                                                                       DRYR5450
      IOBS=IOBS+1                                                       DRYR5460
C                                                                       DRYR5470
C              CORRECT CURRENT EQUILIBRIUM VALUES BY DELTA              DRYR5480
C                                                                       DRYR5490
      DO 30 I=1,N                                                       DRYR5500
   30 EQ(I)=EQ(I)-DELTA(I)*DMC                                          DRYR5510
      IF(IOBS.GE. 5) DMC=.5*DMC                                         DRYR5520
      AD1=ABS(DELTA(1))                                                 DRYR5530
      AD3=ABS(DELTA(3))                                                 DRYR5540
C                                                                       DRYR5550
C              IF EQUILIBRIUM ACCURACY REQUIREMENTS ARE NOT MET         DRYR5560
C              RECALCULATE A BETTER ESTIMATE OF EQUILIBRIUM             DRYR5570
C                                                                       DRYR5580
      IF((AD1.GT..05.OR.AD3.GT..0005).AND.IOBS.LT.10)GO TO 20           DRYR5590
      ICODE(IOBS)=ICODE(IOBS)+1                                         DRYR5600
      RETURN                                                            DRYR5610
      END                                                               DRYR5620
```

```
      SUBROUTINE PARTAL                                                 DRYR5630
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,DC,DEN1,DEN2                       DRYR5640
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS                            DRYR5650
      COMMON/LAYEC  /TO,HO,MO,RHA,TE,HE,ME,ERH,TG,ALB,GLB,ATM,LAYR      DRYR5660
      COMMON/ JORDAN/ A(20),DELTA(4),N                                  DRYR5670
      REAL*4 MO,ME                                                      DRYR5680
      IF(TE.LE.0.) TE=0.                                                DRYR5690
      IF(HE.LE.0.) HE=0.00001                                           DRYR5700
      IF(HE.GE..05) HE=.05                                              DRYR5710
      IF(ME.LE..05) ME=.05                                              DRYR5720
      IF(ERH.LE..05) ERH=.05                                            DRYR5730
      IF(ERH.GT.1.) ERH=.99                                             DRYR5740
      PS=SATPS(TE)                                                      DRYR5750
      A(1)=-.24*ALB-.45*ALB*HE-GLB*CA *(ME+1.)-CB  *GLB*ME              DRYR5760
      A(2)=-1060.8*ALB-.45*ALB*TE                                       DRYR5770
      A(3)=-1.201*GLB*TE                                                DRYR5780
      A(4)=0.                                                           DRYR5790
C                                                                       DRYR5800
C  HEAT BALANCE EQUATION                                                DRYR5810
C                                                                       DRYR5820
      A(5)=.24*ALB*(TO-TE)+1060.8*ALB*(HO-HE)+.45*ALB*(HO*TO-HE*TE)+CA  DRYR5830
     ¬*GLB*(MO+1.)*TG+CB  *GLB*TG*MO-CA *GLB*(ME+1.)*TE-CB  *GLB*ME*TE  DRYR5840
C                                                                       DRYR5850
      A(6)=0.                                                           DRYR5860
      A(7)=ALB                                                          DRYR5870
      A(8)=GLB                                                          DRYR5880
      A(9)=0.                                                           DRYR5890
C                                                                       DRYR5900
C  MASS BALANCE EQUATION                                                DRYR5910
C                                                                       DRYR5920
      A(10)=ALB*HE-ALB*HO+GLB*ME-GLB*MO                                 DRYR5930
C                                                                       DRYR5940
      A(11)=EXP(-PA/(RO*(TE+PC))*EXP(-PB*ME))*(EXP(-PB*ME)*(-PA/(RO*(TE+DRYR5950
     ¬PC)**2)))                                                         DRYR5960
      A(12)=0.                                                          DRYR5970
      A(13)=EXP(-PA/(RO*(TE+PC))*EXP(-PB*ME))*(-PA/(RO*(TE+PC))*EXP(-PB*DRYR5980
     ¬ME)*(-PB))                                                        DRYR5990
      A(14)=-1.                                                         DRYR6000
C                                                                       DRYR6010
C  CHUNG PFOST EQUILIBRIUM RELATIVE HUMIDITY EQUATION                   DRYR6020
C                                                                       DRYR6030
      A(15)=EXP(-PA/(RO*(TE+PC))*EXP(-PB*ME))-ERH                       DRYR6040
C                                                                       DRYR6050
      CALL PARTF4(PF4TE,1)                                              DRYR6060
      A(16)=PF4TE                                                       DRYR6070
      A(17)=1.                                                          DRYR6080
      A(18)=0.                                                          DRYR6090
      CALL PARTF4(PF4ERH,2)                                             DRYR6100
      A(19)=PF4ERH                                                      DRYR6110
C                                                                       DRYR6120
C  PSYCHROMETRIC CHART CHART EQUATION                                   DRYR6130
C                                                                       DRYR6140
      A(20)=HE-((.6219*(ERH*PS))/(  ATM -(ERH*PS)))                     DRYR6150
C                                                                       DRYR6160
      RETURN                                                            DRYR6170
      END                                                               DRYR6180
```

```
      SUBROUTINE PARTF4(ANS,N)                                            DRYR6190
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS                              DRYR6200
      COMMON/LAYRC   /TO,HO,MO,RHA,TE,HE,ME,ERH,TG,ALB,GLB,ATM,LAYR       DRYR6210
      GO TO (1,2) ,N                                                      DRYR6220
C   PARTIAL OF PSYCHROMETRIC EQUATION WITH RESPECT TO  TE                 DRYR6230
  1   B1=F*TR-G*TR*TR                                                     DRYR6240
      B2=PS                                                               DRYR6250
      B3=A1+TR*(B+TR*(C+TR*(D+TR*E)))                                     DRYR6260
      B4=B+TR*(2.*C+TR*(3.*D+TR*(4.*E)))                                  DRYR6270
      B5=B1*B1                                                            DRYR6280
      B6=F-2.*G*TR                                                        DRYR6290
      PPS=B2*(B1*B4-B3*B6)/B5                                             DRYR6300
      IF(TE.LE.32.) PPS=((11236.6/(TR*TR))-(.46057/TR))*PS                DRYR6310
      ANS=((   ATM -ERH*PS)*(-.6219*ERH*PPS)-(-.6219*ERH*PS)*(-ERH*PPS))/DRYR6320
     1((   ATM -ERH*PS)*(   ATM -ERH*PS))                                 DRYR6330
      RETURN                                                              DRYR6340
C   PARTIAL OF PSYCHROMETRIC EQUATION WITH RESPECT TO ERH                 DRYR6350
  2   ANS=((   ATM -ERH*PS)*(-.6219*PS)-(.6219*ERH*PS)*PS)/((   ATM -ERH*PDRYR6360
     1S)*(   ATM -ERH*PS))                                                DRYR6370
      RETURN                                                              DRYR6380
      END                                                                 DRYR6390
```

```
      SUBROUTINE GAUSS                                                  DRYR6400
      COMMON/ JORDAN/ A(20),DELTA(4),N                                  DRYR6410
      DIMENSION ID(4)                                                   DRYR6420
    1 FORMAT(' ','DETERMINANT = 0.0')                                   DRYR6430
    2 FORMAT(' ',12F10.5)                                               DRYR6440
    4 FORMAT(' ',5E16.8)                                                DRYR6450
      DO 5 I=1,N                                                        DRYR6460
    5 ID(I)=I                                                           DRYR6470
      EPS=1.0 E-6                                                       DRYR6480
      N1=N+1                                                            DRYR6490
      DO 120 M=1,N                                                      DRYR6500
      IP=(M-1)*N1                                                       DRYR6510
      IC=M                                                              DRYR6520
      IR=M                                                              DRYR6530
      PIVOT=A(IP+M)                                                     DRYR6540
      AMAX=ABS(PIVOT)                                                   DRYR6550
      DO 20 I=M,N                                                       DRYR6560
      IS=(I-1)*N1                                                       DRYR6570
      DO 10 J=M,N                                                       DRYR6580
      IF(ABS(A(IS+J)).LE.AMAX ) GO TO 10                                DRYR6590
      PIVOT=A(IS+J)                                                     DRYR6600
      AMAX=ABS(PIVOT)                                                   DRYR6610
      IC=J                                                              DRYR6620
      IR=I                                                              DRYR6630
   10 CONTINUE                                                          DRYR6640
   20 CONTINUE                                                          DRYR6650
      IF(IR.EQ.M) GO TO 40                                              DRYR6660
C  INTERCHANGE IRTH ROW (ROW WITH PIVOT) WITH MTH ROW (ROW WITH PIVOT LOCDRYR6670
      IS=(IR-1)*N1                                                      DRYR6680
      DO 30 JJ=1,N1                                                     DRYR6690
      DUMMY=A(IP+JJ)                                                    DRYR6700
      A(IP+JJ)=A(IS+JJ)                                                 DRYR6710
      A(IS+JJ)=DUMMY                                                    DRYR6720
   30 CONTINUE                                                          DRYR6730
   40 CONTINUE                                                          DRYR6740
      IF(IC.EQ.M) GO TO 60                                              DRYR6750
C  INTERCHANGE ICTH COLUMN (COLUMN WITH PIVOT) WITH MTH COLUMN (COLUMN CODRYR6760
      DO 50 II=1,N                                                      DRYR6770
      IS=(II-1)*N1                                                      DRYR6780
      DUMMY=A(IS+M)                                                     DRYR6790
      A(IS+M)=A(IS+IC)                                                  DRYR6800
      A(IS+IC)=DUMMY                                                    DRYR6810
   50 CONTINUE                                                          DRYR6820
C  INTERCHANGE ROW INDICATORS FOR DELTA VALUES ACCORDING TO COLUMN CHANGDRYR6830
      IDUMMY=ID(M)                                                      DRYR6840
      ID(M)=ID(IC)                                                      DRYR6850
      ID(IC)=IDUMMY                                                     DRYR6860
   60 CONTINUE                                                          DRYR6870
C  ABSOLUTE VALUE OF THE PIVOT MEANS THAT MATRIX IS SINGULAR AND DETERMIDRYR6880
      IF(ABS(PIVOT).GT.EPS) GO TO 80                                    DRYR6890
      WRITE(6,1)                                                        DRYR6900
      DO 70 I=1,N                                                       DRYR6910
      IS=(I-1)*N1                                                       DRYR6920
   70 WRITE(6,2) (A(IS+J),J=1,N1)                                       DRYR6930
      RETURN                                                            DRYR6940
   80 CONTINUE                                                          DRYR6950
      DIV=1./PIVOT                                                      DRYR6960
C  DIVIDE THE MTH ROW BY THE PIVOT ELEMENT SARTING WITH THE PIVOT LOCATIDRYR6970
      DO 90 J=M,N1                                                      DRYR6980
      A(IP+J)=A(IP+J)*DIV                                               DRYR6990
```

```
  90  CONTINUE                                                          DRYR7000
C  ELIMINATE ALL ROWS I = 1 TO N EXCEPT THE MTH ROW                     DRYR7010
      DO 110 I=1,N                                                      DRYR7020
      IS=(I-1)*N1                                                       DRYR7030
      IF(I.EQ.M) GO TO 110                                              DRYR7040
      AIM=-A(IS+M)                                                      DRYR7050
      DO 100 J=M,N1                                                     DRYR7060
      A(IS+J)=A(IS+J)+AIM*A(IP+J)                                       DRYR7070
 100  CONTINUE                                                          DRYR7080
 110  CONTINUE                                                          DRYR7090
 120  CONTINUE                                                          DRYR7100
C  END OF GAUSS-JORDAN REDUCTION LOOP                                   DRYR7110
C        MATRIX A NOW IS IN THE FORM :  (A) = (I|D)                     DRYR7120
C                  '|' MEANS AUGMENTED BY                               DRYR7130
C                  (D) = DELTA COLUMN VECTOR EQUIVALENT TO (A-INVERSE)*(DRYR7140
C                                                                       DRYR7150
      DO 130 I=1,N                                                      DRYR7160
C                                                                       DRYR7170
C  PUT THE APPROPRIATE VALUES OF A(ID(I),N1) INTO THE DELTA(I)  ACCORDINDRYR7180
C                  PREVIOUS COLUMN INTERCHANGES RECORDED IN THE ID ARRAYDRYR7190
C                                                                       DRYR7200
      IDEL=(I-1)*N1                                                     DRYR7210
      DELTA(ID(I))=A(IDEL+N1)                                           DRYR7220
 130  CONTINUE                                                          DRYR7230
      RETURN                                                            DRYR7240
      END                                                               DRYR7250
```

```
      FUNCTION EQCO2(T,WB,PD,DB)                                        DRYR7260
      RM=.103*(EXP(455./(DB*100.)**1.53)-.845*DB+1.558)                 DRYR7270
      IF(WB.LE..19)  WB=.19                                             DRYR7280
      IF(WB.GT..28) WB=.28                                              DRYR7290
      RT=32.3*EXP(-3.48*(T/60.))+(WB-.19)*EXP(.61*(T-60.)/60.)          DRYR7300
      IF(T.LT.60.) RT=128.76*EXP(-.081*T)                               DRYR7310
      RD=2.08*EXP(-.0239*PD)                                            DRYR7320
      EQCO2=RT*RM*RD                                                    DRYR7330
      RETURN                                                            DRYR7340
      END                                                               DRYR7350
```

```
FUNCTION SATPS(T)                                                 DRYR7360
COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS                            DRYR7370
TR=T+459.69                                                       DRYR7380
SATPS=EXP((A1+TR*(B+TR*(C+TR*(D+TR*E)))))/(TR*(F-G*TR)))*R        DRYR7390
IF(T.LE.32.) SATPS=EXP(23.3924-(11286.6/TR)-.46057*ALOG(TR))      DRYR7400
RETURN                                                            DRYR7410
END                                                               DRYR7420
```

```
      BLOCK DATA                                                        DRYR7430
      COMMON /SYCHAR/ R,A1,B,C,D,E,F,G,TR,PS                            DRYR7440
      COMMON/GRAIN/ EMC(27),SPHEAT(18),DEN(18),DCS(9),GRAINS(9)         DRYR7450
      COMMON /DRY/ RO,PA,PB,PC,CA,CB,CC,DEN1,DEN2                       DRYR7460
      COMMON/NEWTON/ICODE(10),KCODE(10)                                 DRYR7470
      COMPLEX*16 GRAINS                                                 DRYR7480
C                                                                       DRYR7490
C            BROOKER SATURATION PRESSURE EQUATION CONSTANTS             DRYR7500
C                                                                       DRYR7510
      DATA R,A1,B,C,D /3206.18,-27405.5,54.1896,-.045137,.215321E-4/    DRYR7520
      DATA E,F,G /-.462027E-8, 2.41613 ,.121547E-2 /                    DRYR7530
C                                                                       DRYR7540
C            GRAIN (IG) WHICH MODEL IS APLICABLE TO                     DRYR7550
C                                                                       DRYR7560
      DATA GRAINS/                'YELLOW DENT CORN',  '    ROUGH RICE   ',DRYR7570
     ¬   '  GRAIN SORGHUM ',     '  SOYBEAN SEED  ',  '   MILLET SEED   ',DRYR7580
     ¬   ' CHICK-PEA SEED ',     '   SESAME SEED  ',  'GROUNDNUT IN POD',DRYR7590
     ¬   '   WHEAT SEED   ' /                                           DRYR7600
C                                                                       DRYR7610
C            DENSITY EQUATION CONSTANTS FOR GRAIN (IG) DEN=B0+B1*MW     DRYR7620
C                                                                       DRYR7630
      DATA DEN/49.35405,-27.32596,32.42500,33.000,   49.35405,-27.32596,CHANG007
     ¬          49.35405,-27.32596,49.35405,-27.32596,49.35405,-27.32596,DRYR7650
     ¬          49.35405,-27.32596,49.35405,-27.32596,49.35405,-27.32596/DRYR7660
C                                                                       DRYR7670
C            DIFFUSSION COEFFICIENTS FOR GRAIN(IG)                      DRYR7680
C                                                                       DRYR7690
      DATA DCS / .02,.017, .02, .02, .02, .02, .02, .02, .02 /          CHANG008
C                                                                       DRYR7710
C                                                                       DRYR7720
C            CHUNG-PFOST EMC EQUATION CONSTANTS FOR GRAIN (IG)          DRYR7730
C                 A(IG), B(IG), C(IG)                                   DRYR7740
C                                                                       DRYR7750
      DATA RC /1.987/                                                   DRYR7760
      DATA EMC/1110.4268,16.9534,21.3947,   2126.8260,21.7330,32.2654,  CHANG009
     ¬          1110.4268,16.9534,21.3947,   1110.4268,16.9534,21.3947,  DRYR7780
     ¬          1110.4268,16.9534,21.3947,   1110.4268,16.9534,21.3947,  DRYR7790
     ¬          1110.4268,16.9534,21.3947,   1110.4268,16.9534,21.3947,  DRYR7800
     ¬          2793.2200,23.6036,57.6594     /                         DRYR7810
C                                                                       DRYR7820
C           HASWELL,G.A., (54) SPECIFIC HEAT CONSTANTS FOR GRAIN (IG)   CHANG010
C                                                                       DRYR7840
      DATA SPHEAT/.35,.851,  .265,1.070, .35,.851, .35,.851,  .35,.851, CHANG011
     ¬  .35,.851, .35,.851,  .35,.851,  .35,.851  /                     DRYR7860
      DATA ICODE,KCODE/20*0/                                            DRYR7870
      END                                                               DRYR7880
/*                                                                      DRYR7890
```

APPENDIX

B

LAGRANGE PROGRAM

```
      DIMENSION T(20),AX(20),XB(20),SD(20)
      DIMENSION AUTH(5),G(300),DEPA(20),IFMT(20),ATRIB(5)
      DIMENSION GMW(30),GT(30),SHOUR(400),SM(4800),SHT(960),SINT(960)
      DIMENSION SDEP(30),SDIF(960),HOUR(400)
      DIMENSION OFMT1(20),OFMT2(20),OFMT3(20)
      DIMENSION OML(30)
      DIMENSION OUTPUT(21),TITLE(20)
      DATA SCORE /'----'/
      DATA OUTPUT / 21*'    '/
      DATA ATRIB/'MOIS','TURE','    ','TEMP','ERAT','URE '/
 1    FORMAT(10I3,50X)
 2    FORMAT(20A4)
 3    FORMAT(' ',T40,3X,21A4)
 4    FORMAT('0',T45,'MEAN ABSOLUTE DEVIATION =',  F15.4,//,' ',T54,'MEA
     ¬N DEVIATION =',F15.4,//,' ',T30,'STANDARD DEVIATION =',F15.4)
 5    FORMAT(15F5.1)
 6    FORMAT('1',T25,20A4,//(T40,3X,10F8.2))
 7    FORMAT('0A',I3,'TH ORDER EQUATION WAS USED FOR LAGRANGIAN INTERPOL
     ¬ATION.',/,' THE FITTED DEPENDENT VARIABLE WAS ',3A4,'.')
 8    FORMAT('1',T25,20A4)
 9    FORMAT(4I2,F10.2)
 99   FORMAT('0OUTPUT WILL CONSIST OF:')
 100  FORMAT(6X,'INPUT DATA, DEPTH CORRECTED DATA, TIME CORRECTED DATA,
     ¬AND DIFFERENCED TABLES.')
 101  FORMAT(6X,'DEPTH CORRECTED DATA, TIME CORRECTED DATA, AND DIFFEREN
     ¬CED TABLES.')
 102  FORMAT(6X,'TIME CORRECTED DATA, AND DIFFERENCED TABLES.')
 103  FORMAT('0',I6,' COPIES OF THE DIFFERENCED TABLE WERE PUNCHED.')
 104  FORMAT('0',T25,20A4,//(T40,3X,10F8.2))
 105  FORMAT('0',T25,'DIFFERENCED TABLE FOR GRAIN MOISTURES (ACTUAL - SI
     ¬MULATED) IN PERCENT WET BASIS.'/)
 106  FORMAT('0',T25,'DIFFERENCED TABLE FOR GRAIN TEMPERATURES (ACTUAL -
     ¬ SIMULATED) IN DEGREES FAHRENHEIT'/)
 107  FORMAT(T40,3X,10F8.2)
 108  FORMAT('0')
      READ(5,1) NTOBS,NDOBS,ID,IAT,IPUNCH,IPRINT,IMODEL,ITEST
C
C  NTOBS, NUMBER OF TIME OBSERVATIONS   NDOBS = NUMBER OF DEPTH OBSERVATIONS
C  ID = DEGREE OF THE EQUATION USED FOR SMOOTHING
C  IAT =  ATTRIBUTE INDICATOR  0 = MOISTURE  1 = TEMPERATURE
C  IPUNCH = NUMBER OF PUNCHED COPIES OF THE DIFFERENCOD TABLE FOR AARDVARK ANAL.
C  IPRINT = PRINTING OPTION  0 = PRINT INPUT, AND DATA AFTER EACH INTERPOLATION
C        1 = PRINT ONLY AFTER EACH INTERPOLATION
C        2.= PRINT ONLY AFTER THE 2ND INTERPOLATION
C        3 = PRINT ONLY SIMULATED, ACTUAL, AND DIFFERENCED TABLES
C        4 = PRINT NO HEADING JUST THE TABLES OF #3 ABOVE.
C  IMODEL = INDICATOR VARIABLE FOR MATHEMATICAL MODEL
C        1 = EQ #1
C        2 = EQ #2
C        3= EQ #3
C        4 = KSUDRYER
C  ITEST = INDICATOR VARIABLE FOR ANOVA
C  1,1-N,  2,1-S,  3,2-N,  4,2-S,  5,3-N,  6,3-S
C
      NSCORE=2*NDOBS
      IF(NSCOPE.GT.21) NSCORE=21
      IF(IPUNCH.GT.1) IPUNCH=1
      IF(IPRINT.NE.4) WRITE(6,99)
      IF(IPRINT.EQ.0) WRITE(6,100)
      IF(IPRINT.EQ.1) WRITE(6,101)
```

```
      IF(IPRINT.NE.4.AND.IPRINT.NE.1) WRITE(6,102)
      IF(IPRINT.NE.4) WRITE(6,103) IPUNCH
      READ(5,2) TITLE
C  IAT = ATTRIBUTE TYPE 0= MOISTURE  1= TEMPERATURE
C  IFMT = INPUT FORMAT
      IF(IPRINT.NE.4) WRITE(6,7) ID,(ATRIB(3*IAT+I),I=1,3)
C  OFMT = OUTPUT FORMAT
      READ(5,5) (DEPA(I),I=1,NOOBS)
      READ(5,2) IFMT
C  ECHO CHECK OUTPUT FORMAT OF THE INPUT MATRIX
      READ(5,2) OFMT1
C  FIRST AND SECOND INTERPOLATION TABLE FORMAT
      READ(5,2) OFMT2
C  DIFFERENCE TABLE OUTPUT FORMAT
      READ(5,2) OFMT3
      DO 18 I=1,NTOBS
      IM=(I-1)*NOOBS
   18 READ(5,IFMT) HOUR(I),(G(IM+J),J=1,NOOBS)
      DO 19 I=1,NSCORE
   19 OUTPUT(I)=SCORE
C
      READ(8) T
      IF(IPRINT.EQ.0) WRITE(6,104) T
      READ(8) NC,LAYR
      NY=NC*LAYR
      NYB=NC*NOOBS
      NT=NTOBS*NOOBS
      IT=0
      DO 30 IR=1,NC
      IM=(IR-1)*LAYR
      READ(8) NTIME,SDEP,GMW,GT,DML
      SHOUR(IR)=NTIME
      DO 20 L=1,LAYR
      TEMP=GMW(L)
      IF(IAT.EQ.1) TEMP=GT(L)
      SM(IM+L)=TEMP
   20 CONTINUE
      IF(IPRINT.EQ.0) WRITE(6,OFMT1) SHOUR(IR),(SDEP(J),J=1,LAYR)
      IF(IPRINT.EQ.0) WRITE(6,OFMT1) SHOUR(IR),(SM(IM+J),J=1,LAYR)
      CALL LAGRNG(DEPA,SHT,SDEP,SM,IT,ID,IR,LAYR,NY,NOOBS,NYB)
   30 CONTINUE
C
C  PRINT OUT INTERPOLATED TABLE AFTER DEPTH INTERPOLATION
C
      IF(IPRINT.GE.2) GO TO 45
      WRITE(6,6)   T,(DEPA(I),I=1,NOOBS)
      WRITE(6,3) OUTPUT
      DO 40 I=1,NC
      L=(I-1)*NOOBS
   40 WRITE(6,OFMT2) SHOUR(I),(SHT(L+J),J=1,NOOBS)
   45 CONTINUE
C
      IT=1
      CALL LAGRNG(HOUR,SINT,SHOUR,SHT,IT,ID,NOOBS,NC,NYB,NTOBS,NT)
C
C  PRINT OUT ACTUAL ATTRIBUTE TABLE
C
      WRITE(6,6) TITLE,(DEPA(I),I=1,NOOBS)
      WRITE(6,3) OUTPUT
      DO 35 I=1,NTOBS
```

```
      L=(I-1)*NDOBS
   35 WRITE(6,CFMT2) HOUR(I),(G(L+J),J=1,NDOBS)
C
C  PRINT OUT ATTRIBUTE TABLE AFTER INTERPOLATION ON TIME
C
      WRITE(6,108)
      WRITE(6,103)
      WRITE(6,104) T,(DEPA(I),I=1,NDOBS)
      WRITE(6,3) OUTPUT
      DO 50 I=1,NTOBS
      L=(I-1)*NDOBS
      WRITE(6,CFMT2)  HOUR(I),(SINT(L+J),J=1,NDOBS)
   50 CONTINUE
C
C  CREATION OF DIFFERENCE TABLES
C
      SUM=0.
      ASUM=0.
      SS=0.
      WRITE(6,108)
      WRITE(6,108)
      IF(IAT.EQ.0) WRITE(6,105)
      IF(IAT.EQ.1) WRITE(6,106)
      WRITE(6,107) (DEPA(I),I=1,NDOBS)
      WRITE(6,3) OUTPUT
      DO 170 IR=1,NTOBS
      IS=(IR-1)*NDOBS
      DO 160 L=1,NDOBS
      IF(IAT.EQ.0) SDIF(IS+L)=(G(IS+L)-SINT(IS+L))*100.
      IF(IAT.EQ.1) SDIF(IS+L)=(G(IS+L)-SINT(IS+L))
      IF(G(IS+L).NE.0.0) GO TO 150
      SDIF(IS+L)=0.0
      NT=NT-1
      GO TO 160
  150 CONTINUE
      SS=SS+SDIF(IS+L)*SDIF(IS+L)
      SUM=SUM+SDIF(IS+L)
      ASUM=ASUM+ABS(SDIF(IS+L))
  160 CONTINUE
      WRITE(6,CFMT3) HOUR(IR),(SDIF(IS+J),J=1,NDOBS)
  170 CONTINUE
      XBAR=SUM/NT
      AXBAR=ASUM/NT
      SDEV=SQRT((SS-(SUM*SUM)/NT)/(NT-1))
      WRITE(6,4) AXBAR,XBAR,SDEV
      IF(IPUNCH.EQ.0) GO TO 200
      WRITE(7,2) T
      DO 190 J=1,NTOBS
      DO 180 I=1,NDOBS
      IS=(J-1)*NDOBS
      WRITE(7,9) ITEST,IMODEL,J,I,SDIF(IS+I)
  180 CONTINUE
  190 CONTINUE
  200 RETURN
      END
```

```
      SUBROUTINE LAGRNG(XBAR,YBAR,X,Y,IT,ID,IR,NX,NY,IXB,IYB)
      DIMENSION XBAR(IXB),YBAR(IYB),X(NX),Y(NY)
      NX1=NX-1
      IF(IT.NE.0) GO TO 100
C  IS = ISTART POINT FOR THE (IR)TH ROW
      IS=(IP-1)*NX
C  ISY = ISTART YBAR POINTER FOR THE (IR)TH ROW
      ISY=(IR-1)*IXB
C  XBAR-ARRAY LOOP
      DO 60 IX=1,IXB
C  X-ARRAY SEARCH LOOP
      DO 15 IP=1,NX1
      IF(XBAR(IX).NE.X(IP)) GO TO 10
      YBAR(ISY+IX)=Y(IS+IP)
      GO TO 60
   10 CONTINUE
      IF(X(IP+1).GT.XBAR(IX)) GO TO  20
   15 CONTINUE
   20 CONTINUE
      ILESS=IP-ID/2
      IF(ILESS.LE.0) ILESS=1
      IF(ILESS.GT.NX-ID) ILESS=NX-ID
      IABOVE=ILESS+ID
C---------------------------------------|
C  |  NOW THIS CONDITION EXISTS:         |
C  |  X(ILESS) < XBAR(IX) < X(IABOVE)   |
C  |  AND THESE ARE ID+1 POINTS ON THIS |
C  |  INTERVAL.                         |
C  |                                    |
C  |  LAGRANGIAN COEFFICIENT CALCULATION.|
C---------------------------------------|
      CFACT=1.
      DO 30 I=ILESS,IABOVE
   30 CFACT=CFACT*(XBAR(IX)-X(I))
      YB=0.0
      DO 50 I=ILESS,IABOVE
      XFACT=1.
      DO 40 J=ILESS,IABOVE
      IF(I.NE.J) XFACT=XFACT*(X(I)-X(J))
   40 CONTINUE
      YB=YB+Y(IS+I)*CFACT/(XFACT*(XBAR(IX)-X(I)))
   50 CONTINUE
      YBAR(ISY+IX)=YB
   60 CONTINUE
      RETURN
  100 CONTINUE
C  COLUMN LOOP
C  SMOOTHING ACROSS ROWS 1 THROUGH N
C
      DO 170 IC=1,IR
C  XBAR-SEQUENCE LOOP
      DO 160 IX=1,IXB
      ISY=(IX-1)*IR
C  X-ARRAY SEARCH LOOP
      DO 110 IP=1,NX
      IS=(IP-1)*IR
      IF(XBAR(IX).NE.X(IP)) GO TO 105
      YBAR(ISY+IC)=Y(IS+IC)
      GO TO 160
  105 CONTINUE
```

```
      IF(IP+1.GT.NX) GO TO 120
      IF(X(IP+1).GT.XBAR(IX)) GO TO 120
  110 CONTINUE
  120 CONTINUE
      ILESS =IP-ID/2
      IF(ILESS.LE.0)  ILESS=1
      IF(ILESS.GT.NX-ID) ILESS=NX-ID
      IABOVE=ILESS+ID
C-----------------------------------------------|
C   |  NOW THIS CONDITION EXISTS:               |
C   |  X(ILESS)< XBAR(IX) < X(IABOVE)           |
C   |  AND THERE ARE ID+1 POINTS ON THIS        |
C   |  INTERVAL.                                |
C   |                                           |
C   |  LAGRANGIAN COEFFICIENT CALCULATION.      |
C-----------------------------------------------|
      CFACT=1.
      DO 130 I=ILESS,IABOVE
  130 CFACT=CFACT*(XBAR(IX)-X(I))
      YB=0.
      DO 150 I=ILESS,IABOVE
      XFACT=1.
      DO 140 J=ILESS,IABOVE
      IF(I.NE.J) XFACT=XFACT*(X(I)-X(J))
  140 CONTINUE
      IS=(I-1)*IR
      YB=YB+Y(IS+IC)*CFACT/(XFACT*(XBAR(IX)-X(I)))
  150 CONTINUE
      YBAR(ISY+IC)=YB
  160 CONTINUE
  170 CONTINUE
      RETURN
      END
```

```
//LKED.SYSLMOD DD DSN=DS082.LOADLIB,DISP=(OLD,KEEP),UNIT=SYSDA,SPACE=
//LKED.SYSIN DD *
 INCLUDE SYSLMOD(LAGRANGE)
 ENTRY MAIN
 NAME LAGRANGE(R)
/*
//COMPRESS PROC DSN=
//GO EXEC PGM=IEBCOPY,PARM=COMPRESS,TIME=(,20)
//SYSPRINT DD SYSOUT=A
//SYSUT1 DD DSN=&DSN,DISP=OLD
//SYSUT2 DD DSN=*.SYSUT1,DISP=OLD,VOL=REF=*.SYSUT1,SPACE=(0,0,RLSE)
//SYSIN DD DUMMY
//ENDPROC PEND
// EXEC COMPRESS,DSN='DS082.LOADLIB'
/*
```

APPENDIX

C

KSUDRYER INPUTS

```
//RICEDRY  JOB (510785721,8HA3SKN7,,3),'DONG IL CHANG',TIME=(,12)
//A EXEC FORTGG,P=RICEDRY
//STEPLIB DD DSN=DSKN7.LOADLIB,DISP=OLD
//GO.FT08F001 DD UNIT=SYSDA,
// SPACE=(TRK,(16,1)),
// DCB=(BLKSIZE=13030,RECFM=VS),
// DISP=(,PASS),DSN=&&PASSFILE
//GO.FT13F001 DD SYSOUT=A,DCB=(RECFM=UA,BLKSIZE=133)
//GO.FT03F001 DD DDNAME=SYSIN1
//GO.FT04F001 DD DDNAME=SYSIN2
//SYSIN1 DD *
178 3 0.03 9054 0.00 9244 0.00 8940 0.00 7974 0.00 7290 0.00 7195 0.00TST1NPLN 1
 6998 0.00 8370 0.00 9040 0.00 9235 0.00 9036 0.00 8370 0.00 7894 0.00TST1NPLN 2
 7598 0.00 7299 0.00 8470 0.00 9044 0.00 9240 0.00 9046 0.00 8266 0.00TST1NPLN 3
 7736 0.00 7494 0.00 7099 0.00 8568 0.00 9144 0.00 9241 0.00 9246 0.00TST1NPLN 4
 8274 0.00 7884 0.00 7592 0.00 7395 0.00 8290 0.00 9146 0.00 9244 0.00TST1NPLN 5
 8258 0.00 7876 0.00 7694 0.00 7499 0.00 7299 0.00 8590 0.00 9154 0.00TST1NPLN 6
 9251 0.00 8955 0.00 7984 0.00 7599 0.00 7299 0.00 7594 0.00 8770 0.00TST1NPLN 7
 9250 0.00 9443 0.00 9054 0.00 8275 0.00 7988 0.00 7795 0.00 7598 0.00TST1NPLN 8
 8870 0.00 9446 0.00 9543 0.00 9240 0.00 8294 0.00 7892 0.00 7699 0.00TST1NPLN 9
 7599 0.00 8895 0.00 9552 0.00 9344 0.00 9059 0.00 8286 0.00 7994 0.00TST1NPLN10
 7898 0.00 7699 0.00 8970 0.00 9448 0.00 8765 0.00 8574 0.00 7299 0.00TST1NPLN11
 7399 0.00 7299 0.00 7099 0.00 7898 0.00 8582 0.00 8672 0.00 8674 0.00TST1NPLN12
 8290 0.00 7896 0.00 7699 0.00 7599 0.00 8299 0.00 8676 0.00 8862 0.00TST1NPLN13
 8770 0.00 8292 0.00 7897 0.00 7699 0.00 7599 0.00 7999 0.00 8299 0.00TST1NPLN14
 8678 0.00 8676 0.00 8092 0.00 7598 0.00 7498 0.00 7399 0.00 8588 0.00TST1NPLN15
 9061 0.00 8959 0.00 8574 0.00 8188 0.00 7994 0.00 7897 0.00 7599 0.00TST1NPLN16
 8976 0.00 9058 0.00 8381 0.00 8384 0.00 7896 0.00 7898 0.00 7599 0.00TST1NPLN17
 7499 0.00 8980 0.00 9261 0.00 8965 0.00 8678 0.00 8290 0.00 8096 0.00TST1NPLN18
 7999 0.00 7795 0.00 8784 0.00 9254 0.00 8292 0.00 7992 0.00 7699 0.00TST1NPLN19
 7698 0.00 7497 0.00 7397 0.00 8380 0.00 9055 0.00 9240 0.00 9582 0.00TST1NPLN20
 8199 0.00 7799 0.00 7499 0.00 7299 0.00 8653 0.00 9840 0.00 9240 0.00TST1NPLN21
 9052 0.00 8494 0.00 7898 0.00 7699 0.00 7495 0.00 7470 0.00 9147 0.00TST1NPLN22
 9245 0.00 8951 0.00 8478 0.00 8098 0.00 7799 0.00 7699 0.00 8790 0.00TST1NPLN23
 9259 0.00 8397 0.00 8497 0.00 8199 0.00 7899 0.00 7699 0.00 7599 0.00TST1NPLN24
 8699 0.00 9259 0.00 9154 0.00 8668 0.00 7899 0.00 7399 0.00 7699 0.00TST1NPLN25
 7599 0.00 7880 0.00 8457 0.00 8451 0.00                               TST1NPLN26
//SYSIN2 DD *
         3       .020
//SYSIN DD *
KSUDRYER SIMULATION OF NATURAL-AIR RICE DRYING;   VERIFICATION WITH TEST#1-N-PLN
     19.60       90.0       963.    20413.         9.        20.   10    2
/*
//B EXEC FORTGG,P=LAGRANGE
//GO.FT07F001 DD DUMMY
//STEPLIB DD DSN=DSC82.LOADLIB,DISP=SHR
//GO.FT08F001 DD DSN=&&PASSFILE,DISP=(OLD,PASS)
//SYSIN DD *
  7  3  3     4  4  4
** TEST #1-NPLN ** WEIGHTED GRAIN MOISTURE CONTENTS FROM CNRC ** 8/19/76 @ 1PM
  14.  51.  93.
(F4.0,12F4.4,28X)
(' ',F7.0,1X,'I',12F8.4)
(' ',T40,F7.0,'I',12F8.4)
(' ',T40,F7.0,'I',12F8.2)
  23185019201960                 WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
  75143019201950                 WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
 115135016001960                 WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
 140133016701850                 WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
 163132014301920                 WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
 138136013601730                 WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
 216137013901510                 WEIGHTED  GRAIN MOISTURE DATA TEST#1-N-PLN
/*
```

ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to the members of his graduate committee for their support and guidance in the completion of his work.

Heartfelt thanks are due to Dr. Do Sup Chung, the author's major professor, for his continual guidance and suggestions which led to the completion of this work.

Profound gratitude is extended to the Food and Feed Grain Institute, Kansas State University, for financial assistance provided for this project.

Special thanks go to Mr. D. L. Calderwood, Agricultural Engineer, USDA, ARS at Beaumont, Texas, for furnishing the actual test data of rough rice drying. The author also expresses sincere appreciation to Frank Bolduc of the Grain Science and Industry Department, who checked the English of this thesis.

A lifelong gratitutde is due to the author's wife, MoonHan, for her typing draft copies and her physical and spiritual support during this work.

MODELING FOR DRYER SELECTION AND SIMULATION OF NATURAL AIR DRYING OF ROUGH RICE

by

DONG IL CHANG

B.S., Seoul National University, 1972

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1978

Two subjects were studied; one was the mathematical modeling for dryer selection, and the other was simulation of natural air rough rice drying.

The objectives of the study of the former subject were to analyze the thermal efficiencies of several drying systems, to develop the mathematical modeling method for dryer selection, and to suggest an optimized shelled corn drying system for on-farm drying facilities.

The objectives of the study of the latter subject were to make reasonable modifications to the KSUDRYER (Maurer, 1977) to predict the drying results of rough rice by natural air, to investigate the drying characteristics of rough rice at various drying conditions, and to suggest the design parameters of natural-air drying systems of rough rice.

The steps taken for the former subject were: (a) collecting the specifications of dryers made in the U.S.A. and analyzing these specifications, (b) mathematical modeling of the dependent variables as the functions of the independent variables, (c) development of the dependent cost functions, and (d) optimization of the drying system requirements.

The approaches used for the latter subject were: (a) modifying the KSUDRYER for rough rice drying by natural air, (b) validating the modified simulation model using actual test data, (c) simulating rough rice drying using the official weather data (1962 through 1976) for Beaumont, Texas, (d) developing a fan model from the American Standard (Bulletin B-5121) for natural air drying of rough rice, and (e) analyzing the simulation results.

The following conclusions were drawn from the study:

1. The thermal efficiency of natural air drying system is 63.8 per cent and better than any other drying system and that of a continuous-flow drying system is 31.3 to 36.3 per cent.

2. The thermal efficiencies of drying systems have close relationships with annual drying costs which are usually low when thermal efficiency is high.

3. A natural air dryer is an economical drying system at volumes below 2,700 bushels; a natural air dryer with supplemental heat is economical at 2,700 to 20,000 bushels, and a batch-in-bin dryer, from 20,000 to 70,000 bushels. Portable batch and continuous flow dryers, which are very similar in their characteristics, become economically competitive only at volumes of 70,000 bushels or more per year.

4. The KSUDRYER (Maurer, 1977) can be applicable to rough rice once the properties of specific heat, equilibrium relative humidity, density, the appropriate mass transfer coefficient, and the dry matter loss equations are known.

5. A modified model can predict the changes of moisture content of rough rice drying by natural air accurately.

6. In general, natural air drying can be applicable to rice drying under Texas conditions with the following parameters: minimum airflow rates for 24, 22, 20, and 18 per cent initial moisture contents are 5.0, 3.0, 2.0, and 1.0 cfm per bushel; and maximum bed depths for those initial moisture contents are 3, 5, 7, and 8, respectively. These results show compatibility with the results given by Morrison (1954) and Sorenson and Crane (1960).

This investigation showed a definite potential for natural-air grain drying for rough rice in optimized drying systems using a simulation model.