DESIGN OF MULTISTAGE GRAIN DRYERS

Dissertation for the Degree of Ph. D.

MICHIGAN STATE UNIVERSITY

ROGER CHARLES BROOK

1977

PLACE IN RETURN BOX to remove this checkout from your record.
TO AVOID FINES return on or before date due.

DATE DUE	DATE DUE	DATE DUE
[illegible]		

ABSTRACT

DESIGN OF MULTISTAGE GRAIN DRYERS

By

Roger Charles Brook

Grain as a cash crop or a feed crop is economically important in the United States and Canada for both domestic consumption and for export. Of the various crops harvested, shelled corn requires drying, either as ear corn or more commonly as shelled corn. The equipment used to dry shelled corn can be utilized only during the 4-8 week period of harvest. Drying other agricultural products with the same equipment reduces the investment cost per tonne of grain dried. A second crop often requiring drying in Michigan and in Ontario, Canada is pea beans, which are very susceptible to damage during the drying process. Shelled corn and pea beans are the two crops considered in this thesis.

Previous research has shown that the concurrentflow dryer is more energy efficient than the conventional crossflow dryer. The concurrentflow dryer also results in less damage to shelled corn during the drying process than the crossflow dryer. The objective of the thesis was to simulate and optimize the drying of grain in a multistage concurrentflow dryer with intermediate tempering stages and a counterflow cooler. Experimental tests were conducted using a pilot model of a three-stage concurrentflow dryer.

A new computer model was developed to simulate the drying performance of such a multistage concurrentflow dryer. Diffusion within spherical kernels was used to model the drying and tempering process. Single stage concurrentflow dryer simulations agreed well with previously published results. A tempering period of 1.25 hours was found to be satisfactory for a corn kernel temperature of 51°C. The counterflow cooler was modeled using a modified version of the Effectiveness-NTU method derived for a counterflow heat exchanger. The counterflow cooler simulation was, on the average, within 2°C and 0.4% w.b. of previously published results. The multistage model agreed well with the sample data from the experimental samples: (1) for shelled corn an average difference of 5°C and 2.3% w.b. and (2) for pea beans an average difference of 3°C and 0.9% w.b.

The quality of the pea beans and shelled corn as affected by drying was modeled using data from the experimental tests. An equation for the percentage of breakage in the Stein breakage test was developed for shelled corn and one for the percentage of cracked seed coats for pea beans. The calculations from the quality models agreed well with the results of the experimental tests but did not adequately reflect the beneficial effects of the counterflow cooler.

An optimization scheme using dynamic programming was developed for finding the optimum operational parameters and dimensions of a multistage concurrentflow dryer with intermediate tempering stages. The objective function was based on costs for energy consumed during drying and fixed and variable capital costs. The operational parameters were constrained by the desired final moisture content, the maximum allowable exit temperature of the grain from any drying stage, and the maximum allowable value of an important grain quality factor. Costs of 0.447¢/kg and 0.448¢/kg were found for representative two- and three-stage dryers, respectively. Reuse of the exhaust air reduces the drying costs to 0.424¢/kg and 0.405¢/kg, respectively. A representative drying cost of 0.569¢/kg was found for a single-stage concurrentflow dryer. About half (45%-55%) of the total drying cost for multistage concurrentflow dryers was for energy consumed during the drying process.

Energy costs of 0.302¢/kg for a continuousflow crossflow dryer are greater than an average of 0.230¢/kg for concurrentflow dryers. The internal rate of return for the additional investment in a concurrentflow dryer instead of a crossflow dryer would be approximately 15% for a single-stage; 9% for a two-stage; 8% for a three-stage. An investment decision would also include the beneficial effect on grain quality of a multistage versus a single-stage concurrentflow dryer.

Approved F. W. Bakker-Arkema
Major Professor

Approved D. R. Heldman
Department Chairman

DESIGN OF MULTISTAGE GRAIN DRYERS

By

Roger Charles Brook

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

1977

ACKNOWLEDGMENTS

The author wishes to express sincere thanks to Dr. Fred W. Bakker-Arkema for his guidance and encouragement over the past years, and for serving as major professor.

Appreciation is expressed to the members of the guidance committee, not only for their service but also for help during the course of study--Dr. Steve Harsh, Agricultural Economics; Dr. Ben Holtman, Agricultural Engineering; Professor Robert Maddex, Agricultural Engineering; Dr. Gerald Park, Systems Science.

The partial financial support arranged through the Andersons Agricultural Research Fund, Columbus, Ohio, and Westlake Agricultural Engineering, Inc., St. Marys, Ontario, Canada was much appreciated. A special note of thanks to Mr. Chris Westelaken for his personal support and for service on the examining committee.

Special thanks to Ms. Pat Brook for encouragement and support during the course of study and for helping with the typing.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure | Page

LIST OF SYMBOLS

A	constant
A'	constant
AC	annual cost, \$
B	constant
B_s	Stein breakage, %
BC	budgeted capital cost, ¢/kg product dried
C	mass flow specific heat, kJ/hr-m^2-PC
CC	Capital cost factor, \$
CE	energy cost, ¢/kg product dried
CI	95% confidence interval
D	diffusion coefficient, m^2/hr
E	energy use, kJ/kg product dried
F	statistic for variance ratio test
G	dry weight flow rate, kg/hr-m^2
H	air humidity ratio, decimal d.b.
I	minimum cost summation for dynamic programming
IC	investment cost, \$
II	insurance factor, %
IM	maintenance factor, %
IN	interest rate, %
IRR	internal rate of return, %

K	corn fines correction factor
M	local moisture content, decimal d.b.
Ma	Mach number
$\bar{M}$	average kernel moisture content, decimal d.b.
N	assumed product life, yr
NS	net yearly savings, $
Nu	Nusselt heat transfer number
P	price of energy, ¢/kJ
Pr	Prandtl fluid number
PW	present worth, $
Q	volumetric airflow, m^3/m^2-min
R	gas constant
Re	Reynolds fluid flow number
S	change in pea bean cracks, %
SP	static pressure due to airflow, cm H_2O
SV	equipment salvage value, $
T	air temperature, °C
U	dynamic programming control vector
V	velocity, m/min
X	dynamic programming state vector
X^2	goodness-of-fit statistic
a	product specific surface area, m^2/m^3
c	specific heat, kJ/kg-°C
e	effectiveness ratio for counterflow heat exchanger
f	percentage of corn fines
h	enthalpy flow rate, kJ/hr-m^2

h_c convective heat transfer coefficient, kJ/hr-m^2-°C

h_{fg} latent heat of vaporization for water in product, kJ/kg

$h_{fg'}$ latent heat of vaporization for free water, kJ/kg

i cost function for i$^{\underline{th}}$ stage of dynamic programming

j Colburn convective heat transfer factor

k thermal conductivity, kJ/hr-m-°C

n constant

o observed simulation value

p linear correlation significance

r kernel radial coordinate, m

r_c linear correlation coefficient

r_o equivalent kernel radius, m

rh relative humidity, decimal

t time, hr

u kinematic viscosity, m^2/hr

x bed depth coordinate, m

x_1 total bed depth, m

y expected experimental value

symbols used as subscripts

a air

amb ambient

b bulk

c critical statistical value

e equilibrium

f fuel

fm fan/motor combination

i	summation index
o	initial
p	product
v	water vapor
w	water liquid

1. INTRODUCTION

Grain as a cash crop or a feed crop is economically important in the United States (U.S.) and Canada for both domestic consumption and export. Of the cash crops harvested in Michigan, corn requires drying, either as ear corn or artificially dried as shelled corn. The drying equipment used to dry shelled corn can be utilized only during the 4-8 week period of harvest. Drying other crops with the same equipment can help reduce the investment cost per tonne of grain dried. A second crop which will be considered in the following study is pea beans. While pea beans do not require drying every year, they are very susceptible to damage during the drying process.

Shelled corn production in Michigan ranks tenth in the U.S. (Hines et al., 1976). A projection for production of shelled corn for grain forecasts a decrease in corn acreage in Michigan with a corresponding increase in grain yield resulting in a fairly constant level of production as illustrated in Figure 1 (Anon., 1973).

The field sheller produced dramatic changes in corn harvesting methods in the 1960's. For example, only 18% of the Illinois corn acreage was field shelled in 1960 as compared to 70% in 1969 (Hill and Scott, 1969). Shelled corn is usually harvested when the moisture content in the field is 25-30% w.b. and is commonly dried to 15% w.b. to prevent heating due to respiration and excessive deterioration due to mold growth.

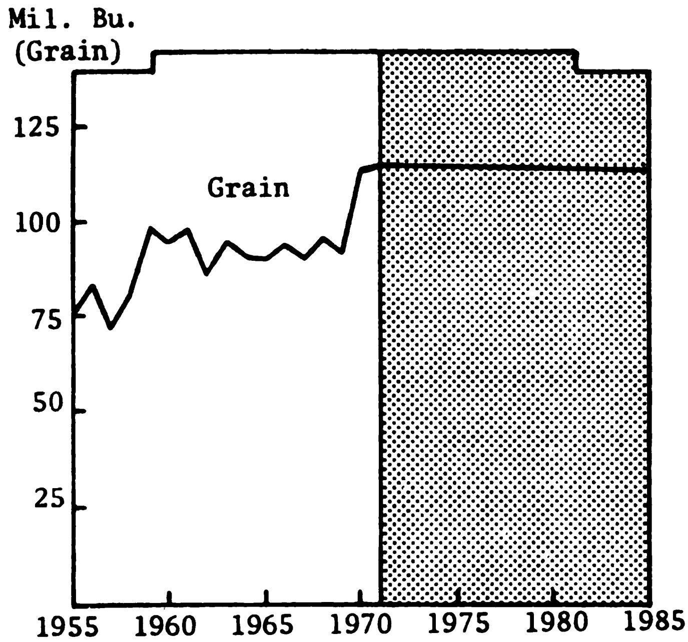


Figure 1. Corn production for grain in Michigan, 1955 to 1971 and projected to 1985.

Source: Anon. (1973).

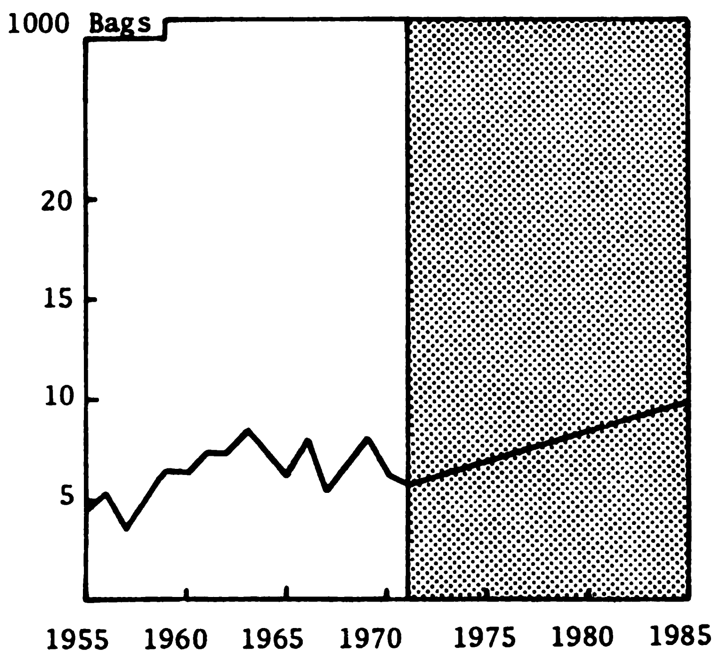


Figure 2. Production of dry beans in Michigan, 1955 to 1971 and projected to 1985.

Source: Anon. (1973).

The necessary decrease in moisture content of shelled corn is accomplished through the use of artificial drying equipment either on the producing farm or at the merchandising elevator. The percentage of the corn crop which was dried on-farm and off-farm for several mid-western states is shown in Table 1. Hill (1970) found on-farm drying to be more profitable than elevator drying when the dried grain is stored and fed on-farm. Hill predicted that, as seasonal labor becomes more expensive and as elevators extend drying capacity at competitive prices, the percentage of grain dried on-farm will decrease.

Table 1.--Drying of corn stored on-farm, 1974-1975.

State	Dried naturally in field or storage		Dried artificially On farm		Off farm	
	1975	1974	1975	1974	1975	1974
			Percent			
MICHIGAN	45.3	40.2	51.0	57.0	3.7	2.8
Illinois	33.5	21.0	65.0	77.5	1.5	1.5
Indiana	12.2	12.0	87.2	86.3	0.6	1.7
Iowa	30.6	37.5	68.4	60.2	1.0	2.3
Wisconsin	45.3	39.7	52.0	57.3	2.7	3.0

Source: Kenyon _et al_. (1976).

Pea beans (often referred to as Navy beans or white beans) are a major cash crop in Michigan. Michigan is the leading state in the U.S. in the production of pea beans (Hines _et al_., 1976). Production of dry beans (pea beans represent three-fourths of the production) in Michigan in 1985 is projected to be 9.9 million bags (100 pounds/bag) as illustrated in Figure 2 (Anon., 1973). Ontario is presenting increasing competition to Michigan in the Navy bean export market as illustrated in Table 2.

Table 2.--Navy bean exports as a percent of North American exports for the 10 year period 1965-1974.

Year	Production (1,000 bags)	
	Ontario	Michigan
1965	35.0	65.0
1966	24.6	75.4
1967	28.3	71.7
1968	32.4	67.6
1969	26.1	73.9
1970	31.8	68.2
1971	50.5	49.5
1972	41.1	58.9
1973	58.1	41.9
1974	49.7	50.3

Source: Anon. (1977).

The weather patterns during growth and maturation of the bean largely determine whether or not any drying is necessary. Most of the beans are marketed directly after harvest. If the moisture content is 20-24% w.b. the beans need to be dried to 17.5-18.0% w.b. for storage. If the moisture content is below 20% w.b. the beans will be placed in aerated storage and the moisture content reduced by aeration. Very little drying is done in Michigan with on-farm dryers (Maddex, 1977). Dry beans stored at 16% w.b. or more can develop mold and musty odors if the storage temperature is greater than 7°C. Storage below 14% w.b. with relative humidities above 70% can also result in mold growth and the development of off-flavors (Adams, 1975).

1.1 Trends in grain dryer design

The on-farm drying of shelled corn started with in-bin drying utilizing a perforated floor which allowed the forced flow of ambient air through the corn mass. This drying process is slow and thus the corn is quite vulnerable to mold for initial moisture contents over 20% w.b. Adding heat to the drying air improves the drying rate but may result in severe overdrying in the bottom layers of the bin. Stirring devices in the bin remove the dry grain from the drying floor and mix it with the partially dried grain. Stirring alleviates to some extent the overdrying problem with little additional energy requirement but at the expense of repeated handling of the dried product.

As the market for corn increased a need arose for high capacity drying systems. In the column batch dryer, which was designed to meet this need, the grain is dried while being held in vertical columns between 40 and 50 cm thick. The natural extension of the column batch grain dryer was the continuous flow crossflow column dryer with integral and rapid cooling. Both drying systems are high capacity, flexible drying devices and are now in common use for drying corn in Michigan. Table 3 shows the distribution of various dryer types used for drying corn on-farm in Michigan during 1974-1975. Corn dried at the elevator is, at the present time, mostly dried in continuous crossflow dryers.

1.2 Dryer energy efficiency

Approximate energy efficiencies for various drying devices are listed in Table 4. Combining these efficiencies with production data

Table 3.--Shelled corn dried artificially by dryer type, Michigan, 1974-1975.

	1974	1975
Continuousflow	45.7	39.5
Batch	38.3	48.1
Bin	14.3	9.2
Natural air	1.7	3.2

and dryer type useage date for Michigan, the increase in energy consumption can be estimated. As shown in Table 5, the energy consumption per kilogram of corn dried has almost doubled during the period 1960-1975.

Increases in energy prices have prompted interest in reducing overall energy consumption. There are several possible alternatives for reducing the energy consumption for drying corn while maintaining the current high-speed drying capacity:

1. Adjust the operating procedure (Morey et al., 1976) or the design (Johnson, 1973) of current high-temperature dryers. An improvement in energy efficiency of 10% would reduce average energy consumption to about 765 kJ/kg corn.
2. Use dryeration (McKenzie et al., 1972) with current or modified high-temperature dryers. Average energy consumption would fall to between 620 and 690 kJ/kg corn.
3. Develop new dryer technology such as the concurrentflow dryer (Graham, 1970; Anderson, 1972).
4. Use heat recovery methods which significantly reduce the energy consumption for drying corn (Bakker-Arkema et al., 1975; Lai and Foster, 1975).

Table 4.--Approximate energy efficiency for various drying technologies.

Drying Technique	Drying Efficiency[a] kJ/kg corn	Comments
1. Drying with ambient air	- -	Slow drying, grain must be below 20% moisture content; vulnerable to mold, weather conditions critical
2. Electric bin[b] drying (1° - 4°C rise)	495	Slow drying rate, mold increase, dependent on weather, good grain quality, limits on moisture content; below 23% w.b.
3. Bin drying[c] without stirring (6°C)	655	Overdrying in bottom layers, difficult to manage for optimum performance
4. Bin drying with stirring (43° - 60°C)	655	Mechanical reliability may be a problem, flexible in grain depth, fast batch procedure
5. Batch or continuousflow with cooling (82° - 104°C)	900	High capacity, flexible, high kernel stress from fast drying and cooling, incomplete air saturation
6. Batch or continuousflow with dryeration[c] (82° - 104°C)	720	Increased capital investment, two handlings to storage, 50-60% increase in throughput, improved product quality

Source: Adapted from Anon. (1975).

[a]Based on drying 10 points (25 to 15% w.b.), 7500 kJ/kg of water for high-temperature dryer, and 5500 kJ/kg of water for bin drying systems.

[b]Electric drying based on 49.6 kJ/kg/point of moisture removed.

[c]Dryeration response is a constant 2 points of drying, assuming a kernel temperature of 49° to 60°C.

Table 5.--Estimated fuel use for Michigan, 1960-1975.

	1960	1965	1970	1975
Corn Production (million kg)[a]	2292	2295	2898	3881
Dryer Types Used, %[b]				
Continuousflow	0	13.2	26.3	39.5
Batch	0	16.0	32.1	48.1
Bin	50	36.4	22.8	9.2
Natural air	50	34.4	18.8	3.2
kJ/kg corn[c]	328	501	675	849
Energy use, 10^{10} kJ	75.2	115.0	195.6	329.5

[a]Adapted from yearly issues of Michigan Agricultural Statistics.

[b]1975 figures from Kenyon et al. (1976). 1960 figures assumed. 1965, 1970 results from linear variation between 1960 and 1975.

[c]Average by dryer type percentage using energy efficiency figures from Table 4.

1.3 Maintaining grain quality

The increased use of the column dryer has increased the susceptibility of the dried corn to breakage during further handling (Thompson and Foster, 1963). Increases in the percentage of broken kernels (BCFM) is not evident in surveys of grain receipts as illustrated in Table 6. However, Paulsen and Hill (1976) have found significant increases in the percentage of broken kernels as corn moves through export market channels. The concurrentflow dryer offers improved quality and reduced susceptibility to breakage as compared to the crossflow dryer (Thompson *et al.*, 1969; Gygax *et al.*, 1974).

Table 6.--Percent of inspected receipts by grade for corn two months following harvest.

Year	#1	#2	#3	#4	#5	Sample
1966	1.4	15.7	27.4	22.1	23.6	9.8
1967	1.6	15.3	30.2	22.1	20.2	10.5
1968	2.0	28.6	35.6	21.6	8.0	4.2
1969	2.1	23.0	30.3	23.7	12.6	8.4
1970	3.1	36.2	27.5	18.2	9.6	5.4
1971	4.8	34.6	33.5	16.0	6.3	4.8

Source: Anon. (1967-1972).

Pea bean drying, when necessary, is usually done at the elevator using crossflow dryers at temperatures of 30°-40°C. Very little is dried on-farm due to problems with cracking of the seedcoat. The grade standard for pea beans is presented in Table 7.

Table 7.--Grade standard for pea beans.

Grade	Comments	Maximum limits of (%)		
		Splits	Damage	FM
US no. 1	Well screened and of good natural color	1.5	trace	trace
US no. 2	Well screened and may be slightly off color	3.0	0.1	0.1
US no. 3	May be of poor color	5.0	0.5	0.5

Source: USDA (1969).

1.4 Objectives

The concurrentflow dryer is more energy efficient than the crossflow dryer (Mühlbauer et al., 1971; Bakker-Arkema et al., 1972) and results in less grain damage due to the drying process (Thompson et al., 1969; Gygax et al., 1974).

The objective of this study is to simulate drying in and to analyze the design of a multistage concurrentflow dryer with intermediate tempering stages and a counterflow cooler. A block diagram of a two-stage concurrentflow dryer is given in Figure 3. The grain enters at the top of the drying column and flows continuously through the drying column at a controlled rate. The heated air flows through a drying stage in the same direction as the grain flow and is used to reduce the moisture content of the grain in that stage. The moisture laden air is exhausted from each drying stage prior to a succeeding tempering stage. Ambient (unheated) air enters the bottom of the counterflow cooler and flows in a direction opposite to the grain. The cooling air is exhausted at the same point as the exhaust air from the previous drying stage.

The first step of the study was to conduct an experimental investigation of a multi-stage concurrentflow dryer using pea beans and shelled corn. In the second step these results were used to verify the computer model developed for the multi-stage drying process. Finally a dynamic programming optimization algorithm using the multi-stage model was constructed to help study the effect of grainflow, staging, tempering and heat recovery on the design and operation of multi-stage concurrentflow drying systems.

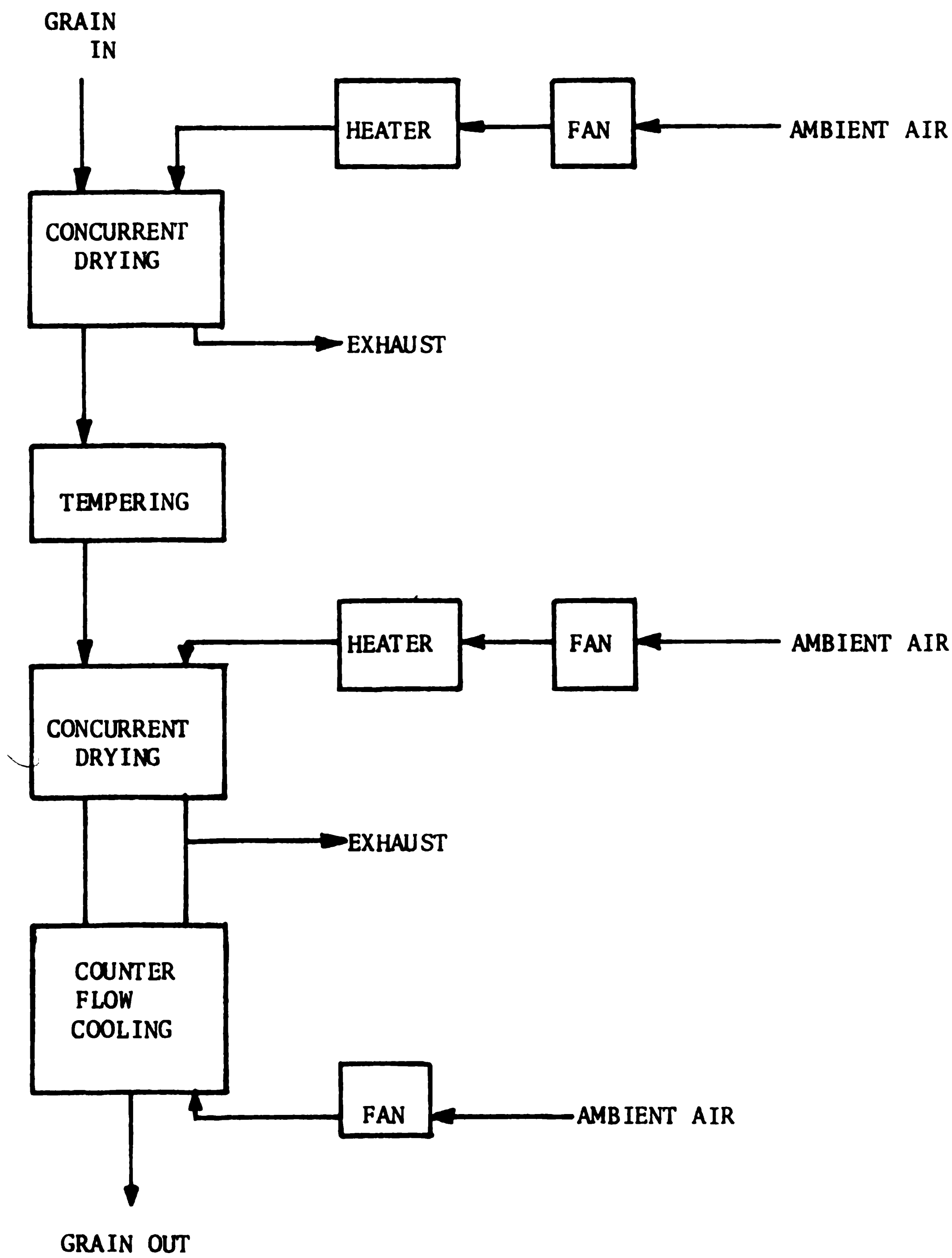


Figure 3. Block diagram of a two-stage concurrent flow dryer with counterflow cooler.

2. LITERATURE REVIEW

The following section presents a literature review of selected areas concerned with the drying of cereal grains.

The review begins with previously published optimization studies concerning the design of convection grain dryers. Next is a summary of the effect of artificial drying on the quality of pea beans and shelled corn. Last is a review of laboratory and computer simulation studies of single-stage concurrentflow dryers.

Other pertinent studies and published results will be reviewed to provide necessary background when needed for a particular subsection in the remainder of the thesis.

2.1 Dryer energy optimization

The design and operational control of cereal grain dryers has been studied using computer simulation for evaluation of dryer performance. The model is often coupled with an optimization algorithm which predicts optimal design and operational parameters.

The objective function used in an optimization procedure varies depending on the specific interest of the program. It may include: (1) drying capacity, (2) various grain quality factors, (3) energy costs for heating and moving the drying air, (4) capital cost considerations for the drying equipment involved, and (5) the amount of moisture removed.

Thompson (1967) defined a general performance function for a dryer operating at fixed drying capacity while removing a specified amount of moisture:

$$\text{Cost} = C_1(\text{drying speed}) + C_2(\text{drying temperature}) + C_3(\text{heat energy supplied}) + C_4(\text{fan energy supplied}) + C_5(\text{size of the dryer required}) \quad (1)$$

where C_1, C_2 are penalty costs for stress cracks and breakage, respectively; C_3, C_4 are the operating costs per unit of energy; and C_5 is the fixed cost per cross-sectional drying area. The optimization algorithm developed was applied to both crossflow and concurrent flow grain dryers using a gradient search technique.

Morey and Peart (1971) studied optimum horsepower and depth in a natural air corn drying system. The objective function was based on the fan energy used and the capital cost of the system. The allowable time before storage (which is a function of grain temperature and moisture content) was used as an operational constraint. Overdrying or underdrying costs were neglected. The optimum system was determined graphically.

Farmer (1972) developed an optimization program for the design and economic analysis of batch-in-bin grain drying systems. The objective function was based on the heat and electrical energy cost equations developed by Bloome (1970). Grain quality was not considered explicitly by the computer program but was constrained implicitly by constraints placed on the dryer operation variables. A two-dimensional optimization routine used a one-dimensional search algorithm to find the optimum values of airflow and heated air temperature. A sensitivity study of operating costs was performed with regard to (Farmer and Bakker-Arkema, 1971): (1) economic conditions, (2) design parameters, and (3) variations in operating and marketing practice.

Thygeson and Grossman (1970) studied the optimum design of through-circulation dryers (crossflow type) for the case of constant rate drying of an arbitrary particulate solid. The objective function was the throughput rate constrained by the power for moving the air and the maximum allowable local final moisture content. Optimization was accomplished through the application of the Kuhn-Tucker optimality conditions.

Brook and Bakker-Arkema (1976) developed a computer simulation model which minimized the operating costs for drying shelled corn in three frequently used dryer types: (1) the continuous crossflow dryer, (2) batch-in-bin dryer, and (3) the column-batch dryer. The objective function is based on the heat and electrical energy costs per bushel of corn dried. After calculating the optimum drying costs, several associated corn quality factors are estimated for the optimum drying conditions: (1) change in test weight, (2) average temperature of the corn leaving the dryer, (3) allowable storage time permitting only 1/2% dry matter loss, and (4) changes in broken kernels due to harvest and drying. Optimization was accomplished through the use of an algorithm which defines a number of points randomly scattered through the variable space. These points are reflected through the centroid until the optimum condition (minimum drying cost) is achieved.

A multiple column crossflow dryer was studied as a means to increase the efficiency of drying and reduce the moisture gradient of the grain at a given drying capacity (Morey and Cloud, 1973). The objective function was based on the moisture content differential, the energy required to move the air and the thermal efficiency (kilograms of water removed per 1000 kJs of energy supplied). A trial and error procedure was used in estimating the relative speeds of grain in the various drying columns to insure that the grain discharged at the desired final average moisture content.

Ahn et al. (1964) proposed dividing the grain column of a conventional crossflow dryer into several sections. The effect of varying the airflow in each section was studied using dynamic programming. The objective was to maximize a profit function based on the amount of moisture removed and the cost of supplying the airflow to each stage. Grain quality was not considered.

Schroeder and Peart (1967) also studied the optimal air distribution pattern in a crossflow dryer using dynamic programming. They defined the "biostrain index," based on the optimal solutions for up to seven sections, as the ratio of the amount of moisture removed in each section to the average moisture content in that section. For the optimal air distribution patterns the biostrain index was essentially constant with a mean of 0.270. The biostrain index for a uniform airflow pattern begins at 0.170 and rises to 0.470 at the end of the drying process.

Bakker-Arkema et al. (1973b) studied a modified crossflow dryer using reversed airflow direction and air recycling in part of the column. Three main parameters were investigated in a sensitivity study: (1) section length, (2) grain column thickness, and (3) drying air distribution. Optimization was accomplished using a bound convergence technique. The objective function was based on the energy requirements for drying with no direct consideration of grain quality factors except the final average moisture content.

The optimal design of the concurrentflow dryer, with or without a counterflow cooler, has also been studied using computer simulation. Thompson (1967) developed a simulation model for a concurrentflow dryer. General performance graphs using the model were developed to study and optimize the design of the dryer. Thompson et al. (1969) compared the performance characteristics of crossflow and concurrentflow grain dryers using general performance graphs for each dryer type.

Farmer (1972) developed a dynamic programming algorithm for a single-stage concurrentflow dryer with a counterflow cooler. The objective function considered energy costs and employed grain quality constraints. Two cases were studied: (1) exhausting the air leaving the dryer and (2) recycling the cooler exhaust air to the inlet of the heater for the drying section. Bakker-Arkema et al. (1973b) compared results obtained using the Farmer algorithm with a commercial concurrentflow grain dryer with a counterflow cooler. The results indicated that the concurrentflow dryer should be operated at higher air temperatures and lower airflow rates (to increase the relative humidity of the outlet air).

Computer simulation for analyzing and optimizing the design of grain dryers is fairly well developed at the academic level. Cost functions for heat and electrical energy use are available for most any air/grain flow configuration (Thompson, 1967; Farmer, 1972; Mühlbauer and Isaacs, 1975; Young and Dickens, 1975). Adequate models for calculating the effect of drying on various grain quality factors are beginning to appear for crossflow and batch dryers (Schroeder and

Peart, 1967; Brook and Bakker-Arkema, 1976). Research work in West Germany is defining some new directions in grain quality determination and its application to grain dryer design and analysis (Mühlbauer and Christ, 1974; Mühlbauer et al., 1976).

Recently dryer manufacturers and dryer operators have become interested in the optimization programs which are available for minimizing energy use in the drying process. The current emphasis on energy conservation and improved grain quality is generating more interest in using computer simulation for establishing standardized ratings for commercially available grain dryers such as proposed by Bakker-Arkema et al. (1973a). Standardized ratings would encourage manufacturers to improve the design of their drying equipment or to be innovative in developing new dryer types (Graham, 1970; Anderson, 1972). The new dryer types can be fairly easily simulated and optimized using established expertise.

2.2 Drying effects on grain quality

Product quality and its determination are important for the marketing and processing of cereal grain. Desirable properties of high quality grain are (Brooker et al., 1974):

1. appropriately low and uniform moisture content
2. low percentage of broken and damaged kernels
3. low susceptibility to breakage
4. high test weight
5. high starch yield
6. high oil recovery
7. high protein quality

8. high viability
9. low mold count
10. high nutritive value

An exhaustive determination of grain quality is not a simple task. The grain dealer is especially interested in (1), (2), (3), and (4); the wet or dry miller in (5), (6), or (7); the farmer seeding corn in (8); the animal feeder in (9) and (10). While not all quality factors are important to every user, they are all affected by the cereal grain drying process.

2.2.1 Stress cracking of pea beans

The U.S. grade standard for pea beans was listed previously in Table 7. Moisture content is not a grade factor. Pea beans which contain more than 18% moisture w.b. are graded according to Table 7 and then designated "high moisture" beans.

Hall and Maddex (1952) dried pea beans at 38°C both with and without partial recirculation of the drying air. As the percentage of recirculation increased the percentage of cracked seed coats (cracks) decreased. No air recirculation resulted in 12 to 18% cracks; cracks decreased to 1.75% at 50% recirculation and 1.25% at 75% recirculation. Even though the drying time increased the reported fuel consumption did not vary significantly due to the increased enthalpy of the air which was recirculated.

Wang (1956) theorized that the cracking of the seed coat was due to unequal shrinkage because of moisture differences between the seed coat and the inner part of the kernel. Applying the theories of engineering mechanics Wang developed an equation for determining whether or not the seed coat was going to crack during a given drying period. The equation was based on: (1) thermal expansion coefficient, (2) moisture contraction coefficient, (3) modulus of elasticity, (4) Poisson's ratio, (5) rate of temperature change, (6) rate of moisture change, and (7) the force exerted on the skin by the kernel due to unequal shrinkage. No attempt was made to define the necessary parameters as a function of drying. An intermittent drying process using air at 38°C was devised consisting of: (1) 15 min. heating at high humidity (adjusted so that the vapor pressure was equal for the air and the beans), (2) 30 min. drying with air at 38°C and 50% RH, (3) 10 min. heating at high humidity, and (4) 30 min. drying with heated air. The process was then repeated after a four hour resting (tempering) period which allowed the strain caused by moisture differences to be relieved as the moisture diffused from the interior of the bean. For beans dried from 20 to 15% moisture, w.b., 1.3% cracks were observed as compared to over 2.0% for a conventional continuous process. Little difference were reported for resting periods of 3, 4, 5, and 6 hours.

Zoerb (1958) studied the mechanical and rheological properties of several grains including pea beans as related to harvesting and handling: (1) yield strength, (2) maximum compressive strength, (3) average shear stress, (4) modulus of elasticity in compression, of resilience, and of toughness, and (5) energy for rupture by both impact and static shear. The parameters which affect these mechanical properties were found to be: (1) moisture content, (2) rate of deformation, and (3) kernel position. The study was made from a macroscopic viewpoint with respect to the pea bean kernel and no attempt was made to separate the effects on the seed coat from those on the interior of the kernel.

Perry (1959) investigated pea bean mechanical damage occurring during commercial handling. The effect of moisture content, temperature and height of drop on mechanical damage was studied. Perry noted that dampening of dry beans restored their ability to resist damage. Bakker-Arkema et al. (1968) modeled the absorption rate in beans as a means to toughen the pea bean kernel to prevent damage during handling.

Narayan (1969) computed the elastic modulus of pea beans for various moisture contents in the range of 11.5-28.8% moisture w.b. for beans quasi-statically loaded. Narayan concluded that beans suffer the least damage due to impact when the moisture content is in the range of 13.4-15.6% w.b.

Soybeans are very similar in structure to pea beans with an outer seed coat and two inner cotyledon halves and thus may be expected to behave very similarly to pea beans. Walker and Barre (1972) studied the effect of drying on soybean germination and cracking. Tests were conducted for the following range of drying conditions: (1) air temperatures 32°C-66°C and (2) 20-60% RH. They concluded that no seed coat cracks developed for relative humidities greater than 40%.

2.2.2 Stress cracks and broken corn

Drying shelled corn with hot air increases the percentage of stress cracks found in the kernels. Stress cracks are cracks in the starchy endosperm inside the kernel which do not rupture the seed coat. Stress cracks are generally divided into three categories according to the pattern formed in the kernel: (1) single, (2) multiple, and (3) checked. The three categories are compared in Figure 4. Thompson and Foster (1963) related the extent of the development of stress cracks for yellow corn dried in a crossflow dryer to the overall drying rate, expressed as moisture loss in percentage points per hour. Drying air temperatures in the range of 60°-117°C were used. The relationship between stress cracks and drying rate has been confirmed for white corn (White and Ross, 1972) and for east European yellow corn varieties (Katic, 1973).

Grain is often cooled as the last step in the drying process. White and Ross (1972) found that rapid cooling of high temperature corn causes a high percentage of stress crack development. Slow cooling (cooling to ambient temperature in a polystyrene insulated chamber) resulted in a significant reduction in the percentage of stress cracked kernels. Foster (1973) reported that while a conventional crossflow dryer with rapid cooling may produce as much as 90% stress cracked kernels, delayed cooling (dryeration) could reduce this to 40% as compared to natural air drying producing 8% stress cracked kernels.

The susceptibility of corn to breakage during handling is related to the amount of stress cracking of the kernels which occurs during the harvesting and drying processes. Thompson and Foster (1963) found that shelled corn artificially dried using heated air was two to three times more susceptible to breakage than corn dried with natural air. McGinty (1970) confirmed that heat dried corn showed higher susceptibility to breakage with increasing drying air temperature and airflow rate.

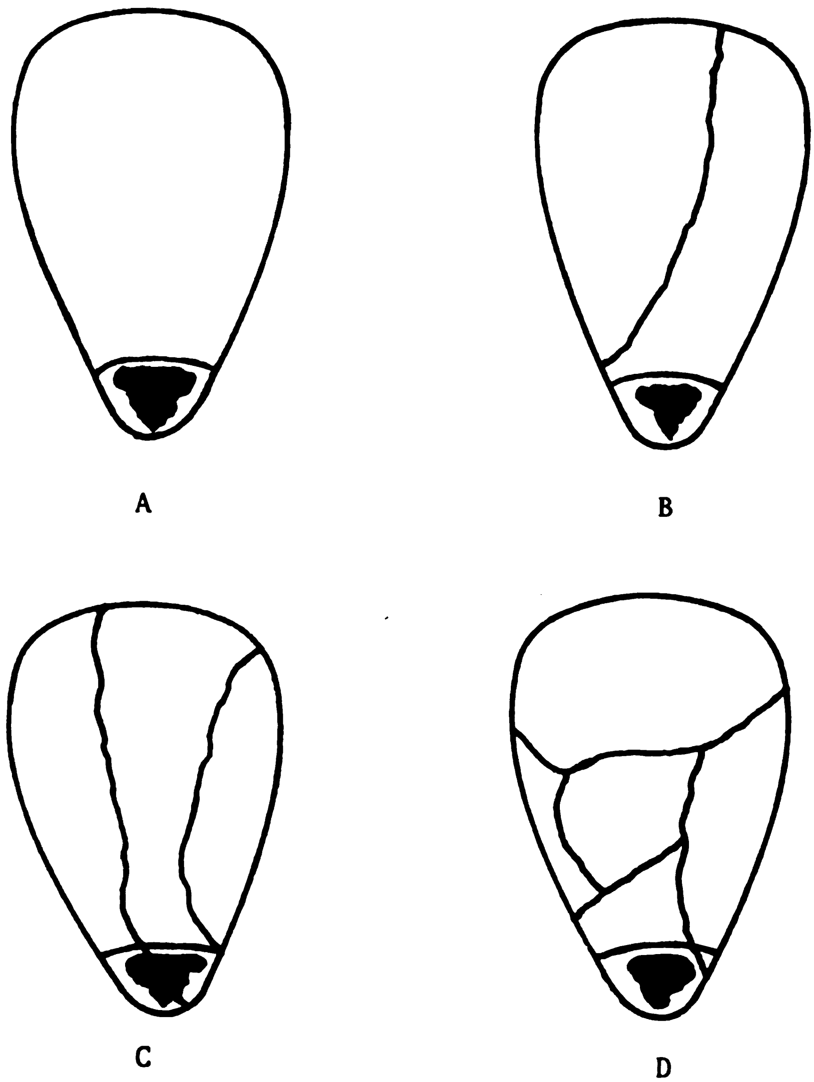


Figure 4. Types of stress cracks in dried corn kernels.
A--Whole kernels
B--Single stress cracks
C--Multiple stress cracks
D--Checked kernels

Source: Thompson and Foster (1963).

Agness (1968) described a breakage test which can be used to provide an evaluation of the mechanical damage inflicted on corn during harvesting, handling and drying. The corn sample is placed in an aluminum container. An impeller revolves around inside the container for a period of two minutes. The sample is removed and the percentage of material passing through a 0.48 cm round-hole screen is the percentage of breakage. The test is commonly referred to as a Stein breakage test. The grain samples should be carefully conditioned to a common moisture content to make comparisons valid. Stephens and Foster (1976) related the amount of breakage due to handling to the results of the Stein breakage test. Corn dried in the field resulted in 3.0% breakage, corn dried in a low temperature (38°-53°C) bin dryer in 11.6%, and corn dried in a high temperature (93°-106°C) batch dryer in 36.6%. Multiple runs with four different spouting arrangements yielded a linear correlation between handling breakage and tester breakage with a correlation coefficient of $r_c = 0.98$.

The theories of engineering mechanics have application in describing stress crack formation in shelled corn. Thompson and Foster (1963) reported that corn kernels dried at 143°C were puffed and the crown almost completely inflated. Ekstrom _et al_. (1966) determined the coefficient of cubical thermal expansion of corn kernels as a function of kernel temperature and moisture content. The strain produced by the expansion can be related to the stress inside the kernel. Hammerle _et al_. (1971) found that the horny endosperm of corn kernels is thermo- and hydro-rheologically simple. Therefore the time behavior of the mechanical properties of the material can be analyzed at one common temperature and moisture content. The properties at other temperatures and moisture contents are computed through multiplication by a temperature or moisture shift-factor based on the standard and the desired temperature or moisture. The complete mechanical behavior of corn horny endosperm was described by the following rheological properties: (1) bulk modulus, (2) shear modulus, (3) tension modulus, (4) Poisson's ratio, (5) failure stress, and (6) the time-temperature and time-moisture shift factors. Mensah et al. (1976) studied the effect of various drying conditions on the impact fracture resistance of different corn varieties as related to: (1) energy absorbed per unit shear area, (2) maximum resistive shear stress, and (3) impulse imparted by an impact apparatus. Overall kernel strength was reduced in kernels dried at 93°C compared to kernels dried at 60°C. Genetic differences were found to be significant; for the three varieties tested, one was found to be more resistant to damage than the other two.

When applying engineering mechanics to grains such as corn one has to recognize that the kernel is not homogeneous. Corn consists of four distinct parts: (1) horny endosperm, (2) floury endosperm, (3) germ, and (4) seed coat. Analysis of the kernel must include all factors and their interrelationships. For structural quality the floury endosperm and the seed coat are most important. For oil recovery or when used for seed the germ is most important. While inroads have been made in this area, there is more research necessary before a useable, stochastic model of the kernel can be developed.

2.2.3 Milling quality

Kernel temperature during drying has a significant effect on starch quality and yield. Lasseran and Boigneville (1973) dried western European shelled corn in a batch dryer at temperatures from 40° to 150°C. When the drying temperature was greater than 100°C a depressive effect on starch yield was observed, decreasing from 67% at 90°C to 58.7% at 150°C. Further tests in a continuous crossflow dryer showed that drying at an air temperature of 140°C resulted in an 11.6% decrease in starch yield as compared to drying at 80°C. Lasseran and Boigneville speculated that two-stage drying with intermediate storage under aeration may be acceptable. French (1973) stated that when native starch (either corn or potato) is gradually heated (up to 55°C) the change in the starch granule is reversible and so the starch remains essentially unaltered after drying and cooling. If heating is continued in the range of 60°-80°C irreversible gelatinization occurs such that after cooling the starch will be a semi-rigid gel.

Oil recovered by wet milling of corn is derived entirely from the germ. Vojnovich et al. (1975) studied quality of corn dried in an experimental fluidized-bed batch dryer. A regression analysis of oil recovery versus drying temperature in the range of 49°-149°C showed that recoverable oil decreased with increasing temperature at the rate of 0.3%/°C ($r_c = 0.95$). Stress cracked and broken kernels may result in a damaged germ. Freeman (1973) reported that as much as 90% of the oil in these damaged germs may be absorbed by the gluten in the endosperm prior to or during processing. Overhults et al. (1975) concluded that the overall quality of the oil obtained from soybeans did not significantly deteriorate when beans were dried in thin layers at air temperatures up to 100°C. Some interior breakdown was evident at the higher temperatures indicating that at temperatures greater than 100°C soybeans may begin to show deterioration in oil quality.

Peplinski et al. (1975) recommended that, on the basis of several quality factors, the temperature of corn used for milling should not exceed 80°C; no time-temperature relationship was established. Mühlbauer and Christ (1974) have shown that not only is the temperature of the corn important but the time at that temperature is equally important. For example, only a light browning of the kernel was evident for exposure to 140°C air for 16 min. while a very strong browning was evident after 30 min. The cause of the browning was suggested to be a chemical reaction between the carbohydrates and the proteins.

2.2.4 Grain viability

Seed grains require a high germination percentage. High kernel temperatures kill the germ and thus grain used for seed cannot be dried under excessive kernel temperature conditions. Kreyger (1972) determined the critical kernel temperature for a number of small grains as a function of equilibrium relative humidity as given in Table 8. It is obvious that there is a significant difference between the various grain species. Wheat germination is the least heat sensitive followed by oats, corn and rye. Germination of all grains is more heat sensitive at high than at low moisture contents.

2.2.5 Nutritive value

A large part of the shelled corn harvested in the U.S. is used as animal feed. Williamson (1975) suggested several physical

Table 8.--Critical kernel temperature as a function of equilibrium relative humidity for several small grains (criterion: less than 5% viability decrease).

RH, %	60	70	80	90
Oats	59	55	50	--
Wheat	63	62	58	52
Corn	52	51	48	46
Rye	53	50	45	41

Source: Kreyger (1972).

characteristics which are important when considering corn for animal feed: (1) provides a uniform and consistent ration, (2) provides a relatively high energy content, (3) provides a palatible ration, (4) generally is free of mold and other toxic factors, and (5) provides a major portion of the protein needs.

Assessing the effect of heat treatment on the nutritive value of corn is a very difficult task; different animals have different nutritive requirements. The energy contained in the starch of a corn kernel provides a consistent energy level in many ruminant rations. However, mink and broilers require a more concentrated energy source in the form of fat for optimum performance (Williamson, 1975). Sullivan et al. (1975) reviewed the work of several researchers on the effect of heat treatment on corn used for swine and beef rations. They concluded that heat treatment has the following effects: (1) increases bulk of the grain, (2) increases feed value for ruminants, and (3) heat damaged corn has a greater economic value than allowed under U.S. grade standards.

Mühlbauer and Christ (1974) investigated the influence of kernel temperature and time at that temperature on the nutritive value of corn used for animal feed. The quality criterion used was the content of the amino acids methionine, cystine and lysine. Rapid drying of corn kernels in a single layer with heated air at 180°C resulted in less decrease in amino acid content than longer drying at lower temperatures (140°, 160°C). Wall et al. (1975) dried corn in a fluidized bed dryer with air temperatures in the range of 15°-143°C. Significant variations in amino acid content were found only for lysine and arginine. They concluded that at grain temperatures less than 100°C little or no damage to amino acids occurs (no time-temperature relationship noted). Vojnovich et al. (1975) concluded that higher drying temperatures affect the solubility of certain proteins and sugars normally present in corn.

Nutritive changes in grain due to drying can be determined using a combination of analytical methods and animal feeding trails. The latter, however, is time consuming and expensive. A rapid method to evaluate the effect of drying on the nutritive value of grain is necessary. Bjarnason and Carpenter (1969) stated that enzyme-resistant linkages between the carbonyl groups of sugars and the free amino groups of proteins, particularly lysine, can make a portion of the amino acids nutritionally unavailable after drying. Mühlbauer et al. (1976) conducted an extensive investigation using various drying conditions and concluded that changes in lysine content (which can be related to nutritive value) could be correlated linearly (r_c = 0.74-0.82) with color changes in the kernels.

2.3 Concurrentflow grain drying

Concurrentflow grain dryers have only recently become available commercially. In a concurrentflow dryer the air and the product both flow in the same direction through the dryer as illustrated in Figure 5. The hottest air encounters the wettest grain so that the air is cooled rapidly due to the high rate of evaporation as illustrated in Figure 6. The kernel temperature remains considerably below the air temperature in the top layers of the dryer because the kernels are not exposed to the heated air for a long period of time during this period of high evaporation (Farmer et al., 1972).

The concurrentflow dryer has advantages over the crossflow dryer because of its favorable energy efficiency, grain quality characteristics, and pollution qualities. The initially high rates of evaporation allow the use of drying air temperatures as high as 148°-260°C without causing excessive grain kernel temperatures. The high drying air temperature results in a high energy efficiency for the dryer. Energy efficiencies between 4185-5120 kJ/kg of water evaporated are common for concurrentflow grain dryers. Crossflow dryers average about 7500 kJ/kg of water evaporated (Mühlbauer and Isaacs, 1975).

The concurrentflow dryer subjects all grain kernels to the same drying treatment thus avoiding non-uniformity in moisture content inherent in crossflow dryers. The grain temperature continually decreases through the last portion of the drying bed (Figure 6). This helps to reduce drying stress, stress cracking, and subsequent mechanical damage when the dried grain is handled. The increase in checked and multiple stress cracked kernels in a crossflow dryer is

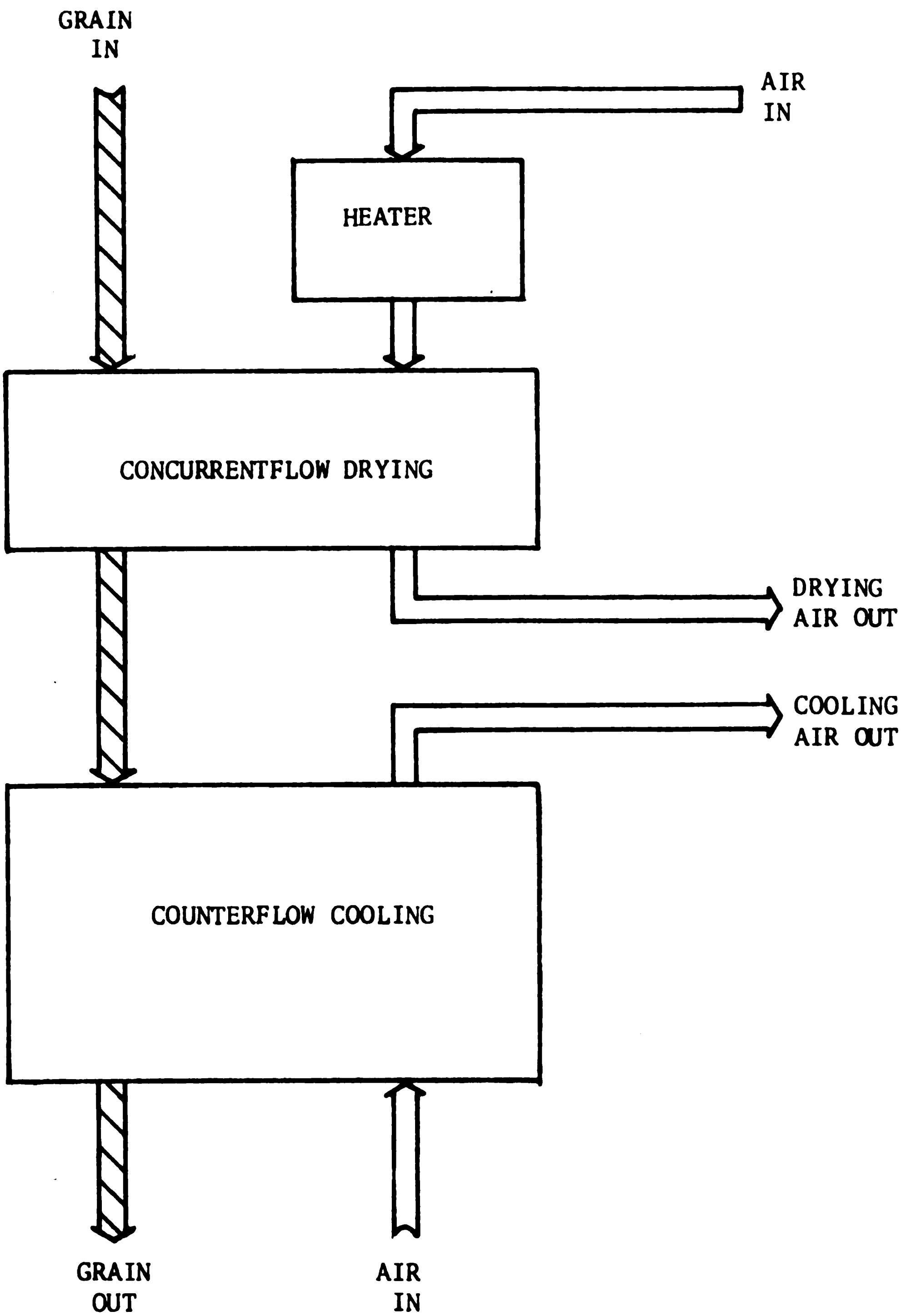


Figure 5. Block diagram of a single-stage concurrentflow dryer with a counterflow cooler.

Source: Brooker et al. (1974).

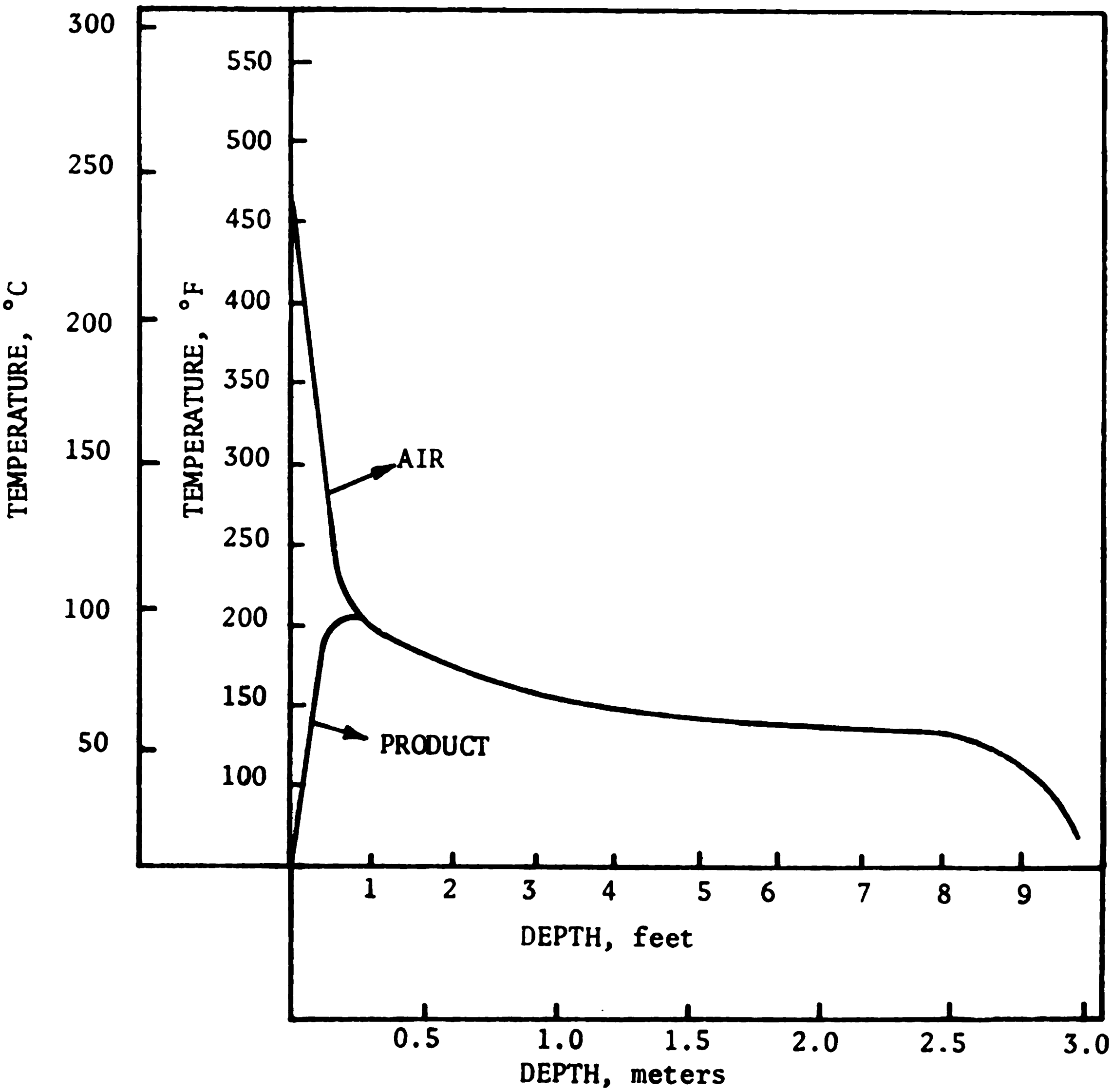


Figure 6. Air and product temperatures versus depth for a single-stage concurrentflow dryer.

Source: Brooker *et al*. (1974).

markedly higher than the increase from a comparable capacity concurrentflow dryer (Thompson et al., 1969; Gygax et al., 1974).

The Clean Air Act of 1970 established standards that must be adhered to by the grain handling industry. The pollution characteristics of the various dryer types differ partially due to differences in the quantities of air discharged to the atmosphere. The air moved and exhausted through a crossflow dryer is eight to ten times as large as in a comparable concurrentflow dryer (Bakker-Arkema et al., 1972).

Several experimental studies of concurrentflow drying have been conducted. Thompson et al. (1969) conducted concurrentflow drying tests under the following drying conditions: (1) drying air temperature 93°-204°C, (2) bed depth 0.61 and 1.22 m, (3) air velocity 30-75 m/min., (4) grainflow rate 22.0-175.0 kg/hr, and (5) initial moisture content 18.0 and 23.0% w.b. Samples of the dried grain were tested for stress cracks, Stein breakage and wet millability based on starch recovery. Drying air temperatures of less than 121°C gave acceptable millability scores. Increasing temperatures resulted in unacceptable and continually decreasing millability scores. The percentage of kernels with a checked stress crack pattern and the Stein breakage percentage both increased with increasing temperature.

Carrano et al. (1971) investigated the design of a laboratory scale concurrentflow dryer with a counterflow cooler for drying shelled corn. They noted that some drying was done in the counterflow cooling section. No quality tests were conducted.

Mühlbauer et al. (1971) conducted concurrentflow drying tests in the drying air temperature range of 125°-250°C. Only slight changes in the nutritive value of the corn dried where observed. They concluded that by correctly balancing the air and grain flow rates any damage to the nutritive value of the corn (which developes because of high grain temperatures) could be avoided. Thus the energy efficiency advantage of the higher temperature air could be safely utilized.

Baughman _et al_. (1971) simulated the drying of shelled corn in a concurrentflow dryer. The model was based on heat and mass balances and radial diffusion in an assumed spherical kernel. Drying parameters were studied for the purpose of controlling the moisture of the grain leaving the dryer. The final moisture content decreased 1.0% d.b. when the initial grain temperature was increased from 11° to 33°C and when the initial air humidity decreased from 0.010 to 0.001. Increasing the airflow rate from 1200 to 2200 kg/hr-m^2 decreased the final moisture content about 5.0% d.b. The inlet air temperature increase from 66° to 177°C resulted in a 9.0% d.b. decrease in final moisture content at a grainflow rate of 500 kg/hr-m^2.

3. EXPERIMENTAL INVESTIGATIONS

The following section presents the conditions and results of field experiments conducted with pea beans and shelled corn. Other cereal grains and agricultural products may also be dried in a concurrentflow dryer. The two products choosen serve to illustrate the advantages and possible limitations of the multistage concurrentflow drying process.

3.1 Multistage drying of pea beans

3.1.1 Equipment and procedures

Drying tests were conducted during the fall, 1976 harvest season using Canadian pea beans (varieties unknown). A three stage concurrent flow dryer with a counterflow cooler was supplied by Westlake Agricultural Engineering, Inc., St. Mary's, Ontario, and erected at the Cook's Elevator, Kirkton, Ontario (Figure 7). Each drying stage consists of a two meter long drying bed followed by a 3.7 meter tempering stage. The third drying stage is followed immediately by a one meter counterflow cooler. The cross-section of the drying and cooling column is 1.5 square meters. The wet inlet grain for the dryer is obtained from the same elevator which fed the wet grain to an Ace model 1850D crossflow dryer already installed at the site. The dry

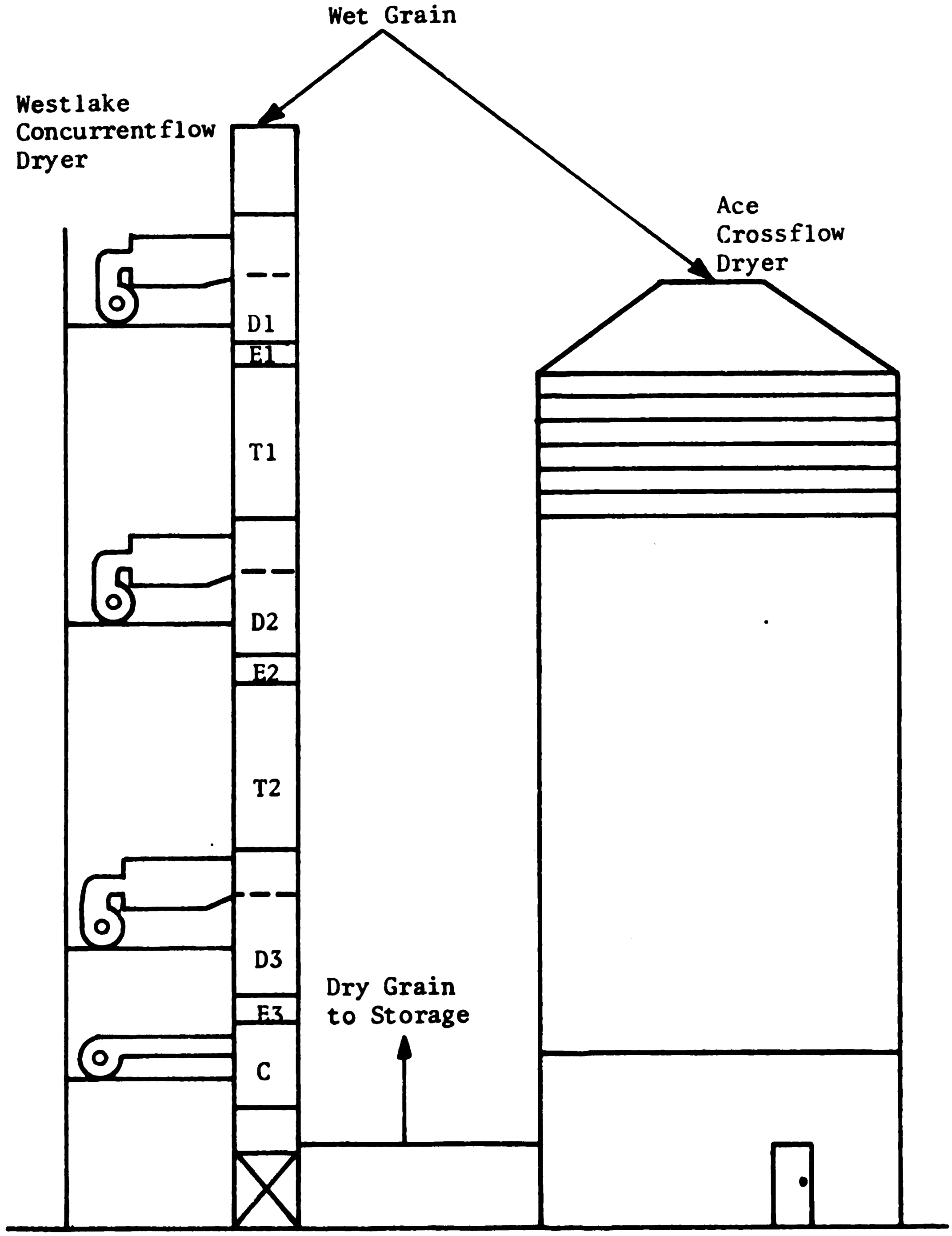


Figure 7. Schematic of installed concurrentflow dryer--
D1, D2, D3--Drying stages
E1, E2, E3--Exhaust ports
T1, T2--Tempering stages
C--Cooling stage

outlet grain is augered into the same elevator leg serving the cross-flow dryer.

Each drying stage employes a separate centrifugal blower with adjustable louvers for supplying the drying air. The airflow rate in each stage was measured using a "Velometer" manufactured by Alnor Instruments. A nine point grid was defined in the one meter square air supply duct ahead of the gas burner. An arithmetic average of these nine points was used to set the air velocity for each stage at 30.5 $\pm$ 3.0 m/min. LP gas was used to heat the air. The drying air temperature for each stage was maintained by a Honeywell controller ($\pm 1°C$) utilizing a platinum resistance feedback thermocouple located in the center of the airduct just prior to the point where the air entered the moving grain mass.

Air/grain temperatures within the dryer were monitored using iron-constantan thermocouples. Temperatures were recorded continuously on a Texas Instruments Multi-Riter multi-point potentiometer. Thermocouples were located in each drying stage in the center of the moving grain mass: (1) 15 cm above the air inlet, (2) 15 cm below the air inlet, (3) 30 cm below the air inlet, and (4) in the air exhaust stream. The cooling stage thermocouples were similarily located: (1) 20 cm below the air exhaust, (2) 40 cm below the air exhaust, and (3) 60 cm below the air exhaust. Ambient dry and wet bulb temperatures were monitored using a Princo hand-held sling-psychrometer.

The flow rate of the grain through the drying column is controlled by a variable speed DC motor connected to the three dryer discharge augers. The grainflow was correlated with the auger RPM. Laboratory tests conducted by Westlake personnel showed that the discharge rate varied linearly with auger RPM as indicated in Table 9. Two grainflow tests were conducted with the Kirkton dryer at a discharge auger speed of 63 rpm with grainflow rates of:

1. 1080 kg at 804 kg/m^3 discharged in 11 min 48 sec
2. 1250 kg at 804 kg/m^3 discharged in 13 min 12 sec

During the drying tests the RPM of the discharge augers was measured and recorded and the grainflow calculated at 1.478 $\pm$ 0.025 kg per auger revolutions.

Table 9.--Laboratory results of grainflow versus discharge auger RPM.

RPM		Grainflow, tonne/hr-m^2
10		0.812
20		1.625
30		2.437
40		3.250
50		4.062
60		4.875
Pea Bean conditions	Moisture	15.8% w.b.
	Test weight	837.0 kg/m^3

Source: Westlaken (1976).

The conditions for each drying test were set up and the dryer operated until an equilibrium condition was achieved (one complete grain pass through the dryer). A total of four samples were taken at 20 minute intervals from five locations: (1) grain inlet, (2) air/grain exit from each of the three drying stages, and (3) outlet from the cooling section. The samples were tested immediately for temperature (mercury bulb thermometer) and moisture content (Motomco moisture meter calibrated by the Canadian Department of Agriculture). The samples were sealed in plastic bags and stored at 5°C for later analysis. After the drying tests were completed, 100 grams of each sample were separated using a Boerner divider and examined visually to determine the percentage of cracked seed coats (cracks) and of beans which had been split into two halves or otherwise damaged (splits). Percentages were calculated by weight using a Pennsylvania mechanical balance scale.

3.1.2 Test conditions and results

A total of twelve drying tests were conducted using pea beans. Tests 1 and 7 were interrupted by mechanical failures and are not reported. The test conditions are presented in Table 10. Tests 2 through 9 were two stage drying tests during which the top drying stage of the dryer was not operated. Tests 10 through 12 were three stage drying tests. The cooler was operated only on test 12.

The results of the analysis on the dried samples are summarized in Table 11. The change in splits for one drying section showed no apparent correlation with the exit temperature or the change in moisture for that stage (Figures 8 and 9). The occurrence of splits is probably due to random factors other than the drying process, such as harvest conditions, method of obtaining samples or variations occurring due to sample analysis.

The change in cracks for one drying stage showed a correlation of $r_c = 0.48$ (significance of $p > 0.01$) with the exit temperature of the grain (Figure 10), and a correlation of $r_c = 0.42$ (significance of $p > 0.01$) with the change in moisture content in that stage (Figure 11).

Table 10.--Pea bean drying test conditions.

Test number	2	3	4	5	6	8	9	10	11	12
Ambient conditions										
dry bulb temperature, °C	17	11	18	20	20	13	18	21	21	18
wet bulb temperature, °C	13	9	14	13	14	12	14	16	16	14
Airflow (all stages), m^3/min	45.3	45.3	45.3	45.3	45.3	45.3	45.3	45.3	45.3	45.3
Drying air temperatures, °C										
stage 1	52	74	93	93	107	121	107	79	121	107
stage 2	52	74	93	74	93	107	93	107	107	93
stage 3								93	93	93
Grainflow, kg/hr	3100	2480	2480	2480	3100	3690	2740	2740	4280	3690
Inlet grain conditions										
temperature °C	19	19	20	20	21	17	18	18	18	18
variance	2.8	2.8	2.2	1.2	0.6	0.0	0.3	0.0	0.0	0.9
moisture, % w.b.	20.6	21.2	20.1	21.0	21.0	22.3	22.6	21.9	22.3	22.1
variance	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.3	0.3
cracks, %	1.3	1.3	1.0	1.0	1.7	0.6	0.7	0.8	1.2	0.6
variance	0.3	0.3	0.1	0.3	1.2	0.1	0.1	0.1	0.2	0.1
splits, %	0.3	0.3	0.3	0.2	0.1	0.1	0.2	0.1	0.3	0.2
variance	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Table 11.--Summary of sample results for pea bean drying tests.*

Test Number	2	3	4	5	6	8	9	10	11	12
Stage 1--temperature, °C	22	22	32	31	36	32	33	29	35	35
variance	0.3	1.9	0.9	2.8	2.5	2.5	0.3	3.7	0.3	7.1
moisture, % w.b.	20.0	20.9	18.6	19.3	19.0	20.9	20.5	21.1	20.8	20.7
variance	0.2	0.3	0.1	0.0	0.1	0.1	0.1	0.4	0.1	0.4
cracks, %	1.4	1.7	5.1	3.6	3.4	1.3	2.3	1.3	2.0	1.5
variance	0.5	0.6	2.3	2.8	0.3	0.7	0.3	0.4	0.3	0.8
splits, %	0.5	0.3	0.4	0.4	0.2	0.1	0.1	0.1	0.2	0.2
variance	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Stage 2--temperature, °C	23	29	37	34	39	42	39	36	36	33
variance	0.3	1.9	0.3	0.0	0.3	0.3	0.3	1.2	0.3	0.3
moisture, % w.b.	19.3	17.7	16.7	17.0	16.9	18.8	18.6	19.5	19.8	20.3
variance	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1
cracks, %	2.2	5.2	8.8	10.1	9.6	8.7	7.2	5.3	2.4	2.2
variance	0.2	2.1	0.3	6.0	0.4	7.1	0.4	4.4	0.1	0.2
splits, %	0.4	0.3	0.4	0.7	0.4	0.1	0.4	0.1	0.2	0.2
variance	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Stage 3**--temperature, °C								40	39	38
variance								1.5	2.5	0.3
moisture, % w.b.								17.8	18.7	18.9
variance								0.1	0.1	0.1
cracks, %								11.8	4.2	3.6
variance								21.6	3.1	4.3
splits, %								0.1	0.2	0.1
variance								0.1	0.1	0.1
Efficiency, kJ/kg water	4989	4417	5277	3726	3675	4500	4191	5456	4675	5696

*The results of all samples are presented in Appendix 9.2.

**Cooler outlet conditions for test 12 were 28°C/19.7% w.b./2.9%/0.2%.

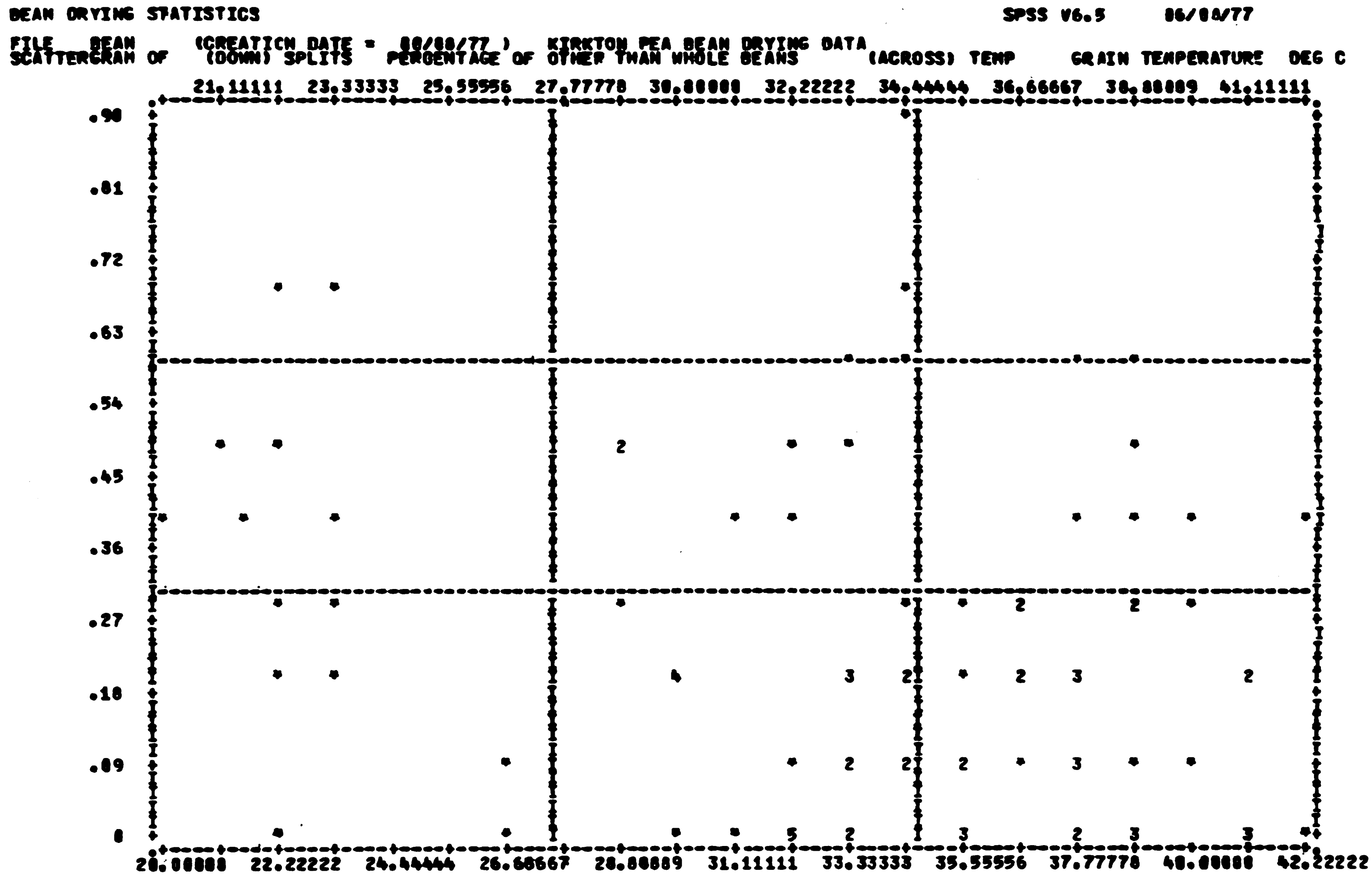


Figure 8. Scattergram of the change in splits with exit grain temperature.

BEAN DRYING STATISTICS SPSS V6.5 06/08/77

FILE BEAN (CREATION DATE = 06/08/77) KIRKTON PEA BEAN DRYING DATA
SCATTERGRAM OF (DOWN) SPLITS PERCENTAGE OF OTHER THAN WHOLE BEANS (ACROSS) DELM CHANGE IN MOISTURE CONTENT FOR ONE STAGE

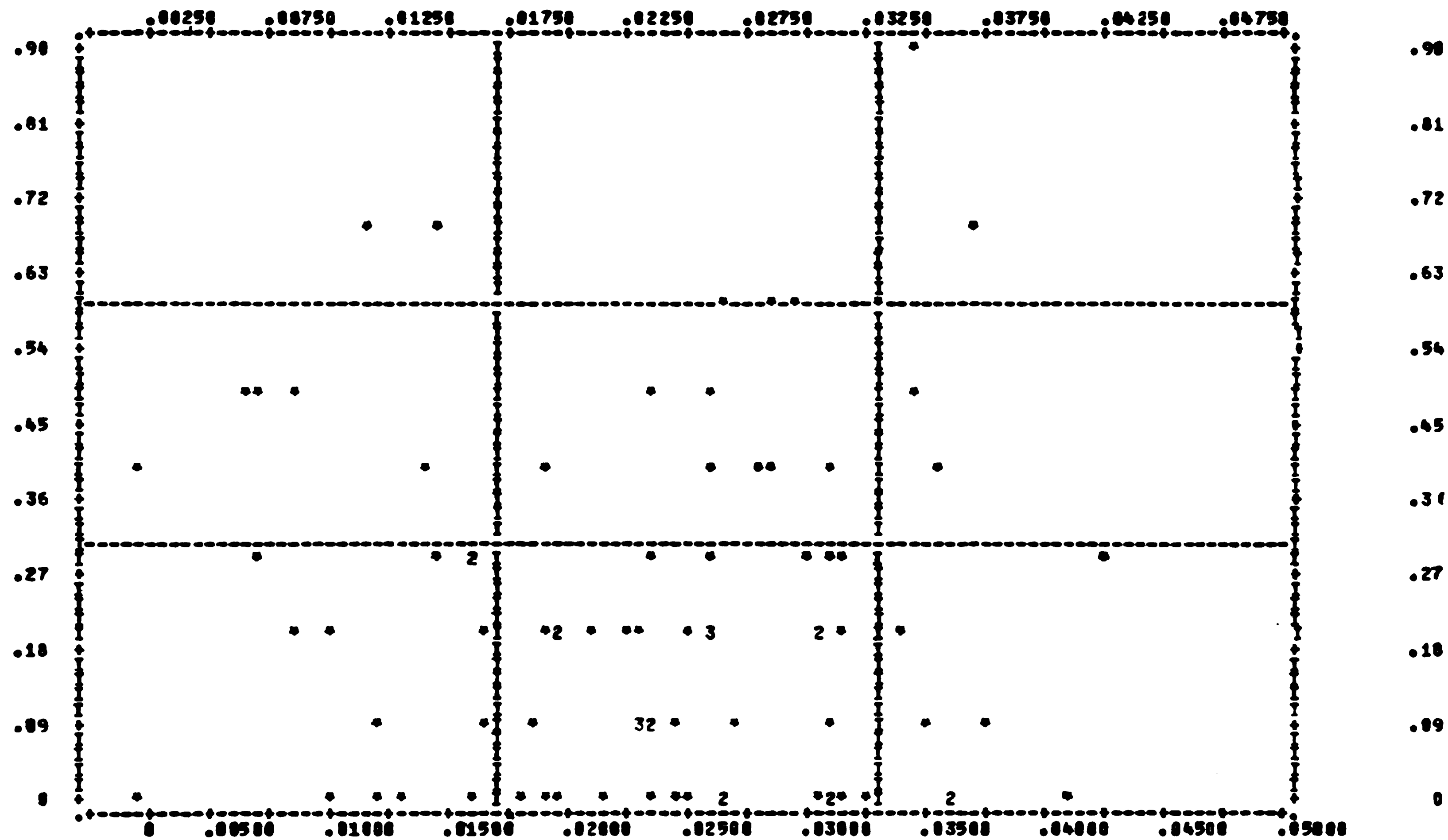


Figure 9. Scattergram of the change in splits with the change in grain moisture.

BEAN DRYING STATISTICS   SPSS V6.5   06/09/77

FILE   BEAN   (CREATION DATE = 06/08/77)   KIRKTON PEA BEAN DRYING DATA
SCATTERGRAM OF   (DOWN) DELC   CHANGE IN CRACKS FOR ONE STAGE   (ACROSS) TEMP   GRAIN TEMPERATURE   DEG C

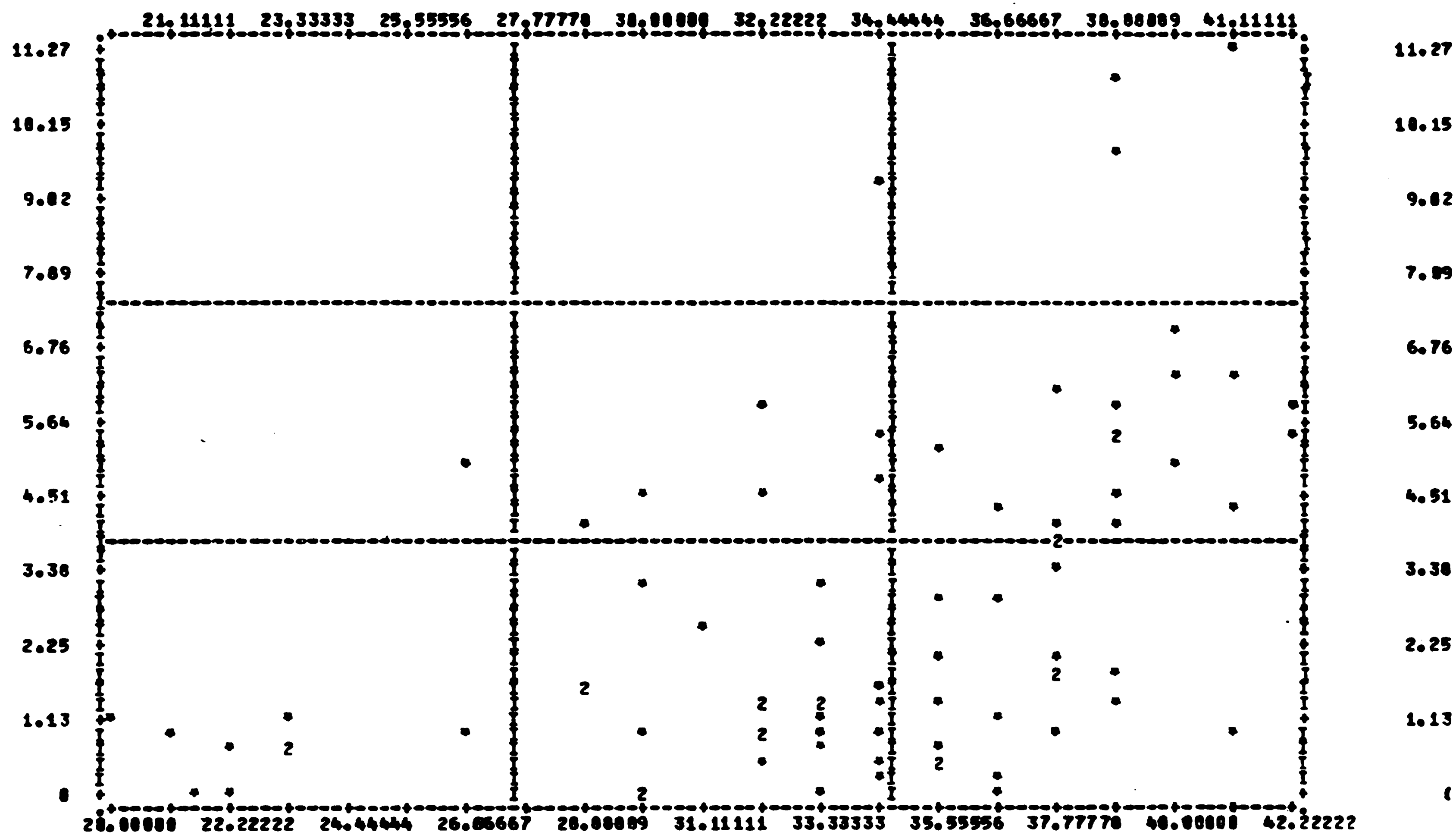


Figure 10. Scattergram of the change in cracks with exit grain temperature.

BEAN DRYING STATISTICS SPSS V6.5 06/08/77

FILE BEAN (CREATION DATE = 06/08/77) KIRKTON PEA BEAN DRYING DATA
SCATTERGRAM OF (DOWN) DELC CHANGE IN CRACKS FOR ONE STAGE (ACROSS) DELM CHANGE IN MOISTURE CONTENT FOR ONE STAGE

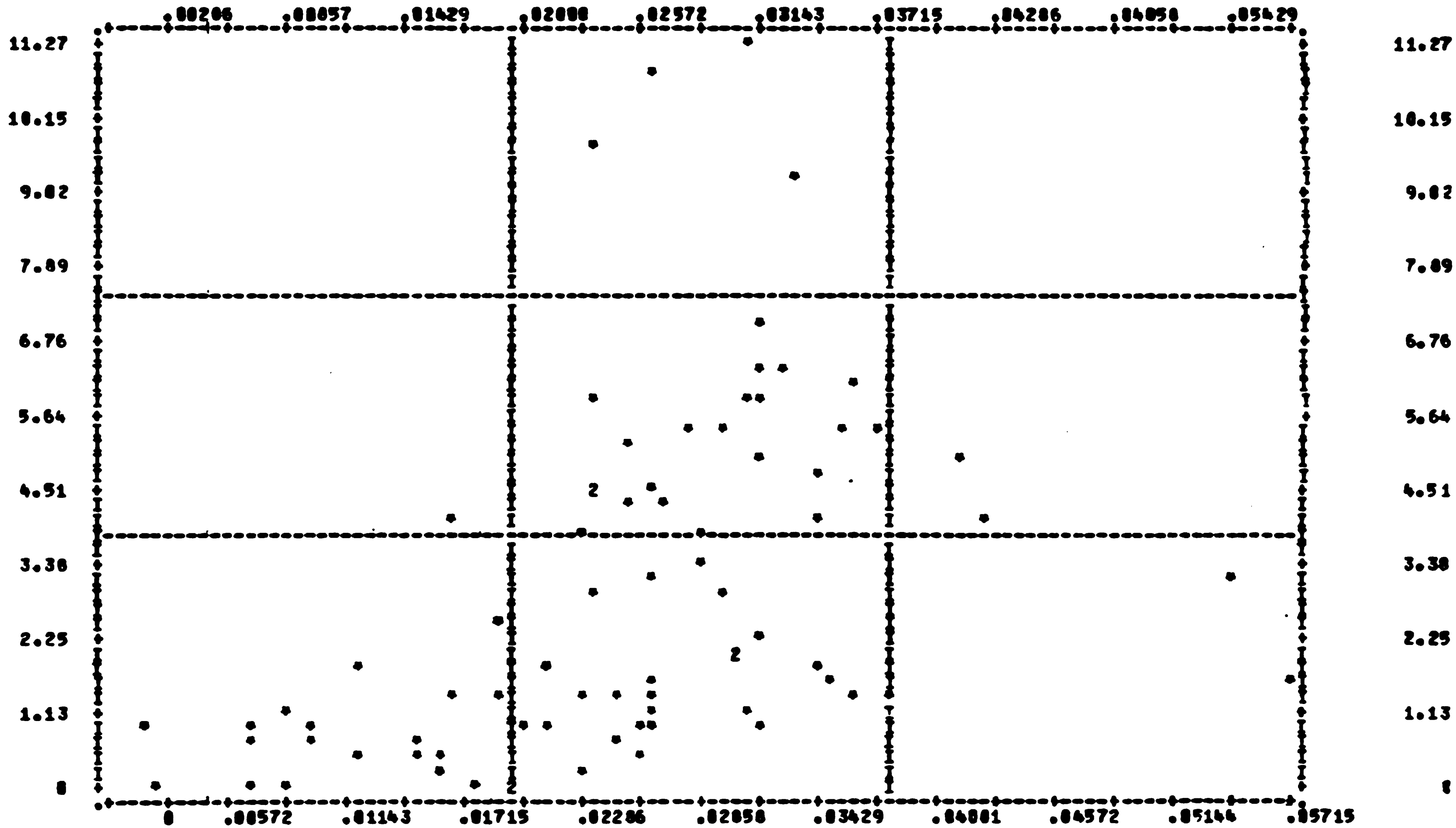


Figure 11. Scattergram of the change in cracks with the change in grain moisture.

3.2 Multistage drying of shelled corn

3.2.1 Equipment and procedures

Drying tests were conducted during the fall, 1976 harvest season using shelled yellow corn (varieties unknown) using a three stage concurrent flow dryer with a counterflow cooler as described in section 3.1.1.

The flow rate of the grain through the drying column was correlated with the discharge auger RPM. Tests were conducted at three different RPM using 12% w.b. corn with a test weight of 721 kg/m^3. The results of the tests are given in Table 12. During the drying tests the RPM of the discharge augers was measured and recorded and the grainflow calculated at 5.289 $\pm$ 0.063 kg per auger revolution.

Table 12.--Results of corn discharge calibrations.

RPM	Discharge		Grainflow
	Weight (kg)	Time (min)	kg/rev
5	1141	43.17	5.286
9	1835	39.00	5.228
13	1531	22.00	5.353
Average	--	--	5.289
Range	--	--	$\pm$0.063

The dryer was operated until an equilibrium condition was achieved (one complete pass through the dryer). Samples at the grain outlet were taken at 15 minute intervals after equilibrium conditions were attained. Samples at the grain inlet were taken hourly. The samples were tested immediately for temperature (mercury bulb thermometer), moisture content (Motomco moisture meter), BCFM (broken corn and foreign material passing through 0.48 cm round-hole screen), and visually inspected for heat damaged kernels. All samples were sealed in plastic bags and stored at 5°C. After the drying tests were completed, the samples were conditioned and subjected to a Stein breakage test to test their susceptibility to damage.

In the conditioner air was circulated through the sample and over a saturated sodium-chloride salt solution. Thus the air was maintained at approximately 75% relative humidity at 27°C. Moisture contents of about 12.5-13.5% w.b. were obtained. The samples were conditioned for a period of six days before being tested in the Stein breakage tester.

One hundred grams of each sample were separated using a Boerner divider. After the two minute breakage test the samples were removed from the tester and screened using a 0.48 cm round-hole screen. The percentage lost through the screen was the percentage of breakage for the Stein breakage test.

3.2.2 Test conditions and results

A total of nine drying tests were conducted using yellow corn (varieties unknown). The results of tests 2 and 9 are questionable due to mechanical problems encountered. Test 6 was invalid due to a fire in the dryer and therefore not reported. The author feels that the fire was due to overdrying caused by intermittent starting and stopping of the dryer because of mechanical problems encountered. Proper start-up and shut-down procedures would eliminate the danger of fire. The test conditions are presented in Table 13 and the results of the sample analysis are summarized in Table 14.

BCFM showed no correlation with either the exit temperature of the corn (Figure 12) or the change in moisture content of the corn (Figure 13). The occurrence of BCFM immediately after drying is probably due to random factors other than the drying process such as corn variety and harvest conditions.

The percentage of breakage in the Stein breakage tester showed no correlation with the exit temperature of the corn (Figure 14). A correlation of $r_c = 0.59$ (significance of $p > 0.01$) was observed between the breakage tester results and the change in moisture content of the corn (Figure 15).

Table 13.--Corn drying test conditions.

Test number	1	2	3	4	5	7	8	9
Ambient conditions								
dry bulb temperature, °C	3	1	8	3	6	8	8	2
wet bulb temperature, °C	1	-3	3	2	3	5	4	-1
Airflow (all stages), m^3/min	61.6	61.6	61.6	61.6	61.6	65.2	65.2	65.2
Drying air temperatures, °C								
stage 1	163	191	191	218	177	163	177	177
stage 2	163	191	191	218	177	163	149	149
stage 3	163	177	191	218				
Grainflow, kg/hr*	3790	3450	2790	3030	1750	1450	1230	1520
maximum	7930	4120	3800	3800	2540	1580	1580	1900
minimum	2860	2860	1910	2540	1270	1270	1120	1270
Inlet grain conditions								
temperature, °C	17	10	12	8	11	16	14	15
std. dev.	1.5	5.1	1.0	2.3	1.4	1.8	0.6	1.6
moisture, % w.b.	27.5	24.8	28.4	28.1	28.7	28.4	30.0	30.7
std. dev.	6.8	2.6	5.2	1.5	2.1	2.9	0.1	1.3
BCFM, %	0.8	0.5	0.6	0.6	0.6	0.7	0.5	0.6
std. dev.	0.2	0.2	0.0	0.2	0.1	0.6	0.2	0.3
Stein breakage, %	15.2	16.3	10.2	11.5	17.3	15.8	21.0	26.6
std. dev.	5.5	5.4	0.8	3.7	4.3	4.8	11.5	8.6

*Time averaged values for duration of test.

Table 14.--Sample results for corn drying tests.*

Test Number	1	2	3	4	5	7	8	9
Outlet grain conditions								
Temperature, °C	21	27	19	23	25	18	30	20
range, ±	2	2	3	2	2	2	7	1
Moisture content, % w.b.	18.2	11.1	16.7	16.9	15.5	15.1	12.6	16.1
range, ±	0.6	0.3	0.4	0.2	0.3	0.9	0.6	1.3
BCFM, %	0.7	0.6	0.7	0.6	0.8	0.7	0.9	0.7
range, ±	0.1	0.2	0.3	0.2	0.0	0.3	0.3	0.1
Breakage, %	12.8	20.7	13.6	17.3	34.3	23.8	24.8	42.5
range, ±	5.5	4.5	5.3	2.0	9.0	8.5	4.5	8.3
Heat damage, %	--	--	0.5	0.7	0.3	0.6	1.5	0.1
range, ±	--	--	0.1	0.2	0.1	0.2	0.6	0.0
Efficiency, kJ/kg	4219	--	4991	5289	4719	5489	5452	5126

*The results of all samples are presented in Appendix 9.3.

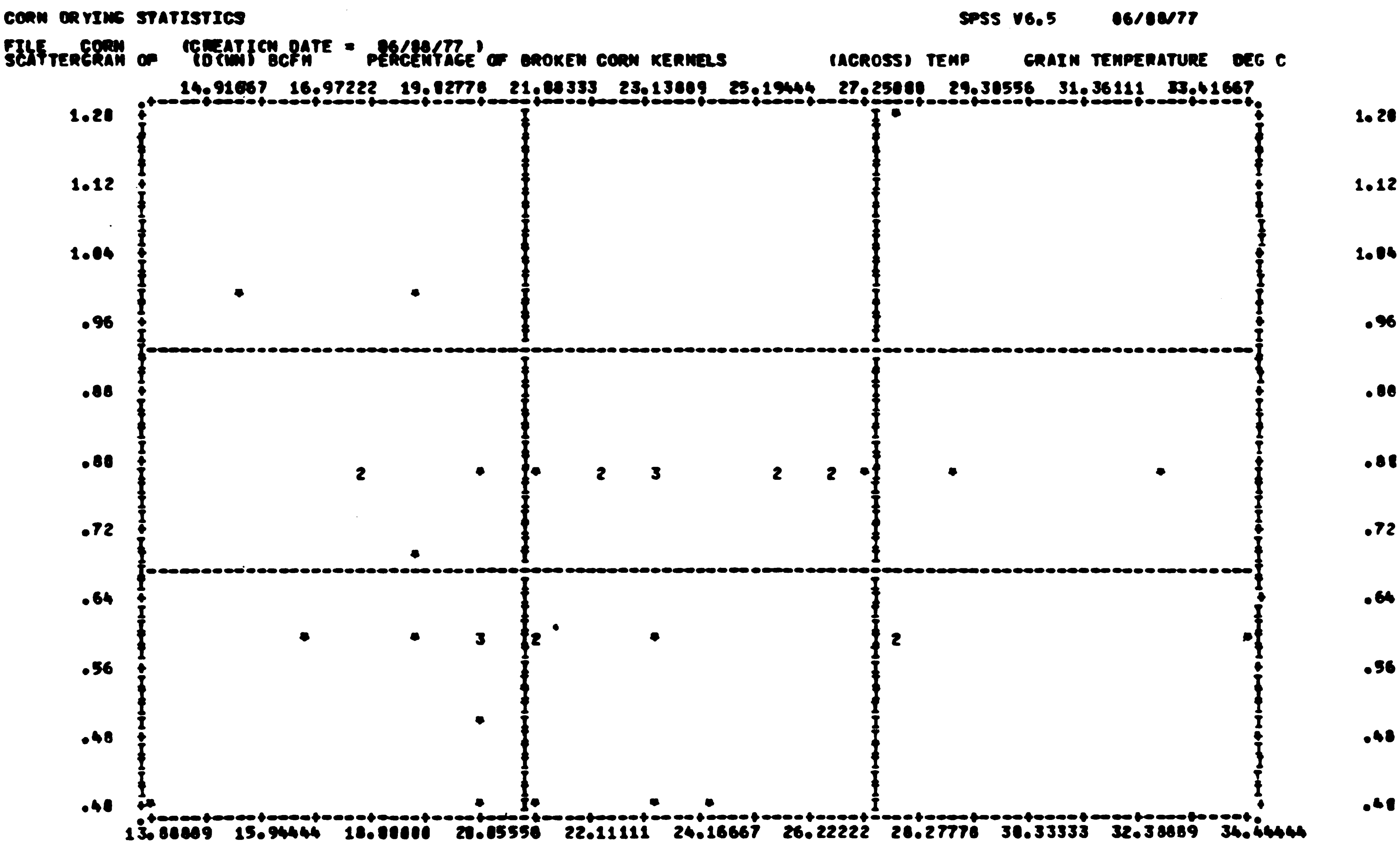


Figure 12. Scattergram of BCFM with the exit temperature of the grain.

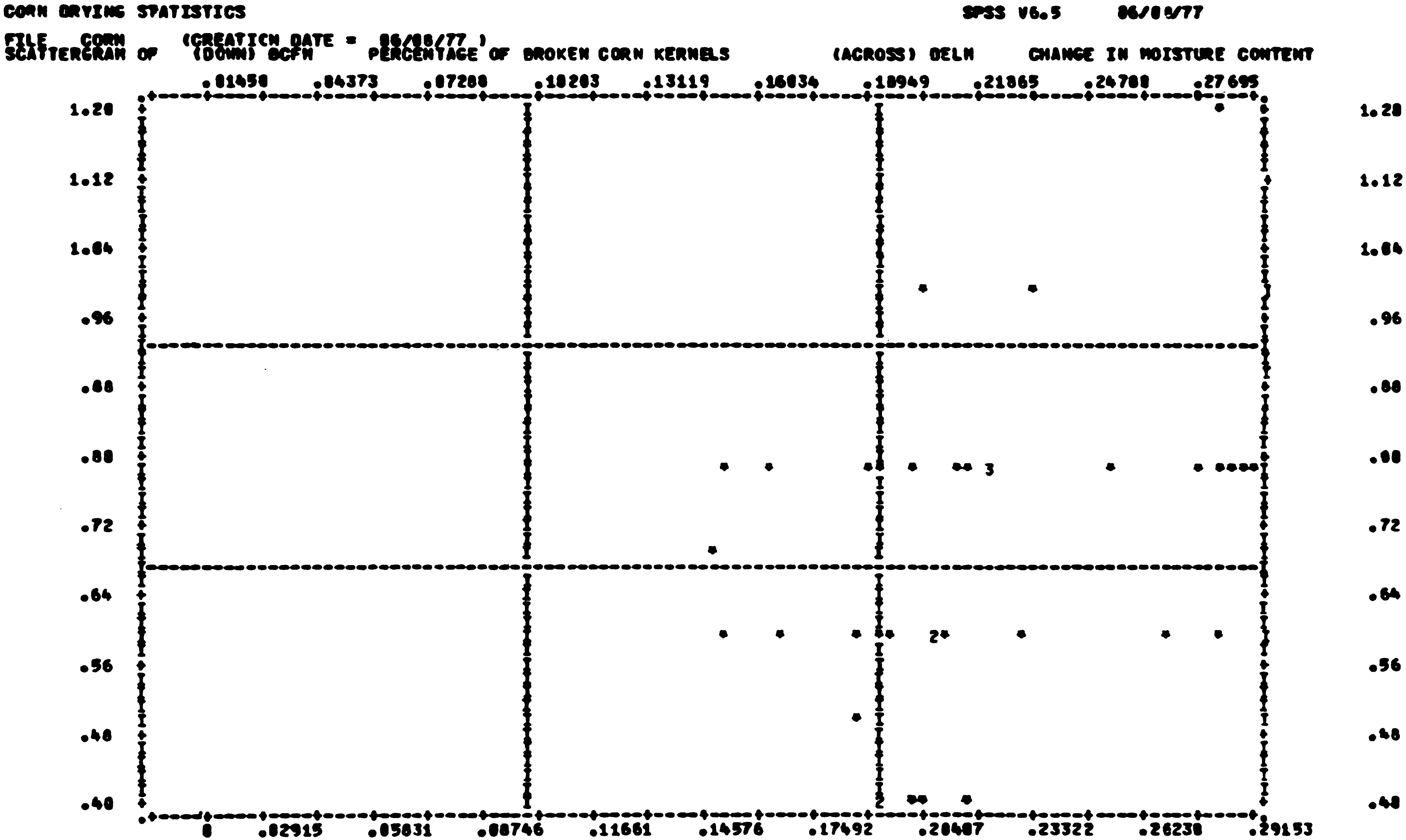


Figure 13. Scattergram of BCFM with the change in grain moisture.

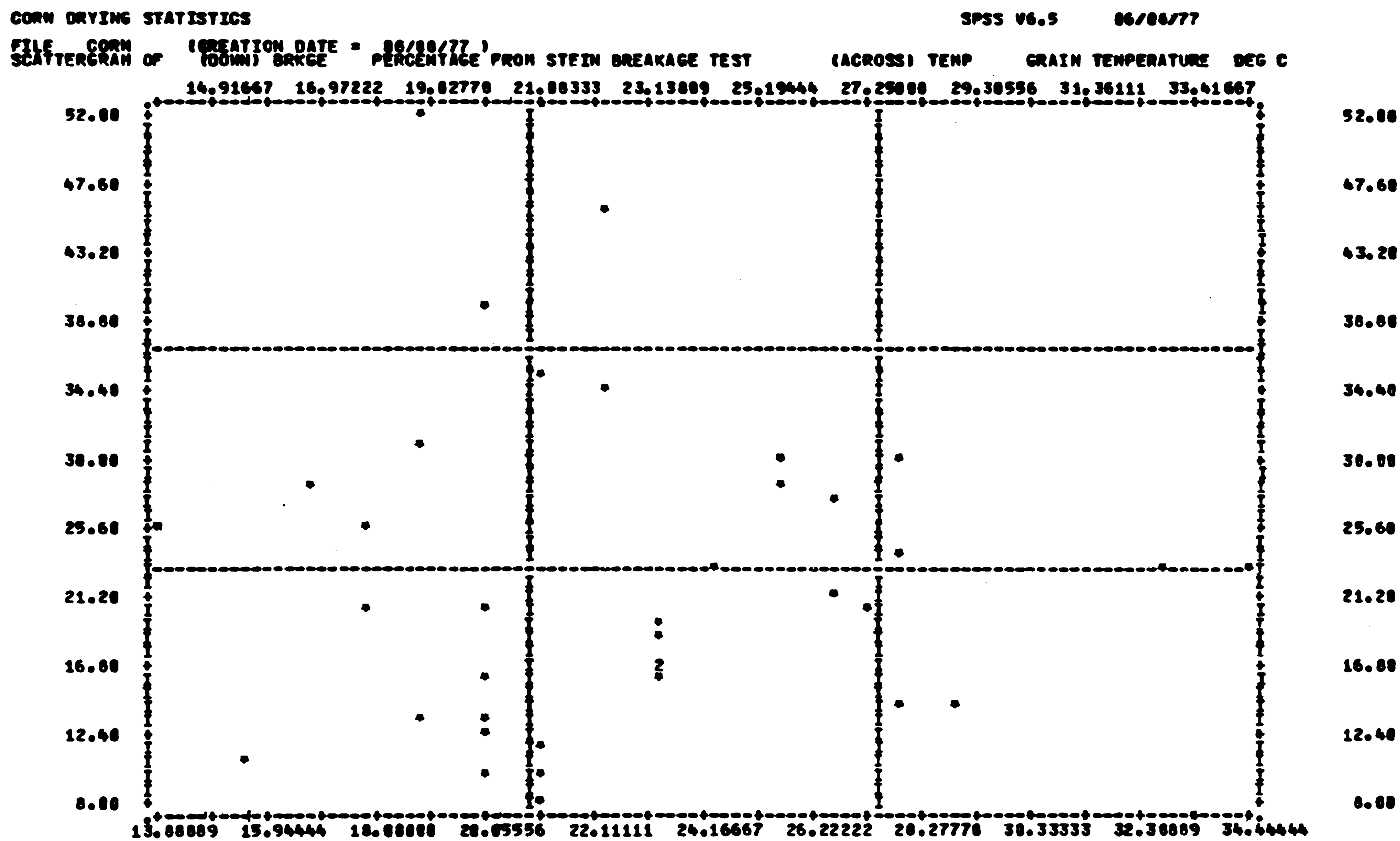


Figure 14. Scattergram of Stein breakage percentage with the exit temperature of the grain.

CORN DRYING STATISTICS SPSS V6.5 06/08/77

FILE CORN (CREATION DATE = 06/08/77)
SCATTERGRAM OF (DOWN) BRKGE PERCENTAGE FROM STEIN BREAKAGE TEST (ACROSS) DELM CHANGE IN MOISTURE CONTENT

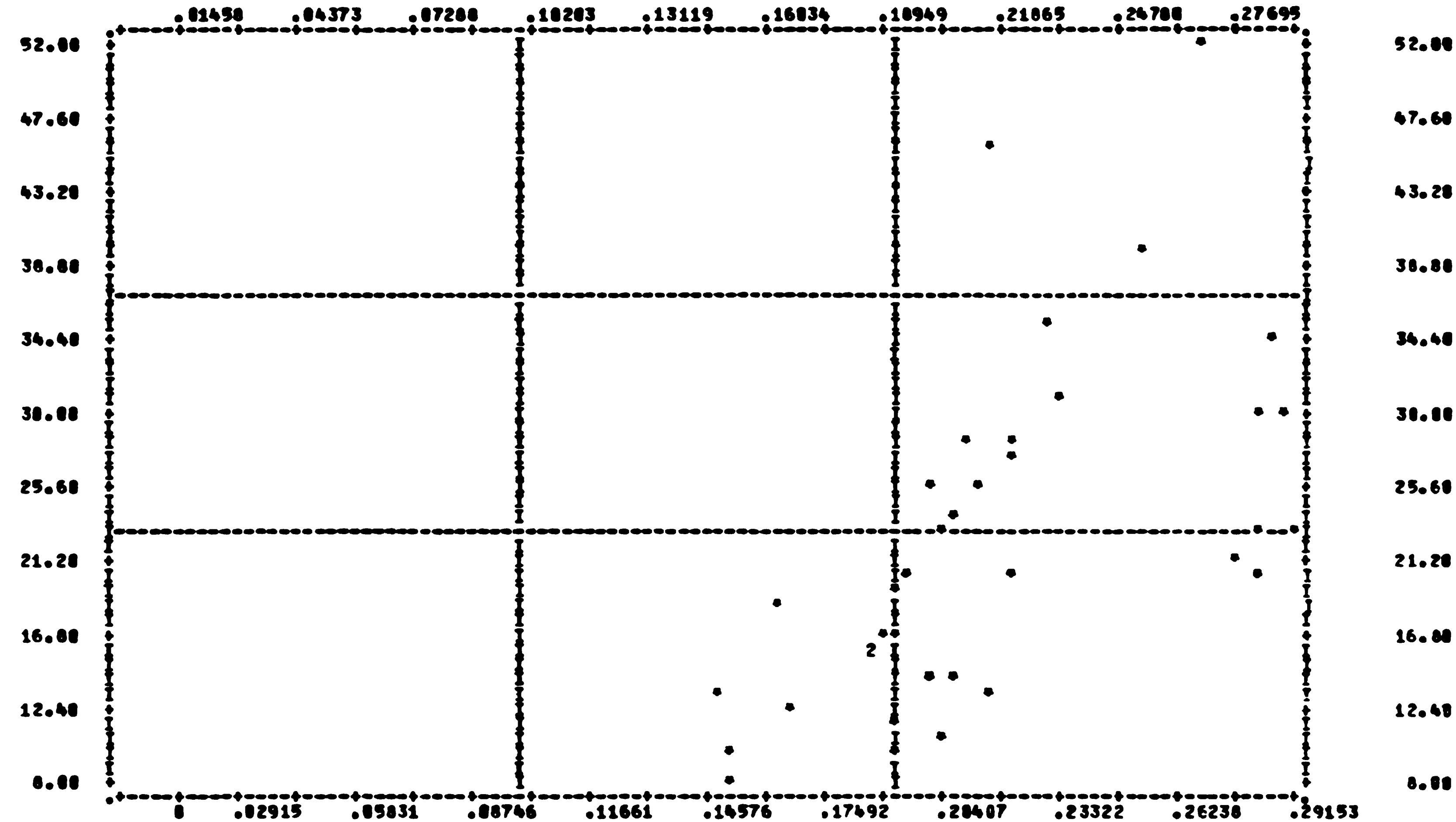


Figure 15. Scattergram of Stein breakage percentage with the change in grain moisture content.

4. MODEL DEVELOPMENT

Previous simulation research for concurrentflow dryers use different models. Thompson (1967) derived a set of algebraic equations based on heat and mass transfer at the kernel surface. The moisture transfer was based on a thin layer equation developed by recording moisture content versus time for a thin layer of kernels when subjected to an airflow of constant temperature and humidity. Bakker-Arkema et al. (1974) derived a set of ordinary differential equations based on heat and mass transfer at the kernel surface with moisture transfer based on Thompson's thin layer equation. The system of equations is solved numerically using an integration routine.

Thin layer models for corn are available for several temperature ranges. A good review of equations available for a limited number of other products is presented by Brooker et al. (1974). The thin layer models suffer from one severe limitation in that they do not consider what is occurring within the kernel. The structure of the kernel is stressed during drying which may lead to cracking of the kernel. The degree of damage has been related to many different variables but the exact cause of the stress is not really known. Possibly it is due to variations of moisture content within the kernel.

A model based on heat and moisture diffusion within the kernel overcomes this limitation. Baughman et al. (1971) derived a set of ordinary differential equations for a concurrentflow dryer using diffusion to account for moisture transfer.

A diffusion model has a number of other advantages. First, it would be easily applicable to a number of agricultural products for which diffusivity coefficients are known. Second, the assumed shape of the product could be easily varied. Differential diffusion equations are available for flat plates, spheres, cylinders and other shapes. As more is learned about what occurs within the grain kernel during drying, a different kernel shape may be necessary. Third, the diffusion model can be used to approximate the tempering period when little or no heat and mass transfer occurs at the kernel surface. During tempering the kernel reacts in some manner to relieve the internal stresses caused by drying.

The following section outlines the development of a computer model for simulating the drying performance of a multistage concurrent-flow dryer with intermediate tempering stages and a final counterflow cooling stage. The model output is compared with previously published data for single-stage concurrentflow drying of shelled corn. The effect produced by the cooling and tempering stages is evaluated. Lastly the multistage model output is compared with the multistage experimental results presented in the previous section.

4.1 Concurrent heat and moisture transfer

The phenomena of heat and mass transfer can be visualized from the viewpoint of the individual kernels. The transfer of heat and mass within the kernel occurs by diffusion. The corn kernel is shaped somewhat like a brick and was analyzed as such by Pabis and Henderson

(1961). The temperature and moisture distributions at any point within the kernel were represented as a function of the three coordinate directions. The diffusion coefficients were assumed to be independent of the location within the kernel; i.e., the kernel was assumed to be homogeneous with respect to heat and moisture diffusion. Chu and Hustrulid (1968) showed that "two solids of different size and shape are considered to be equivalent if their volume-to-surface-area ratios are the same." Thus the corn kernel was represented by a sphere with a properly determined equivalent radius. The equivalent radius approach was also used for wheat by Ingram (1976).

To analyze the drying of a grain kernel one can visualize a sphere of radius r_o with a moisture content distribution which varies from the center radially outward. The surface of the sphere is exposed to varying environmental temperature and humidity as the drying process proceeds along the length of the drying column. The transfer of heat and mass within the kernel occurs by diffusion of heat and mass, respectively. Young and Whitaker (1971) concluded that for most agricultural products (including cereal grains) the diffusion of moisture alone adequately describes the drying process of the grain kernel. Therefore, it can be assumed that no thermal gradient exists within the kernel even though the kernel temperature may change with time as it loses moisture and loses heat with the environmental air. The diffusion of moisture within the kernel can be represented by the diffusion equation for a sphere (Crank, 1957);

$$\frac{\partial M}{\partial t} = \frac{D}{r^2} (r^2 \frac{\partial M}{\partial r^2} \qquad (2)$$

The diffusion equation is a second order partial differential equation. For ease in solving the equation numerically on a digital computer, equation (2) is transformed into a set of coupled ordinary differential equations (ODEs) by the method of lines. The method of lines approximates the spatial derivatives by an appropriate finite difference formula (Carver, 1976). Using a second order difference formula the coupled ODE system becomes:

$$\frac{dM_i}{dt} = \frac{D}{r^2}\,(a_i M_{i+1} - 2M_i + b_i M_{i-1}),\ i=2,3,\ldots,n \qquad (3)$$

where:

$$a_i = i/(i-1) \qquad (4)$$

$$b_i = (i-2)/(i-1) \qquad (5)$$

At the center of the sphere, i=1 and the diffusion is symmetric so that the moisture derivative becomes:

$$\frac{dM_1}{dt} = \frac{6D}{\Delta r^2}\,(M_2 - M_1) \qquad (6)$$

At the surface of the sphere, i=n and the diffusion rate can be calculated by assuming the existence of a psuedo-point outside the kernel with the moisture content equal to the equilibrium moisture content. Therefore the moisture derivative becomes:

$$\frac{dM_n}{dt} = \frac{D}{r_o^2}\,(a_n M_e - 2M_n + b_n M_{n-1}) \qquad (7)$$

The derivation given above may be found in similar form in Crank (1957).

At the surface of the kernel, interaction with passing air transfers both heat and moisture. The conditions of the air and of the grain vary from the inlet point through the length of the dryer. The variation can be described by differential equations developed from energy and mass balances as presented by Brooker _et al_. (1974):

$$\frac{dT}{dx} = \frac{-h_c a(T-\theta)}{G_a(c_a+c_v H)} \tag{8}$$

$$\frac{d\theta}{dx} = \frac{h_c a(T - \theta)}{G_p(c_p+c_w \bar{M})} - \frac{h_{fg}+c_v(T - \theta)}{G_p(c_p+c_w \bar{M})} G_a \frac{dH}{dx} \tag{9}$$

$$\frac{dH}{dx} = \frac{-G_p}{G_a}\frac{d\bar{M}}{dx} \tag{10}$$

$$\frac{d\bar{M}}{dt} = \frac{dM_n}{dt} \tag{11}$$

The basic equations for simulating the concurrent flow drying process are equations 3 through 11. The solution to this system can be obtained numerically with the help of a digital computer. For this purpose a Runge-Kutta fourth-order single-step integration algorithm was used because of its availability at Michigan State University and the author's familiarity with the algorithm. The routine uses an Adams-Moulton technique for starting the integration and features automatic step size adjustment using relative error checking.

4.2 Auxiliary equations and properties

The solution of the ODE system presented in section 4.1 requires knowledge of several grain and air properties. Some vary with the changing grain and air conditions and need to be recalculated after each distance step (e.g., diffusion coefficient and equilibrium moisture content). Some may be considered as dependent only on the initial grain and air conditions (e.g., heat transfer coefficient). Others are independent of the grain and air conditions both before and during drying but may be dependent on the grain type being dryed (e.g., specific heat and specific surface area).

4.2.1 Diffusion coefficient

Chu and Hustrulid (1968) studied diffusion in corn kernels assuming that the kernel can be represented by a sphere of equivalent radius. Previously published experimental results of several thin layer drying studies were used for the following parameters: (1) product temperature 49°-71°C, (2) relative humidity 10-70%, and (3) corn moisture content 5-35% d.b. The following equation was developed:

$$D = 1.513\text{x}10^{-4}\ (0.045\ \theta + 6.806)\bar{M} - \frac{2513.00}{\theta + 273.13} \qquad (12)$$

Sabbah et al. (1976) studied moisture diffusion in soybeans assuming that the kernel can be represented by a sphere of equivalent radius. Unpublished thin-layer data from Ohio State University was used to develop the following equation:

$$D = 0.360[0.049\exp(\frac{-0.590}{M_o - M_e}) + 0.018(\bar{M} - M_e)]\exp(\frac{-3137.67}{\theta + 273.13}) \qquad (13)$$

The ranges of the drying data from which the equation was developed were not reported. The diffusion equation was used in a reversed-air crossflow drying model with good results.

The diffusion coefficient values for shelled corn and pea beans are compared in Table 15. The diffusion coefficient and thus

Table 15.--Diffusion coefficient values (cm^2/hr) for shelled corn (C calculated using equation 12) and for soybeans (B calculated using equation 13) as a function of moisture content and grain temperature. Soybean equilibrium moisture content M_e=5.0% w.b. and initial moisture content M_o=28.0% w.b.

Temperature °C	Moisture content, % w.b.									
	12		16		20		24		28	
	C	B	C	B	C	B	C	B	C	B
100	.0084	.0080	.0155	.0088	.0304	.0097	.0646	.0106	.1460	.0117
80	.0051	.0050	.0089	.0055	.0166	.0060	.0328	.0066	.0703	.0072
60	.0029	.0029	.0049	.0032	.0086	.0035	.0161	.0039	.0324	.0042
40	.0016	.0016	.0025	.0018	.0043	.0019	.0075	.0021	.0141	.0024
20	.0008	.0008	.0012	.0009	.0020	.0010	.0033	.0011	.0057	.0012

the drying rate of pea beans increases as the temperature increases, similar to shelled corn. More importantly, the drying rate of pea beans is less than that of corn and is much less sensitive to increasing moisture content. The cause of this is probably in the structure of the bean: two cotyledon halves surrounded by a fairly impervious seed coat. This can also be seen in the data presented by Kreyger (1972) in Table 16 for peas, which have a similar structure.

4.2.2 Equilibrium moisture content

Pfost _et al_. (1976) gathered and summarized equilibrium moisture content data for many grains and developed the following equation for calculating the equilibrium moisture content:

$$M_e = A-B\{\ell n[-1.987(\theta+A')\ell n(rh)]\} \tag{14}$$

Table 16.--Relative drying rates of various agricultural products as a percentage of wheat drying rate at 18% w.b.

Product	Moisture content, % w.b.				
	14	16	18	20	22
Peas	15	23	35	55	95
Corn	15	30	50	90	135
Wheat	35	65	100	150	210
Rye	35	70	115	175	225
Oats	60	100	150	250	450
Sugarbeet seed	300	500	800	1200	1650
Rapeseed	500	800	1150	1500	--

Source: Kreyger (1972).

Data from several previously published sources was used with a grain temperature of 0°-50°C and a relative humidity range of 20-90%. The values for the constants in equation (14) are given in Table 17. The constants for edible beans (a class of beans which includes pea beans) are given by Pfost _et al_. Calculated values using equation (14) for edible beans are compared with some experimental data from Dexter _et al_. (1955) in Table 18. The equilibrium values for 85% rh and high temperatures were affected by mold development.

Table 17.--Equilibrium moisture content equation constants.

Constant	Corn	Edible beans
A	0.379212	0.480920
B	0.058970	0.066826
A'	30.305000	120.098000
Std. Error	0.012100	0.017400

Source: Pfost _et al_. (1976).

Table 18.--Equilibrium moisture content values for pea beans (% d.b.) as a function of grain temperature and relative humidity. Calculated (C) from equation (14) and data (D) from Dexter et al. (1955).

Temperature °C	Relative Humidity, %							
	55		65		75		85	
	D	C	D	C	D	C	D	C
10	14.84	14.41	16.74	16.60	19.57	19.30	24.33	23.11
21	14.05	13.87	16.27	16.06	19.46	18.75	24.05	22.57
32	13.13	13.36	15.49	15.55	18.09	18.25	21.79	22.07
43	12.47	12.90	14.73	15.09	18.34	17.79	23.87	21.60
54	13.20	12.46	15.25	14.65	19.10	17.75	26.81	21.17

Source: Dexter et al. (1955).

4.2.3 Heat transfer coefficient

McAdams (1954) recommended the following equation for heat transfer between spheres and a flowing gas:

$$Nu = 0.37\ Re^{0.60} \tag{15}$$

where Nu = Nusselt number = $\dfrac{2h_c r_o}{k_a}$ (16)

Re = Reynolds number = $\dfrac{2G_a r_o}{u_a}$ (17)

Equation (15) provides a convenient formula to calculate the convective heat transfer coefficient of grain kernels which are represented by a sphere of equivalent radius. Sabbah (1971) studied heat transfer coefficients for corn kernels and recommended the following:

$$Nu = 0.389\ Re^{0.850} \tag{18}$$

for air velocities in the range 1.74-52.43 m/min.

Ngoddy et al. (1966) studied heat transfer in beds of pea beans. An equation for packed beds of spheres based on the Celburn j-factor was found to be satisfactory for pea beans:

$$j = \frac{Nu}{Re\ Pr^{1/3}} = 0.992\ Re^{-0.340} \tag{19}$$

or

$$Nu = 0.992\ Re^{0.660}\ Pr^{1/3} \tag{20}$$

Referring to Figure 6 a normal air temperature range during concurrentflow drying is 300°-500°K. In this temperature range the thermal conductivity of air varies from 0.026-0.040 W/m-°C; the dynamic viscosity varies from 1.983-2.671 x 10^{-5} kg/m-sec; the Prandtl varies from 0.708-0.680 (Holman, 1976). Average values in these ranges are used in the drying simulation to calculate an average heat transfer coefficient.

4.2.4 Latent heat of vaporization

The latent heat of vaporization is the energy necessary to evaporate moisture from the product being dried. Othmer (1940) proposed the following equation for the latent heat of vaporization:

$$h_{fg} = h_{fg}'[1.0 + A\exp(B)] \tag{21}$$

Equilibrium moisture content curves furnish the necessary data to calculate the product-temperature-moisture dependent constants.

Rodriguez-Arias (1956) developed the constants for corn with equilibrium moisture data in the range 8.70-35.14% d.b. and temperatures in the range 5°-40°C. Using these constants the latent heat of water evaporated from corn kernels was determined:

$$h_{fg} = (2502.100-2.386\ \theta)(1.0+4.349\exp(-28.25\bar{M})) \tag{22}$$

Alam and Shove (1973) developed constants from the equilibrium moisture data for soybeans in the range of 5.66-27.51% d.b. and bean temperatures in the range of 5°-55°C. The constants for soybeans can be used for calculating the latent heat of vaporization of water evaporated from pea beans:

$$h_{fg} = (2502.100-2.386\ \theta)(1.0+0.216\exp(-6.233\bar{M})) \tag{23}$$

The first parenthetical expression in both equations (22) and (23) are expressions for the latent heat of vaporization for free water as a function of water (grain) temperature as determined by Rodriguez-Arias (1956).

4.2.5 Miscellaneous grain and air properties

Brooker _et al_. (1974) described a SYCHART package for calculating any property of moist air given any two other properties. The SYCHART package of routines has been recently converted to SI units by Rugumayo (1976).

Several grain and air properties are independent of the grain or air conditions before or during drying. These properties are listed in Table 19 along with the reference source where they were obtained.

Table 19.--Grain and air properties.

Property		Corn	Pea Beans
Dry bulk density, kg/m^3		620.1[a]	929.0[e]
Equivalent kernel radius, cm		0.488[b]	0.457[e]
Specific heat, kJ/kg-°C		1.122[c]	1.675[c]
Specific surface area, m^2/m^3		784.1[d]	1522.3[e]
Specific heat, kJ/kg-°C	dry air	1.013[f]	
	water vapor	1.884[f]	
	water liquid	4.187[f]	

[a]Bakker-Arkema *et al.* (1974).

[b]Sabbah (1971).

[c]Kazarian and Hall (1965).

[d]Bakker-Arkema *et al.* (1971)

[e]Ngoddy *et al.* (1966).

[f]Holman (1976).

Conversion to SI units was accomplished in all cases using the SI conversion table contained in Appendix 9.1.

4.2.6 Energy and static pressure equations

The energy consumed during the concurrentflow drying process is composed of two components: (1) fuel for heating the drying air, and (2) electricity for running the motor which drives the fan to force the heated air through the drying bed.

The energy to heat the air can be calculated from an enthalpy balance on the air flowing through the heating apparatus assuming an 85% efficiency (Westelaken, 1976):

$$E_a = \frac{G_a(c_a+c_vH)(T-T_{amb})}{.85\ G_p} \tag{24}$$

The humidity value is the ambient humidity when the heat added by combustion is determined from the fuel's lower heat value. The combustion of fuel does add some additional water as a combustion by-product. The main fuel used for grain drying in Michigan is LP gas which is mostly propane (Kenyon et al., 1976). Propane has the chemical formula C_3H_8 and undergoes combustion by the following formula (Raznjevic', 1976):

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O + (48651\ \text{kJ/kg propane}) \tag{25}$$

A typical concurrentflow dryer uses 3000 $kg_{air}/hr\text{-}m^2$ at a temperature rise of 200°C with an ambient humidity of 0.005. In this case the added humidity due to combustion is 0.008 kg_{water}/kg_{air}. The results presented by Baughman et al. (1971) indicate that the added humidity increases the outlet moisture by approximately 0.3% d.b.

The electricity to run the fan is dependent on the static pressure which the fan operates against. The energy required can be calculated as given by Perry et al. (1963) assuming a 50% efficiency (Farmer, 1972):

$$E_{fm} = \frac{5.75(Q_a)SP}{.5\ G_p} \tag{26}$$

Pressure drop data for many agricultural products was presented in graphical form by Shedd (1953). The data was reported for loose filled, clean, relatively dry grains and seeds. The following observations were reported by Brooker et al. (1974):

1. loose filled, clean grain with high moisture content (equilibrium RH greater than 85%) results in about a 20% reduction in pressure drop
2. packing of the grain may cause a 50% higher pressure drop
3. fine material mixed with whole grain increases the pressure drop
4. course material mixed with whole grain decreases the pressure drop

The curves presented by Shedd (1953) have been represented by the following pressure-flow relationship:

$$Q_a = A(SP/x_1)^B \tag{27}$$

Using this form of the pressure-flow relationship, constants A and B for several agricultural products are presented in Table 20.

A comprehensive study on the resistance of grain to airflow was presented by Matthies (1956). Based on Reynold's law of similarity an effort was made to determine the relationship between pressure drop

Table 20.--Constants for the Sheed pressure-flow relationship for different agricultural products.

Product	A	1./B	Airflow Range m^3/m^2-min	Source
Shelled corn	18.90	1.471	3.0-12.2	Shedd (1953)
Shelled corn	17.68	1.528	12.2-45.0	Farmer (1972)
Wheat	9.75	1.250	3.0-12.1	Shedd (1953)
Pea Beans	19.81	1.431	3.0-30.5	Maddex (1953)*

*Data presented fit to the form of the equation by author.

and the independent variables affecting pressure drop. The results confirmed that the pressure drop varied linearly with the depth of the grain mas and inversely with the fourth power of the porosity.

Patterson et al. (1971) calculated static pressure using a modified form of the Ergun equation for packed beds. The equation is based not only on the superficial air velocity but also the porosity of the product bed and an empirical factor which is product temperature and moisture dependent. Matthies and Peterson (1974) have shown that the form of the equation presented by Shedd deviates from the Ergun equation for wheat by only 7.4%. The simplified equation (27) presented above is thus acceptable for use in the concurrentflow model.

A question raised which is pertinent to concurrentflow dryers especially is in regards to the effect of the change in temperature on the pressure drop which the fan senses. Assume the situation to be frictionless flow through a heat duct with heat transfer, a derivation which may be found in fluid mechanics texts such as Streeter (1971). The following four assumptions are made in the derivation: (1) steady, plug flow, (2) air is a perfect gas with constant specific heat,

(3) the duct has a constant cross-section, and (4) friction is negligible. The appropriate equations are:

$$\text{continuity: } G_a = \rho V \tag{28}$$

$$\text{momentum: } SP + \rho V^2 = \text{constant} \tag{29}$$

$$\text{Mach number: } Ma = V/(1.4R(T+273))^{1/2} \tag{30}$$

The continuity equation (28) is substituted into the perfect gas equation giving:

$$SP = G_a R(T+273)/V \tag{31}$$

The Mach number equation (30) is combined with the perfect gas equation giving:

$$SP = \rho V^2/(1.4Ma^2) \tag{32}$$

From the momentum equation (29) the pressure at two points (before and after heating) can be transformed into a ratio:

$$\frac{SP_1}{SP_2} = \frac{1+1.4{Ma_1}^2}{1+1.4{Ma_2}^2} \tag{33}$$

Equation (33) is used to estimate the change in static pressure due to the heating process. A realistic situation for a concurrentflow heater is air entering at 45 m/min. and exiting the heater at 65 m/min with a temperature rise from 25° to 200°C. The Mach number for the two points would then be: (1) $Ma_1 = 2.2 \times 10^{-3}$ and (2) $Ma_2 = 2.4 \times 10^{-3}$. Substituting into equation(33) results in a static pressure ratio of

0.9999987. Therefore, it can be concluded that the effect of the heating is negligible on the static pressure which the fan senses.

Another factor to be considered is the effect of the percentage of fines and foreign material on the static pressure. Henderson (1943) presented a fairly complete set of data for static pressure versus percentage of corn fines. The data can be approximated by a linear equation for a multiplicative correction factor:

$$K = 1.0 - 3.75\ f \tag{34}$$

Haque _et al_. (1976) studied the effect of fines in shelled corn on the static pressure and concluded:

1. for an airflow rate in the range 4.6-12.2 m/min, the pressure drop increased linearly with the increase in percentage of fines in the range 0-20% fines
2. a modification to the Shedd equation (27) allows prediction of pressure drop as affected by corn fines:

$$K = (1.0 + (14.556 - 0.4403\ Q_a)f)/Qa \tag{35}$$

The static pressure data and prediction equations currently available are generally at airflow rates below those in use in commercial concurrentflow dryers. The following simulation and optimization uses the Shedd equation (27) for estimating the static pressure even though the airflow rates may exceed the range for which the equation was developed. In addition it is assumed that the corn has been adequately cleaned such that no effective percentage of fines is left to affect the static pressure. It is further assumed that the continuous flow nature of the dryer does not significantly affect the porosity of the grain mass. The affect of porosity could be included in a porosity multiplicative factor if desired. Such a factor would include the actual value of the porosity which may also be influenced by the moisture of the product being dried. For shelled corn Bern and Charity (1975) studied the effect of varying bulk density on the pressure drop for airflow through corn. The porosity value was replaced by a function of the bulk density and the kernel density:

$$\varepsilon = 1.0 - (\rho_b/1170) \tag{36}$$

Gustafson and Hall (1972) studied the effect of drying temperature in the range 21°-104°C on the change in density of a bed of shelled corn. The true bulk density was found to be a linear function of the moisture content of the corn (constants A and B were not explicitly stated):

$$\rho_b = A - B\,\bar{M} \tag{37}$$

Similar equations can be developed for other agricultural products and for additional airflow ranges following appropriate experimentation.

4.3 Tempering stage

Tempering of warm grain from the first stage of a multistage dryer accelerates the drying rate in the following drying stage. Increased capacity and better grain quality result when corn is dried from 32 to 18% w.b. followed by drying from 18 to 14% in the second crossflow stage after a tempering period as compared to drying directly from 32 to 14% in one crossflow stage (Katic, 1975).

Sabbah (1971) studied tempering as a part of the dryeration process. Tempering had a significant effect on the cooling rate and on the moisture removed during in-bin cooling. An index of tempering was constructed which redefined the initial moisture of the corn after tempering. The index was used to calculate the moisture removed during subsequent cooling. During the tempering period the grain did not exchange heat and moisture with the surrounding air.

The effect of tempering after concurrentflow drying can be estimated using the ODE integretion algorithm previously described for any desired length of tempering time. The derivatives in equations (8) thru (11) become zero since no transfer occurs between the grain and the air. The moisture within the kernel then redistributes by diffusion as shown in Figure 16. As the tempering time increases the moisture concentration at any point within the kernel will asymptotically approach an average value.

Since the moisture loss from the kernel to the air occurs only at the surface, the overall moisture transfer rate would indeed increase after tempering. Figure 17 compares the effect of tempering time on the moisture content profile for a two meter long concurrentflow dryer following the tempering stage. Tempering times beyond 1.25 hours appear to have a negligible effect on the final average moisture content and temperature of the grain. Sabbah _et al_. (1972) found that tempering for eight hours following crossflow drying resulted in a higher moisture removal rate during subsequent cooling than tempering for two, four or twelve hours. The concurrentflow dryer requires less tempering time for maximum tempering effect than the crossflow dryer because of the uniformity of the average moisture contents and temperature between kernels after drying in a concurrent flow dryer.

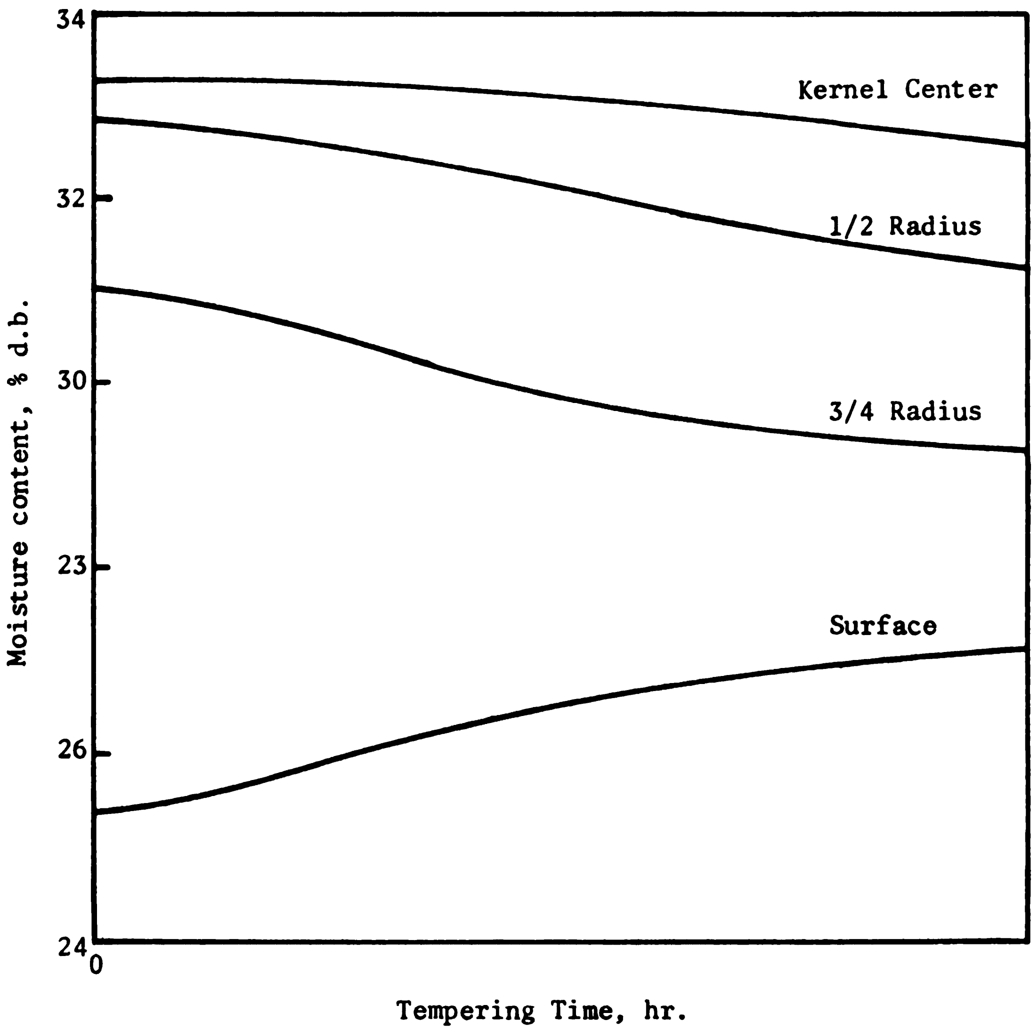


Figure 16. Moisture content versus tempering time for shelled corn after drying from 25.0% w.b. in a concurrentflow dryer. Kernel temperature during tempering 51°C.

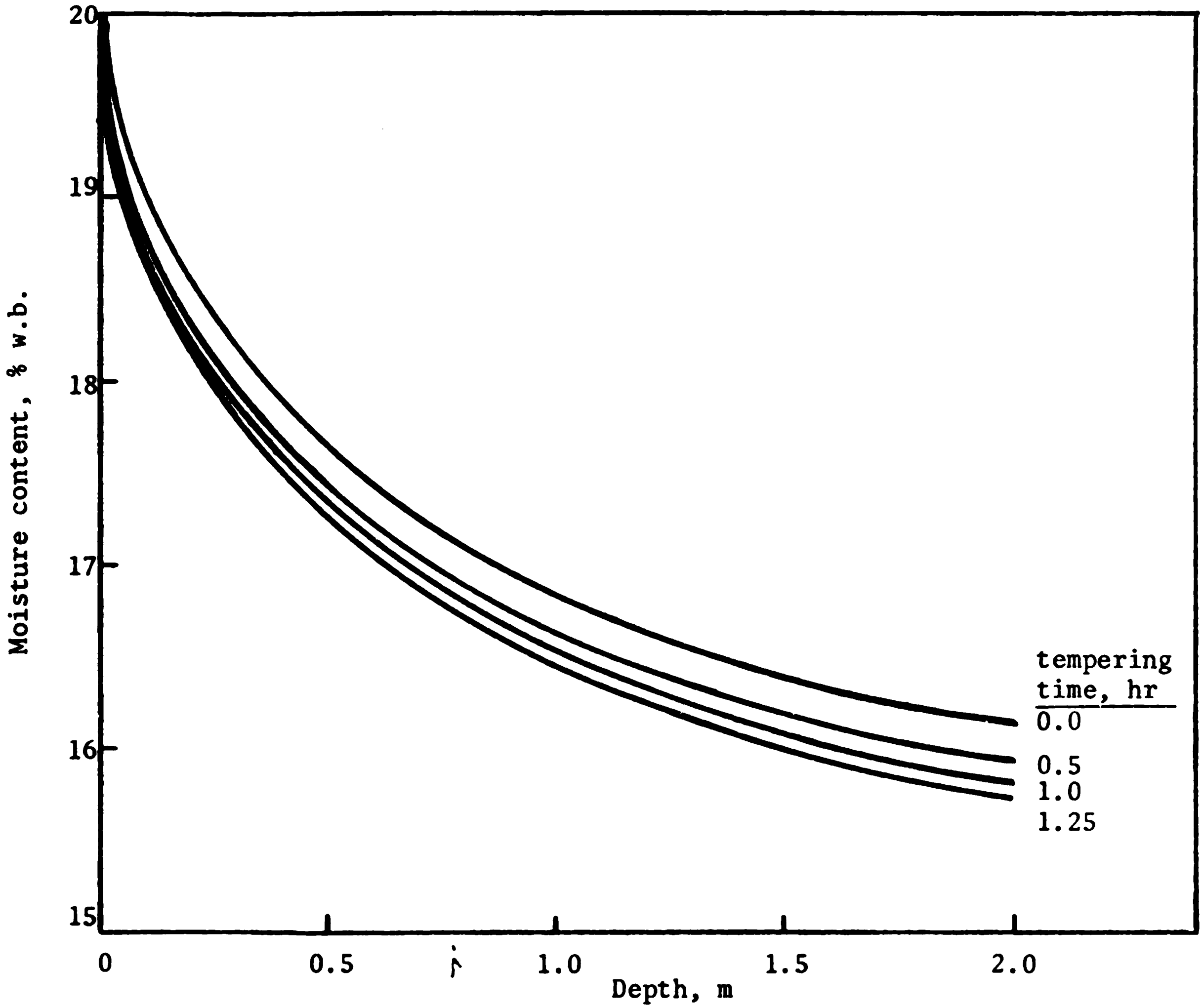


Figure 17. Effect of tempering time on corn moisture content profile in a concurrentflow drying stage following tempering.

Sabbah (1971) found that grain did not change temperature or moisture content significantly during tempering. The corn entering the tempering stage illustrated in Figures 16 and 17 had a temperature of 51°C. If the grain temperature is less than 51°C the moisture removal would decrease (see Table 21) and a longer tempering time would be necessary for a similar tempering effect. Correspondingly, a higher inlet grain temperature would decrease the tempering time for a similar tempering effect.

Table 21.--Effect of various grain conditions on the moisture profile for corn dried in a concurrentflow stage following tempering for 1.25 hours.

Tempering Grain Temperature °C	Depth, m					
	0.0	0.4	0.8	1.2	1.6	2.0
51	19.95	17.55	16.75	16.28	15.98	15.78
43	21.15	18.78	17.98	17.55	17.29	17.14
40	21.74	19.38	18.60	18.19	17.96	17.83
47	20.56	18.15	17.37	16.92	16.63	16.45
39	23.06	20.52	19.77	19.42	19.26	19.20
51	19.63	17.33	16.49	16.00	15.69	15.48
46	19.98	17.75	16.92	16.46	16.17	15.97
42	21.95	19.48	18.72	18.31	18.09	17.97
48	19.29	17.17	16.35	15.87	15.55	15.35
41	23.28	20.57	19.81	19.47	19.33	19.29

4.4 Cooling stage

Simulation of the counterflow cooling stage using heat and mass transfer equations is very difficult because the problem is a two-point boundary value problem (Figure 18). Hence there does not exist a straightforward, short (computer time) solution algorithm for the differential equations describing the heat and mass transfer. Thompson (1967) simulated a counterflow process assuming the bed to be a number of thinlayer which were continuously moving downward. At successive time intervals a layer was removed from the bottom of the stack and another placed on the top. Since the algebraic equations derived assumed a steady-state situation a search algorithm was necessary to find the appropriate solution. Evans (1970) applied invariant programming and invariant imbedding techniques to the simulation of the counterflow process. The approach produces a family of solutions which yield a particular solution upon the application of a dynamic programming type solution retrieval technique. Bakker-Arkema _et al._ (1974) developed a counterflow simulation program which used a shooting technique to arrive at the appropriate solution. The differential equations derived for the heat and mass transfer assumed a steady-state situation. The algorithm's stability was particularly sensitive to the initial guesses and did not always yield a reasonable solution. Roth (1977) used an approach similar to that of Thompson except utilizing a set of differential equation written to include the transient as well as the steady state part of the counterflow process. The counterflow cooler process was simulated as a transient system until steady state operation was achieved.

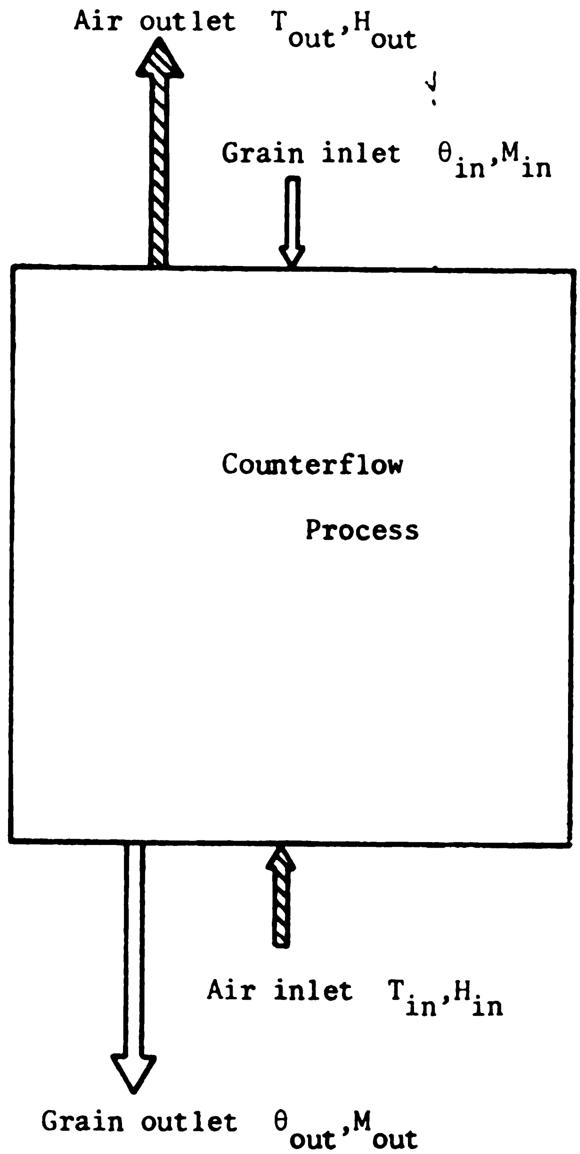


Figure 18. Schematic of counterflow process.

All the algorithms presented above use too much computer time for estimating the effect of the counterflow cooler as a part of the multistage drying system. During the counterflow cooling process the exit grain temperature does not reach thermal equilibrium with the inlet air temperature. Likewise, the exit air temperature does not always reach thermal equilibrium with the inlet grain temperature. The counterflow cooler may be considered as basically a counterflow heat exchanger for transferring heat from the inlet grain to the air flowing through the cooler. Some mass transfer occurs which assists in the heat transfer through evaporative cooling. The counterflow cooler can then be approximated by a modified version of the Effectiveness-NTU method presented by Holman (1976). The effectiveness for a counterflow heat exchanger is defined:

$$e = \frac{\text{actual heat transfer}}{\text{maximum possible heat transfer}} \tag{38}$$

The value of the effectiveness is calculated from a convective heat transfer analysis using the energy capacity flowrate for each product:

$$C_a = [G_a(c_a+c_vH_{in})T_{in} + G_ah_{fg}H_{in}]/T_{in} \tag{39}$$

$$C_p = G_p(c_p+c_wM_{in}) \tag{40}$$

The relations listed above were modified to account for the transfer of energy based on the mass transfer and associated latent heat. There are two distinct cases that could occur during the counterflow cooling process: (1) $C_a \leq C_p$, and (2) $C_p \leq C_a$. The two cases affect the equations to be used for calculating the effectiveness and the associated outlet grain and air temperatures.

Case (1): $e = (1.0\text{-}A)/(1.0\text{-}(C_a/C_p)A)$ (41)

where: $A = \exp((-h_c x_1 a/C_a)(1.0\text{-}C_a/C_p)$ (42)

$$T_{out} = T_{in}+e(\theta_{in}-T_{in}) \quad (43)$$

$$\theta_{out} = \theta_{in}-e(C_a/C_p)(\theta_{in}-T_{in}) \quad (44)$$

Case (2): $e = (1.0A)/(1.0\text{-}(C_p/C_a)A)$ (45)

where: $A = \exp((-h_c x_1 a/C_p)(1.0\text{-}C_p/C_a)$ (46)

$$\theta_{out} = \theta_{in}-e(\theta_{in}-T_{in}) \quad (47)$$

$$T_{out} = T_{in}+e(C_p/C_a)(\theta_{in}-T_{in}) \quad (48)$$

Using the above calculated outlet temperatures the outlet moisture can be estimated from an enthalpy balance on the counterflow cooler:

$$M_{out} = (A\ M_{in}-B)/A' \quad (49)$$

where: $A = G_p(c_v T_{out}-c_w\theta_{in}+h_{fg})$ (50)

$$A' = G_p(c_v T_{out}-c_w\theta_{out}+h_{fg}) \quad (51)$$

$$B = G_a(c_a+c_v H_{in})(T_{out}-T_{in})-G_a H_{in} h_{fg} \quad (52)$$

The calculated outlet moisture is then used in an iterative process where the humidity in equation (39) is replaced by the average of the inlet and outlet humidity (calculated from a mass balance). The moisture in equation (40) is replaced by the average of the inlet and outlet moisture, and the outlet moisture is recomputed. The iterative process is continued until the change in outlet moisture between successive iterations is insignificantly small. Effectively this process recalculates the outlet temperatures based on the evaporative cooling due to the mass transfer taking place in addition to the previously calculated heat transfer.

The calculated results produced by the above described method are compared in Table 22 with results presented by Farmer (1972) for counterflow cooling simulations using a model-fit algebraic algorithm. The model was constructed from simulation output prepared by the counterflow cooler processor described by Bakker-Arkema et al. (1974) for shelled corn. The simulator described above matches well with the results of Farmer and can be applied to products other than corn.

Table 22.--Comparison of counterflow process simulator with previously published data.

	Data set I		Data set II	
	Model (e-NTU)	Farmer	Model (e-NTU)	Farmer
Inlet air conditions:				
temperature °C	11	11	11	11
humidity, decimal d.b.	.003	.003	.003	.003
flow rate, kg/hr-m^2	1275	1275	1275	1275
Inlet grain conditions:				
temperature, °C	62	62	55	55
moisture, % w.b.	16.8	16.8	16.8	16.8
flow rate, kg/hr-m^2	2460	2460	2460	2460
Outlet air temperature, °C	61	62	55	55
Outlet grain conditions:				
temperature, °C	29	26	26	25
moisture, % w.b.	15.9	15.2	15.6	15.5

Source: Farmer (1972).

A sensitivity study using the Effectiveness model is presented in Table 23. One aspect noted by Roth (1977) but not always fully recognized is that there is a point where supplying more airflow to the cooler actually results in less moisture removal. For the results in Table 22 for corn this occurs at an airflow of 25 m/min. At this airflow, the energy capacity flow rates (defined in equations (39), (40)) have inverted in relative magnitude. Before this point the air energy capacity flowrate was less than the grain energy capacity flowrate. When the inversion occurs the outlet air temperature (which had previously been almost equal to the inlet grain temperature) begins to decrease. Therefore the moisture removal will decrease.

4.5 Quality prediction equations

Several grain quality factors may be considered as shown in Section 2. For shelled corn the majority of the U.S. harvest goes for feed grain. The handler and shipper are interested in shipping a product which meets U.S. grade standards at minimum cost. The buyer wants to receive the product in as good a condition as possible. Stress cracks lead to broken corn which is expensive for the handler to remove and downgrades the product received. The results of the Stein breakage test can be used to estimate the effect of drying on the susceptibility to damage of the artificially dried corn. The data collected during the experimental investigations was plotted in Figure 15. The correlation for a straight line yielded the following equation:

$$B_s = 143.65*\Delta M-8.40; \; r_c=0.59, \; p>0.01 \qquad (53)$$

Table 23.--Sensitivity study of cooler operation using the Effectiveness simulator for shelled corn.

Inlet Conditions						Outlet Conditions	
Grain Temp °C	Grain Moisture % w.b.	Air Temp °C	Air Flow Rate m/min	Grain Flow Rate kg/hr-m^2	Length m	Grain Temp °C	Grain Moisture % w.b.
50	16.0	15	10	2000	1.0	34	15.6
30	16.0	15	10	2000	1.0	24	15.9
70	16.0	15	10	2000	1.0	43	14.9
50	14.0	15	10	2000	1.0	34	13.4
50	18.0	15	10	2000	1.0	35	17.4
50	16.0	5	10	2000	1.0	21	15.0
50	16.0	10	10	2000	1.0	29	15.2
50	16.0	20	10	2000	1.0	39	15.6
50	16.0	15	5	2000	1.0	42	15.7
50	16.0	15	15	2000	1.0	27	15.1
50	16.0	15	20	2000	1.0	19	14.9
50	16.0	15	25	2000	1.0	15	14.8
50	16.0	15	30	2000	1.0	15	14.9
50	16.0	15	40	2000	1.0	15	14.9
50	16.0	15	10	1000	1.0	19	14.9
50	16.0	15	10	1500	1.0	29	15.2
50	16.0	15	10	2500	1.0	37	15.5
50	16.0	15	10	3000	1.0	40	15.6
50	16.0	15	10	2000	0.1	34	15.4
50	16.0	15	10	2000	2.0	34	15.4

The results indicate the same trend noted by Thompson and Foster (1963) for crossflow drying of corn. The susceptibility of corn to breakage during subsequent handling (as indicated by the Stein breakage test) increases as the drying rate increases.

Processers of pea beans are concerned about the percentage of cracked seed coats (cracks). Cracks often become beans with loose pieces of skin or even split beans. During the final processing phase the loose skin may separate from the bean. The exposed cotyledons become mushy as solids are released to the surrounding fluid (Anon., 1974). An equation which uses the theory of engineering mechanics similar to that presented by Wang (1956) and recognizing the stochastic properties of the process could be used to predict the percentage of cracks occurring. However, adequate experimental data is not yet available for this type of approach. The data collected during the experimental investigations can be used to develop a prediction equation for the percentage of cracks. Figure 10 showed that the percentage of cracks increases as the exit temperature of the beans increased. Figure 11 showed that the percentage of cracks decreased as the moisture removed in one stage decreased. Taking these two factors into account plus the influence of the grainflow rate, a new variable is defined for estimating the percentage of cracks in pea beans due to the concurrentflow drying process (Figure 19):

$$S = 0.199 + 5.554*\theta*\Delta M/G_p; \; r_c = 0.59, \; p>0.01 \qquad (54)$$

The above equation predicts the change in skin cracks which occurs due to a single concurrentflow drying stage. Again the influence of the drying rate on grain quality is evident. Also included in the above

BEAN DRYING STATISTICS SPSS V6.5 06/08/77

FILE BEAN (CREATION DATE = 06/08/77) KIRKTON PEA BEAN DRYING DATA
SCATTERGRAM OF (DOWN) DELC CHANGE IN CRACKS FOR ONE STAGE (ACROSS) TPTMDM TEMP TIMES DELM DIVIDED BY GRAINFLOW

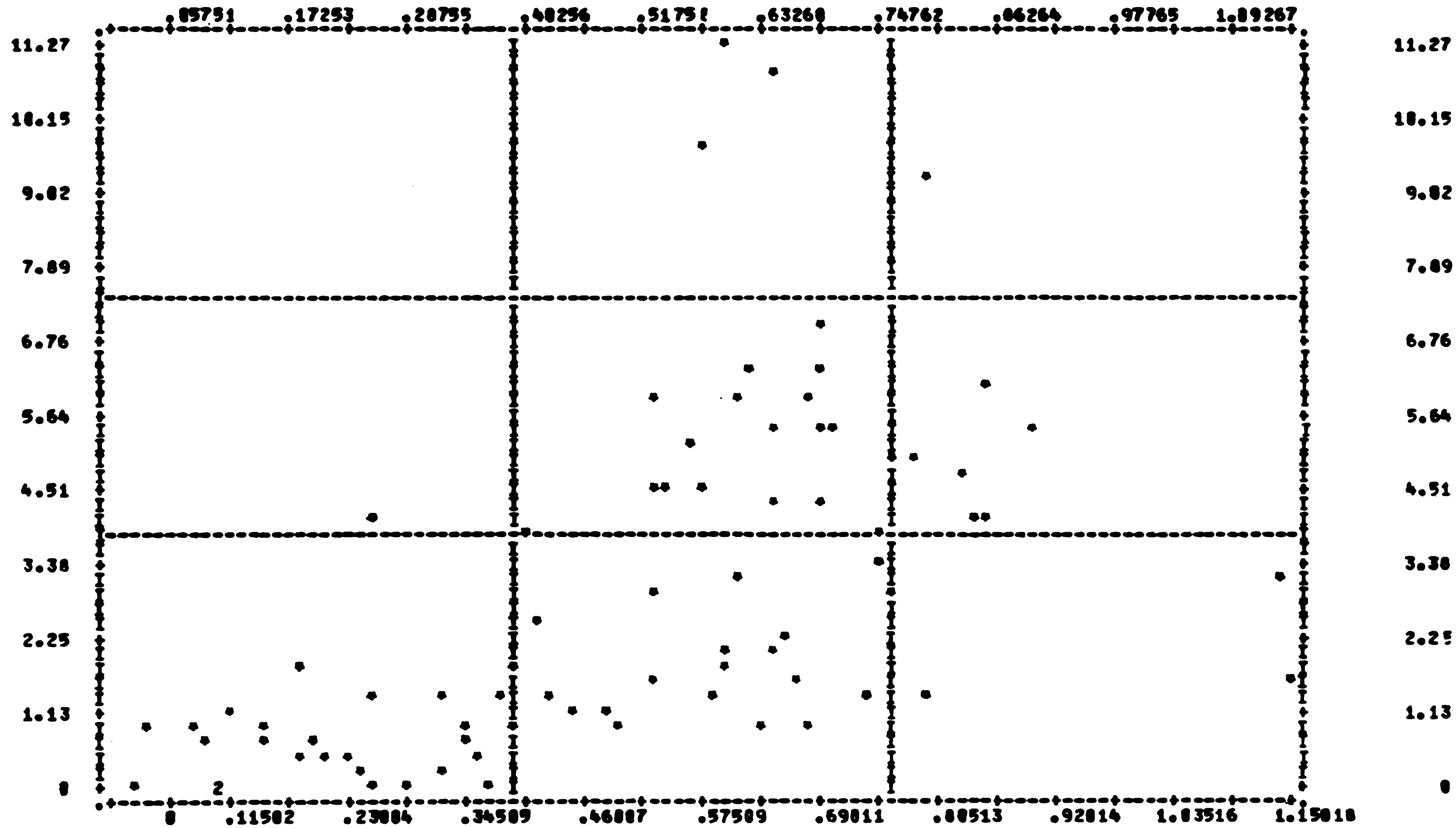
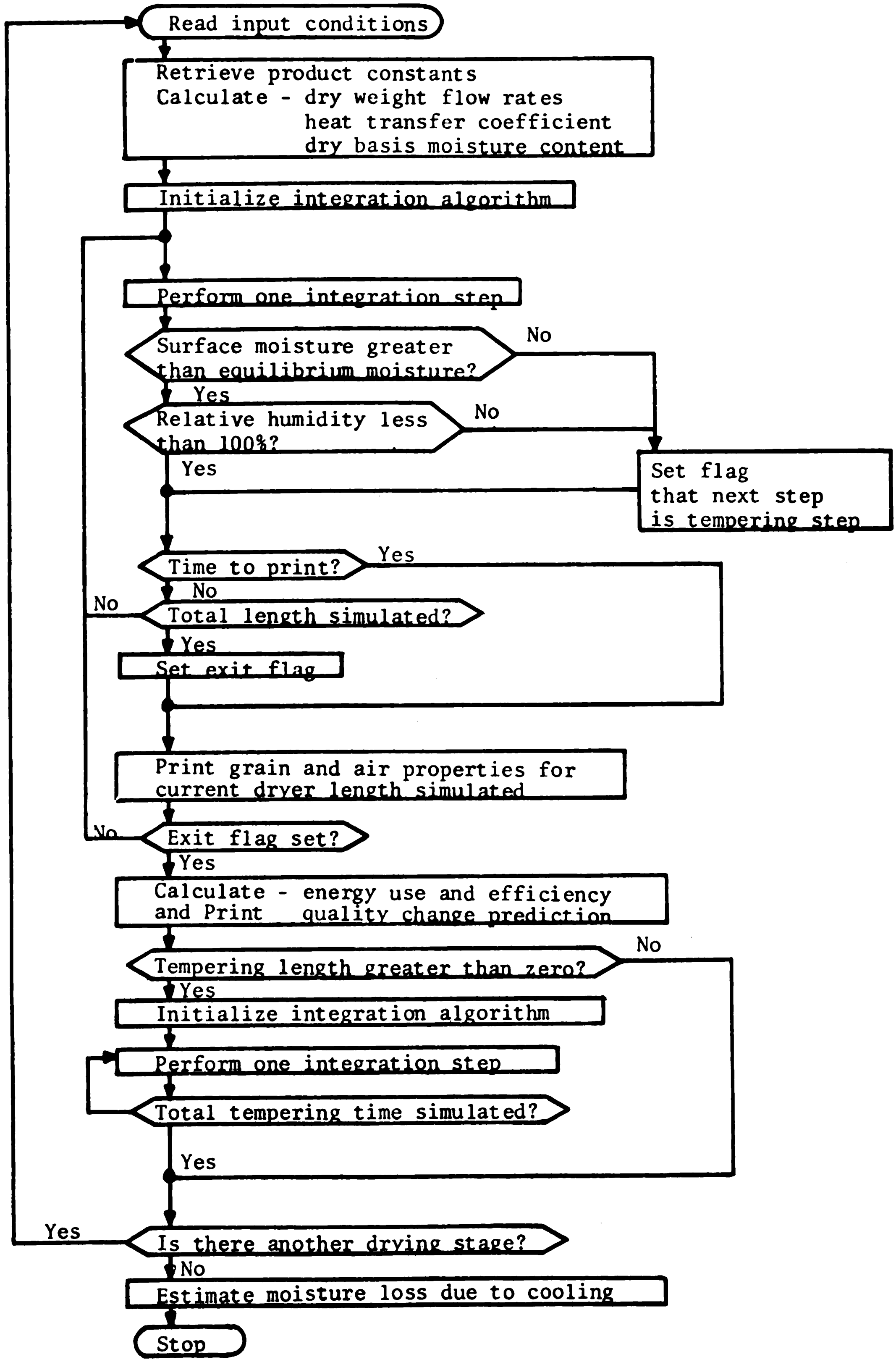


Figure 19. Scattergram of the change in cracks with exit grain temperature times change in moisture content divided by grainflow.

equation is the effect of the grain temperature which is important for beans as noted by Walker and Barre (1972). Not included is the possible influence of the humidity of the drying air. Hall and Maddex (1952) indicated that humidity is an important parameter which affects the percentage of cracked seed coats for pea beans dried with heated air.

4.6 Model flow chart



4.7 Model validation

The experimental results used in this section were results from tests conducted in English units. The conversion of the results to SI (Standard International, see ASAE, 1977) units was done by the author using the conversion table presented in Appendix 9.1.

Several methods may be used for comparing the predictions of the computer simulation model with experimental results. The methods can be grouped into three general categories: (1) graphical, (2) parametric statistical, and (3) non-parametric statistical.

One graphical method is called a correspondence plot. The experimental result for the desired parameter is plotted as the abscissa while the predicted value of the parameter is plotted as the ordinate. Ideally the plotted points would fall along a 45° line beginning at the origin (perfect correspondence). The deviation from this line can be measured by a linear regression coefficient:

$$r_c = \frac{\Sigma(o_i-\bar{o})(y_i-\bar{y})}{[\Sigma(o_i-\bar{o})^2 \ (y_i-\bar{y})^2]^{1/2}} \tag{55}$$

for the matched coordinate pair (o_i, y_i) where o_i is the estimated value of the experimental results y_i.

A second graphical method uses residuals which are the difference between the actual and predicted parameter values. A plot of residuals versus time or versus the actual parameter value may indicate any systematic deviation from perfect linear correspondence. Himmelblau (1970) presented an excellent review of the use of residuals under the heading of "Process Control Charts." Only the correspondence plots will be used in the model validation which follows.

There are several parametric statistical tests. Gilmour (1971) discussed several of these in the context of simulation model validation. The goodness-of-fit test based on the Chi-Square statistic is a measure of the discrepancy between observed and expected frequencies. The goodness-of-fit statistic is calculated:

$$X_2 = \Sigma \frac{(o_i - y_i)^2}{y_i} \tag{56}$$

A value of zero (0) implies perfect correspondence between the actual and predicted parameter values. For a given level of significance the critical X^2 value can be read from a Chi-Squared distribution table. If the X^2 statistic is less than the critical value, the correspondence is acceptable at the given level of significance.

A second parametric statistical test is based on the F-distribution. The F statistic is the ratio of the variances of the two sample sets and may be calculated:

$$F = \frac{\Sigma(o_i - \bar{o})^2}{\Sigma(y_i - \bar{y})^2} \tag{57}$$

The degrees of freedom for the predicted values is one less than the number of tests. The degrees of freedom is one less than the product of the number of tests times the sample replication for each test. An F value of one (1) implies identical variance. For a given level of significance the critical F value can be read from a table of the F distribution. If the F statistic is less than the critical value, the variances of the actual and predicted parameters are considered essentially equal at the given level of significance. Both of the parametric statistical methods reviewed above will be used in the model validation which follows.

Himmelblau (1970) reviews several non-parametric statistical tests which may be used in model validation. The Sign Test may be used instead of the t-test and relates the median difference in paired observations. The Mann-Whitney U test is another acceptable alternative to the t-test and is used to test whether or not two sample populations are identical. The Siegel-Tukey test is an alternative to the F test. The test determines if the dispersions of the underlying population of two independent samples are the same. The non-parametric statistical tests are allowable alternatives to the parametric tests but are not used in the following validation of the computer simulation model primarily due to the lack of readily available computer programs for carrying out the necessary computations.

4.7.1 Single-stage drying of shelled corn

The concurrentflow drying simulation equations presented in the previous section are dependent on the number of interior nodes within the grain kernel. Table 24 shows the effect of the number of interior nodes on the moisture content profile during drying of shelled corn. The simulation results presented in the following subsections use four (4) interior nodes as a reasonable compromise between accuracy and necessary computing time.

The single-stage concurrentflow dryer has been previously studied (Thompson, 1967; Carrano *et al.*, 1971; Baughman *et al.*, 1971; Mühlbauer *et al.*, 1971). Comparison between randomly selected experimental results from several of these studies and the simulated results

Table 24.--Effect of number of interior nodes in a corn kernel on the average moisture content profile during the simulated drying in a concurrentflow dryer.

Depth	Number of Interior Nodes					
	2	3	4	5	6	7
0.00	25.00	25.00	25.00	25.00	25.00	25.00
0.25	22.61	22.03	21.56	21.17	20.83	20.82
0.50	21.69	21.12	20.66	20.32	20.05	20.04
0.75	21.14	20.60	20.20	19.95	19.79	19.78
1.00	20.77	20.27	19.95	19.77	19.71	19.70

Drying conditions: 250°C, 50.0 m/min, 2.5 tonne/hr-m^2 Ambient conditions: 15°C, 0.005 kg/kg

using the above described model are presented in Table 25. Some simulated moisture contents are greater than the experimental results, some are less than the experimental results. The average of the absolute differences in grain moisture content is 0.933% w.b. Likewise some of the simulated grain temperatures are greater than the experimental results, some are less. The average of the absolute differences in grain temperature is 7.73°C. Much of the temperature difference is due to the tests presented by Carrano et al. (1971). In obtaining the data, a single stage concurrentflow dryer with a counterflow cooler was used. Grain samples were taken between the drying and cooling stages and the temperatures reported are a combination of outlet dryer and outlet cooler air temperatures.

Correspondence plots for grain temperature and moisture content are presented in Figure 20. The linear correlation coefficient for grain temperature including all tests is r_c = 0.746; for grain

Table 25.--Comparison of simulated drying conditions with single-stage experimental drying tests reported in the literature. Drying only, no cooling.

Test Number*	T25	T34R	T45	T207	T309	T359	C2	C4	C6A	B10	B11	Bf.4
Ambient Conditions:												
Temperature, °C	16	16	16	16	16	16	28	29	29	25	21	11
Humidity, decimal	.010	.010	.010	.010	.010	.010	.015	.017	.014	.007	.005	.006
Drying Conditions:												
Temperature, °C	93	149	204	93	149	177	232	232	96	83	82	121
Airflow, m/min	21.4	24.1	30.5	21.3	27.4	27.4	21.3	21.3	33.5	30.5	32.9	24.4
Grainflow, kg/hr-m^2	230	266	770	162	419	654	494	1223	799	254	226	273
Length, m	0.61	1.22	0.61	0.61	0.61	0.61	0.34	0.34	0.34	0.61	0.61	0.61
Initial Conditions:												
Temperature, °C	16	16	16	16	16	16	28	29	29	25	21	11
Moisture, % w.b.	17.8	25.2	18.1	23.6	24.7	21.5	26.3	20.3	20.6	25.2	24.7	25.0
Experimental Results:												
Temperature, °C	55	52	79	54	--	75	61	54	32	38	38	43
Moisture, % w.b.	12.5	15.0	13.6	12.7	16.5	14.6	15.2	17.1	17.4	16.5	15.3	15.1
Simulated Results:												
Temperature, °C	54	59	86	48	57	65	71	70	51	41	44	51
Moisture, % w.b.	12.4	12.0	12.1	14.1	15.8	15.0	16.5	17.4	18.4	17.1	15.9	15.4

*T25, T34R, T45 from Thompson (1967), drying tests for 1964 harvest season. T207, T309, T359 from Thompson (1967), drying tests for 1965 harvest season. C2, C4, C6A from Carrano _et al._ (1971), drying tests for 1970 harvest season. B10, B11, Bf.4 from Baughman _et al._ (1971), drying tests for 1970 harvest season.

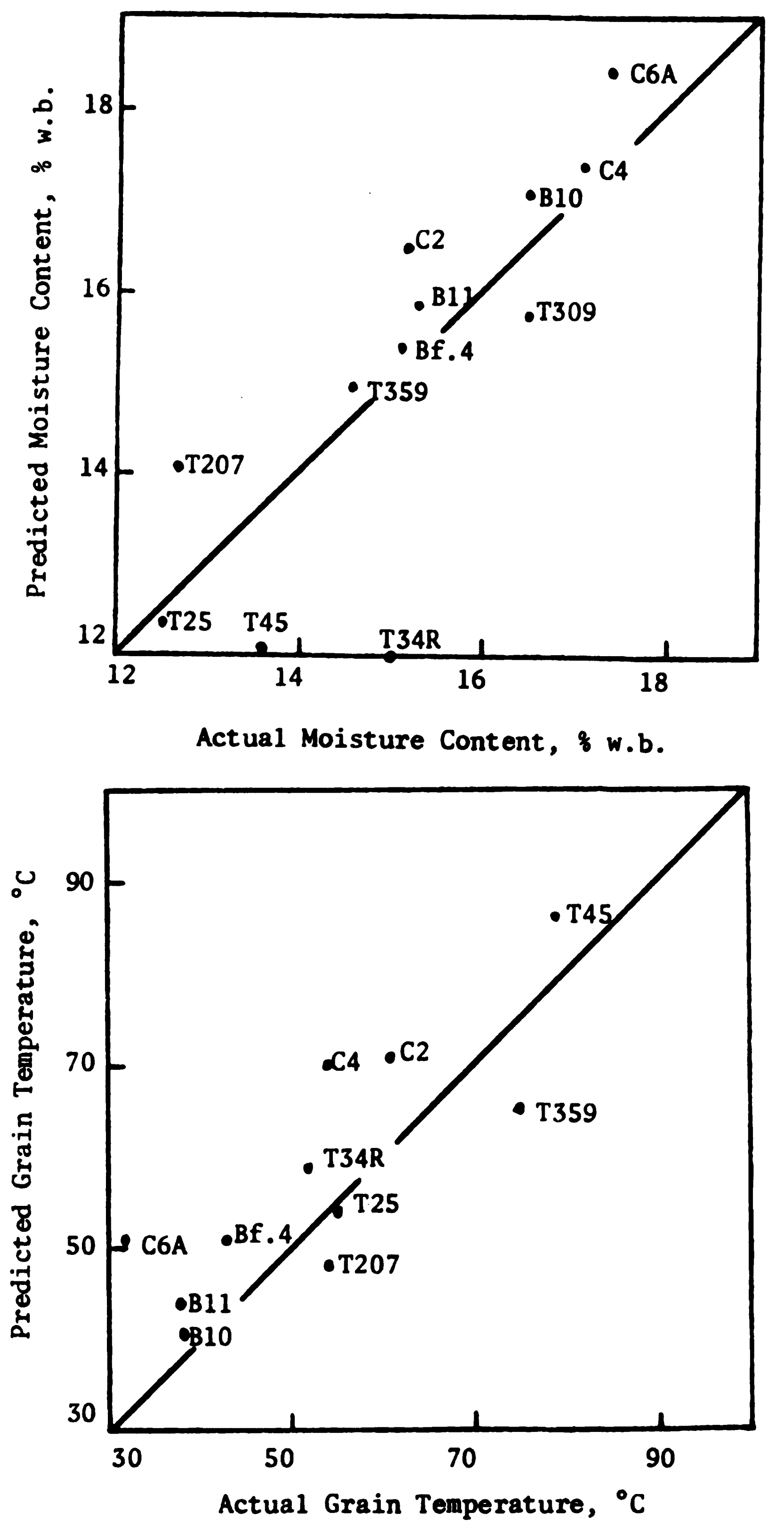


Figure 20. Correspondence plot for single-stage concurrentflow drying: T = Thompson (1967), C = Carrano et al. (1971), B = Baughman et al. (1971).

temperature excluding the Carrano tests $r_c = 0.789$; for moisture content $r_c = 0.743$.

The grain temperature goodness-of-fit test (excluding Carrano tests) yields $X^2 = 6.253$ which is less than the critical Chi-Squared value at 95% significance of $X_c^2 = 14.07$ (CI: 1.69 - 16.01). The F value is $F(7,31) = 1.173$ which is less than the critical value at 95% significance of $F_c = 2.75$ (CI: 0.36 - 2.75). The grain temperature correspondence is significant at the 95% level.

The moisture content goodness-of-fit test yields $X^2 = 1.19$ which is less than the critical value at 95% significance of $X_c^2 = 19.68$ (CI: 3.82 - 21.92). The F value is $F(47, 11) = 1.78$ which is less than the critical value at 95% significance of $F_c = 3.02$ (CI: 0.33 - 3.02). The moisture content correspondence is significant at the 95% level. Therefore the model is accepted for single-stage drying at the 95% significance level.

4.7.2 Multi-stage drying of shelled corn

The previously described multi-stage concurrentflow computer model was used to simulate the drying of shelled corn. The effect of drying on the susceptibility to breakage (Stein breakage test) was determined using equation (53). Computer simulation runs were produced for the test input conditions given in Table 13. The results of the simulations are presented in Table 26.

The test results from Table 14 can be compared with the simulation results in Table 26 to help verify the accuracy of the computer simulation results for use in the design of a multistage concurrentflow grain dryer. Table 27 shows the absolute values of the differences

Table 26.--Simulation results for shelled corn drying tests.

Test Number	1	2	3	4	5	7	8	9
Stage 1								
temperature, °C	36	39	40	41	40	41	43	41
moisture, % w.b.	25.2	21.5	24.5	24.0	22.2	20.2	19.7	22.6
Stein breakage, %	15.2	16.3	12.1	13.8	25.6	28.0	39.0	39.8
Stage 2								
temperature, °C	41	49	46	50	53	60	56	49
moisture, % w.b.	21.8	16.9	18.8	17.8	14.0	11.3	11.9	14.3
Stein breakage, %	21.2	26.1	25.5	28.2	43.4	46.1	50.1	57.9
Stage 3								
temperature, °C	44	60	58	66				
moisture, % w.b.	18.1	12.8	13.1	11.8				
Stein breakage, %	29.6	34.2	37.0	40.0				
Cooler**								
temperature, °C	23	23	28	24	29	29	23	17
moisture, % w.b.	17.3	11.6	12.0	10.5	13.1	10.3	10.8	13.2
Efficiency, kJ/kg H_2O*	3778	4197	3738	3910	3832	3981	3853	3986

*Does not include the energy used or the removed during cooling.

**Cooler airflow 10 m/min test 1-4, 5 m/min tests 5-9.

Table 27.--Average differences between test conditions and simulation results for the shelled corn drying tests.

	Average	Maximum	Minimum	X^2*	F**
Before cooling					
temperature, °C	33	43	23	--	--
moisture, % w.b.	2.3	5.1	0.1	--	--
Stein breakage, %	18.9	25.7	9.1	--	--
After cooling					
temperature, °C	5	11	1	14.54	1.06
moisture, % w.b.	3.2	6.4	0.5	6.49	1.06
Stein breakage, %	18.9	25.7	9.1	155.60	1.27

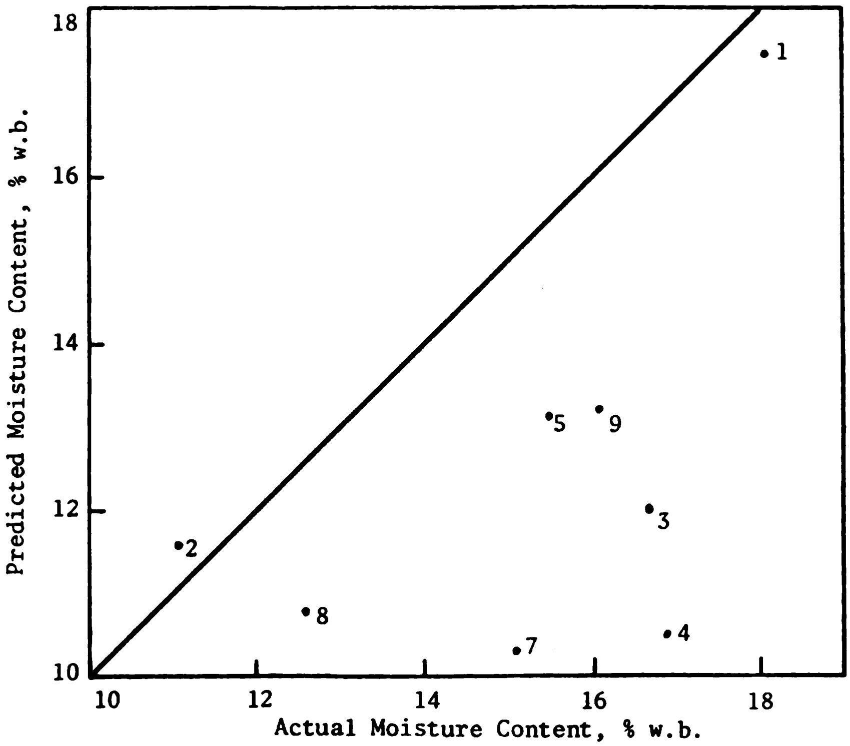
*X_c^2 = 14.07 (CI: 1.69 - 16.01) at 95% significance.

**$F_c(7,31)$ = 2.75 (CI: 0.36 - 2.75) at 95% significance.

between the test results and the simulation results for exit grain temperature, moisture content and percentage for the Stein breakage test. The discrepancy between the simulation and test results for moisture content is fairly large. This is primarily due to the way in which the test data was obtained. The corn drying tests were conducted as would be done commercially, i.e., varying the grainflow rate in order to achieve a uniform moisture product from the dryers. This was indeed accomplished as can be seen in the range of moisture contents given in Table 14 which is about $\pm$ 0.5% w.b. The grainflow rates used in the simulation are time-weighted averages and do not account for all the effects of variable grainflow.

Correspondence plots for grain temperature and moisture content are presented in Figure 21. The linear correlation coefficient for grain temperature is r_c = -0.136; for moisture content r_c = 0.454; for Stein breakage percentage (not shown) r_c = 0.729.

The goodness-of-fit and F-value statistics are included in Table 27. The variance comparison (F-test) of all three parameters is significant at the 95% level. Only the moisture content correspondence is significant at the 95% level. The variation in the moisture content causes most of the deviation in Stein breakage percentage. Likewise the grain temperature is dependent on the moisture content. The correspondence is marginally significant at the 95% level. It is expected that the correspondence in all parameters would improve for multistage tests conducted with relatively constant inlet conditions. The agreement between the simulation model and the experimental tests is considered sufficient for the model to be used in the design of multistage concurrentflow grain dryers.



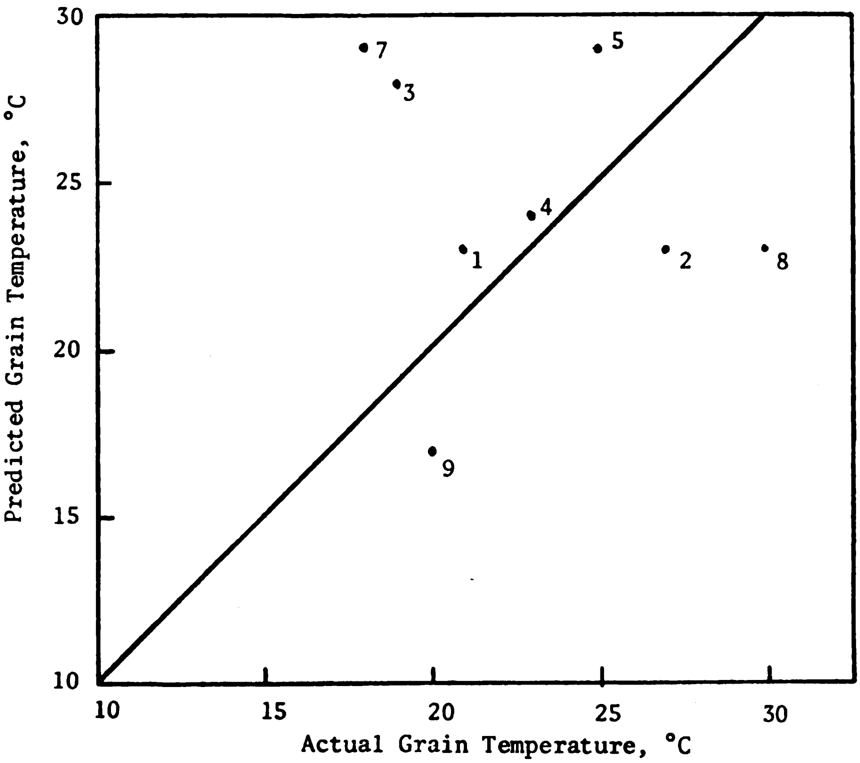


Figure 21. Correspondence plots for multistage shelled corn drying tests. Numbers refer to test number listed in Table 26.

It should be noted here that the overall breakage for the tests listed in Table 13 and 14 of 23.7% is lower than a previously reported average of 36.6% for a high-temperature crossflow dryer (Stephens and Foster, 1976). It is also lower than the average of 52.6% for samples taken from an Ace crossflow dryer operated at 104°C which was tested at the same time as the concurrentflow drying tests were conducted.

4.7.3 Multi-stage drying of pea beans

The previously described multi-stage concurrent flow computer model was used to simulate the drying of pea beans. The effect of drying on the percentage of cracked beans was determined using equation (54). Computer simulation runs were produced for the test conditions given in Table 10. The results of the simulations are presented in Table 28.

The test results from Table 11 can be compared with simulation results in Table 28 to verify the accuracy of the computer simulation results for use in the design of a multistage concurrentflow grain dryer. Examination of Tables 11 and 28 shows that some simulation results are greater than and some less than the test results. Table 29 shows the absolute values of the differences between the test results and the simulation results for exit grain temperature, moisture content, and percentage of cracked beans. The percentage of cracks calculated is, in most cases, less than the observed percentage. Some of the difference is attributed to the variability in moisture contents (the change in moisture content is one factor in the estimation equation). The estimation equation for cracks is representative of the test data. However, the test samples were removed hot from each

Table 28.--Simulation results for pea bean drying tests.

Test Number	2	3	4	5	6	8	9	10	11	12
Stage 1										
temperature, °C	24	29	35	33	35	33	33	29	32	32
moisture, % w.b.	20.3	20.4	19.2	20.0	20.1	21.5	21.5	21.2	21.7	21.4
cracks, %	1.9	2.7	2.9	3.0	3.2	1.8	2.7	2.0	2.0	1.6
Stage 2										
temperature, °C	28	34	41	36	40	39	37	38	38	36
moisture, % w.b.	19.8	19.4	17.8	18.9	19.0	20.4	20.2	19.8	20.8	20.5
cracks, %	2.6	4.7	5.8	5.2	5.2	3.5	5.2	4.7	3.2	3.0
Stage 3										
temperature, °C								41	40	39
moisture, % w.b.								18.4	19.9	19.5
cracks, %								7.6	4.5	4.6
Cooler										
temperature, °C	23	21	22	24	28	21	23	27	32	27
moisture, % w.b.	19.8	18.7	17.3	18.6	18.7	19.8	19.7	18.1	19.7	19.2
Efficiency,* kJ/kg H_2O	6197	6138	5774	5172	5408	6011	5045	4770	5101	5208

*Does not include the energy used or the moisture removed during cooling.

Table 29.--Average differences between test conditions and simulation results for pea bean drying tests. Includes cooling only for test 12.

	Temperature °C	Moisture % w.b.	Cracks %
First stage--average*	2.0	0.65	0.62
maximum	5.0	1.10	2.20
minimum	0.0	0.10	0.00
Second stage--average*	2.9	1.20	2.26
maximum	5.0	2.10	5.20
minimum	1.0	0.20	0.40
Third stage--average**	1.0	0.80	1.83
maximum	1.0	1.20	4.20
minimum	1.0	0.60	0.30
Total weighted average	3.1	0.91	1.49
X^2***	2.92	1.11	11.00
F(9, 35)****	2.09	1.34	5.72

*Average of 10 absolute differences.
**Average of 3 absolute differences.
***X_c^2 = 16.92 (CI: 2.70 - 19.02).
****F = 2.51 (CI: 0.40 - 2.51).

drying section it is felt that the sudden exposure to the cooler air increased the percentage of cracks observed. Second, the counterflow cooler provides a gentle cooling process as compared to a crossflow cooler. The beans leaving the cooler in Test 12 showed 2.9% cracks.

Correspondence plots for grain temperature and moisture content are presented in Figure 22. The linear correlation coefficient for grain temperature is $r_c = 0.825$; for moisture content $r_c = 0.714$; for the percentage of cracked seed coats (not shown) $r_c = 0.651$.

The goodness-of-fit and F-value statistics are included in Table 29. The parameters are all significant at the 95% level except

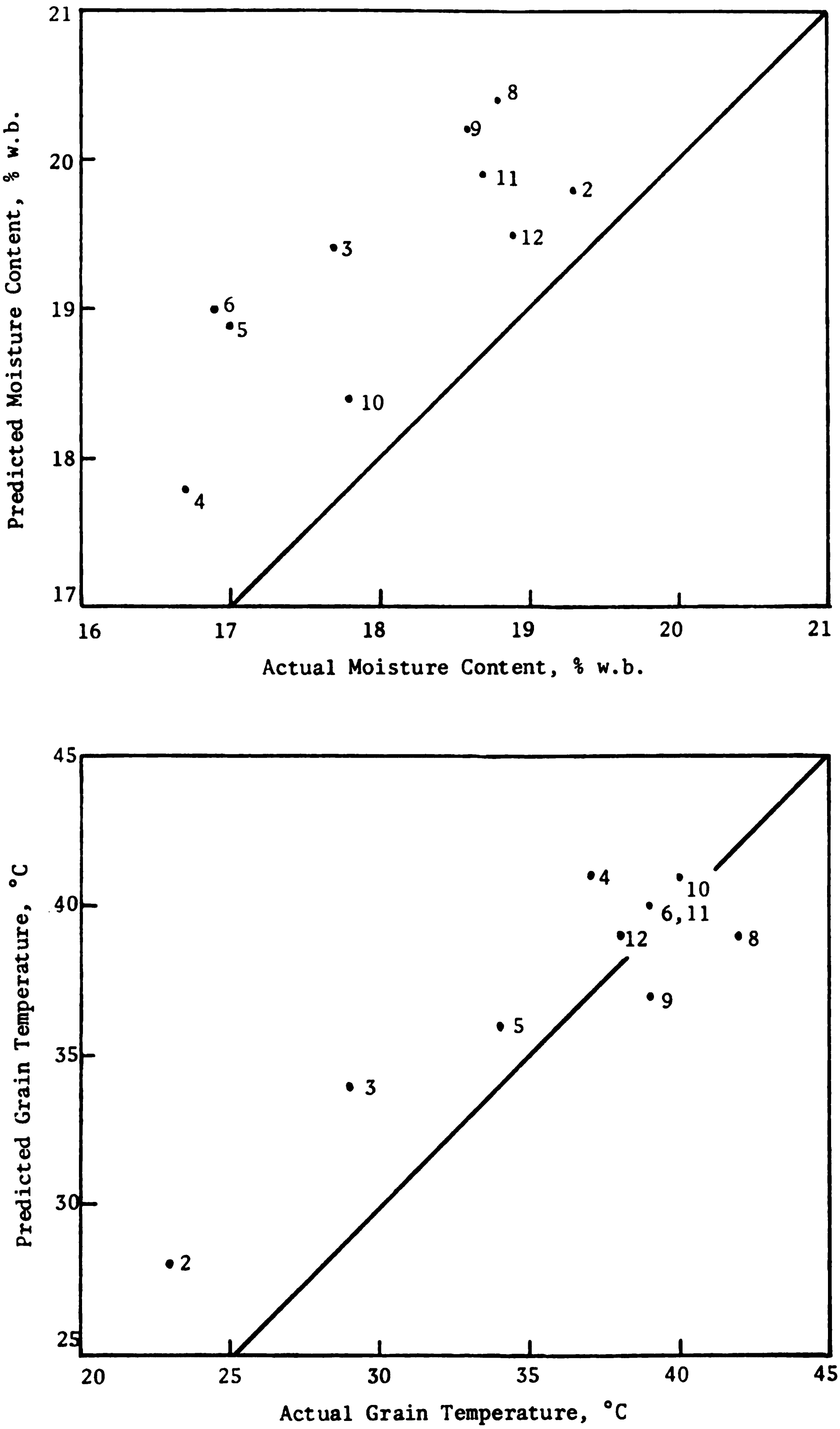


Figure 22. Correspondence plots for multistage pea bean drying tests. Numbers refer to test number listed in Table 28.

the cracks which fail the F-test. The correspondence between the simulation model and the experimental tests is considered sufficient for the model to be used in the design of multistage concurrentflow grain dryers.

4.7.4 Crossflow dryer comparison--Pea beans

Pea bean samples were collected and tested form the Ace crossflow dryer on a regular basis by Cook's personnel. Each sample was immediately tested for temperature, moisture, and percentage of splits and cracks. The procedure used by the Cook's personnel was different and less critical than the procedure employed by MSU personnel for determining the percentage of cracked beans in a sample. Therefore direct comparison of the two is difficult. From personal observations the author feels that an analysis by MSU personnel would show cracks at a level of 1.5-2.0 times that observed by Cook's personnel.

Silo measurements were kept to determine the total quantity of beans dried and thus the average grainflow rate through the crossflow dryer. The total gas used was recorded and used to calculate the average energy efficiency of the crossflow dryer. Table 30 presents average inlet and outlet conditions for the pea beans dried in an Ace crossflow dryer operated at a heated air temperature of 32°C.

A multistage concurrentflow dryer could be operated and perform as well as, if not better than, a crossflow dryer with respect to grain damage. The major advantage of the multistage concurrentflow dryer is in regard to energy consumption which is less than for a crossflow dryer. The smaller air exhaust area would also allow easier reuse of air exhausted from the concurrentflow dryer for additional energy and operating cost savings.

Table 30.--Average inlet and outlet conditions for pea beans dried in an Ace crossflow dryer with a heated air temperature of 32°C.

	Average	Variance	N
Inlet--moisture, % w.b.*	21.5	0.84	38
cracks, %*	1.0	0.32	38
splits, %*	0.2	0.02	38
Outlet--temperature, °C	22.0	3.90	253
moisture, % w.b.	17.0	0.10	253
cracks, %	2.0	1.23	243
splits, %	1.0	0.38	249
Efficiency, kJ/kg water removed	5552	--	--

*Calculated from inlet samples taken from the concurrentflow dryer.

5. OPTIMIZATION MODEL

The previously developed multistage concurrentflow dryer model can be utilized with a trial and error approach to help design a multistage concurrentflow dryer for field use. Alternatively one can construct an optimization algorithm to help find a design which dries grain with a minimum value of a specified objective (cost) function. The objective function may include drying costs, capital equipment cost, costs for changes in grain quality, or other important factors.

The following section outlines the development of a dynamic programming algorithm for finding the optimum operational parameters and size of a multistage concurrentflow dryer with intermediate tempering stages. The objective function is based on costs for energy consumed during the drying and for fixed and (design) variable costs. The operational parameters are constrained by the desired final moisture content, the maximum allowable exit temperature of the grain from each drying stage, and the maximum allowable value of an important grain quality factor. For shelled corn the quality factor used is the susceptability to breakage as measured by the Stein breakage test. For pea beans a quality factor is the percentage of cracked beans. For wheat one is interested in an index based on baking quality factors.

5.1 Optimization algorithm

Thompson (1967) and Farmer (1972) developed multi-variable search techniques, based on a single-dimensional search algorithm, for study of the optimal design of convection grain dryers. Thompson studied single-stage crossflow and concurrentflow, and Farmer the optimum design of batch-in-bin dryers.

Dynamic programming, developed by Bellman (1957), is an extremely powerful approach for solving optimization problems. Dynamic programming is especially applicable to multistage optimization problems. Ahn et al. (1964) and Schroeder and Peart (1967) applied dynamic programming to the study of optimal air distribution along the length of a crossflow dryer column. Farmer (1972) used dynamic programming in the optimization of a single-stage concurrentflow dryer with counterflow cooler (a two stage process); the effect of recycling the exhaust air from the cooler to the dryer inlet was also studied.

The standard form of dynamic programming used in the previously cited references was "backward" dynamic programming. Backward dynamic programming begins the computations at the final time and proceeds to the initial time in order to find the optimum solution. A useful technique outlined by Larson (1968) is "forward" dynamic programming where the computations begin at the initial time and proceed to the final time in order to find an optimal solution. Forward dynamic programming is utilized in this thesis because of the form of the drying system equations involved. The following outline of forward dynamic programming is adapted from Larson (1968):

1. Let X denote the state vector which describes the dynamic behavior of the multistage system,

2. Let U denote the control vector, the components of which are varied by the dynamic programming algorithm so that the progress of the state vector with time is controlled in an optimal fashion.

3. The system equations relate the dynamic behavior of the state vector to the applied control vector. The system equations are usually non-linear, time-varying differential equations; e.g.:

$$\frac{dX}{dt} = F(X,U,t) \tag{58}$$

4. The objective function (cost function) determines the effectiveness of the applied control vector and is minimized by the dynamic programming procedure. The cost function is dependent on the applied control vector and the associated state vector for the $n^{\underline{th}}$ stage and also the minimum of the sum of the cost functions for the preceeding stages:

$$I(X,n) = i(X,U,n) + \min \sum_{j=1}^{n-1} i(X_{j-1}, U_{j-1}, j) \tag{59}$$

The procedure starts at the intial time (t=0) with an initial state vector (X_o) and divides the feasible range of state vector values at the end of the first stage into a suitable number of feasible sets. For each set of state vector end points the set of feasible control vectors is applied. The resultant set of cost function values is searched to find the value of the control vector which minimizes the cost function. The procedure is then repeated for each set of state vector end points.

The succeeding stages have a feasible set of initial state vectors defined from the preceeding stage. A feasible set of state vector end points is again defined. The set of feasible control vectors is applied for each set of vector end points for all sets of the initial state vector. The resultant set of cost function values is searched to find the value of the control vector which minimizes the cost function. The procedure is then repeated for each set of state vector end points and for each succeeding stage.

The final result is a super-set of control vectors which defines the dynamic behavior of the system for the initial state vector and a terminal set of state vector end points. The super-set will yield the overall optimal set of control vectors necessary to proceed from the initial state vector to any particular terminal set of state vector end points.

The state vector for the multistage concurrentflow dryer problem studied consists of a single component--the moisture content of the grain. The control vector consists of three components for each stage: (1) heated air temperature, (2) airflow, and (3) stage length. The objective of the dynamic programming algorithm is to find the optimum values of the three components of the control vector for each stage which result in the minimum possible cost for drying grain from a specified initial moisture to a desired final moisture content.

5.2 Objective function

The objective function (total cost) utilized consists of three parts: (1) operating cost based on energy consumption, (2) capital investment cost, and (3) grain quality constraints. The total cost is the sum of the energy and capital investment costs budgeted per unit mass of grain dried. If the quality factors exceed a preset value, a large cost is added to the above total cost.

5.2.1 Operating cost

The two operational parameters included in the control vector are: (1) heated air temperature, and (2) airflow. The cost for the energy used to heat the air is based on the air energy equation (24) and the price of the fuel per unit of energy supplied:

$$CE_a = \frac{G_a(c_a+c_vH)(T-T_{amb})P_{fuel}}{.85\ G_p} \tag{60}$$

The cost for the energy used to operate the fan is based on the fan energy equation (26) and the price of electricity per unit of electricity supplied:

$$CE_{fm} = \frac{5.575(Q_a)(SP)P_{electricity}}{.5\ G_p} \tag{61}$$

5.2.2 Capital investment cost

The two parameters included in the control vector which influence the capital cost are: (1) length of the drying stage, and (2) airflow. In addition to these two design variable capital costs, there is a fixed capital cost for auxiliary equipment which is not affected by changing the length of the drying stages or the operational parameters. The total investment is calculated from:

$$IC = CC_{fixed} + CC_{fan}Q_a + CC_{length}x_1 \tag{62}$$

The investment cost must be converted to an equivalent annual cost. Riggs (1977) describes two methods for calculating annual costs for a given investment: (1) approximate calculation, and (2) exact calculation.

The <u>approximate annual cost</u> calculation is based on straight-line depreciation and average interest. A grain dryer would have an annual cost of:

$$AC = \frac{IC-SV}{N} + \frac{IC+SV}{2} \left(\frac{IN}{100}\right) \tag{63}$$

Brake (1976) suggested an expanded version of the approximate annual cost calculation which includes yearly maintenance and insurance costs:

$$AC = \frac{IC-SV}{N} + \frac{IC+SV}{2} \left(\frac{IN+IM+II}{100}\right) \tag{64}$$

The <u>exact annual cost</u> calculation given by Riggs (1977) includes the time value of money. The discounting of the annual cash flow is normally the preferred means for investment analysis and capital budgeting. However, for use in the optimization procedure the simplicity of equation (64) is preferred. The author feels that the optimization results are not affected by using the approximate instead of the exact annual cost calculations.

Dividing the annual cash flow by an assumed yearly throughput yields budgeted capital cost (cost per kilogram of grain dried) values that can be directly incorporated with the operational costs. The multistage concurrentflow dryer will be used mainly at an elevator. Operational time is estimated at 24 hours/day and 30 days per corn harvest season. The resulting budgeted capital cost is calculated from:

$$BC = \frac{(AC*100)}{(24*30)G_p} \tag{65}$$

5.2.3 Grain quality constraints

The cost associated with deterioration in grain quality can be used as an additional cost factor. At the present time the estimation models for grain quality are not sufficiently accurate for this approach. In addition, if the quality factors are maintained within a reasonable range they do not affect the value of the grain when it is later marketed. One factor for corn is the kernel temperature at the end of each drying stage. Corn to be used for feed can withstand a higher temperature than corn which is to be used for wet or dry milling. Corn which is to be used for seed is very sensitive to high grain temperatures (see Table 8). A second constraint for corn is the kernels' susceptibility to breakage as measured by the Stein breakage test. The breakage test percentage is estimated using equation (53).

During the analysis of the cost function in the dynamic programming procedure, the quality cost is initially set to zero. If either of the quality parameters (temperature or breakage percentage) exceed some predetermined limit the quality cost is set to a value high enough to effectively render the current set of control vector values infeasible.

5.3 Optimization implementation

Dynamic programming (DP), unlike linear programming or other optimization techniques, is not supported by a standard computational package. The software programmer must tailor the DP procedure for each application.

The basic flowchart for the DP optimization algorithm used in this study is presented in Figure 23. The problem being studied

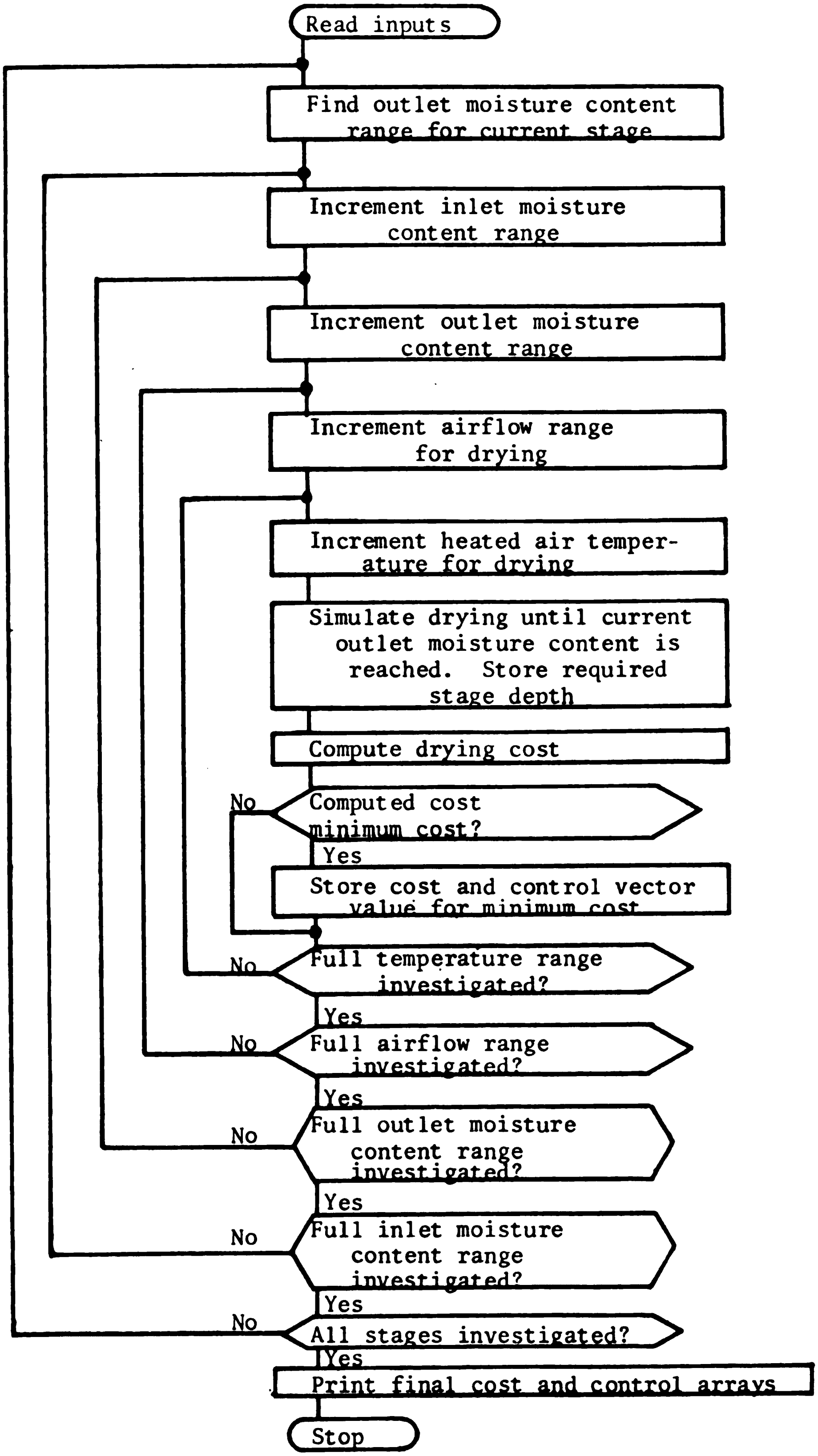


Figure 23. Basic flowchart of dynamic programming optimization.

involves known initial and final values for the state vector (moisture content of the grain). Therefore, during computations for the first stage, the inlet moisture content range consists of a single point. Similarily for the last stage the outlet moisture content range consists of a single point. Making use of these known points considerably reduces the number of calculations required.

As the calculations proceed the specified ranges of the controls (heated air temperature, airflow, and stage length) are investigated to find the proper combination which results in a minimum overall drying cost. The cost value used for the minimization process is the sum of two costs (see equation (59)): (1) the cost using the current set of control values to dry the grain from the current inlet moisture content to the current outlet moisture content for the current stage (from equations (60), (61), and (65)), and (2) the minimum cost to dry the grain from the initial moisture content of the first stage to the current inlet moisture of the current stage. In this way the cost obtained and the associated control vector is always for the minimum overall total cost.

Here again knowledge of the process being optimized helps reduce the number of calculations required. Several such heuristic methods are used in the optimization algorithm of this study.

The outlet moisture content range is determined for each stage using the minimum and maximum, respectively, allowable values of the control vector elements. The minimum value of the range thus defined is checked and reset to, if less than, the desired overall final moisture content. In this way the outlet moisture range used for each stage is always a set of feasible points, and moisture contents less than the desired final moisture are not included in the computations.

The reader can note in Figure 23 that the innermost loop is the dryer length for the current stage. The algorithm then determines the necessary dryer length for the current values of inlet and outlet moisture content, heated air temperature, and airflow. This is accomplished by starting the drying simulation at the current inlet moisture content (for the specified temperature and airflow) and continuing along the length of the dryer until the grain reaches the current outlet moisture content. The necessary dryer depth is stored and used for later cost calculations. The above procedure is allowable because the grain moisture content is a continuously decreasing function of depth during drying. The author does not feel that this method introduces any bias in the optimization in regard to minimizing the cost. Generally the minimum cost will occur when the dryer length trends toward a minimum value.

The next outermost loop shown in Figure 23 is for heated air temperature. The first step in this loop (before any simulation as previously described) is to check the moisture content obtained using the maximum allowable heated air temperature and the maximum allowable dryer length for the current stage. If this calculated moisture content is greater than the current outlet moisture content, there is no allowable temperature and length combination for the current airflow. Since the airflow starts at the maximum allowable and decreases during the calculations, when the condition stated above occurs, the current and all lower airflow values are infeasible for the current outlet moisture content. The program then terminates the airflow loop and increments the outlet moisture content loop. If the calculated moisture content is equal to the current outlet moisture content, the program calculates an approximate cost using the current heated air temperature and the minimum allowable length for the current stage (no drying simulation necessary). If the approximate cost is greater than the current minimum cost then no further calculation is necessary for the current heated air temperature. The temperature is incremented (increased) and the approximate cost recalculated. When a temperature is found where the approximate cost is less than the current minimum cost, the necessary stage length is found as described previously. The exact cost is then calculated and compared against the current minimum cost. If the exact cost is less than the minimum cost, the exact cost becomes the minimum cost to dry the grain from the initial moisture content to the current outlet moisture content. The associated control vectors and an index indicating the current inlet moisture content are also stored.

The above procedures are repeated for all possible sets of inlet and outlet moisture content for all desired stages. After all computations are complete the optimal trajectory for the moisture content is obtained starting at the outlet moisture content of the last stage. The printed output indicates the inlet moisture content index for finding the outlet moisture content from the previous stage. Then the associated cost and control vector elements are found. Backing up one stage to the indicated moisture content the process is repeated through the first stage.

The performance of the optimization algorithm can be estimated based on knowledge of the concurrentflow drying process and the associated cost functions. The algorithm will attempt to maximize the heated air temperature (maximum drying rate), minimize the airflow (maximum utilization of the energy in the drying air), and minimize the dryer length (minimum capital cost) for each stage.

5.4 Results of optimization for shelled corn

The dynamic programming type optimization routine described above is used to analyze the design of a multistage concurrentflow dryer for shelled corn. Like any design tool, the optimization routine is not an end in itself. Four comparisons are made:

1. Staging: Compare one-, two-, and three-stage dryers.
2. Tempering: A good tempering time was found to be 1.25 hours for a concurrentflow dryer. Compare tempering times less than 1.25 hours for their effect on total drying cost.
3. Heat recovery: One method of heat recovery is to use the exhaust air from one drying stage as the input air to the following drying stage. Compare the dryer performance using this feed-forward recycling with a conventional concurrentflow configuration.
4. The predominant dryer for drying shelled corn currently is the column crossflow dryer. Compare the drying and capital costs for this type of dryer with the multistage concurrentflow two- and three-stage dryers.

Each comparison is conducted at three grainflow levels using the standard conditions listed in the following section. The grainflow rates are based on advertised rates for multistage concurrentflow dryers manufactured by Westlake Agricultural Engineering, Inc., St. Marys, Ontario, Canada.

5.4.1 Standard input conditions

Simulation of grain drying and optimization of the performance of a grain dryer is accomplished using any reasonable set of input conditions. However, when comparing basic parameter changes or different dryer types, the performance evaluation requires a standard set of input conditions in order to have an adequate basis for comparison. Bakker-Arkema et al. (1973a) proposed the standard conditions listed in Table 31 for the drying of shelled corn. These conditions are used in obtaining the optimization results in the following sections. The optimization routine assumes that the counterflow cooler will remove 1% d.b.

Table 31.--Standard conditions for the simulation of dryer performance for the drying of shelled corn.

Inlet corn moisture content, % w.b.	25.0
Outlet corn moisture content, % w.b.	15.0*
Ambient air temperature, °C	15.0
Ambient air humidity ratio, decimal d.b.	.0065
Inlet corn temperature, °C	15.0
Inlet corn foreign material, %	3.0
Inlet corn breakage, %	10.0
Outlet corn temperature, °C**	20.0

*Original table value from Bakker-Arkema et al. (1973a) was 20.0% w.b. The author feels that for the drying of shelled corn the value given is more representative of actual field practice.

**The final reduction in grain temperature is accomplished using a counterflow cooler which is not considered in the optimization.

The optimization routine includes two grain quality constraints. The first is the temperature of the grain which leaves a concurrentflow drying section. The grain temperature within the dryer will be greater than the exit temperature at some time during the drying process, but drops rapidly as drying progresses (see Figure 6). Mühlbauer and Christ (1974) have shown that the time-temperature relationship is important for grain. The time-temperature history during drying is a more accurate quality criterion. However, the author feels that outlet grain temperature is an adequate quality constraint. Using the results and conclusions of Peplinski et al. (1975) a value of 80°C is used as a constraint in obtaining the optimization results in the following sections.

The second quality factor for shelled corn is the kernel breakage percentage obtained from the Stein breakage test. The U.S. grade standards for shelled corn limit broken corn to 3.0% for no. 2 yellow corn (the most common trade grade). Stephens and Foster (1976) found that a handling breakage of 3.0% resulted from repeated handling of shelled corn with a Stein breakage percentage of 17.0-23.0%. A value for the maximum allowable Stein breakage percentage of 23.0% is used in obtaining the optimization results in the following sections.

The optimization routine includes three capital cost factors: (1) fixed cost independent of variable design factors, (2) fan costs per unit of air velocity (m/min), and (3) cost per meter of drying column length based on the combined drying and tempering lengths. Sales costs for 1976 were obtained from Westlake Agricultural Engineering, Inc. for one-, two-, and three-stages concurrentflow dryers. The sales costs and a non-linear least-squares algorithm (Meeter and Wolfe, 1965) were used to approximate the capital cost factors in equation (62). The values of the three cost factors obtained are listed in Table 32. Also listed in Table 32 are the fuel and electrical energy costs used in the optimization. The cost factors were

Table 32.--Capital and energy cost values used for obtaining optimization results for shelled corn.

Fixed cost, $\$/m^2$/stage	$7225.00	(bottom stage)
	3270.00	(top stages)
Fan cost, $/(m/min)	5.00	
Length cost, $\$/m^3$	975.00	(bottom stage)
	250.00	(top stages)
Fossil fuel cost, ¢/kJ*	0.0004	
Electricity cost, ¢/kJ**	0.0014	

*Based on L.P gas at 40¢/gal and 96532 kJ/gal.

**Based on electricity cost of 5¢/kWh.

determined as cost per square meter of dryer column area so as to be applicable for a wide range of dryer sizes. Realistically, an economy of scale does exist (approximately -$ $172/m^2$) which is not considered by the optimization routine.

Five capital budgeting factors are used in equation (64):

1. Salvage value--Assume zero salvage value. The dryer is made of mostly sheet metal. While the metal may have some scrap value, the cost of dissassembling the dryer would make the total salvage value negligible.
2. Equipment life--Assume a ten year life for the drying equipment.
3. Interest rate--Assume an interest rate of 8%.
4. Maintenance factor--Woods (1975) gives a range for maintenance factors of 2-15% of investment cost per year. A grain dryer is a relatively simple piece of equipment. Assume a maintenance factor of 5% of investment cost per year.
5. Insurance factor--Woods (1975) gives a range for insurance factors of 0.4-1.0% of investment cost per year. A grain dryer is a relatively high risk piece of equipment due to the open

flame used to heat the air. Assume an insurance factor of 1% of investment per year.

The optimization algorithm as previously flowcharted considers three variables for each drying stage: (1) heated air temperature, (2) airflow rate, and (3) length. The tempering time and thus the length of the tempering stages is, in most cases, set at a length resulting in 1.25 hours tempering time. The range of the variables listed in Table 33 are used to obtain the results in the following sections.

Table 33.--Ranges for variable design factors.

		One-Stage	Two-Stage	Three-Stage
Stage 1:	temperature, °C	150-200	200-230	200-230
	airflow, m/min	30-60	30-60	30-60
	length, m	1-2	1-2	1-2
Stage 2:	temperature, °C		150-200	150-200
	airflow, m/min		30-60	30-60
	length, m		1-2	1-2
Stage 3:	temperature, °C			150-200
	airflow, m/min			30-60
	length, m			1-2

5.4.2 Effect of staging

Results for one-, two-, and three-stage concurrentflow dryer optimizations are given in Tables 34 through 36. Each different staging configuration is presented for three grainflow rates chosen to be representative of commercial concurrentflow dryers. The grainflow ranges overlap and cover the composite range of 1.0-4.0 tonne/hr-m^2. Generally, within each configuration the total drying cost decreases as the grainflow increases. The decrease is primarily due to drying

Table 34.--Optimization results for one-stage concurrentflow dryer at three grainflow rates.

	Grainflow, tonne/hr-m^2		
	1.0	1.5	2.0
Inlet air temperature, °C	200	200	200
Airflow, m^3/min-m^2	42	60	60
Dryer length, m	1.5	2.0	2.0
Tempering time, hr	--	--	--
Inlet moisture, % w.b.	25.0	25.0	25.0
Outlet grain temperature, °C	53	53	45
Outlet moisture, % w.b.	15.7	16.2	18.5
Stein breakage, %	22.7	21.7	16.9
Outlet air temperature, °C	53	53	45
Outlet air humidity, decimal d.b.	.0559	.0559	..0563
Drying cost, ¢/kg	.569	.464	.348

more grain with similar capital investment cost. When reviewing Table 34 the reader should note that the single stage dryers with grainflows of 1.5 and 2.0 tonne/hr-m^2 did not dry the grain to the desired final moisture content; the results presented are the maximum possible with the design factor ranges used (Table 33).

The cost breakdown for the one-, two-, and three-stage dryers are given in Tables 37, 38, and 39, respectively. The total energy costs does not vary significantly between the various drying configurations. The average energy efficiency for the one-stage dryers is 3858 kJ/kg water; for the two-stage dryers, is 3819 kJ/kg water; for the three-stage dryers 3857 kJ/kg water. The variation in energy cost and energy efficiency between the three configurations is not considered significant. The proportion of the drying cost due to capital equipment investment is similar between the two- and three-stage configurations. At higher grainflows the capital cost is about 45%

Table 35.--Optimization results for two-stage concurrentflow dryer at three grainflow rates.

	Grainflow, tonne/hr-m^2		
	2.0	2.5	3.00
Stage 1--			
inlet air temperature, °C	230	230	230
airflow, m^3/min-m^2	48	48	60
dryer length, m	1.0	1.1	2.0
tempering time, hr	1.25	1.25	1.25
inlet moisture, % w.b.	25.0	25.0	25.0
outlet grain temperature, °C	51	48	46
outlet moisture, % w.b.	19.4	20.7	20.3
Stein breakage, %	14.3	11.9	12.9
outlet air temperature, °C	51	48	46
outlet air humidity, decimal d.b.	.0610	.0593	.0621
drying cost, ¢/kg	.243	.198	.200
Stage 2--			
inlet air temperature, °C	190	200	200
airflow, m3/min-m^2	30	48	54
dryer length, m	1.1	1.7	1.9
tempering time, hr	--	--	--
inlet moisture, % w.b.	19.4	20.7	20.3
outlet grain temperature, °C	62	62	63
outlet moisture, % w.b.	15.7	15.7	15.7
Stein breakage, %	22.7	22.7	22.7
outlet air temperature, °C	62	62	63
outlet air humidity, decimal d.b.	.0580	.0618	.0600
drying cost, ¢/kg	.238	.245	.219
Total drying cost, ¢/kg	.481	.443	.418

Table 36.--Optimization results for three-stage concurrentflow dryer at three grainflow rates.

	Grainflow, tonne/hr-m^2		
	3.0	3.5	4.0
Stage 1--			
inlet air temperature, °C	200	200	212
airflow, m^3/min-m^2	30	30	60
dryer length, m	1.0	1.0	1.1
tempering time, hr	1.25	1.25	1.25
inlet moisture, % w.b.	25.0	25.0	25.0
outlet grain temperature, °C	43	41	43
outlet moisture, % w.b.	23.5	23.8	22.3
Stein breakage, %	10.0	10.0	10.0
outlet air temperature, °C	44	41	43
outlet air humidity, decimal d.b.	.0381	.0359	.0506
drying cost, ¢/kg	.120	.105	.143
Stage 2--			
inlet air temperature, °C	190	180	200
airflow, m^3/min-m^2	54	60	54
dryer length, m	1.1	1.1	1.3
tempering time, hr	1.25	1.25	1.25
inlet moisture, % w.b.	23.5	23.8	22.3
outlet grain temperature, °C	56	54	57
outlet moisture, % w.b.	19.5	20.3	19.1
Stein breakage, %	14.7	12.8	15.5
outlet air temperature, °C	56	54	57
outlet air humidity, decimal d.b.	.0572	.0533	.0589
drying cost, ¢/kg	.161	.145	.130
Stage 3--			
inlet air temperature, °C	200	200	190
airflow, m^3/min-m^2	42	60	54
dryer length, m	1.2	1.8	1.5
tempering time, hr	--	--	--
inlet moisture, % w.b.	19.5	20.3	19.1
outlet grain temperature, °C	67	66	68
outlet moisture, % w.b.	15.7	15.7	15.7
Stein breakage, %	22.7	22.7	22.7
outlet air temperature, °C	67	66	68
outlet air humidity, decimal d.b.	.0624	.0630	.0587
drying cost, ¢/kg	.186	.197	.156
Total drying cost, ¢/kg	.467	.447	.429

Table 37.--Cost breakdown and efficiency for one-stage concurrentflow dryer at three grainflow rates.

	Grainflow, tonne/hr-m^2		
	1.0	1.5	2.0
Inlet temperature, °C	15	15	15
Inlet humidity, decimal, d.b.	.0065	.0065	.0065
Fixed cost, $	7225	7225	7225
Fan cost, $	210	300	300
Length cost, $	1463	1950	1950
Electrical energy cost, ¢/kg	.0037	.0081	.0061
Fuel energy cost, ¢/kg	.226	.215	.161
Total drying cost, ¢/kg	.569	.464	.348
Efficiency, kJ/kg water	3867	3881	3827

Table 38.--Cost breakdown and efficiency for two-stage concurrentflow dryer at three grainflow rates.

	Grainflow, tonne/hr-m^2		
	2.0	2.5	3.0
Stage 1--			
inlet temperature, °C	15	15	15
inlet humidity, decimal d.b.	.0065	.0065	.0065
fixed cost, $	3270	3270	3270
fan cost, $	240	240	300
length cost, $	1250	1525	2000
electrical energy cost, ¢/kg	.0017	.0015	.0040
fuel energy cost, ¢/kg	.150	.120	.125
total drying cost, ¢/kg	.243	.198	.200
Stage 2--			
inlet temperature, °C	15	15	15
inlet humidity, decimal d.b.	.0065	.0065	.0065
fixed cost, $	7225	7225	7225
fan cost, $	150	240	270
length cost, $	1073	1658	1853
electrical energy cost, ¢/kg	.0006	.0023	.0029
fuel energy cost, ¢/kg	.076	.101	.097
total drying cost, ¢/kg	.238	.245	.219
Two-stage drying cost, ¢/kg	.481	.443	.418
Efficiency, kJ/kg water	3860	3782	3814

Table 39.--Cost breakdown and efficiency for three-stage concurrentflow dryer at three grainflow rates.

	Grainflow, tonne/hr-m^2		
	3.0	3.5	4.0
Stage 1--			
inlet temperature, °C	15	15	15
inlet humidity, decimal d.b.	.0065	.0065	.0065
fixed cost, $	3270	3270	3270
fan cost, $	150	150	300
length cost, $	1750	2000	2275
electrical energy cost, ¢/kg	.0004	.0002	.0017
fuel energy cost, ¢/kg	.054	.055	.086
total drying cost, ¢/kg	.120	.105	.143
Stage 2--			
inlet temperature, °C	15	15	15
inlet humidity, decimal d.b.	.0065	.0065	.0065
fixed cost, $	3270	3270	3270
fan cost, $	270	300	270
length cost, $	1775	2025	2325
electrical energy cost, ¢/kg	.0017	.0019	.0015
fuel energy cost, ¢/kg	.092	.081	.073
total drying cost, ¢/kg	.161	.145	.130
Stage 3--			
inlet temperature, °C	15	15	15
inlet humidity, decimal d.b.	.0065	.0065	.0065
fixed cost, $	7225	7225	7225
fan cost, $	210	300	270
length cost, $	1170	1755	1463
electrical energy cost, ¢/kg	.0010	.0031	.0017
fuel energy cost, ¢/kg	.075	.092	.069
total drying cost, ¢/kg	.186	.197	.156
Three-stage drying cost, ¢/kg	.467	.447	.429
Efficiency, kJ/kg water	3779	3908	3883

of the total cost. As grainflow decreases the proportion increases to about 53% at the lowest grainflow rates. Therefore, within each configuration the total drying cost decreases as the grainflow increases. Comparing the one-, two-, and three-stage configurations, the one-stage dries corn for a total cost of 0.569¢/kg; the two-stage for an average total cost of 0.447 ¢/kg; the three-stage for 0.448 ¢/kg. The multistage dryers have an apparent cost advantage as compared to the single-stage dryer. There is no significant advantage (on the basis of average total drying cost) of two- or three-stage concurrentflow grain dryers.

5.4.3 Effect of tempering

The optimization and cost breakdown results for two-stage dryers with different tempering times are presented in Tables 40 and 41. Again the total fuel cost does not vary significantly; 0.223¢/kg for tempering times of 1.20 and 1.00 hours as compared to 0.236¢/kg for a tempering time of 0.75 hours.

One factor not adequately covered by the optimization routines is the effect of tempering on the quality of the corn which has been dried. Very likely a longer tempering time is beneficial for the kernel to relieve some of the internal stress caused by the drying process. The tempering time and thus the length of the tempering stage has a significant effect on the drying cost. The capital cost of the additional volume of drying column required by tempering indicates a small tempering length should be used for minimum drying cost (see Table 32). A decision about tempering length would have to be balanced against the effect of tempering on grain quality and the

Table 40.--Optimization results for two-stage concurrentflow dryer at three tempering lengths for a grainflow of 2.5 tonne/hr-m^2.

	Tempering length, m		
	3.0	4.0	5.0
Stage 1--			
inlet air temperature, °C	230	230	230
airflow, m/min	48	48	48
dryer length, m	1.1	1.1	1.1
tempering time, hr	0.75	1.00	1.25
inlet moisture, % w.b.	25.0	25.0	25.0
outlet grain temperature, °C	48	48	48
outlet moisture, % w.b.	20.7	20.7	20.7
Stein breakage, %	11.9	11.9	11.9
outlet air temperature, °C	48	48	48
outlet air humidity, decimal d.b.	.0593	.0593	.0593
drying cost, ¢/kg	.191	.194	.198
Stage 2--			
inlet air temperature, °C	200	200	200
airflow, m/min	54	48	48
dryer length, m	1.1	1.8	1.7
tempering time, hr	--	--	--
inlet moisture, % w.b.	20.7	20.7	20.7
outlet grain temperature, °C	69	62	62
outlet moisture, % w.b.	15.7	15.7	15.7
Stein breakage, %	22.7	22.7	22.7
outlet air temperature, °C	69	62	62
outlet air humidity, decimal d.b.	.0556	.0620	.0618
drying cost, ¢/kg	.249	.246	.245
Total drying cost	.440	.441	.443

Table 41.--Cost breakdown and efficiency for two-stage concurrentflow dryer at three tempering lengths for a grainflow of 2.5 tonne/hr-m^2.

	Tempering length, m		
	3.0	4.0	5.0
Stage 1--			
inlet temperature, °C	15	15	15
inlet humidity, decimal d.b.	.0065	.0065	.0065
fixed cost, $	3270.00	3270.00	3270.00
fan cost, $	240.00	240.00	240.00
length cost, $	1025.00	1275.00	1525.00
electrical energy cost, ¢/kg	.0015	.0015	.0015
fuel energy cost, ¢/kg	.120	.120	.120
total drying cost, ¢/kg	.191	.194	.198
Stage 2--			
inlet temperature, °C	15	15	15
inlet humidity, decimal d.b.	.0065	.0065	.0065
fixed cost, $	7225.00	7225.00	7225.00
fan cost, $	270.00	240.00	240.00
length cost, $	1073.00	1755.00	1658.00
electrical energy cost, ¢/kg	.0020	.0025	.0023
fuel energy cost, ¢/kg	.116	.103	.103
total drying cost, ¢/kg	.249	.246	.246
Two-stage drying cost, ¢/kg	.440	.441	.443
Efficiency, kJ/kg water	4036	3817	3816

necessity to provide the adequate physical separation between drying stages.

5.4.4 Effect of heat recovery

The small exhaust area of the concurrent dryer as compared to the crossflow dryer makes it readily amendable to some type of reuse of the exhaust air. One type of recycling considered is the use of the exhaust air from one drying stage as the input air to the heater of the next drying stage. Such situations are illustrated in Figure 23 for a two-stage drying configuration.

The extra humidity in the inlet air to each drying stage has little effect on the amount of drying which occurs. Therefore the optimization results remain essentially the same as presented in Tables 35 and 36. The cost breakdown for the two-stage and three-stage configurations with the feed-forward recycling of the exhaust air are presented in Tables 42 and 43, respectively. The recycling does indeed decrease fuel energy consumption and thus total drying costs. However, the capital cost (as given in Table 43) does not include the necessary ducting to accomplish the recycling. Using this heat recovery method the three-stage drying configuration has a distinct advantage over the two-stage dryer with respect to the energy consumed during drying.

5.4.5 Effect of quality constraints

The optimization runs previously presented used an exit temperature limit of 80°C. No problems were encountered in satisfying this constraint. Tables 44 and 45 present the optimization and cost-breakdown results for one two-stage and two three-stage concurrentflow dryers using a temperature limit of 60°C. In the first two cases the

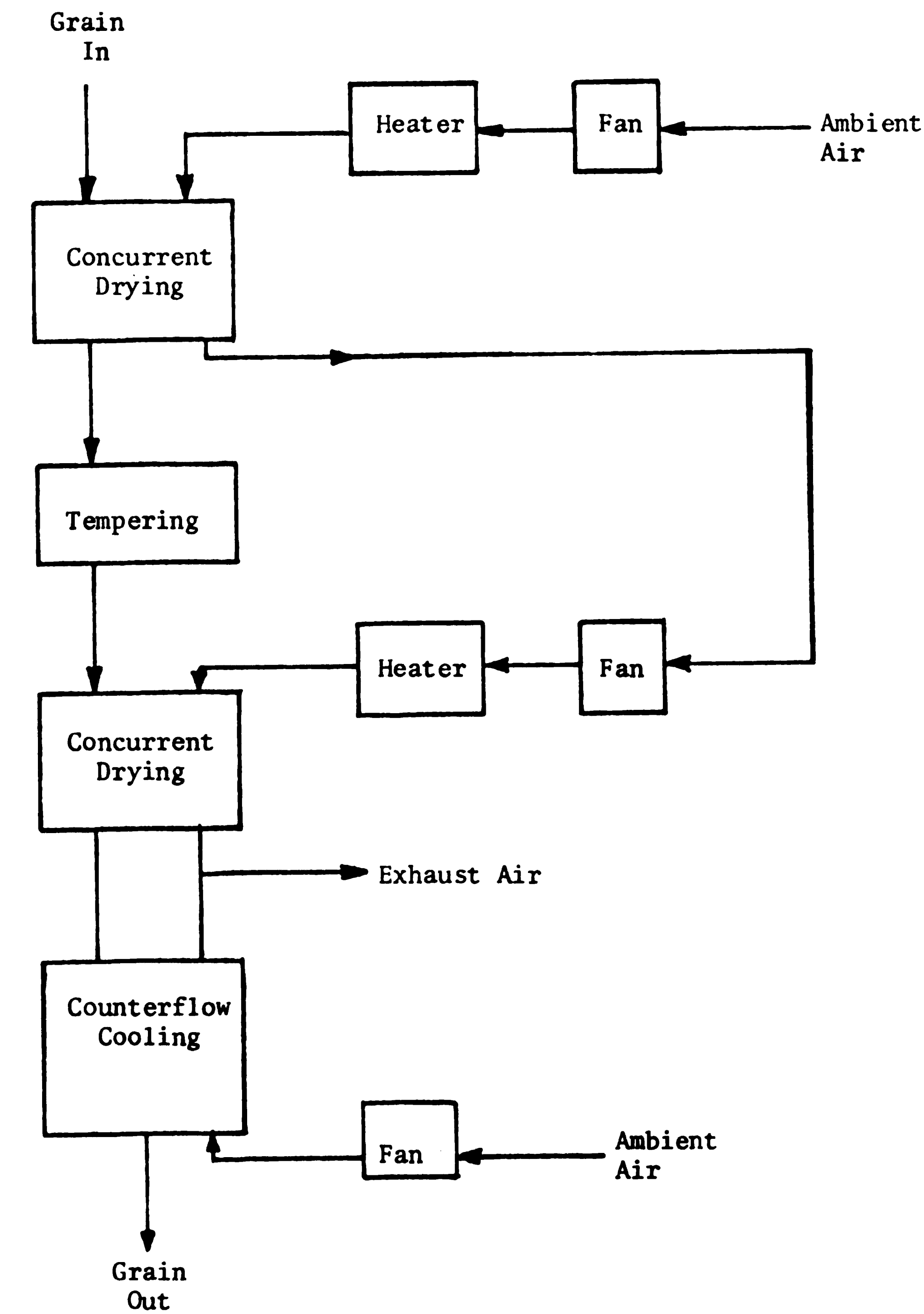


Figure 24. Schematic of a two-stage concurrentflow dryer with feed-forward recycling of exhaust air.

Table 42.--Cost breakdown and efficiency for two-stage concurrentflow dryer at three grainflow rates with feed-forward recycling of exhaust air.

	Grainflow, tonne/hr-m^2		
	2.0	2.5	3.0
Stage 1--			
inlet temperature, °C	15	15	15
inlet humidity, decimal d.b.	.0065	.0065	.0065
fixed cost, $	3270.00	3270.00	3270.00
fan cost, $	240.00	240.00	300.00
length cost, $	1250.00	1525.00	2000.00
electrical energy cost, ¢/kg	.0017	.0015	.0040
fuel energy cost, ¢/kg	.150	.120	.125
total drying cost, ¢/kg	.242	.198	.200
Stage 2--			
inlet temperature, °C	51	48	46
inlet humidity, decimal d.b.	.0610	.0593	.0621
fixed cost, $	7225.00	7225.00	7225.00
fan cost, $	150.00	240.00	270.00
length cost, $	1072.00	1658.00	1852.00
electrical energy cost, ¢/kg	.0006	.0023	.0029
fuel energy cost, ¢/kg	.055	.077	.078
total drying cost, ¢/kg	.216	.219	.196
Two-stage drying cost, ¢/kg	.459	.417	.395
Efficiency, kJ/kg water	3502	3373	3491

Table 43.--Cost breakdown and efficiency for three-stage concurrentflow dryer at three grainflow rates with feed-forward recycling of exhaust air.

	Grainflow, tonne/hr-m^2		
	3.0	3.5	4.0
Stage 1--			
inlet temperature, °C	15	15	15
inlet humidity, decimal d.b.	.0065	.0065	.0065
fixed cost, $	3270.00	3270.00	3270.00
fan cost, $	150.00	150.00	300.00
length cost, $	1750.00	2000.00	2275.00
electrical energy cost, ¢/kg	.0004	.0002	.0017
fuel energy cost, ¢/kg	.054	.055	.086
total drying cost, ¢/kg	.120	.105	.143
Stage 2--			
inlet temperature, °C	44	41	43
inlet humidity, decimal d.b.	.0381	.0359	.0506
fixed cost, $	3270.00	3270.00	3270.00
fan cost, $	270.00	300.00	240.00
length cost, $	1775.00	2025.00	2325.00
electrical energy cost, ¢/kg	.0017	.0019	.0015
fuel energy cost, ¢/kg	.070	.064	.057
total drying cost, ¢/kg	.139	.127	.114
Stage 3--			
inlet temperature, °C	56	54	57
inlet humidity, decimal d.b.	.0888	.0827	.1030
fixed cost, $	7225.00	7225.00	7225.00
fan cost, $	210.00	300.00	270.00
length cost, $	1170.00	1755.00	1463.00
electrical energy cost, ¢/kg	.0010	.0031	.0017
fuel energy cost, ¢/kg	.052	.065	.048
total drying cost, ¢/kg	.163	.169	.134
Three-stage drying cost, ¢/kg	.422	.402	.391
Efficiency, kJ/kg water	3012	3159	3277

Table 44.--Optimization results for two- and three-stage concurrentflow dryer with an outlet temperature limit of 60°C.

	Number of Stages		
	2	3	3*
Stage 1--			
inlet air temperature, °C	214	230	200
airflow, m/min	40	48	30
dryer length, m	1.0	1.0	1.0
tempering time, hr	1.25	1.25	1.25
inlet moisture, % w.b.	25.0	25.0	25.0
outlet grain temperature, °C	47	45	41
outlet moisture, % w.b.	21.0	21.6	23.8
Stein breakage, %	11.3	10.0	10.0
outlet air temperature, °C	47	45	41
outlet air humidity, decimal d.b.	.0543	.0572	.0362
drying cost, ¢/kg	.207	.168	.105
Stage 2--			
inlet air temperature, °C	166	200	180
airflow, m/min	50	42	60
dryer length, m	2.0	1.2	1.1
tempering time, hr	--	1.25	1.25
inlet moisture, % w.b.	21.0	21.6	23.8
outlet grain temperature, °C	58	53	54
outlet moisture, % w.b.	15.7	18.1	20.3
Stein breakage, %	22.7	17.7	12.8
outlet air temperature, °C	58	53	54
outlet air humidity, decimal d.b.	.0512	.0619	.0532
drying cost, ¢/kg	.293	.143	.145
Stage 3--			
inlet air temperature, °C		170	200
airflow, m/min		30	60
dryer length, m		1.2	1.8
tempering		--	--
inlet moisture, % w.b.		18.1	20.3
outlet grain temperature, °C		54	66
outlet moisture, % w.b.		15.7	15.7
Stein breakage, %		22.7	22.7
outlet air temperature, °C		54	66
outlet air humidity, decimal d.b.		.0555	.0630
drying cost, ¢/kg		.154	.196
Total drying cost, ¢/kg	.500	.466	.447
Grainflow, kg/hr-m^2	2000	3000	3500

Table 45.--Cost breakdown and efficiency for two- and three-stage concurrentflow dryer with an outlet temperature limit of 60°C.

	Number of Stages		
	2	3	3*
Stage 1--			
inlet temperature, °C	15	15	15
inlet humidity, decimal d.b.	.0065	.0065	.0065
fixed cost, $	3270.00	3270.00	3270.00
fan cost, $	200.00	240.00	150.00
length cost, $	1250.00	1750.00	2000.00
electrical energy cost, ¢/kg	.0011	.0012	.0003
fuel energy cost, ¢/kg	.116	.100	.046
total drying cost, ¢/kg	.207	.168	.105
Stage 2--			
inlet temperature, °C	15	15	15
inlet humidity, decimal d.b.	.0065	.0065	.0065
fixed cost, $	7225.00	3270.00	3270.00
fan cost, $	250.00	210.00	300.00
length cost, $	1950.00	1800.00	2025.00
electrical energy cost, ¢/kg	.0038	.0010	.0019
fuel energy cost, ¢/kg	.110	.075	.082
total drying cost, ¢/kg	.293	.143	.145
Stage 3--			
inlet temperature, °C		15	15
inlet humidity, decimal d.b.		.0065	.0065
fixed cost, $		7225.00	7225.00
fan cost, $		150.00	300.00
length cost, $		1170.00	1755.00
electrical energy cost, ¢/kg		.0004	.0031
fuel energy cost, ¢/kg		.045	.092
total drying cost, ¢/kg		.154	.196
Three-stage drying cost, ¢/kg	.500	.466	.447
Efficiency, kJ/kg water	3873	3759	3772

drying cost increased in order to satisfy this temperature constraint. The fuel energy costs are not significantly different among the three cases. Cost differences are due to necessary changes in the airflow and length of the drying stages.

The third analysis is included to indicate some possible limitations of the constaint checking method used in the optimization procedure. In this case the optimization algorithm could not find any conditions which accomplish the required amount of drying and still meet the temperature constraint. However, this may not necessarily be true. The calculations are done in a sequential manner on the basis of minimum cost. The temperature constraint does not usually become effective until the last drying stage; only then does the grain temperature approach the temperature limit. The effect of the drying in the first stage on the grain temperature in the last stage is not adequately represented not accounted for in the program. Consequently, a set of operational parameters for the first two stages may exist (e.g., higher temperature and lower airflow) which results in a higher drying cost without satisfying the temperature constraint. It is especially in this regard where knowledge of the process involved is very helpful in choosing the ranges for the variables used during the optimization procedure.

5.4.6 Comparison with crossflow drying

In a 1970 study of on-farm drying costs in Illinois, the drying cost data shown in Table 46 were computed (Anon. 1976). The capital investment cost included the necessary auxilliary storage costs, erection costs and costs for other needed equipment for a complete

Table 46.--Costs for drying and storing corn on-farm in Illinois, 1976.

	Capital Cost $	Variable Cost ¢/kg	Fixed Cost ¢/kg	Total Cost ¢/kg
Low temperature, in-bin				
305 tonne	15,000	.394	.591	.984
915 tonne	42,500	.394	.512	.905
1525 tonne	68,600	.394	.472	.945
High temperature, in-bin batch with multiple auger stirring				
305 tonne	15,100	.433	.591	1.024
915 tonne	31,200	.276	.354	.630
1525 tonne	41,800	.276	.315	.591
Automatic batch				
305 tonne	23,600	.354	.945	1.299
915 tonne	44,100	.276	.512	.787
1525 tonne	70,500	.276	.472	.750
Continuous crossflow				
305 tonne	22,200	.354	.866	1.220
915 tonne	42,700	.276	.512	.787
1525 tonne	72,200	.276	.472	.750

Source: Anon. (1976).

drying and storage system. A drying time of 20 days was used for removing 10 points of moisture from the corn.

The drying costs in Table 46 will be used along with the previously presented costs for multistage concurrentflow dryers for evaluation of investment feasibility. The comparison method used is the Internal Rate of Return (IRR) as presented by Riggs (1977).

The IRR method is based on present worth calculations which include the time value of the future yearly cash-flows. Essentially, the IRR method seeks to determine at what rate of cash flow discounting does the present worth of the yearly increase in returns equal the additional investment for the two projects being compared. The present worth is calculated from:

$$PW = \sum_{i=1}^{N} NS_i(A,IRR,i) - \Delta IC = 0 \qquad (66)$$

where: $(A,IRR,i) = 1/(1+IRR)^i$ (67)

The IRR figure computed from equation (66) is a percentage which is the approximate yield for the particular use of capital involved.

A single-stage concurrentflow dryer rated at 8.0 tonne/hr can be purchased for $43,000*; an equivalent two-stage dryer for $48,000; an equivalent three-stage dryer for $49,000. All concurrentflow dryers were shown previously to have an operating cost of about 0.230¢/kg. The average operating cost for an equivalent crossflow dryer is 0.302¢/kg as given in Table 46 and can be purchased for approximately $21,000 (based on 30% of capital investment cost listed in Table 46). Based on the previous assumption of 720 yearly operating hours, the net yearly savings would be $4150. The corresponding IRR for the additional investment in a concurrentflow dryer instead of a crossflow dryer would be:

1. 14.6% for a single stage dryer; additional investment $22,000,
2. 8.7% for a two-stage dryer; additional investment $27,000,
3. 7.9% for a three-stage dryer; additional investment $28,000.

The corresponding break-even periods for the three concurrentflow drying configurations are 5.3/6.5/6.7 years.

---

*Concurrentflow dryer purchase costs supplied by Westelaken (1976).

The above analysis does not include the effect of inflation and (possibly) steeply increasing energy prices which are tied very closely to oil prices. Woods (1975) has tabulated and compared several indices which can be used for evaluating the effect of inflation. Inflation of the evenly prices will improve the advantage of the concurrentflow dryer over the crossflow dryer.

6. CONCLUSIONS

On the basis of either operating costs or IRR figures the multistage concurrentflow dryer is preferrable to a crossflow dryer. The two- or three-stage dryers have a higher investment cost than a single-stage dryer, but, on a per square meter of column area basis, the single-stage concurrentflow dryer is more expensive to operate than a two- or three-stage concurrentflow dryer.

The quality of the end-product is affected by the drying process. The concurrentflow dryer produces dried corn which is less susceptible to damage than that produced by a crossflow dryer. Since the increase in Stein breakage (and thus increased susceptibility to breakage) is related to the moisture removal rate, a multistage concurrentflow dryer with tempering is preferrable to a single-stage concurrentflow dryer, and also to a conventional crossflow dryer. Imposing a 60°C temperature limit versus an 80°C temperature limit during the drying of shelled corn increases the drying cost. Changing constraints on the quality factors of shelled corn and other agricultural products produces similar results.

Feed-forward recycling of exhaust air significantly reduces the energy use in the concurrentflow dryer. A three-stage dryer with recycling has about a 16% advantage in energy cost over a similar two-stage dryer. However, the added capital cost required for the equipment necessary to capture and conduct the exhausted air is not considered. A dryer purchased today has a known capital cost which is budgeted over the estimated life of the equipment. At the same time inflation causes energy purchase costs to increase (perhaps dramatically) during the same time period. Therefore, a dryer using recycling has a continuously increasing advantage over a dryer not using recycling, and also over a conventional crossflow dryer.

The numerical results obtained are dependent on the factors used for estimating capital costs. However, operational and design factors calculated by the optimization routine are unaffected by even major changes in the capital cost factors. The IRR figures are computed assuming zero inflation. Inflation and other market factors are a fact of life which increase energy purchase costs and thus increase the advantage of the concurrentflow dryer over the crossflow dryer.

7. SUMMARY

A computer model was developed to simulate the drying performance of a multistage concurrentflow dryer with intermediate tempering and a counterflow cooler. Diffusion within spherical kernels was used to model the drying and tempering process. The counterflow cooler was modeled using a modified version of the Effectiveness-NTU method derived for a counterflow heat exchanger. The multistage model agreed reasonably well with sample data obtained from field experiments for the multistage drying of shelled corn and pea beans.

The quality of the shelled corn and pea beans as affected by drying was modeled. An equation for the percentage of breakage in the Stein breakage test was developed for shelled corn and for the percentage of cracked seed costs for pea beans. The calculations from the quality models agreed well with the results of the experimental tests but did not adequately reflect the beneficial effects of the counterflow cooler.

An optimization model using dynamic programming was developed for finding the optimum operational parameters and size of a multistage concurrentflow dryer with tempering. The objective function was based on energy costs for energy consumed during drying and capital investment costs budgeted over a 10 year period. The operational parameters were constrained by the desired final moisture content, the maximum allowable exit temperature of the grain from any drying stage, and the maximum allowable value of an important grain quality factor. Comparisons were made for different number of stages, and with a conventional crossflow dryer. The effect of feed-forward recycling of exhaust air was investigated for the multistage concurrentflow dryer.

Costs of 0.447¢/kg and 0.448¢/kg were found for representative two- and three-stage dryers, respectively. Feed-forward recycling of the exhaust air reduces the drying costs to 0.424¢/kg and 0.405¢/kg, respectively. A representative drying cost of 0.569¢/kg was found for a single-stage concurrentflow dryer. About half (45%-55%) of the total drying cost for multistage concurrentflow dryers was for energy consumed during the drying process.

Energy costs of 0.302¢/kg for a continuousflow crossflow dryer are greater than an average of 0.230¢/kg for concurrentflow dryers. The internal rate of return for the additional investment in a concurrentflow dryer instead of a crossflow dryer would be approximately 15% for a single-stage; 9% for a two-stage; 8% for a three-stage. An investment decision would also include the beneficial effect on grain quality of a multistage versus a single-stage concurrentflow dryer.

8. SUGGESTIONS FOR FUTURE RESEARCH

The concurrentflow drying model used was based on uniform diffusion within an assumed spherical kernel. A mass transfer surface convection coefficient of infinity was assumed. It has been theorized that a grain kernel does not lose moisture uniformly over the whole surface but rather at one point (the germ) unless there are open cracks in the seed coat and underlying aleurone layer. The impervious nature of the seed coat of pea beans helps explain why the bean exhibits a relatively constant diffusion coefficient with respect to changing kernel moisture content. A better understanding of the moisture diffusion process within grain kernels is necessary, not as much for calculation of drying rates, but for its importance in understanding how the quality of the grain kernel is affected by drying and tempering.

The tempering period apparently has an important effect on the quality of the grain. The beneficial effect may be related to stress caused by moisture gradients which are relieved as the moisture migrates during tempering. Improved knowledge of the extent to which tempering affects grain quality is important for determining not only the necessary tempering time but also the number of drying stages to be utilized.

The overall effect of drying and tempering on the quality of agricultural products is not well understood. Attempts have been made to relate average quality changes to drying conditions. Engineering mechanics approaches have mostly assumed that grain kernels are homogeneous which is not actually true. Research is necessary to study the interrelationships of the various parts of the kernel. When developing quality prediction equations it must be recognized that different kernels will react in different manners; the stochastic nature of the process must be included. As understanding of these factors is improved they can be incorporated into the quality models used for optimization.

The optimization algorithm developed was applied only to the drying of shelled corn. The pea bean drying equations presented can also be used to study dryer design. The equation determined for predicting seed coat cracking is fairly representative of the data collected, however a better understanding of the effect of drying and tempering is needed. Counterflow cooling and recycling of exhaust air may have a beneficial effect on quality, as well on the energy used during drying. Higher humidities during drying reduce the moisture difference between the seed coat and the cotyledon halves thereby reducing the relative difference in the amount of shrinkage and the resulting stress on the seed coat structure.

9. APPENDICES

APPENDIX 9.1

CONVERSION FACTORS

Unit Conversions	English or Metric	SI
Area	1 ft^2	$9{\cdot}290\ x10^{-2}m^2$
Convective Heat-Transfer coefficient	1 Btu/h ft^2 °F	$5{\cdot}678$ W/m^2°C
Density	1 lb/ft^3	$1{\cdot}602\ x10kg/m^3$
Energy	1 kcal	$4{\cdot}187\ x10^3J$
	1 Btu	$1{\cdot}055\ x10^3J$
	1 kWh	$3{\cdot}600\ x10^6J$
Enthalpy, specific	1 Btu/lb	$2{\cdot}326\ x10^3J/kg$
Force	1 lbf	4·448 N
Heat flux	1 kcal/h m^2	$1{\cdot}163\ W/m^2$
	1 Btu/h ft^2	$3{\cdot}155\ W/m^2$
Heat release rate (mass)	1 Btu/h lb	$6{\cdot}461\ x10^{-1}W/kg$
Length	1 ft	$3{\cdot}048\ x10^{-1}m$
Mass	1 lb	$4{\cdot}536\ x10^{-1}kg$
	1 tonne	$1{\cdot}000\ x10^3kg$
	1 ton	$1{\cdot}016\ x10^3kg$
Power	1 Btu/h	$2{\cdot}931\ x10^{-1}W$
	1 hp	$7{\cdot}457\ x10^2W$
Pressure	1 standard atmosphere	$1{\cdot}013\ x10^5N/m^2$
	1 bar	$1{\cdot}000\ x10^5N/m^2$
	1 lbf/in^2	$6{:}895\ x10^3N/m^2$
	1 in water	$2.491\ x10^2N/m^2$
	1 mm Hg	$1{\cdot}333\ x10^2N/m^2$

Unit Conversions	English or Metric	SI
Surface per unit volume	1 ft^2/ft^3	3·280 m^2/m^3
Specific heat	1 Btu/lb F	4·187 $\times 10^3$ J/kgK
Temperature difference	1 deg F (deg R)	5/9 deg C (deg K)
Thermal Conductivity	1 Btu/h ft^2 (°F/ft)	1·731 W/m^2(°C/m)
Velocity	1 ft/h	8·467 $\times 10^{-5}$ m/s
Viscosity, absolute (or dynamic)	1 lb/ft h	4·134 $\times 10^{-4}$ kg/m s
Viscosity, kinematic	1 ft^2/h	2·581 $\times 10^{-5}$ m^2/s
Volume	1 bu (volume)	3·523 $\times 10^{-2}$ m^3
	1 ft^3	2·832 $\times 10^{-2}$ m^3
	1 U.S. gal	3·785 $\times 10^{-3}$ m^3

Miscellaneous Conversions	English or Metric	SI
Airflow	1 cfm	2·832 $\times 10^{-2}$ m^3/min
	1 cfm	4·719 $\times 10^{-4}$ m^3/sec
	1 cfm/ft^2	3·048 $\times 10^{-1}$ m/min
	1 cfm/ft^2	5·080 $\times 10^{-3}$ m/sec
Drying Cost	1 ¢/bu	3.937 $\times 10^{-2}$ ¢/kg corn
		3·392 $\times 10^{-2}$ ¢/kg beans
Grainflow (corn)	1 bu/hr	2·540 $\times 10^{-2}$ tonne/hr
		2·540 x10 kg/hr
	1 bu/hr/ft^2	2·734 $\times 10^{-1}$ tonne/hr/m^2
		2·734 $\times 10^{2}$ kg/hr/m^2
Grainflow	1 bu/hr	2.948 $\times 10^{-2}$ tonne/hr
		2·948 x10 kg/hr
	1 bu/hr/ft^2	3·174 $\times 10^{-1}$ tonne/hr/m^2
		3·174 $\times 10^{2}$ kg/hr/m^2

APPENDIX 9.2

PEA BEAN TESTS SAMPLE DATA

```
BEAN TEST 2  SAMPLE DATA      125/125 F      105 BU/HR
MEANINLT 3   66.66667   20.53333    1.30000     .30000
VAR INLT 3    9.33333     .17333     .31000    0.00000
SDEVINLT 3    3.05505     .41633     .55678    0.00000
0001INLT 1   70.00000   20.40000    1.20000     .30000
0001INLT 2   66.00000   20.20000     .80000     .30000
0001INLT 3   64.00000   21.00000    1.90000     .30000

MEAND2EX 4   71.25000   19.95000    1.40000     .47500
VAR D2EX 4     .91667     .15000     .54000     .02917
SDEVD2EX 4     .95743     .38730     .73485     .17078
000102EX 1   72.00000   19.50000     .90000     .30000
000102EX 2   72.00000   19.80000     .80000     .70000
000102EX 3   70.00000   20.10000    2.40000     .50000
000102EX 4   71.00000   20.40000    1.50000     .40000

MEAND3EX 4   73.50000   19.32500    2.15000     .42500
VAR D3EX 4    1.00000     .04917     .17667     .04917
SDEVD3EX 4    1.00000     .22174     .42032     .22174
000103EX 1   74.00000   19.40000    2.60000     .20000
000103EX 2   74.00000   19.00000    2.10000     .70000
000103EX 3   74.00000   19.50000    2.30000     .30000
000103EX 4   72.00000   19.40000    1.60000     .50000

BEAN TEST 3  SAMPLE DATA      165/165 F       84 BU/HR
MEANINLT 4   66.50000   20.90000    1.32500     .27500
VAR INLT 4    9.00000     .04667     .25583     .03583
SDEVINLT 4    3.00000     .21602     .50580     .18930
0003INLT 1   68.00000   20.60000     .70000     .40000
0003INLT 2   62.00000   21.10000    1.20000     .30000
0003INLT 3   68.00000   20.90000    1.50000     .40000
0003INLT 4   68.00000   21.00000    1.90000    0.00000

MEAND2EX 4   71.50000   20.85000    1.70000     .25000
VAR D2EX 4    6.33333     .33667     .59333     .03667
SDEVD2EX 4    2.51661     .58023     .77028     .19149
000302EX 1   74.00000   20.00000    1.20000     .40000
000302EX 2   72.00000   21.10000    2.20000     .20000
000302EX 3   72.00000   21.30000     .90000    0.00000
000302EX 4   68.00000   21.00000    2.50000     .40000

MEAND3EX 4   83.50000   17.67500    5.17500     .25000
VAR D3EX 4    6.33333     .30917    2.10250     .04333
SDEVD3EX 4    2.51661     .55603    1.45000     .20817
000303EX 1   86.00000   17.30000    4.90000     .20000
000303EX 2   84.00000   17.10000    3.30000     .50000
000303EX 3   84.00000   18.10000    5.80000     .30000
000303EX 4   80.00000   18.20000    6.70000    0.00000

MEANOUTL 2   77.00000   18.15000    6.45000     .35000
VAR OUTL 2    2.00000     .24500     .04500     .00500
SDEVOUTL 2    1.41421     .49497     .21213     .07071
00030UTL 1   76.00000   17.80000    6.60000     .30000
00030UTL 2   78.00000   18.50000    6.30000     .40000

BEAN TEST 4  SAMPLE DATA      200/200 F       84 BU/HR
MEANINLT 4   67.50000   20.12500    1.00000     .27500
VAR INLT 4    3.66667     .04917     .08000     .00917
SDEVINLT 4    1.91485     .22174     .28284     .09574
0004INLT 1   70.00000   19.90000     .80000     .30000
0004INLT 2   66.00000   20.40000    1.40000     .20000
0004INLT 3   68.00000   20.00000    1.00000     .20000
0004INLT 4   66.00000   20.20000     .80000     .40000

MEAND2EX 4   90.00000   18.62500    5.10000     .40000
VAR D2EX 4    2.66667     .04250    2.30667     .04667
SDEVD2EX 4    1.63299     .20616    1.51877     .21602
000402EX 1   90.00000   18.60000    7.00000     .50000
000402EX 2   90.00000   18.60000    5.60000     .10000
000402EX 3   92.00000   18.40000    4.20000     .60000
000402EX 4   88.00000   18.90000    3.60000     .40000

MEAND3EX 4   99.00000   16.70000    8.80000     .35000
VAR D3EX 4    1.33333     .00667     .30000     .04333
SDEVD3EX 4    1.15470     .08165     .54772     .20817
000403EX 1  100.00000   16.70000    8.50000     .40000
000403EX 2  100.00000   16.70000    9.10000     .60000
000403EX 3   98.00000   16.80000    9.40000     .10000
000403EX 4   98.00000   16.60000    8.20000     .30000

BEAN TEST 5  SAMPLE DATA      200/165 F       84 BU/HR
```

MEANINLT	3	68.00000	20.96667	.96667	.23333
VAR INLT	3	4.00000	.04333	.25333	.06333
SDEVINLT	3	2.00000	.20817	.50332	.25166
0005INLT	1	66.00000	20.90000	1.50000	.50000
0005INLT	2	70.00000	20.80000	.90000	0.00000
0005INLT	3	68.00000	21.20000	.50000	.20000
MEANO2EX	3	86.66667	19.30000	3.56667	.36667
VAR O2EX	3	9.33333	0.00000	2.81333	.02333
SDEVO2EX	3	3.05505	0.00000	1.67730	.15275
000502EX	1	84.00000	19.30000	2.70000	.50000
000502EX	2	90.00000	19.30000	2.50000	.40000
000502EX	3	86.00000	19.30000	5.50000	.20000
MEANO3EX	3	94.00000	16.96667	10.10000	.73333
VAR O3EX	3	0.00000	.02333	5.97000	.02333
SDEVO3EX	3	0.00000	.15275	2.44336	.15275
000503EX	1	94.00000	16.80000	9.00000	.70000
000503EX	2	94.00000	17.10000	12.90000	.60000
000503EX	3	94.00000	17.00000	8.40000	.90000

BEAN TEST 6 SAMPLE DATA 225/200 F 105 BU/HR

MEANINLT	4	69.00000	20.95000	1.65000	.07500
VAR INLT	4	1.33333	.05667	1.24333	.00250
SDEVINLT	4	1.15470	.23805	1.11505	.05000
0006INLT	1	70.00000	21.10000	2.90000	.10000
0006INLT	2	68.00000	20.80000	1.90000	0.00000
0006INLT	3	70.00000	20.70000	.20000	.10000
0006INLT	4	68.00000	21.20000	1.60000	.10000
MEANO2EX	4	96.00000	19.00000	3.37500	.15000
VAR O2EX	4	8.00000	.06000	.29583	.01667
SDEVO2EX	4	2.82843	.24495	.54391	.12910
000602EX	1	94.00000	18.70000	3.40000	.10000
000602EX	2	94.00000	19.30000	2.60000	.30000
000602EX	3	96.00000	19.00000	3.80000	.20000
000602EX	4	100.00000	19.00000	3.70000	0.00000
MEANO3EX	4	103.00000	16.92500	9.62500	.35000
VAR O3EX	4	1.33333	.00250	.42250	.04333
SDEVO3EX	4	1.15470	.05000	.65000	.20817
000603EX	1	102.00000	16.90000	9.30000	.30000
000603EX	2	104.00000	16.90000	10.50000	.40000
000603EX	3	102.00000	17.00000	9.00000	.60000
000603EX	4	104.00000	16.90000	9.70000	.10000
MEANOUTL	4	97.00000	17.47500	7.42500	.12500
VAR OUTL	4	1.33333	.01583	2.80250	.00917
SDEVOUTL	4	1.15470	.12583	1.67407	.09574
0006OUTL	1	96.00000	17.60000	7.40000	0.00000
0006OUTL	2	96.00000	17.30000	6.30000	.20000
0006OUTL	3	98.00000	17.50000	9.80000	.20000
0006OUTL	4	98.00000	17.50000	6.20000	.10000

BEAN TEST 8 SAMPLE DATA 250/225 F 125 BU/HR

MEANINLT	4	62.00000	22.30000	.62500	.02500
VAR INLT	4	0.00000	.16667	.06250	.00250
SDEVINLT	4	0.00000	.40825	.25000	.05000
0008INLT	1	62.00000	21.70000	.50000	0.00000
0008INLT	2	62.00000	22.60000	.50000	0.00000
0008INLT	3	62.00000	22.50000	.50000	0.00000
0008INLT	4	62.00000	22.40000	1.00000	.10000
MEANO2EX	4	90.00000	20.87500	1.32500	.05000
VAR O2EX	4	8.00000	.12917	.64917	.01000
SDEVO2EX	4	2.82843	.35940	.80571	.10000
000802EX	1	92.00000	20.40000	1.80000	.20000
000802EX	2	90.00000	21.10000	.50000	0.00000
000802EX	3	92.00000	20.80000	2.20000	0.00000
000802EX	4	86.00000	21.20000	.80000	0.00000
MEANO3EX	4	107.00000	18.80000	8.65000	.10000
VAR O3EX	4	1.33333	.02000	7.10333	.04000
SDEVO3EX	4	1.15470	.14142	2.66521	.20000
000803EX	1	106.00000	18.80000	7.80000	0.00000
000803EX	2	106.00000	18.90000	12.60000	0.00000
000803EX	3	108.00000	18.60000	6.80000	.40000
000803EX	4	108.00000	18.90000	7.40000	0.00000
MEANOUTL	4	95.00000	19.67500	7.25000	.10000
VAR OUTL	4	4.00000	.02917	.62333	.01333

```
SDEVOUTL 4     2.00000     .17078      .78951      .11547
0008OUTL 1    96.00000   19.50000     6.30000      .20000
0008OUTL 2    92.00000   19.70000     6.90000     0.00000
0008OUTL 3    96.00000   19.60000     7.90000      .20000
0008OUTL 4    96.00000   19.90000     7.90000     0.00000

BEAN TEST 9 SAMPLE DATA      225/200 F      105 BU/HR
MEANINLT 4    61.50000   22.62500      .67500      .15000
VAR INLT 4     1.00000     .08250      .13583      .01000
SDEVINLT 4     1.00000     .28723      .36856      .10000
0009INLT 1    60.00000   22.40000     1.10000      .20000
0009INLT 2    62.00000   22.70000      .70000      .20000
0009INLT 3    62.00000   23.00000      .20000     0.00000
0009INLT 4    62.00000   22.40000      .70000      .20000

MEAND2EX 4    91.00000   20.52500     2.30000      .07500
VAR D2EX 4     1.33333     .04250      .31333      .00917
SDEVD2EX 4     1.15470     .20616      .55976      .09574
0009D2EX 1    90.00000   20.70000     1.80000     0.00000
0009D2EX 2    92.00000   20.30000     2.20000      .10000
0009D2EX 3    90.00000   20.40000     2.10000     0.00000
0009D2EX 4    92.00000   20.70000     3.10000      .20000

MEAND3EX 4   102.50000   18.62500     7.15000      .37500
VAR D3EX 4     1.00000     .08917      .35667      .00917
SDEVD3EX 4     1.00000     .29861      .59722      .09574
0009D3EX 1   102.00000   18.30000     6.50000      .50000
0009D3EX 2   104.00000   18.50000     7.30000      .30000
0009D3EX 3   102.00000   19.00000     6.90000      .30000
0009D3EX 4   102.00000   18.70000     7.90000      .40000

MEANOUTL 4    92.00000   19.77500     6.75000      .07500
VAR OUTL 4     2.66667     .08917     1.60333      .00917
SDEVOUTL 4     1.63299     .29861     1.26623      .09574
0009OUTL 1    90.00000   19.90000     6.10000      .20000
0009OUTL 2    94.00000   19.40000     8.00000      .10000
0009OUTL 3    92.00000   19.70000     5.30000     0.00000
0009OUTL 4    92.00000   20.10000     7.60000     0.00000

BEAN TEST 10 SAMPLE DATA      175/225/200 F      105 BU/HR
MEANINLT 4    64.00000   21.90000      .80000      .05000
VAR INLT 4     0.00000     .06000      .12667      .01000
SDEVINLT 4     0.00000     .24495      .35590      .10000
0010INLT 1    64.00000   21.60000      .50000     0.00000
0010INLT 2    64.00000   22.20000     1.20000     0.00000
0010INLT 3    64.00000   21.90000      .50000     0.00000
0010INLT 4    64.00000   21.90000     1.00000      .20000

MEAND1EX 4    85.00000   21.10000     1.27500      .12500
VAR D1EX 4    12.00000     .40667      .40917      .00917
SDEVD1EX 4     3.46410     .63770      .63966      .09574
0010D1EX 1    80.00000   22.00000     1.80000      .10000
0010D1EX 2    88.00000   21.10000      .50000     0.00000
0010D1EX 3    86.00000   20.60000     1.80000      .20000
0010D1EX 4    86.00000   20.70000     1.00000      .20000

MEAND2EX 4    97.00000   19.45000     5.30000      .02500
VAR D2EX 4     4.00000     .21667     4.38667      .00250
SDEVD2EX 4     2.00000     .46547     2.09444      .05000
0010D2EX 1    96.00000   19.60000     4.40000      .10000
0010D2EX 2    96.00000   19.50000     6.60000     0.00000
0010D2EX 3    96.00000   19.90000     2.80000     0.00000
0010D2EX 4   100.00000   18.80000     7.40000     0.00000

MEAND3EX 4   104.00000   17.77500    11.77500      .05000
VAR D3EX 4     5.33333     .00917    21.56250      .01000
SDEVD3EX 4     2.30940     .09574     4.64354      .10000
0010D3EX 1   106.00000   17.80000     9.60000      .20000
0010D3EX 2   102.00000   17.90000    15.00000     0.00000
0010D3EX 3   106.00000   17.70000     6.30000     0.00000
0010D3EX 4   102.00000   17.70000    16.20000     0.00000

MEANOUTL 4    95.50000   18.65000     8.47500      .15000
VAR OUTL 4     1.00000     .01667     1.34917      .00333
SDEVOUTL 4     1.00000     .12910     1.16154      .05774
0010OUTL 1    94.00000   18.70000     8.70000      .10000
0010OUTL 2    96.00000   18.50000     9.90000      .10000
0010OUTL 3    96.00000   18.60000     7.10000      .20000
0010OUTL 4    96.00000   18.80000     8.20000      .20000

BEAN TEST 11 SAMPLE DATA      250/225/200 F      135 BU/HR
```

MEANINLT	4	64.00000	22.30000	1.20000	.30000
VAR INLT	4	0.00000	.28667	.22667	.02000
SDEVINLT	4	0.00000	.53541	.47610	.14142
0011INLT	1	64.00000	23.00000	.90000	.40000
0011INLT	2	64.00000	22.30000	.90000	.10000
0011INLT	3	64.00000	22.20000	1.10000	.40000
0011INLT	4	64.00000	21.70000	1.90000	.30000
MEAN01EX	4	94.50000	20.82500	2.02500	.15000
VAR 01EX	4	1.00000	.00917	.24917	.00333
SDEV01EX	4	1.00000	.09574	.49917	.05774
001101EX	1	94.00000	20.70000	1.70000	.20000
001101EX	2	96.00000	20.80000	2.10000	.10000
001101EX	3	94.00000	20.90000	1.60000	.20000
001101EX	4	94.00000	20.90000	2.70000	.10000
MEAN02EX	4	97.00000	19.77500	2.37500	.20000
VAR 02EX	4	1.33333	.01583	.02250	.02000
SDEV02EX	4	1.15470	.12583	.15000	.14142
001102EX	1	98.00000	19.60000	2.20000	.20000
001102EX	2	96.00000	19.90000	2.50000	.30000
001102EX	3	98.00000	19.80000	2.30000	.30000
001102EX	4	96.00000	19.80000	2.50000	0.00000
MEAN03EX	4	102.00000	18.67500	4.22500	.15000
VAR 03EX	4	8.00000	.08250	3.12917	.00333
SDEV03EX	4	2.82843	.28723	1.76895	.05774
001103EX	1	106.00000	18.30000	2.20000	.20000
001103EX	2	100.00000	19.00000	4.30000	.10000
001103EX	3	102.00000	18.70000	3.90000	.10000
001103EX	4	100.00000	18.70000	6.50000	.20000
MEANOUTL	4	96.00000	19.60000	4.17500	.10000
VAR OUTL	4	0.00000	.72000	.28917	.02000
SDEVOUTL	4	0.00000	.84853	.53774	.14142
0011OUTL	1	96.00000	19.00000	4.80000	.30000
0011OUTL	2	96.00000	19.60000	3.50000	.10000
0011OUTL	3	96.00000	19.00000	4.30000	0.00000
0011OUTL	4	96.00000	20.80000	4.10000	0.00000

BEAN TEST 12 SAMPLE DATA 225/200/200 F 125 BU/HR

MEANINLT	4	64.00000	22.12500	.57500	.17500
VAR INLT	4	2.66667	.28250	.06250	.00250
SDEVINLT	4	1.63299	.53151	.25000	.05000
0012INLT	1	64.00000	22.90000	.90000	.10000
0012INLT	2	66.00000	21.90000	.60000	.20000
0012INLT	3	64.00000	21.70000	.30000	.20000
0012INLT	4	62.00000	22.00000	.50000	.20000
MEAN01EX	4	95.00000	20.72500	1.47500	.12500
VAR 01EX	4	22.66667	.36917	.84250	.00917
SDEV01EX	4	4.76095	.60759	.91788	.09574
001201EX	1	90.00000	21.40000	1.10000	0.00000
001201EX	2	92.00000	21.00000	.40000	.10000
001201EX	3	98.00000	20.50000	1.90000	.20000
001201EX	4	100.00000	20.00000	2.50000	.20000
MEAN02EX	4	91.50000	20.27500	2.20000	.17500
VAR 02EX	4	1.00000	.05583	.18667	.05583
SDEV02EX	4	1.00000	.23629	.43205	.23629
001202EX	1	92.00000	20.60000	2.60000	0.00000
001202EX	2	92.00000	20.10000	2.20000	.20000
001202EX	3	90.00000	20.10000	2.40000	0.00000
001202EX	4	92.00000	20.30000	1.80000	.50000
MEAN03EX	4	100.50000	18.87500	3.82500	.10000
VAR 03EX	4	1.00000	.00917	4.30250	.00667
SDEV03EX	4	1.00000	.09574	2.07425	.08165
001203EX	1	100.00000	18.80000	6.10000	.10000
001203EX	2	102.00000	18.90000	4.10000	0.00000
001203EX	3	100.00000	18.80000	1.10000	.10000
001203EX	4	100.00000	19.00000	3.20000	.20000
MEANOUTL	4	83.00000	19.65000	2.85000	.17500
VAR OUTL	4	1.33333	.03667	.36333	.02917
SDEVOUTL	4	1.15470	.19149	.60277	.17078
0012OUTL	1	84.00000	19.90000	3.40000	.10000
0012OUTL	2	84.00000	19.70000	2.90000	.40000
0012OUTL	3	82.00000	19.50000	2.00000	0.00000
0012OUTL	4	82.00000	19.50000	3.10000	.20000

APPENDIX 9.3

SHELLED CORN TESTS SAMPLE DATA

```
CORN TEST 01    325/325/325 F    136 CFM    11.25/10.15/10.15 BPH
MEANINLT 5  62.80000   27.52000    .80000  15.20000   0.00000
VAR INLT 5   7.20000    6.76700    .04000  30.70000   0.00000
SDEVINLT 5   2.68328    2.60135    .20000   5.54076   0.00000
0001INLT 1  60.00000   30.20000   1.00000  15.00000   0.00000
0001INLT 2  64.00000   27.70000   1.00000  24.00000   0.00000
0001INLT 3  64.00000   28.50000    .80000  11.00000   0.00000
0001INLT 4  66.00000   28.00000    .60000  10.00000   0.00000
0001INLT 5  60.00000   23.200000    .60000  16.00000   0.00000

CORN TEST 01
MEANOUTL 5  69.20000   18.20000    .70000  12.80000   0.00000
VAR OUTL 5   9.20000     .26000    .01000  17.70000   0.00000
SDEVOUTL 5   3.03315     .50990    .10000   4.20714   0.00000
00010UTL 1  74.00000   17.70000    .80000  19.00000   0.00000
00010UTL 2  70.00000   18.50000    .80000   8.00000   0.00000
00010UTL 3  68.00000   18.50000    .60000  10.00000   0.00000
00010UTL 4  68.00000   17.60000    .60000  13.00000   0.00000
00010UTL 5  66.00000   18.70000    .70000  14.00000   0.00000

CORN TEST 02    375/375/350 F    136 CFM    8.07/8.59/8.59 BPH
MEANINLT 4  50.00000   24.77500    .50000  16.25000   0.00000
VAR INLT 4  82.66667   27.06917    .04000  28.91667   0.00000
SDEVINLT 4   9.09212    5.20280    .20000   5.37742   0.00000
0002INLT 1  42.00000   26.80000    .40000  17.00000   0.00000
0002INLT 2  62.00000   27.40000    .80000  10.00000   0.00000
0002INLT 3  52.00000   27.90000    .40000  15.00000   0.00000
0002INLT 4  44.00000   17.00000    .40000  23.00000   0.00000

CORN TEST 02
MEANOUTL 4  81.00000   11.05000    .60000  19.25000   0.00000
VAR OUTL 4  12.00000     .04333    .02667  24.25000   0.00000
SDEVOUTL 4   3.46410     .20817    .16330   4.92443   0.00000
00020UTL 1  84.00000   11.30000    .80000  15.00000   0.00000
00020UTL 2  82.00000   10.80000    .60000  15.00000   0.00000
00020UTL 3  82.00000   11.00000    .60000  24.00000   0.00000
00020UTL 4  76.00000   11.10000    .40000  23.00000   0.00000

CORN TEST 03    375/375/375 F    136 CFM    7.09/7.55/5.08 BPH
MEANINLT 5  53.20000   28.42000    .60000  10.20000   0.00000
VAR INLT 5   3.20000    2.26700    .00000    .70000   0.00000
SDEVINLT 5   1.78885    1.50566    .00000    .83666   0.00000
0003INLT 1  52.00000   29.40000    .60000  10.00000   0.00000
0003INLT 2  52.00000   29.80000    .60000  11.00000   0.00000
0003INLT 3  52.00000   27.10000    .60000  10.00000   0.00000
0003INLT 4  54.00000   29.30000    .60000   9.00000   0.00000
0003INLT 5  56.00000   26.50000    .60000  11.00000   0.00000

CORN TEST 03
MEANOUTL 4  67.00000   16.70000    .65000  13.62500    .50000
VAR OUTL 4  22.66667     .11333    .06333  24.56250    .01333
SDEVOUTL 4   4.76095     .33665    .25166   4.95606    .11547
00030UTL 1  60.00000   16.20000   1.00000  11.00000    .60000
00030UTL 2  70.00000   16.90000    .40000  12.00000    .60000
00030UTL 3  70.00000   16.90000    .60000  10.50000    .40000
00030UTL 4  68.00000   16.80000    .60000  21.00000    .40000

CORN TEST 04    425/425/425 F    136 CFM    8.82/7.37/6.44 BPH
MEANINLT 5  46.80000   28.14000    .56000  11.50000   0.00000
VAR INLT 5  17.20000    1.31300    .02800  14.00000   0.00000
SDEVINLT 5   4.14729    1.14586    .16733   3.74166   0.00000
0004INLT 1  42.00000   28.40000    .80000  10.00000   0.00000
0004INLT 2  44.00000   29.00000    .60000  11.00000   0.00000
0004INLT 3  46.00000   29.30000    .60000  18.00000   0.00000
0004INLT 4  52.00000   27.50000    .40000  10.00000   0.00000
0004INLT 5  50.00000   26.50000    .40000   8.50000   0.00000

CORN TEST 04
MEANOUTL 4  72.50000   16.87500    .57500  17.25000    .65000
VAR OUTL 4   9.00000     .04250    .02917   3.58333    .03667
SDEVOUTL 4   3.00000     .20616    .17078   1.89297    .19149
00040UTL 1  74.00000   17.10000    .60000  16.00000    .40000
00040UTL 2  68.00000   17.00000    .50000  16.00000    .80000
00040UTL 3  74.00000   16.70000    .40000  17.00000    .60000
00040UTL 4  74.00000   16.70000    .80000  20.00000    .80000

CORN TEST 05    350/350 F    136 CFM    4.16/4.78 BPH
MEANINLT 5  52.00000   28.72000    .56000  17.30000   0.00000
VAR INLT 5   6.00000    4.57700    .00800  18.70000   0.00000
SDEVINLT 5   2.44949    2.13939    .08944   4.32435   0.00000
0005INLT 1  48.00000   30.80000    .60000  17.00000   0.00000
```

```
0005INLT 2  54.00000  25.10000    .60000  12.00000   0.00000
0005INLT 3  52.00000  29.00000    .40000  19.00000   0.00000
0005INLT 4  54.00000  29.30000    .60000  15.00000   0.00000
0005INLT 5  52.00000  29.40000    .60000  23.50000   0.00000

CORN TEST 05
MEANOUTL 3  76.66667  15.50000    .80000  34.33333    .26667
VAR OUTL 3  17.33333    .07000    .00700 102.33333    .01333
SDEVOUTL 3   4.16333    .26458    .00000  10.11599    .11547
00050UTL 1  80.00000  15.30000    .80000  28.00000    .20000
00050UTL 2  78.00000  15.40000    .80000  29.00000    .20000
00050UTL 3  72.00000  15.80000    .80000  46.00000    .40000

CORN TEST 06 (FIRE) 400/400 F   136 CFM
MEANINLT 5  58.00000  26.98000    .92000  16.40000   0.00000
VAR INLT 5   6.00000  25.77200    .01200  18.42500   0.00000
SDEVINLT 5   2.44949   5.07661    .10954   4.29244   0.00000
0006INLT 1  62.00000  26.80000   1.00000  20.00000   0.00000
0006INLT 2  56.00000  19.00000   1.00000  12.00000   0.00000
0006INLT 3  58.00000  26.40000    .80000  11.50000   0.00000
0006INLT 4  58.00000  30.70000    .80000  20.00000   0.00000
0006INLT 5  56.00000  32.00000   1.00000  18.50000   0.00000

CORN TEST 07   325/325 F   144 CFM   3.90/3.49 BPH
MEANINLT 8  61.12500  28.38750    .72500  15.81250   0.00000
VAR INLT 8  10.12500   8.28982    .34786  23.42411   0.00000
SDEVINLT 9   3.18198   2.87920    .58979   4.83985   0.00000
0007INLT 1  64.00000  22.40000    .80000  19.50000   0.00000
0007INLT 2  66.00000  27.20000    .30000   9.50000   0.00000
0007INLT 3  62.00000  29.30000    .30000  17.50000   0.00000
0007INLT 4  62.00000  28.20000    .30000   9.50000   0.00000
0007INLT 5  56.00000  28.80000    .30000  11.50000   0.00000
0007INLT 6  58.00000  31.90000    .80000  18.00000   0.00000
0007INLT 7  60.00000  28.20000   1.00000  21.00000   0.00000
0007INLT 8  61.00000  31.10000   2.00000  20.00000   0.00000

CORN TEST 07
MEANOUTL 6  66.33333  15.45000    .73333  23.00000   3.93333
VAR OUTL 6  18.26667   1.04300    .04267  46.00000  69.91467
SDEVOUTL 6   4.27395   1.02127    .20656   6.78233   8.36150
00070UTL 1  64.00000  15.60000    .80000  26.00000    .60000
00070UTL 2  74.00000  17.10000    .80000  17.00000    .40000
00070UTL 3  68.00000  15.40000    .40000  14.00000    .60000
00070UTL 4  62.00000  15.70000    .60000  29.00000    .40000
00070UTL 5  66.00000  14.00000   1.00000  31.00000    .60000
00070UTL 6  64.00000  14.90000    .80000  21.00000    .80000

CORN TEST 08   350/300 F   144 CFM   2.92/2.73 BPH
MEANINLT 3  56.66667  29.96667    .50000  21.00000   0.00000
VAR INLT 3   1.33333    .00333    .03000 133.00000   0.00000
SDEVINLT 3   1.15470    .05774    .17321  11.53256   0.00000
0008INLT 1  56.00000  30.00000    .60000  10.00000   0.00000
0008INLT 2  58.00000  30.00000    .30000  33.00000   0.00000
0008INLT 3  58.00000  29.90000    .60000  20.00000   0.00000

CORN TEST 08
MEANOUTL 6  84.33333  12.56667    .83333  24.83333   1.53333
VAR OUTL 6  42.66734    .16267    .03867  16.56667    .26667
SDEVOUTL 6   6.53202    .40332    .19664   4.07022    .51640
00080UTL 1  78.00000  12.30000    .80000  30.00000   1.00000
00080UTL 2  81.00000  12.60000    .80000  21.00000    .80000
00080UTL 3  94.00000  12.60000    .80000  23.00000   2.00000
00080UTL 4  91.00000  12.00000    .80000  23.00000   1.60000
00080UTL 5  82.00000  12.70000   1.20000  30.00000   2.00000
00080UTL 6  80.00000  13.20000    .80000  22.00000   1.80000

CORN TEST 09   350/350 F   144 CFM   4.00/3.20 BPH
MEANINLT 7  58.14286  30.70000    .58571  26.85714   0.00000
VAR INLT 7   8.80952   1.76667    .08810  74.47619   0.00000
SDEVINLT 7   2.96808   1.32916    .29681   8.62996   0.00000
0009INLT 1  56.00000  31.60000    .60000  33.00000   0.00000
0009INLT 2  60.00000  32.60000    .60000  17.00000   0.00000
0009INLT 3  60.00000  30.00000    .30000  30.00000   0.00000
0009INLT 4  62.00000  30.70000    .60000  33.00000   0.00000
0009INLT 5  58.00000  29.90000    .40000  18.00000   0.00000
0009INLT 6  53.00000  28.60000    .40000  19.00000   0.00000
0009INLT 7  58.00000  31.50000   1.20000  38.00000   0.00000

CORN TEST 09
MEANOUTL 5  68.60000  16.26000    .84000  37.70000    .04000
VAR OUTL 5  33.80000   5.23300    .02800  89.70000    .00300


SDEVOUTL 5   5.81378   2.28758    .16733   9.47101    .05477
00090UTL 1  72.00000  13.50000    .80000  35.00000    .10000
00090UTL 2  66.00000  14.90000    .60000  52.00000   0.00000
00090UTL 3  68.00000  16.00000    .80000  40.00000    .10000
00090UTL 4  70.00000  17.50000    .60000  35.50000   0.00000
00090UTL 5  57.00000  19.40000    .40000  26.00000   0.00000
02.01.08..000036 PAGES PRINT. 001335 LINES PRINT. FOR $ 001.52 AT RG2.
```

10. REFERENCES

Anon. 1967-1972. Grain Crop Quality. C & MS 44. Consumer Mark. Serv., USDA: Washington, D.C.

Anon. 1973. Highlights and summary of project '80 & 5. Research Report 180. Agr. Exp. Station, Mich. State Univ.: East Lansing, MI.

Anon. 1974. Mechanical Damage to Dry Beans. Ext. Bull. E-540. Coop. Ext. Serv., Mich. State Univ.: East Lansing, MI.

Anon. 1975. Energy for Agricultural Production. PPAB/75/69 (DP). FAO: Rome, Italy.

Anon. 1976. Costs of Drying and Storing Grain from the Farmer's Point of View. Research Report. Comm. Div., Ill. Farm Bureau, IL.

Anon. 1977. Navy bean exports 1963-1975. Mich. Dry Bean Digest 1:12.

Adams, W. 1975. Bean storage: Problems to consider. Mich. Bean Comm. News; February, 1975.

Agness, J. B. 1968. Measuring mechanical damage to corn kernels. ASAE Paper No. 68-620. Am. Soc. Agr. Eng.: St. Joseph, MI.

Ahn, Y. K., Chen, H. C., Fan, L. T., and Wan, G. G. 1964. Optimum design of a moving bed grain dryer by dynammic programming. Can J. Chem. Eng. 42:117-120.

Alam, A., and Shove, G. C. 1973. Simulated drying of soybeans. Trans. ASAE 16:134-136.

Anderson, R. J. 1972. Commercial concurrent flow heating--counterflow cooling grain dryer. ASAE Paper No. 72-846. Am. Soc. Agr. Eng.: St. Joseph, MI.

ASAE. 1977. Agricultural Engineers Yearbook. Am. Soc. Agr. Eng.: St. Joseph, MI.

Bakker-Arkema, F. W., Bickert, W. G., and Dexter, S. T. 1968. Environmental control during storage to prevent cracking of pea beans--An analysis. Trans. ASAE 11:380-383.

Bakker-Arkema, F. W., Rosenau, J. R., and Clifford, W. H. 1971. Measurements of grain surface area and its effect on the heat and mass transfer rates in fixed and moving beds of biological products. Trans. ASAE 14:864-867.

Bakker-Arkema, F. W., Brooker, D. B., and Hall, C. W. 1972. Comparative evaluation of crossflow and concurrent flow grain dryers. ASAE Paper No. 72-849. Am. Soc. Agr. Eng.: St. Joseph, MI.

Bakker-Arkema, F. W., DeBoer, S. F., Lerew, L. E., and Roth, M. G. 1973a. Energy conservation in grain dryers: I. Performance evaluation. ASAE Paper No. 73-324. Am. Soc. Agr. Eng.: St. Joseph, MI.

Bakker-Arkema, F. W., Farmer, D. M., and Lerew, L. E. 1973b. Optimum dryer design through simulation. In: Preservation of Wet Harvested Grains, ed. by J. L. Multon and A. Guilbot. Inst. Nat. Recherche Agronomique: Paris, France.

Bakker-Arkema, F. W., Lerew, L. E., DeBoer, S. F., and Roth, M. G. 1974. Grain Dryer Simulation. Research Report 224. Agr. Exp. Sta., Mich. State Univ.: East Lansing, MI.

Bakker-Arkema, F. W., Sokhansanj, S., and Farmer, D. M. 1975. Heat pipes for saving energy in grain drying. ASAE Paper No. 75-3516. Am. Soc. Agr. Engr.: St. Joseph, MI.

Baughman, G. R., Barre, H. J., and Hamdy, M. Y. 1971. Experimental study and simulation of concurrent flow dryers. ASAE Paper No. 71-319. Am. Soc. Agr. Engr.: St. Joseph, MI.

Bellman, R. 1957. Dynamic Programming. Princeton Univ. Press: Princeton, NJ.

Bern, C. J., and Charity, L. F. 1975. Airflow resistance characteristics of corn as influenced by bulk density. ASAE Paper No. 75-3510. Am. Soc. Agr. Engr.: St. Joseph, MI.

Bjarnason, J., and Carpenter, K. J. 1969. Mechanisms of heat damage in proteins. Br. J. Nutr. 23:859-868.

Bloome, P. D. 1970. Simulation of low temperature drying of shelled corn leading to optimization. Unpublished Ph.D. Thesis. Univ. of Illinois: Urbana, IL.

Brake, J. R. 1976. Personal Communications. Agr. Econ. Dept., Mich. State Univ.: E. Lansing, MI.

Brook, R. C., and Bakker-Arkema, F. W. 1976. Batch and crossflow corn dryers: TELPLAN program. Special Research Report. Agr. Eng. Dept., Mich. State Univ.: East Lansing, MI.

Brooker, D. B., Bakker-Arkema, F. W., and Hall, C. W. 1974. Drying Cereal Grains. AVI: Westport, CT.

Carrano, J. A., Bickert, W. G., and Bakker-Arkema, F. W. 1971. Design and testing of a laboratory scale concurrent-counterflow high temperature corn dryer. ASAE Paper No. 71-320. Am. Soc. Agr. Eng.: St. Joseph, MI.

Carver, M. B. 1976. The choice of algorithms in automated method of lines solution of partial differential equations. In: Numerical Methods for Differential Systems, ed. by L. Lapidus and W. E. Schiesser. Academic Press, New York, NY.

Chu, S. T., and Hustrulid, A. 1968. Numerical solution of the diffusion equation. Trans. ASAE 11:705-710, 715.

Crank, J. 1957. The Mathematics of Diffusion. Clarendon Press: Oxford, England.

Dexter, S. T., Anderson, A. L., Pfahler, P. L., and Benne, E. J. 1955. Response of white pea beans to various humidities and temperature of storage. Agronomy J. 47:246-250.

Ekstrom, G. A., Liljedahl, J. B., and Peart, R. M. 1966. Thermal expansion and tensile properties of corn kernels and their relationship to cracking during drying. Trans. ASAE 9:556-561.

Evans, W. E. 1970. Simulation of counterflow drying. Unpublished M.S. Thesis. Mich. State Univ.: East Lansing, MI.

Farmer, D. M. 1972. Optimization techniques for grain dryer design and analysis. Unpublished Ph.D. Thesis, Mich. State Univ.: East Lansing, MI.

Farmer, D. M., and Bakker-Arkema, F. W. 1971. Sensitivity studies of minimum cost--high quality stationary bed corn drying. ASAE Paper No. 71-818. Am. Soc. Agr. Eng.: St. Joseph, MI.

Farmer, D. M., Bakker-Arkema, F. W., DeBoer, S. F., and Roth, M. G. 1972. Simulation and optimal design of a commercial concurrent-counterflow grain dryer--The Anderson model. ASAE Paper No. 72-847. Am. Soc. Agr. Eng.: St. Joseph, MI.

Foster, G. H. 1973. Heated air drying and corn quality. In: Preservation of Wet Harvested Grains, ed. by J. L. Multon and A. Guilbot. Inst. Nut. Recherche Agronomique: Paris, France.

Freeman, J. E. 1973. Quality factors affecting value of corn for wet milling. Trans. ASAE 16:671-678.

French, D. 1973. Chemical and physical properties of starch. J. of Anim. Sci. 37:1048-1061.

Gilmour, P. 1971. Development of a dynamic simulation model for planning physical distribution systems: Validation. Ph.D. Thesis, Mich. State. Univ.: East Lansing, MI.

Graham, D. L. 1970. Concurrent-flow grain dryer design study and proposal. Special Report M. & W. Gear Co.: Gibson City, IL.

Gustafson, R. J., and Hall, G. E. 1972. Density and porosity changes of shelled corn during drying. Trans ASAE 15:523-526.

Gygax, R. A., Diaz, A., and Bakker-Arkema, F. W. 1974. Comparison of commercial crossflow and concurrent flow dryers with respect to grain damage. ASAE Paper No. 74-3021. Am. Soc. Agr. Eng.: St. Joseph, MI.

Hall, C. W., and Maddex, R. L. 1952. A recirculating drier for drying pea beans with heated air. Mich. Agr. Exp. Sta. Quart. Bull. 35:83-86. Mich. State Univ.: East Lansing, MI.

Hammerle, J. R., White, R. K., and Mohsenin, N. N. 1971. The rheological properties of corn horny endosperm. Cereal Science Today 16:60-68, 72.

Haque, E., Foster, G. H., Chung, D. S., and Lai, F. S. 1976. Static pressure drop across a corn bed mixed with fines. ASAE Paper No. 76-3523. Am. Soc. Agr. Engr.: St. Joseph, MI.

Henderson, S. M. 1943. Resistance of shelled corn and bin walls to airflow. Agric. Eng. J. 24:267-269, 274.

Hill, L. D. 1970. Adjustments in Drying and Storage Capacity at Farm and Elevator. AERR 105. Agr. Exp. Sta., Univ. of Ill.: Urbana, IL.

Hill, L. D., and Scott, J. T., Jr. 1969. Trends in Harvesting, Conditioning, and Storing Illinois Corn. Research Report AERR 93. Ill. Agr. Exp. Sta., Univ. of Ill.: Urbana, IL.

Himmelblau, D. M. 1970. Process Analysis by Statistical Methods. John Wiley: New York, NY.

Hines, C. A. et al. 1976. Michigan Agricultural Statistics. Mich. Dept. Agr.: Lansing, MI.

Holman, J. P. 1976. Heat Transfer. 4th ed. McGraw-Hill: New York, NY.

Ingram, G. W. 1976. Deep bed dryer simulation with intra-particle moisture diffusion. J. Agr. Eng. Res. 21:263-272.

Johnson, H. K. 1973. Opportunities to conserve energy in dryer design. Presented at Energy for Agriculture Conference. Purdue Univ.: West Lafayette, IN.

Katic, Z. 1973. Maiskornbeschaligung bei kunstlicher Trocknung. Mühle und Mischfuttertechnik 110:534-539.

Katic, Z. 1975. Drying of different corn varieties and hybrids. Mühle und Mischfuttertechnik 112:561-568.

Kazarian, E. A., and Hall, C. W. 1965. Thermal properties of grain. Trans. ASAE 8:33-37, 48.

Kenyon, E., Hines, C. A., and Pscodna, S. J. 1976. Michigan Corn Harvesting and Marketing Statistics, 1975. Mich. Crop Rpt. Serv.: Lansing, MI.

Kreyger, J. 1972. Drying and Storing Grains, Seeds and Pulses in Temperate Climates. Institute for Storage and Processing of Agricultural Produce: Wageningen, Netherlands.

Lai, F. S., and Foster, G. H. 1975. Improvement in grain dryer fuel efficiency through heat recovery. ASAE Paper No. 75-3517. Am. Soc. Agr. Engr.: St. Joseph, MI.

Larson, R. E. 1968. State Increment Dynamic Programming. Am. Elsevier: New York.

Lasseran, J. C., and Boignesville, E. 1973. Incidence of drying and storage conditions of corn on its quality for the starch industry. Stärke 25:257-262.

Maddex, R. L. 1977. Personal communication. Agr. Eng. Dept., Mich. State Univ.: East Lansing, MI.

Matthies, H. J. 1956. Der stromungswiderstand beim beluften landwirtschaftlichen Ernteguter. VDI-Forschungheft 456: Dusseldorf, Germany.

Matthies, H. J., and Peterson, H. 1974. New data for calculating the resistance to airflow of stored granular materials. Trans. ASAE 17:1144-1148.

McAdams, W. H. 1954. Heat Transmission. McGraw-Hill: New York, NY.

McGinty, R. J. 1970. Development of a standard grain breakage test. ARS 51-34. USDA: Washington, D.C.

McKenzie, B. A., Foster, G. H., Noyes, R. T., and Thompson, R. A. 1972. Dryeration--Bettern Corn Quality with High Speed Drying. Bull. AE-72. Coop. Ext. Serv., Purdue Univ.: West Lafayette, IN.

Meeter, D. A., and Wolfe, P. S. 1965. Non-linear least squares (GAUSHAUS). Program Documentation 00000087. Computer Lab., Mich. State Univ.: East Lansing, MI.

Mensah, J. K., Herum, F. L., Blaisdell, J. L., and Stevens, K. K. 1976. Impact fracture resistance of selected corn varieties due to drying conditions. ASAE Paper No. 76-3042. Am. Soc. Agr. Eng.: St. Joseph, MI.

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

Morey, R. V., and Peart, R. M. 1971. Optimum horsepower and depth for a natural air corn drying system. Trans. ASAE 14:930-934.

Morey, R. V., Cloud, H. A., and Lueschen, W. E. 1976. Practices for the efficient utilization of energy for drying corn. Trans. ASAE 19:151-155.

Mühlbauer, W., Scheuiemann, A., and Bliemel, K. 1971. Drying of corn in a concurrentflow dryer at high air temperatures. Grundl Landtech. 21(1)1-5.

Mühlbauer, W., and Christ, W. 1974. Die zulässige Einwirkungszeit verschiedner Korntemperaturen bie der Trocknung von Mais für die tierische Ernährung. Grundl. Landtechnik 24:161-164.

Mühlbauer, W., and Isaacs, G. W. 1975. Wärmerückgewinnung bei Körnerfruchttrocknungsanlagen. Landtechnik 11:3160-3165.

Mühlbauer, W., Huss, W., and Kuppinger, H. 1976. Farbmetrisshe Schnellmethode zum Erkennen einer Proteinschädigung bei der Trocknung von Maiskörnern mit hohen Lufttemperaturen. Grundl. Landtechnik 26:128-134.

Narayan, C. V. 1969. Mechanical checking of navy beans. Unpublished Ph.D. Thesis. Mich. State Univ.: East Lansing, MI.

Ngoddy, P. O., Bakker-Arkema, F. W., and Bickert, W. G. 1966. Heat transfer in a deep bed of peabeans. Quart. Bull. Mich. Agr. Exp. Station 49:132-143.

Othmer, D. F. 1940. Correlating vapor pressure and latent heat data. Ind. Eng. Chem. 32:841-846.

Overhults, D. G., White, G. M., Hamilton, H. E., Ross, I. J., and Fox, J. D. 1975. Effect of heated air drying on soybean oil quality. Trans. ASAE 18:942-945.

Pabis, S., and Henderson, S. M. 1961. Grain Drying Theory. II. A critical analysis of the drying curve of shelled maize. J. Agr. Eng. Res. 6:272-277.

Patterson, R. J., Bakker-Arkema, F. W., and Bickert, W. G. 1971. Static pressure--airflow relationships in packed beds of granular biological materials such as grain. II. Trans. ASAE :172-174, 178.

Paulsen, M. R., and Hill, L. D. 1976. Corn beakage in overseas shipments--Two case studies. ASAE Paper No. 76-3029. Am. Soc. Agr. Eng.: St. Joseph, MI.

Peplinski, A. J. et al. 1975. Corn quality as influenced by harvest and drying conditions. Cereal Foods World 20:145-149, 154.

Perry, J. S. 1959. Mechanical damage to pea beans as affected by moisture, temperature, and impact loading. Unpublished Ph.D. Thesis. Mich. State Univ.: East Lansing, MI.

Perry, J. H. et al. 1963. Chemical Engineers Handbook. 4th ed. McGraw-Hill: New York, NY.

Pfost, H. B., Maurer, S. G., Chung, D. S., and Milliken, G. A. 1976. Summarizing and reporting equilibrium moisture data for grains. ASAE Paper No. 76-3520. Am. Soc. Agr. Eng.: St. Joseph, MI.

Raznjevic', K. 1976. Handbook of Thermodynamic Tables and Charts. Hemisphere Pub.: Washington, D.C.

Riggs, J. L. 1977. Engineering Economics. McGraw Hill: New York, NY.

Rodriguez-Arias, J. H. 1956. Description isotherms and drying rates of shelled corn in the temperature range of 40° to 140°F. Unpublished Ph.D. Thesis. Mich. State Univ.: East Lansing, MI.

Rodriguez-Arias, J. H., Hall, C. W., and Bakker-Arkema, F. W. 1963. Heat of vaporization for shelled corn. Cer. Chem. 40:676-683.

Roth, M. G. 1977. Personal communication. Mich. State Univ.: East Lansing, MI.

Rugumayo, E. 1976. Personal communication. Mich. State Univ.: East Lansing, MI.

Sabbah, M. 1971. Convective heat transfer and tempering effects on cooling rate of shelled corn. Unpublished Ph.D. Thesis. Purdue Univ.: West Lafayette, IN.

Sabbah, M. A., Foster, G. H., Haugh, C. G., and Peart, R. M. 1972. Effect of tempering after drying on cooling shelled corn. Trans. ASAE 15:763-765.

Sabbah, M., Meyer, G. E., Keener, H. M., and Roller, W. L. 1976. Reversed-air drying for fixed bed of soybean seed. ASAE Paper No. 76-3023. Am. Soc. Agr. Eng.: St. Joseph, MI.

Schroeder, M. E., and Peart, R. M. 1967. Dynamic programming method for air allocation in a grain dryer. Trans. ASAE 10:96-99.

Shedd, C. K. 1953. Resistance of grains and seeds to air flow. Agr. Eng. 34:616-619.

Stephens, L. E., and Foster, G. H. 1976. Breakage tester predicts handling damage in corn. ARS-NC-49, USDA: Washington, D.C.

Streeter, V. L. 1971. Fluid Mechanics. McGraw Hill: New York, NY.

Sullivan, J. E. et al. 1975. The effect of heat on the nutritional value of corn. In: Corn Quality in World Markets, ed. by L. D. Hill, pp. 45-63. Interstate Printers and Publishers: Danville, IL.

Thompson, R. A., and Foster, G. H. 1963. Stress cracks and breakage in artificially dried corn. Market Research Report 631, USDA: Washington, D.C.

Thompson, T. L. 1967. Predicted performances and optimal designs of covection grain dryers. Unpublished Ph.D. Thesis. Purdue Univ.: West Lafayette, IN.

Thompson, T. L., Foster, G. H., and Peart, R. M. 1969. Comparison of concurrent-flow, crossflow and counterflow grain drying methods. Market Research Report 841. USDA: Washington, D.C.

Thygeson, J. R., and Grossmann, E. D. 1970. Optimization of a continuous through-circulation dryer. AIChE Journal 16:749-754.

USDA. 1969. United States Standards for Beans. USDA: Washington, D.C.

Vojovich, C., Anderson, R. A., and Griffin, E. L. 1975. Wet-milling properties of corn after field shelling and artificial drying. Cereal Foods World 20:333-335.

Walker, R. J., and Barre, H. J. 1972. The effect of drying on soybean germination and crackage. ASAE Paper No. 72-817. Am. Soc. Agr. Eng.: St. Joseph, MI.

Wall, J. S., James, C., and Donaldson, G. L. 1975. Corn proteins: Chemical and physical changes during drying of grain. Cereal Chem. 52:779-790.

Wang, J. 1956. Drying pea beans intermittently at 100°F. Unpublished M.S. Thesis. Mich. State Univ.: East Lansing, MI.

Westelaken, C. M. 1976. Personal communications. Westlake Agr. Eng.: St. Marys, Ontario, Canada.

White, G. M., and Ross, I. J. 1972. Discoloration and stress cracking in white corn as affected by drying temperature and cooling rate. Trans. ASAE 15:504-507.

Williamson, J. L. 1975. Nutritional requirements of livestock as related to corn quality. In: Corn Quality in World Markets, ed. by L. D. Hill, pp. 17-22. Interstate Printers and Publishers: Danville, IL.

Woods, D. R. 1975. Financial Decision Making in the Process Industry. Prentice-Hall: Englewood Cliffs, NJ.

Young, J. H., and Dickens, J. W. 1975. Evaluation of costs for drying grain in batch or crossflow systems. Trans. ASAE 18:734-739.

Young, J. H., and Whitaker, T. B. 1971. Numerical analysis of vapor diffusion in a porous composite sphere with concentric shells. Trans. ASAE 14:1051-1057.

Zoerb, G. C. 1958. Mechanical and rheological properties of grain. Unpublished Ph.D. Thesis. Mich. State Univ.: East Lansing, MI.